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Course Material

P.G. DIPLOMA (GIS AND REMOTE SENSING LAWS)

1.1.2. Remote Sensing Technology and Laws

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MODULE-I: INTRODUCTION TO REMOTE SENSING AND TECHNOLOGY

Introduction: The use of remote sensing perhaps goes all the way back to prehistoric times when early man stood on a platform in front of his cave and glanced at the surrounding landscape. These humans were remotely sensing the features in the landscape to determine the best places to gather food and water and how to avoid becoming a food for the other inhabitants of the landscape. The term "photography" is derived from two Greek words meaning "light" (phos) and "writing" (graphein). All cameras and sensors utilize the same concept of light entering a camera or a sensor and being recorded on a film or on a digital media.

The term remote sensing as used for Earth observation has experienced major changes since the 1960s. It was not until the 1960s that "remote sensing" moved beyond black and white aerial photography and began to evolve towards its usage today in the twenty-first century. The past 50 years have seen the development of remote sensing platforms for high-altitude aircraft and satellites and the development of imaging sensors for collecting data from various regions of the electromagnetic spectrum. In concert with these advances in image acquisition capabilities were the developments of image display and processing techniques and algorithms. With the increase in processing power, these image processing software have migrated from mainframe computers to desktops to handheld mobile smart devices.

Along with the advances in technology, there has been a rapid and growing social acceptance of remote sensing. At first, remote sensing was a concern to the public with the "eye in the sky" and "Big Brother" concept. This perception, however, has eroded to a very large extent (but may be returning). Today, a large variety of sensors are deployed on numerous satellites and airborne platforms that collect vast amounts of remotely sensed data around the globe and around the clock. These data of various characteristics in spectral, spatial, radiometric, and temporal resolutions are commonly utilized in the areas of environmental and natural resource management, climate change, disaster management, law enforcement, military, and military intelligence gathering. Remote sensing has permeated our daily lives through Google Earth; global positioning systems (GPS); weather forecasting, wildland fire, hurricane, and disaster management; precision agriculture; and natural resources inventory and monitoring. We cannot live without it.

A Brief History of Remote Sensing: According to the late John E. Estes and Jeff Hemphill, one can trace the history of photography to Leonardo da Vinci (1490) describing the light entering the dark room (obscura) through a pinhole on one of the walls of a dark room; Angelo Sala (1614) observing the darkening of silver salts when exposed to sunlight; Sir Isaac Newton (1666) experimenting with a prism; Johann Christopher Sturm (1676) discovering the lens; Sir William Herschel (1800) observing the visible colors and temperature; and Thomas Young (1802) describing the basic concepts of the Young-Von Helmholtz theory of color vision to the first photograph by Joseph Niépce in 1827.

The invention of photography helped to lay the groundwork for the field of remote sensing by enabling the near-instantaneous documentation of objects and events. The French inventor Joseph Niépce is generally credited with producing the first permanent photograph in 1827, which depicted the view from his upstairs workroom window

(Hirsch 2008). In 1839, it was announced that Louis Daguerre— who collaborated with Niépce until his death in 1833—had invented a process for creating a fixed silver image on a copper plate, called a daguerreotype. One of his daguerreotypes, "Boulevard du Temple, Paris", taken in 1838 or 1839, is reputedly the oldest surviving photograph of a person. The image appears to show an empty street, but this is an artifact; the long exposure of more than 10 minutes prevented the capture of moving carriage and pedestrian traffic. However, Daguerre was able to capture a man who stopped to have his shoes shined. Notably, Daguerre's "Boulevard Du Temple" image has many characteristics of what is now called an oblique aerial photograph (i.e., an aerial photograph captured from an angle rather than vertically, or directly overhead).

The potential cartographic applications of photography were recognized almost immediately. In 1840, François Arago, director of the French Académie des Sciences and the man who publicly announced Daguerre's process, advocated the use of photographs to produce topographic maps. Credit for the first actual aerial photograph is given to the French photographer Gaspar Felix Tournachon, who used the pseudonym "Nadar." Nadar patented the concept of using aerial photography for cartography and surveying in 1855, but experimented unsuccessfully until 1858, when he captured a photograph from a balloon tethered 80 m above the Bievre Valley (PAPA International 2011). None of Nadar's early efforts is believed to have survived. The oldest existing aerial photograph is a view of Boston, taken from a balloon by James Wallace Black in 1860.

During the latter part of the nineteenth and into the early twentieth century, a number of people experimented with the use of aerial photography from balloons, kites, and even birds as an effective means of mapmaking and surveying. In 1889, Canadian Dominion Lands Surveyor General E.G.D. Deville published Photographic Surveying, a seminal work that focused on balloon-based photography. French photographer Arthur Batut is usually credited with the first successful photograph from a kite, taken in 1887 or 1888, and published the first textbook on kite photography in 1890. In 1908, Julius Neubronner, a German apothecary and inventor, patented a breast-mounted aerial camera for carrier pigeons (PAPA International 2011). The lightweight camera took automatic exposures at 30-s intervals. Although faster than balloons, the pigeons did not always follow their expected flight paths. When the aerial photographs taken by the pigeons were introduced at the 1909 Dresden International Photographic Exhibition, postcards created from them became popular with the public (PAPA International 2011). Camera-equipped pigeons have also been used for military surveillance.

In 1880, George Eastman patented a machine for rapidly preparing a large number of "dry" photographic plates (i.e., glass plates coated with a gelatin emulsion). Searching for a lighter and less temperamental alternative to glass plates, he developed rolled paper film, but found that paper was not an ideal film base because the resulting photographs tended to be grainy and have inadequate contrast. Eastman addressed these limitations through the introduction of flexible celluloid film in 1887. In 1900, Eastman's company, Kodak, released the Brownie, an inexpensive box camera for rolled film, making photography accessible to a mass audience for the first time.

Eastman's innovations shortly preceded the Wright Brothers' first successful flight, in 1903, which took place in the shores of the Outer Banks of North Carolina. Photographic images of various kinds were followed. As an example is the oblique aerial photograph of the City of San Francisco in 1906 taken by a kite.

Five years later, Wilbur Wright took the first aerial photograph from an airplane (PAPA International 2011). Quickly embraced by military forces, airplane-based aerial photography was used extensively for reconnaissance during World War I. Near the end of the war, US entrepreneur Sherman Fairchild began to develop what became the first true aerial camera system.

In 1921, Fairchild demonstrated the utility of his system for cartography, employing more than 100 overlapping aerial images to create a photo-mosaic of New York City's Manhattan Island. During the period between World Wars I and II, aerial photography was also applied in other civilian contexts, including forestry, geology, and agriculture.

Aerial photography experienced dramatic refinement during World War II—a period that also saw the introduction of the first infrared-sensitive instruments and radar imaging systems. In fact, the basic elements of aerial photography as we know it today largely arose out of these wartime developments and related technological advances during the next two decades. False-color infrared film was first developed during World War II for camouflage detection, and by the 1950s, it was already being applied for air-photo-based mapping of vegetation. Live plants typically exhibit strong spectral reflectance in the near-infrared portion of the electromagnetic spectrum.

The Space Age was an era initiated by the Soviet Union's launch of the first man-made satellite, Sputnik-1, in 1957, from Baikonur Cosmodrome at Tyuratam (370 km southwest of the small town of Baikonur) in Kazakhstan, then part of the former Soviet Union. The Russian word "Sputnik" means "companion" ("satellite" in the astronomical sense).

The term "remote sensing" was coined in the mid-1950s by Evelyn Pruitt, a geographer with the US Office of Naval Research, allegedly because the term "aerial photography" did not sufficiently accommodate the notion of images from space. After the launch of Sputnik-1, the US and Soviet governments raced to design and implement new space-related technologies, including both manned spacecraft and satellites. While the first (and rather crude) satellite image of the Earth was captured by NASA's Explorer 6 in 1959, the US Department of Defense's CORONA (also known as "Discoverer") Reconnaissance Satellite Program, which remained classified until 1995, may be seen as a key forerunner to present-day Earth-observing satellite programs. During its period of operation (1958–1972), the CORONA Program developed an increasingly sophisticated series of high-resolution, film-based camera systems (Cloud 2001). The first photograph of the Soviet territory from space, taken in August 1960, shows an air base at Mys Shmidta, Siberia. Within a decade, CORONA satellites had extensively mapped the United States and other parts of the world. Before the CORONA program ended, its science team had begun to experiment with color (i.e., spectral) photography, thus serving as a precursor to the sensors used by the Landsat program and present-day satellite imaging systems.

In the 1960s and the early 1970s, the US and Soviet Union launched an assortment of reconnaissance, meteorological, and communications satellites into the orbit. Also during this period, astronauts from NASA's Mercury, Gemini, and Apollo space missions took thousands of photographs of the Earth using handheld and automated cameras. The "Blue Marble," a photograph taken in December 1972 by the crew of Apollo 17, is often cited as the most widely reproduced image of the Earth. In 2002, NASA released a new version of the "Blue Marble," a mosaic of images from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the Earth Observing System (EOS) Terra satellite.

A more formative event for modern remote sensing occurred in July 1972, when NASA launched ERTS-A (Earth Resources Technology Satellite—Mission A), the first satellite dedicated to monitoring environmental conditions on the Earth's surface. Shortly after its launch, the satellite's name was changed to ERTS-1. It was followed by ERTS-2 (launched in January 1975) and ERTS-3 (launched in March 1978). Later, the names for these satellites were changed to Landsat-1, -2, and - 3, respectively. The Landsat Program (along with a few other US satellite programs) served as the primary source of space-based Earth imagery until the 1980s, when a number of other countries began to develop their own Earth-observing satellite programs, particularly France and the European Union, Canada, Japan, India, Russia, China, and Brazil. More recently, a number of private companies have emerged as providers of satellite imagery, demonstrating the feasibility of commercial, space-based remote sensing.

The European Space Agency (ESA) estimates that between the 1957 launch of Sputnik and January 1, 2008, approximately 5600 satellites were launched into the Earth's orbit. The vast majority of these are no longer in service, raising concerns and the formation of an international committee regarding the high volume of space debris encircling the planet. Today, just fewer than 1000 operational satellites are orbiting the Earth, approximately 9% of which are dedicated to Earth observation and remote sensing (plus roughly 4 % for meteorology and related applications). These satellites, carrying a wide range of sensors optimized for various applications, represent a rich potential source of data for remote sensing analysts. Furthermore, they also extend the nearly four-decade-old satellite image record started by Landsat-1.

What Is Remote Sensing, and Why Do It? Today, the field of remote sensing is a well-recognized interdisciplinary field across the globe. This field is often coupled with the disciplines of image processing (IP), geographic information systems (GIS), and GPS to create the broad field of geospatial science and technologies.

Remote sensing is defined as the acquisition and measurement of information about certain properties of phenomena, objects, or materials by a recording device not in physical contact with the features under surveillance. This is a rather broad definition that encompasses, for instance, medical technologies such as X- rays and magnetic resonance imaging. In an environmental context, remote sensing typically refers to technologies for recording electromagnetic energy that emanates from areas or objects on (or in) the Earth's land surface, oceans, or atmosphere. Essentially, the properties of these objects or areas, in terms of their associated levels of electromagnetic energy, provide a way to identify, delineate, and distinguish between them. Because the electromagnetic energies of these features are commonly collected by instruments mounted on aircraft or Earth-orbiting spacecraft, remote sensing also gives scientists the opportunity to capture large geographic areas with a single observation or scene.

Another potential advantage of remote sensing, especially when done from satellites, is that geographic areas of interest can be revisited on a regular cycle, facilitating the acquisition of data to reveal changing conditions over time. For a given instrument, or sensor, onboard a satellite, the revisit time depends on the satellite's orbit and the navigational speed as well as the width of the sensor's swath, which is the track the sensor observes as the satellite travels around the Earth. Remotely sensed data are geospatial in nature, meaning that the observed areas and objects are referenced according to their location in a geographic coordinate system, such that they may be located on a map. This allows the remotely sensed data to be analyzed in conjunction with other geospatial data sets, such as data depicting road networks or human population density. Remotely sensed data with sufficient detail can be used to characterize such things as the growth or health status of vegetation, or to identify habitat edges or ecotones (i.e., transition zones between ecological communities) that could not otherwise be discerned effectively from maps created from field observations.

This point illustrates the unique importance of remote sensing as a data source for GIS, which are organized collections of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, and analyze all forms of geographically referenced information. In turn, *geographic information science (geomatics or geoinformatics)* is concerned with conceptual and scientific issues that arise from the use of GIS, or more broadly, with various forms of geographic information. Ultimately, the value of a GIS depends upon the quality of the data it contains. Because remote sensing serves as the primary source of GIS data, it is important for users to understand how these data are generated so they can evaluate subsequent geospatial analyses more critically.

Process in Remote Sensing: In much of remote sensing, the process involves an interaction between incident radiation and the targets of interest. This is exemplified by the use of imaging systems where the following seven elements are involved. Note, however that remote sensing also involves the sensing of emitted energy and the use of non-imaging sensors.

1. ***Energy Source or Illumination (A)*** - the first requirement for remote sensing is to have an energy source which illuminates or provides electromagnetic energy to the target of interest.

2. ***Radiation and the Atmosphere (B)*** - as the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes through. This interaction may take place a second time as the energy travels from the target to the sensor.

3. ***Interaction with the Target (C)*** - once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation.

Fig: An illustration of the remote sensing concept: An instrument (i.e., sensor or scanner) mounted on an aircraft or satellite records information about objects and/or areas on the ground. Typically, these data are spectral in nature, meaning that they document the amount of electro- magnetic energy associated with the targeted objects and/or areas. The extent, or footprint, of the geographic area captured in a single-sensor scene depends on the sensor's design and the altitude of the aircraft or spacecraft on which it is mounted.

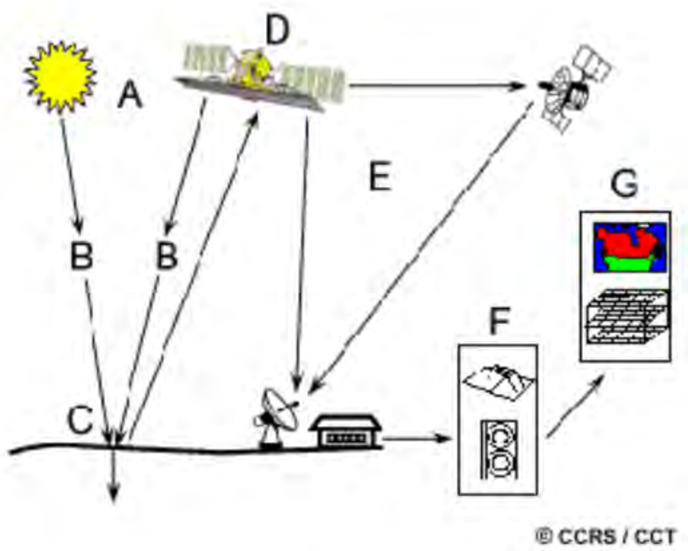
4. ***Recording of Energy by the Sensor (D)*** - after the energy has been scattered by, or emitted from the target, we require a sensor (remote - not in contact with the target) to collect and record the electromagnetic radiation.

5. ***Transmission, Reception, and Processing (E)*** - the energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image (hardcopy and/or digital).

6. ***Interpretation and Analysis (F)*** - the processed image is interpreted, visually and/or digitally or electronically, to extract information about the target which was illuminated.

7. ***Application (G)*** - the final element of the remote sensing process is achieved when we apply the information we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem.

These seven elements comprise the remote sensing process from beginning to end.



Electromagnetic Radiation:

As was noted in the previous section, the first requirement for remote sensing is to have an energy source to illuminate the target (unless the sensed energy is being emitted by the target). This energy is in the form of electromagnetic radiation.

All electromagnetic radiation has fundamental properties and behaves in predictable ways according to the basics of wave theory. Electromagnetic radiation consists of an electrical field(E) which varies in magnitude in a direction perpendicular to the direction in which the radiation is traveling, and a magnetic field (M) oriented at right angles to the electrical field. Both these fields travel at the speed of light (c).

Two characteristics of electromagnetic radiation are particularly important for understanding remote sensing. These are the wavelength and frequency.

The wavelength is the length of one wave cycle, which can be measured as the distance between successive wave crests. Wavelength is usually represented by the Greek letter lambda (λ). Wavelength is measured in metres (m) or some factor of metres such as nanometres (nm, 10^{-9} metres), micrometres (μm, 10^{-6} metres) (μm, 10^{-6} metres) or centimetres (cm, 10^{-2} metres). Frequency refers to the number of cycles of a wave passing a fixed point per unit of time. Frequency is normally measured in hertz (Hz), equivalent to one cycle per second, and various multiples of hertz.

Wavelength and frequency are related by the following formula:

$$c = \lambda \cdot \nu.$$

Where: λ is the wavelength (m), ν is the frequency (cycles per second, Hz), and c is the speed of light (which is constant at 3×10^8 m/s in a vacuum).

Therefore, the two are inversely related to each other. The shorter the wavelength, the higher the frequency. The longer the wavelength, the lower the frequency. Understanding the characteristics of electromagnetic radiation in terms of their wavelength and frequency is crucial to understanding the information to be extracted from remote sensing data. Next we will be examining the way in which we categorize electromagnetic radiation for just that purpose.

The Electromagnetic Spectrum:

The electromagnetic spectrum ranges from the shorter wavelengths (including gamma and x-rays) to the longer wavelengths (including microwaves and broadcast radio waves). There are several regions of the electromagnetic spectrum which are useful for remote sensing.

For most purposes, the ultraviolet or UV portion of the spectrum has the shortest wavelengths which are practical for remote sensing. This radiation is just beyond the violet portion of the visible wavelengths, hence its name. Some Earth surface materials, primarily rocks and minerals, fluoresce or emit visible light when illuminated by UV radiation.

The light which our eyes - our "remote sensors" - can detect is part of the visible spectrum. It is important to recognize how small the visible portion is relative to the rest of the spectrum. There is a lot of radiation around us which is "invisible" to our eyes, but can be detected by other remote sensing instruments and used to our advantage. The visible wavelengths cover a range from approximately 0.4 to 0.7 μm. The longest visible wavelength is red and the shortest is violet. Common wavelengths of what we perceive as particular colours from the visible portion of the spectrum are listed below. It is important to note that this is the only portion of the spectrum we can associate with the concept of colours.

- Violet: 0.4 - 0.446 μm
- Blue: 0.446 - 0.500 μm
- Green: 0.500 - 0.578 μm
- Yellow: 0.578 - 0.592 μm
- Orange: 0.592 - 0.620 μm
- Red: 0.620 - 0.7 μm

Blue, green, and red are the primary colours or wavelengths of the visible spectrum. They are defined as such because no single primary colour can be created from the other two, but all other colours can be formed by combining blue, green, and red in various proportions. Although we see sunlight as a uniform or homogeneous colour, it is actually composed of various wavelengths of radiation in primarily the ultraviolet, visible and infrared portions of the spectrum. The visible portion of this radiation can be shown in its component colours when sunlight is passed through a prism, which bends the light in differing amounts according to wavelength.

The next portion of the spectrum of interest is the infrared (IR) region which covers the wavelength range from approximately 0.7 μm to 100 μm - more than 100 times as wide as the visible portion! The infrared region can be divided into two categories based on their radiation properties - the reflected IR, and the emitted or thermal IR. Radiation in the reflected IR region is used for remote sensing purposes in ways very similar to radiation in the visible portion. The reflected IR covers wavelengths from approximately 0.7 μm to 3.0 μm. The thermal IR region is quite different than the visible and reflected IR portions, as this energy is essentially the radiation that is emitted from the Earth's surface in the form of heat. The thermal IR covers wavelengths from approximately 3.0 μm to 100 μm.

The portion of the spectrum of more recent interest to remote sensing is the microwave region from about 1 mm to 1 m. This covers the longest wavelengths used for remote sensing. The shorter wavelengths have properties similar to the thermal infrared region while the longer wavelengths approach the wavelengths used for radio broadcasts.

Interactions with the Atmosphere: Before radiation used for remote sensing reaches the Earth's surface it has to travel through some distance of the Earth's atmosphere. Particles and gases in the atmosphere can affect the incoming light and radiation. These effects are caused by the mechanisms of **scattering and absorption.**

Scattering occurs when particles or large gas molecules present in the atmosphere interact with and cause the electromagnetic radiation to be redirected from its original path. How much scattering takes place depends on several factors including the wavelength of the radiation, the abundance of particles or gases, and the distance the radiation travels through the atmosphere. There are three (3) types of scattering which take place. They are -

Rayleigh scattering occurs when particles are very small compared to the wavelength of the radiation. These could be particles such as small specks of dust or nitrogen and oxygen molecules. Rayleigh scattering causes shorter wavelengths of energy to be scattered much more than longer wavelengths. Rayleigh scattering is the dominant scattering mechanism in the upper atmosphere. The fact that the sky appears "blue" during the day is because of this phenomenon. As sunlight passes through the atmosphere, the shorter wavelengths (i.e. blue) of the visible spectrum are scattered more than the other (longer) visible wavelengths. At sunrise and sunset the light has to travel farther through the atmosphere than at midday and the scattering of the shorter wavelengths is more complete; this leaves a greater proportion of the longer wavelengths to penetrate the atmosphere.

Mie scattering occurs when the particles are just about the same size as the wavelength of the radiation. Dust, pollen, smoke and water vapour are common causes of Mie scattering which tends to affect longer wavelengths than those affected by Rayleigh scattering. Mie scattering occurs mostly in the lower portions of the atmosphere where larger particles are more abundant, and dominates when cloud conditions are overcast.

The final scattering mechanism of importance is called **nonselective scattering**. This occurs when the particles are much larger than the wavelength of the radiation. Water droplets and large dust particles can cause this type of scattering. Nonselective scattering gets its name from the fact that all wavelengths are scattered about equally. This type of scattering causes fog and clouds to appear white to our eyes because blue, green, and red light are all scattered in approximately equal quantities (blue+green+red light = white light).

Absorption is the other main mechanism at work when electromagnetic radiation interacts with the atmosphere. In contrast to scattering, this phenomenon causes molecules in the atmosphere to absorb energy at various wavelengths. Ozone, carbon dioxide, and water vapour are the three main atmospheric constituents which absorb radiation.

Ozone serves to absorb the harmful (to most living things) ultraviolet radiation from the sun. Without this protective layer in the atmosphere our skin would burn when exposed to sunlight.

You may have heard **carbon dioxide** referred to as a greenhouse gas. This is because it tends to absorb radiation strongly in the far infrared portion of the spectrum - that area associated with thermal heating - which serves to trap this heat inside the atmosphere. Water vapour in the atmosphere absorbs much of the incoming longwave infrared and shortwave microwave radiation (between 22µm and 1m). The presence of water vapour in the lower atmosphere varies greatly from location to location and at different times of the year. For example, the air mass above a desert would have very little water vapour to absorb energy, while the tropics would have high concentrations of water vapour (i.e. high humidity).

Because these gases absorb electromagnetic energy in very specific regions of the spectrum, they influence where (in the spectrum) we can "look" for remote sensing purposes. Those areas of the spectrum which are not severely influenced by atmospheric absorption and thus, are useful to remote sensors, are called **atmospheric windows**. By comparing the characteristics of the two most common energy/radiation sources (the sun and the earth) with the atmospheric windows available to us, we can define those wavelengths that we can use most effectively for remote sensing. The visible portion of the spectrum, to which our eyes are most sensitive, corresponds to both an atmospheric window and the peak energy level of the sun. Note also that heat energy emitted by the Earth corresponds to a window around 10 μm in the thermal IR portion of the spectrum, while the large window at wavelengths beyond 1 mm is associated with the microwave region.

Now that we understand how electromagnetic energy makes its journey from its source to the surface (and it is a difficult journey, as you can see) we will next examine what happens to that radiation when it does arrive at the Earth's surface.

Radiation - Target Interactions: Radiation that is not absorbed or scattered in the atmosphere can reach and interact with the Earth's surface. There are three (3) forms of interaction that can take place when energy strikes, or is incident (I) upon the surface. These are: absorption (A); transmission (T); and reflection (R). The total incident energy will interact with the surface in one or more of these three ways. The proportions of each will depend on the wavelength of the energy and the material and condition of the feature.

Absorption (A) occurs when radiation (energy) is absorbed into the target while transmission (T) occurs when radiation passes through a target. Reflection (R) occurs when radiation "bounces" off the target and is redirected. In remote sensing, we are most interested in measuring the radiation reflected from targets. We refer to two types of reflection, which represent the two extreme ends of the way in which energy is reflected from a target: **specular reflection** and **diffuse reflection**.

When a surface is smooth we get **specular** or mirror-like reflection where all (or almost all) of the energy is directed away from the surface in a single direction. **Diffuse** reflection occurs when the surface is rough and the energy is reflected almost uniformly in all directions. Most earth surface features lie somewhere between perfectly specular or perfectly diffuse reflectors. Whether a particular target reflects specularly or diffusely, or somewhere in between, depends on the surface roughness of the feature in comparison to the wavelength of the incoming radiation. If the wavelengths are much smaller than the surface variations or the particle sizes that make up the surface, diffuse reflection will dominate. For example, fine- grained sand would appear fairly smooth to long wavelength microwaves but would appear quite rough to the visible wavelengths.

Let's take a look at a couple of examples of targets at the Earth's surface and how energy at the visible and infrared wavelengths interacts with them.

Leaves: A chemical compound in leaves called chlorophyll strongly absorbs radiation in the red and blue wavelengths but reflects green wavelengths. Leaves appear "greenest" to us in the summer, when chlorophyll content is at its maximum. In autumn, there is less chlorophyll in the leaves, so there is less absorption and proportionately more reflection of the red wavelengths, making the leaves appear red or yellow (yellow is a combination of red and green wavelengths). The internal structure of healthy leaves act as excellent diffuse reflectors of near-infrared wavelengths. If our eyes were sensitive to near-infrared, trees would appear extremely bright to us at these wavelengths. In fact, measuring and monitoring the near-IR reflectance is one way that scientists can determine how healthy (or unhealthy) vegetation may be.

Water: Longer wavelength visible and near infrared radiation is absorbed more by water than shorter visible wavelengths. Thus water typically looks blue or blue-green due to stronger reflectance at these shorter wavelengths, and darker if viewed at red or near infrared wavelengths. If there is suspended sediment present in the upper layers of the water body, then this will allow better reflectivity and a brighter appearance of the water. The apparent colour of the water will show a slight shift to longer wavelengths. Suspended sediment (S) can be easily confused with shallow (but clear) water, since these two phenomena appear very similar. Chlorophyll in algae absorbs more of the blue wavelengths and reflects the green, making the water appear more green in colour when algae is present. The topography of the water surface (rough, smooth, floating materials, etc.) can also lead to complications for water-related interpretation due to potential problems of specular reflection and other influences on colour and brightness.

We can see from these examples that, depending on the complex make-up of the target that is being looked at, and the wavelengths of radiation involved, we can observe very different responses to the mechanisms of absorption, transmission, and reflection. By measuring the energy that is reflected (or emitted) by targets on the Earth's surface over a variety of different wavelengths, we can build up a **spectral response** for that object. By comparing the response patterns of different features we may be able to distinguish between them, where we might not be able to, if we only compared them at one wavelength. For example, water and vegetation may reflect somewhat similarly in the visible wavelengths but are almost always separable in the infrared. Spectral response can be quite variable, even for the same target type, and can also vary with time (e.g. "green-ness" of leaves) and location. Knowing where to "look" spectrally and understanding the factors which influence the spectral response of the features of interest are critical to correctly interpreting the interaction of electromagnetic radiation with the surface.

Passive vs. Active Sensing: So far, throughout this chapter, we have made various references to the sun as a source of energy or radiation. The sun provides a very convenient source of energy for remote sensing. The sun's energy is either **reflected**, as it is for visible wavelengths, or absorbed and then **re-emitted**, as it is for thermal infrared wavelengths. Remote sensing systems which measure energy that is naturally available are called **passive sensors**. Passive sensors can only be used to detect energy when the naturally occurring energy is available. For all reflected energy, this can only take place during the time when the sun is illuminating the Earth. There is no reflected energy available from the sun at night. Energy that is naturally emitted (such as thermal infrared) can be detected day or night, as long as the amount of energy is large enough to be recorded.

Active sensors, on the other hand, provide their own energy source for illumination. The sensor emits radiation which is directed toward the target to be investigated. The radiation reflected from that target is detected and measured by the sensor. Advantages for active sensors include the ability to obtain measurements anytime, regardless of the time of day or season. Active sensors can be used for examining wavelengths that are not sufficiently provided by the sun, such as microwaves, or to better control the way a target is illuminated. However, active systems require the generation of a fairly large amount of energy to adequately illuminate targets. Some examples of active sensors are a laser fluorosensor and a synthetic aperture radar (SAR).

Characteristics of Images: Before we go on to the next chapter, which looks in more detail at sensors and their characteristics, we need to define and understand a few fundamental terms and concepts associated with remote sensing images.

Electromagnetic energy may be detected either photographically or electronically. The photographic process uses chemical reactions on the surface of light-sensitive film to detect and record energy variations. It is important to distinguish between the terms **images** and **photographs** in remote sensing. An image refers to any pictorial representation, regardless of what wavelengths or remote sensing device has been used to detect and record the electromagnetic energy. A **photograph** refers specifically to images that have been detected as well as recorded on photographic film. The black and white photo to the left, of part of the city of Ottawa, Canada was taken in the visible part of the spectrum. Photos are normally recorded over the wavelength range from 0.3 μm to 0.9 μm - the visible and reflected infrared. Based on these definitions, we can say that all photographs are images, but not all images are photographs. Therefore, unless we are talking specifically about an image recorded photographically, we use the term image.

A photograph could also be represented and displayed in a **digital** format by subdividing the image into small equal-sized and shaped areas, called picture elements or **pixels**, and representing the brightness of each area with a numeric value or **digital number**. Indeed, that is exactly what has been done to the photo to the left. In fact, using the definitions we have just discussed, this is actually a **digital image** of the original photograph! The photograph was scanned and subdivided into pixels with each pixel assigned a digital number representing its relative brightness. The computer displays each digital value as different brightness levels. Sensors that record electromagnetic energy, electronically record the energy as an array of numbers in digital format right from the start. These two different ways of representing and displaying remote sensing data, either pictorially or digitally, are interchangeable as they convey the same information (although some detail may be lost when converting back and forth).

In previous sections we described the visible portion of the spectrum and the concept of colours. We see colour because our eyes detect the entire visible range of wavelengths and our brains process the information into separate colours. Can you imagine what the world would look like if we could only see very narrow ranges of wavelengths or colours? That is how many sensors work. The information from a narrow wavelength range is gathered and stored in a **channel**, also sometimes referred to as a **band.** We can combine and display channels of information digitally using the three primary colours (blue, green, and red). The data from each channel is represented as one of the primary colours and, depending on the relative brightness (i.e. the digital value) of each pixel in each channel, the primary colours combine in different proportions to represent different colours.

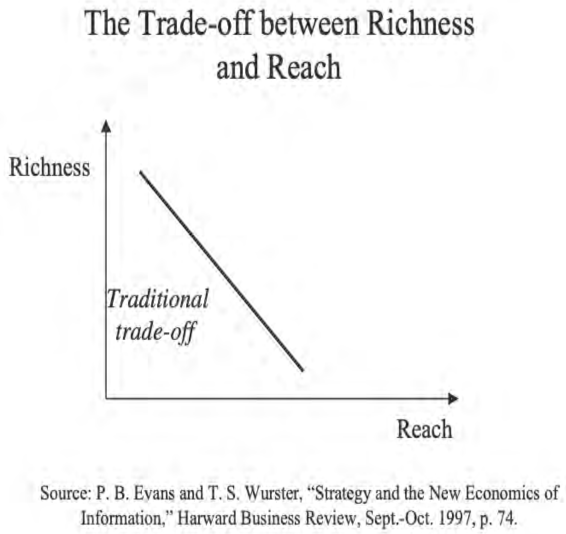
When we use this method to display a single channel or range of wavelengths, we are actually displaying that channel through all three primary colours. Because the brightness level of each pixel is the same for each primary colour, they combine to form a **black and white image**, showing various shades of gray from black to white. When we display more than one channel each as a different primary colour, then the brightness levels may be different for each channel/primary colour combination and they will combine to form a **colour image**.

Photo Interpretation, Photogrammetry, and Image Processing: Prior to the widespread availability of satellite imagery, aerial photography served as the principal foundation for a wide variety of cartographic efforts and geographic analyses. During its period of prominence, analytical techniques emerged that involved mostly nonspectral aspects of aerial photographs. Air photo interpretation uses characteristics such as tone, texture, pattern, shadow, shape, size, and site (location), to identify objects and areas in photographs. In contrast, photogrammetry uses aerial photographs to make reliable spatial measurements of objects. (The word photogrammetry is derived from three Greek roots meaning "light-writing-measurement.") The types of measurements that a photogrammetrist might collect include the distances between features in an area of interest or the heights of particular features. In recent decades, photogrammetric methods have been increasingly applied to digital rather than film-based aerial photographs, and in some cases, to imagery captured by satellite- based sensors.

In particular, digital image processing, which is a concept that encompasses a wide variety of computer algorithms and approaches for visualization, enhancement, and interpretation of remotely sensed images. Pattern recognition is used in digital image processing algorithms with the goal of providing a reasonable answer for all possible inputs and to perform "most likely" matching of the inputs, taking into account the statistical properties of the image data. Key products of digital image processing include thematic maps and color-coded, classified images that depict the spatial pattern of certain characteristics of objects and features, such as the boundaries between the surface water and land. For instance, remote sensing is commonly applied to map the variety and extent of land cover; in turn, these maps serve as critical information for other applications such as ecological studies, urban planning, water resource monitoring, and environmental impact assessment, as well as for policy making.

The Importance of Accuracy Assessment: A key consideration regarding the use of remotely sensed data is that the resulting outputs must be evaluated appropriately. When the output is a classified map, it is critical to assess its accuracy. A map is an imperfect representation of the phenomena it is meant to portray. In other words, every map contains errors, and it is the responsibility of the remote sensing analyst to characterize these errors prior to a map's use in subsequent applications. The most widely accepted method for the ac- curacy assessment of remote-sensing-derived maps is by comparison to reference data (also known as "ground truth") collected by visiting an adequate number of sample sites in the field. The key instrument in this comparison is an error matrix, which quantifies the accuracy for each map class of interest as well as the overall map accuracy (i.e., combining all of the classes) and the concepts of Producer's Accuracy and User's Accuracy and the Kappa statistics.

Cost Effectiveness and Reach Versus Richness of Remote Sensing Technology: Remotely sensed data can be collected over a very large area in a very short period. For example, Landsat collects a scene covering 185 km × 185 km in 26 s. With the advent of sophisticated computing hardware and software and image processing techniques, these data can be transformed into useful digital maps depicting a variety of applications in a geospatial context. However, one needs to be aware of not overselling this technology as a key to most solutions. Remember, all models are wrong, but some are useful. In order for a remote-sensing-derived product to be useful, one must verify the models being used, assess the accuracy of the results, and state the limitations associated with it. Questions such as who controls the data acquisition and distribution become concerns for the use of remotely sensed data.



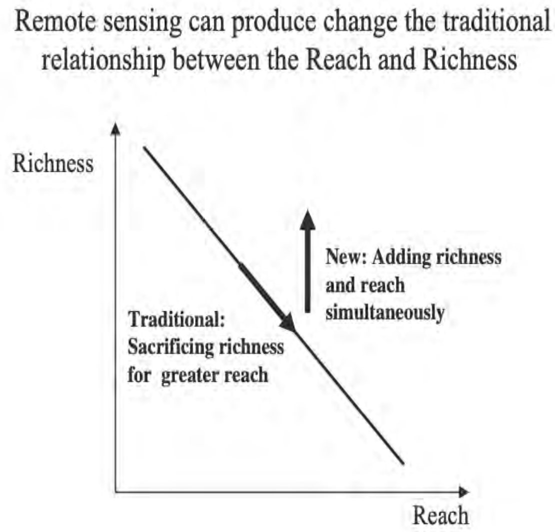


Fig: The availability of rich remote sensing data can blow up the reach/richness trade-off

It is possible to share extremely rich information with a very small number of people, and less rich information with a large number. In a traditional channel of distribution of information, there is a fundamental "trade-off" between "richness" and "reach" (Fig). Reach simply means the number of people exchanging in- formation. Richness can be defined as the amount of information that can be moved from a provider to a user in a given time.

The explosion of connectivity (thanks to open electronic networks), and the adoption of common information standards are now making possible for a very large number of people to exchange very rich information. This is fundamentally altering the traditional trade-off between richness and reach. Remote sensing provides data with high richness values (high spectral and spatial, spectral, and radiometric resolution) that reach a very broad user community (global). This is another example of disrupting the relationship between the reach and richness.

Data Acquisition: Remotely sensed data are collected by a diverse array of passive and active sensors mounted on aircraft (including airplanes, helicopters, and uninhabited aerial systems) or spacecraft (usually satellites). During the latter half of the twentieth century, large-scale space programs such as National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) were primarily responsible for the development of new remote sensing technologies. Such programs remain key sources of technological innovations, but the expansion of commercial remote sensing has contributed greatly to the proliferation of sensors that provide high-quality data for a variety of applications. The main goal of this chapter is to provide an overview of the types of sensors currently available to analysts, including details about the data they acquire and some of their potential applications. Prior to this discussion, we first introduce the concept of resolution in remote sensing. One common definition of resolution is the ability to discern individual objects or features in a captured image or in the "real world." In this context, it is related to the concept of scale as used by cartographers: a large-scale map—whether constructed from remote sensing imagery or other geospatial data sources—shows more details than a small-scale map, thus making it possible to dis- cern smaller objects or finer features. Nevertheless, the term resolution also relates to several other aspects of remotely sensed data. We illustrate these aspects with examples of commonly used satellite sensors and imagery.

Data Resolution: When we talk about "remotely sensed data," we are usually referring to digital images (i.e., two-dimensional arrays of pixels). These data are typically described by four types of resolution: spatial, spectral, temporal, and radiometric. Spatial resolution, which corresponds most closely to the definition of resolution provided in the preceding paragraph, is a measure of the clarity or fineness of detail of an image. For digital images, this translates to the ground area captured by a single image pixel; because pixels are typically square, resolution is generally expressed as the side length of a pixel. Spectral resolution, represented by the width of the wavelength interval and/or the number of spectral channels (or bands) captured by a sensor, defines the storage of recorded electromagnetic energy and the sensor's ability to detect wavelength differences between objects or areas of interest. The amount of time it takes for a sensor to revisit or reimage a particular geographic location is referred to as its temporal resolution. Finally, the sensitivity of a sensor to incoming electromagnetic energy (i.e., the smallest differences in intensity that the sensor can detect) is known as its radiometric resolution. This metric is usually expressed in terms of binary bit-depth (Jensen 2005), which refers to the number of tonal levels at which data for a given spectral band are recorded by a particular sensor. Digital images, like other forms of digital data, are stored as bits (i.e., 0 s and 1 s), so a sensor's bit-depth defines the number of unique values, on a binary scale, at which the incoming data can be stored for a pixel. This number is equal to 2n, where n is the stated bit-depth. For example, a bit-depth of 3 means that incoming data can be stored as one of the eight unique values: 000, 001, 010, 011, 100, 101, 110, and 111. The binary bit-depth of most contemporary sensors is at least 8-bit, meaning that image pixels have at least 256 (0–255) possible values.

Each of these resolution types is discussed in subsequent paragraphs. In addition, the different resolution characteristics of some currently operational satellite sensors are presented in Table 2.1. The sensors described in this table are highly variable with respect to resolution. For example, the WorldView-3 satellite's onboard sensor has a spatial resolution of 31 cm for panchromatic (or black-and-white) imagery, while data collected by the "VEGETATION" sensor on the Système Probatoire d'Observation de la Terre (SPOT) 5 satellite are stored in 1150-m pixels. Temporally, the sensors listed in Table 2.1 have resolutions ranging from 15 min to 52 days; in other words, the satellite carrying a particular sensor—or the sensor itself, depending on certain aspects of its configuration—has the capacity to revisit a particular location on the Earth's surface every 15 min (i.e., Geostationary Operational Environmental Satellites, GOES) to every 52 days (i.e., the panchromatic and multispectral camera (PANMUX) sensor on the CBERS-4 satellite).

Spatial Resolution The ability to discern spatial structure is an important element of any remote sensing analysis. It is only in recent years that satellite imagery has supplanted aerial photography as the primary image data source for analyses such as the classification of urban land use. In an urban landscape, surface features such as roads, office buildings, parks, and residential neighborhoods comprise a mosaic, where many small constituent units or pieces are interspersed by a few large ones. Roads and buildings are typically some of the smallest of these units. When viewed from above (e.g., from an airplane), the net visual effect of these units is an aggregate patchwork of various land uses and cover types, but the degree of patchwork detail portrayed by a remotely sensed image, and thus the level of specificity at which it can be classified, depends on its spatial resolution. For example, a 30-m pixel (i.e., the spatial resolution provided by several sensors listed in Table 1) stores one digital number per spectral band of information for any landscape feature smaller than 900 m^2. The pixel could, in fact, accommodate 6 one-story square houses, each having a 1500 ft^2 (139 m^2) footprint. In contrast, an Advanced

Very High Resolution Radiometer (AVHRR) pixel, with its 1100-m resolution (see Table 2.1), could incorporate more than 8700 of these houses, if arranged regularly. Increases in spatial resolution have been a persistent trend in sensor innovation. Within a decade of the 1986 launch of the first SPOT satellite, whose 10-m panchromatic spatial resolution opened up new land cover mapping possibilities, space agencies in Japan, India, and Europe had produced satellites with finer spatial resolutions than any of the first five Landsat satellites. The latest generation of commercial satellite ventures, including Pléiades 1A and 1B, as well as WorldView-2 and WorldView-3, all provide spatial resolutions of 1 m or less.

Table 2.1 Characteristics of selected satellite sensors. (Adapted from Rogan and Chen 2004; updated for this publication)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands
MSS (Landsat 1–5)	NASA, US	1972–1992	185	80 (MS), 240 (TIR)[c]	16–18 days	8-bit	0.5–1.1, 10.4–12.6[c]	4–5[c]
TM (Landsat 4, 5)	NASA, US	1982–2011	185	30 (MS), 120 (TIR)	16 days	8-bit	0.45–2.35, 10.4–12.5	7
ETM+ (Landsat 7)	NASA, US	1999	185	15 (PAN), 30 (MS), 60 (TIR)	16 days	8-bit	0.52–0.9 (PAN), 0.45–2.35, 10.4–12.5	7+ PAN
OLI (Landsat 8)	NASA, US	2013	185	15 (PAN), 30 (MS)	16 days	12-bit	0.5–0.68 (PAN), 0.433–0.453 (coastal/aerosol), 0.45–2.3, 1.36–1.39 (cirrus)	8+ PAN
TIRS (Landsat 8)	NASA, US	2013	185	100	16 days	12-bit	10.6–11.2, 11.5–12.5	2
MODIS (EOS Terra and Aqua)	NASA, US	1999	2300	250 (PAN), 500 (VNIR), 1000 (SWIR)	1–2 days	12-bit	0.620–2.155, 3.66–14.385	36
ASTER (EOS Terra)	NASA,US; METI, Japan	1999	60	15 (VNIR), 30 (SWIR), 90 (TIR)	4–16 days	8-bit (VNIR/ SWIR), 12-bit (TIR)	0.52–0.86, 1.60–2.43, 8.125–11.65	14
Hyperion (EO-1)	NASA, US	2000	7.5	30	16 days	12-bit	0.353–2.577	220
ALI (EO-1)	NASA, US	2000	37	10 (PAN), 30 (MS)	16 days	12-bit	0.48–0.69 (PAN), 0.433–2.35	9+ PAN
OMI (EOS Aura)	NIVR, Netherlands; FMI, Finland; NASA, US	2004	2600	13,000 × 48,000, 13,000 × 24,000[d]	1 day	12-bit	0.27–0.5	740
CALIOP (CALIPSO)	NASA, US; CNES, France	2006	0.1	333	16 days	22-bit[e]	0.532, 1.064	2[f]

Table 2.1 (continued)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands
VIIRS (Suomi NPP)	NASA, US; NOAA, US	2011	3000	375 or 750 depending on application	12 h	12-bit	0.41–12.5	21 + Day/Night PAN
Aquarius (SAC-D)	NASA, US; CONAE, Argentina	2011	390	150	7 days		3 L-band microwave radiometer beams + radar	N/A
AVHRR (NOAA 6–19; Metop-A, -B)	NOAA, US; EUMETSAT	1978[g]	2700	1100	12 h	10-bit	0.58–12.5	6[h]
I-M Imager (GOES 12–15)	NESDIS, US	1975[i]	8	1000 (VNIR), 4000 (SWIR), 8000 (moisture), 4000 (TIR)	0.25–3 h	10-bit	0.55–12.5	5
HICO (International Space Station)	Office of Naval Research (ONR), US; NASA, US	2009–2014	42 × 192[j]	90	~3 days	14-bit	0.353–1.08 (0.4–0.9)[k]	128 (87)[k]
SAR (RADARSAT-2)	CSA, Canada	2007	20–500[l]	3-100[l]	24 days[m]		C-band radar	N/A
VEGETATION (Proba-V)	ESA	2013	2250	100/350[n]	1–2 days[o]	12-bit	0.438–1.634	4
SAR (Sentinel-1 A)	ESA	2014	20–250[l]	5–40[l]	12 days		C-band radar	N/A
PMC (Gaofen-1)	CNSA, China	2013	69	2 (PAN), 8 (MS)	4 days	10-bit	0.45–0.9 (PAN), 0.45–0.89	4 + PAN
WFI (Gaofen-1)	CNSA, China	2013	830	16	4 days	10-bit	0.45–0.89	4
HROI (Gaofen-2)	CNSA, China	2014	48	0.8 (PAN), 3.2 (MS)	?[p]	?[p]	?[p]	?[p]
MUXCAM (CBERS-4)	CBERS, China/Brazil	2014	120	20	26 days	8-bit	0.45–0.89	4
PANMUX (CBERS-4)	CBERS, China/Brazil	2014	60	5 (PAN), 10 (MS)	52 days	8-bit	0.51–0.73 (PAN), 0.52–0.89	3 + PAN

Table 2.1 (continued)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands
IRSCAM (CBERS-4)	CBERS, China/ Brazil	2014	120	40 (NIR/SWIR), 80 (TIR)	26 days	8-bit	0.77–12.5	4
WFICAM (CBERS-4)	CBERS, China/ Brazil	2014	866	64	5 days	10-bit	0.45–0.89	4
LISS-IV (RESOURCESAT-2)	ISRO, India	2011	70	5.8	24 days	10-bit	0.52–0.86	3
LISS-III (RESOURCESAT-2)	ISRO, India	2011	141	23.5	24 days	10-bit	0.52–1.70	4
AWiFS (RESOURCESAT-2)	ISRO, India	2011	740	56	24 days	12-bit	0.52–1.70	4
TANSO-FTS (GOSAT/Ibuki)	JAXA, Japan	2009	160[q]	10.5	3 days		0.758–14.3	4
Geoton-L1 (Resurs-P No. 1, No. 2)	Roscosmos, Russia	2013, 2014	32 (PAN), 38 (MS)	1 (PAN), 3–4 (MS)	3 days	10-bit	0.58–0.8 (PAN), 0.45–0.80	5 + PAN
KShMSA-VR/SR (Resurs-P No. 1, No. 2)	Roscosmos, Russia	2013, 2014	97 (VR mode), 440 (SR mode)	VR: 12 (PAN), 24 (MS); SR: 60 (PAN), 120 (MS)	3 days	12-bit	0.43–0.7 (PAN), 0.43–0.9	5 + PAN
GSA (Resurs-P No.1, No.2)	Roscosmos, Russia	2013, 2014	25	30	3 days	14-bit	0.4–1.1 nm band width	130
COSI (KOMPSAT-5)	KARI, South Korea	2013	5-100[l]	1–20[l]	28 days		X-band radar	N/A
AEISS-A (KOMPSAT-3 A)	KARI, South Korea	2015	12	0.55 (PAN), 2.2 (MS)	28 days	14-bit	0.45–0.9 (PAN), 0.45–0.9	4 + PAN
IIS (KOMPSAT-3 A)	KARI, South Korea	2015	12	5.5	28 days	14-bit	3.3–5.2	1
HRVIR (SPOT 4)	Airbus Group, France[r]	1998–2013	60	10 (PAN), 20 (MS)	26 days[s]	8-bit	0.61–0.68 (PAN), 0.50–1.75	4 + PAN

Table 2.1 (continued)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands
VEGETATION (SPOT 4,5)	Airbus Group, France[r]	1998–2013, 2002–2014	2250	1150	26 days[s]	10-bit	0.43–1.75	4
HRG (SPOT 5)	Airbus Group, France[r]	2002	60	2.5–5 (PAN), 10 (VNIR), 20 (SWIR)	26 days[s]	8-bit	0.48–0.71 (PAN), 0.50–1.75	4 + PAN
SPOT 6, 7	Airbus Group, France/ Azercosmos, Azerbaijan[t]	2012, 2014	60	1.5 (PAN), 6 (MS)	26 days[u]	12-bit	0.45–0.745 (PAN), 0.45–0.89	4 + PAN
Pléiades 1 A, 1B	CNES/Airbus Group, France	2011, 2012	20	0.5 (PAN), 2 (MS)	26 days	12-bit	0.45–0.83 (PAN), 0.43–0.94	4 + PAN
IKONOS	DigitalGlobe, US[v]	1999	11.3	1 (PAN), 4 (MS)	3–5 days	11-bit	0.526–0.929 (PAN), 0.445–0.853	4 + PAN
QuickBird	DigitalGlobe, US	2001	18	0.65 (PAN), 2.62 (MS)	2.5–5.6 days	11-bit	0.405–1.053 (PAN), 0.43–0.918	4 + PAN
GeoEye-1	DigitalGlobe, US[v]	2008	15.2	0.41 (PAN), 1.65 (MS)	<3 days	11-bit	0.45–0.80 (PAN), 0.45–0.92	4 + PAN
WorldView-2	DigitalGlobe, US	2009	16.4	0.46 (PAN), 1.85 (MS)	1.1–3.7 days	11-bit	0.45–0.80 (PAN), 0.45–1.04	8 + PAN
WorldView-3	DigitalGlobe, US	2014	13.1	0.31 (PAN), 1.24 (MS), 3.7 (SWIR), 30 (CAVIS)[x]	<1 day	11-bit (PAN and MS), 14-bit (SWIR)	0.45–0.80 (PAN), 0.4–1.04, 1.195–2.365, 0.405–2.245 (CAVIS)	28 + PAN
RapidEye	BlackBridge, Germany	2009	77	5	1 day	12-bit	0.44–0.85	5
HiRAIS (Deimos-2)	Elecnor Deimos, Spain	2014	12	1 (PAN), 4 (MS)	4 days[y]	10-bit	0.45–0.9 (PAN), 0.42–0.89	4 + PAN

Table 2.1 (continued)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands

[a] *NASA* National Aeronautics and Space Administration, *METI* Ministry of Economy, Trade, and Industry, *NIVR* The Netherlands Agency for Aerospace Programmes, *FMI* Finnish Meteorological Institute, *CNES* Centre National d'Études Spatiales, *NOAA* National Oceanic and Atmospheric Administration, *NESDIS* National Environmental Satellite, Data, and Information Service, *CSA* Canadian Space Agency, *ESA* European Space Agency, *CNSA* China National Space Administration, *CBERS* China-Brazil Earth Resources Satellite Program, *CONAE* Comisión Nacional de Actividades Espaciales, *EUMETSAT* European Organisation for the Exploitation of Meteorological Satellites, *JAXA* Japanese Aerospace Exploration Agency, *ISRO* Indian Space Research Organization, *KARI* Korean Aerospace Research Institute

[b] Acronyms used in describing sensor channels/configurations: *PAN* panchromatic, *MS* multispectral, *VNIR* visible and near-infrared, *SWIR* short-wave infrared *TIR* thermal infrared

[c] The MSS sensor on Landsat 3 had a fifth spectral band for thermal infrared. The MSS sensors on other Landsat missions had four-band configurations

[d] The OMI sensor aboard EOS Aura has one channel recording at 0.27–0.31 μm (in the ultraviolet spectral range) and another recording at 0.306-0.5 μm (ultraviolet and visible spectral range); the pixel size of the former channel is larger (13×48 km vs. 13×24 km)

[e] Each receiver channel on the CALIOP sensor, a spaceborne LiDAR system, has dual 14-bit digitizers that jointly provide a 22-bit dynamic range

[f] The CALIOP sensor produces simultaneous laser pulses at two wavelengths, 0.532 and 1.064 μm

[g] The NOAA satellite program began in 1978. Currently, NOAA-19 is designated as the program's operational satellite. The AVHRR sensor is also carried as a "heritage" instrument on the Metop-A and Metop-B satellites

[h] While the AVHRR sensor has six spectral channels, only five are transmitted to the ground at any time. The bands designated 3A and 3B are transmitted only during daytime and nighttime, respectively

[i] Although the GOES program has been active since 1975, only GOES-13 through GOES-15 are currently operational. GOES-14 was launched in 2009 but remains in on-orbit storage mode

Table 2.1 (continued)

Sensor (mission)	Organization[a]	Operation period	Swath width (km)	Spatial resolution (m)[b]	Temporal resolution	Radiometric resolution	Spectral resolution (μm)	Spectral bands

[j] Operated as a demonstration instrument, the HICO sensor captured only a single 42 × 92 km scene per orbit. Over its 5-year period of operation, HICO collected > 10,000 scenes worldwide

[k] Collected HICO data have 128 bands spanning the 0.353–1.08 μm range of wavelengths, but the data from outside the 0.4–0.9 μm range are less accurate and therefore only 87 bands are included in the output files made available to users

[l] The radar systems in this table (i.e., SAR/RADARSAT-2, SAR/Sentinel-1 A, and COSI/KOMPSAT-5) operate in a variety of scan modes with different swath widths and spatial resolutions

[m] RADARSAT-2 has a repeat cycle of 24 days, but its left- and right-looking modes may provide more rapid revisits

[n] The spatial resolution of the VEGETATION sensor on Proba-V is 100 m at nadir but 350 m over the full field of view (i.e., at the scene edges)

[o] The VEGETATION sensor provides daily coverage for the following latitudes: 35–75°N and 35–56°S. It offers full global coverage every 2 days

[p] Few details about Gaofen-2 are available, but it is likely similar to Gaofen-1 in terms of spectral resolution and revisit time

[q] The FTS sensor on the GOSAT satellite records 10.5 × 10.5 km images that are spaced 150 km apart in a grid (see Kuze et al. 2009)

[r] Spot Image, a company created by the French Space Agency (CNES), developed and operated the SPOT satellites. Spot Image became a subsidiary of Astrium, a European Aeronautic Defense and Space (EADS) company in 2008. EADS was reorganized as the Airbus Group in 2014

[s] The SPOT satellites have the capacity to record data off-nadir (i.e., to record data in areas that are not directly below the satellite). This may reduce the revisit time to 2–3 days (1 day for the wide-swath VEGETATION sensor), but the images will have different observation geometry, which may affect image processing

[t] Unlike the first five SPOT satellites, SPOT 6 and 7 were developed by the Airbus Group without financial support from the French government. In 2014, SPOT 7 was sold to Azerbaijan's space agency Azercosmos, who renamed it Azersky. Per agreement, Azercosmos has commercial rights to imagery from both satellites for the southern Asia region, while Airbus Group retains the rights elsewhere

[u] The SPOT 6 and 7 satellites are a constellation, operating on the same orbit but phased 180° apart. With the satellites' capacity to record data off-nadir, the constellation can provide 1-day revisit time

[v] GeoEye, the company that originally operated IKONOS and GeoEye-1, merged with DigitalGlobe in 2013

[x] *CAVIS* Clouds, Aerosols, Vapors, Ice, and Snow

[y] The 4-day revisit time of the HiRAIS sensor on Deimos-2 is enabled by a ±45° off-nadir viewing capability

Spectral Resolution: The spectral component of remote sensing data is also critical to appropriate data selection. The spectral resolution of a sensor is a description of the range and partitioning of the electromagnetic energy (or reflectance) recorded by the sensor. In this context, sensors can be divided into one of three loose classes of spectral sensitivity: panchromatic (one spectral band), multispectral (multiple spectral bands), or hyperspectral (many, possibly hundreds, of spectral bands). Fundamentally, both multispectral and hyperspectral images can be thought of as "stacks" of identically geo-referenced (i.e., covering the exact same geographic area) panchromatic images, where each image in the stack corresponds to a particular portion of the electromagnetic spectrum. Most satellite-derived remote sensing data are captured in a panchromatic and/or multispectral format (although spaceborne hyperspectral sensors are becoming more commonplace). For example, the Operational Land Imager (OLI) onboard NASA's Landsat-8 satellite records data in nine bands, including one panchromatic band. Each of these bands is sensitive to different wavelengths of visible and infrared radiation. The sensor on the WorldView-2 satellite also records data in nine bands, including a panchromatic band. Most multi- spectral sensors have several bands targeted at the visible-to-near-infrared (VNIR) range (0.4–1.4 μm) of the electromagnetic spectrum, as do OLI (six bands in this range) and WorldView-2 (all eight of its multispectral bands). This is because, in many geographic areas, ambient electromagnetic reflectance is strongly shaped by the distribution and condition of vegetation and water features, particularly in the VNIR range. WorldView-2 is noteworthy for two specialized bands within the VNIR range that are not found on any other spaceborne multispectral sensor: a "yellow" band, aimed at detecting the yellowness of terrestrial and aquatic vegetation, which may help distinguish between vegetation types; and a "red-edge" band, focused on the narrow range of wavelengths where vegetation reflectance transitions from low to high, which may be useful for measuring plant health. While the OLI sensor does not have as many bands in the VNIR range as WorldView-2, it does have two bands in the short-wave infrared (SWIR) portion of the electromagnetic spectrum, as well as a band at the edge of the VNIR range intended specifically for cirrus cloud detection.

Unlike these multispectral sensors, NASA's Hyperion, the first hyperspectral sensor carried aboard a satellite, provides a virtually continuous recording of electromagnetic reflectance across 220 narrow spectral bands in the VNIR and SWIR wavelengths. Although the processing complexity of hyperspectral data has hindered its widespread applicability in many land cover studies, these data provide a great deal of information about the unique reflectance behavior of vegetation stress and diversity. The high spectral resolution also provides an increased ability to dis- criminate between features that have similar response profiles, or signatures, across the electromagnetic spectrum, such as forest stands composed of different deciduous tree species. It is important to note, however, that the first generation of satellite-based, "true" hyperspectral sensors (i.e., sensors with >100 bands), such as Hyperion or the now-defunct Hyperspectral Imager for the Coastal Ocean (HICO) that operated from the International Space Station, have typically been too coarse in terms of spatial resolution to be used for fine-scale analyses. Such applications remain the purview of airborne hyperspectral sensors, although this trend is likely to change with future advances in hyperspectral imaging technology.

Temporal Resolution:

Temporal resolution, or revisit time, is usually expressed in terms of days. For example, Landsat-8 has a 16-day orbit cycle, meaning that the satellite, and thus the OLI sensor and the thermal infrared sensor (TIRS), returns to a given location on the Earth's surface every 16 days. However, some satellites, such as the GOES, have a revisit cycle of less than an hour in certain locations. The GOES have a coarse, 8-km spatial resolution, which gives them limited utility for local land cover studies, but their temporal resolution makes them highly suitable for meteorological and climatological applications. By contrast, the balance of spatial and temporal resolutions achieved by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)—with a spatial resolution of 250–1000 m and a temporal resolution of 1–2 days—has made the sensor applicable to a variety of regional- to continental-scale research efforts. MODIS data make it possible to examine land cover changes and patterns affecting environmental quality that may not be obvious unless viewed at the daily or near-daily replication offered by this sensor. In addition, a number of satellites (e.g., SPOT 6 and 7) have the capacity to capture off-nadir imagery (i.e., to record data from areas that are not directly below the satellite sensor). This can reduce their typical revisit time, but it also affects the sensor geometry and subsequent image processing. Furthermore, off-nadir image capture may also alter spatial resolution, particularly for high-resolution sensors; for instance, the spatial resolution of multispectral data from WorldView-3 is 1.38 m at 20° off-nadir versus 1.24 m at nadir.

Radiometric Resolution Many of the current generation of both government and commercial satellites have onboard sensors with high radiometric resolutions. Commonly, these sensors have 10-, 11-, or 12-bit collection depths (also known as their level of "data quantization"), which represents a substantial improvement over the 8-bit resolution typically exhibited by predecessors such as the older Landsat and SPOT sensors. Certain sensors, such as the Advanced Earth Imaging Sensor System-A (AEISS-A) aboard KOMPSAT-5, as well as the Cloud-Aerosol LiDAR with Orthogonal Polarization (CALIOP) instrument aboard NASA's CALIPSO satellite, have even higher radiometric resolutions (14- and 22-bit, respectively). Fundamentally, a sensor's radiometric resolution defines the dynamic range (i.e., the number of possible data values) recorded in each image band, so higher radiometric resolution means that a sensor is more sensitive to variations in electromagnetic reflectance. This increased sensitivity has been shown to be very useful in the land cover classification of complex (e.g., urban and suburban) landscapes.

Ultimately, each of the four resolution types must be considered in light of the intended purpose of the data. For example, except near cities, most terrestrial land- scapes are dominated by vegetation, water, or other natural surfaces, even amid production land uses such as agriculture or mining. Spatial resolution might be relatively less important for mapping or monitoring efforts in these settings because of high landscape homogeneity. In heavily forested or vegetated environments, data that are high in temporal and spectral resolutions rather than spatial resolution, such as AVHRR imagery, could be a powerful tool for evaluating seasonal or annual change in photosynthetic activity. With respect to other types of analyses, hyperspectral data have demonstrated strong applicability for geological, mineralogical, and soil studies. In addition, radar systems such as the C-band radar on the RADARSAT-2 satellite can be useful for observing sea surface conditions and other aspects of coastal areas, for detecting oil spills, and for monitoring sea ice.

Regardless, in any remote sensing analysis, the appropriate input data should primarily be a function of the individual project objectives. For instance, the level of detail offered by high-spatial-resolution satellite imagery may not be well suited for mapping forested areas because of certain limitations (e.g., the presence of shadows and high spectral variability within forest type classes), but such images have been used successfully in large, homogeneous tracts of rain forest for the assessment of old-growth tree mortality. As this specialized application suggests, there is no one "best" sensor for mapping a particular type of landscape. Although the sensors listed in Table 2.1 are only a sample of the instruments currently producing remotely sensed data for use in scientific applications, they illustrate the wide diversity of options that an analyst should consider before choosing a particular sensor. While that ultimate selection will likely also be a function of other factors, such as budget and processing capabilities, it should be guided foremost by the analyst's evaluation about which choice will provide the most meaningful information.

MODULE-II

REMOTE SENSING TECHNOLOGIES AND ITS APPLICATION

MODULE-II: REMOTE SENSING TECHNOLOGIES AND ITS APPLICATION

The Mechanism of Remote Sensing: Data is collected through either passive or active instruments, which differ fundamentally in their processes for measurement. Passive instruments detect the radiation reflected off or emitted by the sensed objects from a source other than the instruments, such as sunlight. An example of a passive instrument is an optical sensor. It relies on recording of reflected solar energy; thus, it is only able to take imagery during the day. On the other hand, active instruments transmit energy toward the target and then record the reflected or backscattered energy from the object. Active sensors such as radar, including synthetic aperture radar (SAR), have the advantage over passive remote sensing because they enable monitoring even at night, can penetrate cloud cover and rain, and are largely unaffected by the weather. Furthermore, SARs are particularly well suited for studying geological structures, partly because of their ability to penetrate foliage and view the underlying surface formations. Active sensors are valuable tools for such applications as monitoring forest clearings in very cloudy regions.

Although satellite remote sensing includes those satellites circling around other celestial bodies such as the Moon, this book focuses on the remote sensing of the Earth. Satellites need to be placed in certain orbital trajectories around the Earth to acquire remote sensing data. Remote sensing is conducted principally from two different types of orbits: the geostationary orbit and low-Earth orbit. Satellites in polar orbits can cover the entire surface of the globe over a period of time as the Earth turns below them. The altitude of the orbit determines the size of objects that can be identified: the lower the altitude, the smaller the objects that can be discerned.

The smallest size of an object that can be identifiable in an image is referred to as spatial resolution, which is a major element in determining the capabilities of the satellite. An image with a spatial resolution of 1 metre means that the smallest object that can be discernible in the image is approximately 1m, depending upon such factors as contrast ratio or signal-to-noise ratios; hence the geometrically defined term, Ground Sample Distance (GSD), is more frequently used. Of course, images with higher spatial resolutions give the users enhanced capabilities to assess the specific areas of interest in detail; however, there are other factors that are also important in determining the capability for remote sensing, such as image swath width, spectral resolution, and temporal resolution. Spectral resolution enables objects of similar sizes but different mate- rial to be distinguished, whereas temporal resolution – also referred to as 'revisit time' – defines how often a satellite can observe the same location and measure the change in observed phenomena. A temporal resolution/revisit of 16 days means that a satellite passes over the same area for sensing every 16 days, which is suitable for monitoring slowly changing or seasonal phenomena, but insufficient for disaster monitoring, which requires observations of the same location at least daily to monitor the progress of the disaster and its aftermath.

The width of the Earth's surface that a satellite's sensors can observe is called the swath width. Spatial resolution and swath width are typically linked. For a low spatial resolution sensor with the ability to cover a wide swath, high temporal resolution can often be achieved with a single satellite. These satellites are best suited for large-scale environmental measurements. High resolution sensors limit the swath width to tens of kilometres, so a constellation of satellites is needed to achieve the combined capabilities of high spatial resolution and high temporal resolution simultaneously. With the advent of small lower cost satellites, such constellations are increasingly used for different applications.

The operational flow of remote sensing activities includes all of the processes from data collection to data handling activities. The Scientific and Technical Sub-Committee of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) identified the following phases involved in remote sensing:

- Data acquisition;
- Data reception;
- Data pre-processing;
- Data storage;
- Data analysis; and
- Information Utilization.

Wherever data is collected, as the satellite acquires information about the observed phenomena it is transmitted to a ground station, where data is received and processed by computers for human viewing and interpretation. Each receiving station has a set of processes to generate a certified product. Once the data has gone through pre-processing, it is analyzed so as to deliver useful information: the data may simply be enhanced, or further value may be added to create maps. Advanced data analysis and value-adding are the processes that convert data into relevant knowledge ready for immediate use; thus, data goes through various stages of handling operations before it is delivered to the end users.

The Principles Relating to Remote Sensing of the Earth from Outer Space (hereafter: UN Remote Sensing Principles), which is the only international document addressing the sensing activities from space, categorizes three different types of data products: primary data, processed data, and analyzed information. In practice, however, various other terms are used: for instance, 'raw data' or 'unenhanced data' for primary data; 'enhanced data' for processed data; and 'derived products' and 'value added products' for analyzed information. Furthermore, different processing levels are adopted by different entities. No uniformity has yet been achieved for referring to different types of products from different systems, and this generates complexities for both data comparison and data integration by different systems into a final product.

Remote Sensors: Remote sensing instruments are of two primary types—

- active
- passive

Active sensors, provide their own source of energy to illuminate the objects they observe. An active sensor emits radiation in the direction of the target to be investigated. The sensor then detects and measures the radiation that is reflected or backscattered from the target. Passive sensors, on the other hand, detect natural energy (radiation) that is emitted or reflected by the object or scene being observed. Reflected sunlight is the most common source of radiation measured by passive sensors.

Active Sensors:

The majority of active sensors operate in the microwave portion of the electromagnetic spectrum, which makes them able to penetrate the atmosphere under most conditions. An active technique views the target from either end of a baseline of known length. The change in apparent view direction (parallax) is related to the absolute distance between the instrument and target.

- *Laser altimeter*—An instrument that uses lidar to measure the height of the platform (spacecraft or aircraft) above the surface. The height of the platform with respect to the mean Earth's surface is used to determine the topography of the underlying surface.
- *Lidar*—A light detection and ranging sensor that uses a laser (light amplification by stimulated emission of radiation) radar to transmit a light pulse and a receiver with sensitive detectors to measure the backscattered or reflected light. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance traveled.
- *Radar*—An active radio detection and ranging sensor that provides its own source of electromagnetic energy. An active radar sensor, whether airborne or spaceborne, emits microwave radiation in a series of pulses from an antenna. When the energy reaches the target, some of the energy is reflected back toward the sensor. This backscattered microwave radiation is detected, measured, and timed. The time required for the energy to travel to the target and return back to the sensor determines the distance or range to the target. By recording the range and magnitude of the energy reflected from all targets as the system passes by, a two-dimensional image of the surface can be produced.
- *Ranging Instrument*—A device that measures the distance between the instrument and a target object. Radars and altimeters work by determining the time a transmitted pulse (microwaves or light) takes to reflect from a target and return to the instrument. Another technique employs identical microwave instruments on a pair of platforms. Signals are transmitted from each instrument to the other, with the distance between the two determined from the difference between the received signal phase and transmitted (reference) phase. These are examples of active techniques. An active technique views the target from either end of a baseline of known length. The change in apparent view direction (parallax) is related to the absolute distance between the instrument and target.
- *Scatterometer*—A high-frequency microwave radar designed specifically to measure backscattered radiation. Over ocean surfaces, measurements of backscattered radiation in the microwave spectral region can be used to derive maps of surface wind speed and direction.
- *Sounder*—An instrument that measures vertical distribution of precipitation and other atmospheric characteristics such as temperature, humidity, and cloud composition.

Passive Sensors: Passive sensors include different types of radiometers and spectrometers. Most passive systems used in remote sensing applications operate in the visible, infrared, thermal infrared, and microwave portions of the electromagnetic spectrum. Passive remote sensors include the following:

- *Accelerometer*—An instrument that measures acceleration (change in velocity per unit time). There are two general types of accelerometers. One measures translational accelerations (changes in linear motions in one or more dimensions), and the other measures angular accelerations (changes in rotation rate per unit time).
- *Hyperspectral radiometer*—An advanced multispectral sensor that detects hundreds of very narrow spectral bands throughout the visible, near-infrared, and

mid-infrared portions of the electromagnetic spectrum. This sensor's very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands.

- *Imaging radiometer*—A radiometer that has a scanning capability to provide a two-dimensional array of pixels from which an image may be produced. Scanning can be performed mechanically or electronically by using an array of detectors.
- *Radiometer*—An instrument that quantitatively measures the intensity of electromagnetic radiation in some bands within the spectrum. Usually, a radiometer is further identified by the portion of the spectrum it covers; for example, visible, infrared, or microwave.
- *Sounder*—An instrument that measures vertical distributions of atmospheric parameters such as temperature, pressure, and composition from multispectral information.
- *Spectrometer*—A device that is designed to detect, measure, and analyze the spectral content of incident electromagnetic radiation. Conventional imaging spectrometers use gratings or prisms to disperse the radiation for spectral discrimination.
- *Spectroradiometer*—A radiometer that measures the intensity of radiation in multiple wavelength bands (i.e., multispectral). Many times the bands are of high-spectral resolution, designed for remotely sensing specific geophysical parameters

Remote Sensing Platforms: Remote sensing means acquiring and measuring information about an object or phenomenon via a device that is not in physical or direct contact with what is being studied.To collect remotely sensed data, a platform – an instrument that carries a remote sensing sensor – is deployed. From the mid 1800's to the early 1900's, various platforms such as balloons, kites, and pigeons carried mounted cameras to collect visual data of the world below. Today, aircraft (both manned and unmanned) and satellites collect the majority of remotely sensed data. The sensors typically deployed on these platforms include film and digital cameras, light-detection and ranging (LiDAR) systems, synthetic aperture radar (SAR) systems, and multi-spectral and hyper-spectral scanners. Many of these instruments can be mounted on land-based platforms, such as vans, trucks, tractors, and tanks. In this part, we will explore the different types of platforms and their resulting remote sensing applications.

Brief History of Aerial Imagery Platforms: Remote sensing is both an art and science. A skilled observer is tasked to view and measure items on the Earth's surface from a distance. This observer must possess knowledge about photography itself (imagery, film, processing techniques, development, etc.), but also know various ways to capture imagery. And, if there is no way to capture the image, then it must be invented!

Evelyn L. Pruitt of the U.S. Office of Naval Research first introduced the term "remote sensing" in 1960. However, years before satellites and digital imaging started dominating the field of remote sensing, people were taking pictures of the Earth's surface using various methods. Taking these pictures was difficult and often dangerous work.

Remote Sensing Platform Issues: Suffice it to say, designing a system that would take imagery from above the ground was (and is) not a simple task. The remote sensing "platform" needs to be able to carry the weight of a sensor, go up to and stay at a specific altitude, remotely take an image (or set of images) at a specific exposure (and possibly at a specific time), and then return that imagery back to the operator. These are issues that were not only faced by early remote sensing pioneers but continue today (with an added challenge of navigating air charts and controlled airspace!). They are issues that are constant across the development of remote sensing platforms and must be dealt with regardless of the platform: from balloons to pigeons to aircraft to satellites and even to today's small unmanned aircraft vehicals (UAV's). As we review the history of remote sensing platforms, we'll examine these various challenges and see how they were (and are) ultimately being addressed.

Balloons: In the mid-19th century, several inventors took to the air to experiment with balloon-based photography. In 1858, Gaspard Felix Tournachon (Felix Nadar) captured the first recorded aerial photography from a balloon tethered over the Bievre Valley, in France. Nadar continued his various endeavors to improve and promote aerial photography, taking "military photos" for the French Army's 1859 campaign in Italy, and later ascending several hundred feet to taking oblique photos of Paris from a tethered balloon (Figure 1a). In 1860, James Wallace Black and Sam King ascended to an altitude of 1200 feet and photographed portions of the city of Boston, managing to capture the oldest conserved aerial photograph (Figure 1b).

Balloons are not ideal platforms for aerial photography that required the use of slow exposures and wet photographic plates. Constant movement produced blurry images and flowing hydrogen compromised the plates themselves.

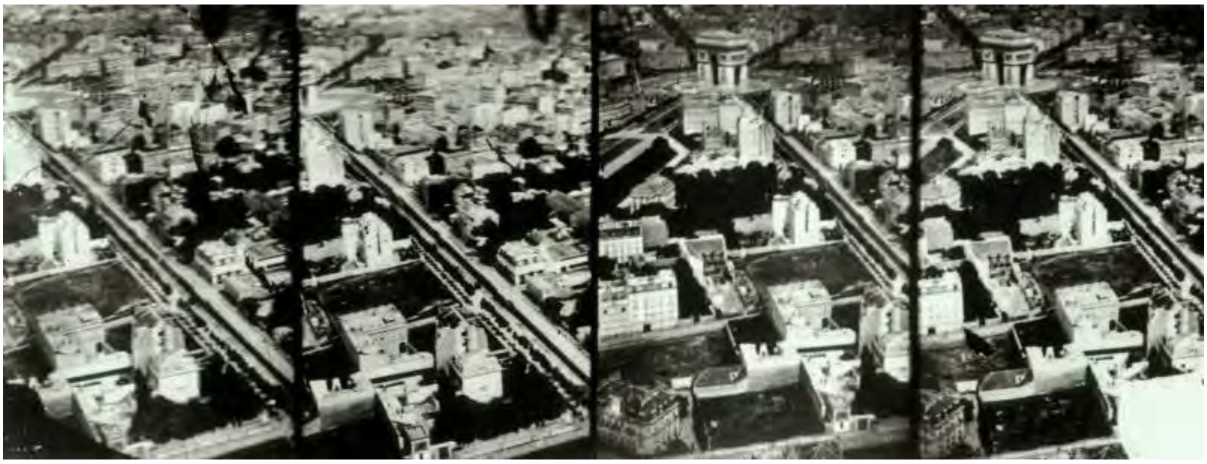


Figure 1a. Nadar's 1868 aerial image of Paris, taken from a tethered balloon.

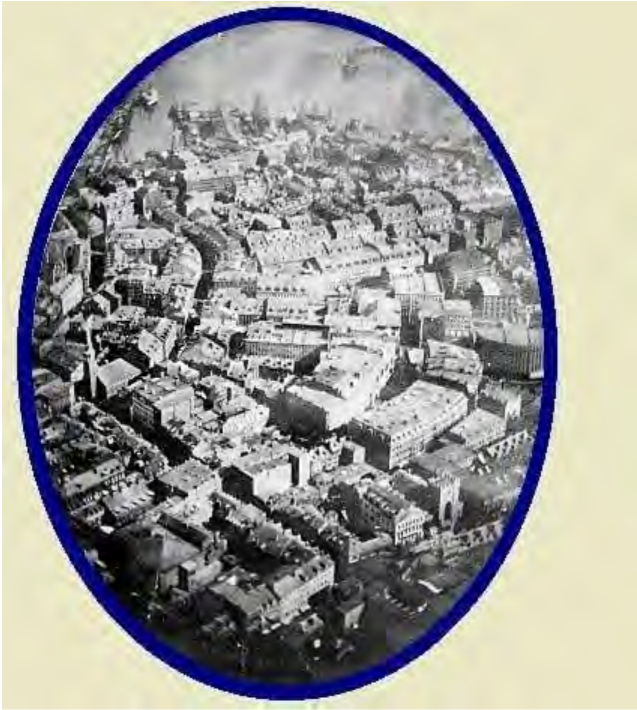


Figure 1b. James Wallace Black's 1860 aerial image of Boston

Kites: In 1884, Kodak revolutionized reconnaissance with its invention of roll film. Eliminating the need for heavy, glass plates allowed for the development of smaller, lighter cameras. This in turned allowed operators to transition from taking cameras up in hot air balloons to sending them up on kites—with explosives to trigger the shutter.

In 1888, Arthur Batut took the first aerial photographs over Labruguiere, France using a kite. The camera, attached directly to the kite, had an altimeter that encoded the exposure altitude on the film (allowing for scaling of the image). A slow burning fuse actuated the shutter within a few minutes after the kite was launched. A small flag dropped once the shutter was released to indicate that it was time to bring down the kite.

Pigeons: In 1903, camera miniaturization had become advanced enough that small, light cameras could even be attached to pigeons. Julius Neubranner designed a breast-mounted aerial camera specific for carrier pigeons. The 70-gram camera took automatic exposures at 30-second intervals along the pigeon flight line. Although faster than balloons, the flight path of the pigeon was not always reliable.

Airplanes: In 1909, a passenger flying with Wilbur Wright took the first documented aerial photograph from an airplane. But the first use of airborne surveillance and reconnaissance occurred during World War I, when Kodak K-1 cameras were attached to the side of planes to map trench networks. This method supplanted the traditional technique of aerial reconnassaince by sketching and drawing. Battle maps used by both sides were eventually created from these aerial photographs.

U-2 Aircraft: After World War II and through the 1950s, the Cold War with the Soviet Union created a need for reconnaissance planes to capture imagery in was that were more surreptitious than ever before, and required new types of planes that could fly high enough that Soviet planes and surface-to-air missiles could not shoot them down.

In 1954, President Dwight Eisenhower had the CIA -- working in conjunction with the U.S. Air Force -- negotiate an arrangement with Lockheed to develop such an airplane, the U-2 Aircraft. The U-2 first flew over of the Soviet Union on July 4, 1956 with a flight that began in West Germany and traveled over Poland, Belorussia, Moscow, Leningrad, and the Soviet Baltic states. It flew at 70,000 feet - about 25,000 feet higher than any other plane could fly at the time - and exposed 3,600 feet of film per mission using two high-resolution cameras. One camera with an especially long focal length allowed it to spot items on the ground that were two to three feet across. Eventually, on May 1, 1960, the Soviet Union was able to shoot down a U-2 over its territory with a cluster of missiles. The plane's pilot, Francis Gary Powers, survived, and in August 1960 the Soviets staged a highly publicized trial. The United States agreed to cease flying reconnaissance planes across the Soviet Union, Communist China, and Eastern Europe, though the U-2 was later used in other sections of the world, most noticeably Cuba and Vietnam.

Remote Sensing Platforms Today: The period from 1960 to today has experienced some major changes in the field of remote sensing in a variety of ways, including (but not limited to):

- The 1960s and 1970s saw the primary platform used to carry remotely sensed instruments shift from airplanes to satellites. Satellites can cover much more land space than planes, and can monitor areas on a regular basis.
- Also during this time, imagery became digital in format rather than analog. The digital format made it possible to display and analyze imagery using computers, a technology that was also undergoing rapid change during this period. In addition, digital sensors permitted the transmission of imagery from the platform itself to the ground station without a problematic film return system as was used on CORONA and other satellites.
- Sensors were becoming available that recorded the Earth's surface simultaneously in several different portions of the electromagnetic spectrum. One could now view an area by looking at several different images, some in portions of the spectrum beyond what the human eye could view. This technology made it possible to see things occurring on the Earth's surface that one could not detect by simply looking at a visual image.
- The turbulent social movements of the 1960s and 1970s awakened a new and continuing concern about the changes in the Earth's physical environment. Remotely sensed imagery from satellites - analyzed and enhanced with computers - made it possible to detect and monitor these changes. Societal support was and generally continues to remain strong for remote sensing technology.

Modern aerial sensors collect data using film, digital, LiDAR, synthetic aperture radar (SAR), and several other methods. Although satellites are considered primary platforms (collecting much of the data used by governmental and research organizations), other platforms such as ground-based and airborne platforms (including both manned and unmanned aircraft) are quite prevalent and popular. Different platforms can carry different types of sensors depending upon the needs of the user, and each platform offers advantages and disadvantages in terms of range, cost, stability, frequency, scale, and accuracy.

Type of Platforms: Three types of platforms are used to mount the remote sensors –

- Ground Observation Platform
- Airborne Observation Platform, and
- Space-Borne Observation Platform

Ground-based Platforms: Ground-based platforms include hand held cameras (film or digital), cranes, ground vehicles, tethered balloons, and even towers. Ground-based platforms typically provide up to 50 meters elevated remote sensing data and are useful for acquiring low altitude imagery with frequent coverage for dynamic phenomena. These types of platforms are relatively inexpensive, stable, and due to their low altitude, provide high-resolution data.

Airborne Platforms: Airborne platforms include airplanes, helicopters, unmanned aerial systems (UAS), high-altitude aircraft, and free-floating balloons. They range from the slow (single engine or light twin engine), low flying (less than 30,000 feet) aircraft to the faster (twin-engine turboprops or jet) that is capable of flying at altitudes above 30,000 feet. Airborne platforms can provide up to 50 km of elevated remote sensing data, and are useful for acquiring atmospheric data, can pin-point locations, and can be used for specific tasks such as precision agriculture, building maintenance, emergency response, mapping, and environmental monitoring.

Advantages	Disadvantages
User can control variables such as altitude	Can be expensive to rent aircraft
Time of coverage can be controlled	Aerial platforms can drift off-course (e.g., balloons)
Easy to mobilize in response to short-term disruptions (e.g., passing clouds)	Turbulent motions can be caused by unexpected altitude changes
Cost of small UAS relatively inexpensive to own and operate	Motion blurring can occur
	Lower atmosphere is heavily subject to airspace regulations that control UAV usage

The National Aerial Photography Program (NAPP) was coordinated by the United States Geological Survey (USGS) as a project to acquire cloud-free aerial photographs at an altitude of 20,000 feet above mean terrain elevation. NAPP photographs were taken with a 6-inch focal length lens at a scale of 1:40,000. Coverage over the conterminous United States includes both black-and-white (BW) and color infrared (CIR) aerial photographs. The NAPP program, which was operational from 1987 to 2007, consists of more than 1.3 million images.

Another aerial imagery program is the National Agriculture Imagery Program (NAIP). NAIP acquires aerial imagery during the agricultural growing seasons in the continental U.S. NAIP is administered by the United States Department of Agriculture’s (USDA's) Farm Service Agency (FSA) through the Aerial Photography Field Office in Salt Lake City. Imagery is acquired at a one-meter ground sample distance (GSD) with a horizontal accuracy that matches within six meters of photo-identifiable ground control points, which are used during image inspection. The default spectral resolution is natural color (Red, Green and Blue, or RGB) but beginning in 2007, some states have been delivered with four bands of data: RGB and Near Infrared.

The Remote Sensing Division at the National Oceanic and Atmosphere Administration (NOAA) is responsible for providing data to support the Aeronautical Survey Program (ASP), the Coastal Mapping Program (CMP) and Emergency Response efforts through the use of remotely sensed data. The ASP program collects data using field survey and photogrammetric methods to create runway approach procedures and airport obstruction charts. The CMP program works to provide a regularly updated national shoreline for supporting marine navigation, defining territorial limits, and managing coastal resources. Stereo photogrammetry and LiDAR are used to produce a digital database for a national shoreline. In addition, the Remote Sensing Division often acquires and rapidly disseminates a variety of spatially referenced datasets to federal, state, and local government agencies, as well as the general public. In its largest response effort, the NOAA collected over 8,000 aerial images of the hardest hit areas in Alabama, Mississippi, and Louisiana after Hurricane Katrina made landfall. These images were made available to emergency personnel and the public on the NOAA/NGS (National Geodetic Survey) website.

Unmanned Aerial Systems or Unmanned Autonomous System (UAS):UAS is an aircraft without an onboard pilot that is operated autonomously or manually by a remote-control operator. The terms unmanned aerial vehicle (UAV), unmanned aircraft systems/vehicles, remotely piloted aircraft (RPA), and drone, are often used interchangeably. They can be used to collect remotely sensed data for a variety of purposes, including business, agriculture, research, videography, journalism, and numerous others. UAS platforms typically adopted by geospatial researchers are considered small UAS (sUAS), weighing between 0.55 lbs (~0.2 kg) and 55 lbs (~25 kg) as designated by the U.S. Federal Aviation Administration (FAA; weight limits may vary in other countries).

UAS's are revolutionizing how researchers and practitioners model and analyze our world. Compared to traditional remote sensing approaches, UAS provide a largely inexpensive, flexible, and relatively easy-to-use platform to capture high spatial and temporal resolution geospatial data. Capturing imagery is the most common applicaion, and off-the-shelf, point-and-shoot digital cameras are a popular sensor option. Non-imagery applications of UAS include collecting measurements of temperature, pressure, humidity, and wind for atmospheric sampling and meteorology or environmental surveillance using sensors that can detect CO2, methane, and other gases for pipeline monitoring. LiDAR sensors have been employed for terrain and 3D mapping. Please see the DC-24 (Unmanned Aerial Systems) (link is external) for a more indepth discussion of drones and their applications.

Drone:Drone is a miniature remotely piloted aircraft. It is designed to fulfill requirements for a low cost platform, with long endurance, moderate payload capacity and capability to operate without a runway or small runway. Drone includes equipment of photography, infrared detection, radar observation and TV surveillance. It uses satellite communication link. An onboard computer controls the payload and stores data from different sensors and instruments. The payload computer utilizes a GSM/GPRS (where available) or independent satellite downlink, and can be monitored its position and payload status from anywhere in the world connected to the internet.

Drone was developed in Britain during World War-II, is the short sky spy which was originally conceived as a military reconnaissance. Now it plays important role in remote sensing. The unique advantage is that it could be accurately located above the area for which data was required and capable to provide both night and day data.

High Altitude Sounding Rockets:High altitude sounding rocket platforms are useful in assessing the reliability of the remote sensing techniques as regards their dependence on the distance from the target is concerned. Balloons have a maximum altitude of approximately 37 km, while satellites cannot orbit below 120 km. High altitude sounding rockets can be used to a moderate altitude above terrain. Imageries with moderate synoptic view can be obtained from such rockets for areas of some 500,000 square kilometers per frame. The high altitude sounding rocket is fired from a mobile launcher. During the flight its scanning work is done from a stable altitude, the payload and the spent motor are returned to the ground gently by parachute enabling the recovery of the data. One most important limitations of this system is to ensure that the descending rocket not going to cause damage.

Aircraft: Special aircraft with cameras and sensors on vibration less platforms are traditionally used to acquire aerial photographs and images of land surface features. While low altitude aerial photography results in large scale images providing detailed information on the terrain, the high altitude smaller scale images offer advantage to cover a larger study area with low spatial resolution.

The National High Altitude Photography (NHAP) program (1978), coordinated by the US Geological Survey, started to acquire coverage of the United States with a uniform scale and format. Beside aerial photography multi spectral, hyperspectral and microwave imaging is also carried out by aircraft; thereafter multi spectral, hyperspectral and microwave imaging were also initiated.

Aircraft platforms offer an economical method of remote sensing data collection for small to large study areas with cameras, electronic imagers, across- track and along-track scanners, and radar and microwave scanners. AVIRIS hyperspectral imaging is famous aircraft aerial photographic operation of USGS.

Spaceborne platforms: Spaceborne platforms include the space station as well as both low-level (700 to 1500 km) and high-level (~ 36,000 km) satellites. These types of platforms can acquire large areas of data in a short amount of time, which can be used to monitor Earth resources, atmospheric dynamics, and other applications.

Advantages of spaceborne remote sensing:

Spaceborne remote sensing provides the following advantages:

- Large area coverage;
- Frequent and repetitive coverage of an area of interest;
- Quantitative measurement of ground features using radiometrically calibrated sensors;
- Semi-automated computerised processing and analysis;
- Relatively lower cost per unit area of coverage.

CORONA: Satellites can trace their origins first back to the CORONA and then the Landsat programs. CORONA was a secret military reconnaissance program that continues in a modified form today, and Landsat (Land Remote Sensing Satellite Platform) was (and is) an open Earth resources program.

From the beginning of the U-2 program, there was concern that the Soviet Union would rapidly develop technology to intercept and down the spy airplane. Thus the United States (in 1956) embarked on developing a reconnaissance system that came to be called CORONA.

From the start, figuring out how to take an aerial image from space, and then bring the film back down to Earth, was a primary challenge. Ultimately, a satellite was designed to release a film canister in a parachute-wearing capsule that was to be recovered in mid-air by a specially equipped aircraft. The capsules were designed to float in water for a short period of time, and then sink if the mid-air recovery failed. On August 19, 1960, the first successful air catch was made of a capsule of exposed film ejected from a photographic reconnaissance satellite. The satellite had made seven passes over the "denied territory" of the Soviet Union, China, and the Eastern Europe, and 17 orbits of Earth. This successful launch started the age of space reconnaissance and revolutionized remote sensing.

Overall, the CORONA Program was extremely successful. Keyhole-1 (KH-1), the first CORONA satellite, carried a single panoramic camera that had a ground resolution of 40 ft by 40 ft. Advances were made with each mission and by 1967 and KH-4, cameras had 5 by 5 ft resolution and the separation angle allowed stereoscopic images to be created. A single CORONA mission could record more photographic coverage than all of the U-2 missions combined. By the time the CORONA Program was completed in 1972, over 800,000 images had been acquired in 121 launches and 156 recoveries. Keyhole reconnaissance satellites, though, continue to be developed today with the present KH-13's.

When CORONA ended in 1972 the United States launched the first Landsat satellite. Landsat is a spaceborne platform used for commercial, academic, and government uses, and has grown dramatically since its first launch.

Spaceborne Platforms: According to the Index of Objects Launched into Outer Space, maintained by the United Nations Office for Outer Space Affairs (UNOOSA), there are over 4800 satellites currently orbiting the planet in 2018 (link is external), and nearly 600 of them carry sensors that are used for Earth observation (Figure-2). The type of data that a sensor collects will span the electromagnetic sectrum, including sensors that detect visible light, thermal infrared, and radio (specifically, SAR – Synthetic Aperature Radar). The type of sensor residing on the platform and the type of orbit that the platform travels will be based upon the type of monitoring and data collection needed.

The monitoring capabilities of a satellite sensor are to a large extent determined by the type of satellite orbit. An orbit is a circular or elliptical path described by the satellite in its movement around the Earth. Different types of orbits are required to achieve continuous monitoring (meteorology), global mapping (land cover mapping), or selective imaging (urban, rural, or agricultural areas) to name a few.

Figure-2: Spaceborne platforms orbiting Earth.

Polar Orbit (or near-polar orbit): Polar orbit is an orbit with an inclination angle between 80 and 100 degrees. Such a polar orbit enables observation of virtually the whole globe as the Earth rotates underneath it. It takes approximately 90 minutes for the satellite to complete one orbit. This satellite is typically placed in orbit at 600 km to 1000 km altitude. These satellites have many uses such as measuring ozone concentrations in the stratosphere or measuring temperatures in the atmosphere. Advantages of polar orbits include: 1) They provide global coverage, and 2) because the orbits are relatively low altitude, they provide fairly high data resolution. The disadvantage of a polar orbit is that they cannot provide continuous viewing of one location.

Sun-Synchronous Orbit: The Sun-synchronous orbiting satellite passes over any given point on Earth's surface at the same local solar time (Figure 3). Because of the consistent lighting in Sun-synchronous orbits, scientists leverage this in various remote sensing applications, such as change detection monitoring.

Satellites that maintain Sun-synchronous orbits cover each area of the world at a constant local time of day called local Sun time. Therefore, at any given latitude, the position of the Sun in the sky as the satellite passes overhead will be nearly the same within the same season. This ensures consistent illumination conditions when acquiring images in a specific season over successive years, or over a particular area over a series of days. This is an important factor for monitoring changes between images or for mosaicking adjacent images together, as they do not have to be corrected for different illumination conditions. Altitudes of Sun-synchronous orbits are typically around 700 km to 850 km, with orbital periods between 90 to 100 minutes (or, about 14 orbits per day).

Earth resource satellites that are Sun-synchronous include (but are not limited to) Landsat, SPOT, Sentinel, POES, Quickbird, IKONOS, Beijing-1, Terra, Aqua, Aura, Skysat, and ZY-3. More information regarding these different satellites is in the Various Spaceborne Platforms and Their Characteristics section below.

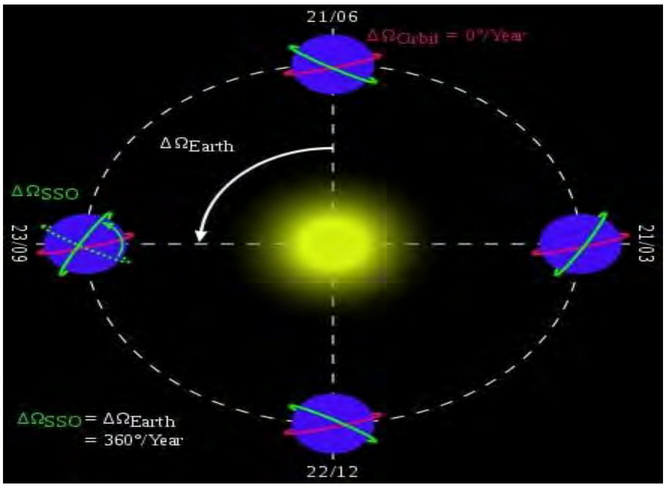


Figure 3: Sun-synchronous orbit. Diagram showing the orientation of a Sun-synchronous orbit (green) at four points in the year. A non-Sun-synchronous orbit (magenta) is shown for reference.

Geostationary Orbit: Geostationary orbits are located at a distance of 36,000 km above the Equator (inclination angle of 0 degrees) (Figure 4). At this distance, the orbital period of the satellite is equal to the rotational period of the Earth. The result is that the satellite is at a fixed position relative to the Earth. Geostationary orbits fall in the same category as geosynchronous orbits, but with that one special quality of being parked over the Equator.

Geostationary satellites are positioned at different longitudes in order to increase global coverage. Benefits of a geostationary platform include: 1) They can make repeated observations over a given area, and 2) one can achieve high temporal resolution data. For example, the GOES (Geostationary Operational Environmental Satellites) satellites provide a temporal resolution of 1 minute, effectively monitoring severe weather environments in real time. The disadvantage of geostationary platforms is that -- due to the high orbit -- the spatial resolution of the data is much lower than polar-orbiting satellites. Today's meteorological weather satellite systems use a combination of geostationary satellites and polar orbiters. The geostationary satellites offer a continuous hemispherical view of almost half the Earth while the polar orbiters offer a higher spatial resolution.

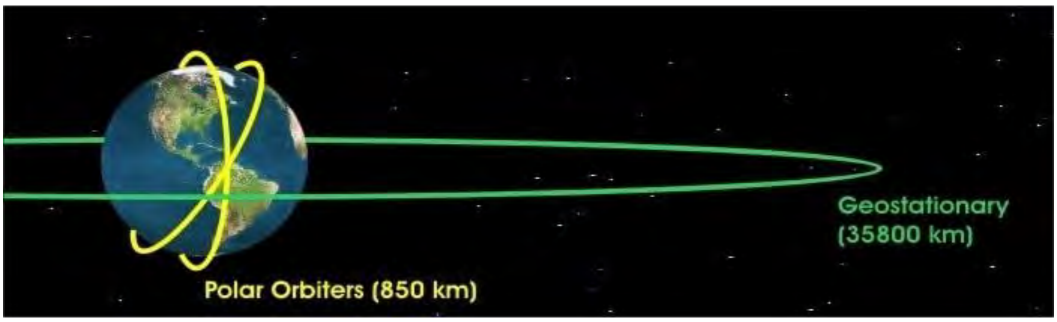


Figure 4. Geostationary versus polar orbiters.

Various Spaceborne Platforms and their Characteristics:

Landsat

In 1972, the National Aeronautics and Space Administration (NASA) began the Earth Resources Technology Satellite (ERTS-1), which later became Landsat-1. Each Landsat mission has been named in numerical order, with different sensor platforms defining what data is collected by its sensors. The Landsat-1 mission was a "proof-of-concept" that Earth orbiting satellites could effectively monitor natural and cultural resources. To date, there have been eight Landsat missions, with the 9th planned for launch in 2020 (Table 2).

Table 2. Characteristics of Landsat Missions

Satellite	Launched	Retired	Orbit (minutes)	Orbit Cycle (days)	Alt (km)	TM* Bands	MSS *** Bands	RBV*****Bands
Landsat 1	23 July 1972	1 June 1978	103	18	900	--	4,5,6,7	1,2,3
Landsat 2	22 January 1975	25 February 1982	103	18	900	--	4,5,6,7	1,2,3
Landsat 3	5 March 1978	31 March 1983	103	18	900	--	4,5,6,7, 8	--
Landsat 4	16 July 1982	15 June 2001	99	16	705	1 to 7	4,5,6,7	--
Landsat 5	1 March 1984	5 June 2013	99	16	705	1 to 7	4,5,6,7	--
Landsat 6	5 October 1993	Failed Launch						
Landsat 7	15 April 1999	still active	99	16	705	1 to 8**	--	--
Landsat 8	11 February 2013	still active	99	16	705	OLI and TIRS ****	--	--
Landsat 9	December 2020	yet to launch	99	16	705	OLI-2 and TIRS-2	--	--

* TM = Thematic Mapper (30m resolution, 120m resolution thermal).

** TM+ (30m resolution, 60m resolution thermal; 30m resolution for band 8 = panchromatic = 0.5-0.9mm).

*** MSS = Multispectral Scanner (80m resolution). 4=green, 5=red, 6=NIR, 7=NIR, 8=thermal

**** RBV = Return Beam Vidicon (80m resolution). 1=blue-green (475-575nm); 2=orange-red (580-680nm); 3=red-NIR (690-830nm)

***** OLI = Operational Land Imager (link is external); TIRS = Thermal Infrared Sensor (link is external)

Landsat provides a unique historical resource to assist a broad range of specialists in managing the world's food, water, forests, and other natural resources for a growing world population. Open access to its full image collection has been made possible via several online interfaces and this has enabled many geospatial applications.

SPOT

SPOT is the Système Pour l'Observation de la Terre, initiated by the French space agency in the late 1970's. SPOT was designed to improve the knowledge and management of Earth by exploring Earth's resources, detecting and forecasting phenomena involving climatology and oceanography, and monitoring human activities and natural phenomena. SPOT's off-nadir viewing gives the possibility to create stereo views of the landscape.

ZY-3A

China's first civilian high-resolution surveying and resource satellite, Zi Yuan-3A or ZY-3A, was launched in September 2012. The satellite sensors provide panchromatic imagery at 2.1m resolution and 3.6 m resolution for its forward- and backward-looking sensors. It also collects multi-spectral imagery at 5.8 m resolution. It is a near-polar, Sun synchronous satellite, flying at an altitude of 506 km, with a repeat orbital cycle of 5 days.

POES (Polar Operational Environmental Satellites): The POES satellite system offers the advantage of daily global coverage, by making nearly polar orbits 14 times per day at approximately 832 km above the surface of the Earth. The Earth's rotation allows the satellite to see a different view with each orbit, and each satellite provides two complete views of weather around the world each day. The National Oceanic and Atmosphere Administration (NOAA) partners with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) to constantly operate two polar-orbiting satellites: one POES and one European polar-orbiting satellite called Metop. The POES instruments include the Advanced Very High Resolution Radiometer (AVHRR) instrument (Table 3 and the Advanced TIROS Operational Vertical Sounder (ATOVS) suite. Data from the POES satellites supports a broad range of environmental monitoring applications including weather analysis and forecasting, climate research and prediction, global sea surface temperature measurements, atmospheric soundings of temperature and humidity, ocean dynamics research, volcanic eruption monitoring, forest fire detection, global vegetation analysis, search and rescue, and many other applications.

Table 3. Advanced Very High Resolution Radiometer (AVHRR) Bands

Band	Wavelength (µm)	Principle Applications
1	0.58 - 0.68	Daytime cloud and surface mapping, snow and ice extent.
2	0.725 - 1.0	Land-water boundaries, snow and ice extent.
3A	1.58 - 1.64	Vegetation and soil moisture. Delineate snow from clouds.
3B	3.55 - 3.93	Detecting hot targets such as forest fires, night cloud mapping, sea surface temperature.
4	10.30 - 11.30	Determining cloud and surface temperatures, day or night cloud mapping.
5	11.50 - 12.50	Determining cloud and surface temperatures, day or night cloud mapping, water vapor correction.

GOES (Geostationary Operational Environmental Satellites): The first GOES satellite launched in 1974. GOES satellites (GOES-13, -14, -15, and -16), operated by the NOAA, orbit the Earth in geosynchronous orbits. Because GOES satellites stay above a fixed spot on the surface, they provide constant monitoring of any atmospheric "triggers" that would cause severe weather conditions such as tornadoes, flash floods, hail storms, and hurricanes. When these conditions develop, the GOES satellites are able to monitor storm development and track their movements. GOES satellite imagery is also used to estimate rainfall during thunderstorms and hurricanes, as well as estimate snowfall accumulations and overall extent of snow cover. Satellite sensors also detect ice fields and map the movements of sea and lake ice.

Sentinel: The European Space Agency (ESA) is developing a new family of missions called Sentinels (Figure 5). Each Sentinel mission is based on a constellation of two polar-orbiting satellites that carry a range of technologies such as radar and multi-spectral imaging instruments for land, ocean, and atmospheric monitoring.

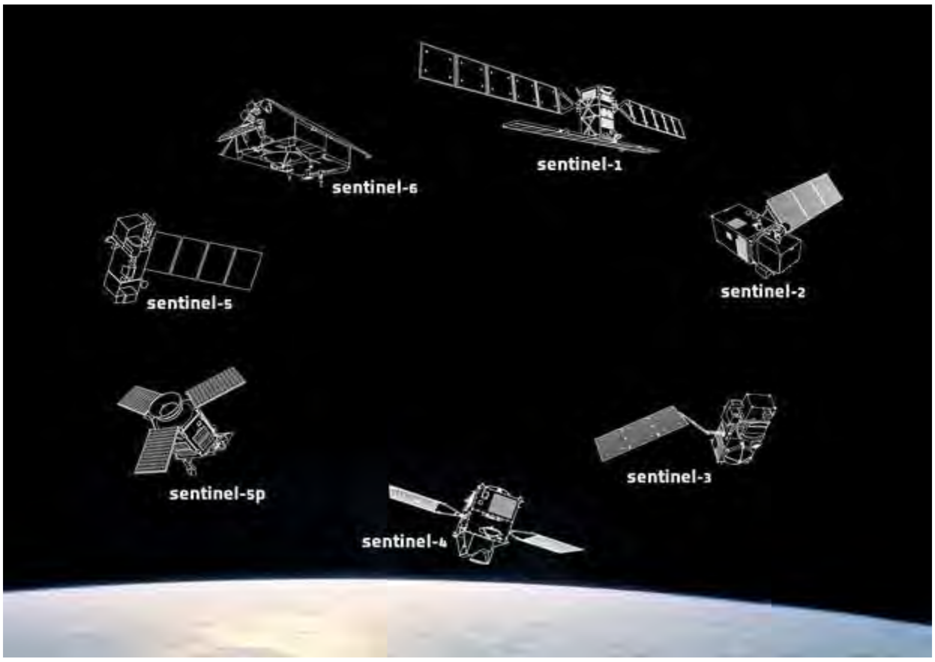


Figure 5: Sentinel family of satellites.

Commercial and Small Satellites: Commercial, small satellites are those satellites with low orbits and less mass compared to major satellites. They usually collect high-resolution data, are relatively low cost, and are flexible to launch. They can be designed, manufactured and launched by private companies, research institutions, or universities, and they are generally designed for special purposes.

In 1984, Congress established the legal framework for licensing and regulating a private satellite industry, but no industry emerged until 1993, when WorldView Inc. became the first U.S. company licensed to operate a commercial land observation satellite. NOAA (under the umbrella of the U. S. Department of Commerce) maintains information (link is external) on the Licensing of Private Remote Sensing Space Systems. The site is intended to provide U.S. laws, regulations, policies, and related information pertaining to the operation of private and commercial remote sensing satellite systems. The Mission of the NOAA Commercial Remote Sensing Regulatory Affairs (CRSRA) is to "regulate the operation of private Earth remote sensing space systems, subject to the jurisdiction or control of the United States, while preserving essential national security interests, foreign policy and international obligations. Its Vision is to balance commercial viability of private Earth remote sensing space systems and sound regulatory practices and policies while protecting national security, foreign policy and international obligations."

In 2014, the U.S. Department of Commerce (with support from the U.S. Departments of Defense and State), relaxed regulations regarding the distribution and sale of high-resolution imagery. Consumers can now purchase imagery at up to 0.25 m (25 cm) panchromatic and 1.0 m multispectral resolution. Prior to 2014, the U.S. federal government prevented companies from selling imagery with resolutions sharper than 0.50 m (50 cm).

The companies in the satellite imaging market sell images to businesses such as Google Maps and Apple Maps and governments by licensing the images to them. Consumers of remote-sensing data also include farmers, city planners, map-makers, environmentalists, emergency response teams, news organizations, surveyors, geologists, mining and oil companies, timber harvesters, and domestic as well as foreign military planners and intelligence organizations. The rising demand for high resolution and advanced satellite imagery across these various fields has led to the increased use of commercial satellites.

Some examples of commercial satellites include:

IKONOS: IKONOS was the first commercial Earth observation satellite to collect publicly available high-resolution imagery at 1m panchromatic resolution and 4m multispectral resolution. IKONOS (launched by a company called GeoEye) orbits at an altitude of 681km (with a revisit frequency of 3-5 days off nadir, and 144 days for true nadir). IKONOS brought imagery rivaling that of military spy satellites to the commercial market. IKONOS imagery began being sold on 1 January 2000. The spacecraft was retired in 2015, but the imagery is available in the DigitalGlobe library.

Digital Globe: Digital Globe is one of the bigger companies in the commercial satellite image collection industry. DigitalGlobe was founded in 1992 under the name WorldView Imaging Corporation (in 2013, DigitalGlobe combined with GeoEye). Today, DigitalGlobe owns and operates a sophisticated constellation of high-resolution commercial Earth imaging satellites. Together, WorldView-1, GeoEye-1, WorldView-2, WorldView-3 and WorldView-4 are capable of collecting well over one billion square kilometers of quality imagery per year and offering intraday revisits around the globe. Table 4 below highlights some of the major characteristics of presently operational DigitalGlobe satellites.

Table 4. DigitalGlobe Constellation of Commercial Satellites

Feature	WorldView-1	GeoEye-1	WorldView-2	WorldView-3	WorldVIew-4
Operational Altitude	496 km	681 km	770 km	617 km	617 km
Spectral Characteristics	Panchromatic	Panchromatic + 4 multispec	Panchromatic + 8 multispec	Panchromatic + 8 multispec + 8 shortwave/IR	Panchromatic + 4 multispec
Panchromatic Resolution (nadir)	0.50 m	0.41 m	0.46 m	0.31 m	0.31 m
Multispectral Resolution	NA	1.64 m	1.85 m	1.24 m	1.24 m
Average Revisit at 40ºN Lat.	1.7 days	< 3 days	1.1 days	1.0 day	1.0 day

QuickBird: QuickBird is a high-resolution commercial Earth observation satellite owned by DigitalGlobe that launched in 2001 (and decayed in 2015). The satellite collected panchromatic imagery at 61 cm resolution and multispectral imagery at 2.44 m - 1.63 m resolution (at 450 km and 300 km altitude, respectively). The orbit altitude lowered during the end of its mission life. At this resolution, details such as buildings and other infrastructure were easily visible.

Beijing-1: Beijing-1 is a low-cost Earth observation satellite established by a private company (BLMIT) to manage commercial data distribution and services. The platform carries two payloads that provide high-resolution (4 m) panchromatic images alongside medium-resolution (32 m) multi-spectral images. Beijing-1 provides the Chinese government and commercial users with information on agriculture, water resources, environmental, and disaster monitoring throughout China. The satellite is also used for monitoring urban development and pollution. Beijing-1 is capable of continuously imaging Chinese territory even at the longest landmass track (3000 km) and transmits images to the groundstation in Beijing in real-time. Beijing-1 orbits at an altitude of 699 km, and is a member of the Disaster Monitoring Constellation.

SkySat: SkySat is a constellation of sub-meter resolution Earth observation satellites owned by Planet Labs that provide high-resolution panchromatic and multispectral imagery, high-definition video, and analytics services. Planet Labs acquired the satellites with their purchase of Terra Bella (formerly Skybox Imaging) from Google in 2017. The resolution of the SkySat satellite imagery and videos is high enough to observe objects that impact the global economy such as terrain, cars and shipping containers. The satellites can capture video clips lasting up to 90 seconds at 30 frames per second. When Skybox originally developed the satellites, they planned to "change the nature" of the satellite industry by building satellites with "off-the-shelf" electronics that cost under $50 million. The SkySat satellites are based on the CubeSat concept, using inexpensive automotive grade electronics and fast commercially available processors, but scaled up to approximately the size of a minifridge. CubeSat is a type of miniaturized satellite that is made up of multiples of 10x10x10 cm cubic units, having a mass of no more than 1.33 kg per unit. SkySat satellites are approximately 80cm long and weigh 220 lbs. The satellites operate in a polar inclined, circular orbit at approximately 450 km above the earth.

EROS: EROS is a series of Israeli commercial Earth observation satellites, designed and manufactured by Israel Aircraft Industries (IAI). The satellites are owned and operated by ImageSat International, another Israeli company. EROS A was launched on December 5, 2000 to an altitude of 480 km. The satellite provides commercial images with an optical resolution (link is external) of 1.8 m. The satellite orbits Earth in a Sun-synchronous orbit, so that its imaged target is always in daylight. EROS A always crosses the equator (link is external) at 9:45am local time. EROS A has a height of 2.3 m and a diameter of 1.2 m. It weighs 250 kg. EROS B was launched on April 25, 2006. The satellite offers an optical resolution of 70 cm (about two feet).

NASA's Earth Observing System (EOS): NASA's Earth Observing System (EOS) is a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans (Figure 6). The satellite component of the program was launched in 1997. Table 5 shows some of the active platforms of the EOS system, their launch date, and their mission description.

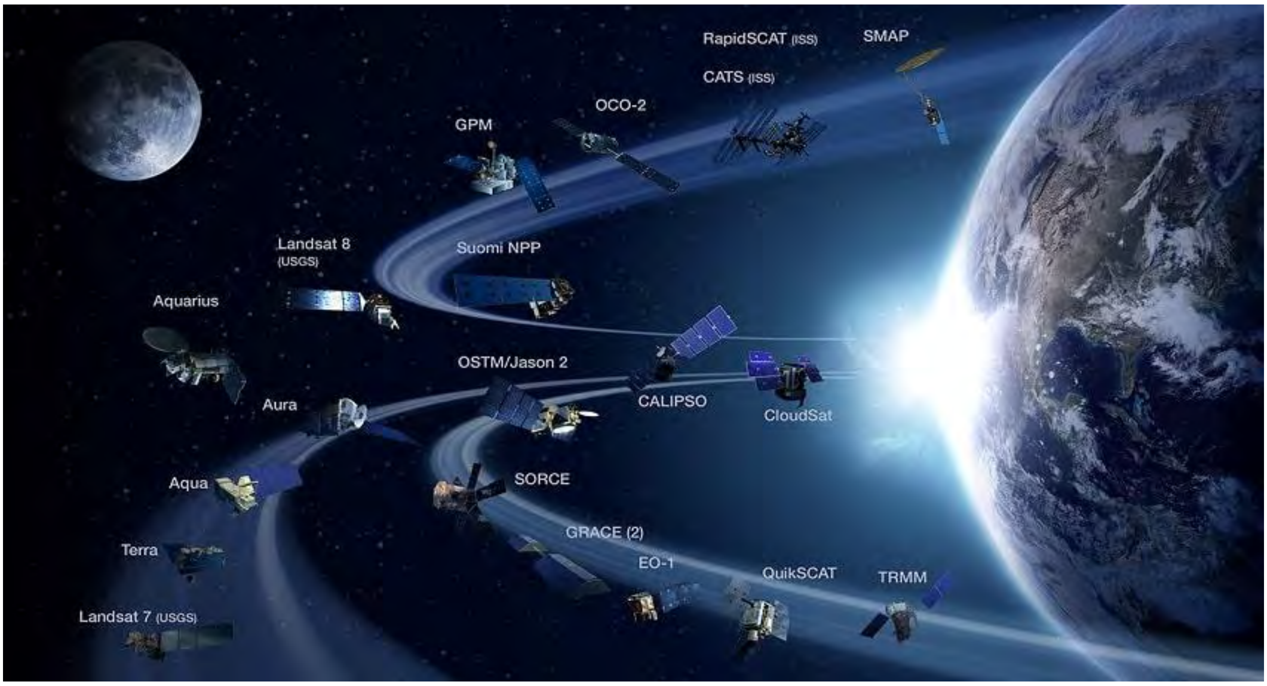


Figure 6. NASA's Earth Observing Satellites (EOS) and their Mission Descriptions

Table 5. Earth Observing Satellites (EOS) and their Mission Description

Satellite	Launch Date	Mission Description
Landsat-7	15 April 1999	Supply the world with global land surface images
Terra ("Earth")	18 December 1999	Monitor the state of Earth's environment and ongoing changes in its climate system
Aqua ("Water")	4 May 2002	Study the precipitation, evaporation, and cycling of water
Aura ("Air")	15 July 2004	Study the Earth's ozone layer, air quality, and climate
CloudSat	28 April 2006	Provide the first direct global survey of the vertical structure and overlap of cloud systems and their liquid and ice-water contents
Landsat-8	11 February 2013	Supply the world with global land surface images
OCO-2	2 July 2014	Provide space-based global measurements of atmospheric carbon dioxide
SMAP	31 January 2015	Measure surface soil moisture and freeze-thaw state

Remote Sensing Applications: Once data or derived products are delivered to the users, they are utilized for a wide range of applications. Applications include, but are not limited to: map making, land use, crop monitoring, natural resource management, registry of lands, urban planning, studies of environment, and verification of claims. Amongst other uses, satellite remote sensing is suited for monitoring and protection of the environment. This book focuses on the environmental and disaster management applications.

The Earth's environment includes the atmosphere, land, and oceans. Environmental applications include the assessment of land mass (including forests), and air and marine pollution. Global warming is an imminent environmental problem; satellite remote sensing is useful in monitoring the oceans, ice, atmosphere, and forests to provide key information on the environmental components, as well as evidence of global warming. Present data and past data can be compared to assess the extent and rate of deforestation, desertification, and loss of polar ice. Deforestation in the Amazon, for instance, has been the subject of many studies. Satellite images are also used for verification of environmental harm in specific areas of interest. Many lawsuits centre on the presence of toxic material in the air, water, or soil and satellite data is an effective tool to verify such claims. In particular, detection of oil slicks is a major application for verification purposes.

Satellites have provided data on earthquakes, floods, landslides, and fires. Satellites can monitor the progress of hurricanes and fires as well as measure the extent of damage from earthquakes and floods in the aftermath. The data becomes a vital tool to identify the damaged areas for an effective disaster response. Indeed, following the 2004 Indian Ocean Tsunami, a number of satellite images were provided and used to assess the location and the extent of the devastation, and to direct relief services and aid agencies most effectively by comparing these images with those taken before the tsunami. Critical decisions were made based on the satellite images to identify the overall extent of the disaster, as well as to conduct street level damage assessment to give the necessary direction for aid.

Some Remote sensing applications and uses:

- Determining soil moisture content using active and passive sensors from space
- Mapping with laser precision using Light Detection and Ranging technology
- Catching tax-evaders red-handed by locating new construction and building alterations
- Spinning the globe with mapping services like Google Earth, Bing Maps and OpenStreetMaps
- Predicting retail earnings and market share by counting cars in parking lot
- Snapping aerial photos for military surveillance using messenger pigeons in World War II
- Charging higher insurance premiums in flood-prone areas using radar
- Doing the detective work for fraudulent crop insurance claims
- Searching for aircrafts and saving lives after fatal crashes
- Detecting oil spills for marine life and environmental preservation
- Counting polar bears to ensure sustainable population levels
- Uncovering habitat suitability and fragmentation for panda bears in protected areas
- Identifying forest stands and tallying their area to estimate forest supplies
- Navigating ships safely with the most optimal route

- Measuring wind speed and direction for wind farms, weather forecasting and surfers
- Spying on enemies with reconnaissance satellites
- Delineating and assessing the health of riparian zones to conserve lakes and rivers
- Estimating surface elevation with the Shuttle Radar Topography Mission
- Extracting mineral deposits with hyperspectral remote sensing
- Watching algae grow as an indicator of environmental health
- Forecasting weather to warn about natural disasters
- Detecting land cover/use types for decision making
- Monitoring the environment with the ESA's Copernicus Program
- Mapping soil types for agriculture planning
- Preventing the spread of forest disease types
- Fighting wildfires by planning firefighter dispatch
- Monitoring air quality in the lower atmosphere
- Assessing terrain stability using interferometry in the oil and gas sector
- Unearthing ancient archaeological sites like the Mayans and ancient Egypt
- Pinpointing your position on Earth with Global Positioning Satellites
- Optimizing solar panel energy output with global horizontal irradiance
- Finding the driving factors that contribute to poverty
- Observing the flow of ocean currents and circulation
- Studying glacier melts and effects on sea levels
- Providing a base map for visual reference and assisting orient the map reader
- Snorkeling in an oasis of marine vegetation with the coastal channel
- Tracking hazards for better response and recovery
- Keeping tabs on the shift from rural to urban growth
- Quantifying crop conditions with Normalized Difference Vegetation Index (NDVI)
- Preventing the degradation and loss of wetland ecosystems
- Tracking sediment transport into rivers and lakes
- Saving money and time on the farm with precision farming
- Reversing illegal rainforest cutting in Brazil
- Putting illegal boat dumping under the microscope
- Inventorying and assessing rural road conditions with UAVs
- Driving with no hands (autonomous vehicles)
- Measuring gravity with the GRACE satellites
- Deriving elevation and contours using photogrammetry
- Watching the aurora borealis from another angle
- Comparing the past and present with human impact change
- Planning an optimal telecom network capacity
- Tracking displaced refugees to help deliver aid and services
- Keeping a watchful eye to prevent future atrocities from happening
- Designing a lift irrigation system to supply water in India
- Measuring the volume difference at a uranium enrichment site using 3D mapping

Terrestrial Applications of Remote Sensing: Each day, millions of individual images and observations collect an enormous variety of information about the Earth's surface and subsurface. This routine surveillance enables the monitoring and modeling of ecosystem health, detecting seismic activity, identifying surface vegetation, promoting sustainable agriculture, and characterizing the physical and social vulnerability of human settlements.

Continuous advances in satellite remote sensing and geospatial technology have dramatically accelerated our understanding of environmental phenomena— extracting data which is often invisible (or less visible) from the ground—allowing us to develop innovative solutions to ever more complex social, environ- mental, and economic challenges. Decreasing costs of computing technology and satellite imagery; increasingly robust proprietary and open source software; rapid availability of geospatial data easily acquired online; higher quality image resolutions (e.g., under 1 m); and the ever-greater number of satellite sensors have all contributed to transformational changes in every field of study and professional practice.

Terrestrial applications of remote sensing include mapping, change detection, monitoring, modeling, and other observations of land uses stemming from human activities. For example, remote sensing has shown great promise to map and monitor land use and land cover change (LULCC) in an efficiently and cost-effective manner. Utilizing remotely sensed data may be the only viable mechanism for tracking LULCC changes at the subregional, regional, and global scales. An exhaustive review of terrestrial remote sensing applications is beyond the scope of this chapter. However, this chapter does provide examples of demonstrative case studies of the diverse and exciting ways that remote sensing has been put into use in tackling difficult local, regional, and global challenges.

Classifying Land Use and Land Cover: One of the most frequently used applications of remote sensing is in the creation of land use and land cover (LULC) maps. LULC maps are created by taking an image and categorizing natural and artificial features into representative groups or “classes”. Resource managers and researchers use LULC maps to study everything from plant composition to human settlement patterns, as well as to answer questions such as “how is vegetation changing and why?” Several large- scale LULC studies include the European Environmental Agency’s classification of 25 European Union member states and other European countries and the UN Food and Agricultural Organization’s (UNFAO) LULC mapping of the Sahel region of West Africa. In addition, new initiatives are increasingly being taken by agencies acting at national, regional, or global level in an effort to establish a base data layer for LULC to enable the monitoring of LULCC at all scales.

In 2010, China initiated the Global Land Cover (GLC) mapping project, the aim of which was to produce a 30 m GLC data product (GlobeLand30) with ten land cover classes for the years 2000 and 2010 within a 4-year period. Over 10,000 Landsat-like satellite images were combined to cover the entire Earth at 30 m resolution. The project thus far has produced many interesting datasets relating to various aspects of land cover and its relation with the availability of water and other natural resources. As always, accuracy is an important consideration. According to Gong et al. (2013), the first attempt to conduct an accuracy assessment on the GLC dataset was an experimental evaluation on the usability of existing automated classification techniques. Four classifiers, that is, Maximum Likelihood Classifier (MLC), J4.8 Decision Tree Classifier (DT), Random Forest Classifier (RF), and Support Vector Machine (SVM) were tested with more than 8000 images captured during the year 2000. It was found that the highest overall classification accuracy (OCA) was produced by SVM, at 64.9 %.

There are other major programs of interest at national level in the US involving LULCC mapping. A good example is the Multi-Resolution Land Characteristics (MRLC) Consortium involving a number of the US Federal agencies. Starting in the mid-1990s, MRLC has grown into a group of ten agencies that coordinate the production of five different products, including the National Land Cover Database (NLCD), the Coastal Change Analysis Program (C-CAP), the Cropland Data Layer (CDL), the Gap Analysis Program (GAP), and the Landscape Fire and Resource Management Planning Tools (LANDFIRE). As described by Wickham et al. (2014), these products include almost every aspect of land cover from impervious surface to detailed crop and vegetation types to fire fuel classes. Some products can be used for land cover change assessments because they cover multiple time periods. The MRLC Consortium has become a collaborative forum, where members share research, methodological approaches, and data to produce products using established protocols, and we believe it is a model for the production of integrated land cover products at national to continental scales.

Another example is the North American Landscape Characterization (NALC) project that has produced LULC data for the entire US. The NALC project was sponsored by the US Environmental Protection Agency's (EPA) and the US Geological Survey, EROS Data Center. This project is a component of the National Aeronautics and Space Administration's (NASA) Landsat Pathfinder program of experiments to study global change issues.

At the regional scale, monitoring urban growth is one of the questions social scientists, urban planners, and decision makers deal with most frequently. The direct impacts of urban expansion on physical, ecological, and social resources have made research on urban sprawl an issue of increased interest. Traditional census sources are extremely useful in that they capture changes in the socioeconomic and demographic structure of cities, but they lack spatial details and are not frequently updated.

Remote sensing, in contrast, makes available a vast amount of data with continuous temporal and spatial coverage and can, therefore, provide a successful means for monitoring urban growth and changes. Current research is oriented toward the use of remotely sensed data in conjunction with demographic and socioeconomic data to study urban change dynamics or to better understand the spatial distribution of population and socioeconomic phenomena.

This has been particularly important in developing countries where many cities are experiencing a rapid increase in population and consequential urban expansion, and where remote sensing may provide fundamental observations of urban growth that are not available from other sources.

Most of the research on urban growth is still based on traditional land cover classifications and change detection methodologies, but recently there has been a shift toward the development of integrated datasets that can be used in planning and urban monitoring efforts. Such relatively new trends include, for example, the development of urban environmental quality and quality-of-life indices to monitor physical and social changes in cities.

Turning to the local scale, Hester et al. (2009) produced LULC maps from high-resolution satellite (Quickbird) data of an area in Raleigh, North Carolina that was subsequently used for impervious area estimation, land use change detection, and water quality studies.

Understanding and Protecting Biodiversity through Wildlife Tracking: Our understanding of large animal movement, migration patterns, and habitat utilization patterns are largely tied to the landscape. As these animals move over large geographic areas, our understanding of their movement patterns can often be quite limited. Common approaches have involved tagging and recapturing animals in different locations, whereas more modern approaches involve monitoring active animal movement with radio telemetry applications. Newer approaches include the process of "bio-logging". Bio-logging, which uses small animal-attached tags for recording and/or relaying of data about an animal's movements, behavior, physiology, and/or environment, has led to important new discoveries about migratory patterns, habitats, breeding and wintering grounds, speed of migration, orientation, the influence of weather conditions and climate change, and an enormous host of other factors.

Studies conducted in the field offer unique opportunities to observe natural phenomena; however, there are many challenges—from being prohibitively expensive to logistically difficult. Wildlife biology has advanced through an influx of technology in which audio and video recordings, GPS, and satellite remote sensing are important aids in gaining biological and physical information from free-ranging species. The ARGOS satellite system, created in 1978 by the French Space Agency (CNES) to collect and relay meteorologic and oceanographic data, is one of the most established satellite-based systems used to track mammals, marine animals, and birds across the globe.

Direct remote sensing from aerial platforms has also been applied to larger animal movement studies. Often, all of these approaches are limited to observing only a few animals at a time, and within a manageable/limited spatial scale, due to cost, the labor involved, and the time necessary to complete the study. Satellite remote sensing, despite its potential to provide data over a large spatial scale and at a relatively low cost, has been applied a lot less to larger animal inventories and tracking animal movement studies. However, large, region-scale, satellite imagery has been useful in monitoring associated vegetation and landscape usage of animals.

Verlinden and Masogo (1997) used Normalized Difference Vegetation Index (NDVI) data products generated from the Advanced Very-High-Resolution Radiometer (AVHRR-NOAA) sensor to correlate habitat greenness estimates with species density distributions of ostrich populations (*Struthio camelus*) and large, grazing herbivores: wildebeest (*Connochaetes taurinus*), hartebeest (*Alcelaphus buselaphus*), eland (*Taurotragus oryx*), and gemsbok (*Oryx gazella*). This study was carried out in the semi-arid region of the Kalahari Desert, Africa. The Kalahari Desert comprises an area of over 900,000 km^2 and encompasses much of Botswana, and parts of Namibia and South Africa. Larger animal species in this region must travel over large distances in search of grass "greenness" patches in order to fulfill their water and nutrient requirements. The green patches of grasses result from rainfall, which may be highly variable both temporally and spatially. For this study computer-generated density and distribution models were developed for each species, coupled with rainfall data and field observations made from aircraft. The generated density and distribution estimates were compared to NDVI data. The NDVI data used consisted of 10-day composite data and were derived from corrected and georeferenced Global Area Coverage (GAC) data with a resolution of approximately 4 × 4 km. The GAC dataset is comprised of a reduced resolution image data that is processed while onboard the AVHRR satellite platform. The AVHRR-GAC data are resampled by extracting one line out of every three captured and averaging four of five adjacent samples along the sensor's scan line. This process results in a reduced resolution image apart from the original 1.1 km resolution image data.

The Verlinden and Masogo (1997) NDVI model results showed low, but significant, correlations to aerial survey greenness scores (Spearman rank correlation was 0.43, $p<0.001$). NDVI model results also showed low, but significant, correlations to ground-sampled greenness scores (Spearman rank correlation was 0.33, $p < 0.001$). These significant positive relationships between NDVI and grass greenness (both aerial survey and ground sampled) suggested that, with some caution, NDVI estimates could be used in this area to monitor greenness. Relationships between NDVI and animal distribution proved more difficult to determine. However, the NDVI-greenness correlations may show a means of assessing habitat suitability, on a regional scale in the Kalahari, for a few of the species examined (i.e., wildebeest, hartebeest, and ostrich).

Researchers and environmental managers may be beginning to view image analysis applications derived from remote sensing as an efficient and promising means of confronting data gaps in inventory challenges, status and trend monitoring, recovery planning, and predictive assessments of species biodiversity and wildlife population management. Current limitations of spaceborne remote sensing and the development of effective management approaches in tracking and monitoring animal movement include identifying an appropriate scale of study, as well as the availability and appropriateness of the type and resolution of the remotely sensed data or remotely sensed data product required. However, with the continuing evolution of sensor technologies ever expanding, as well as higher sensor ground spatial resolutions becoming more commonly available, the ability to use spaceborne sensors may provide an efficient means of investigating animal movements over larger spatial scales. The potential of integrating remote sensing and geospatially derived data-driven analyses may additionally have a huge impact on the public, as well as on professionals within the field, and further increase the possibility for the use of these technologies to create opportunities for greater public and scientific discussion.

Water Resources: Surface water supply, reservoir mapping and monitoring, water quality mapping and modeling, runoff forecast modeling, drainage network mapping, hydrologic research, watershed characterization, and surface water impairment are all water-resources-related candidates for remotely sensed data applications.

Changes in land use and land cover may have severe impacts on aquatic ecosystems. Activities such as agriculture, urbanization, and erosion are primary sources of sediment and nutrient input into water bodies. A few examples of the consequences of increased sediment and nutrient loading on water bodies include the loss of littoral or coastal zone habitat, eutrophication, depletion of oxygen, and changes in food webs dynamics.

Nonpoint source pollution (NPS) is the term used to describe loadings to water bodies from diffuse sources within the landscape. These sources make up nutrient and chemical pollutants from developed areas, construction sites, paved surfaces, cultivated fields and pasture lands, and atmospheric deposition. However, despite the variety of pollutants classified as NPS, sediments are the largest amounts of material transported to surface waters. Approximately 60 % of all sediment and sediment-associated contaminants delivered to the US's rivers, lakes, and coastal regions are from agricultural soil loss.

Remote sensing provides a unique technological advantage in monitoring aquatic systems due to its ability to capture data over large areas, and assorted spatial and temporal resolutions. However, satellite remote sensing of aquatic systems has been less studied as a result of the difficulties inherent in interpreting reflectance values of water. Clear water provides little spectral reflectance because longer wavelengths are absorbed and the reflected shorter wavelengths, which sensors rely on for surface feature detection, are subject to higher atmospheric scattering. Due to the absorption of longer wavelengths, most deep and clear water bodies appear dark on unclassified satellite imagery. Sensors, such as the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM), were primarily designed for land studies, and thus are not completely applicable to aquatic studies. Recent improvements in sensor technologies have allowed for better spatial and spectral resolutions than previously available, which may improve their usefulness to aquatic studies.

In a study by Nelson et al. (2003), Landsat-7 data were used to investigate the relationship between spectral values extracted from Landsat Enhanced Thematic Mapper (ETM+) data and water clarity using Secchi disk transparency (SDT) measurements The SDT measurements incorporated the range of SDT values found within a geographic region comparable to 80 % of the lakes within the lower peninsula of Michigan, US. The Secchi depth is inversely proportional to the absorbance of light by water and dissolved or particulate substances, such as algal biomass.

This study represented an assessment of water clarity on a regional scale using remotely sensed data and identified an important consideration necessary for modeling water clarity on such a large scale—models developed for large regions must incorporate the full range of lake SDT values found throughout the region in the model calibration. Models that incorporate this complete range of SDT values, such as the one developed in this study, may not produce statistical relationship results as high as models that are developed for groups of lakes that do not incorporate the full regional range of SDT values. In addition, these results suggest that Landsat may be better suited for predicting shallow SDT values (i.e., eutrophic- higher algal biomass) than clearer water containing deeper SDT values. These types of models, based on remotely sensed data, have the capacity to provide managers with a method to inventory shallow SDT lakes across the entire state where in situ data are difficult to obtain. In particular, regulatory and management agencies would be able to monitor private lakes without spending resources on these lakes and without requiring the permission of the property owner. Additionally, models developed from remotely sensed data may be useful in the historical analysis of watershed changes that may have caused lake eutrophication to occur over time. This application is a very attractive use of remote sensing since historical imagery may be obtained for aquatic systems that have become eutrophic over time.

Beyond this specific study, despite current limitations, remote sensing does possess the potential to provide a valuable tool for monitoring freshwater systems. Several studies have successfully used remote sensing to measure characteristics of aquatic systems such as chlorophyll and SDT suspended sediments, and dissolved organic matter. Other studies have used remote sensing to map aquatic plant abundance in large areas of homogenous cover or for species detection in smaller areas they have used high-resolution hand or aircraft sensors. While remote sensing has been used in large-scale land change studies for many years, few studies have used currently available remotely sensed data to develop standardized methods for measuring water quality parameters across a wide range of aquatic environments, over large regions, or covering multiple images.

Accessing water quality parameters on a regional scale provides a challenge in that regional remote sensing requires that multiple remotely sensed images be combined from multiple dates or regions of varying atmospheric influences (i.e., haze, cloud cover, etc.). Multitemporal image-to-image differences are a result of atmospheric absorption and light scattering, which can be highly variable from one period of time to the next (Moore 1980). This difference can have a pronounced effect on the interpretation of imagery for trend analyses when using multiple images that are collected on different days, months, or years. Song et al. (2001) found that atmosphere corrections are necessary when using two or more satellite images collected on different dates, such as imagery used in land use/cover change studies. For example, for aquatic studies, Brivio et al. (2001) found that without the appropriate corrections for atmospheric scattering and transmittance effects, successful remote sensing of water quality parameters could not be accurately achieved from four Landsat TM images. Brivio et al. (2001) were able to develop two image-based rectification models which were used to correct regional atmospheric effects in multi-seasoned Landsat images of Lake Lseo and Lake Garda, Italy. However, accurate and simple procedures to correct for these effects are still an area of future research.

These atmospheric limitations may be reduced by many recent technological advances. A few of the newest sensors include IKONOS, the Earth-Observing System (EOS) Terra sensors, and the Landsat ETM+. These sensors will ultimately employ more advanced data calibrations than was possible with some of the older sensors. However, the advantage of the older Landsat platforms is that they provide consistent historical data not yet available from new sensors, and the temporal and spatial resolutions provided by Landsat MSS and TM are still more effective in monitoring landscape changes. For example, since the early 1980s, remote sensing techniques have become commonly used to detect wetland change. However, few studies have taken advantage of the wealth of historical data available from the satellite platforms that have been operating across several decades, and that are becoming widely available and inexpensive. Images obtained using the Landsat MSS sensor presently represent our longest, continuous satellite remotely sensed historic record.

The availability of newer data will, however, allow for the integration of cross-platform data in developing band and image sharpening algorithms which will serve to fill in the gaps present in the older system data acquisitions (clouds, haze, etc.) and enhance the ability to develop multi-image calibrations for cross referencing. Furthermore, three of the main Terra sensors (MODIS—Moderate Resolution Imaging Spectrometer, ASTER—Advanced Spaceborne Thermal Emission and Reflectance Radiometer, and MISR—Multi-angle Imaging Spectroradiometer) have been identified as being particularly useful in the remote sensing of large-area land cover and land use changes and vegetation dynamics studies. However, aquatic remote sensors have yet to see the production of sensors specifically designed to monitor aquatic environments.

Currently, Landsat provides one of our richest data sources for the remote sensing of historical changes in large areas of wetlands, water quality, and aquatic plants. This is evident from the high revisit cycle, spatial resolutions, and 30 years of operation provided by these sensors.

Forest Resources: Applications of remotely sensed data to forest resources and environmental management are numerous. Examples may include any of the following applications:

- Forest canopy extent and structure mapping
- Forest health mapping and monitoring
- Timber inventory
- Forest-type mapping
- Timber stand conditions assessment
- Harvesting and procurement priority implementation
- Reforestation
- Deforestation

Deforestation, the clear-cutting of forests for subsequent conversion to other land uses, is common throughout much of the world, especially in tropical regions. During the past decade, the five countries with the highest rates of forest loss (Brazil, Papua New Guinea, Gabon, Indonesia, and Peru) lost a combined 3.6 million hectares of primary forest each year. Large-scale deforestation has major implications for ecosystem function and biodiversity, as well as climate change, since it affects regional carbon storage and sequestration. In addition, selective logging is widespread in rapidly deforesting areas such as the Amazon, further exacerbating the ecological impacts.

Deforestation is typically driven by economic pressure (i.e., a perceived economic incentive for forest conversion rather than conservation) and is usually facilitated by limited governmental oversight in the affected regions. Because of the lack of regulatory enforcement, illegal logging is often rampant, encroaching upon (and reaching into) supposedly protected forest areas. Unfortunately, governments in those world regions with the highest deforestation rates typically lack resources for monitoring or predicting patterns of forest conversion. However, a number of recent studies have shown that remote sensing can be a cost-effective approach for monitoring deforestation (due to both legal and illegal logging) and for identifying management priority areas. The typical remote-sensing-based strategy is to analyze a time series of Landsat images (or similar moderate-resolution imagery) captured over a period of many years. Time series analyses of moderate-resolution satellite images have been used to study deforestation in many regions of the world: Southeast Asia, the Amazon, Central Africa, and Eastern Europe. Below, we highlight a few such applications.

Instead of focusing on actual changes in forest cover, Laporte et al. (2007) mapped the expansion of logging roads over a 27-year period (1976–2003) in the humid forests of Central Africa. Despite the persistence of cloud cover in this region (an estimated 1.6% of which was completely obscured by cloud cover), the researchers typically had multiple images available to delineate an area; in total, they used more than 300 Landsat images to map their four-million-square-kilometer study area. The images were contrast stretched to optimize road detection, and then the roads were manually digitized. Basically, the researchers found that this manual approach outperformed semiautomated approaches, particularly when delineating older roads or working from older imagery. The researchers also used IKONOS imagery of a 25 km2 area in the northern Republic of Congo to examine the finer-scale impacts of logging activities, finding that canopy gaps in logged areas were five to six times larger than gaps in adjacent unlogged areas.

Laporte et al. (2007) mapped nearly 52,000 km of road in the study region. Overall, logging roads accounted for 38% of the length of all roads. The most rapidly changing region was the northern Republic of Congo, where the rate of road construction increased from 156 km per year for 1976–1990 to 660 km per year after 2000. The researchers estimated that approximately 5 % of the total forested area was disturbed. In summary, this effort yielded the first comprehensive dataset on the status of logging in Central Africa, and so will serve as a key resource for future planning and management.

Deforestation in the Amazon region of South America is a well-known problem, but actually less than 1 % of the region was deforested prior to 1975. Deforestation rates increased exponentially in subsequent decades because of economic incentives for conversion to agriculture (e.g., favorable credit policies for cattle ranchers). The state of Rondônia in western Brazil has become one of the most rapidly deforested parts of the Amazon. Many migrants have been brought to the state through government colonization projects, placing a huge burden on the state's remaining forests. While only 4200 km2 of forest had been cleared in Rondônia in 1978, by 2003 the amount of cleared forest had increased to nearly 68,000 km^2.

The 2000 and 2010 MODIS true-color-composite images from the remote north- western corner of Rondônia. The time series illustrates the typical pattern of initial deforestation along (both legal and illegal) roads, which permits small farmers to colonize previously inaccessible areas (NASA 2011). Over time, this leads to the establishment of large settlements and the clearing of most forest parcels.

Like the state of Rondônia, the southeastern Asian nation of Papua New Guinea has similarly seen a large population increase in recent decades, combined with an increased demand for timber and other resources. A team of researchers from the University of Papua New Guinea and Australian National University analyzed deforestation and forest degradation in the nation—home to the world's third largest rain forest (BBC 2008)—over a 30-year period. They used Landsat, Spot 4, and Spot 5 imagery to create a map of land cover as of 2002, which they then compared to a 1972 land cover map created by the Australian Army. The researchers found that 15% of Papua New Guinea's forest had been cleared over the 30-year period, while an additional 9% was severely degraded by logging. They also found that the rate of forest conversion had generally risen since 1990; by 2001, the estimated deforestation rate was just over 3600 km2 per year. The current rate of conversion could result in the loss of more than half the nation's forest cover by 2021.

Two satellite images from Papua New Guinea's Gulf Province, the first captured in 1988 and the second in 2002. Because Papua New Guinea is a mountainous island country, logging has mostly been limited to accessible areas (i.e., valleys and coastal lowlands). However, Shearman et al. (2009) estimated that 13 % of upper montane forests were also lost between 1972 and 2002.

Forest Health: In recent years, disturbances from extensive wildfire, drought, nonnative insect/pest species invasions, and climate change have threatened the health of forest throughout the globe. These threats, which can stretch across periods of time that last many years, may result in shifts in the dominant forest tree and animal species, as well as extensive forest mortality. Satellite and aircraft remote sensing techniques have relied on the capture of spectral color and infrared data to access forest health. From acquired remotely sensed data, the NDVI has been used as a traditional tool for forest vegetation health assessments. The NDVI is an essential index of vegetation greenness that results from light interacting with the vegetation canopy. Chlorophyll pigments found in the leaves of healthy vegetation, that make up the forest canopy, interact with incoming solar radiation by strongly absorbing visible light in the blue (0.45 μm) and red range (0.67 μm) of the electromagnetic spectrum, which is primarily used for the process of photosynthesis. Alternatively, light is reflected within the green range (0.5 μm) and even more so strongly reflected in the near-infrared portion (0.7–1.3 μm) of the electromagnetic spectrum. This strong reflection of light in the near-infrared portion of the electromagnetic spectrum is largely due to the leaf's internal structure. The response of the absorption and refection regions within the electromagnetic spectrum of the vegetation depicts the typical spectral signature curve for healthy vegetation when comparing the relationship of wavelength with percent reflectance.

The spectral signature response curve for healthy vegetation may vary slightly over time as a plant canopy changes from early spring growth to late-season maturity and senescence. However, when vegetation becomes stressed as a result of disturbances, reflectance in the infrared range of the electromagnetic spectrum may also change, becoming significantly lower. In fact, stressed vegetation will typically reflect more light in the visible range of the spectrum, since less is being taken up for photosynthesis, and reflect less light in the near-infrared range. Thus assessing these differences (i.e., healthy vegetation vs. stressed vegetation) remote-sensing- derived NDVI results can reveal where vegetation is thriving and where it is under stress.

The US Forest Service, in collaboration with NASA-Stennis Space Center, DOE Oak Ridge National Laboratory, and the USGS EROS Data Center, developed a near-real-time regional monitoring system for forest disturbances. This system is known as ForWarn and was developed in response to the 2003 US Healthy Forest Restoration Act, which mandated that a national forest threat Early Warning System (EWS) be enacted due to the increased extent and threat of forest disturbances across the country. ForWarn started online operations in 2010. This system uses multiple historical baseline datasets and satellite-derived NDVI values from the MODIS Aqua and Terra satellites (232 m ground spatial resolution) to derive weekly forest change products across the lower 48 United States.

Data products are accessed through the ForWarn website, and ForWarn's geospatial data viewer provides user access to forest disturbance dynamics throughout the year of interest. ForWarn products have also been used to identify and track regional disturbances, including defoliation and mortality from insects, to drought, to wildfire, to severe storm events, and to human deforestation activities. Disturbance maps are available online through the ForWarn Change Assessment Viewer.

Biomass Estimation: The term biomass in the terrestrial environment, from an ecological perspective, often refers to the numbers, weight, or mass of living organisms. For vegetation, the term biomass typically refers to a dry weight calculation of the aboveground components of larger vegetation, such as grasses, shrubs, and trees, whereas smaller algae and fungi species are often less considered, particularly in satellite remote sensing studies. For animals, few studies capture carnivores and herbivores with remote sensing. Thus, satellite remotely sensed estimates of terrestrial biomass largely include studies of the latter, macro-vegetation. However, estimates of vegetative terrestrial biomass can be ecologically very important and provide great capacities for assessing ecosystem biodiversity and implications for management strategies. The definition of biomass typically implies the measurement of the mass of living biological organisms in a given area at a given time. This measurement may come in the form of weights, or even less commonly referred to as an in situ value, or natural state, such as standard vegetation indices (e.g., NDVI, etc.) as previously discussed. However, traditional methods of estimating of terrestrial biomass are usually made from field-based measurements collected over extremely small areas and usually nonrepresentative of a larger region in which synoptic sampling would be prohibitive. Satellite remote sensing offers advantage in vegetative terrestrial biomass inventorying, monitoring, and analyses in that the platform's sensors have the unique ability for large-area, repetitive sampling.

TheNDVI (a ratio of red to near-infrared), a leaf area index (or LAI—a vegetation biophysical parameter that consists of a dimensionless variable and a ratio of leaf area to per unit ground surface area), and the fraction of vegetation cover (fCOVER) were used to evaluate the performance of SPOT imagery in estimating grassland biomass in a study by Dusseux et al. (2015). Linear regression models applied to 15 samples were developed to determine relationships between bio- mass measurements and variables estimated from SPOT sensor imagery. Biomass measurements were taken in the field from nine agricultural sites in the region of Brittany, in northwestern France, throughout the 2011 growing season. The remote sensing variables were developed from five cloud-free SPOT 4 images (20 m ground spatial resolution) that were acquired throughout the 2011 growing season. The image acquisition dates and field samples varied by a range of 2–11 days, with the imagery being corrected for both radiometric and atmospheric effects. The results of this study suggested that significant statistical relationships were possible between the observed biomass measurements and the remote-sensing-derived measurements (NDVI and LAI values; R2 values of 0.30 and 0.68, respectively, at a level of significance $p < 0.01$), thus providing improved estimates of grassland productivity corresponding to varying climate conditions.

Remote-sensing-derived estimates of aboveground biomass have also been implemented by other recent studies. Latifi et al. (2015) developed biomass estimate of stratified and non-stratified forest stands using a combination of data from Li- DAR (2 m height threshold) and an airborne hyperspectral data scene (4 m pixel size, 125 spectral bands). For further details on the use of hyperspectral data and combined LiDAR data. Finally, Barrachina et al. (2015) also used linear regression analyses based on field samples and vegetation indices (vegetation wetness index/VWI and NDVI) derived from Landsat-5 TM to estimate grass aboveground biomass in mountain meadows and pasture lands of the Pyrenees region of southwest France. Linear regression results (R2) ranged between 0.76 (2008 and 2009 mid-summer) and 0.74 (2008 and 2009 end of summer), respectively, at a level of significance $p < 0.01$.

Estimates of aboveground biomass are critically important to enhance our understanding of biodiversity, species richness, and primary productivity. More recently, remotely sensed data, both airborne and satellite, are increasing in popularity and are contributing to improved biomass estimates for modeling the dynamics of carbon fluxes occurring between the atmosphere and the terrestrial ecosystem. As more sophisticated models of global carbon balance are being developed, researchers need synoptic and conterminous estimates of aboveground terrestrial biomass that are limited by local-area field samples that may only provide estimates relative to a specific local. Remote sensing provides a larger regional capacity for sampling larger areas within certain geographic and temporal windows. As presented in this discussion, remote-sensing-derived estimates of terrestrial biomass have been used in combination with routinely applied vegetation indices, such as NDVI and statistical regression modeling, and have been found to produce promising results. Although the results produced from these types of studies are not perfect, newer methods involving emerging sensor technologies (e.g., LiDAR, hyperspectral data, higher resolution multispectral data, and interferometry synthetic aperture radar data, etc.) may help to improve current methodologies.

Carbon Estimation: Forests worldwide contain a large portion of terrestrial carbon stocks and depending on the decisions humans make in the face of continued climate and land use change, forests will be either net carbon sinks or sources. However, the exact amount of carbon contained in the earth’s forests is not known to even one significant figure, ranging from 385 to 650 PgC. Furthermore, there are unacceptably large variations and uncertainties in the estimates of terrestrial emissions, with a northern terrestrial uptake ranging from 0.5 to 4 Pg C year−1, and tropical terrestrial emissions of − 1 to + 4 Pg C year−1. At least half of the uncertainty in carbon emission estimates from land use change results from uncertain estimates of biomass.

Recent multinational initiatives, such as the United Nations Reducing Emissions from Deforestation and Degradation (REDD+), are seeking to decrease tropical forest emissions and turning them from net carbon sources to net carbon sinks. In the Sierra Nevada forests of California, strategic placement of treatments (SPLATS) areas across the landscape are being implemented as part of the Sierra Nevada Forest Plan Amendment to interrupt potential wildland fire spread, to reduce the extent and severity of these fires, and to improve the continuity and distribution of old forests across landscapes. The United Nations Blue Carbon Program aims to increase carbon storage from coastal ecosystems by producing credits for mangrove and wetland conservation.

The success of these new policy initiatives requires accurately quantifying and detecting changes in forest structure, biomass, and carbon stocks at spatio-temporal scales that are simultaneously relevant from an ecological, policy, and management perspective. Utilizing remote-sensed data provides the best path forward. Currently, three complementary remote-sensed technologies: (i) Terrestrial Laser/LiDAR Scanning (TLS), (ii) Airborne Laser/LiDAR Scanning, and (iii) Synthetic Aperture Radar (SAR) are being used in conjunction with field data to estimate forest structure, biomass, and carbon.

Necessity of ground truthing None of the remote sensing technologies discussed below directly measure biomass or forest carbon. Rather they all measure a variety of structural parameters of vegetation (e.g., canopy height, canopy volume, stem diameter) that can then be used with field-derived allometric equations to estimate vegetation volume, biomass, and carbon. Allometric relationships or allometry are mathematical equations describing the relationship between one or more parameters of an object and its shape. In the case of biomass estimation, information on wood specific density is needed and in the case of carbon both the wood-specific density and carbon content of tissue are needed. With regards to biomass and carbon estimation, most allometric equations estimate these using tree diameter and/or height. Chave et al. (2004) reviewed the literature on the use of allometric equations to estimate forest biomass and carbon. They found four types of uncertainty that could affect biomass estimates: (i) errors related to tree parameter estimates; (ii) errors related to the selection of allometric equations; (iii) sampling error due to sample plot size; and (iv) how representative the study plots were of the entire ecosystem. Overall, they concluded that the choice of allometric equations was the most important source of uncertainty. These findings point to the care that must be taken when using remote-sensed data to estimate forest biomass and carbon. Significant uncertainty can enter into the estimates both from the measurement uncertainty in the sensor and from the uncertainty embedded in the allometric measurements.

Terrestrial laser/LiDAR scanning (TLS) TLS is a relatively new technology that uses a rotating laser scanner to produce 3-D maps of various structures. It has seen widespread application in a diversity of disciplines, including archaeology, criminology, engineering, geology, and forestry. TLS is capable of giving the coordinates (x, y, z) of any object with high resolution (mm level) and accuracy. The technology has been applied to vegetation structure characterization and monitoring since the mid-2000s. TLS datasets provide high- resolution reconstructions (point clouds) of trunks, branches, and leafs distributions. Furthermore, tree biomass can be estimated by multiplying the volume of its structure by its respective wood density.

Airborne laser/LiDAR scanning Airborne LiDAR systems are able to provide canopy height measurements over fairly large areas. It fills the gap between high-resolution below the canopy data provided by TLS (discussed above) and coarser satellite-based SAR measurements (discussed below). The current airborne LiDAR system can estimate vegetation height with an accuracy of ~ 1 m. From a technical perspective, airborne LiDAR is similar to TLS in that the scanner emits a laser pulse that is reflected back from target objects and recorded by the scanner. In the case of airborne LiDAR the sensor is mounted on an aircraft with an Inertia Measurement Unit (IMU) and Global Position

System (GPS). The IMU gives the precise orientation of the scanner and the GPS gives the precise location.

Synthetic aperture radar (SAR) Although airborne biomass and 3-D structure measurement methods (e.g., LiDAR) have significantly improved over the past decade, they are still too expensive to be conducted routinely on a global scale. Thus, the only current and near future available remote sensing technology capable of monitoring global vegetation structure, biomass, and carbon stocks is from the new generation of multiband and multi-polarization SAR satellites (TerraSAR-X, TanDEM-X, RADARSAT-2, ALOS-PALSAR). This method works because the SAR signal interacts with different vegetation structures depending on the signal wavelength. A short wavelength signal (X-band) interacts mainly with canopies, an intermediate wavelength signal (C-band) penetrates deeper into the vegetation and interacts also with branches, and a long wavelength signal (L-band) can penetrate throughout the vegetation and interact also with tree trunks. Thus, multiwavelength observations can provide useful estimates of vegetation structure and forest biomass. Another important advantage of SAR observations is the ability to acquire data in all weather conditions, which is extremely helpful in overcast tropical regions.

While promising early uses of SAR monitoring has been only partially successful mainly due to signal saturation problems. SAR-based biomass estimations are valid up to a certain threshold where saturation occurs. The X- and C-band backscatter saturates at low biomass levels (30–50 Mg/ ha), although a more recent study suggests the C-band estimate at a higher saturation level such as 250 Mg/ha. An estimate for the L-band saturation level ranges from 40 to 600 Mg/ha. Most of the wide variation in biomass saturation estimates reflects different estimation methods as well as a different number of ground validation sites. A recent study by Englhart et al. (2011) that used both L-band ALOS and X-band TerraSAR-X data to measure aboveground biomass in tropical forests used about 400 validation points and obtained good biomass estimates up to 600 Mg/ha.

SAR data provide two main observables: amplitude and phase. Moving forward, we expect to see greater use of the Interferometric SAR (InSAR) technique to mea- sure vegetation biomass and carbon. The InSAR technique is currently widely used to quantify changes and deformation of the earth due to earthquakes, volcanic activity, subsidence, and water level changes. The InSAR technique uses information on phase differences through the creation of an interferogram between two SAR acquisitions of the same area. This may be done using either a repeat-pass (two-pass) or a single-pass bistatic acquisition (one-pass). For vegetation applications, single-pass bistatic InSAR is preferable as it avoids problems associated with coherence loss, temporal decorrelation, and wind decorrelation.

Wildland Fire Risk Assessment: Wildland fire, defined as the relatively fast spreading of unintentional fire across a large areal extent of forested land, remains one of the greatest potentials to alter or disrupt ecosystem patterns and processes across the globe. These altered patterns and processes include terrestrial vegetation distribution and structure, LULCC dynamics, deforestation and desertification, global carbon cycle, and global climate change. Whether this fire is caused by natural forces or human activity, the ecological consequences can be tremendous. Wildland fire is a significant source of harmful emissions worldwide with important implications for human health and carbon budget estimation. Many federal agencies have come to recognize the need for a unified approach to managing lands for prescribed and wildfires (Wildland Fire Executive Council 2009). However, the estimation of fire emissions is often based on the total replacement of forest or other ecosystems that, if the burn area is correctly estimated, undoubtedly overestimates the amount of emissions. In most circumstances, burn severity is not quantitatively estimated. The relative probability of wildland fire in California is shown as an example. Other parts of the US and most regions of the world also have significant fire risk.

Recent estimates suggest that wildland fires contribute to global greenhouse gas emissions at an alarming rate (approximately 6 % of global carbon emissions). The current threat is changes in climate may be altering fire regimes and increasing wildfire contributions to global greenhouse gas emissions, further limiting humans' and the natural environment's capacity to reduce these impacts.

Advanced fire modeling for calculating wildland fire risk has relied on vegetation, weather, and meteorological inputs to calculate fire spread, fuel loads, and smoke production. However, despite numerous technological advances, our ability to manage fire and fire threat has been relatively limited. Additionally, the quantification of global greenhouse gas emissions as a result of fire is still poorly understood and inadequately represented in global emission models. However, remote sensing, beyond the commonly applied meteorological and weather applications, provides greater capacity to model fire characteristics in that both aerial and spaceborne sensors have the ability to overcome costly field-collected data, which is often labor and time consuming, as well as requires lengthy processing intervals, thus minimizing the possibility of real-time model development.

(Khorram et al. 2014) have shown the applicability of airborne synthetic aperture (Unmanned Air Vehicle Synthetic Aperture Radar;UAVSAR) and Landsat TM multispectral data for modeling smoke emissions from wildland fires in northern California. The following images illustrate the utilization of the Berkeley Emission Estimation System (EES), which is used by several resource agencies as a decision support tool for their wildland fire management decision-making activities. The EES uses First Order Fire Effects Model (FOFEM) as a framework and is based on the spatially specific inputs. The EES is based on a number of parameters, many of which can be estimated from remote sensing data.

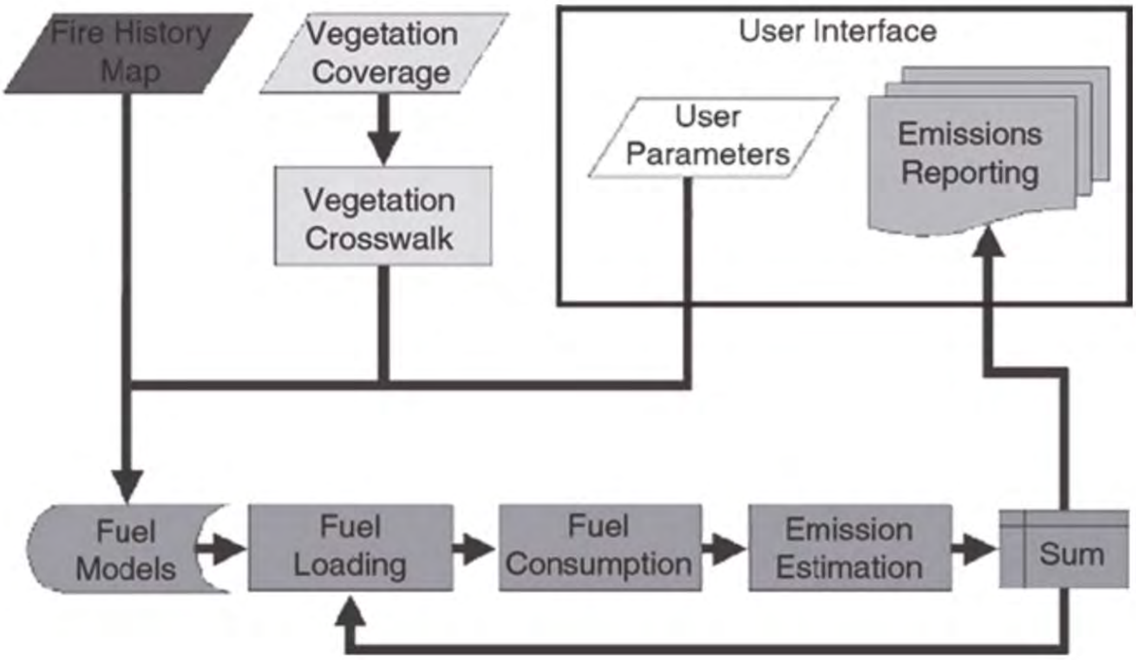


Fig: Emission estimation system (EES) parameters, many of which can be estimated from remote sensing data

Another study of wildland fire was conducted by Hernandez-Leal et al. (2006), in which they used NDVI derived from the Advanced Very-High Resolution Radiometer (AVHRR-NOAA) sensor data over the Tenerife Island in Canary Islands, Spain to define a new wildland fire risk index. The new wildland fire risk index, which incorporated the NDVI values, is known as the Fire Risk Dynamic Index (FRDI. It is an extension of the Fire Risk Static Index (FRSI). The FRSI model is generated from land cover and environmental variables, which includes altitude and slope, solar insolation, proximity to main roads, and type of vegetation cover. The FRSI model output produces a static map of the probability model of fire occurrence by means of the included land cover and environmental variables within a logistic multivariate regression that incorporates past fire ignition events that took place between 1992 and 1995. The FRDI goes a step beyond FRSI in that it is a dynamic index that takes into account areas' gradual increasing in water stress (i.e., decrease in NDVI values), thus dynamically illustrating the changing probability of ignition across the landscape. The FRDI model, which integrates the multiple fire risk variables of FRSI, and further incorporates the NDVI variables derived from the AVHRR satellite sensor as an indirect indicator of vegetation water stress, improved the identification of the fire risk level on Tenerife Island, Spain.

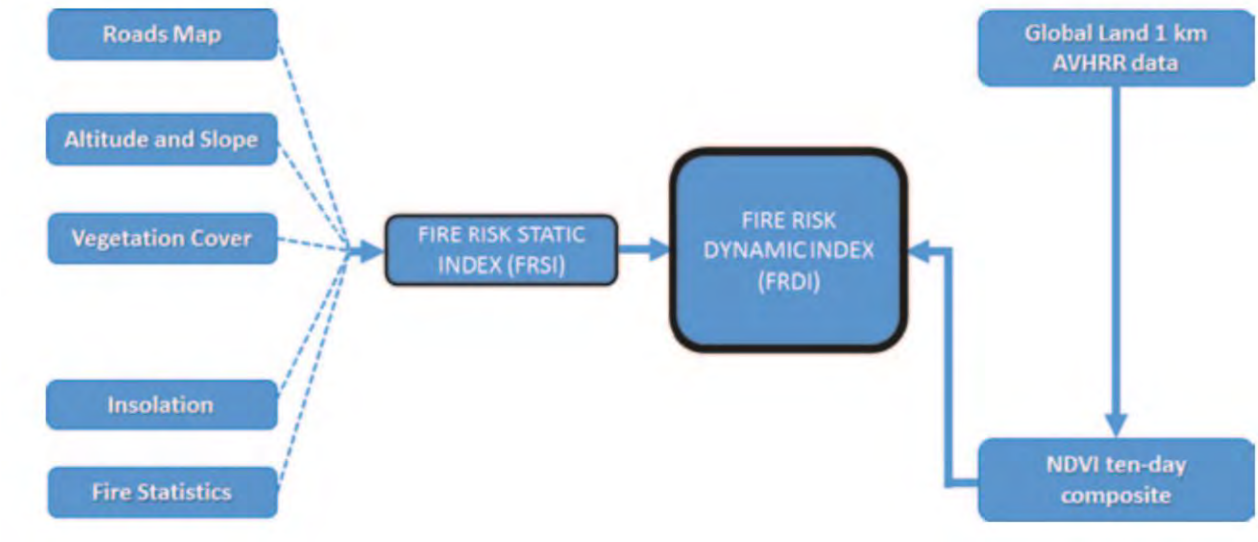


Fig: Diagram of data used to develop the Fire Risk Static Index (FRSI) and Fire Risk Dynamic Index (FRDI) from land cover and environmental variables and Normalized Difference Vegetation Index (NDVI) estimates derived from Advanced Very-High-Resolution Radiometer (AVHRR-NOAA) sensor data.

An FRDI probability map is produced by utilizing NDVI values along with the FRSI model outputs. For the NDVI data, seven NDVI multitemporal composite images were analyzed, covering a period from June 20–30 to August 21–30, 1995. These 10-day composite images were used in order to obtain cloud-free scenes. The AVHRR-NOAA data were acquired from the Global Land 1 km AVHRR Project dataset. The AVHRR-NOAA dataset is composed of five channel, 10-bit, raw AVHRR data, at 1.1-km resolution (at nadir) for every daily afternoon pass over all land and coastal zones using data from NOAA's polar-orbiting TIROS. The data were initially to be collected continuously for 18 consecutive months, from April 1, 1992 through September 30, 1993. However, the acquisition period was extended to September 30, 1996 and is currently available through the USGS AVHRR Global Land 1 km internet portal. Advantages of using data from AVHRR-NOAA in fire risk modeling include the satellite's global coverage, and high temporal resolution. In addition there are two overpasses per day.

By incorporating the NDVI values into the FRSI model, areas of vegetation water stress may be accounted for in that decreases in the NDVI values across adjacent time periods may be used as a surrogate for water stress in areas of previous fire events.

Other studies have also used optical remote sensing for fire risk mapping. Remote sensing data can play a vital role in identifying wildland fires, delineating burn area, deriving indices of burned and non-burned vegetation, and recording the frequency at which different vegetation types are affected. Hernandez-Leal et al. (2006) demonstrated that FRDI could have a vital role in the prevention of fires, supporting existing fire propagation models, or developing effective strategies for extinguishing an ongoing fire event through the identification of the dryer, water-stressed areas.

Remotely sensed data can collect timely measurements over larger fire-prone areas. Optical remotely sensed data have been used to provide estimates of fire characteristics that are relevant for ecosystem and fire fuel load parameters; such as species composition, biomass estimates, landscape structure, fire history, fuel moisture content, and fuel availability. With the evolution of newer and higher resolution sensors, improved estimates of vegetation species and cover class may serve to further enhance model performance, as well as wildland fire carbon contributions to global greenhouse gas emissions.

Optimizing Sustainable Food and Fiber Production through Remote Sensing: Precision agriculture—information-based management of agricultural production systems—combines satellite remote sensing and GIS to be able to increase food and fiber production to a growing population. The goals of precision agriculture are to (1) optimize the use of resources to reduce farmer costs and increase sustainability of the farm operation, (2) reduce harmful environmental impacts, and (3) improve the quality of the work environment and the social aspects of farming and ranching.

Remote sensing has been used in a variety of agricultural applications for well over 20 years. Some applications are fairly simple while others are complex and innovative. Due to the lack of cartographic data, many Argentinean farm managers and agronomists use satellite images, in combination with soil maps, to determine the productive aptitude of soils before buying or renting land. Remotely sensed images offer high-quality data, frequent recurrence cycles, and cost effectiveness.

Entire fields are easily captured in one image, allowing farmers to detect bio- physical variability in crops such as water stress, lack of nutrients, diseases, weeds and insect damage. Much of the remotely sensed data used in precision agriculture to detect variability in crop conditions rely on spectral characteristics, predominantly using the red (RED, chlorophyll a and b absorption) and near-infrared (NIR, internal leaf scattering) wavelength bands. Various combinations of the two bands—spectral vegetation indices—are highly sensitive to vegetation cover and density. Successful mapping of LAI—the area of leaves per unit area of ground (m2/m2)—using IKONOS imagery was shown by Johnson et al. (2003) to be a useful indicator of plant growth and health, as an equilibrium generally exists between climate–soil conditions and LAI. Lack of foliage—either fewer or smaller leaves—usually means that plants are stressed by insects or disease and are dying; more vigorous plants will have more foliage and different spectral reflectance.

Spatial data have been used extensively to increase productivity and yield in croplands—enabling farmers to apply the right treatment in the right place at the right time by adapting fertilizer distribution to varying soil conditions. More recently, additional practices have evolved to improve the sustainability of the food supply. Adapting production in- puts site-specifically within a field and individually for each animal allows for better use of resources to maintain the quality of the environment while reducing costs.

Innovative approaches in applied remote sensing have been successfully implemented to enable product traceability and advance the management of a wide range of agricultural products including viticulture, orchards, livestock and animal fiber production, and turf management.

Improving Wine Harvest and Quality: Aerial views of vineyards provide a better perspective of canopy conditions than relying on ground observations. This, in turn, allows for better management prescriptions.

A number of studies using radiometric, high-resolution spectral analysis have demonstrated that grape varieties have detectable systematic differences in reflectance intensity and in the spectral form that matches up with vineyard inventory data.

More recently, Cemin and Ducati (2011) conducted a study to see whether the NDVI could distinguish not just the unique spectral qualities of particular grape varieties, but whether their terroir could also be detected. Terroir—the relationship between the attributes of a grape and the particular location it is grown—is a determinant of wine quality, identity, and organoleptic descriptors. The ability to distinguish a terroir's imprint on the spectra of the same grape cultivar is a powerful tool for certifying the geographic origin and authenticity of the product. The researchers examined plots in Bordeaux and Champagne (France), the Aconcagua and Colchagua valleys in Chile, and the Encruizilhada do Sul (Rio Grande do Sul State, Brazil) using all nine spectral bands from ASTER images to investigate whether there were detectable differences in cabernet sauvignon, pinot noir, merlot, and chardonnay grapes at each location. Cemin and Ducati (2011) con- firmed that the four grape varieties did in fact have characteristic spectra that could be distinguished through the NDVI. Additionally, they found that region grouping indicated some spatial influences on spectral behavior reminiscent of terroir effects; however, they were using known field data. Remote sensing techniques are sensitive to changes in reflectance; therefore, further investigation would be worthwhile.

Oenoview®, a joint commercial venture between *Institut Coopératif du Vin* (Groupe ICV) and Infoterra, a subsidiary of EADS Astrium has benefited French viticulturalists. Using aerial and multispectral images (covering nearly 3000 km2) taken at the rate of 1000 plots every 8 s, Oenoview has a precision range of approximately 3 km^2. The images are used to map the surface area and variation of leaf canopy across vineyards—a vital statistic to identify subtle nuances in vineyard vigor, soil moisture levels, bunch and grape weight, and the presence of minerals. Wine growers provide information on their fields, vines, and grape varieties. SPOT-5 and Formosat-2 images are taken in July and August during the period of véraison (when grapes begin to ripen, about 3–4 weeks before grape harvest).

Wine grapes require a moderate amount of water stress to produce top quality wine, although at the expense of reduced grape yield. Berry quality largely depends on achieving an optimum balance between sugars and titratable acidity at harvest. Spectrally, green areas of dense foliage reveals excess soil moisture, while red to purplish areas indicate less moisture, thus pointing to a good vintage. Spatial data are then supplied in a GIS-ready format to be used by the growers to determine when grapes are mature for harvesting and assess variations in grape quality within plots. Rather than acquire plot information empirically over several decades, the data allow growers to separate out lower-grade bunches for vin de table and reserve the superior grapes for higher end grands crus. Vats containing as little as 20% immature grapes lessen the quality of wine at the end of the process, resulting in lower economic returns. The data also allow growers to optimize pruning, fertilizer inputs, and irrigation needs for each vineyard.

Using Remote Sensing to Optimize Grazing and Improve Wool Quality: Australia's vast expanse of crop and pasture land has fostered innovative uses of remote sensing techniques. The Commonwealth Scientific and Industrial Research Organization's (CSIRO) Pastures from SpaceTM program uses spatial informatics and remote sensing to provide farmers with a suite of tools to accurately estimate the amount of feed in their pastures and how quickly their pastures are growing in order to make efficient use of feed resources. This enables farmers to increase the profitability and sustainability of their lands, which has seen extreme drought conditions. Satellite data are used to estimate pasture biomass or "feed on offer" (FOOTM). Pasture biomass data have been combined with climate and soil information to produce "pasture growth rate" (PGRTM) estimates at the national, regional, farm, and paddock scale. This information is updated weekly on the Internet, broad- cast on Australian radio, and signposted in regional areas. Farmers can obtain weekly subscriptions for paddock-level information to assist them with grazing rotations, feed budgeting, and fertilizer applications. Longitudinal data indicate variations in vegetation due to climatic changes and human interventions.

Whelan et al. (2007) have been developing a simulation model to provide an improved and more precise forecast of wool production across the Australian continent. The goal is to predict wool fiber diameter of the wool clip before it is shorn directly from remotely sensed data by using monthly NDVI values and fiber diameter profiles of sheep at the paddock level. Researchers also hope to predict the effects of modeled future climate change on future wool supplies.

Exploring and Monitoring Oil, Gas, and Mineral Resources: Ortho-rectified high-resolution satellite images are indispensable in the search for and the development of new oil and gas fields and mineral deposits. Using airborne magnetic or ground gravity surveys to facilitate interpreting sub- surface features, geologists and engineers are able to narrow down the search area for performing more detailed 2-D or 3-D seismic surveys for exploratory drilling.

Satellite imagery is also used to develop digital elevation models (DEMs) to plan the least environmentally damaging route for pipelines, access roads, and facilities by creating a computer visualization of the site area. The use of satellite remote sensing has greatly reduced the time and cost involved in reconnaissance and the placement of oil wells. Remotely sensed spatial data also allow managers and government officials the ability to monitor wellfields and obtain information on the extent of oil spills and how best to mitigate and remediate these areas.

High-resolution providers, such as GeoEye-1, WorldView-2, Worldview-1, QuickBird, IKONOS, SPOT-5, LANDSAT 7 +ETM, and ASTER, have been extensively employed in the quest for surface indicators of subsurface oil and gas along with risk assessment and well field monitoring (to identify security and environ- mental problems).

Using Remote Sensing for Humanitarian and Peace-Keeping Operations: Tracking the movements of refugees and internally displaced people (IDP), verifying burned and razed villages, documenting the existence of mass graves, and other humanitarian work would be utterly impossible without very-high-resolution satellite imagery. Very high spatial resolution (VHSR) imagery is particularly crucial in assessing the extent of violent conflict, environmental or social justice cases, forced displacement, or other human rights atrocities where field-based assessments are all but impossible in remote, prohibited, dangerous, and/or inaccessible locations. The United Nations High Commissioner for Refugees (UNHCR) and the Internal Displacement Monitoring Center (IDMC) methodology for characterizing and monitoring the nearly 34 million forcibly displaced people worldwide uses GIS, aerial, and satellite imagery.

Refugees and IDPs are a very mobile and fluid type of human settlement, living in small makeshift shelters comprised of thatched huts, clay constructions with flat roofs, and tent-like structures covered with bright materials (e.g., UN tent fabrics or plastic sheets). Estimating the total number of dwellings is extremely complex because of the spectral variability and reflectance of the building material. Bright soil backgrounds and scattered scrub vegetation can make overestimation of rooftops a common classification error in arid regions (false alarms) in the automatic recognition of built-up areas. Rooftops can be under- or overestimated in arid regions as they are misclassified as scattered scrub vegetation. As well, the spatial distribution of scattered vegetation and their contrast with the background is very similar to the spatial distribution of the built-up structures in some part of the human settlement, including scattered buildings and refugee camps. In particular, the size of tree canopies and their average distance in some cases are similar to the size of built-up structures and their average distance, and then producing overestimation of built-up areas. However, the ability to determine how many IDPs there are is critical to planning and managing effective humanitarian responses. Remotely sensed data allow for continuous monitoring and corroboration of on-the-ground reports with the aim of decreasing or preventing humanitarian disaster and human rights crimes in politically unstable and chronic conflict areas.

Satellite images have effectively been used in legal proceedings and diplomatic negotiations to provide compelling, visual proof and resolve current and future conflicts over highly contested territories. SPOT images were used to achieve the 1995 Dayton Peace Accord. Imagery from India's IRS-1C and US IKO- NOS satellites was used to monitor human activity and mitigate potential conflicts in Spratly Islands in the South China Sea. International humanitarian relief efforts in Thailand, Mexico, Africa, and Europe—particularly Kosovo, Macedonia, and Albania—were made possible by imagery provided by India's IRS-1C, Russia's KVR-1000, and France's SPOT satellites to monitor and mitigate the plight of refugees.

The well-known Eyes on Darfur project, a collaborative initiative between Amnesty International and the American Association for the Advancement of Science (AAAS), is one case study of an active monitoring project. Images allow the ability to track vulnerable villages and monitor changes that may have occurred.

The potential of geospatial visualization for the international human rights community was highlighted by the September 2004 use of QuickBird satellite imagery by the US Agency for International Development (USAID) and the US Department of State in confirming the extent of ethnic cleansing in Darfur. These agencies were able to view and interpret conditions on the ground in Darfur when eyewitness reporting was difficult to verify. Used in conjunction with classified sources, analyses of the imagery led to confirmation of reports of widespread destruction of villages, livestock, and crops as part of an ethnic cleansing campaign. The remotely sensed imagery also proved effective in diplomatic campaigns and alerting the global public.

Archaeology and Cultural Heritage: The evolution of satellite image analysis has vastly transformed the field of archaeology, allowing researchers to exploit more fully an enormous wealth of data of the earth's surface and subsurface contained in various types of satellite images along with aerial photography. Archaeologists can examine a broad spectrum of reflectivity signatures and bands within the remotely sensed data to focus on perspective archaeological sites to determine if there are subsurface structures.

The South Sinai Survey and Excavation Project in Egypt (SS-SEPE) led by Drs. Gregory Mumford and Susan Parcak of University of Alabama, Birmingham (US), used supervised and unsupervised land use/land cover applications of Landsat TM images as well as QuickBird imagery to detect vegetation signatures throughout Egypt. This allowed the researchers to isolate water sources in an arid environment and thus identify existing and potential archaeological sites. Infrared images can differentiate between various subsurface materials. Since ancient Egyptians used mud bricks in building construction, which are substantially denser than the surrounding soils, the shapes of houses, temples, and tombs can be detected most easily using winter images. Sites meeting the classification parameters are then "ground-truthed" to verify already identified archaeological sites (i.e., assess the accuracy of the classification) and conduct initial excavations on potential (but unknown) sites. As a consequence of creating this specialized classification, the enormous amount of time and high costs associated with surface detection of vegetation and water signatures in a vast geographical area can be significantly reduced, and the possibility for new discoveries greatly increased.

This innovative technique rewarded the SS-SEPE team with one of the most significant discoveries in Egypt—in May 2011, 17 previously unknown pyramids along with more than 1000 tombs and 3000 settlements were revealed.

The vastness and remoteness of Mongolia, along with the lack of surface remains, has meant that it has been largely unexplored by archaeologists. Starting in 2008, a German research team led by Dr. Jan Bemman of the University of Bonn, used a combination of aerial photographs, satellite images, and surveys. Digital surface models were converted into interactive 3-D models of the area, and superconducting quantum interference devices (SQUIDS) on the ground were used to obtain rapid, high-resolution images of the magnetic field. The combination of advanced techniques allowed for detection of compacted construction materials underneath the soil. In 2011, the team detected a massive settlement in the Orkhon Valley of central Mongolia dating from the eighth and ninth centuries C.E. at the time of the Uighur (Uyghur) Empire.

Safeguarding archaeological sites and antiquities has been aided by remotely sensed images. Authorities can monitor images to detect if a site has been looted and contact Interpol to watch out for antiquities that may be sold illegally.

Summary: This pert provides just a few of the many terrestrial applications of remote sensing. While not exhaustive, presented here are examples of case studies found in the literature that use data directly acquired from satellite and airborne remote sensing, or data derived from remotely sensed data. It is notable to consider that as remote sensing technologies evolve, resolutions increase, and access improves, the attractiveness of a synoptic tool like remote sensing will also increase. The next chapter will provide examples of how remote sensing is used to better understand atmospheric phenomena.

MODULE-III

ATMOSPHERIC APPLICATIONS OF REMOTE SENSING

MODULE-III - ATMOSPHERIC APPLICATIONS OF REMOTE SENSING

The discovery that the stratospheric ozone layer can be eroded by human activities along with the existence of a larger-than-expected hole over Antarctica more than 30 years ago propelled the use of remote sensing of Earth's atmospheric structure for more than weather forecasting; it became central to observation re- search and a tool for the development of environmental policy such as the Montreal Protocol on Substances that Deplete the Ozone Layer. These concurrent discoveries spurred the application of satellite remote sensing to atmospheric and climate modeling as a way of better understanding our atmosphere and grappling with the impacts on both human and natural ecosystems.

Monitoring gases, air pollutants, radiation, water vapor, and other data using remotely sensed imagery has led to a better understanding of the dynamic physical and chemical processes in our atmosphere—both regionally and globally. LiDAR has been used to monitor trace gases from the ground level up to the stratosphere with a high-range resolution. Radar has been used for weather forecasting and tracking trends in other weather-related phenomena. Forecasting air quality and predicting climatic changes are now a societal imperative as airborne pollutants harm human and natural systems. This part illustrates some of the many ways remote sensing has been used to advance our knowledge of atmospheric phenomena and airborne vectors; bring about critical advances in public health, safety, and welfare; and generate early warning systems.

Weather Forecasting and Extreme Weather Events: The local weather forecasts that you rely on each day are the most commonplace atmospheric applications of remotely sensed data. In the US, the Geostationary Op- erational Environmental Satellites (GOES) have 4-km spatial resolution and 30-min temporal resolution. The images viewed on television in the US are from GOES satellites; METEOSAT is used throughout Europe and METEOR in Russia.

The basic mechanisms of how the ocean and atmosphere interact to form weather have been known for a long time. What is rather poorly understood are the *microphysics*—the relatively small interactions between temperatures and movements of water droplets and ice particles within a band of clouds—that can rapidly gain strength within a larger system, transforming an ordinary storm into an extreme weather event[1].

Meteorological scientists depend on both satellite and airborne sensors to better understand the phase changes of water—from ocean vapor to ice crystals—within the clouds of a storm system.

Measuring Precipitation from Space: Hydrometeorological events—either too much or too little precipitation—have severe consequences such as flooding, deadly landslides, and devastating droughts. Understanding the variability of precipitation events is an essential component in developing improved models to predict extreme weather scenarios. Space-borne sensors provide the tools for obtaining quantitative precipitation measurements globally on sub-daily to decadal time scale. Remotely sensed precipitation

[1] Extremeweatherincludesunusual,severe,orunseasonalweather;weatherattheextremesofthe historical distribution—the range that has been seen in the past. Extreme events are typically based on a location′s recorded weather history and defined as lying in the most unusual

data products are particularly useful in locales with a lack of rain measurement instruments or radar networks, where extreme meteorological events regularly cause significant agricultural losses.

In 1997, the Tropical Rainfall Measuring Mission (TRMM) was launched as a means of confirming the validity of tropical rainfall estimates. Subsequently, the Global Precipitation Measurement (GPM) Mission improves upon the TRMM by using a number of satellites along with an advanced radar–radiometer system on a GPM "core satellite" to deliver near real-time estimates of rain and snow every 2–4 h globally. GPM was designed to advance scientific understanding of the Earth's water and energy cycle to improve predictions of weather and to track trends.

Public Health: Health providers, health effects researchers, and public health officials rely on environmental data to study and understand the geographic, environmental, and meteorological differences in disease and the effects of airborne pollutants. Geospatial technologies support enhanced understanding of how pollutants and vectors travel within the atmosphere. Health-related monitoring focuses on measuring airborne pollutants to better understand human and ecosystem health effects, and develop strategies to lessen the effects through better collaborative partnerships, environmental policies, and land planning measures.

Measuring Air Pollution to Understand Human and Ecosystem Health Impacts: Regulatory initiatives have improved air quality in North America and Europe; however, developing countries and rapidly growing megacities are still grappling with massive air pollution challenges. Many complex scientific questions remain, calling for innovative research. It has become increasingly clear that exposure to pollutants harms human and natural ecosystem health. The US Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) for six major pollutants (criteria pollutants): ozone, particulate matter <2.5 μm ($PM_{2.5}$), carbon monoxide (CO), sulfurdioxide (SO_2), nitrogen oxides (NO_x), and lead. Poor air quality results in a variety of adverse respiratory and cardiovascular effects, cancer, and reduced lifespans. Air pollution also has been linked to adverse effects on ecosystems through wet (e.g., fog and precipitation) and dry (e.g., wind) deposition processes. Sulfur can lead to acidification of lakes and streams and dam- age plants and soils. Nitrogen in the atmosphere has been found to harm fish and other aquatic life. Elevated concentrations of ground-level ozone are also extremely harmful to human and ecosystem health.

Remotely sensed data are integral to harmonizing weather, air quality, and climate models with aquatic and terrestrial ecosystem models to better understand the atmospheric–biogeochemical drivers of ecosystem exposure and the resulting effects. The Dutch–Finnish Ozone Monitoring Instrument (OMI), a part of NASA's Aura satellite, is a UV–visible spectrometer observing reflected sunlight in the 270–500 nm range that can measure criteria pollutants such as ozone, NO_2, SO_2, and aerosols. Aerosol optical depth (AOD), retrieved from MODIS Terra and Aqua satellites, measures light extinction by aerosol scattering and absorption in the atmospheric column. AOD values are highly correlated with $PM_{2.5}$ concentrations.

Case Study: Measuring China's Air Pollution

A team of researchers from Yale University and Battelle Memorial Institute mapped ground-level $PM_{2.5}$ concentrations in China using total column AOD from MODIS and MISR (Multiangle Imaging Spectroradiometer) satellites and coincident vertical profiles from the GEOS-Chem global chemical transport model. AOD measurements and ground-based $PM_{2.5}$ measurements were related using algorithms and models. Satellite-based air quality measurements can help to fill in spatial and information gaps where ground-based (in situ) monitoring stations are not available or practical. Satellite observations provide consistent, repeated data recording that allow for comparison over time and locations.

The data indicate that all but four provinces have average annual exposures above levels recommended by the World Health Organization (WHO).

Appraising and Predicting Episodic Events: *Episodic events* are geologic and weather events that occur on an irregular, but periodic basis. Predicting the intensity of these often-catastrophic events is tricky—too many false alarms and people ignore warnings, while delayed information can result in avoidable tragedy. Episodic events include volcanic eruptions, earthquakes, dust storms, wildfires, and other such dramatic phenomena.

Satellite remote sensing has been used for both early warning of human and natural disasters and for post-disaster assessments. Images gathered during and in the immediate aftermath of an earthquake, flood, fire, or any other natural or human disaster have dramatically extended the ability of international organizations, government agencies, and information nongovernmental organizations (NGOs) to quickly gather, analyze, and distribute reliable. Images illustrate the extent of damage and locations that are impacted, providing a vital tool for emergency responders and aid agencies to properly size up the situation and develop appropriate responses. This information guides efforts on the ground such as pinpointing still- passable roads and bridges and finding safe locations for mobile medical units or refugee shelters.

Monitoring and Forecasting Volcanic Activity: Numerous small earthquakes, surface deformations, thermal changes, and the release of magmatic gases are all indicators of an eminent volcanic eruption. Historically, due to the costs involved, only active volcanoes were monitored; most volcanoes around the world are not monitored effectively, if at all. Utilizing satellite-based methods for detecting activity has increased substantially, and advanced models of volcanic processes are helping to interpret monitoring data. The challenges include first distinguishing between magmatic, hydrothermal, and even atmospheric errors, and then figuring out which processes will culminate in eruption.

Interferometric synthetic aperture radar (InSAR) uses the phase component of radar images to determine the position of the Earth's surface. *Digital elevation models* (DEMs)—crucial in predicting pyroclastic flows and lahars—with centimeter-scale accuracy are produced from simultaneously recorded images from different radars. Deformation is measured using time-separated images. Satellite data pro- vide a global perspective, mapping tectonic strain across continents and allowing the exploration of volcanoes in remote, underfunded, or inaccessible locations. Vol- canoes long thought to be dormant or inactive have been revealed as showing signs of activity. Space-based observations enable limited financial and staff resources to be used more efficiently for locations that require detailed monitoring.

Thermal and radiant flux (power) changes—vital information taken from fumaroles and hot springs by intrepid scientists—have been measured using infrared hyperspectral data. Using visible through short-wave infrared (Vis-NIR-SWIR) optical spectra data recorded in the 900–2500 nm wavelength range by the ARTEMIS sensor (flown on the TacSat-3 spacecraft), Cipar and his colleagues estimated the temperature and heat flux of an active lava lake within the Halema'uma'u crater of Kilauea caldera (Hawaii, US). Elevated radiance in the NIR–SWIR wavelength regions recorded a portion of the blackbody radiation function from small, hot areas of the lava lake, which were inverted to determine the temperature and power output of the crater. Corrections in the NIR–SWIR were needed to account for absorption and scattering by atmospheric constituents, primarily water vapor.

Monitoring gases—particularly SO_2—contained within volcanic ash clouds through remote sensing has yielded valuable information for air quality and public health, furthered the science in volcanology, enabled char- acterization of aviation hazards, and validated the global circulation model (GCM) in climate science. Sulfate in air pollution is well known for producing acid rain and fog, which in turn acidifies vegetation and water bodies, and causes adverse health effects. Hyperspectral instruments are able to easily detect SO_2 and differentiate between volcanic sources (which typically are launched into the stratosphere), and plumes from sulfate ore smelters, power plants, and industry (which are found at lower altitudes of the boundary layer and troposphere).

Satellite data from thermal infrared instruments have been used to assess volcanic ash clouds and dispersal for several decades, but in order to make reasonably reliable forecasts of ash concentrations, an estimate of the thickness of the volcanic cloud is necessary. Volcanic ash is potentially dangerous for aircraft because, among other problems, the micron-size silicate particles melt below the operating temperatures of the engines, collect on turbine components, and block air flow to the point that engines may potentially shut down (International Civil Aviation Organization. Information is insufficient about the exact tip- ping point of atmospheric ash concentrations that would cause engine shutdown; making judgments about aviation risk is further complicated by the differing characteristics of jet engines, the amount of time spent flying through ash clouds, and the characteristics of the ash cloud itself in terms of composition, particle size, spatial distribution, dispersion, particle removal rates and patterns, etc. Consequently, aviation authorities typically use a very cautious approach and close airspace, creating massive travel disruptions. Using multispectral satellite measurements from the Spin Enhanced Visible and Infrared Imager (SEVIRI), Prata and Prata (2012) performed a retrospective study of the April–May 2010 Eyjafjallajökull volcano (Iceland) eruption to develop ash mass loading forecasts in order to improve ash/aviation risk assessments.

Using Remote Sensing for Early Warning of Dust Storm: Dust storms are common episodic events in dryland areas—deserts and semi-arid rangelands—around the world. In addition to severely reducing visibility and drastically impacting air quality, dust storms have deleterious effects on human health, particularly children and elderly populations, and people with respiratory or pulmonary illnesses.

Dust storms reduce visibility and irritate eyes, nasal passages, and lungs; they also contain an enormous variety of harmful pollutants.

Plant pollens, particulate matter, minerals such as phosphorous, pesticide residues, industrial pollutants (e.g., heavy metals and toxic chemicals), radioactive particles, as well as carcinogenic hydrocarbon compounds and living microorganisms—bacteria, fungi, and viruses—transmit diseases thousands of miles across continents to humans and livestock based on wind patterns and steering currents.

Annual volumes of dust transported from African deserts have been estimated at over 1 billion tons. Dust-borne particles from the African Sahara and Sahel deserts provide a much-needed source of minerals for nutrient-poor Amazon rainforest soils and phytoplankton in the Atlantic Ocean, but have been found to contribute to coral reef bleaching and degraded air quality in South America, the southern US, and the Caribbean. Korea and Japan experience storms of yellow dust from China and dust clouds from the Gobi, and Taklimakan deserts in Asia reach the northwestern US.

Seasonal outbreaks of meningitis and silicosis lung disease in Africa and Kazakhstan have been attributed to dust storms. Thus, if there is a pandemic, such as avian flu, West Nile virus, or other disease, it can very quickly move into other areas. Prolonged droughts and climatic changes can increase the occurrence of dust storms. Scientists had originally thought that fungi, bacteria, and viruses contained within dust clouds would die on exposure to ultraviolet radiation and cold temperatures; however, viable microbes have been detected in dust tracked as far as 6500 km.

This sobering discovery prompted the UN's World Meteorological Organization (WMO) to develop a satellite-based modeling system to track dust storms globally and alert those in its path. In addition, researchers Stanley Morain of University of New Mexico (Albuquerque, NM, US) and William Sprigg of University of Arizona (Tucson, AZ, US) collaborated with NASA and the WMO to develop better forecasting capabilities from satellite data. Since 2004, NASA's Public Health Applications in Remote Sensing (PHAiRS) project has worked to create a forecasting model that takes into account wind speed and direction, near-surface temperature, surface topography, surface roughness, and the proportion of land to water using data from NASA's Terra and Aqua satellites. The resulting model has been able to predict the timing of two out of three dust storms in Phoenix, AZ (US).

The ultimate goal is to produce a reporting system that public health officials can use to warn the public approximately 48 h in advance and anticipate dust-related pandemics.

Global Climate Change: Remote sensing plays a prominent and ongoing role in the monitoring of phenomena associated with global climate change. For instance, in keeping with the methodology and findings of the IPPC Fourth Assessment Report, NASA's Global Climate Change Web site (http://climate.nasa.gov/index.cfm) provides summary data about five key quantitative indicators, all of which are currently tracked by satellite-based sensors: (1) the extent of arctic sea ice, (2) the extent of land ice, (3) sea level rise, (4) the atmospheric carbon dioxide concentration, and (5) global temperature. Below, we provide examples where specific spaceborne sensors have been applied to provide information about these five interrelated topic areas.

Arctic Sea Ice In the Arctic Ocean, sea ice reaches its minimum annual extent each September. In September 2007, Arctic sea ice fell to its lowest extent ever, which was 24% lower than the previous record minimum (September 2005) and 37% below the historical average. Giles et al. (2008) used data from the RA-2 radar altimeter aboard the European Space Agency's Envisat satellite to look at sea ice thickness anomalies in the Arctic region. They found that average ice thickness during winter 2007–2008 was 0.26 m less than the average winter-season thickness for the previous 6 years (winter 2002–2003 to winter 2006–2007). The decline in ice thickness was particularly pronounced in the Western Arctic, where the winter 2007–2008 thickness was 0.49 m below the average of the previous 6 years.

Land Ice In the context of climate change, the phrase "land ice" especially refers to the major ice sheets of Antarctica and Greenland. Temperatures on the Antarctic Peninsula have risen more than 0.1 °C per decade for the past 50 years, while temperatures have risen sharply in Greenland since 1990. As a result of these rising temperatures, the Antarctic and Greenland ice sheets have been losing mass at an accelerating rate. Based on data from NASA's GRACE (Gravity Recovery and Climate Experiment) satellite mission, Velicogna (2009) estimated that the mass loss of the Greenland ice sheet increased from 137 Gt/year in 2002–2003 to 286 Gt/year in 2007–2009. Similarly, in Antarctica, the mass loss increased from 104 Gt/year in 2002–2006 to 246 Gt/year in 2006–2009.

On the Antarctic Peninsula, accelerating ice loss led to two major collapses of the Larsen Ice Shelf in the last two decades. First, synthetic aperture radar (SAR) images from the European Space Agency's ERS-1 satellite documented the breaking away of a 4200 km^2 section of the Larsen-A ice shelf in January 1995, which disintegrated almost completely within a few days. Similarly, ERS SAR images documented the rapid breakup of 2300 km^2 of the Larsen-B ice shelf during 1 week in March 2002, representing a large portion of the decrease in the ice shelf's total area from approximately 11,500 km^2 in 1995 to less than 3000 km^2 in 2003.

While rising temperatures have increased surface melting of the Greenland Ice Sheet in the last couple of decades, Howat et al. (2005) argued that much of the ice sheet's rapid thinning (up to 10 m/year) may be due to recent acceleration of outlet glaciers (i.e., glaciers that flow through narrow fjords and out to sea). The researchers used RADARSAT and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery to look at ice flow velocities on Greenland's Helheim Glacier. They found that the outlet glacier's margin retreated landward more than 7.5 km between 2000 and 2005. Because of this retreat, the mass of ice that restricted the glacier's speed was released, allowing the glacier to accelerate. Increased ice melt due to rising temperatures may lead to a feedback loop: thinning ice near the glacier's margin leads to increased calving (i.e., creation of icebergs) and further glacial retreat, releasing more ice and allowing the glacier to accelerate, which causes even more thinning (http://earthobservatory. nasa.gov/IOTD/view.php?id=6207).

Sea Level Rise Sea level rise is caused by the thermal expansion of sea water due to warming temperatures, as well as melting of nonpolar glaciers, ice caps, and the polar ice sheets. In the twentieth century, the global average sea level rose approximately 1.7 mm/ year; moreover, sea level rise accelerated significantly (by 0.013 ±0.006 mm/year) during this period. In the last two decades, a series of satellite altimetry missions have facilitated global mapping of ocean surface topography, including sea surface height: TOPEX/Poseidon (launched in 1992), Jason-1 (launched in 2001), and Jason-2 (launched in 2008). The Jason-2 satellite is operated by the Ocean Surface Topography Mission (OSTM), which is a joint effort of NASA, the National Oceanic and Atmospheric Administration (NOAA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and France's Centre National d'Etudes Spatiales (CNES).

Atmospheric Carbon Dioxide Concentration Carbon dioxide (CO_2) is the most prominent of the "greenhouse gases" implicated in the warming of the Earth's surface. Global CO_2 emissions come from natural (e.g., volcano eruptions) and anthropogenic sources; by far, the largest source of anthropogenic emissions is fossil fuel use. Other greenhouse gases with anthropogenic sources, such as methane (CH_4) and nitrous oxide (N_2O), have also been linked to increases in global temperature during the industrial era, and particularly in the last 50 years.

A principal tool in current greenhouse gas monitoring and research is the Atmospheric Infrared Sounder (AIRS) instrument, which is mounted on NASA's Aqua satellite. The AIRS sensor was designed to measure the levels of atmospheric gases that influence global climate, including CO_2, carbon monoxide, methane, and ozone; it also provides profiles of atmospheric and surface (i.e., sea- and land-surface) temperature, relative humidity and water vapor, and various cloud properties. The observed concentration patterns result from the transportation of CO_2 around the Earth by the general circulation of the atmosphere. The northern hemisphere mid-latitude jet stream serves as a northern limit of enhanced CO_2. A belt of enhanced CO_2 circles the globe in the southern hemisphere, in this case corresponding to the flow of the southern hemisphere mid-latitude jet stream. This belt is fed by biogenesis activity in South America (i.e., the release of CO_2 through the respiration and decomposition of vegetation), forest fires in South America and Central Africa, and clusters of gasification plants in South Africa and power generation plants in southeastern Australia (http://photojournal.jpl.nasa.gov/catalog/PIA12339).

Global Surface Temperature One of the most reliable parameters for tracking cli- mate change is sea surface temperature (SST). In short, heat is a major determinant of global climate, and the oceans serve a major role as massive heat reservoirs (http://science.nasa.gov/earth-science/oceanography/physical-ocean/temperature/).
Sensors that provide long-term SST data suitable for climate change detection include the Advanced Very High Resolution Radiometers (AVHRR) onboard NOAA's polar-orbiting satellites, as well as the Along-Track Scanning Radiometer (ATSR) series of instruments onboard the European Space Agency's ERS-1, ERS- 2, and Envisat satellites. To cite one application example, Good et al. (2007) used AVHRR data to estimate global trends in sea surface temperature for a 20-year period (1985–2004). They found that daytime and nighttime temperatures increased 0.18 (±0.04) and 0.17 (±0.05) °C per decade, respectively.

Observing Coastal and Ocean Ecosystems

Introduction : Marine environments contain substantial biological diversity, deliver vital ecosystem services[2], supply valuable natural resources, and are a core component of our weather and climate system. However, the ocean environment is complex and ever-changing. Examining how our oceans, atmosphere, and landmasses interact would be virtually impossible without the use of a wide variety of sensors and platforms. Satellite observation sensors work in concert with in situ sensors (e.g., buoys and high-frequency radars), research vessels and ships of opportunity, aircraft, gliders (unmanned underwater robots), autonomous undersea vehicles (AUVs), drifters, animal telemetry, and tripod LiDAR to provide cohesive information regarding deep ocean, coastal, and shelf areas in order to understand the complexity, function, and structure of these systems.

There is a large variety of sensors that provide remotely sensed data for coastal and marine applications such as:

- Color scanners: used for ocean color mapping (chlorophyll and suspended sediments, diffused attenuation coefficients, etc.)
- Multispectral data: used for water quality studies (chlorophyll *a*, suspended solids, and turbidity)
- Infrared radiometer data: used for sea surface temperature (SST) and currents mapping
- Synthetic aperture radar: used for surface waves, swells, internal waves, oil slicks, etc.
- Hyperspectral data: used for water quality and pollution detection studies
- Altimeter data: used for sea surface topography, currents, and surface roughness
- Scatterometer data: used for amplitude of short surface waves (surface wind velocity and roughness)
- Microwave radiometer data: used for microwave brightness temperature (salinity, surface temperature, and water vapor).

Various airborne and satellite sensor products, derived from different wavelengths of the electromagnetic spectrum, include (but are not limited to) the following:

- Ocean color
- Phytoplankton
- Chlorophyll *a* and other parameters
- Total suspended sediment (TSS) and turbidity
- Surface temperature
- Ocean currents
- Submerged aquatic vegetation (SAV)
- Bathymetric data

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[2] Ecosystem services as defined by Costanza et al. (1997) and accepted by the United Nations are the benefits people obtain—directly or indirectly—from the habitats, biological, and system properties and processes of ecosystems. Seventeen discrete benefits have been identified: atmospheric gas regulation, soil formation, climate regulation, water supply, nutrient cycling, waste assimilation, pollination, disturbance regulation, biological control, refugia, food production, raw materials, genetic resources, erosion control/sediment retention, regulation of hydrological flows, recreation, and cultural benefits.

- Oil slicks and their spatial distributions
- Coral reefs

There are other water quality parameters in lakes and inland waters that can be added to this list including: turbidity, suspended solids (organic and inorganic), salinity, and nutrient load. Coastal and ocean waters can be further defined as Case 1 or Case 2. Case 1 waters are characterized by a ratio in which the concentration of phytoplankton (chlorophyll *a*) is higher compared with other dissolved inorganic particles in the water column. In Case 2 waters, the dissolved inorganic particles are higher compared with the level of the chlorophyll *a* concentration in the ratio. Thus, optical properties in Case 1 waters are determined primarily by phytoplankton and related colored dissolved organic matter (CDOM), and optical properties in Case 2 waters are largely influenced by constituents other than phytoplankton concentration. The relative contributions of phytoplankton, CDOM, and suspended inorganic matter to the spectral properties of Case 1 and Case 2 waters are illustrated in Figure.

The research community has developed models for estimating the biogeochemical products in open oceans, globally and on a routine basis from satellite data. However, the complexity of coastal water, the atmosphere above the surface of the water, and the variability in time and space require more complex algorithms for handling these nonlinear multivariate bio-optical systems. For these reasons, a single algorithm to be transportable in time and space on an operational basis requires further development. As illustrated through Fig. 2 and Table 1, the spectral characteristics of coastal and marine water components indicate that no single wavelength range (band) can account for various coastal and sea surface conditions. Therefore, a more complex modeling approach is needed to address them. Surface and subsurface information on ocean chemistry, physics, and biology is only practically possible through global-scale ocean observations.

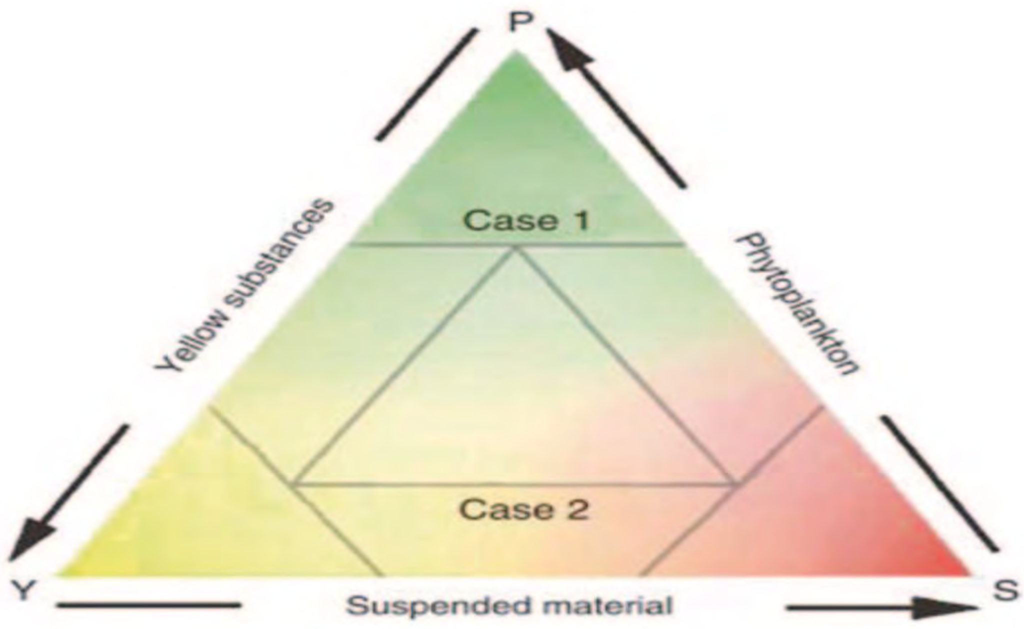

Fig1 The triangular diagram illustrating the relative contribution of phytoplankton, dissolved organic matter *(yellow substances)* and *suspended material* (non-algal particles), and the division between Case 1 and Case 2 waters.

Product name	Critical spectral range (nm)
Chlorophyll and other pigment concentration	443–445 (max. abs.), 550–560 (min. abs.)
	490, 548, 640 (for other pigments)
Red tides	510
Sediment concentration	530–650, NIR
CDOM	410–420
Seabed reflectance	490–580
Chlorophyll fluorescence	680–685
Aerosol optical properties	700–NIR
Atmospheric corrections	TIR
Sea surface temperature (SST)	NIR; TIR

CDOM colored dissolved organic matter, *NIR* near infrared, *TIR* thermal infrared

Table 1 An example of spectral range for coastal waters applications

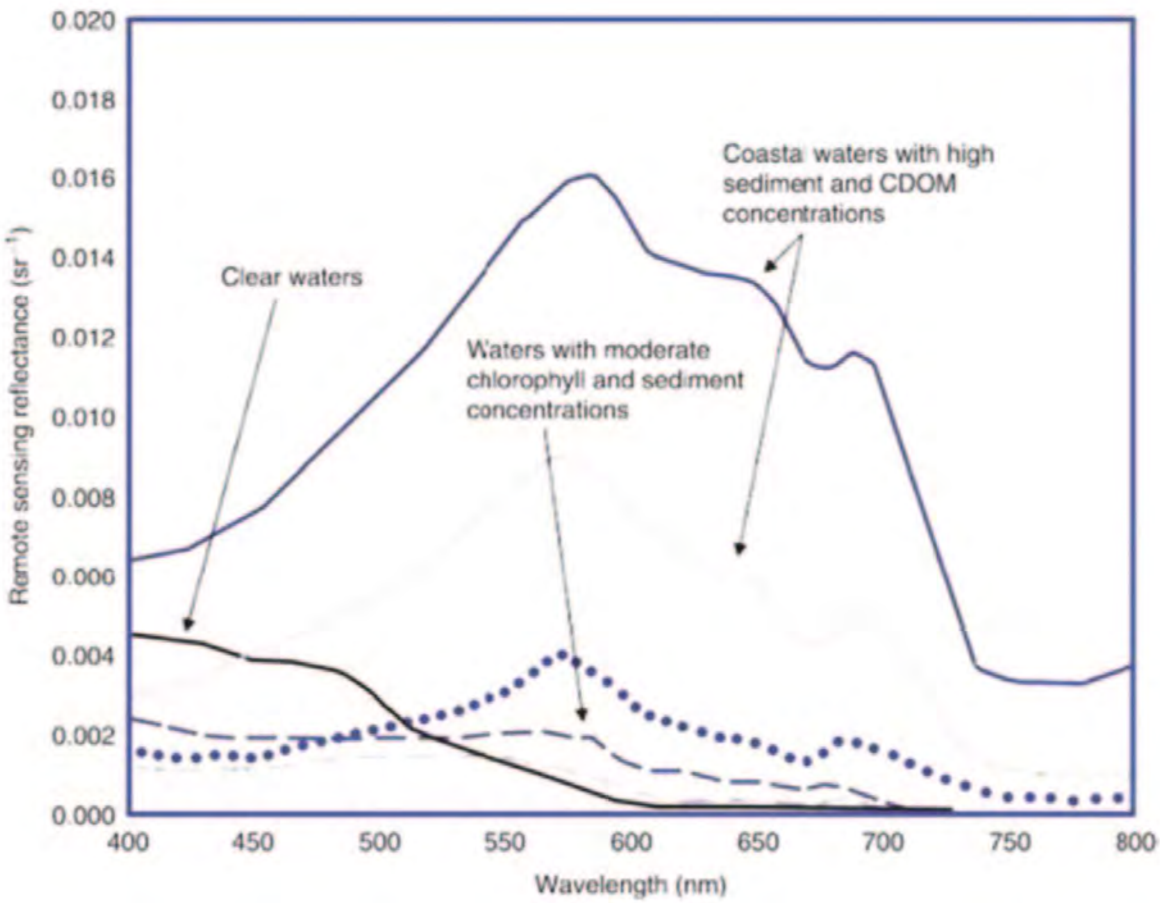

Fig. 2 The reflectance properties of various water types.

Using Remote Sensing to Map Ocean Color, Phytoplankton, and Chlorophyll Concentration: Airborne and satellite remotely sensed data are commonly used for mapping ocean color. The Ocean Biology Processing Group (OBPG) at NASA's Goddard

Space Flight Center conducted a satellite ocean color measurements in June 2015 of the Bering and Chukchi seas (Alaska/Siberia). The OBPG ocean color map was developed using the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data. The VIIRS scanning radiometer is a sensor on board the Suomi National Polar- orbiting Partnership weather satellite. This sensor collects imagery and radiometric measurements of the land, atmosphere, cryosphere, and oceans in the visible and infrared bands of the electromagnetic spectrum. The OBPG ocean color map is shown in Fig.3

Figure 4 was captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on December 21, 2010. This image shows a massive phytoplankton bloom located off the Atlantic coast of Patagonia. Scientists used seven separate spectral bands to highlight the differences in the plankton communities across this swath of ocean. The milky green and blue phytoplankton blooms displayed are likely coccolithophores, single-celled plants that form calcite scales. Calcite is a carbonate mineral often found in limestone chalk. Blooms of coccolithophores and diatoms are common in these waters during the southern hemisphere's spring and summer where warmer, saltier coastal waters and currents from the subtropics meet the colder, fresher waters flowing up from the south. Where these currents collide—known to oceanographers as a shelf-break front—turbulent eddies and swirls form, pulling nutrients up from the deep ocean. In addition, the nearby Rio de la Plata (La Plata River) runs off the land and deposits nitrogen and iron-laden sediment into the sea just north of the area as shown in the image (http://oceancolor.gsfc.nasa.gov/cms/).

Chlorophyll distributions in the upper ocean are a unique proxy for phytoplankton biomass—a basic component in primary production—as well as a useful indicator for ocean upwelling. Phytoplankton (Fig. 5) serve a crucial biogeochemical function, converting CO_2 to particulate organic matter and releasing oxygen. The rate of marine primary production is determined by temperature, light (strongly influenced by surface turbulent mixing depths), and limiting nutrients—particularly nitrogen, phosphorus, iron, and silicon for some plankton.

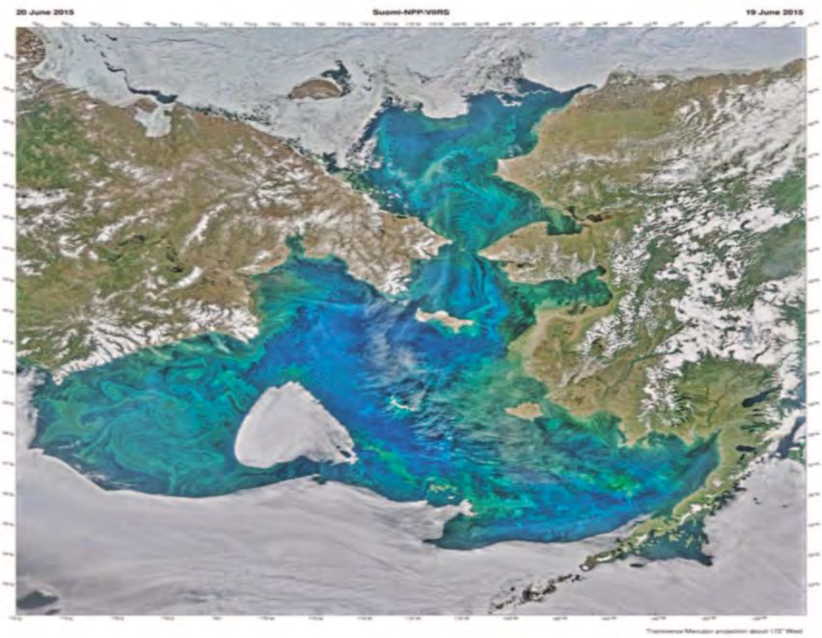

Fig. 3 The VIIRS satellite data collected this view on June 19/20, 2015 showing ocean color in the Bering and Chukchi seas (Alaska/Siberia). (Image source: http://oceancolor.gsfc.nasa.gov/ cms/)

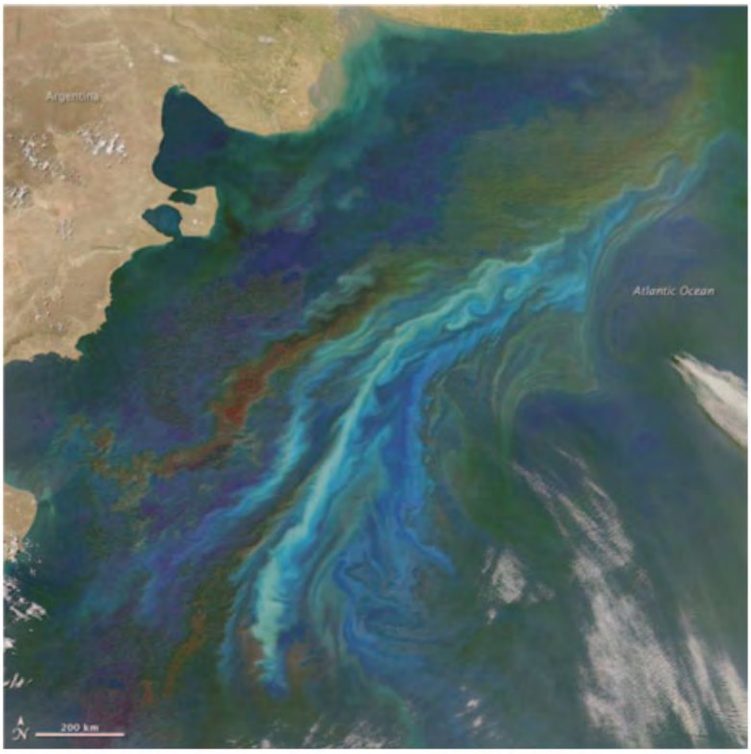

Fig. 4 MODIS Aqua image of the massive phytoplankton bloom off the Atlantic coast of Patagonia on December 21, 2010 (NASA 2010). (© NASA image created by Norman Kuring, Ocean Color Web. Caption by Michael Carlowicz)

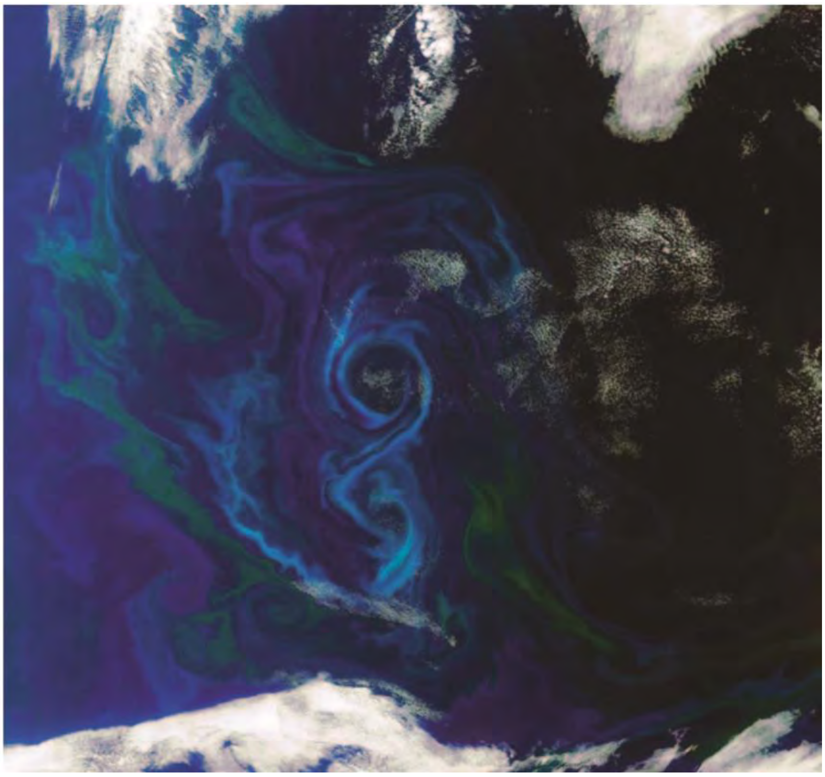

Fig. 5 Phytoplankton bloom swirls a figure-eight in the south Atlantic ocean, about 600km east of the Falkland Islands, on December 2, 2011. Different types and quantities of phytoplankton exhibit different colors. Once a bloom begins, ocean color sensors can identify its chlorophyll pigment, and therefore its species and toxicity. (© Envisat/ESA)

Satellite sensors developed to quantify global ocean chlorophyll levels and produce biological data include sensors such as the SeaWIFS (Sea-Viewing Wide Field-of-View Sensor). The SeaWIFS sensor was launched on August 1, 1997, onboard GeoEye, Inc.'s OrbView-2/SeaStar satellite. The SeaWIFS, although designed to operate for a period of only 5 years, began collecting data on September 18, 1997 and was retired from operation data on December 11, 2010.

The sensor collected data at a 1.1 km local area coverage (LAC) in the following optical bands: 1 (402–422 nm), 2 (433–453 nm), 3 (480–500 nm), 4 (500–520 nm), 5 (545–565 nm), 6 (660–680 nm), 7 (745–785 nm), and 8 (845–885 nm).

Optical remote sensing in coastal waters typically provides quantitative estimates of phytoplankton biomass (indexed by chlorophyll concentrations), total suspended matter, and dissolved organic substances, with accuracies as good as the same types remote sensing-derived estimate within open ocean (approximately 30–40 % in biomass) when using regional dedicated algorithms. These components, in turn, influence the light attenuation coefficient in the water which is also directly retrieved from the satellite, providing information on water transparency. The latter represents an important quality parameter to assess the ecological status of lakes and coastal waters. Remotely sensed chlorophyll concentration and light attenuation are also used to estimate water-column primary production, which represents a critical indicator to assess coastal eutrophication, and to analyze the carbon budget directly associated with the continental shelf pump health and resilience.

As an image captured by the NASA MODIS Aqua satellite, both the Yangtze River and Hangzhou Bay, to the south, are filled with thick brown sediment. The sediment extends both to the north and the south along China's coast, and is joined by sediment from smaller watercourses along the coast. As the sediment flows into the East China Sea, it begins to sink and the reflectance properties change; as less light is reflected, the color becomes greenish, then blue. The city of Shanghai is likely a major contributor to these changes in the Yangtze River.

Remote Sensing of Eutrophication and Ocean Hypoxia: Nutrients can be present in two major forms: inorganic (or mineral) and organic (both living and detrital). Nitrogen and phosphorus are the most significant nutrients, and their main species include dissolved (nitrate, nitrite, ammonium, organic N, phosphate, organic P) and particulate (organic N, organic P) components. Silica is also a fundamental nutrient in coastal systems because diatoms, a predominant phytoplankton group in estuaries and coastal systems, require silica in their structural composition. Complex models frequently address all of these properties, accounting for the explicit parameterization of several element cycles, thus tracing each nutrient and carbon source in the system. Figure 6 illustrates some of these results, with an example of spatial maps for chlorophyll, silicate acid, and semilabile organic matter in a mesotidal estuary. It should be noted that complex models are usually based on the assumption of variable internal nutrient composition, allowing for the tracing of the evolution of C:N ratios in time for phytoplankton, and providing relevant clues on the influence of nutrient deficiency.

Urban development and agricultural operations produce high concentrations of nutrients. These nutrients impact coastal watersheds, causing upwellings and algal blooms in many estuaries and coastal waters. Algal blooms are harmful in that they cause eutrophic conditions, depleting oxygen levels needed by organic life and limiting aquatic plant growth by reducing water transparency. Most algal blooms can be observed from satellites, due to their distinct color, location, or repetitive seasonal appearance. Concentrations of chlorophyll *a* (chl-*a*) and TSS can be used as indicators of the severity of eutrophication and turbidity, respectively.

Eutrophication is the biological process by which aquatic primary production is augmented through an increase in the rate of organic matter and nutrients (e.g., nitrogen and phosphorus from fertilizers, sewage effluent, and other pollutants) delivered to surface water (e.g., river, lake, estuary, and coastal waters). Eutrophication promotes excessive algae and plankton growth and can cause a severe reduction in water quality. Algae and plankton blooms (Figure-7), in turn, disrupt normal ecosystem functioning, consuming vast amounts of oxygen thereby decreasing the amount of oxygen needed for fish, shellfish, seagrass beds, and coral reefs to survive. The water typically turns cloudy and colored a shade of green, yellow, brown, or red.

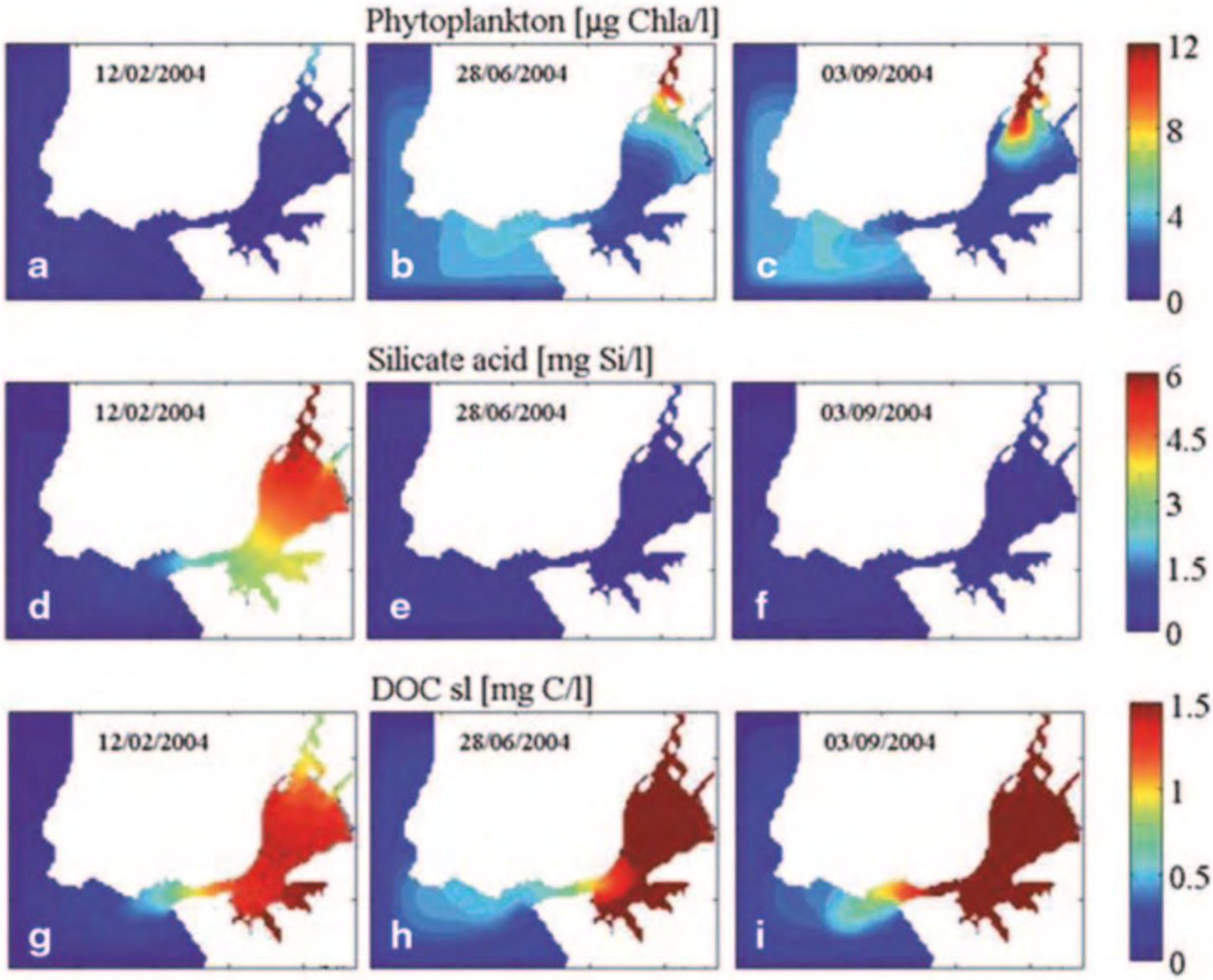

Fig. 6 Spatial maps for chlorophyll, silicate acid and semi-labile organic matter in a mesotidal estuarine system.

Excessive algae growth in coastal waters may also lead to a condition known as "hypoxia", as surface layer algae begin to die, then sink, then decompose, robbing the subsurface water layers of oxygen. Hypoxia may also arise as a consequence of other pollutants in the water column, such as sediment, chemicals, or sewage. Hypoxia can also occur naturally in open-ocean and coastal environments from a combination of weak vertical mixing of fresh and salt water within the water column and/or strong organic matter degradation. Dissolved oxygen (DO) is essential for aerobic respiration; low oxygen levels adversely affect the physiology of higher animals, leading to mass mortality or "dead zones" where marine life is absent. Hypoxia occurs when DO falls below 2 ml of O_2/liter. Worldwide, there are now more than 400 coastal hypoxic systems covering an area of >245,000 km^2. Population growth and further coastal urbanization will only exacerbate coastal hypoxia without careful land and ocean management.

Fig. 7 After a nearly ice- free winter, Lake Erie (US) was filled with suspended sediment and algae. *Muddy, tan-colored* water along the shoreline reveals sediment from rivers. *Milky green, light blue,* and *white* shades may also be sediment-rich waters as the lake bottom is rich in quartz sand and cal- cium carbonate (chalk) from limestone. (© Jeff Schmaltz, MODIS/Terra/NASA)

One future area of satellite remote sensing ocean color research is to improve the classification of phytoplankton pigment concentrations, which would then serve to improve our understanding of algal biodiversity and taxonomic composition. This improved understanding would also provide a better understanding of the impacts of pollution and excess nutrients on marine ecosystems. For example, some pigments are unique biomarkers for particular phytoplankton in coastal waters (e.g., alloxanthin in cryptophytes, peridinin in some dinoflagellates, and zeaxanthin from cyanobacteria). Thus, further improved remote sensing capabilities in the identification and classification of these phytoplankton species may provide vital information on the seasonal and regional distribution of these species.

Newer and enhanced sensors will further increase our capacity to assess optical water quality characteristics (e.g., chlorophyll *a*) that leads to coastal eutrophication and hypoxia episodes. However, there is still much research to be done with currently available sensor data (e.g., the Landsat 8 sensor, as well as the upcoming launch of the ESA Sentinel-2 satellite sensor) and the expanding availability of hyperspectral data. In addition, an increased understanding of mesoscale ocean features (e.g., fronts, filaments, eddies, Lagrangian coherent structures, and river plumes) may also provide associative data that will be helpful in developing remote sensing-based models of the occurrence, distribution, and duration of ocean and coastal eutrophication and hypoxia episodes. Mesoscale ocean features have been shown to be associated with enhanced productivity and fish aggregation, span spatiotemporal scales that range from one to thousands of kilometers and from hours to weeks. Finally, hydrodynamic-biogeochemical models developed from the remotely sensed optical properties of seawater are capable of providing tools that reveal the present state of the ecosystem in three dimensions, as well as forecasting future conditions in relation to nutrient inputs. Understanding the relationship of the coastal and ocean systems to these nutrient inputs may also aid in assessment and identification of coastal eutrophication and areas of hypoxia.

Using Remote Sensing to Map the Sea Surface Temperature and Circulation Patterns:

Satellite instruments, other than optical sensors, can provide additional information of importance to coastal water management. Microwave sensors collect data either passively or actively in that part of the electromagnetic spectrum ranging from 3 mm to 1 m wavelength. These instruments provide significant advantages in viewing the Earth under all weather conditions–even through clouds and day and night capabilities. However, their spatial resolution, which depends on the physical dimension of the antenna, is often not adequate for coastal applications. Sophisticated synthetic aperture radars (SARs) are an exception to that rule and can retrieve surface features at extremely fine resolution, of the order of meters.

Numerical ocean circulation models are widely used for such predictions. Although satellites cannot provide direct measurements of ocean surface currents, a combination of several sensors such as scatterometers, altimeters, and radiometers may be used to infer these currents. Such a product, known as Ocean Surface Cur- rents Analyses Real-time (OSCAR), is currently being freely distributed to the user community.

Ocean color measurements have been combined with satellite data on SST and other physical properties of the ocean to explain the processes that regulate primary production in the sea. Examples of MODIS satellite and Japanese ADEOS/OCTS satellite applications for SST mapping are shown in Figs. 8 and 9, respectively.

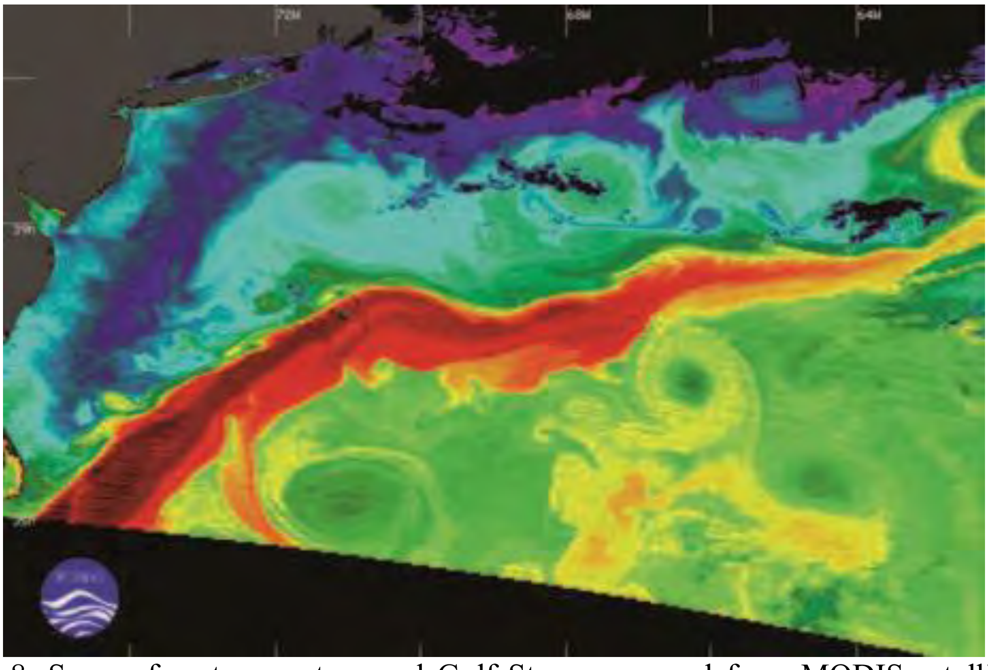

Figure-8: Sea surface temperature and Gulf Stream mapped from MODIS satellite. (© Bob Evans, Univ. of Miami (FL, US) and NASA)

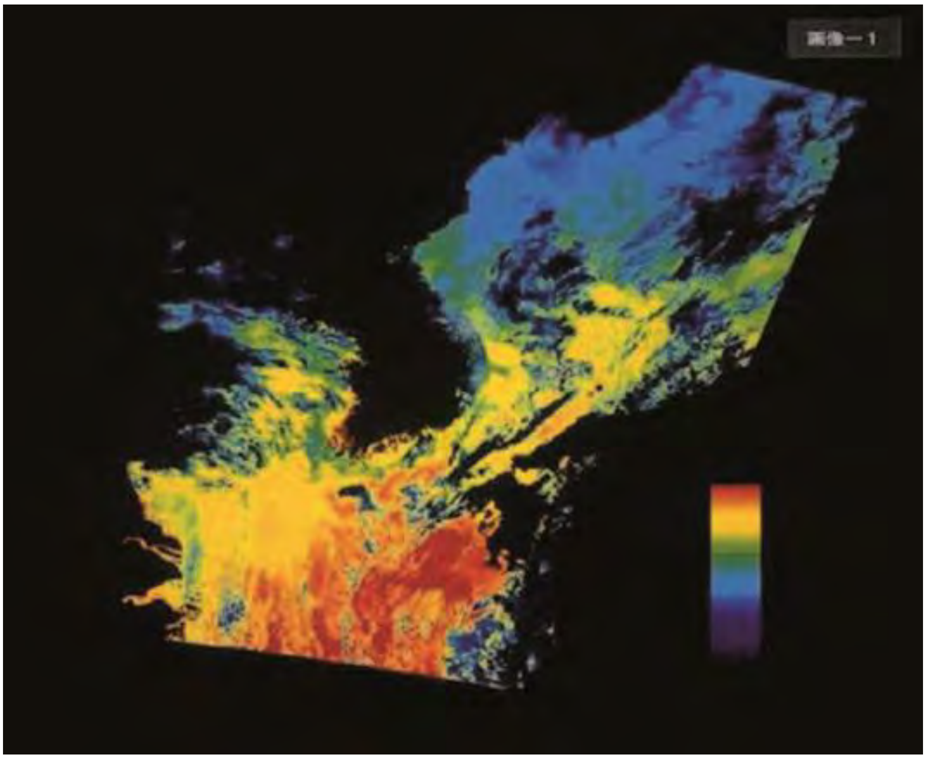

Figure-9: Sea surface temperature mapping from ADEOS/OCTS over the Sea of Japan

Spatial Analysis of Submersed Aquatic Vegetation: An additional area of growing popularity in marine and freshwater remote sensing studies is the identification, detection, and analysis of spatial distributions of submersed aquatic vegetation (SAV). Aquatic vascular plant populations are found in various freshwater bodies, coastal and ocean environments worldwide. Emergent and submersed aquatic vegetation in these environments provides critical habitat for aquatic species, also a trophic and food source, enhanced water quality, reduced turbidity and sedimentation, bank and shoreline stabilization, and increased oxygen within the water column. However, monitoring, management, and assessment of the environment where these plants are found are greatly hindered by limitations of size and access within the aquatic environment. Understanding the dynamics of aquatic plant populations has been recognized as much more important in more recent years due to global declines in native populations concomitant with invasions of nonnative species through global human movement.

The monitoring, management, and assessment of emergent aquatic vegetation may present less of a challenge, in that as the name implies, these plants have part of their growing cycle above the surface of the water. However, SAV typically remain completely submerged below the water surface. The disappearance of native SAV species or the introduction and dispersal of invasive SAV species can cause severe ecological and economic impacts. Ecological impacts are centered on the fact that the entire food web dynamics can be significantly altered by the addition or removal of a single keystone or exotic species. Invasive submersed species, in particular, displace native plants and can shift balanced, heterogeneous ecosystems to monocultures with severely altered food web dynamics. Invasive SAV can also promote lethal impacts affecting higher trophic levels. For example, an epiphytic cyanobacterium commonly found on invasive *Hydrilla verticillata* has been shown to produce a neurotoxin(s) that causes avian vacuolar myelinopathy (AVM). AVM is an often-lethal neurological disease of waterfowl and their predators in the southeastern United States, from coots *(Fulica americana)* to bald eagles *(Haliaeetus leucocephalus)*. Furthermore, large quantities of invasive SAV biomass are prime habitat for mosquitoes, which can carry a number of diseases. Major economic loss has been sustained from invasive SAV whose growth inhibits flood control, hydropower generation, irrigation, navigation, and recreation in infested water bodies. Related loss of native SAV species can result in the collapse of fish populations. Many have quantified the direct economic losses associated with both native losses and invasive introductions as ranging from tens of thousands to millions of US dollars. Indirect economic losses, more difficult to define and sometimes of major importance, only add to this deficit. Thus, the methods by which to detect, monitor, and assess SAV, including evaluation of the efficacy of management actions, have become increasingly important.

Large-scale SAV surveys are rarely performed due to logistical difficulties and the high costs incurred when obtaining survey data over large areas. In past years, remote sensing coupled with modeling and interpolation techniques has shown the potential to be an important tool to obtain survey information on SAV over large areas.

Remote sensing has the potential to be an important tool to obtain survey information on SAV measurements across large geographic areas. In a study conducted in multiple lakes within the state of Michigan, Nelson et al. (2006) found significant relationships between SAV plant cover types and SAV abundance measures using Landsat 5 TM values in logistic regression models.

Data provided through remote sensing applications have a tremendous potential for also detecting the status and distribution of nuisance aquatic vegetation (NAV) over large geographic areas. NAV such as Eurasian watermilfoil *(Myriophyllum spicatum)* now impact many freshwater systems of the US. Other species, such as hydrilla *(Hydrilla verticillata),* although primarily a freshwater invasive aquatic plant, have been shown to tolerate tidal- and brackish-water environments. This tolerance for low salinity environments may threaten the spread of this plant into near - shore coastal environments. These NAV species tend to be highly aggressive aquatic plants that outcompete native aquatic plants, altering habitats for birds and fish, as well as leading to situations of overgrown plant materials that congest waterways, thus limiting travel and recreation. Current field-based surveillance methods for nuisance and invasive submerged plants are labor-intensive, time-consuming, and costly. However, remote sensing approaches provide certain advantages over traditional methods, allowing for repeated image coverage over large areas and synoptic analysis techniques for detection, mapping, and monitoring of submerged aquatic invasive species.

Although the combination of satellite remote sensing and statistical modeling techniques for the application of SAV distribution and abundance monitoring has shown promise, the technology still must overcome the difficulties inherent in interpreting reflectance values of water. For example, clear water provides little atmospheric reflectance, with the majority of the shortwave radiation scattered in the atmosphere and longer wavelengths absorbed within the few millimeters of the water surface. Adding to this challenge, currently, the majority of the optical satellite sensors are still primarily designed for detecting land features. However, despite the potential limitations of using existing sensors, newer sensors with improved spatial, radiometric, and spectral resolutions may, in the near future, prove to be applicable for aquatic studies.

Remote Sensing of Coastal Bathymetry: In shallow coastal waters, remote sensing is being used to monitor benthic structure and classify bottom types. At present, satellites most commonly exploited for that purpose are equipped with radiometers, such as the SPOT-HRV and Landsat TM series with typically 10–30 m spatial resolution, or even IKONOS with spatial resolution better than 10 m. Even though these sensors have a limited set of wave- lengths (three to four broad spectral bands in the visible), the spectral contrast be- tween various bottom structures (e.g., corals and non-coral objects) can be used to construct classification algorithms based on differential reflectance.

LiDAR data integrated with global positioning systems (GPS) can be used in obtaining accurate topographic and bathymetric maps, including shoreline positions. LiDAR surveys can produce a 10 cm vertical accuracy at spatial densities greater than one elevation measurement per square meter. This is important for various coastal research applications of LiDAR, such as mapping change along barrier is- land beaches and other sandy coasts. The ability of LiDAR to rapidly survey long, narrow strips of terrain is very valuable in this application, as beaches are elongate, highly dynamic sedimentary environments that undergo seasonal and long-term erosion or accretion, and are also impacted by severe storms.

Remote Sensing of Coral Reefs: Coral reefs are extremely vulnerable to changes in ocean temperature, pollution, and algal levels. Tropical and subtropical corals exist in a symbiotic relationship with zooxanthellae that live within their tissues, provide the coral with oxygen and nutrients, and give the coral its color. When stressed, corals respond by expelling their symbionts, losing their pigmentation in the process. This results in a white or bleached appearance, which occurs most frequently with warm water events. Warm water events occur when strong solar insolation is coupled with stratification in the water column. Water temperature stratification occurs when there are calm winds, an absence of waves, and low currents, creating warm surface temperatures in the shallow waters where tropical corals are found. Prolonged periods of bleaching (i.e., warm temperatures and lack of the algae’s nutrients) lead to coral mortality.

One of the threats to coral reefs and coastal waters are oil spills from various oil rigs and oil transportation devices. Oil slicks and their spatial distributions can be readily detected and mapped from remotely sensed data. The massive 2010 oil spill in the Gulf of Mexico, as imaged by the Scan SAR by InfoTerra.

According to the Global Coral Reef Monitoring Network, approximately 19% of the world’s coral reefs are dead with another 15 % expected to die by 2025. Reefs are important as both fish habitats and buffers against high waves.

A first step in determining conditions ripe for coral bleaching is to evaluate the magnitude of the current needed to produce tidal mixing. DiMassa et al. (2011) examined surface current speed measured by twin high-frequency radar systems monitoring the Capricorn/Bunker groups of island and reefs in the Great Barrier Reef of Australia and compared it with Simpson–Hunter (1974) threshold values determined throughout the radar coverage area along with local bathymetry measurements. Areas in which the surface currents exceeded the Simpson–Hunter threshold values were determined to be well mixed, even in the absence of wind or waves, while regions in which surface currents did not exceed the threshold values were assumed to have some degree of stratification. The extent of mixing or stratification was used as an indicator for coral bleaching. DiMassa et al. (2011) produced maps which indicate relative susceptibility to coral bleaching based on tidal currents and the generation of tidal mixing fronts.

Remotely sensed data can be used for modeling the resilience of coral reefs. IKONOS and Quickbird satellite data were used in a spatial predictive modeling context by Knudby et al. (2014) to map four of the resilience indicators to predict the stress-tolerant coral taxa, coral diversity, herbivore biomass, and coral recruitment (quantified as the density of juvenile corals), as well as herbivore functional group richness and the live cover of corals and coralline algae, both of which may also influence reef resilience.

The results from Knudby et al. (2014) suggest that, based on the data available, the spatial distribution of stress-tolerant coral taxa and herbivore biomass could be reasonably well predicted using the random forest model, while the density of juvenile corals could only be poorly predicted using the universal kriging model and coral diversity was essentially unpredictable. An example output, the predicted spatial distribution of juvenile coral density from each of the two models.

A global assessment of locations most at risk to coral bleaching was performed by Australian scientists, led by Joseph Maina of Macquarie University in Sydney. The researchers used nearly 30 years of satellite and tidal data to examine temperature, wind speed, tidal dynamics, ultraviolet radiation levels, sediment, and nutrient levels, and combined that information with stress-reducing factors to identify which reefs would be likely to survive additional stressors and which ones would be more vulnerable to adverse regional conditions. The resulting map assists managers in the strategic use of conservation efforts and funds, as well as informing policymakers of changing conditions.

Mapping of coral reefs requires high-resolution (1–4 m) imagery. Coral reef ecosystems usually exist in clear water and can be classified to show different forms of coral reef development (i.e., living coral, dead coral, coral rubble, algal cover), bottom structure, and seagrass densities. Higher resolution multispectral imagers (e.g., IKONOS) have been used to map coral reefs; however, hyperspectral imagers should improve the results significantly.

Achieving Sustainable Fisheries and Aquaculture Management: Overfishing of the world's open and coastal regions has been a huge issue ecologically, as well as politically. Countries economically-dependent on ocean harvesting of various fin and shellfish species and their by-products are typically regulated by their own sovereign and national laws. However, if these laws do not provide regulations that prevent overfishing, the impact of this activity can have a devastating effect on the global population of fish species that may be far reaching beyond the jurisdictional boundaries of the country (or countries) involved. The ramifications of these activities may serve to reduce or eliminate populations of targeted harvest species and bycatch. In addition, overharvesting may also serve to pollute fishing grounds from increased boat activity, as well as destroy critical habitat and spawning grounds, and greatly weaken the ability to sustainable native stocks.

Sustainable fisheries techniques largely function by developing management plans that map out critical fisheries habitats and nursery grounds, as well as limit the number of species caught in a particular area to prevent overfishing. Traditional approaches to the use of remote sensing in fisheries relied on aerial photographic imagery that was transferred to fishing vessels at sea with the data being converted into charts showing locations of large shoals of fish. Fishing fleets rely on GPS technologies to locate catches that are within reach and fuel costs. Simpson (1992) and Chassot et al. (2011) point out the use of satellite sensors, such as the Advanced Very High Resolution Radiometer (AVHRR), Nimbus-7 coastal zone color scanner (CZCS), SeaWIFS, MODIS, and MERIS have been used to augment stock assessment tools by mapping the distribution of phytoplankton pigment (i.e., chlorophyll *a*) in the ocean. The presence of phytoplankton has been shown to be correlated to the shoaling of many pelagic and non-pelagic fish species, as these species may feed on the phytoplankton or the zooplankton and associated smaller fish that feed on the plankton. In addition for improving stock assessments, satellite-derived mesoscale oceanographic features may also be used to improve the understanding of species habitat distributions in larger areas. Finally, other work focuses on food webs, temperature, and salinity gradients for a better understanding of population movements.

Satellite remote sensing for sustainable fisheries management, although under utilized, provides important information for assessing sustainable fisheries stocks. While stock assessment models must rely on the combination of additional data (e.g., chlorophyll, sea surface temperate, salinity, mesoscale ocean structures), many of these model variables can be derived from currently available sensors. In the consideration of climate change, the collection of data is imperative at a comprehensive scale necessary to provide global management decisions for sustainable fisheries, commercial harvest, and stock utilization. Newer satellite sensors, promising repetitive, synoptic, high-resolution imagery, will serve to improve these global models that are necessary for understanding not only current fish species spatiotemporal distribution, composition, and population dynamics but also how these dynamics will be altered in light of global warming events.

Ocean Observation Networks: The vastness of our oceans requires a global framework in collaborative data collection. From a remote sensing perspective, most parameters, other than physical, are poorly sensed. For example, remote sensing data are rare to nonexistent for long time series that include data from the deep oceans, under-ice measurements, and geochemical, biological, and ecosystem parameters. There is, however, an extensive use of proxies and many sensors are not optimized for autonomous systems. A major proportion of the current ocean observation system—comprising different observing units and networks— was built and driven by climate observing requirements. The data products help inform climate research and aide in decisions about climate change. However, there are many more motivations than climate and weather for conducting ocean observations such as monitoring biodiversity, regional seas and regional fisheries management organizations, global marine resource agreements and assessments, and the development of ecosystem-based approaches for management of the ocean environment.

Several of the major ocean observation networks are described here. No single asset or suite of sensors addresses all spatial and temporal scales of ecosystem variability; it is necessary to integrate an appropriate mix of fixed and mobile platforms, remote sensing, process studies, models, and data management to advance a better understanding of the effects of climatic phenomena and human activity on ecosystem variability.

Global Ocean Observing System (GOOS): The Global Ocean Observing System (GOOS) is a voluntary collaborative network of observations, where the components of the system are funded by national sources. As of 2015, global participation in the observing networks in GOOS varies—from a high of 77 countries contributing to tide gauge observations of sea level to about 10 countries involved in the resource-heavy global network of repeat hydrographic lines, measuring every feasible variable from the platform of a research ship. The GOOS system includes in situ and satellite observations along with operational observing networks and sustained research-funded observing networks and platforms, and is designed to serve many different objectives and users. For the essential (ocean) climate variables that can be measured on the surface of the ocean from satellites, GOOS examines the adequacy of commitments to missions in order to maintain a continuous and high-quality climate record.

Australia's Integrated Marine Observing System (IMOS): As a marine country with the third largest ocean territory on Earth, Australia's weather patterns are highly sensitive to ocean influences. Australia also realizes an enormous economic benefit from its ocean territory. In response to these opportunities and challenges, Australia's Integrated Marine Observing System (IMOS) was created to observe and manage marine resources based on a national strategic approach addressing five major themes: multi-decadal ocean change, weather variability and weather extremes, major boundary currents and inter-basin flows, continental shelf processes, and ecosystem responses. The data are open-access and free of charge. IMOS collaborates with GOOS and other ocean observing networks.

European Marine Observation and Data Network (EMODnet): The European Marine Observation and Data Network (EMODnet) is the fulfillment of an objective of the European Union's maritime policy to integrate existing, but fragmented and often inaccessible marine data (e.g., SeaDataNet, MyOcean, Euro- GOOS, EuroARGO, EuroSITES, and other national and regional ocean observing systems) into interoperable, continuous, and publicly available data streams. EMODnet contains several portals including bathymetry, biology, chemistry, geology, hydrography, physics, and physical parameters.

US Integrated Ocean Observing System (IOOS®) : The US Integrated Ocean Observing System (IOOS®) is a national–regional partnership created to ensure the sustained observation of US coastal areas, oceans, and the Great Lakes, and to develop near real time and retrospective information products from those observations to assist people in their lives and livelihoods. The primary focus is to provide timely information through national and regional collaboration.

The Pacific Islands Ocean Observing System (PacIOOS) is one of 11 regional associations in the IOOS. The Pacific Island region spans 2 days and 8 time zones; it takes 11 h for PacIOOS to traverse from one end to the other. PacIOOS addresses familiar question such as where are the fish today? Which beaches are safe to visit today? Can I bring my vessel into the harbor safely? Is my home going to be inundated? Thematic areas include marine operations, ecosystem information, coastal hazards, water quality, numeric modeling, outreach and education, and data management and visualization. PacIOOS reports to the public and local groups, through its governing council, and directly relate the value of ocean observation to them at a very local and personal level, while still serving data to inform research and science at the global scale. Direct economic benefit, environmental preservation, and public health/safety are primary drivers. Science and research are secondary drivers of regional observing systems. PacIOOS is managed as nonprofit and governed by public stakeholders, providing connectivity to local people and a conduit for their voice.

Physical models include high-resolution wind models, wave models, and ocean circulation models down to 60 m. PacIOOS runs three suites of numerical models.

Atmospheric models are run for the HI Island chain and then for each individual island at a higher resolution. Wave models are run basin-wide, and then nested down to the Hawaii regional and island scales. The ocean model is run at the Hawaii regional scale and then nested at high resolution to individual coastlines. It may be possible to expand this modeling capacity in both spatial area and increased resolution in the coming years.

Planetary and Extrasolar Observation

Introduction : In 2012, NASA issued the final version of an “all-sky atlas” that consists of 18,000 image mosaics constructed from 2.7 million images captured by its Wide-Field Infrared Survey Explorer (WISE) satellite. Figure 10 is one of those image mosaics, showing the entire sky in infrared light. The Space Sciences Laboratory at the University of California, Berkeley has identified and labeled a number of noteworthy features in the mosaic image, such as the Andromeda Galaxy, the Tarantula Nebula, and Puppis A, a supernova remnant. The bright strip across the middle of the image is the Milky Way. Among the many discoveries made by WISE is a remote galaxy that is more luminous than 300 trillion suns, making it the most luminous galaxy ever identified by astronomers. This luminosity may be related to a supermassive black hole at the galaxy’s core.

Like supernovae, gamma-ray bursts are explosive events associated with the deaths of massive stars. Gamma-ray bursts are actually more extreme events, exhibiting luminosity that is a million times greater than the peak luminosity of an exploding-star supernova. Although first discovered in the 1960s, much remained unknown about gamma-ray bursts until the launch of NASA’s Swift (i.e., the Swift Gamma-Ray Burst Mission) and Fermi (i.e., the Fermi Gamma-Ray Space Telescope) satellites in 2004 and 2008, respectively. The two satellites carry instruments that have contributed significantly to research regarding the gamma-ray burst phenomenon, which is believed to relate to the gravitational collapse of matter that leads to black hole formation. Figure 11 shows the December 2011 explosion of a gamma-ray burst, designated GRB 111209A, which was captured by the Swift satellite. While some gamma-ray bursts produce a signal (including both gamma-rays and X-rays) that lasts only a couple of seconds, GRB 111209A produced a signal that lasted 7 h, making it the longest-duration gamma-ray burst ever recorded.

The preceding are just two examples of recent developments in the remote sensing of space. Indeed, many of the types of sensors commonly used for remote sensing of the Earth have similarly been applied to the other planets in our solar system or, as illustrated above, for viewing phenomena beyond our system. In fact, many technological developments in remote sensing are at least partially rooted in space exploration efforts; for instance, imaging spectroscopy—hyperspectral imaging—was developed in parallel for terrestrial and planetary applications. Of course, what are perhaps the best-known space exploration efforts have actually involved direct (i.e., non-remote-sensing) measurements: the Apollo missions, which landed astronauts on the Earth’s Moon during the late 1960s and early 1970s, and more recently, the unmanned Mars Exploration Rovers *Spirit* and *Opportunity*, which began collecting data from the Martian surface in 2004 (*Opportunity* was still active as of July 2015; see http://marsrover.nasa.gov/home/ index.html), as well as the rover *Curiosity*, which has been collecting data since 2012 as part of NASA’s Mars Science Laboratory mission (http://mars.jpl.nasa.gov/ msl/). Notably, all of these surface investigation missions have coincided with re- mote sensing by orbiting spacecraft. For example, the Apollo Command and Service Modules, which orbited the Moon while their corresponding Lunar Modules were on the surface, were equipped with a variety of remote sensing instruments, and there are currently five different spacecraft orbiting Mars. Ultimately, orbiting or fly-by spacecraft have collected remotely sensed data, in varying amounts, for all of the planets in our solar system and some of their moons, as well as asteroids and the Sun (e.g., NASA's Solar Dynamics Observatory). Furthermore, the number of satellite-based instruments targeted at deep space continues to increase. In this part, we highlight some prominent historical missions as well as some active efforts.

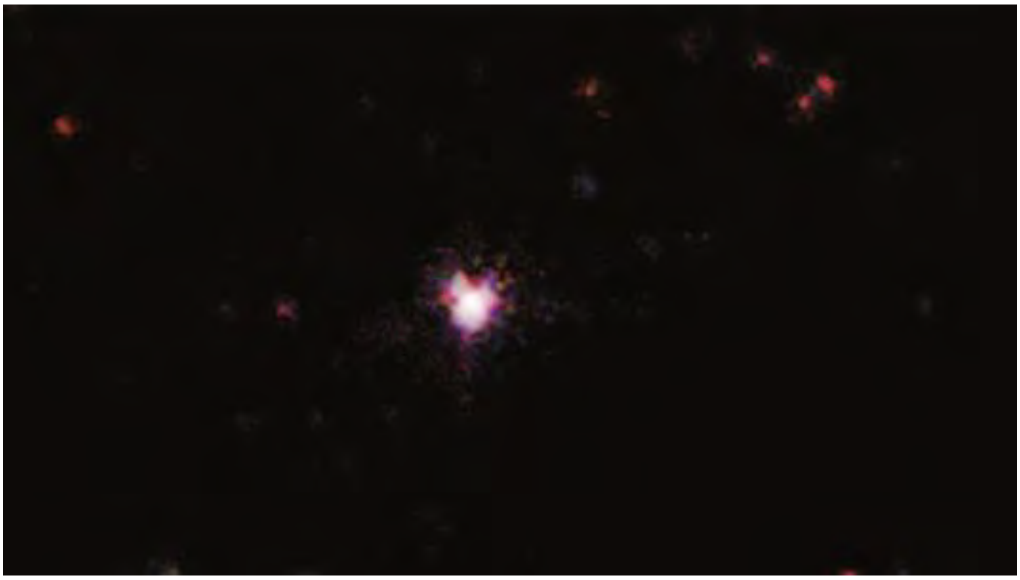

Fig. 11 False-color image showing the explosion of GRB 111209A in December 2011. The image was captured by the X-ray telescope aboard the Swift satellite. (Image courtesy of NASA/ Swift/B. Gendre)

Fig. 10 Mosaic image of the entire sky, as captured by NASA's Wide-Field Infrared Survey Explorer *(WISE)* satellite. (Image courtesy of NASA and the Space Sciences Laboratory, University of California, Berkeley)

Lunar Exploration : The Earth's Moon was the first target of non-terrestrial remote sensing. Prior to the Apollo missions, the former Soviet Union sent a series of spacecraft to the Moon, including Luna 3, which captured the first images of the far side of the Moon in 1959. NASA's Lunar Orbiter program similarly sent five spacecraft to the Moon between 1966 and 1967, with the primary objective to find candidate landing sites for the Apollo Lunar Modules.

After the final Apollo mission (Apollo 17) in 1972, the next major lunar exploration mission was the 1994 Clementine spacecraft, built and operated by the U.S. Naval Research Laboratory. The main accomplishment of the Clementine mission was the first acquisition of global-scale compositional and topographic data for the Moon. The instruments on the Clementine spacecraft included ultraviolet-visible, near infrared, longwave infrared, and high-resolution cameras, a LiDAR system, and a radar-like unit transmitting in the S-band radio frequency. Specialized products from the Clementine mission included distribution maps of compositional elements determined from recorded spectral reflectance at certain wavelengths. Experiments performed with Clementine's S-band transmitter were also the first to suggest the possibility of water, in the form of ice, in the Moon's polar regions.

NASA's Lunar Prospector, launched in January 1998 and operated until 1999 (when the spacecraft intentionally impacted the lunar surface), had a goal to further investigate Clementine's apparent finding of polar ice on the Moon; to accomplish this, its instrumentation was designed to obtain high-resolution gravity, magnetic, and compositional data. The instruments on board the Lunar Prospector included gamma ray and neutron spectrometers to create global maps of the concentrations of elements such as iron, potassium, and hydrogen; a magnetometer/electron reflectometer to measure low-intensity magnetic fields; and a Doppler gravity experiment to derive a lunar gravity field map.

Although the US and, previously, the Soviet space programs historically dominated lunar exploration, a number of other space agencies have sent spacecraft to the Moon. For example, the European Space Agency (ESA) launched its first lunar mission, SMART-1, in 2003; the spacecraft orbited the Moon from November 2004 to September 2006. Other orbiting spacecraft have been sent to the Moon by China (Chang'e-1 in 2007 and Chang'e-2 in 2010), Japan (Hagoromo in 1990 and SELENE/Kaguya in 2007), and India (Chandrayaan-1 in 2008). The Selenological and Engineering Explorer (SELENE), commonly referred to by its Japanese nickname *Kaguya*, carried 13 instruments, and also deployed two micro-satellites, *Okina* and *Ouna*. In particular, Kaguya carried a high-definition television (HDTV) instrument with both wide-angle and telephoto cameras, which provided the first high-resolution videography of the Moon.

The Moon exhibits asymmetry between its near (i.e., visible from Earth) and far sides, as demonstrated by very few basaltic "mares," or plains, on the far side, as well as high concentrations of radioactive elements on the near side. One theory proposes that the asymmetry was caused by a large impact early in the Moon's history. Nakamura et al. (2012) used spectral data from two Kaguya instruments, the Spectral Profiler and Multiband Imager, to show the presence of a mineral, low-calcium pyroxene, in the 3000-km diameter Procellarum basin. This discovery suggests that the basin was in fact caused by a massive, ancient impact, thereby sup- porting the impact origin theory of the Moon's asymmetry.

The Chandrayaan-1 spacecraft, which orbited the Moon from November 2008 until August 2009, had instruments from several nations. In particular, a Brown University and NASA Jet Propulsion Laboratory research team contributed the Moon Mineralogy Mapper, an imaging spectrometer for collecting data at visible and near-infrared wavelengths. Significantly, measurements by the Moon Mineralogy Mapper indicated the presence of very low levels of water over most of the lunar surface. Another NASA-commissioned research team designed and constructed an SAR instrument known as the Mini-SAR, with the objective of estimating the water content of the Moon's polar regions. Figure 11 is a Mini-SAR map of the lunar north pole, which suggests that more than 600 million m^3 of water may be found in the region's craters.

NASA's Lunar Reconnaissance Orbiter (LRO) was designed to expand upon previous lunar missions by collecting surface morphological data of sufficient resolution to support future manned exploration, including the possibility of a permanent outpost on the Moon. Launched in 2009 and still operational as of 2015, the LRO contains a variety of instruments similar to those on previous lunar spacecraft; for example, it includes an SAR instrument known as the Mini-RF (Miniature Radio Frequency), which continues the search for polar water- ice deposits initiated by the Mini-SAR instrument aboard Chandrayaan-1. However, its most distinctive instrument is the Lunar Reconnaissance Orbiter Camera (LROC). The LROC consists of three imaging subsystems: two Narrow Angle Cameras for capturing high-resolution (0.5 m) panchromatic images, and a multispectral Wide Angle Camera, which captures 75-m resolution images in the visible and 384-m images at ultraviolet wavelengths. Notably, the LROC has recorded roughly 10,000 before-and-after image pairs that can be used to identify lunar surface changes, including new impact craters.

Other recent NASA-sponsored orbital missions include the Gravity Recovery and Interior Laboratory (GRAIL) and the Lunar Atmosphere and Dust Environment Explorer (LADEE). The GRAIL mission consisted of twin satellites, GRAIL-A (Ebb) and GRAIL-B (Flow), that orbited the Moon in 2012. Each satellite was outfitted with a Lunar Gravity Ranging System; working in concert, the two satellites constructed a high-resolution map of the Moon's gravitational field and found that more than 98% of the gravitational signature is associated with topographic features, including impact craters, tectonic structures, and volcanic landforms. The GRAIL mission also found the Moon's upper crust to be more porous than what was originally thought, emphasizing the influence of large impact events early in the Moon's history, although widespread magmatic dykes also suggest an early period of expansion, during which time the Moon's radius may have increased by 0.6–4.9 km.

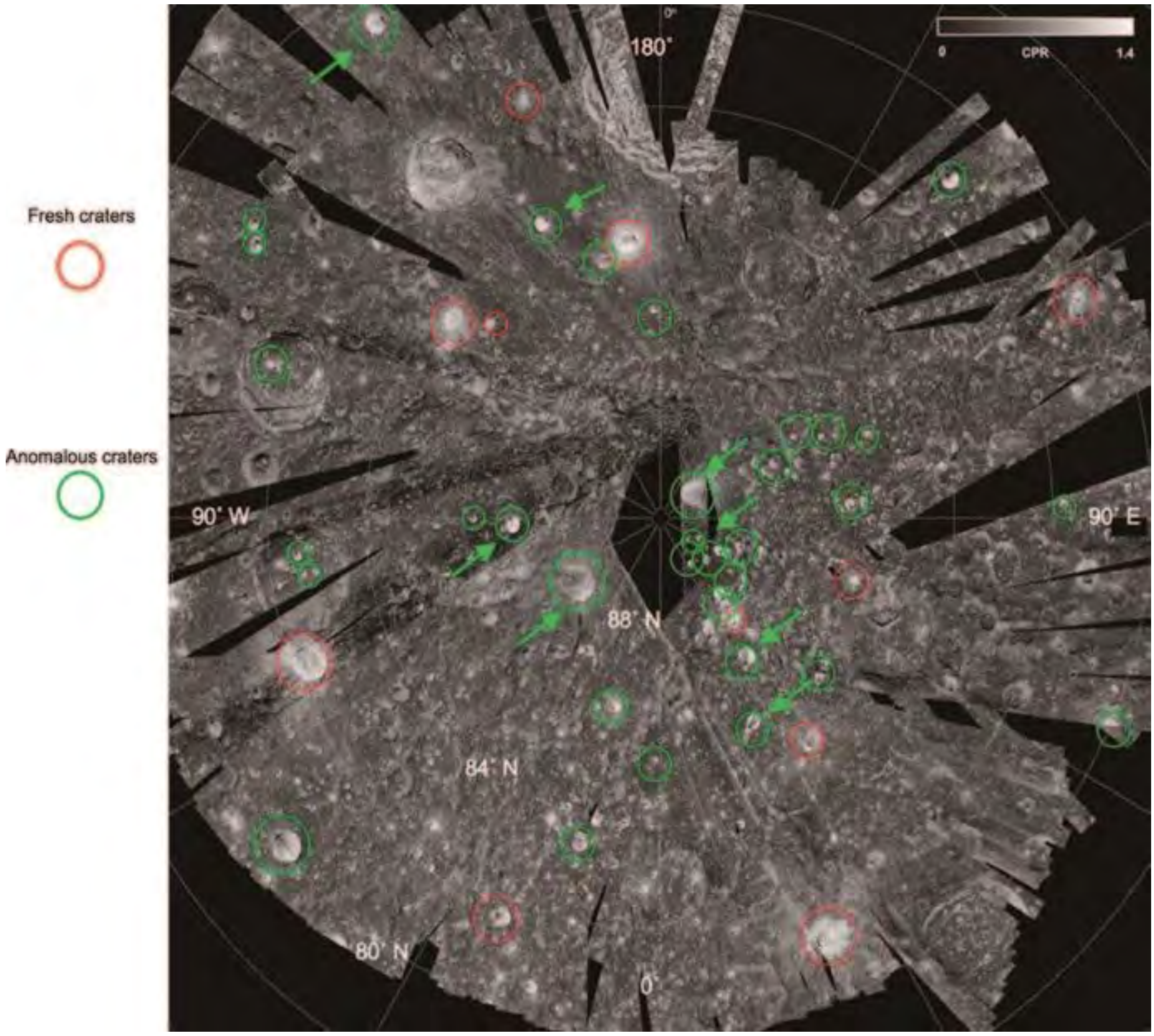

Fig. 11 Chandrayaan-1 Mini-SAR map of the Moon's north pole. The image documents the circular polarization ratio (CPR) values of surface features. The *red circles* indicate craters with high CPR values both inside and outside their rims, which is typical of young impact craters. The *green circles* indicate craters that have high CPR values only within their permanently shadowed interiors, which is indicative of water-ice presence. (Image courtesy of NASA)

LADEE was intended to answer key questions about the composition of the lunar atmosphere, including the distribution of dust at high altitudes. The spacecraft collected data for 140 days (September 2013–April 2014) from a near-equatorial (±23°) band around the Moon. The neutral mass spectrometer (NMS) instrument aboard LADEE yielded the first global characterization of the dynamics of two prominent atmospheric gases, helium and argon, which had been previously detected by Apollo 17, and discovered that a third gas, neon, also comprised a significant portion of the lunar atmosphere. The Lunar Dust Experiment (LDEX) instrument uncovered a substantial dust component to the lunar atmosphere, largely concentrated on the morning side of the Moon where meteoroids most commonly impact the lunar surface.

The Sun : The term "heliophysics" refers to the study of the interactions of our Sun with the Earth and the rest of the solar system. Heliophysics is one of the four main research areas within NASA's current science mission, along with earth science, planetary science, and astrophysics. While other space organizations have also invested in satellite-based heliophysics research (e.g., the ESA's Solar Orbiter, expected to launch in 2018), NASA has been especially active in this field; as of July 2015, 17 different NASA-sponsored or jointly sponsored spacecraft are collecting data on various aspects of the Sun–solar system connection.

One of the main concerns of these missions is to provide researchers with a better understanding of "space weather." In addition to solar flares and high-speed solar winds, the Sun periodically emits huge clouds, known as coronal mass ejections, which carry strong magnetic fields and energetic particles. These emissions cause geomagnetic storms that can disrupt power and communications systems on Earth as well as in orbiting spacecraft. Data from ongoing heliophysics missions should help scientists to forecast these occurrences. For example, the Solar Terrestrial Relations Observatory (STEREO) consists of two satellites launched in 2006: one positioned in front of Earth in its orbit, the other positioned behind it. Together, the two satellites provide stereoscopic (i.e., three-dimensional) images of the Sun. Davis et al. (2009) presented such an image that depicted an Earth-impacting coronal mass ejection, which was considered a major success for the STEREO mission. Similarly, NASA's Solar Dynamics Observatory (SDO), launched in 2010, was developed to study the Sun's interior and magnetic field, and to learn how stored magnetic energy is released as solar wind and other space-weather-related emissions. Instruments aboard the SDO collect spectral data in a variety of wavelengths, including extreme ultraviolet (10– 124 nm) wavelengths. Figure 12 is an SDO image, captured in February 2014, of an X4.9-class solar flare. X-class flares are the most intense, while the number further describes its strength, e.g., an X4.9-class flare is 4.9 times as intense as an X1 flare.

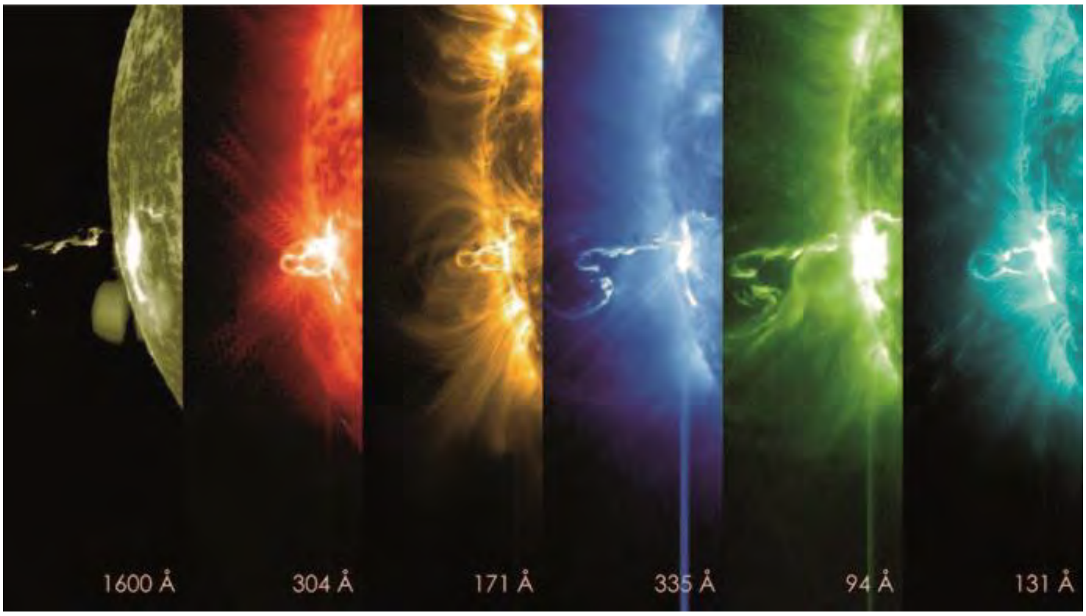

Fig. 12 Solar Dynamics Observatory images, in different wavelengths, showing the early moments of an X4.9-class solar flare. The images were captured on February 24, 2014. (Image courtesy of NASA/SDO/Goddard's Scientific Visualization Studio)

Extrasolar Remote Sensing : The introduction to this chapter presented examples of spacecraft that were developed to observe deep space phenomena. NASA's WISE, Fermi, and Swift satellites are all Earth-orbiting telescopes in the tradition of the Hubble Space Telescope. Launched in 1990, the Hubble Space Telescope is considered one of NASA's four "Great Observatories" along with the Compton Gamma Ray Observatory (1991–2000), the Chandra X-ray Observatory (1999–current), and the Spitzer Space Tele- scope, an infrared observatory (2003–current). It carries a highly versatile instrument suite that is targeted at near-ultraviolet, visible, and near-infrared wavelengths (115–2500 nm) (STScI 2015). Designed with the expectation that it would be periodically upgraded by astronauts, the Hubble Space Telescope has undergone a series of modifications and updates in its 25-year history, such that it may continue to operate successfully for another two decades, or even longer. It will eventually be replaced by the Webb Space Telescope, which will be as capable of viewing infrared wavelengths as the Hubble is at viewing visible wavelengths (STScI 2015).

The Hubble Space Telescope has made numerous scientific breakthroughs, including the most accurate estimate yet of the age of the universe: 13.82 billion years. It also enabled researchers to discover that the universe is expanding at an increasing speed, a still little-understood phenomenon known as "dark energy." Perhaps most notably, the Hubble Space Telescope provided evidence that supermassive black holes can be found at the centers of most galaxies, including the Milky Way. For example, **Fig. 13** shows a disk of dust spiraling around a massive black hole at the center of a galaxy, NGC 4261, which is 100 million light-years from Earth. The mass of this black hole is estimated to be 1.2 billion times the mass of our Sun, but concentrated in an area roughly the size of our solar system.

In 2008, Paul Kalas, an astronomer at the University of California, Berkeley, reported the first visible-light images of an exoplanet, captured with the Hubble Space Telescope's Advanced Camera for Surveys. Exoplanets are planets orbit- ing stars other than our Sun; the planet observed by Kalas and his colleagues was designated Fomalhaut b in reference to the star it orbits, which is located roughly 25 light-years from Earth. Fomalhaut b takes 872 years to orbit Fomalhaut at a distance of 119 astronomical units (≈17.8 million km), and is believed to have a mass similar to that of Jupiter.

Since that first discovery, spacecraft-mounted telescopes such as the Hubble Space Telescope have detected hundreds of exoplanets. As of July 2015, nearly 1600 confirmed exoplanets have been documented in the Exoplanet Orbit Data- base, which compiles details about exoplanets reported in peer-reviewed literature. A major advantage of space telescopes for exoplanet detection is that they avoid atmospheric turbulence and haze that impede observations by ground-based telescopes. Nevertheless, detection remains challenging because exoplanets are light-years away and orbiting stars that are far larger and brighter than our Sun. The remote sensing techniques involved in these analyses are simple yet provide a great deal of information. One approach is to measure the "wobble" of a star—caused by the gravitational pull of an orbiting planet—using the Doppler Effect (i.e., a shift in the wavelength of the visible light from the star). Another method, the transiting method, looks at the drop in a star's brightness when an orbiting planet passes in front of it. Through these and other techniques, scientists are able to glean characteristics such as the planet's mass and radius, and in some cases, even more; in 2007, a team of researchers used the Spitzer Space Telescope to create the first-ever map of the surface temperature of the extrasolar planet: HD 189733b, a Jupiter-like gas giant approximately 63 light-years from our solar system. Figure 14 shows a global temperature map for planet HD 189733b (expressed in terms of infrared brightness). The fact that the brightest (i.e., hottest) spot on the planet's map is offset from the center point, which receives the most light from the star it orbits, suggests the influence of powerful, super rotating winds. Subsequent research suggests the presence of water vapor, oxygen, and methane in the atmosphere of HD 189733b, and that the planet has a deep blue color.

Fig. 13 Image captured by the Hubble Space Telescope in 1995, showing a disk of dust spiraling around a super- massive *black hole* at the *center* of galaxy 4261, which is 100 million light-years from Earth. (Image courtesy of L. Ferrarese (Johns Hopkins University) and NASA)

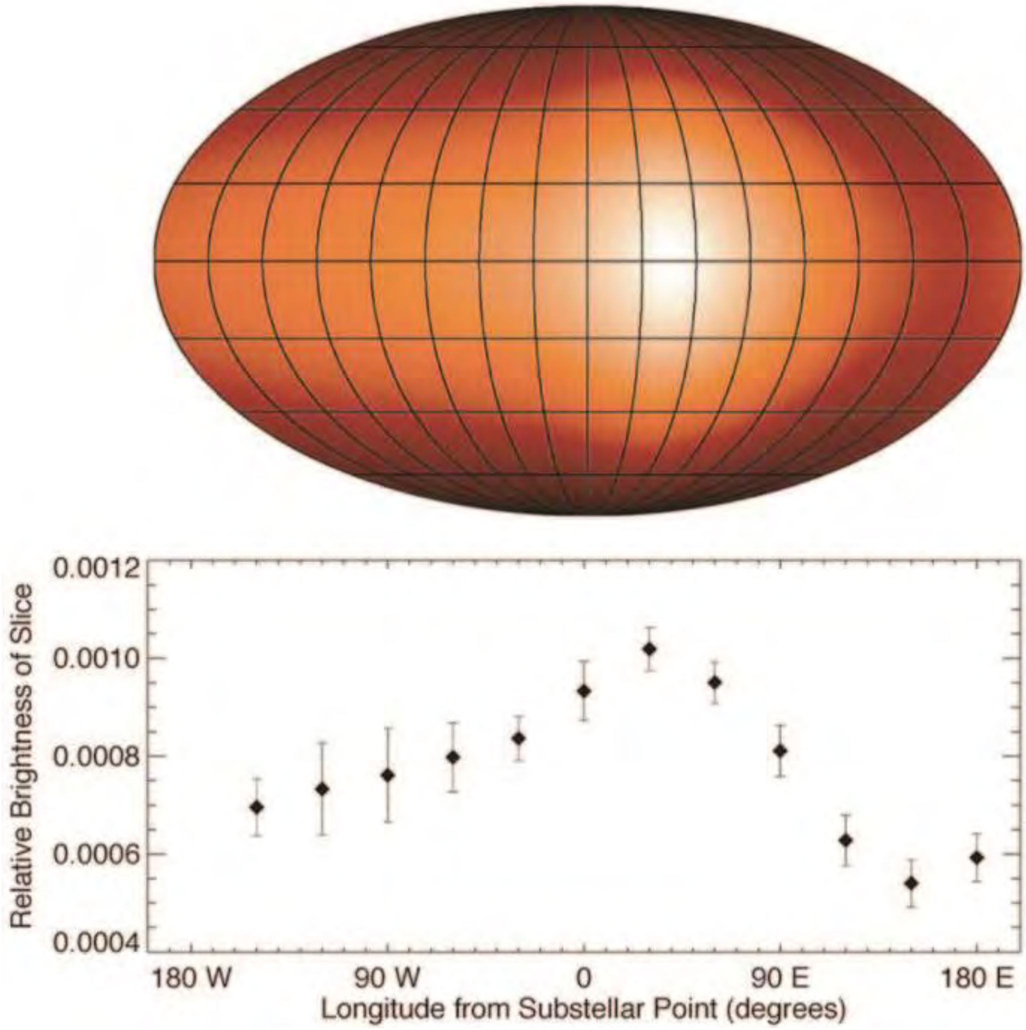

Fig. 14 Global temperature map for exoplanet HD 189733b, expressed in terms of infrared brightness. Note the pronounced brightness "hot spot" offset to the *right* of map *center*. (Image courtesy of NASA/JPL-Caltech/H. Knutson (Harvard-Smithsonian CfA)

Similarly, scientists used the Hubble Space Telescope to construct a temperature map and to measure water abundance in the atmosphere of WASP-43b, a Jupiter-like exoplanet 260 light-years from Earth. The planet orbits closely to its parent star, completing one orbit in 19.5 h. The planet is thus very hot, but unlike other giant planets in its solar system, WASP-43b always has one side of the planet facing its star (i.e., it does rotate on an axis). As a result, there are substantial temperature differences between the two sides: the bright area on the daytime side reaches temperatures above 1500°C, while nighttime side temperatures fall below 500 °C. At these temperatures, all of the water in the planet's atmosphere is vaporized, rather than condensed into icy clouds, as seen on Jupiter.

The French Space Agency (Centre National D'études Spatiales), in conjunction with the ESA and other partners, launched the COnvection ROtation et Transits planétaires (CoRoT) space telescope in December 2006. After a computer failure, CoRoT was decommissioned in 2013. NASA launched the Kepler Space Telescope in 2009. Despite mechanical problems in 2014 that affected its targeting capabilities, the Kepler telescope continues its primary mission, which was also the mission of CoRoT: the detection of exoplanets, especially Earth-sized planets orbiting within the "habitable zone" (i.e., the zone likely to support life) of their parent stars. Research suggests that such planets are commonplace throughout the universe, and the Kepler and CoRoT telescopes made some significant discoveries in this regard. For instance, in 2009, CoRoT provided the first characterization of a rocky "super-Earth" planet: CoRoT-7b, which is approximately 1.58 times the size of the Earth. In 2011, the Kepler telescope discovered its first rocky planet, Kepler-10b, which is only 1.42 times the size of the Earth. Two years later, Borucki et al. (2013) reported on Kepler's observation of a five-planet system with two planets that fall within the habitable zone and are 1.41 and 1.61 times the size of the Earth; both planets are believed to be rocky or composed of mostly solid water. Regardless, future research is likely to move beyond the identification of additional rocky exoplanets to more detailed analyses of these planets 'atmospheric properties, in an effort to find those with conditions most analogous to Earth. Des Marais et al. (2002) argued that remote sensing efforts aimed at terrestrial exoplanets should focus on mid-infrared wavelengths (7–25 μm) and visible to near-infrared wavelengths (0.5 to ≈1.1 μm), as these wavelength ranges should provide useful information about planetary properties (e.g., size and mass) as well as potential "biosignatures" (i.e., compounds such as O_2, O_3, H_2O, and CO_2) that may indicate habitability.

Satellite Remote Sensing Applications to Disaster Management

Remote sensing is a key tool in supporting disaster-related operations from both inside and outside the affected state by providing critical information about the disaster and/or the devastated area. The afflicted state can benefit from a satellite system in their possession, or from other states or entities that can utilize their systems to provide assistance to the afflicted state. Satellite images provide critical information on disaster-prone areas, progress of disasters, and the aftermath of disasters, which cannot be obtained by other means. With increased availability, particularly through constellations of satellites or a combination of different satellites operating under a coordinated framework, satellite remote sensing permits users to gain understanding of the precise situations related to disasters in time to help the governments and other actors make critical decisions, and to provide them with up-to-date information on the rapidly changing developments during disasters.

Satellite images serve as a source of critical information to aid disaster operations and the use of satellites for disaster management dates back several decades. Weather monitoring satellites have monitored hurricanes and tornados since the 1960s, and scientists have used satellite data, such as Landsat data, to monitor patterns of flood, drought, coastal erosion, and volcanic activities. Satellite remote sensing supports different phases of disaster management and has proved to be particularly beneficial in large-scale disasters, where the extent of the damage is not immediately known.

The Application of Satellite Remote Sensing in Different Phases of Disaster Management:

An examination of the diverse operations involved in the different phases of disaster management has shown that states with low capability to respond to disaster can aggravate the impact of disasters. Capacities are strongly linked to the ability to access timely and accurate information. In every phase of disaster management, satellite images can serve as a significant source of information upon which to base actions or decisions related to disaster operations, and satellite images are utilized to support a variety of operations.

Prevention : Risk assessment is a major operation for disaster prevention and satellite images are useful for hazard mapping, such as tectonic and flood plain maps. Tectonic maps are used in combination with other geological and geophysical data to identify earthquake hazards, and to supplement missing information on seismic history to plot the boundaries of various flood levels and the probability for recurrence.

Preparedness: Satellite images can assist in preparing for impending disasters, or may be used to prepare for possible future disasters. There are several areas where satellite data can support disaster management, including warning and prediction. The development of a disaster warning capability must be accompanied by the development of a disaster warning delivery system. For instance, active microwave satellites are useful in facilitating flood warnings during storm surges through the determination of wind velocities over the oceans. Furthermore, data on surface wind velocities may also help enhance capabilities in prediction of tropical cyclones.

Response: The extent of disasters and damage can be assessed effectively using satellite images, which can capture large-scale disasters across boundaries or provide detailed scenes of specific area of interest hit by a disaster. Images taken before and after the disasters are compared to identify damaged areas effectively. Appropriate direction for aid can be given based on such assessment. Satellite images can be combined with other sources of information to produce useful knowledge. Following Hurricane Katrina, the combination of satellite images and GPS technology was used to provide the necessary GIS information to the aid workers for rescue operations. It was particularly helpful in this case because the affected population asking for rescue indicated their location using their street address; however, since the land was completely flooded and many of the rescue services were from out of state, there were no visible landmarks so there was no way to locate people. Satellite images combined with GPS data helped identifying the exact location of the people in peril. Furthermore, high resolution images such as Quickbird were used for detailed assessment of the conditions in the aftermath, such as flooding and levee break locations. Maps indicating locations of flooded areas provided critical assistance to search and rescue operations.

Beneficiaries of satellite images are not just space agencies and companies that operate systems and generate satellite imagery. Many international actors, including UN organizations, benefit from using satellite images for their relief efforts. Other examples include UNICEF, UNHCR, UNDP, WHO, and FAO - to name a few. Specifically, UNICEF has used IRS and Landsat imagery of areas exposed to earthquakes in order to plan special relief and assistance programs directed toward children in affected areas.

Recovery and Reconstruction: Satellite-derived information can be extensively used for the purpose of recovery and reconstruction. The images are used to map affected populations and to facilitate effective planning for reconstruction activities such as rebuilding bridges and schools. Following Hurricane Katrina, images from Landsat, Spot-4 and 5, and NigeriaSat-1 (DMC) were provided; these were used to support clean-up efforts, and to estimate the impact on public health. Images have been used for reconstruction efforts by relief entities such as the Red Cross.

Satellite data and derived information have been used for both national disaster management and to assist other countries. Increasing numbers of space agencies and other EO entities voluntarily participate or plan to take part in international or regional disaster management programmes and initiatives in which they provide assistance under preferential conditions. Some entities have voluntarily provided images free of charge in response to particular disasters, without adherence to specific programmes.

The foregoing examples show that data uses have been dedicated more to post-disaster response and recovery phases – mainly assessment of damage and aftermath – than to the pre-disaster phase. Still, there are increasing uses of satellite remote sensing to assist with operations during prevention, preparation, and real time monitoring. Insufficient international assistance and cooperation in these phases of general disaster management can be corrected with the use of satellite remote sensing, because assistance is achieved more easily through data provision and sharing, without much intrusion. Applications in these phases are still limited: the accuracy of prediction using satellite data is not always reliable, or the monitoring is in need of more frequent information updates of disaster situations – at minimum, a revisit of approximately every three hours would suffice. Utilization of data in these phases will be more active and widespread if the accuracy of the data is ensured and data is willingly and generously supplied by the data generators.

Operational EO Based Programmes for Disaster Management: There are an increasing number of programmes to utilize satellite data for disaster management, such as the International Charter on Space and Major Disasters (hereafter: the Disaster Charter), and the Disaster Monitoring Constellation (hereafter: the DMC) – both EO applications are coordinated mechanisms for disaster response. The key advantage of these programmes is that the beneficiaries can gain access to necessary information more promptly to make appropriate decisions thanks to a combination of data from different satellites that each entity contributes.

The Disaster Charter establishes extensive international cooperation amongst remote sensing satellite operators to provide satellite images free-of-charge to the countries affected by disasters. This programme strengthens the legal regime of disaster management through establishing a predictable mechanism of assistance to afflicted states through effective information distribution. The Disaster Charter was initiated by ESA and CNES following the Third United Nations Conference on the Exploration and Peaceful Use of Outer Space (UNISPACE) III in 1999, and has been operational since November 2000. Satellite imagery has been provided to afflicted states in response to diverse disasters – from floods, fires, and earthquakes, to rescuing ships stranded in ice. The Charter now embraces 10 partners: CNES, ESA, the Canadian Space Agency (CSA), NOAA, the Indian Space Research Organisation (ISRO), Comision Nacional de Actvidades Espaciales (CONAE), the Japanese Exploration Agency (JAXA), the United States Geological Survey (USGS) – on behalf of US partners such as Digital Globe and GeoEye, the British National Space Centre (BNSC) acting on behalf of the international Disaster Monitoring Constellation, and the China National Space Administration (CNSA). There are also other non-partner organizations serving as intermediaries. In response to authorized requests, partner space agencies provide data from their satellites free-of-charge to the states affected by natural or man-made disasters.

The Disaster Charter is triggered by certain intermediaries, referred to as Authorized Users. The unique feature of the Disaster Charter is that neither the Charter partners nor afflicted states can initiate the process for activation. It is only the pre-designated

Authorized Users – being the relief agencies of the countries whose jurisdiction covers the member space agencies or other authorized entities – who can request the activation of the Charter, and it is the appointed Project Manager that organises the tasking of satellites, and directs data acquisition to member space entities. There are three major ways to activate the Charter: 1) direct activation- activation by the Authorized User of a member country; 2) activation via an Authorized User on behalf of a user from a non-member country; 3) activation via the UN for the UN users. In this manner, the Disaster Charter provides a mechanism to make critical space assets available to communities affected by disasters under a single point of contact. The afflicted states can use the data to monitor their disasters, assess the course of the disasters, and then respond to the aftermath of these disasters. The Charter has been operating successfully since November 2000 and the Charter activation takes place on a regular basis: the average number of calls per month requesting Charter activation is 1.9.

The DMC, which contributes to the Disaster Charter, is the result of extensive international cooperation to share EO space assets leading to the creation of a constellation of EO micro-satellites led by Surrey Satellite Technology Limited (SSTL) in the United Kingdom. With the capability of providing 32 m spatial resolution over a 600 km swath of any location in the world within 24 hours, DMC is designed to serve both national EO needs and global humanitarian needs for disaster relief. The constellation was initiated with the launch of Alsat-1 for Algeria in 2002, followed by the launches in 2003 of BILSAT- 1 for Turkey, NigeriaSat-1 and UK-DMC, and then, in 2005, the launch of Beijing-1 for China. Each of these DMC partners – Algeria's Centre National des Technicques Spatiales, Turkey's Scientific and Technological Research Council, Nigeria's Research Council, China's Ministry of Science and Technology, and the British National Space Centre – owns its satellite for its own purposes and exchanges images within the consortium; however, they also provide images to non-partners free of charge in response to declared disasters. DMC is distinctive in that the constellation of five satellites can provide daily image revisit worldwide and thus provide fresh data to governments, as well as to relief and aid agencies. Whilst a certain capacity of the DMC is provided to aid agencies (including the framework of the Disaster Charter), other capacities are made available to commercial users through DMCii, which distributes the data on a commercial basis.

Case Study: The 2004 Indian Ocean Tsunami: This section discusses further the operational services of the Disaster Charter, which includes contribution from DMC, provided in response to the 2004 Indian Ocean Tsunami and how assistance based on satellite remote sensing can be coordinated effectively in terms of an institutional framework.

On 26 December 2004, an undersea earthquake of magnitude 9 occurred150 kilometres off the west coast of the northern Sumatra island in Indonesia. The resulting Tsunami devastated the shores of a large number of countries in Southeast Asia, including: Indonesia, Sri Lanka, India, Thailand, the Maldives, Somalia, Myanmar, and Malaysia and resulted in the loss of more than 200,000 lives. There were no effective warning systems in the Indian Ocean to detect tsunamis, and there was no effective communications system to disseminate warnings to the endangered populations.

Unfortunately, space assets were not helpful to predict or to prepare for the tsunami this time and did not contribute very much to real-time monitoring of the tsunami, although by coincidence the satellites TOPEX/Poseidon and Jason-1 happened to pass over the tsunami as it was crossing the ocean.

Satellite images were helpful in providing immediate assessment and direction of aid efforts in response to the Tsunami; three days after the tsunami hit, the Disaster Charter was activated and extensive amounts of data were provided. The way satellite imagery contributes to the disaster response effort merits a discussion. An immediate assessment of the scale of the disaster effectively took place within the following day or two through satellite images such as Landsat and those from DMC. Immediately after the tsunami, nobody knew precisely the scale of the disaster: contrary to the original predictions, the death tolls climbed higher and higher. The DMC supplied satellite images from its archives for Sri Lanka and the Maldives, showing the area before the disaster occurred for comparison with post-disaster images, so that damaged areas could be detected easily.

The DMC data was very effective for immediate assessment because with the medium resolution and large-scale swath, it could cover very long stretches of coastline, so that damaged areas can be identified quickly. The DMC provided comprehensive coverage for the initial stage of damage assessment and facilitated a smooth transition to directing delivery of aid through effective targeting by high-resolution satellites. The high resolution satellites could detect at street level where the resources should be allocated; many high-resolution images including SPOT 5, Quickbird, and IKONOS were provided.

Satellite images were also used during the reconstruction period. For instance, high resolution Digital Globe satellite imagery helped relief workers in Indonesia establish refugee camps and medical teleconferencing Images were provided to various UN and NGO organizations for the rebuilding effort. A French technical engineering group, Geosciences Consultants, volunteered its expertise to non-governmental organisations, providing maps of the devastated areas: they had a data-base of world maps and a data-base of all infrastructures – such as airports, populated areas, and harbours, which allowed them to identify the spread of disasters and the exact areas affected. The Indian Ocean Tsunami case has demonstrated clearly how space technology contributes to assessment and recovery.

Coordination of Operations Based on Satellite Remote Sensing: Various organizations are involved in provision of assistance; however, operations are fragmented and not well coordinated. In the field of satellite remote sensing, coordination is increasingly taking place to provide effective assistance. There are successfully operating programmes providing information based on satellite remote sensing, such as the Disaster Charter – a good example of coordinated disaster relief under a single point of contact. Institutionally, a network for information on space technology-based disaster management is being implemented. During the 43rd session of the UN Scientific and Technical Subcommittee in 2006, the group of experts presented a study on the possibility of creating a Disaster Management International Space Coordination Entity. A more concrete step was taken on December 2006 by the adoption of the General Assembly Resolution to establish United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) as a UN Programme, in order to "ensure that all countries and international and regional organizations have access to and develop the capacity to use all types of space-based information to support the full disaster management cycle." The UN-SPIDER program aims to serve as central access point to space information for disaster management support, as a bridge to connect the disaster management and space communities. and to facilitate capacity- building and institutional strengthening. The anticipated role of UN-SPIDER is to coordinate space-based disaster management information – not just from remote sensing, but also derived from different space technologies such as GPS and telecommunications. The successful examples of disaster response in the field of satellite remote sensing can serve as a good model for information coordination in general disaster management.

MODULE-IV

INTERNATIONAL SPACE LAW AND REMOTE SENSING

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Introduction: Space law is a newly developed field of law with a relatively short history. The discussion of space law began in the 1950s following related technological developments achieved by the end of World War II. Space development originated with the invention of a long-range liquid fuel rocket by the German army. The German V-2 rocket, completed in 1942, was able to fly outside the Earth's atmosphere and became the foundation for the first artificial satellite. The incentive for space technology was then driven forward by the subsequent Cold War, in the form of an arms race between the Soviet Union and the United States.

On October 4, 1957, the Soviet Union took the lead in the race – first by placing Sputnik-I, the first man-made satellite, successfully into orbit in outer space. Following the launch of Sputnik, the need for a legal regime governing outer space became apparent and the legal status of outer space suddenly became an urgent and real question to resolve – rather than merely a theoretical and speculative matter.

The fundamental question was the legal status of outer space in terms of sovereignty: specifically, whether or not sovereignty recognized in airspace extended to outer space. US air law expert J.C. Cooper contended that sovereignty did not extend to outer space; this view prevailed, and the legal status of outer space based on that view continued to be recognized in the context of reconnaissance satellites.

The permissibility of observing foreign territories from space was first proposed by the United States. The official step toward legitimizing remote sensing for reconnaissance purposes was the proposal for an Open Skies Policy by President Eisenhower to allow the United States and the Soviet Union to monitor each other's territory to avoid a surprise attack. Although rejected by Moscow at the time, afterwards the policy was accepted by the two superpowers on a de facto basis as they started to monitor each other's territories with reconnaissance satellites in the 1960s.

The next question concerned where the boundary between airspace and outer space lay. There was no clear answer, since air law had never established a definition of airspace with a precise boundary. After Sputnik, numerous theories were proposed in attempts to determine the demarcation of outer space. Cooper and common law experts believed that outer space simply stopped at the point below which an orbit could not be sustained. The higher boundary of airspace meant more protection against unfriendly overflights, as sovereignty was extended in airspace. In the UN COPUOS, the Soviet Union proposed to fix the boundary line at an altitude of 100–120km above sea level, and most delegates were in agreement. At present, there is still no agreement as to the From this history, one can clearly see that space law boundary of outer space. From this history, one can clearly see that space law developed in a political context, as the major space powers attempted to codify their particular interests.

Today there are two primary sources of space law under which satellite remote sensing activities are addressed: space law derived from international legal rules, and space law derived from national laws developed in several countries. This Module provides an overview of the legal regime of outer space from the standpoint of satellite remote sensing by examining international multilateral trea- ties, national laws, and national policies.

International Space Law: International space law is a product of the Space Age, an offspring of the scientific and technological revolution. Unlike most other branches in international law, it has been developed in a relatively short period of time. Space law has been formulated by instantaneous custom rather than by customary law, which is formed over a long period of general state practice. Indeed, the first treaty law of outer space was born in 1967, just ten years after the launch of Sputnik, and a set of international space laws including five conventions and three principles have developed in less than thirty years. In fact, sometimes the development of space law outpaced technology. For instance, law applicable to the Moon and other celestial bodies was established back in 1979 when most states hardly had access to such bodies. The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (hereafter: the Moon Agreement) had addressed issues regarding utilization of the Moon, such as the complete demilitarization of the Moon and the retrieval of samples from the Moon – ideas that were only theoretical back then.

International space law is unique in character: it is a special branch of international public law, and yet not autonomous. The international law of outer space is derived from several sources, particularly maritime law, air law, treaty law applicable to Antarctica, and legislation of the United Nations. That space law has no autonomy is most notably illustrated by the fact that there is no institution mandated to regulate activities in outer space such as the International Civil Aviation Organization (ICAO), the specialized agency of the United Nations that governs air navigation.

A brief analysis of the ICAO is useful to highlight the peculiarity of the regime governing space activities. ICAO has functions that are not a part of the structure in which space operations are conducted, such as law-making power and competencies to exercise powers over member states. ICAO itself is a legal entity that has competency to enter into agreements with other legal entities, including other international organizations, and can also adopt binding regulations by majority decision. It has played an important role in: addressing the issues on aviation insurance and establishing an insurance mechanism; performing mandatory audits on states in the fields of aviation safety and security; and establishing a funding mechanism to finance aviation safety projects. In addition, the Council of ICAO is given the authority to monitor the conduct of contracting states and can impose obligations upon disagreeing states.

In contrast, space law making and its implementation has taken a different path. Rather than establishing an agency within UN systems, the United Nations has served as a focal point for international cooperation on the use of outer space and the UN Committee on the Peaceful Uses of Outer Space (COPUOS) was established within the General Assembly as a forum for negotiation to develop a legal framework. COPUOS became the first UN body to adopt a method of consensus where member must reach unanimous agreement on the particular subject matter before any action or document can be confirmed. Consensus has been somewhat successful and has given birth to a series of legal instruments related to space.

The sources of international space law are primarily found in international legal rules and international custom, and the general principles of law fill the gap between the two in the absence of an exclusive source of law. International space law framework has three components: the general regime of space law, the law governing certain space applications, and declarations. The first component is called *corpus juris spatialis*, a body of treaty law negotiated amongst states within the framework of the United Nations: the Treaty on Principles Governing the Activities of states in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies; the 1968 Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched Into

Outer Space; the 1972 Convention on International Liability for Damage Caused by Space Objects; the 1974 Convention on Registration of Objects Launched Into Outer Space; and the 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies.

The second component is law concerning satellite applications: the Direct Broadcasting Principles of 1982; the 1986 Principles of Remote Sensing; and the Nuclear Power Source Principles of 1992. The declarations component includes: the 1963 Declaration of Legal Principles governing the Activities of States in Exploration and Use of Outer Space; and the 1996 Resolution on Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interests of All States, Taking into Particular Account the Needs of Developing Countries.

A basic regime governing outer space is reflected in the five multilateral treaties that establish the basic principles governing outer space and the fundamental rules for engaging in space activities. It is crucial to provide an understanding of the legal framework and its implications for remote sensing activities; there- fore, this section first examines the legal regime of outer space and then discusses laws specific to remote sensing.

Toward Formulation of Rules Governing Outer Space: As discussed, the background for the establishment of a space law regime was highly political in the vigorous competition between the United States and the Soviet Union for national pre-eminence in space development. As a consequence, the outer space legal regime is largely the result of negotiation and compromise over the views held by these early space powers.

The formulation of the Outer Space Treaty started right after the launch of Sputnik-1. Two years after the launch of Sputnik, the UN COPUOS was established as a permanent body of the United Nations and given the responsibility to negotiate for a legal framework for space activities. The series of General Assembly Resolutions following the Resolution of 1958 that approved the establishment of the UN COPUOS became the foundation of space law, in particular Resolutions 1721A (XVI) of 20 December 1961 and 1962 (XVIII) of 13 December 1963.

The freedom of use and exploration of outer space and, hence, the legality of the flight of space objects, was confirmed and the prohibition on the appropriation of outer space was formulated in the General Assembly Resolution 1721A (XVI) on December 20, 1961, and reiterated in the General Assembly Resolution 1962 (XVIII) that also established other fundamental rules governing outer space entitled, the "Declaration of Legal Principles governing the Activities of States in Exploration and Use of Outer Space." Indeed, much of the content of the Outer Space Treaty had been agreed upon in this Resolution, prior to its formal introduction as a binding, multilateral treaty in 1967. Such was the birth of international space law by means of the Outer Space Treaty, which has been ratified by 98 states parties, and is often referred to today as the 'Magna Charta 'of space law.

Outer Space Treaty: It is important to have a clear understanding of what the Outer Space Treaty establishes and its position within international public law. The scope of the Outer Space Treaty consists of the nature of space activities, the subjects conducting space activities, and the applicability of other international law to the Outer Space Treaty.

Space activities can be roughly categorized into three types: scientific activities, military activities, and commercial activities. Article I of the Outer Space Treaty stipulates that "there shall be freedom of scientific investigation in outer space", and therefore, space activities referred in the Outer Space Treaty undoubtedly include scientific activities.

Various scientific programmes, such as planetary exploration and other Earth-focused scientific studies, have been extensively conducted in accordance with the Outer Space Treaty, and continue to be planned. The question arises as to whether the Outer Space Treaty also applies to military activities and commercial activities.

Military activities are not straightforward. The Outer Space Treaty has established two distinct regimes applicable to different parts of outer space – outer space in general and celestial bodies in particular, including the Moon. Article VI states that "the Moon and celestial bodies shall be used by all States Parties to the treaty exclusively for peaceful purposes." Article VI specifically bans establishment of military bases, installations, and fortifications, the testing of any type of weapons, and the conduct of military manoeuvres on celestial bodies; however, it permits the use of military personnel for scientific research or other peaceful purposes.

The term 'peaceful purposes 'needs closer attention. The definition is not provided under the Outer Space Treaty and it is worth noting that back in 1967 'peaceful purposes 'had two interpretations: non-military on one hand, and non-aggressive on the other. The Soviet Union insisted on banning all military activities, which is clearly interpreting the Outer Space Treaty as 'non-military'; but since the United States carried out satellite observation for military reconnaissance purposes, it interprets the Outer Space Treaty language as referring to 'non-aggressive'. Through the examination of the provisions of the Outer Space Treaty, one can see that the meaning of 'peaceful purposes 'at the time of drafting was perceived as 'non-military';45 but what has gained general acceptance at the present time is the interpretation that 'non-aggressive 'military uses are peaceful.

With the exception of the Moon and celestial bodies, non-aggressive military uses are not prohibited in outer space. In fact, the ambit of permissible military applications under Article IV of the Outer Space Treaty is relatively broad. Under Article IV, military space activities that are banned specifically are: (1) placing objects carrying nuclear weapons and weapons of mass destruction, and (2) the installation or stationing of such weapons in outer space or on celestial bodies.

Following the above line of argument, permissible military uses of space are not limited to defensive space applications such as reconnaissance satellites. Strictly speaking, anti satellite weapons (ASATs) are not prohibited under Article IV, as they neither fall under the 'nuclear weapon 'nor 'weapon of mass destruction 'definitions. On 11 January 2007, China tested an ASAT missile and destroyed its defunct weather satellite in a polar orbit. The test raised concern internationally, mainly because China attempted to conceal the test and the harmful impact on the environment caused by the resulting debris. The ASAT test itself was not in contravention of Article IV of the Outer Space Treaty. Likewise, intercontinental ballistic missiles (ICBMs) also fall outside the scope of the prohibition, as they are launched from one place and hit the target elsewhere on the Earth via outer space, but are neither 'placed in orbit 'nor 'installed or stationed in outer space'. There are also no rules with regard to intercepting missiles from outer space. Space-based military applications beyond the defensive scope such as ASATs, ICBMs, and missile defence are not specifically banned and remain a controversial issue under the current regime.

In reference to defensive space applications, historically satellites have been extensively utilized for military purposes. In fact, 75% of the 2,200 satellites launched from 1958 to 1984 are allegedly military satellites. The use of outer space for military purposes, which has constituted a substantial part of space activities up until now, is within the scope of legitimate space activities, provided that states comply with the provisions under international law, including the UN Charter. The partial authorization of military uses of outer space also invokes the need for a more comprehensive legal regime governing military activities, which are often outside the scope of specific regulations, at both international and national levels. This is particularly relevant, since remote sensing satellites can serve a dual-use purpose (e.g., both military reconnaissance and civilian remote sensing). Commercial activities are not directly mentioned in the Outer Space Treaty. It was not that such activities were intended to be excluded; rather, in 1967, space activities were state-based and reserved solely for a few space powers, so extensive commercial activities were simply not foreseen at that time. Although INTELSAT was created at the beginning of the 1960s, applying military systems to civil and commercial uses such as reconnaissance by civil remote sensing satellites or employing navigation systems for public use, was hardly conceivable. Yet the use of outer space appears to have included the notion of exploitation during the Outer Space Treaty's formulation process. The ad hoc Committee for space treaties in 1959 had employed the term 'exploitation'53 and, during the discussion to clarify the meaning of 'use', the representative of France suggested that 'use 'was equivalent to 'exploitation'.

Furthermore, commercial satellite communications activities utilising the geostationary orbit were widely known then, and no objection or exception to those activities was raised either in the text of the Outer Space Treaty or during its negotiation. Also, a comparison with the Antarctic Treaty and legal status of Antarctica supports the conclusion that commercial activities in outer space can be considered consistent with its legal status. Commercial activities being within the scope of the Outer Space Treaty is supported by a more recent legal instrument, the Declaration on International Cooperation, which incorporates specifically the concepts of commercial activities. This declaration has a concrete provision on contractual terms, stating that: "Contractual terms in such cooperative ventures should be fair and reasonable, and they should be in full compliance with the legitimate rights and interests of the parties concerned as, for example, with intellectual property rights."

Today, commercial space activities can be seen in various arenas. Examples include, but are not limited to, commercial launchers such as Sea Launch and Space X, Satellite TV, car navigation systems using GNSS, and the increasing number of companies dedicated to space business such as Virgin Galactic, which specializes in space tourism. The applicability of the Outer Space Treaty to commercial activities is not much questioned, but gaps and discrepancies do exist between the provisions of a treaty intended primarily for state-based space activities and the current situation, which includes remote sensing from space that has been conducted more and more by non-state based operations, thus presenting critical issues not addressed sufficiently under the present regime.

As to subjects for conducting space activities and implications, many differ- ent actors participate in space activities, including states, international organizations, and private entities. Only the subjects of international law – states, international intergovernmental organizations, and the other traditionally recognised entities – can conclude treaties under international law. It is evident that states are directly bound by the Outer Space Treaty but the question arises as to how non-state actors are covered.

Article XIII of the Outer Space Treaty clarifies the Treaty's applicability to an individual state even when activities are conducted within the framework of an intergovernmental organization. Consequently, state parties will not be exempt from complying with the Outer Space Treaty just because the particular space activity was conducted by the international organization to which they belong. Article XIV only specifies a state as a subject for being a party to the treaty. Whilst an international organization cannot be held as a party to the Outer Space Treaty, its language assigns consequential rights and obligations: Article VI states that "(...) responsibility for compliance with this Treaty shall be borne both by the international organization and by the State Party to the Treaty (...)". For example, responsibility for an activity of ESA led by the United Kingdom rests with both ESA and the United Kingdom. Still, the question arises as to the responsibility of an IGO when the participating state is not a party to the Outer Space Treaty.

Private entities by themselves are not subject to international law; hence they are neither given rights nor obligations directly under international law. Under the Outer Space Treaty, however, private entities are bound by it through their own state parties under Article VI. Article VI serves as a bridge between the international regime and the national regime as it imposes international responsibility upon state parties for conducting space activities, regardless of whether they are governmental or private in nature. States may thus be held responsible for space activities under their jurisdiction, including those of their national space agencies, private entities, and international organizations in which the state parties participate for any part of the activities of the organization. This provision was a result of a compromise between the United States, who supported the provision, and the Soviet Union, who believed in excluding private entities from engaging in space activities. Actually, it is common that national laws contain a licensing regime for conducting space activities in general, and with respect to launching operations in particular; some deal specifically with remote sensing activities, which will be examined later in this Module.

Another important characteristic of international space law is the applicability of general international law to space activities. The Outer Space Treaty establishes the applicability of international law to the regime in outer space; therefore, international legislation, the United Nations Charter, international customary law, as well as other general principles of law are applicable, complementing the Outer Space Treaty. This Article III provision needs further analysis. At first glance, there seems to be a certain amount of contradiction. Since the Outer Space Treaty establishes that neither the concept of sovereignty nor that of territory exist in outer space, it appears inappropriate to apply international law on the basis of state sovereignty to exploration of space and to those activities that take place wholly within outer space.

It is, therefore, much more logical to conclude that Article III of the Outer Space Treaty applies to Earth-oriented activities such as: 1) activities from space to the Earth; 2) activities within outer space, as far as these directly affect the relations among states on the Earth; 3) activities from the Earth or its airspace to outer space; and 4) activities from the Earth or its airspace via outer space back to the Earth or its airspace. Major Earth-oriented activities such as launching a space object to outer space, GNSS, and remote sensing of the Earth from space, specifically and directly affect the relations between/amongst states on Earth. Such activities are subject to application of international law, and are also in need of more specific regulations.

Overview of the Regime Governing Use and Exploration of Outer Space: This section addresses the elements critical to an understanding of the outer space legal regime. It discusses the basic principles governing outer space, as well as the obligations associated with conducting space activities, which are endorsed by the Outer Space Treaty and the other relevant documents in the *corpus juris spatialis*. The basic principles underlie the concept of outer space and set forth the norms for conducting space activities. The section then discusses the specific obligations involved in outer space:

state responsibility in conducting space activities, liability for damage caused by space objects and registration of space objects.

The Freedom of Outer Space: The freedom of space activities was clearly established by the Outer Space Treaty, which states: “Outer Space, including the Moon and other celestial bodies, shall be free for exploration and use by all States (...) and there shall, be free access to all areas of celestial bodies.” Freedom of space means that space is open and accessible to all and freedom to conduct space activities is secured to all states, including those not parties to the Outer Space Treaty; hence, no state can impede any part of space activities carried out by other state.

Freedom cannot be detached from the notion of sovereignty. Freedom to conduct certain activities outside the state’s own national territories rests on the foundation that either sovereignty of a state does not apply in the area (e.g., the high seas) or permission is granted by the sovereign state to other states that wish to conduct a particular activity inside the territory of that sovereign state (e.g., right to fly over the foreign state through commercial carriage). As mentioned earlier, space law derives from other branches of international law, and the legal status of outer space open for free exploration and use originates in the principle established by the law governing the seas and Antarctica. The 1982 United Nations Convention on the Law of the Sea is worthy of further analysis.

The issue that is of particular relevance to outer space is the legal status of high seas established by the Law of the Sea. Article 87 of the Law of the Sea states that: “The high seas are open to all States.” The high seas may be used freely by the ships of all nations; several different types of freedom are recognized; amongst others, freedom of navigation, freedom of fishing, freedom to lay submarine cables and pipelines, and freedom to fly over the high seas.

The Law of the Sea Convention generally recognizes that the legal status of the air space above the high seas is analogous to that of the high seas proper, that is, *res omnium communis*, meaning that no state may exercise sovereign rights over the high seas or the airspace over the high seas.

One can argue that freedoms associated with the high seas could be applicable to outer space. As mentioned earlier, the Outer Space Treaty provides for four freedoms in outer space: the freedoms of exploration, use, access, and scientific investigation. It can be suggested that freedom of navigation in the high seas is analogous to freedom of exploration in outer space; freedom to lay submarine cables and pipelines is analogous to freedom of use of outer space; and overflight right is analogous to ‘access ’to outer space. An exception would be the freedom of fishing. This freedom does not appear to fit into outer space activity unless an aspect of mining is considered. Freedom to fish can be comparable to retrieving samples from celestial bodies as stipulated under the Moon Agreement; but, theoretically, the right to collect samples is reserved solely for parties to the Moon Agreement, which has not been ratified by many spacefaring nations, since such right is not specifically referred to under the Outer Space Treaty.

The four freedoms of outer space allow states to use or explore outer space freely using manned or unmanned spacecrafts for a variety of applications, both to enhance life on Earth and to conduct scientific investigations insofar as they are in accordance with the provisions of the Outer Space Treaty.

Space applications such as remote sensing, navigation, and telecommunications demonstrate the free use of outer space by operating in certain orbits. Similarly, satellite remote sensing advances the free use of outer space, since, in contrast to aerial remote sensing, it permits the states to conduct information gathering without intruding upon territorial sovereignty. For instance, one can find the practice of securing the freedom of use at the geostationary orbit. Since the geostationary orbit is regarded as a limited natural resource and is overcrowded with myriad satellites, the failure of a state to launch its satellite(s) to the designated slot within a certain time period would be seen by other states as hampering their use of this space resource. The International Telecommunication Union (ITU) regulates the allocation of communications frequencies and occupancy of orbital positions (often referred as 'slots') around the geostationary orbit. A state that fails to launch a satellite within an agreed period would be deprived of its right of use of frequency and access to the slot, as it would be hampering the opportunity for other space community members to use this limited resource.

The launching and re-entry of spacecraft is based on the freedom of access to space. The idea of freedom of access needs to be treated with caution, since – in contrast to an activity which takes place solely in outer space – initial access to space is an Earth-oriented activity as any space object is launched from the ground of the Earth; hence, it is subject to international law. At present, a considerable number of states need to depend upon the use of foreign launch sites, so the absolute freedom of access to space is limited in one way or another. Indeed, launching and re-entry of space objects that take place from a foreign state affect the legal rights and interest of that state. A state with a launch site may deny a request from other states to launch their satellite for any reason whatsoever.

Since the launch and re-entry of a spacecraft involves passing through air-space, it is useful to refer to the international law governing airspace. The regime applicable in airspace, as stipulated in Article I of the Chicago Convention, is that "every State has complete and exclusive sovereignty over the airspace above its territory." Therefore, passage through territorial airspace must be authorized either through a contractual arrangement or by expressed permission. If a space object is launched from a foreign territory, whether it is a state or commercial launch service, the launching takes place with the consent, or at least with the knowledge, of the state where the launch takes place. In that sense, authorization is granted to the state prior to the launch, which, in a sense, follows the air law regime.

On the other hand, the re-entry of a space object via foreign airspace back to the launch site of its own state is much more complex. It is much less obvious, and probably much less formally authorized. Unlike air law, in which a right of passage through the foreign airspace is pre-arranged for that particular purpose (e.g., the right to discharge commercial carriage in a foreign state), the return of a space object from outer space to the Earth sometimes inevitably accompanies passage through foreign airspace without prior legal arrangement. Considering the circumstances, one can draw a closer analogy with the concept of innocent passage, which grants foreign ships a right of passage through another state's territorial water under the 1982 Law of the Seas. The passage is construed as 'innocent 'if the ship is (a) "traversing that sea without entering internal waters or calling at a roadstead or port facility outside internal waters; or, (b) proceeding to or from internal waters or a call at such roadstead or port facility insofar as the passage is continuous and expeditious." Both launch and re-entry are sufficiently analogous to the circumstances in which right of innocent passage is granted, as the pass through the foreign airspace is only temporary and on the way to a final destination, specifically outer space or the home state.

In fact, precedents do exist such as the Soviet spacecraft flying over the airspace of adjacent states in its return to the Soviet Union; or the space shuttle Challenger on 13 October 1984 crossing the US-Canadian air border at an altitude of approximately 68 km on its way to landing in US territory. Whilst for these two cases it is not certain as to whether the states were informed either prior to or after the launch with respect to their overflight, there is a precedent of prior notification of re-entry: In March 1990, during the flight stage of the Atlantis, the United States informed Russia, as a courtesy, of the planned descent of a space-craft through the airspace of Soviet Union territory a few hours before the overflight took place.

Whilst these precedents do not deny the possibility of the right of a spacecraft to pass through foreign airspace after re-entry, it should be noted that there is no sufficient support for a customary rule for the right of innocent passage specific to spacecraft. The issue of the right of free passage for a state's spacecraft through the airspace of other states is of growing importance. In the future, with the advent of commercial space tourism, re-entry of a manned vehicle through foreign airspace is likely to take place more frequently.

The principle of freedom establishes the rule that states do not have to obtain permissions for engaging in space activities and cannot prevent other states from conducting such activities, insofar as they do not interfere with the sovereignty of other states. In theory, states not party to the Outer Space Treaty may be engaged in space activities. Although it can be construed that the right to conduct space activities also establishes the legality of sensing from space, the Outer Space Treaty does not set forth under what conditions states are free to conduct remote sensing from space; therefore, freedom of space established by Article I of the Outer Space Treaty itself cannot substitute for a concrete code of conduct for remote sensing activities.

The Principle of Non-Appropriation: Another major principle is the principle of non-appropriation. Article II of the Outer Space Treaty states that: "Outer Space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or any other means."86 This means that sovereignty does not extend to outer space and no state can claim outer space or any celestial body as its territory and exercise sovereignty rights therein. Article II precludes any individual state from obtaining legal rights (e.g., ownership rights) over outer space or any parts thereof. Consequently, the status of outer space is not *res nullius* or *terra nullius* – unclaimed land open to acquisition by any state – but would qualify as *terra communis* – land jointly managed by all states – or res extra commercium – areas outside state's sovereignty. This means that only a community of all states acting collectively can regulate legally any activity in outer space.

Incorporating the principle of non-appropriation of outer space was welcomed by the super powers because, at the time of formulation of the Outer Space Treaty, both of them were unsure which one would land on the moon first. As seen earlier, the inclusion of the non-appropriation principle met with unanimous approval in General Assembly Resolution 1721 A (XVI) in 1961. Indeed, the principle articulated in Article II was the main impetus for the existence of the Outer Space Treaty. From this one can infer that the formulation of the Outer Space Treaty was political in nature.

In recent years, the application of the principle of non-appropriation has become a subject for debate with the emergence of companies with a business model taking advantage of the status of celestial bodies. Some companies, such as Lunar Embassy, have virtually sold land of celestial bodies on the Internet, claiming that they own them. Lunar

Embassy's argument was based upon the provision's language "(...) is not subject to national (emphasis added) appropriation (...)", which it interpreted as constituting a loophole in a literal sense. What is not given to a state is given neither to natural or juridical persons;93 therefore, one can argue that any entity claiming the ownership of celestial bodies has no legal standing. The principle is likely to be challenged more as commercial exploitation of celestial bodies advances.

The Principle of Cooperation and Mutual Assistance: As mentioned previously, the historical development of a legal framework for space activities came through negotiation and consensus within the UN COPUOS, which served as a forum for cooperation. The principle of cooperation constitutes one of the central principles governing the regime of outer space. Whilst most provisions referring to international cooperation in the Outer Space Treaty are recommendatory in nature, certain Articles do create an obligation to cooperate on specific matters. One example is the obligation to cooperate with regards to the protection of the environments of outer space and the Earth.

Article IX of the Outer Space Treaty obligates party states to undertake inter- national consultation in case of a potential threat of environmental harm. Article IX states that: "States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose." In addition, Article IX requires states to undertake prior consultation in case of potential harm: "If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities of other State parties in the peaceful use of outer space, it shall undertake appropriate international consultations before proceeding with any such activity or experiment." As mentioned earlier, intentionally destroying a satellite in the manner of the 2007 ASAT test conducted by China is in contravention of this principle that requires prior consultations for activities that impact others. The fact that no prior warning was given by China resulted in criticism from international society. Furthermore, with the February 2009 in-orbit crash of two full sized satellites – a first-time incident – the ongoing issues concerning space debris came under renewed scrutiny. The more space activities that are undertaken, the more concerns over the impact on the environment will grow. It is highly conceivable that obligations associated with space debris will be elaborated into more concrete guide- lines; or there may be separate legislation devoted to the issue addressed under Article IX.

Another obligation concerns the cooperation in disclosing the details of space activities undertaken. Article XI stipulates that: "In order to promote international cooperation ... Signatories are obliged to inform the United Nations Secretary General, as well as the public, and the international scientific community, to the greatest extent feasible and practicable, of the nature, conduct, locations, and results of space activities." One can contend that the language of this provision is too soft to impose any concrete obligation to disseminate the information concerning space activities so as to share it with the relevant communities. The phrase, "to the greatest extent feasible and practicable" reduces any obligation that may derive from this Article to a level purely within the discretion of the space power concerned. The interpretations of, and the positions with respect to, this provision are not uniform. The Soviet delegation adhered to the position that reporting of activities in outer space generally should be on a voluntary basis. The United States has interpreted this obligation to require the widest practical dissemination of data and information obtained from the civil space program to provide improved space services to itself and to the rest of the world. ESA promotes the view that member states shall share and exchange information amongst themselves, but they are not required to do so if they believe it would be against their own national interests. This implies that the national interest prevails over the obligation to share information; also, it appears to support the earlier conclusion that no obligation for cooperation is established, so sharing of information related to space activities is not required.

The recommendation to share information on space activities has significant implications for remote sensing activities, as the 'result of space activities 'infers the inclusion of data and information derived from satellite remote sensing. 'Informing 'is an active obligation and, if applied to remote sensing, it could become an automatic obligation to disclose every time new remote sensing data is gathered. One can see the implementation of this provision in reality through the practice of US governmental entities such as NASA and NOAA making their data available in archives through the Internet at marginal cost, but at an international level that practice can only occur if such a commitment has been agreed upon – as in the case of the International Charter on Space and Major Disaster (hereafter: Disaster Charter) where data and maps are created to assist disaster relief and humanitarian operations within these frameworks via the internet, and which are free of charge to download.

In practice, it appears that the sharing of all data and information from remote sensing is not required of states, otherwise it would be difficult to explain the presence of multilateral data exchange principles, Memoranda of Understanding (MOUs), or other forms of agreements specifying authorisation of mutual access to data and/or assistance to provide data.

With regard to the form of cooperation in space activities in general, when states cooperate with other states on specific matters, they tend to enter into treaties, bilateral and multilateral agreements, or soft forms of agreement such as MOUs. Historically, there has been extensive cooperation in various forms in the field of space; international cooperation has resulted in the establishment of numerous international organisations through conventions such as the International Telecommunications Satellite Organisation (INTELSAT), the Council on International Cooperation in the Study and Utilisation of Outer Space (INTERCOSMOS), the International Organisation of Space Communications (INTERSPUTNIK), and the European Space Agency (ESA). In the conventions establishing the aforementioned organisations, concrete terms of cooperation are provided.

In contrast to the multilateral conventions establishing international organizations, cooperation in the field of satellite remote sensing is commonly seen in voluntary forms of cooperation; that is, neither strictly binding nor completely lacking in legal significance, such as exchange of letters and MOUs. Cooperation has been particularly extensive in the field of developing remote sensing satellites, as well as in acquiring and processing data from satellites. Ground station arrangements are often based on MOUs[3].

[3] For instance, the United States of America and India: Memorandum of Understanding concerning remote sensing and acquisition of satellite data, 31 January 1975; and the Memorandum of Understanding between the European Space Agency and the United States National Aeronautics and Space Administration concerning ERS-1 data acquisition at Fairbanks, 14 January 1986. Landsat ground station agreements have been in the form of MOUs such as Memoranda of Understanding between the National Space Development Agency of Japan and the United States Department of Commerce National Oceanic and Atmospheric Administration, July 5 1983. For a discussion of Landsat

Successful emergence and operation of a framework for cooperation such as the Disaster Charter to be discussed later, is not based upon legal obligations born of treaty-based law, but on a voluntary effort amongst the willing partners. The international collaborative effort under the Disaster Charter framework is based on voluntary cooperation and good endeavours. Within such programmes, the beneficiaries can receive assistance through access to critical information derived from a combination of satellites. The partners 'will to set up such mechanisms signifies the success of voluntary forms of cooperation in the field of satellite remote sensing.

State Responsibility in Conducting Space Activities

Whilst the rules addressed in previous sections were fairly general, some provisions of the Outer Space Treaty establish explicit obligations. They endorse concrete rules on responsibility, liability, and control of a space object, and state how the obligations are implemented.

The Outer Space Treaty articulates the important rule that states are free to conduct space activities, but are obligated to be internationally responsible. Gorove contends that "it seems that when we speak of responsibility, we are dealing primarily with obligations imposed on people and institutions who are supposed to carry out certain activities or are accountable in given situations though not necessarily in the form of compensation for damages."107 By man- dating international responsibility to the state party for its national activities in outer space, the Outer Space Treaty denies anarchy in outer space and establishes a regime where space activities are controlled by state parties.

State parties have responsibility over their national space activities, whether conducted by governmental agencies or non-governmental entities. This particular provision imposing a direct responsibility on states for national activities conducted by non-governmental entities is unique under international law.

Since a state has responsibility for national activities including those con- ducted by private persons, it is particularly important to clearly define the scope of 'national activities'. They can be interpreted as those activities over which states can exercise legal control, that is, activities that take place under their jurisdiction, including: activities carried out by nationals of a state; activities which take place within a territory of that state; and activities which are under the jurisdiction of a state through a registration of a space object (quasi- territorial jurisdiction); and possibly by other arrangement. The ambit of 'national 'space activities can be relatively broad.

Article VI further states that "The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty." As a consequence of this responsibility, the appropriate state needs to have a control regime with respect to the activities by non-governmental entities within its jurisdiction.

The definition of 'appropriate state 'is absent from the entire Outer Space Treaty, and requires further analysis. The fact that there is no specific definition allows flexibility to extend the interpretation of 'appropriate state 'to states concerned, instead of limiting that interpretation to 'launching state 'or 'state of registry'. In principle, any state that exercises control over said activities – whether that control be national, territorial, quasi

arrangement, see further P.A. Salin, Landsat Contracts Signed by US Agencies with Foreign Ground Stations: Commercial Remote Sensing from NASA Scientific Experiments to EOSAT Private Endeavours.

territorial, or designated specifically by agreement – qualifies as an ‘appropriate state’. Since the term ‘appropriate state ’is in a singular form, only one state can exercise jurisdiction, even if more than one state may be involved in the activity in question.

The fact that ‘appropriate state ’is put in a singular form has some implications. It would clarify where the responsibility for non-governmental activities lies, and would allow the discretion of those states concerned as to which one will actually exercise jurisdiction, in case more than one state party is involved in the activity in question. In the meantime, authorization and supervision by a single appropriate state would also avoid overlapping jurisdictions and promote effective control over a particular space activity undertaken.

The extent of the concept of international responsibility is ambiguous. It is not clear as to whether the responsibility extends beyond compliance with the Outer Space Treaty to a wider scope of international and national law as well as to contracts. Such scope of responsibility needs to be defined more precisely in the national context.

A state’s responsibility in conducting space activities could result in international liability for damage caused to other states. Article VII of the Outer Space Treaty states that: “Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party.” This provision is elaborated in the 1972 Liability Convention.

Liability for Damage Caused by Space Objects: Liability involves the legal consequences of a particular action or omission that result in damage, that is, a loss or injury to person or property. The 1972 Liability Convention addresses the legal consequences for a state when either its launch or operation of a spacecraft in orbit leads to damage to another state, and provides a civil remedy. The Convention establishes a victim-oriented international scheme for the compensation of damage resulting from launching activities that provides the maximum protection for potential victims. The Liability Convention establishes the fundamental rules regarding international liability for damage caused by space objects so that different circumstances of such accidents are satisfactorily addressed.

Overall, the Liability Convention sufficiently foresees different settings and clarifies what measures of protection are available to potential victims under differing circumstances. First, it makes clear that the damage caused within a launching state is an internal matter and sets such situations outside the scope of the Liability Convention. The Convention only applies to damage done to foreign territories as well as to foreign nationals not participating in launch and/or operation of a satellite[4]. For example, the Liability Convention did not apply to the instance of the disintegration of the space shuttle Columbia on 1 February 2003, and the consequent precipitation of debris over US territory. The Liability Convention predominantly relies on a state-based compensation; however, it does not exclude the possibility of individual compensation as an alternative as Article XI(2) provides that “Nothing in this Convention shall prevent a State, or natural or juridical persons it might represent from pursuing a claim in courts or administrative tribunals or agencies of a launching state.”[5] This gives victims opportunities to seek

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4 Article VII of the Liability Convention.

5 Article XI (2) of the Liability Convention

recovery in a civil suit without having to rely on the government; however, claims for the same damage cannot be presented in parallel on a state-to-state and individual basis.[6]

Closer examination of the mechanism for state-based compensation reveals that measures for dispute settlement are available at two levels: first, through diplomatic negotiation; second, through settlement by a Claims Commission. The former measure needs to be exhausted before application of the latter, within the time limit of one year[7]. If the dispute is not settled by diplomatic negotiation within this timeframe, a Claims Commission consisting of three members appointed by the claimant state, launching state, and both states respectively[8] is established. The Commission shall give its decision or award, and the decision of the Commission shall be final and binding if the parties have so agreed; otherwise the Commission shall render a final and recommendatory award, which the parties shall consider in good faith[9].

Pursuant to Article VII of the Outer Space Treaty, the Liability Convention establishes an inseparable link between the launching state and damage caused by its space object. The Liability Convention adopts two distinct bases of liability, depending on the location where damage is caused. It imposes absolute liability on a launching state in case of damage on Earth: “A launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight.”[10] It imposes faultbased liability in outer space: “In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State.”[11] There is no ceiling on the amount of compensation under the Liability Convention and this adds to the financial burden imposed on launching states.

When the damage takes place on the surface of the Earth, it is not necessary to prove fault; the only required element of proof is causation; that is, the damage was actually caused by the space object. Therefore, just by being qualified as a launching state, that state would potentially be held liable in case of damage on the Earth’s surface. The only circumstance in which exoneration from liability is possible is when “the damage has resulted from gross negligence or an act or omission done with intent to cause damage on the part of a claimant State or natural or juridical persons it represents.”[12] If a private entity is grossly negligent, the government may be exonerated from international liability over such an act by that entity. On the other hand, the Convention does not refer to exoneration in case the damage is caused by the fault of a third party or is due to *force majeure* (e.g., natural disasters).

For damage caused either elsewhere than the Earth’s surface or aircraft in flight, a launching state is liable only if it is at fault for damage caused in outer space (e.g., collision of/with a satellite)[13]. In contrast to damage on the surface of the Earth, the

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[6] Article XI (2) of the Liability Convention states that: “A state shall not, however, be entitled to present a claim under this Convention in respect of the same damage for which a claim is being pursued in the courts or administrative tribunals or agencies of a launching state or under another international agreement which is binding on the States concerned.”

[7] Article XIV of the Liability Convention.

[8] Article XIV of the Liability Convention. For the details of the Claims Commission, see Article XV.

[9] Article XVIII of the Liability Convention

[10] See Article II of the Liability Convention

[11] Article III of the Liability Convention.

[12] Article VI (1) of the Liability Convention.

[13] Article II of the Liability Convention.

claimant launching state has to demonstrate that the other launching state was at fault in causing such damage in outer space. If the collision was because of an inevitable accident with no fault on either side, no liability is invoked.

As discussed above, the point of departure for determining compensation is the identification of a launching state. For a close analysis of the terms of the Liability Convention, the critical requirement is the definition of 'launching state'. "The term launching State means (i) a State which launches or procures the launching of a space object; and (ii) a State from whose territory or facility a space object is launched."[14] Whilst a 'State that launches a space object 'is fairly straightforward, a 'State which procures the launching 'is not. The term is not defined concretely and is open to different interpretations. It is logical to regard a state with jurisdiction over the entity requesting launch services con- ducted from the foreign territories as a 'State which procures the launching'. The term may also be interpreted as including those states whose jurisdiction covers the activities of entities in manufacturing and arranging the launch of a satellite on behalf of its customer. Through such differences in interpretation, the term, 'launching state 'could offer potential victims more than one choice of targets to from which to seek recovery. The other side of the coin is, of course, that there is more potential risk for liability to all states that are in some way involved in launching operations either as a customer or service provider.

The Liability Convention holds launching states jointly and severally liable if more than one launching state is responsible for damage[15]. Given the four types of launching states coupled with the open definition of a 'State that pro- cures launching', it is very common to have more than one launching state; it is increasingly so nowadays, with the growing number of commercial satellite manufacturers and launcher services that are offering customers around the globe the opportunities to get their satellites manufactured and launched outside their home states.

By providing for joint and several liability, the Liability Convention aims to implement proper allocation of costs as well as to minimise the burden of a potential claimant. This procedural measure can particularly be characterized as 'victim oriented 'since an injured state reserves its right to seek the entire compensation from any or all of the launching states[16] without requiring them to identify which launching state(s) are liable for what portions of the damage. In case one launching state paid the compensation to a victim state, that state may request reimbursement from other responsible launching states. In this fashion, the Liability Convention has established a mechanism to provide remedies promptly to victims and leaves the rest of the business of settling claims to the launching states concerned.

In case launching states are jointly liable for damage, the foremost question concerns how liability is apportioned between/amongst them. Article IV states that "(...) the burden of compensation for the damage shall be apportioned between the first two States in accordance with the extent to which they were at fault; if the extent of the fault of each of these States cannot be established, the burden of compensation shall be apportioned equally between them." This provision, however, appears to be rather inadequate to address cases where more than two states are responsible for damage and the degrees of

14 Article I(c) of the Liability Convention.

15 Article V of the Liability Convention. Article V (2) stipulates that burden of compensation for damage shall be apportioned.

16 See Article V(2) of the Liability Convention.

contribution to the damage by each party do not clearly show which states are the 'first two States'. Furthermore, the Liability Convention does not describe how the launching state that has given compensation may get reimbursement from the other states that share liability. Since harmonized regulations for reimbursement are absent at present, and in case specific agreements arranged amongst launching states concerned are also absent, it is conceivable that one launching state will bring actions against another to shift the responsibility for the loss.

In terms of application of the Liability Convention to satellite remote sensing, the matter of highest relevance is perhaps the interpretation of 'damage caused by its space object'. Damage is defined as "loss of life, personal injury or other impairment of health or loss of or damage to property." The Liability Convention does not define a space object fully, but clarifies that it "(...) includes the component parts of a space object as well as its launch vehicle and parts thereof." This can be interpreted to cover manned vehicles such as the Space Shuttle; unmanned vehicles; and payloads for activities such as telecommunication, Earth observation, and navigation.

The common interpretation of 'damage caused by its space object 'is that it would only cover direct damage. It is logical to interpret that 'damage 'refers to the physical impact, since it specifies a location where damage is caused. As a result, consequential damage associated with remote sensing is not likely to be covered under the Liability Convention. Yet such damage may be incurred from a particular action or through decisions taken on the basis of data. The ambiguities identified in the issues of responsibility and liability also exists with respect to control of a space object.

Registration of Space Objects: As has been discussed, identification of a launching state is a critical starting point for settlement of international disputes over damage caused by a space object. Nevertheless, with growing complexities of business configurations, it may not always be simple to assign blame to a single state. In this regard, registration of a space object by one state performs an essential function to identify a single state that officially takes charge of the space object. Pursuant to Article VIII of Outer Space Treaty, which establishes a rule that a state that registers a launched space object retains jurisdiction and control over such object, the 1975 Registration Convention elaborates a mechanism of control of a launched space object.

Article II of the Registration Convention establishes that a single launching state registers the space object and, in case of more than one launching state, they shall jointly determine which one registers the space object. This makes clear the indisputable rule; that is, only one state of registry exists for a launched space object. The rule to document the single state of registry may involve a selection process of the 'principal 'launching state amongst several states that fall within the scope of broadly defined 'launching states 'with distinct forms and/ or degree of participation/involvement in a launch. A determined state of registry is then registered both at a national and international level and the international registry is maintained by the Secretary General of the United Nations.

The question arises as to how a state of registry is determined. Then, the discussion comes back to the analysis of different type of launching states. Amongst the four definitions of 'launching state–'that is, a state that: launches the space object, procures the launching of a space object, from whose territory the space object is launched, or from whose facility a space object is launched – which one is most suited to be the state of registry?

State practice appears to reflect that the state of registry is determined less on the basis of the location of launch of a space object than on who procures the launch. For instance, the

United States would not register space objects just because they were being launched from US territory, but only if they were owned or controlled by "[the] State's private or governmental entities." Likewise, France registers its national satellites irrespective of the state from which they were launched. From these examples, one can recognize the possibility that a state operating commercial launch services from its territory, although construed as a launching state, does not necessarily become the state of registry just because an arrangement was made to launch a satellite from its territory.

The Registration Convention imposes upon the state of registry the duty to control the registered space object. The status most commonly assumed by the Registration Convention is that in which a single state qualifies as the launching state, the state of registry, and the state that retains control of a launched satellite. The Convention nevertheless indicates the possibility that jurisdiction and control may be exercised by a launching state other than the state of registry through certain arrangements. In case a specific arrangement creates the situation that the launching state and state retaining control of a launched satellite are different, the links established through registration amongst a launching state, the state of registry, and the state that actually controls the space object become much less effective, if not invalid; also confusion may arise as to where responsibility lies.

Finally, the extent of control by the state of registry is not clear from the provisions of the Registration Convention. It is uncertain as to what type of control should be exercised. With respect to satellite remote sensing, it is particularly important to establish the extent of control, such as the control on the dissemination of data from the satellite, and whether control extends to potential damage arising from the data.

In summary, the Outer Space Treaty together with the Liability Convention and Registration Convention spells out the basic legal norms in conducting space activities and serves as an overall framework for space applications, including satellite remote sensing. It is, however, both ambiguous and too limited to address sufficiently rules for satellite remote sensing. It is therefore necessary to look further at the regime specifically dealing with satellite remote sensing to see whether rules for remote sensing could be better addressed under specialized legislation, and to clarify the rights and obligations that are currently established in association with remote sensing activities.

Specific Law for Remote Sensing: As introduced briefly, the body of law specifically dealing with remote sensing was adopted by consensus in the form of the UN General Assembly Resolution in 1986. Christol contends that the UN Remote Sensing Principles gave formal approval for states to engage in information gathering activities from space as international customary law, that is, practices and beliefs that are so vital and intrinsic a part of a social and economic system that they are treated as if they were laws. Indeed, the UN Remote Sensing Principles are a re-establishment of legitimacy for data collection from space, which was already an accepted practice inferred under the Outer Space Treaty and, for the first time, establishing concrete rules with regard to data access and availability at an international level.

Drafting History of the UN Remote Sensing Principles: Following the initial considerations to codify principles at the United Nations in the late 1960s, it took more than fifteen years for states to come to a consensus in 1986 on the general principles regarding remote sensing. The lengthy drafting history is attributed to difficulties in achieving a consensus amongst various nations with different positions and conflicting interests. The stances adopted by states were fundamentally split between those COPUOS members representing developed nations with sensing capabilities on the one hand and the developing nations that lacked such technology on the other. The former position was taken by the United States and many Western states, who insisted upon the freedom of acquiring and imparting information as a human right; the latter position was held by those states amongst the develop- ing and Soviet-led socialist countries, who insisted upon the principle of state sovereignty over natural resources as well as the information concerning such resources."

The disparate positions stemmed from the interpretation of the term sovereignty, and location where the sovereignty in question was stressed. The first question was whether freedom of sensing was permissible. The location of a target for sensing, in which the sovereign right of states was exercised, was stressed by developing nations;146 the developed nations stressed the location from which sensing takes place, where sovereignty does not extend. The second question was whether sovereignty extends to acquired information. Whilst developing nations claimed their sovereign right over acquired information relating to natural resources in their territory, developed nations argued other- wise. The conflicting positions seemed to be impossible to reconcile at first. Indeed, the drafting history of the UN Remote Sensing Principles had been a difficult process of compromise between the dissenting views, which progressed gradually over a period of time.

The initial examination of the subject by the UN COPUOS started in 1968 in Vienna. Until the text of what is now the UN Remote Sensing Principles was adopted, a series of proposals by different nations were presented. The major proposals to be examined in this Chapter are as follows:

- 1970 Proposal by Argentina[17]
- 1973 Proposal by the Soviet Union co-sponsored by France[18]
- 1974 Joint draft by the Soviet Union and France[19]
- 1974 Joint Draft by Argentina and Brazil[20]
- 1975 Proposal by the United States[21]
- 1981 Proposal by Mexico[22]
- 1982 Proposal by Brazil[23]
- 1984 Proposal by Chile[24]

The content of the proposals, which were subject to negotiation, can be categorized into three critical elements: conditions for sensing, conditions for access and distribution of data, and international responsibility regarding conducting remote sensing activities.

The negotiation was put forward mainly in two stages: first, debates on conditions for sensing – such as prior consent, limit on location, and veto right; and second, debates on rules concerning the resulting information – such as priority access and control on

17 UN Doc. A/AC.105/C.2/L.73, 26 (1970)
18 UN Doc. A/AC/105/111 (1973).
19 UN Doc. A/AC.105/C.2/L.99 (1974).
20 UN Doc. A/AC/1/1047, Oct 15, 1974.
21 UN Doc. A/AC.105/C.2/L.103 (1975).
22 UN Doc. A/AC.105/288 (1981).
23 WG/RS (1982)/WP.11 (1982).
24 WG/RS (1984)/WP.12 (1984).

dissemination of data. The detailed examination of drafting history can be roughly divided into three periods: 1) the era prior to the 1978 Moscow Convention on the Transfer and Use of Data of Remote Sensing of the earth from Space;[25] 2) the Moscow Convention and International Satellite Monitoring Agency; and 3) post Moscow Convention towards the 1986 UN Remote Sensing Principles. The debate regarding the freedom of sensing took place primarily during period 1 and the debate regarding access and dissemination characterising priority access and control on the dissemination of data took place in periods 2 and 3. It is important to look at how divergent were the views and positions presented, how they met opposition from the other side, and how gradual convergence to agreement resulted in each period.

The initial formulation phase of the UN Remote Sensing Principles began with a 1970 proposal by Argentina, which claimed that prior consent was required from the sensed state before another state conducted remote sensing. This position was based on the contention that, since certain UN General Assembly Resolutions provide that states have permanent sovereignty over their own natural resources, information on the these assets was also included in the concept of sovereignty.

The 1974 Brazil and Argentina draft proposal again insisted on prior consent for sensing any foreign territory and rigid control over sensing natural resources – a proposal so extreme that it would have denied the remote sensing practice that had been conducted by space powers at that time, and would have made remote sensing activities practically impossible to conduct. That proposal was not acceptable to space-faring nations. The United States strongly opposed this position for legal, technical, and practical reasons, contending that it was legally inconsistent with the provisions of the Outer Space Treaty and that the legality of sensing should depend upon the site of the sensing device rather than the location of the sensed object. Furthermore, the United States argued, from a technological standpoint it is not possible for remote sensing equipment to distinguish international borders; and besides, it would be financial impracticable to develop such capability.

The United States maintained its stance for freedom of sensing, adhering to the Open Skies Policy and recognizing the commercial potential of remote sensing data. The United States did not mention the sovereignty issues in its proposal, a working paper entitled *Legal Implications of the Earth from Space*. The United States contended that the disclosure of useful information derived from sensing would contribute to the "(...) preservation of environment and effective management and control by states of their natural resources." Freedom of sensing was proposed by only a few states then.

The Soviet Union and France made a joint proposal in 1974. This proposal also required prior consent and the legality of sensing was limited in its location, suggesting that freedom of sensing be permitted only in the areas outside the national jurisdiction of any state. The proposal also introduced the notion of control over the dissemination of data and suggested a requirement of prior consent from sensed states.

Under the French-Soviet proposal, data was divided into two types. Data acquired with a spatial resolution greater than 50m would be classified as 'global 'and would not be subjected to restrictions imposed for sensing and dissemination; data of higher than 50m resolution would be classified as 'local 'and would be subject to control. This proposal was based on the view that sovereignty of sensed states extended to acquired information

[25] UN Doc. A/33/162, 29 June, 1978. [Hereafter: Moscow Convention]

by sensing states, rather than any grant of superior rights to sensing states to have access to critical information on natural resources in the territory of sensed states.

The only exception to the application of prior consent and the right of veto in the French–Soviet proposal was distribution for the purpose of disaster management and environmental protection. The draft stipulated that no veto rights would be exercised in the event of a natural disaster or phenomena detrimental to the environment; and the sensing state could distribute data without the knowledge or approval of the sensed state(s). Because it called for 1) classification of data by ground resolution with consequential dissemination policies, and 2) giving preferential treatment for data availability for public benefit, the proposal can be regarded as an attempt to establish concrete data policies hitherto not adopted for inclusion in the final document.

The 1974 Soviet-French proposal led to the 1978 Moscow Convention on the Transfer and Use of Data of Remote Sensing of the Earth from Space. This convention set forth the detailed rules with respect to the dissemination of data, which can be seen as a data policy. The convention was signed in Moscow by Cuba, Czechoslovakia, the German Democratic Republic, Hungary, Mongolia, Poland, Romania, and the Soviet Union. At the time of this convention, the argument was shifting from the freedom of sensing from space to the control of resulting information and attempts to regulate the access and dissemination of data. The control over dissemination specifically imposed in Article IV of the Moscow Convention stipulates that "A Contracting Party in possession of initial data of the remote sensing of the Earth from outer space, with a better than 50 metres ground resolution on the terrain, relating to the territory of another Contracting Party, shall not disclose or make them available to anyone except with an explicit consent thereto of the Contracting Party."

Article IV of the Moscow Convention therefore required prior consent from sensed states for dissemination of initial data and derived information concerning natural resources of the sensed states, and also established international responsibility for use of remote sensing data. The intention was clear: Article IV attempted to protect the sovereign rights and interests of sensed states through control of dissemination of the information. Prior consent for the dissemination of data infers veto rights by sensed states, and it can be construed that if a party considers the dissemination of the data as detrimental to them, they can hamper the dissemination by exercising their right of veto.

The Soviet Union was specifically opposed to the free dissemination of data and rejected the idea that remote sensing data should be freely purchased, as that would constitute a free market in remote sensing data. At the time of the convention, the Soviet Union also proposed that the sensing state should have international responsibility for any serious damage caused by the dissemination of the data; however, such proposal was not taken into account.

The Moscow Convention was not ratified by any further states apart from the first signatories of the socialist nations and failed to become a globally accepted legislation on remote sensing. Over time, it was clear that the convention had been discarded. This was a natural outcome, as communism came to an end in the 1990s; the former Eastern-bloc nations – which comprised the majority of the parties to the convention – have joined the western systems since then. Today, an increasing number of states that were strictly the subjects of sensing activities back in 1986 now have their own space capabilities.

It should be noted that in 1978 – during the first special session of the UN General Assembly devoted to disarmament, France proposed establishment of the International Satellite Monitoring Agency (ISMA), a specialized agency of the UN, responsible for collecting, processing, and disseminating data and information gathered by satellites. The proven capability of satellite remote sensing to verify the bilateral agreements such as the SALT and ABM treaties led to this proposal, which would also apply such capability to multilateral agreements. The main functions for ISMA were to be the monitoring of the implementation of multilateral arms control and disarmament agreements and the investigation of crisis situations. The ISMA was to be established in three phases: 1) it would operate an international data processing and interpretation facility and disseminate resulting information to member states where data would be acquired from states that operate surveillance satellites; 2) it would establish ground receiving stations, possibly working with national satellites; and 3) it would establish its own space segment as a supplement to national systems.

In response to the submission for a vote on the ISMA to the United Nations, the United States and the Soviet Union abstained and the General Assembly created a committee of experts to conduct a feasibility study. The feasibility study concluded that establishing the ISMA was technically feasible and not in conflict with international law. The ISMA did not come into existence, however, because both superpowers were against its establishment. The Soviet Union argued that allowing an international agency to gain control of military or strategic information would have violated the principle of national sovereignty, whilst the United States contended that such an agency would have permitted states to engage in espionage or activities that were inconsistent with national security or national policies. The failure to establish the ISMA indicates that, even amongst the developed nations with remote sensing capabilities, their interests were not uniform.

The Moscow Convention did not resolve the fundamental problem associated with achieving consensus for a set of principles governing remote sensing; thus, during the period from 1976 to 1981 no progress was made toward an agreement on the principles of state sovereignty and prior consent.

With the 1981 Mexico proposal, meaningful debate toward agreement resumed. Mexico proposed priority access as well as prior notification. The phrase 'prior notification ' instead of 'prior consent 'was a reflection of some attitudes of compromise shown by developing states, as 'prior notification– 'in contrast to 'prior consent – 'does not imply veto rights. The proposal also required that sensing states provide preliminary information and final results, whilst prohibiting dissemination of information without the prior consent of sensed states. The debate was shifting more towards the conditions necessary for access and dissemination, together with the responsibility of states to carry out remote sensing activities.

The 1982 Brazilian working paper provided a compromise solution by way of a restriction of state responsibility as well as data availability. It advocated for priority access and international responsibility on dissemination, and it pro- posed priority access by sensed states as: a "Sensed State shall have timely and non-discriminatory access to primary data obtained by remote sensing of the Earth from outer space concerning territory under its jurisdiction before access is granted to any third party." The Brazilian proposal suggested that sensing states should be held internationally responsible for dissemination of data that adversely affect the interests of sensed states.

Both socialist nations and developing countries were ready to agree to this proposal; however, it proved unacceptable to sensing states as it would have meant that state responsibility extended to monitoring data dissemination by private entities conducting remote sensing.

Specific responsibility for the use of remote sensing data was also proposed in a working paper by Chile in 1984. Principle XI states that "States shall bear international responsibility for improper or discriminatory use of analysed information resulting from remote sensing." This language can be construed to mean that the misuse of data that could be detrimental to the interests of sensed states is prohibited.

The emergence of civilian-operated remote sensing satellites made the developed states adhere even more to their position for freedom of sensing with unregulated dissemination of data. The United States began operating Landsat in 1972, and its position on remote sensing reflected a clear intention to vitalise the Landsat system and its data dissemination. The United States intended to commercialize the remote sensing system through the 1984 US Land Remote Sensing Commercialization Act. France initially supported the Soviet view for requiring prior consent, but shifted to follow the US position in anticipation of the development of the French SPOT – the first non-US civilian satellite – in 1986.

The final UN Remote Sensing Principles mainly reflect the US view and are clearly the product of a high degree of compromise by the developing states. None of the proposals from developing nations with regard to the rights of sensed states and obligations of sensing states were incorporated in the way that these sensed states originally wished. The major contention of developing nations – including, but not limited to, prior consent for sensing and dissemination of data, privileges in accessing data by sensed states, concrete data policies, and responsibility for dissemination of data – were discarded; only ambiguous phrases on international responsibility and the respect of the interests of sensed states remained, and these were incorporated into the final UN Remote Sensing Principles. It was a victory for the proponents of sensing, represented by the United States, which managed to codify most of its contention that the freedom of sensing and the unregulated dissemination of data were consistent with the Open Skies Policy. The only matter that was not incorporated into the Remote Sensing Principles was the US view regarding intellectual property rights. The United States has claimed that once collected data is transformed into product though processing and analysis, it becomes the intellectual property of its owner and thus subject to copyright law. This view is now incorporated in data policies of individual entities and widely practiced, but this practice invokes questions as to the applicability of such data policies to different types of products.

The UN Remote Sensing Principles were adopted after a long period of difficult negotiations. In the end, the Principles adopted turn out to be ambiguous; they do not impose specific obligations, and they contain significant loopholes. The resulting Principles reiterate general concepts of international law or formalize existing customary practice. Even after the formulation of the Remote Sensing Principles, dissatisfaction – particularly amongst the developing countries – remained undiminished. For example, the Latin American nations 'claim for more regulated legislation came to a concrete proposal in 2003. Argentina, Brazil, and Mexico submitted a working paper to the UN COPUOS on a new agenda item calling for an international convention for remote sensing.

The Legal Value of the UN Remote Sensing Principles: The legal value of the UN Remote Sensing Principles is often debated. In examining their legal value, it is necessary to approach the issue from two stand- points: the analysis of UN General Assembly Resolutions amongst international law instruments, and the actual practice associated with remote sensing.

The UN Remote Sensing Principles are in the form of a UN General Assembly Resolution. It is generally perceived that a UN General Assembly Resolution is not binding as a document in itself, as it is clearly distinguished from a binding instrument such as a treaty or a convention. A binding instrument is a law made, executed, and ratified by governments. In fact, the Assembly is considered to be an advisory body with binding decisions only on issues of threats to international peace and security as adopted by its Security Council. Hence, it is understood that the UN General Assembly Resolution itself is recommendatory in nature – as a recommendation made to the member states of the United Nations in accordance with the UN Charter.

Although commonly perceived as recommendatory, different types of UN General Assembly Resolutions have varying degrees of value. Particularly, a distinction should be made between a declaration and mere principles. Kopal compares the 1963 Declaration of Legal Principles to the UN Remote Sensing Principles; he contends that only the former is called a 'declaration 'and declared principles qualify as legal. In addition, the 1963 Declaration opened a treaty-making process that lead to the conclusion of legally binding instruments such as the Outer Space Treaty. In that respect, the UN Remote Sensing Principles were not designated as a declaration, nor did they open a treaty-making process; therefore, they do not go beyond the status of a recommendation.

Even non-declaration types of General Assembly Resolutions (such as the UN Remote Sensing Principles) address the general code of conduct for all UN member states, or even for all states around the globe; hence, they possess not only political meaning but moral weight. A certain view exists that the significance and weight is increased for a General Assembly Resolution that is unanimously adopted; this means that no states found shortcomings in the resolution and did not vote against it to block its adoption. Indeed, delegates of states such as the United Kingdom and India distinguish between ordinary General Assembly Resolutions and those that are unanimously accepted, and India even contends that unanimously accepted resolutions are accepted as part of international law. Since the UN Remote Sensing Principles document is accepted unanimously, it is considered authoritative – if not universally recognized as a binding document.

Even if the UN Remote Sensing Principles document does not gain sufficient support for it to be binding in nature, its content can be considered to reflect an element of international customary law. Article 38 of the International Court of Justice (ICJ) Statute recognizes international custom as evidence of general practice accepted as law. The element of international custom requires *opinio juris* and state practice, and the UN Remote Sensing Principles satisfy both. First of all, as previously discussed, large numbers of proposals from states including Argentina, the Soviet Union, Brazil, France, Chile, Mexico, Venezuela, and Austria were taken into account in the drafting process prior to the adoption of the Resolution. It can be considered, therefore, that the Resolution is a final synthesis of different countries 'views on remote sensing from space.

The UN Remote Sensing Principles have been serving as general guidelines for activities in the field of remote sensing from outer space and no disputes have arisen thus far with regard to their application. As far as freedom of sensing is concerned, the Open Skies Policy is a clear indication of *opinio juris* between the United States and Russia since 1960, and have been accepted later by many other states.

The UN Remote Sensing Principles are incorporated into continuing state practice. Over two decades, the UN Remote Sensing Principles have been widely followed by various states and entities. With regard to the most fundamental of these Principles, namely, the principle of sensing from space without prior consent, states have sought no permission and such practice has not encountered protests from the states whose interests were affected. Non-discriminatory access to data is also realized worldwide through an extensive availability of satellite data and derived products via the Internet. These Principles are viewed as a codification of customary legal principles that are binding on nations, pursuant to years of practical implementation, as nations continue specifically to refer to the Principles in domestic, bilateral, and multilateral legal documents. The Principles are actually the only source of legislation devoted to satellite remote sensing at an international level, and other relevant legislation or principles tend also to follow them. For instance, the phrase 'non-discriminatory basis 'is used in international data exchange instruments such as the WMO Resolution, as well as in data policies of space agencies such as NASA and ESA. However, in the absence of confirmation given by the ICJ on its customary value, the binding value of UN General Assembly Resolutions has to be treated with caution.

The Scope of the UN Remote Sensing Principles: To understand the scope of the UN Remote Sensing Principles, it is necessary to look at the precise applications, activities, and types of data to which they apply. Principle I provides the various definitions and scope of the Principles, as discussed in detail below.

Unlike the Outer Space Treaty, which allows for certain military uses of outer space and is open to commercial activities, the scope of the UN Remote Sensing Principles pertains to civil remote sensing for limited applications – specifically natural resource management, land use, and protection of the environment. From this provision, it can be interpreted that military applications fall outside the scope of the Principles, thus excluding satellites used for reconnaissance or intelligence purposes. A question remains as to whether or not dual use remote sensing satellites, which serve for both civil and military purposes such as Global Monitoring for Environment and Security (GMES), are covered under these Principles. Indeed, GMES is intended to monitor the Earth's environment as well as to serve for security purposes; thus, the programme is partially covered under the Principles. Furthermore, it is difficult to construe that commercial applications other than the three purposes stated above are covered under the UN Remote Sensing Principles. A particular issue may be raised with respect to applying the Remote Sensing Principles to high resolution satellites, which are nowadays a critical source of information in various decision-making activities. These satellites have the capability to reveal very sensitive information and the application of the UN Remote Sensing Principles to remote sensing activities of such a nature would affect the concerned parties extensively.

Today there are many other applications apart from natural resource management, land use, and protection of environment in civil and commercial remote sensing – regardless of their humanitarian, commercial, or military nature – to name but a few: disaster management, registry of land, archaeology, urban planning, map making, agriculture, and the variety of verification purposes already mentioned in the Introduction. The use of data for these applications may not fall within the scope of the UN Remote Sensing Principles and issues associated with these applications are not addressed under the present regime, which needs improvement with regard to this point.

The UN Remote Sensing Principles give clear definitions with regard to the extent of remote sensing activities: 1) the operation of remote sensing space systems; 2) the operation of primary data collection and storage stations; 3) the activities in processing; 4) interpreting; and 5) disseminating the processed data. Although data handling activities and data distribution are covered under the scope of the Principles, the use, as well as the application of remote sensing information is not covered.

It is significant to point out that data handling activities and dissemination, which take place on the Earth, are within the scope of remote sensing activities defined under the UN Remote Sensing Principles. Indeed, only the first and second activities listed above take place in space; the rest are conducted on the Earth. Long before the formulation of the Remote Sensing Principles, W.P. Heere stated that Earth resources are a terrestrial matter, and thus should fall under terrestrial law and not space law; likewise, Franco Fiorio suggested that a distinction should be made between remote sensing activity itself and the use made of the resulting picture. Contrary to such opinions, the Principles do not distinguish between data collection taking place in outer space and data handling operations taking place on the Earth. The Principles apply even if states are involved in only terrestrial operations such as data processing, interpretation, value-adding activities, or just information extraction, as long as satellites are the original source. Although remote sensing takes place in outer space where there is no sovereignty, the data are collected for potential use on Earth, where state sovereignty prevails over territory and airspace. The international community needs to recognize that the situs of remote sensing activities lie on the Earth, where the information acquired is transformed into useful media. The transformation to useful knowledge, as well as use of such knowledge, is the part that should be regulated and the current legal framework needs improvement in this regard.

It is also important to examine the coverage of the UN Remote Sensing Principles with regard to activities conducted by private entities. The UN Remote Sensing Principles provide nothing more than is provided by the Outer Space Treaty. They are silent as to private entities except for Principle XIV, which makes a link between state activities and those of private entities, recalling Article VI of the Outer Space Treaty. This means that private entities are bound by the regulations imposed by the states whose jurisdiction covers such entities but neither Article VI of the Outer Space Treaty nor Principle XIV of the UN Remote Sensing Principles give details as to how non-governmental entities should be authorized and supervised. Either the particular national jurisdiction exercises control through a licensing regime, or such activities are left unregulated.

As mentioned in the Introduction, remote sensing data are classified in three types: primary data, processed data, and analysed information. In reality, there are many other terms apart from the three definitions used, such as: raw data, unenhanced data, derived product, and value-added product. The elaboration of what constitutes analyzed information is of particular importance from the standpoint of intellectual property rights, as it addresses the critical question of whether or not the information includes content that has been modified to the extent that it does not retain the original pattern and, as such, may not then be subject to protection under intellectual property laws. The coordination of these definitions with actual practice, as well as elaboration, may be necessary.

Contents of the UN Remote Sensing Principles: As has been discussed, the UN Remote Sensing Principles were the codification of the interests of the spacefaring nations in safeguarding their right to gather information from space. A number of propositions on the rights of sensed states and their obligations associated with sensing arose during the formulation process, but were not incorporated. The Remote Sensing Principles proposed a general framework with respect to data collection, data availability, and a state's responsibility for conducting remote sensing activities, all of which allowed for flexible interpretation. The resulting Principles have established new rules whilst repeating the provisions that were already in place. This section analyzes the content through key elements newly established in the UN Remote Sensing Principles, and reiteration of principles established by the Outer Space Treaty.

The newly established Principles clearly set forth the fundamental norms and rules regarding data collection but are limited to the issues of access, distribution, and use of data. The key elements the UN Remote Sensing Principles can be divided into three categories: freedom of remote sensing, respect of rights and interests of sensed states, and data rules.

Principle IV is a core provision and one of the two most critical Principles of all fifteen. Principle IV stipulates that "Remote sensing activities shall be conducted in accordance with Article I of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space" which establishes the free use of outer space. Although not explicitly stated, Principle IV establishes the right of states in sensing the entire globe from outer space using satellites. Accordingly, this provision established the data collection rule as: 1) there is no restriction on areas for observation based on geography or objects for observation including natural resources or sensing sea surface beyond national jurisdiction; 2) no prior consent, consultation, or notification is required before sensing and, therefore, no veto right is granted to sensed states for their territories being sensed; and, 3) no conditions are imposed for sensing capabilities in terms of spatial and temporal resolution, or type of sensors such as radar or optical.

All states are given the right of data collection from outer space. Later in Principle IV, the sovereign rights of sensed states are respected, in that: "These activities shall be conducted on the basis of respect for the principle of sovereignty of all States, and peoples over their own wealth and natural resources (...). Such activities shall not be conducted in a manner detrimental to the legitimate rights and interests of the sensed State." As seen earlier, the sovereignty of sensed states was the major issue of contention during the negotiation process before formulation. Yet both sentences are ambiguous and fail to clarify what the principles of sovereignty and the legitimate rights of sensed states actually entail. The obligation not to conduct remote sensing activities against the legitimate rights and interests of sensed states appears to refer only to the conduct of remote sensing itself and not to what may happen after the dissemination of data. The interest of sensed states is most commonly affected by the use and misuse of the resulting data, but the Principles impose neither specific obligations on sensing states (such as the obligation to be liable for damage suffered by sensed states for misuse of data), nor clarify the specific rights of sensed states (such as control of access and dissemination for data concerning natural resources). Those who are concerned that data gathered from outer space might be used or misused to their detriment by others – either by the sensing state or by third parties – cannot confidently rely on the provision of the UN Remote Sensing Principles.

Principle XII addresses data rules, establishing the rule regarding data access and dissemination, and thus determining the general availability of remote sensing data. Principle XII stipulates that: "As soon as the primary data and the processed data concerning the territory under its jurisdiction are produced, the sensed state shall have access to them on a *non-discriminatory basis* and on *reasonable cost terms"*. There are several important implications of this provision. It can easily be inferred from the provision that prior consent before dissemination is not required. Neither veto rights nor control on information for dissemination are granted to sensed states; hence, theoretically, sensed states can neither choose the states to which their territorial information is disclosed nor determine the type of data to disseminate, such as data of high ground resolution.

Principle XII means that sensing states have an obligation to provide the data to sensed states under the same conditions as they provide the data to other interested states. Indeed, sensed states do not have an exclusive, free, or preferential right of access to the data. No privilege is given to sensed states in terms of timing or cost to access to the data. Sensed states are not granted the right of access to the data prior to the sensing states – or any other state – which may affect their interests extensively. Likewise, no financial privilege is given to sensed states, such as data provision either free of charge or at a lower cost than for other states. The provision 'reasonable cost terms 'is ambiguous and open to different interpretations, as it is not defined under the UN Remote Sensing principles. It could mean marginal cost (which is more specifically phrased on a domestic level as the data policy set by different data generators), or it could mean commercial market price if it is considered to be 'reasonable 'for a particular image.

Non-discriminatory access within Principle XII generates an obligation to make imagery available to the sensed states; however, whether sensing states actually make the data available hinges on their good faith. There are no means to force sensing states to release data to sensed states in case the sensing state does not follow this rule. It is practically impossible for sensed states to keep track of the precise time and location of observation of their territories by all the satellites. Whether data is actually accessed by the sensed state is entirely at the discretion of the data generators and the interested state's ability to pay for the data. Therefore, this Principle can be construed as a 'passive 'obligation to disseminate data to any other states if requested.

Principle XII is based upon the presumption that a distinction is made only on the basis of sensing states and other states, and not on consideration of other factors such as the purpose for which the data is used. Principles X and XI oblige the disclosure of information for environmental protection and disaster management, but they do not stipulate the conditions for such disclosure. In reality, certain data use – such as for disaster relief – and certain types of users under governmental space programmes receive preferential treatment, including a price waiver. The practical questions of under what conditions free provision of data is allowed, and the subsequent implications arising are not addressed anywhere.

Another issue to be addressed is the availability of analysed information derived from remotely sensed data. There is a loophole in Principle XII, and the provision becomes even more complicated regarding this analysed information, specifically, "The Sensed States shall also have access to the available analysed information concerning the territory under its jurisdiction in the possession of any state participating in the remote sensing activities on the same basis and terms." Strictly speaking, this may exclude cases where the analysed information is not in possession of any state. The obligation to provide analysed information may not extend to individuals or juridical persons engaged in analysing information, such as a processing wholesaler and/or information extractor. This is again a loophole and results in a gap between the implied position and the reality of current practice. The mechanisms surrounding data availability should be phrased differently in the context of data policy.

The other principles endorsed by the UN Remote Sensing Principles fundamentally repeat the provisions established under the Outer Space Treaty. Yet, some reiterated principles are tailored to situations specifically associated with remote sensing from space and worthy of attention. This section reviews the issues of application of international law, international cooperation, and responsibility and liability.

Principles II and III fundamentally reiterate the provisions of the Outer Space Treaty, stipulating that remote sensing activities are to be conducted for the benefit and interests of all countries and in accordance with international law. Application of general international law means that remote sensing activities are carried out under the rubric of the UN Charter and the Outer Space Treaty.

Several principles refer to the issue of strengthening international cooperation, which basically repeat the norm established by the Outer Space Treaty, but adapted to remote sensing activities. Principle V and Principle XIII share the common objective to promote international cooperation through remote sensing activities. Principle V states that “States carrying out remote sensing activities shall promote international cooperation in these activities. To this end, they shall make available to other States opportunities for participation therein.” This principle is slightly further elaborated in Principle XIII, which states that “To promote and intensify international cooperation, especially with regard to the needs of developing countries, a State carrying out remote sensing of the Earth from space shall, upon request, enter into consultations with a State whose territory is sensed in order to make available opportunities for participation and enhance the mutual benefits to derived therefrom.” These Principles, however, do not impose any obligation for price waivers or mutual exchange of data.

Principles VI, VII, and VIII provide concrete guidance on how to promote international cooperation. Principle VI encourages states to conclude agreements for the establishment and operation of data collecting and storage stations and processing and interpretation facilities, and likewise, Principle VII encourages remote sensing operating states to give technical assistance to other interested states. Principle VIII invokes the role of UN agencies and the relevant agencies in promoting cooperation and technical assistance. Principle IX calls for the transparency of remote sensing activities, requiring the sensing states to report their activities to the UN Secretary General, and encourages the dissemination of information to those states affected by the activity; however, nothing substantial is added to the rights of sensed communities.

Principles X and XI affirm that states must warn of danger in cases of harm to the environment or impending disasters by rapidly and freely disclosing the relevant information. These two concepts had been supported from the initial phase of negotiation on the formulations of the UN Remote Sensing Principles; indeed, remote sensing has been used extensively for assessing damage resulting from natural disasters. For example, when flooding occurred around the city of Saint Louis, Missouri, in the United States, the ERS-1 satellite assessed the extent of the flooded area and its effect on cultivation. The Disaster Charter, originally started as an agreement between CNES and ESA, is a now viable example of extensive international cooperation making satellite data and derived information available for any state affected by disaster.

Finally, Principle XIV of the UN Remote Sensing Principles that deals with international responsibility also needs to be examined. Principle XIV makes reference to Article VI of the Outer Space Treaty and stipulates that: “States operating remote sensing bear international responsibility for their activities.” It is possible to argue that the state is internationally responsible for remote sensing activities, including the dissemination of data, but not for what happens afterwards as a result of any activity by the state or a third party. Furthermore, a loophole exists in Principle XIV where it states that: “*States operating remote sensing satellites* (emphasis added) bear international responsibility for their activities (...) whether such activities are carried out by governmental or non-governmental entities. Although government entities are not the only entities carrying out remote sensing activities, the language in Principle XIV raises questions as to its coverage for all potential parties who may be held responsible. Therefore, the provision may be construed literally – that responsibility is imposed only on states operating remote sensing satellites.

Strictly speaking, the UN Remote Sensing Principles do not impose responsibilities on either those states or entities that are not operating satellites but who are actually receiving images and/or engaged in data handling activities as well as distribution, or on the third parties who use the data. In fact, there are many states and entities that do not operate satellites, but rather house value-added resellers where the users should also be held responsible for the misuse of data. This can be seen as a significant loophole and the gap needs to be filled.

Overall, the UN Remote Sensing Principles succeed in codifying basic norms to govern sensing from space and derived operations. They clarify the conditions for sensing as well as data dissemination, and establish the general responsibilities expected of sensing states. The rights and obligations provided by the Remote Sensing Principles are: 1) the right of any state to sense anywhere on the earth from space without prior consent; 2) the obligation of sensing states to provide data to sensed states on a non-discriminatory basis; 3) the right of sensed states to access data on a non-discriminatory basis; 4) the obligation not to infringe the right of sensed states in sensing; and 5) the obligation to bear international responsibility in conducting remote sensing.

On the other hand, the UN Remote Sensing Principles are ambiguous and inadequate because they do not address some critical issues. There are gaps, shortcomings, and loopholes, which result in the Principles not being entirely effective.

There are major shortcomings in that the rights and obligation of concerned parties in remote sensing are not properly addressed in the UN Remote Sensing Principles. They are ambiguous with regard to responsibility and the liability associated with remote sensing data and its use in terms of consequential dam- age. Another shortcoming is that issues with respect to data availability and accessibility are not sufficiently addressed. Principle XII is the only provision related to the practical issues of data availability and pricing policy, but it does not serve as a concrete guideline for the variety of policies on satellite remote sensing data that exist today. With regard to data accuracy and data validation, the Principles are completely silent. The present legal framework is inadequate in terms of data policy, criteria for data accuracy, and guidelines for data authentication – all of which affect widespread use of data for applications such as disaster management and protection of the environment.

It should be reemphasized that the content of the UN Remote Sensing Principles centres on the rights and obligation of sensing states and the interests of sensed states, which highlight a gap and discrepancy with reality. The Principles reflect the politics and technologies of the 1980s, rather than the present day; they were sensible back then, since the most important issue at that time was to reconcile the interests of sensed states and sensing states. Only a few sensing states existed, and the rest of the world was composed of sensed states. Over the two decades since the Principles were adopted, increasing numbers of nations that were once standing on the ‘sensed ’side, now possess their own remote sensing capabilities in orbit. Consequently, the debate has shifted more to considering the rights and obligations of data providers, data recipients, and third parties. The debate that is now of importance focuses on issues related to data policy, data accuracy, and authentication as well as the responsibility associated with the provision and use of data. The question is whether these issues that are not sufficiently regulated internationally are covered in the national context. In order to make the analysis complete, it is necessary to look at the national measures related to space activities and remote sensing.

Revisit of Legal Principles Surrounding Satellite Remote Sensing in Disaster Management: The use of remote sensing for mitigating the impact from disasters is supported by the UN Remote Sensing Principles. A review of the provisions of the UN Remote Sensing Principles is necessary for further examination of the rights and obligations associated with disaster management. There is only one principle addressing natural disasters. Principle XI encourages the supply of disaster related information to affected or potentially afflicted states: "Remote sensing shall promote the protection of mankind from natural disasters. To this end, States participating in remote sensing activities that have identified processed data and analysed information in their possession that may be useful to States affected by natural disasters, or likely to be affected by impending natural disasters, shall transmit such data and information to States concerned as promptly as possible." This provision stands on the presumption that imaging of states takes place without prior consent.

The major reason remote sensing can contribute to disaster management is that it enables disaster response unaffected by political impediment, at least in terms of information gathering. Since remote sensing permits data collection of afflicted states without their consent, case-by-case response from outside is improved. Foreign states and external entities that wish to render assistance do not have to wait for the approval of the afflicted state to sense and, even in case of refusal of such offer, the stricken country can still be sensed from space without intrusion. On the other hand, even in case of a deadly disaster, sovereignty concerns by affected countries are still of great importance. Following the 2004 Indian Ocean Tsunami, India was sensed only by its own satellite IRS series.

Critical information can be obtained externally about the extent of disasters as well as identification of priorities of affected areas, regardless of the capacity of the afflicted state. On the basis of such information, useful knowledge can be provided, and international bodies and NGOs can send in relief teams more effectively and efficiently. Constant updates of data collection covering all of the damaged areas through effective coordination minimizes the overlapping services and reduces the level of disparities in served areas.

Legal Analysis of a Successful Model Based on the Disaster Charter: As discussed in earlier chapter, the Disaster Charter is a successful model for the effective coordination of disaster relief based on supply of satellite images. At this point, the stance of operations will be analyzed from the legal standpoint including the legal nature, and the implications for the responsibility and liability associated with the provision of aid.

The Disaster Charter is a non-binding legal instrument based on goodwill and best endeavours; the cooperation is voluntary. Throughout the provisions of the text, the voluntary nature is confirmed by the language: "shall use best endeavours." For instance, Article 4.5 states: "The parties shall use their best endeavours, in accordance with the identified crisis scenarios, to supply associated bodies and, where appropriate, beneficiary bodies with data, and if necessary associated information and services, gathered by the space facilities." No liability is involved in its whole course of operations; indeed, any liability is clearly waived under the Charter. Article 5.4 of the Disaster Charter clearly states that: "The parties shall ensure that associated bodies which, at the request of the country or countries affected by disaster, call on assistance of parties undertakes to confirm that no legal action will be taken against the parties in the event of bodily injury, damage or financial loss arising from the execution or non-execution of activities, services, or supplies arising out of the Charter." In short, the services are not guaranteed: members will not be held liable either in the case in which the Charter was not activated for a particular disaster, nor where actual provisions of images did not lead to successful rescue operations. The intention of those who drafted the Disaster Charter was clearly that they do not wish to be held responsible for their favours; however, it is questionable whether the free provision of service is sufficient to waive any potential liability. The waiver of liability is not agreed upon by all potential afflicted states or concerned parties, such as families of aid workers. It is uncertain whether a unilateral waiver of liability is enforceable, and this situation emphasizes the need for clarification of liability.

The Need for an Improved Regime: There is an urgent need for a clear legal regime governing disaster relief to enhance effectiveness, as well as an unambiguous liability regime associated with the supply of satellite data. A better coordination with the division of responsibility will improve effectiveness. Furthermore, the liability associated with disasters (such as liability of volunteers) needs clarification.

How a Better Coordination with Division of Responsibilities will Enhance Effectiveness: The earlier section demonstrated that, in most disasters, the competence to provide assistance to the victims is shared amongst a number of actors; however, such operations are often uncoordinated. For instance, following the flash floods and landslide that hit Venezuela in December 1999, the issue of division of responsibilities and decision-making between central and decentralized powers became a source of conflict. The coordination and division of responsibilities is also a key issue in provision of disaster relief using satellite remote sensing as various actors are involved before the delivery of final products. A better coordination is critical to minimize possible conflicts that may arise amongst diverse actors and enhance the effectiveness of operations.

Disaster response in the past has occasionally involved inappropriate assistance and/or unwanted side effects. For instance, following the Indian Ocean Tsunami, an unknown NGO had vaccinated some of the children without leaving any vaccination records, thus generating confusion as to who had and had not been served. Obviously, there is the need for establishing clear mandates and responsibilities for each organization and/or specific tasks to enhance effectiveness and avoid serious mistakes.

The Disaster Charter demonstrates a well-coordinated disaster response that includes a predictable mechanism with the division of responsibility and effective direction of aid based on the provision of disaster information. Since a project manager appointed for each case is responsible for directing specific satellite operators to provide data to the appropriate Charter partner for imaging a particular location, data collection is effectively arranged, overlaps are minimized, and response time is improved.

Minimizing errors is crucial to achieve effective operations. A clear mandate and division of responsibilities of the authorized users and Charter partners would contribute to error reduction; however, minimizing errors involves cost. Providing assistance is already costly and covering the cost of accidents can place a severe burden on donors, who already bear the costs for liability risks. The aid provided is often not sufficient both in terms of quantity and quality, particularly following deadly large scale and prolonged disasters, where the need usually exceeds the offers of assistance.

The provision of aid should be something appreciated and praised; however, it is also true that the victims sometimes do not look at the efforts made or the surrounding circumstances; rather they can only see the loss they or their family have actually incurred.

Issues of Clarification of Liability: Analysis of Lawsuits following Disasters against Volunteers: Lawsuits have been brought on unreasonable grounds following disasters. Volunteers who have rendered assistance in good faith are not exceptions, and they, too, have become the target of lawsuits. For instance, Mark Morice, a local New Orleans lawyer who used boats to rescue reportedly more than 200 Hurricane Katrina victims, was sued by the boat owner although the lawsuit was not pursued.

A large scale lawsuit that arose in relation to the Indian Ocean Tsunami is striking and worth examining in detail. A group of Austrian and German victims have since brought action against the NOAA Pacific Early Warning Centre, together with the Thai government and the French hotel chain Accor for not responding properly to the disaster. The case is notable, as this type of lawsuit is the first of its kind. The NOAA Pacific Center is accused of having registered the earthquake but failing to alert Indian Ocean countries of the impending tsunami. NOAA is a member of the Disaster Charter. Although the lawsuit is irrelevant to the operations of the Disaster Charter, it raises an important question as to risks of exposure to liability and the uncertain outcome of claims. Another question is whether the Good Samaritan doctrine applies in this case.

The Pacific Tsunami Warning Center of NOAA had no obligations to warn, since it was covering only the Pacific Region, but it attempted to contact the affected countries in vain, so it can be considered that the Center was a 'Good Samaritan'. In contrast, the Charter partners may *not* be considered as Good Samaritans, particularly taking into account the fact that the relationship of dependence does not necessarily require the existence of a contract or a personal relationship between the rescuer and rescued – insofar as the one aided counts on the aid by the rescuer. The primary reasons for the status of the Charter partners in this scenario are:

- The initiators of the Disaster Charter actually set up the mechanism deliberately in advance to help the potential crisis victims, and followers appreciate this philosophy;
- The Disaster Charter service takes place after the request from the afflicted states;
- Under the Disaster Charter, there is no contract; but the degree of dependency by the crisis victims is high;
- A certain degree of duty of care is assumed; and
- Waiver of liability is unilateral; since there is no agreement between the afflicted states and partners or potential claimant(s), a waiver may not be enforceable.

Compared to NOAA's case in the Indian Ocean Tsunami, the Disaster Charter service appears to have a greater exposure to liability. In fact, as with any operation, assistance cannot be 100% successful. With respect to the Disaster Charter, services provided were not completely successful due to late response, unavailability of data, and the limited usefulness of the products that were supplied. According to the 6th Annual Report of the Disaster Charter, following the Suriname flood of early May 2006, it was found that the delivered products were of limited use because they focused on the initial area of interest and did not cover the main flood areas that were later discovered. The Report shows that end users of the Disaster Charter were by and large appreciative of and benefited from the information provided, even if it was not completely useful. It is not possible to completely eradicate the risk that inaccuracies will lead to inappropriate decisions or actions that may result in unexpected loss. It is less likely that beneficiaries would bring actions against Disaster Charter partners for their aid that turn out to be unsuccessful; however, Disaster Charter partners may be at risk, for example, with regard to claims brought by families of aid workers against Charter partners for providing inaccurate images leading to loss of the aid workers 'lives. In case of deadly disasters, the possibility of aid workers becoming victims is high. Rescue operations can be dangerous and aid workers are vulnerable to numerous risks, including endemic diseases. In fact, infectious diseases accounted for over 75% of the emergency evacuations of humanitarian workers. If the families of victims sue data suppliers for inaccurate data that indirectly led to their deaths, the outcome of possible lawsuits is not easily predicted under the current uncertain legal regime.

In the Indian Ocean Tsunami lawsuit case, since it was brought in the US court, the application of the Good Samaritan doctrine is foreseeable. Since the Good Samaritan Principle is well recognized, the US Congress has considered a Samaritan act specifically addressing natural disasters. A bill entitled "The Good Samaritan Liability Improvement and Volunteer Encouragement Act of 2005" has been introduced to grant certain immunities from liability to both national and international disaster relief volunteers, as well as to governmental and intergovernmental organizations. Many countries lack comprehensive Good Samaritan laws and, consequently, foreign relief personnel and organizations are exposed to liability risks arising as a result of unsuccessful aid. Considering the international nature of disaster management, particularly assistance based on satellite remote sensing, clarification and universal applicability of the Good Samaritan Principle is essential.

States or organizations would become more confident about providing or receiving aid if they know precisely the scope of their responsibility and that they will not be held liable, even if assistance is unsuccessful. Indeed, concern about vicarious liability was one of the factors contributing to the decision by FEMA and other United States agencies to refuse any international offers of certain types of aid, including blood products, medical kits, and most search and rescue personnel arriving to assist the people affected by Hurricane Katrina. The fear of being sued in association with providing aid has also generated reluctance to accept aid.

Reluctance to accept aid may arise with respect to assistance based on satellite remote sensing as well. The close examination of the Good Samaritan Principle in association with the Indian Ocean Tsunami lawsuit case and the Disaster Charter has reaffirmed the need for establishing a clear liability regime applicable to the operation of systems and data provision. Establishing a more comprehensive legal regime that clarifies responsibility and liability would mitigate unwillingness and hesitation, and facilitate data supply as both donors and beneficiaries would then be able to accept or provide data without concern for the outcome of the assistance.

National Laws and Policies: As noted earlier, the *corpus juris spatialis* provides the general framework for member states to regulate national space activities through more specific rules. National laws are the concrete implementation of Article VI of the Outer Space Treaty, which requires the authorization and continuing supervision by the appropriate state party of the national activities conducted by its non-governmental entities. The provision, in reality, requires national licensing and regulatory legislation; in fact, domestic legislation devoted to space activities has been endorsed in several nations.

National Legislation on Space Activities: Currently, states that possess national space legislation relating to space activities include: the United States[26], Sweden[27], the United Kingdom[28], Russia[29], South Africa[30], Ukraine[31], Hong Kong[32], Australia[33], Belgium[34], Korea[35], the Netherlands[36], Japan[37], and France[38]. The fundamental role of national legislation is to provide a regulatory means for a government to authorize actors under its jurisdiction to engage in space activities and to exercise control over them. By and large, rules established by national legislation comprise the concrete obligations under Articles IV, VII, and VIII of the Outer Space Treaty – namely, measures for authorization, continuing supervision, sanctions, responsibility, and liability, as well as for exercising jurisdiction and control through the registration of space objects. It is common that authorization is given through a permit or license to conduct space activities, particularly regarding launch operations; the government supervises continuously to ensure that licensed entities are in compliance with the requirements established under such licenses. This section examines the scope of government authorization for, and continuing supervision of, space activities carried out by domestic actors.

Scope: The scope of space activities covered under domestic laws of different countries varies by legislation, but primarily extends to one or a combination of the following: 1)

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26 National Aeronautics and Space Act, Public Law 85–568, 85th Congress, H.R. 12575, 29 July 1958, Commercial Space Launch Act, Public Law 98–575, 98th Congress, H.R. 3942, 30 October 1984, Land Remote Sensing Commercialization Act, Public Law 98–365, 98th Congress, H.R. 5155, 17 July 1984, Land Remote Sensing Policy Act 1992, Public Law 102–555, 102nd Congress, H.R. 6133, 28 October 1992.

27 Act on Space Activities 1982: 963, 18 November 1982. [Hereafter: Swedish Space Act].

28 Outer Space Act, July 18, 1986, 1986 Chapter 38. [Hereafter: UK Outer Space Act]

29 Law of Russian Federation on Space Activity, August 20, 1993, Presidential Edict No. 185. [Hereafter: Russian Space Act]

30 Space Affairs Act, September 6, 1993. [Hereafter: South African Space Act]

31 Ordinance of the Supreme Soviet of Ukraine on Space Activity Law of Ukraine, 15 November 1996. [Hereafter: Ukrainian Space Act]

32 Outer Space Ordinance of 1997, 13 June 1997.

33 Space Activities Act, December 21, 1998, No. 123. [Hereafter: Australian Space Act]

34 The Law of 17 September 2005 (Belgian Official Journal of 16 November 2005) on the Activities of Launching, Flight Operation or Guidance of Space Objects.

35 Space Exploration Promotion Act, 1 December, 2005. [Hereafter: Korean Space Exploration Promotion Act]

36 Rules Concerning Space Activities and the Establishment of a Registry of Space Objects, 13 June 2006. [Dutch Space Activities Act]

37 Basic Law for Space Activities adopted 13 May 2008.

38 French Law on Space Operations, Act no. 2008–518 du 3 juin 2008 [Hereafter: French Space Operations Act]

launching of a space object and/or operation of a launch facility; 2) operation of a space object in orbit; and 3) conducting any other activities in outer space. Domestic law is less likely to apply to simply manufacturing a satellite or receiving signal from a satellite at the ground station.

Generally speaking, national space legislation applies to space activities carried out by nationals, and those space activities that take place from its territory – including activities conducted by foreign nationals. A noteworthy example that is distinctive from others is the United States. In contrast to other states, the United States requires licenses from foreign persons even if they conduct space activities from outside US territory or areas outside its jurisdiction if the controlling interest is held by either US nationals or entities incorporated under US law. In addition, foreign nationals need to obtain a license in cases where there is an agreement between the United States and a foreign state stating that the United States exercises its jurisdiction over a specific activity such as launching operation. In this way, the US Commercial Space Launch Act illustrates how the terms 'national activities 'and 'appropriate state party 'can be broadly interpreted in the national context.

Authorization: Authorization is required for entities wishing to carry out space activities if required under domestic law of the state whose jurisdiction covers the activities of the entities in question. Although not always stated explicitly, in accord with the 'appropriate state party 'language of the Outer Space Treaty, authorization appears to be required from a single jurisdiction even if an activity may fall under multiple jurisdictions. For instance, the UK Outer Space Act states that a license is not required "for activities in respect of which it is certified by Order in Council that arrangements have been made between the United Kingdom and another country to secure compliance with the international obligations of the United Kingdom."261 In Australia, with regards to overseas launches, space legislation states that overseas launch requires an overseas launch certificate if "a space object is launched from a launch facility located outside Australia and the launch is not authorized by an overseas launch certificate held by any person; and an Australian national is a responsible party for the launch."

Whilst there are several elements required for authorization, this section focuses primarily on the discussion of liability and financial aspects, specifically a regime of reimbursement, a regime surrounding third party loss, and a regime surrounding inter-party liability.

Given the high risk of space activities, financial capability of a licensee – particularly in terms of preparedness for liability – is one of the essential elements needed for government authorization. Since the responsibility for national space activities falls upon states, states seek certain security in the event of accident or negligent failures. Accordingly, a state has an imperative to properly arrange the measures for reimbursement between the state and entities that are subject to its jurisdiction and control. Most of the time, domestic legislation – as endorsed by the United Kingdom, the Netherlands, Sweden, and France– requires indemnification for the loss caused by the licensee to the government when the respective state is held internationally liable under the scope of the Liability Convention. More often than not, failure occurs during a launching phase, so an agreement between a government and a launch operator is not uncommon. For instance, with regard to a launch by an Ariane rocket, it is agreed that Arianespace would be required to reimburse the French government up to a maximum of € 60 million. This was the practice for years in Ariane operations and the approach seen in the agreement was codified into the French Space Operations Act, which states that in case the government paid compensation for damage, it may then present a claim for indemnification against the operator that caused the damage for which France was held internationally liable – to the extent that the government has not already benefited from the insurance or financial guarantees of the operator up to the amount of the compensation. As commercial launch services emerge and grow in an increasing number of states, such an arrangement or domestic law referring to the rule is deemed essential and likely to proliferate in the future.

As a reasonable measure to prepare for risks, some states such as Australia, Russia, Ukraine, Korea, and the Netherlands make a compulsory insurance regime part of their licensing requirements. Most compulsory insurance is coverage for a third party loss; thereby, a state secures de facto a measure of protection in case of failures. The United States has a detailed liability regime applicable to launch operations. The Commercial Space Launch Act requires the licensees either to purchase insurance or demonstrate financial capability so as to cover the potential third party loss. The maximum amount of obligation a licensee owes for the third party loss is US$ 500 million, and US$ 100 million with respect to the loss of or damage incurred to government property.

On the other hand, the government would pay up to US$ 1.5 billion for damages that exceed US$ 500 million insofar as the damage was not due to wilful misconduct of the licensee. The French Space Operations Act takes a similar approach by obliging licensees to obtain insurance or another financial guarantee whilst placing a ceiling on the maximum amount that operators need to pay for third party loss during the launch phase. Claims by the government to operators for indemnification are limited to that amount: operators can benefit from the state guarantee if the amount exceeds € 60 million. This state guarantee - that is, reimbursement of indemnifications by the government if liability exceeds € 60 million – is also available in the cases where operators are sued in any court.

Inter-party liability is less addressed within a legislative context; rather, it is tailored to each contractual agreement. Some legislation, however, does address and refer specifically to this matter, such as the US Commercial Space Launch Act and the French Space Operations Act. The Commercial Space Launch Act contains a reciprocal waiver of liability regime that applies to all the parties involved in a launch, including the government, any of its agencies, licensee, contractors, subcontractor, customers, and their contractors and subcontractors. Likewise, the French regime holds inter-party waiver of liability in case of damage to a person taking part in the space operation or the production of space object(s) except in the case of wilful misconduct.

Even if it is not established in legislation, the stance taken by the parties engaged in launch activities is to waive liability amongst them. For instance, ESA agrees to waive all claims for compensation against France as far as these claims result from launch operations at the Centre Spatial Gyuanais. This minimizes the risk of inter-party claims. The practical tendency in the exercise of inter-party waiver of liability logically follows the rule of the Liability Convention, which does not offer protection for damage incurred to persons participating in the launch.

For the most part, the government's intention is to minimize the potential cost incurred in the instances of its international liability resulting from irresponsible operations of national actors, as well as in the instances of loss incurred amongst the concerned parties. These measures help the concerned parties to quantify properly the involved risk.

Continuing Supervision: Continuing supervision is more complex and difficult to exercise. The term infers the obligation to 'keep an eye 'on the authorized person after the initial authorization. Continuing supervision can well be associated with the monitor- ing and control of the licensed entity and launched space object that are subject to the jurisdiction of a particular state. This part reviews the measures for monitoring compliance with licensing conditions, sanction, and control of a space object, as related to registration.

Overall, national legislation attempts to control licensees through monitor- ing their compliance for license requirements and, in case of non-compliance, suspend or revoke the license. In South Africa, the United Kingdom, and Sweden, licenses may be withheld if the licensing requirement is breached. Conditions for suspension differ in each state, but they all perform a function of continuous supervision and regulation of the licensed activity. In the case of South Korea, the license is withheld if the launch does not take place within one year from the scheduled launch date. as launch delays are frequent. This may be a stringent condition, Continuing supervision of national space activities and control of a space object can also be enforced through punitive measures. Some states specifically provide measures for sanctions in case of breach of the provisions of the legislation. The type of sanction imposed is usually fine or imprisonment, or both.

For instance, the Swedish Space Act establishes that persons conducting space activities without a license, whether wilfully or through negligence, are fined or sentenced to imprisonment for up to one year. The US Commercial Space Launch Act holds any person convicted of committing a prohibited act liable for civil penalties of not more than US$ 100,000 per day for each violation. A fine imposed in such a manner generates great incentives to offenders to cease the prohibited act immediately. Sanctions serve as a powerful incentive for actors to refrain from engaging in space activities without authorization from the appropriate jurisdiction, as well as for licensees not to breach licensing provisions.

Continuing supervision can be exercised through control over a space object based on the registration of that space object established by Article VIII of the Outer Space Treaty. Several nations including Ukraine, Russia, Australia, the Netherlands, and Korea require the registration of space objects and have established a national registry in accordance with the Registration Convention. Pursuant to the Registration Convention that obliges state parties to register domestically, national space legislation establishes a mechanism of state registry with more specific rules as to how the domestic registration of a space object takes place. There are two major rules with regard to registration established under the Registration Convention: control of a satellite to be exercised effectively by a state of registry – that is, usually the launching state – and prohibition of double registration; both are incorporated into national space legislation.

In reality, with the increasing lifespan of satellites, conceptual separation between the launching and operational phase of a satellite is feasible; the gap is growing between the law and practice. The situation is even more complicated recently with the cases of lease or transfer of ownership in orbit, including sale of a spacecraft after it is placed in orbit. Such complexities could give rise to at least five different possibilities for the status of a satellite in terms of its link with a launching state, state of registry, and controlling state, as shown in the table below:

Table:1: Possible Status of Satellites with Different Types of Configurations

Launching State	State of Registry	Controlling State
A	A	A
A	A	B
A	B	B
A	B	A
A	B	C

*A signifies as state A, B signifies as state B and C signifies as state C.

The first case A-A-A is the orthodox situation that is assumed under the Registration Convention – A single launching state registers and controls the launched space object. The second case, A-A-B, would be best explained by a situation of a lease of a satellite. State A launched, and registered the launched space object, but later leased it to state B; therefore, state B controls the space object, even though state A still owns it. The A-B-B case could be illustrated by the situation that would involve certain transfer of ownership after the launch. The foremost example is the sale/purchase of a satellite in orbit. State A launched the space object and later transferred its ownership to state B, which re-registers and controls the object. For the A-B-A case, one can envisage a scenario as follows: State B, a developing state, bought a satellite in orbit from state A, a developed state. Later, from a technical reason, state B becomes no longer able to control the space object; state A agrees to resume the operation for the benefit of state B. The last A-B-C case could be explained by the combination of a transfer of ownership of a satellite from state A to state B, who then leases it to state C.

The above described situations are not at all hypothetical. In reality, there have been cases where an original state of registry does not exercise jurisdiction and control over a space object later in the operational phase due to its change of ownership. Such examples concern four communication satellites returned from the United Kingdom to China in accordance with the return of Hong Kong. Following the return of Hong Kong on 1 July 1997, the United Kingdom informed the United Nations on 27 March 1998 that it was no longer the state of registry and then requested an amendment to the UN registry as well as removal of those satellites from its national registry. Even though a launching state is no longer linked with a state of registry, this case is relatively simple because jurisdiction and control is transferred along with the change of ownership so that only one state of registry exists for those satellites in orbit. This case illustrates the A-B-B scenario in the table above.

A more complex situation exists when jurisdiction and control may be exercised by more than one state. An example of such a case concerns a broadcasting satellite BSB-1A. BSB-1A was originally registered by the United Kingdom in 1990, but purchased in orbit by Sweden in 1996. n contrast to the case discussed above, although Sweden registered BSB-1A nationally as Sirius-1 in 1999 and notified the United Nations with specific mention of the United States as the launching State, the United Kingdom did not remove BSB-1A from its registry. Therefore, BSB-1A is ‘doubly ’registered, and this creates a situation that is not envisaged by the Registration Convention: the launching state is the United States; the state of registry is both the United Kingdom and Sweden; and the controlling state is Sweden. This situation is a slightly complicated version of the A-B-C case; that is, the state of registry is really two states, B/C rather than just state B. The cases like BSB-1A diminish the effectiveness of the control regime established by the Registration Convention.

Not only was the BSB-1A type of situation not addressed under the Registration Convention, there is no national legislation at present that adequately fills the existing gap – particularly with regard to either leasing or the transfer of ownership of a space object and the subsequent impact on the juris- diction and control over the space object. The ongoing and future practice of lease, sale, and transfer of ownership of a satellite may require adaptation of the rule in accordance with the practice at a domestic level.

Overall, there is no national legislation addressing how the responsibility associated with a space object are divided between the concerned parties when the state of registry and the state that actually controls the space object are different. Such cases may be increasingly common in the future, and there is a need for further clarification.

Finally, national legislation is inadequate to address how control by the state of registry over its space object should take place. The obligation to exercise jurisdiction and control by the state of registry is particularly relevant to remote sensing since information acquired by the satellite affects the interests of both the state and the international community. Increasingly, states with remote sensing capabilities are adopting laws and/or policies to control the data collection and subsequent dissemination. The next section reviews those regulations relevant to remote sensing and analyses the overall tendencies and implications for remote sensing activities.

National Regulations Associated with Remote Sensing: National regulations addressing space activities in general are written to implement concrete measures for continuous supervision of the actors under a government's jurisdiction. A similar role is performed by national regulations on satellite remote sensing. There are two main purposes for governmental control of remote sensing activities imposed on commercial remote sensing satellite systems: 1) to protect national security by denying or restricting access to information; and 2) to guarantee that the government has priority access to the system's capabilities during times of crisis. The measures taken to achieve these goals can be divided into restrictions on data collection and/or data dissemination. This section first examines those states that have legislation specialising in remote sensing, and then reviews other states that have adopted certain policies with regard to data collection and dissemination.

Although some provisions of national space legislation addressing launching and general space activities have some implications on satellite remote sensing operations, generally speaking, existing domestic legislation on space activities does not address properly the rules applicable to remote sensing. Corresponding to the emergence of private actors and commercial remote sensing satellites, the United States, Canada, Germany, and France have established specific regulations/legislation devoted to remote sensing from space. It is notable that amongst these, the legislation of Canada and Germany addresses solely the matters regarding satellite remote sensing, whilst neither country possesses domestic legislation addressing overall space operations. The existing legislation on remote sensing authorizes and controls the actors.

The United States: As stated earlier, the United States has enacted several pieces of space legislation, one of which is dedicated to remote sensing activities. The legislation on remote sensing has evolved in accordance with the trends surrounding remote sensing from space, particularly reflecting advances in technology and market development as well as changing policies. Compared to legislation from other countries, US legislation addresses practical matters such as data policies as well as measures of protection to maintain the competitiveness of domestic actors.

Looking at the historical evolution of US laws and policies associated with remote sensing, the major rationale for making both law and policy reflects the government's striving to maintain the leadership in this field whilst safeguarding national security and foreign policy interests. Starting its operation in 1972 under the auspices of NASA, by the late 1970s the United States started to consider privatizing the Landsat system. That attempt was codified into the Land Remote Sensing Commercialisation Act of 1984. This Act was adopted to commercialise the Landsat programme by transferring remote sensing operations to the private sector.

The Earth Observation Satellite Corporation (EOSAT), a partnership of Hughes Aircraft and Radio Corporation of America (RCA), was selected as the executor of the project to commercialize Landsat under a ten year contract. The original plan was to delegate a private sector operation of the Landsat system that would become commercially viable through data sales and then to develop the successive Landsat series on a private-sector-driven basis. Commercialisation did not progress as planned because of the sharp increase in data price which resulted in a sharp drop in data needs. Coupled with the 1986 emergence of the powerful competitor, SPOT, which benefited from funding by the French government – and the significant market share attained by SPOT soon afterwards – the United States relinquished the attempt at commercialization.

Having experienced the unsuccessful attempt to privatize Landsat, at least in the short term, the US government was compelled to return to the regime to support the Landsat system. The Land Remote Sensing Commercialisation Act of 1984 was then supplanted by the Land Remote Sending Policy Act in 1992. The 1992 Land Remote Sensing Policy Act gave the operation of Landsat back to the public sector under the Department of Defense (DOD) and NASA, whilst leaving the licensing authority under the Secretary of Commerce through NOAA.

In the longer term, United States had not renounced its plan for commercialization. The strategy was to let the public recognize the value of the Landsat data. In the Land Remote Sensing Policy Act, availability and affordability of Landsat data was set up to diffuse its utility. Cost hurdles based on the market price were lifted and a standard for pricing of unenhanced data was established. The Act states that "to maximize the value of the Landsat program to the American Public, unenhanced Landsat 4 through 6 data should be made available at a minimum to US agencies, to global environmental change researchers, and to other researchers who are financially supported by the US government at cost of fulfilling user requests, and unenhanced Landsat 7 data should be made available to all users at the cost of fulfilling user requests." Furthermore, US government and affiliated users could access the unenhanced data at a reduced rate.

In an attempt to stimulate the development of the commercial market, exclusive rights for Landsat data sale were no longer granted to a single entity. Under the Land Remote Sensing Policy Act, a data policy for Landsat 7 was set to allow competition within the private sector for distribution of unenhanced data and value added services. This provision assumes the possibility of competition amongst different licensed entities that provide unenhanced data and, particularly, value added services at a non-uniform price. The Act emphasizes that the license application should not be rejected on the basis of protection of existing thus permitting data collection and sale of licensees from competition, Landsat data worldwide.

The Land Remote Sensing Policy Act addresses the issue of licensing for the operation of private remote sensing systems. The Act anticipated that commercial players would operate remote sensing systems other than the Landsat and undertake subsequent data dissemination. The Act required persons under US jurisdiction and control to obtain a license to operate private remote sensing systems. Conditions of operation were imposed on licensees carrying out the operation in a manner to preserve US national security, to make unenhanced data available to the government of any country, and to inform the Secretary of Commerce on both the characteristics of the system and any intentions of conclusing agreements with foreign states. The Act contains an enforcement mechanism similar to that in the aforementioned Commercial Space Launch Act, but the penalty is much lower – US$10,000 per day per violation.

The 1992 Land Remote Sensing Policy Act remains as the principal legislation governing US remote sensing activities today and serves as an overall framework, updated, complemented, or implemented concretely by relevant policies and regulations, namely: Presidential Decision Directive 23 (PDD-23); the US Policy on Foreign Access to Remote Sensing Capability;303 the Kyl- Bingaman Amendment to the 1997 National Defense Authorization Act; the 2003 Commercial Remote Sensing Policy; and the 2006 Regulation on Licensing of Private Land Remote Sensing Space Systems. The following chronological progression of law and policy developments serves to capture the essential transitions in the field of remote sensing in the United States.

In 1994 PDD-23 was announced, recognizing the emergence of non-US remote sensing capability and the need to ensure continued US industrial competitiveness in the global arena. The objective of PDD-23 is roughly three- fold: 1) to relax restrictions placed on data sale; 2) to clarify the operational regime of Landsat; and 3) to specify national security measures as a licensing requirement. As to the first objective, PDD-23 addressed the question of which agency develops and operates the Landsat system and markets the resulting data by establishing an operational regime for Landsat that delegates different operations to three agencies: the operation of satellites is conducted by NOAA; archiving and distribution is conducted by the US Geological Survey under the Department of the Interior; and the development of satellites is conducted by NASA.

As to the second objective, in order to allow the national actors to compete internationally, PDD-23 – for the first time – allowed US entities to sell satellite images up to one metre ground resolution. PDD-23 relaxed the restrictions, encouraged the sale of high resolution data services from US providers, and even permitted the export of turnkey systems and sensitive components on a case-by-case basis, subject to export controls and requirements for government-to-government agreements.

As to the last objective, a concrete measure was taken toward ensuring US national security and foreign policy interests. An explicit provision to justify the interruption of operation, which is known as ‘shutter control’, was introduced: “[W]hen national security or international obligations and/or foreign policy may be compromised as defined by the Secretary of Defense or the Secretary of State, respectively, the Secretary of Commerce may after consultation with the appropriate agencies, require the licensee to limit data collection and or distribution by the system to the extent necessitated by the given situation.” This provision remains today to be invoked and enforced if necessary.

An earlier provision of the Land Remote Sensing Policy Act on a licensee’s obligation to preserve US national security and foreign policy interests was implemented concretely with the Kyl-Bingaman Amendment to the 1997 National Defense Authorization Act. The amendment prohibits licensees from disseminating imagery of Israel that is more detailed or precise than what is available from foreign commercial sources. This section on prohibition of collection and release of detailed satellite imagery relating to Israel states that "A department or agency of the United States may issue a license for the collection or dissemination by a non-Federal entity of satellite imagery with respect to Israel only if such imagery is no more detailed or precise than satellite imagery of Israel that is available from commercial sources."

At present, limitation of spatial resolution is implemented through a two-tiered policy. Electro-optical imagery of 0.5 meters can be marketed generally, whereas imagery higher than 0.25 meters can only be disseminated with specific authorization to recipients individually authorized by the US government. For the latter case, before such authorization is granted to a US firm, the State Department must first obtain assurances from the foreign government that the imagery will not be disseminated further without authorization. It is worth noting the policy for implementation of de facto shutter control. This policy is known as 'buy to deny 'because all the data for specific locations was bought up by the government to hamper the access to data by any other users for a certain period of time. The notable example is the invocation of this policy in 2001 when US Federal agencies essentially restricted access to satellite imagery over Afghanistan by acquiring exclusive rights to all IKONOS satellite imagery.

Realizing that remote sensing was not yet commercially viable, the United States recognized the need to actively support its national remote sensing actors and to foster the industry. In 2003, the US government issued a Commercial Remote Sensing Policy that supersedes the earlier PDD-23. The objective of the 2003 Commercial Remote Sensing Policy was to enhance the competitive- ness of national actors by freeing restrictions as well as supporting the national remote sensing industry.

The 2003 Commercial Remote Sensing Policy further realizes the deregulation of the earlier PDD-23. The policy has taken away the restrictions on spatial, spectral, and radiometric resolution and encourages US companies to build and operate commercial remote sensing systems, inferring the favourable review of license applications.

The key feature of the 2003 Commercial Remote Sensing Policy is the enhancement of governmental reliance on US commercial remote sensing capabilities. The policy states that the US government will "rely to the maximum practical extent on US commercial remote sensing space capabilities for filling imagery and geospatial needs." The policy also states that the US government should fill the gap only "if fulfilling their data needs cannot be effectively, affordably, and reliably satisfied by commercial providers." This confirms the government's intention to become a major customer for data from US private remote sensing systems.

In order to implement the policy concretely, the 2003 Commercial Remote Sensing Policy calls for the establishment of the National Imagery and Mapping Agency (NIMA) that is responsible for acquisition and dissemination of data for national security and foreign policy requirements to enhance the governmental reliance on US commercial remote sensing capabilities. The 2003 Commercial Remote Sensing Policy is clearly aimed at encouraging operations of domestic commercial remote sensing actors through deregulation and the 'data buy 'approach.

To effectively implement the 1992 Land Remote Sensing Policy Act on private actors, the United States adopted the Licensing of Private Land Remote Sensing Space Systems in 2006 (Remote Sensing Licensing Regulations). This latest licensing regulation endorses detailed procedures for licensing terms and conditions, review procedures, and monitoring compliance pursuant to the provisions related to the US Remote Sensing Licensing Regulations under the Land Remote Sensing Policy Act.

In addition to the first time authorization to operate remote sensing systems, any new actions are closely monitored. The regulation requires a license holder to file an application in case of amendment to the license as well as to notify when a license holder intends to enter into an agreement with any foreign nation or foreign entity. Moreover, the regulation requires licensees to undergo an annual audit, as well as to record their data for one year and report on the data acquisition and dissemination related to Israel.

Audits are undertaken annually to review compliance with licensing conditions and changes associated with the licensee. The licensees are obligated to report at different time frames: 12 months before launch; six month prior to launch; when the system is in operation; and every three months afterwards. Specifically, the regulations implement shutter control measures on a regular basis: four times a year, licensees are obliged to report on estimated resolution of all images collected and disseminated on the state of Israel. The Licensing Regulations require licensees to keep all records and data from the previous 12 months, including tasking information and associated metadata. Under the requirement, the government is able to ascertain the time and locations of images collected from private remote sensing systems. This close monitoring mechanism enables the systematic and regulated control on different satellites operated by different entities.

Another notable provision of the Remote Sensing Licensing Regulations establishes data policies that take satellite funding mechanism into account. The Regulations distinguish three different situations: 1) remote sensing systems that are not funded by the US government; 2) systems that are partially funded by the US government; and 3) systems fully or significantly funded by the US government. As to the non-government- funded systems, a licensee is allowed to provide access to its unenhanced data at reasonable commercial terms and conditions, subject to the requirement of providing data to the government of any sensed state. As to the systems that are partially funded by the US government, it will be determined "whether the interest of the United States in promoting widespread availability of remote sensing data on reasonable cost terms and conditions requires that some or all of the unenhanced data from the system be made available on a non-discriminatory basis in accordance with the Act." For fully or significantly funded systems, a licensee is required to make all data available on a non-discriminatory basis.

Canada: Canada, like the United States, has comprehensive domestic law relating to remote sensing – specifically, an Act governing the Operation of Remote Sensing Space Systems (hereafter: the Remote Sensing Space Systems Act) complemented by the Remote Sensing Space Systems Regulations that implemented the detailed rules of the Act. Whilst the law was adopted in 2005, steps to formulate certain rules on satellite remote sensing date back to the late 1990s. The rationale behind the formulation of rules lies in the planned change in the operational regime of a Canadian radar satellite system, RADARSAT, which was first launched in 1995. Following the success of RADARSAT-1 – owned and operated by the Canadian government – Canada decided to increase the private sector involvement in its remote sensing missions starting with RADARSAT-2. Since RADARSAT-2 was funded by the private sector, the government of Canada was forced to consider the need for legally established controls on the collection and dissemination of data, which were not required in the case of the earlier RADARSAT-1 system. The first legal instrument for establishing rules on satellite remote sensing was the conclusion of a bilateral agreement between Canada and the United Stated, the Agreement between the Government of Canada and the Government of the United States of America Concerning the Operation of Commercial Remote Sensing Satellite Systems, in 2000.

The Remote Sensing Space Systems Act regulates the overall activities of remote sensing actors through licensing and continuous supervision using measures of enforcement of regulations such as inspections by the authorities, and imposition of sanctions.

The scope of the Act is broad: it applies to public, private, and public-private systems; this means that the Act not only applies to commercial satellites, but also covers satellites of the Canadian Space Agency (CSA) as well as other governmental satellites. The coverage for 'public 'systems exists because commercial operations under the framework of CSA and the government remain subject to the data distribution controls set by the Minister of Foreign Affairs. The intended use of a satellite is irrelevant to the application of the Act;332 hence, the Act could apply to dual use satellites. The fact that the law applies to public systems is distinctive, as most domestic legislation is intended to regulate only private and public-private systems.

The wide scope of this Act is evident in other aspects as well. A 'remote sensing satellite ' is defined broadly as "a satellite that is capable of sensing the surface of the Earth through the use of electromagnetic waves," and satellites that are subject to control include satellites with optical, radar, thermal infrared, multi-spectral, and other types of sensors. Application of the Act is not limited to high resolution satellites; furthermore, it applies to operations from inside and outside Canada. As to the operation outside Canada, the law is applicable to certain persons such as 1) Canadian citizens; 2) permanent residents; 3) Canadian corporations; and 4) classes of persons as maybe specified in the Regulations.

Whilst the Act holds virtually every possible Canadian remote sensing system within its scope, the Minister of Foreign Affairs is authorized to exempt any persons, satellite systems, or data, on an individual or class basis from any or all aspects of the licensing regime. This exemption would avoid the situation where the Canadian government unnecessarily exercises jurisdiction over operations that are primarily in the hands of other states. With respect to the operation of remote sensing satellite systems by CSA or the Department of Defense, the Governor in Council may issue an order to adapt the provision of this Act or the regulations. It is anticipated, therefore, that the operation of a purely governmental satellite could be excluded from the application of the Act at any time. In this way, Canada takes the approach to first cover all potential remote sensing activities that may fall under Canadian jurisdiction, and can later make exemptions to the Act on a case specific basis.

The Remote Sensing Space Systems Act establishes a licensing regime to authorize persons under the jurisdiction of Canada to carry out remote sensing activities. Licenses are granted by the Ministry of Foreign Affairs and can be amended, suspended for a period of up to 90 days, or cancelled at the discretion of the government. Conditions include licensee compliance with restrictions that may be placed upon communication of raw data from the licensee to any persons other than the licensee, as well as on the provision of remote sensing products from the licensee to any persons other than the licensee.

A large portion of the Act is devoted to the obligations of the licensee and rights of government in relation to managing the operation of the remote sensing system and control of subsequent data distribution. In fact, the government can issue orders in order to exercise governmental control of operations. One such order concerns the licensed person's obligation to follow measures deemed appropriate by the government upon the cancellation or suspension of a license considering the national security and system disposal plan. Others concern interruption of service and priority access. For the orders described here, opportunity for making representation within a limited period of the receipt of the notice of an order is granted to licensees.

The Act establishes the government's right to interrupt remote sensing services by actors subject to the jurisdiction and control of Canada. Both the Minister of Foreign Affairs (hereafter: the Minister) and Minister of Defence may order a licensee to restrict or interrupt any operation for a specified period if the Minister believes that continuation of that operation would harm the national interest of Canada. The Act is silent as to the specific spatial resolution subject to the interruption of service by the government. As to the concrete measures of restriction, it is understood that a licensee is not required to stop data collection and distribution, but the distribution could be delayed, and the spatial resolution of data may be reduced as well. Since such restrictive measures could affect commercial business operations, interruption of service is only invoked at a ministerial level and only in the rarest of circumstances.

The Canadian government retains the right of priority access to the data. Priority access to services means that the Act permits the Minister, the Minister of Defence, and the Minister of Public Safety and Emergency Preparedness to order a licensee to provide any remote sensing service to the government of Canada for the purpose of international relations and national defence interests of Canada. More specifically, priority access to service is available to her Majesty, the Royal Canadian Mounted Police, and to the Canadian Intelligence Service. The Act guarantees the Canadian government's right to priority access to data in case of emergency. Whilst it is anticipated that priority access will not be invoked regularly, it could be invoked more frequently than shutter control, since priority access can be invoked at the Deputy Minister level.

Whilst the government may cover the cost associated with priority access, no right to compensation is granted to a licensee against the government for any financial losses resulting from actions taken in good faith by the government under this act. Such actions include: amendment of a system disposal plan; amendment, suspension, or cancellation of a license; ordering licensees to take measures upon cancellation or suspension of a license; interruption of service; and priority access. Hence, the government is not liable for the loss suffered by licensees unless the government intentionally caused such loss.

The Remote Sensing Space Systems Act establishes how continuing supervision by the governmental authority is exercised effectively through operations by inspectors and enforcement officers. The Act authorises inspectors designated by the Minister to enter and inspect, at any reasonable time, any place owned by or under the control of a licensee, a system participant, or any other person who may be carrying on a controlled activity in the operation of a remote sensing space system. An inspector then could serve as an enforcement officer, and may issue a notice of violation in any case in which he believes there are reasonable grounds that a violation has been committed.

The Act has a detailed enforcement mechanism. There are two levels of breach of the provisions of the Act: one is 'violation 'and the other is 'offence'. Violation is not a criminal act and a licensee is entitled to make representation upon a notice of 'violation ' within 30 days, whereas a licensee who commits an offence is liable on summary conviction with no reference to the opportunity to respond. Whilst a violation may concern the breach of any of 43 provisions of the Act and regulations, an offence concerns only four provisions: 1) operation of satellite systems without a license; 2) letting a person outside Canada command the satellite; 3) not complying with the

Minister's order to take measures upon suspension or cancellation of a license; and 4) not complying with the Minister's order with regards to interruption of service.

Sanctions for breaches of the Act are set at two tiers. Any individual committing a violation will be fined up to $ 5,000; the fine is $ 25,000 for other cases. It should be noted that the amount is imposed per day and adds up as long as the violation continues. This approach is equivalent to that taken by the US Land Remote Sensing Policy Act. By contrast, a person guilty of an offence can be fined up to $ 50,000, receive 18 month imprisonment, or both. In other cases, most notably, a juridical person committing an offence is fined up to $250,000. Certain illegal acts are regarded as both violations and offences, but a person cannot be charged for the same act first as a violation and again as an offence.

Germany: Germany, without a launch site in its territory, had no pressing need for developing domestic space legislation. This changed, however, with the development of high resolution remote sensing satellites and private sector involvement. In fact, the drafting for a law specific to remote sensing from space began during the implementation of the first large scale Public-Private Partnership (PPP) in the field of Earth observation, TerraSAR-X. Drafting for the German Act on Satellite Data Security, *Satellitendatensicherheitsgestz*, came into force on December 1, 2007. The law established governmental control over collection and dissemination of data from high performance remote sensing satellites to minimize any threat to the security of Germany and the security of other nations.

The German Act on Satellite Data Security applies to 1) the operation of high-grade remote sensing systems; and 2) the handling of data generated by a high-grade remote sensing system. A 'high grade remote sensing system 'is defined as "a space-based transport or orbital system, including the ground segment, by means of which data about the Earth are generated, where its sensor is itself/sensors are themselves technically capable either alone or in combination with one or more other sensors of generating data with a particularly high information content within the meaning of Paragraph 2." Information content must be determined according to 1) geometric resolution, 2) spectral coverage, 3) the number of spectral channels and the spectral resolution, 4) the radiometric resolution, and 5) the temporal resolution. In addition, the information content of microwave sensors or radar sensors must also be determined according to the polarization characteristics and phase history. The German Act on Satellite Data Security limits its scope to high grade remote sensing systems and appears to exclude its application to low resolution satellites. The Act applies to both the operation of high-grade earth remote sensing systems and to the handling of data generated from those systems by: a) German nationals – juridical persons or associations under German law; b) foreign juridical persons or associations of foreign nationals having their head office within the territory of Germany; and c) if the command to the system is given from the territory of the Federal Republic of Germany.

It is notable that the German Act on Satellite Data Security distinguishes between remote sensing system operators and data distributors, and imposes different types of authorization, respectively. Whereas the Act requires a remote sensing system operator to obtain 'approval', it requires a data distributor to obtain a 'license. 'Considering that other legal systems tend to have only one type of license – usually, for a system operator – it is unique to hold two distinctive types of authorizations related to remote sensing actors. This corresponds well to the growing tendency of separation between the satellite operation phase and operations related to data exploitation and distribution.

The approved and licensed persons share common obligations such as the duty to notify the responsible authority for any changes after the authorization; the duty to provide information requested by the authority; and the duty to let the responsible authority inspect the operations and undertake examinations. Furthermore, both remote sensing system operators and data providers have a duty to prioritize government requests in terms of generation and distribution of data. These governmental rights will be restricted to rare cases of crisis, and transaction costs can be charged to the government at a market price.

Obligation for documentation is distinct for system operators and data distributors. A system operator is required to record: command sequences to control the sensor, orbital, or transport systems; time and path of the command sequences; and details of encryption processes, and they must maintain the record for at least five years. For data distributors, obligations with respect to duty of documentation seem much more detailed and burdensome. All data requests need to be recorded, regardless of their sensitivity. The information data distributors need to record are, among others: requesting party (ies) and their usual places of residence; procedure for, and the result of, sensitivity checks; data generation order; reports on the processing sequences of the ground segment; metadata – including the location of observation, time of data generation, sensor operating mode, and data processing parameters; and invoices. In short, a data distributor is obliged to record the precise detail of every transaction. Again, the records must be maintained for at least 5 years and need to be available for inspection.

When a data distributor wishes to comply with the data request, a sensitivity check is required. The sensitivity of the data request is determined by considering the elements of the information content of data, the location observed, who purchases the data, the country of destination, and the time between data acquisition and the processing of the data request. As to the information on the purchaser, the data provider must check the identity of the requesting party, as well as the names of the persons who necessarily come into contact with the data and their places of residence. Some areas are excluded for almost all the customers, for instance, military operation zones. This can be construed as ban on the data collection for customers rather than a ban on data dissemination.

The sensitivity check consists of a twofold process: first, to be performed by, and in the full responsibility of, the data distributor; second, to be conducted on a case-by-case basis by the Federal Office of Economics and Export Control. As to the first stage, evaluation of the sensitivity of a data request is undertaken by the data distributor in accordance with a set procedure and clearly established criteria with no room for discretionary assessment. If the data request is classified 'not sensitive', the data distributor is allowed to deliver the requested data without further approval from the government.

In case a data request is found to be sensitive as a result of the evaluation by the distributor, and yet the distributor wishes to proceed with the data request, the data distributor files an application for a permit to the Federal Office. The Federal Office then conducts a case by case review evaluating the risks involved in complying with the data request. A permit is required to comply with sensitive data requests, and cases where data are to be distributed without data request are treated likewise. The Federal Office issues a permit if the data request in question would not endanger the security of Germany.

In case compliance with the data request is found to be risky, a permit may be conditionally granted through measures such as reduced spatial resolution of data, time delay, reduced processing quality of the data, or the avoidance of certain target areas. The flow for the evaluation of sensitivity and resulting action taken is depicted in the Figure 1.

Although the government reserves its right to prohibit data distribution, approximately 99% of permit applications is usually granted; therefore, the restriction imposed on data distribution is considerable but not at the level to seriously disrupt the commercial operation. In addition, to avoid hampering the commercial transaction unnecessarily, the fundamental policy is to limit the duration of a case specific review by governmental authority to maximum one month.

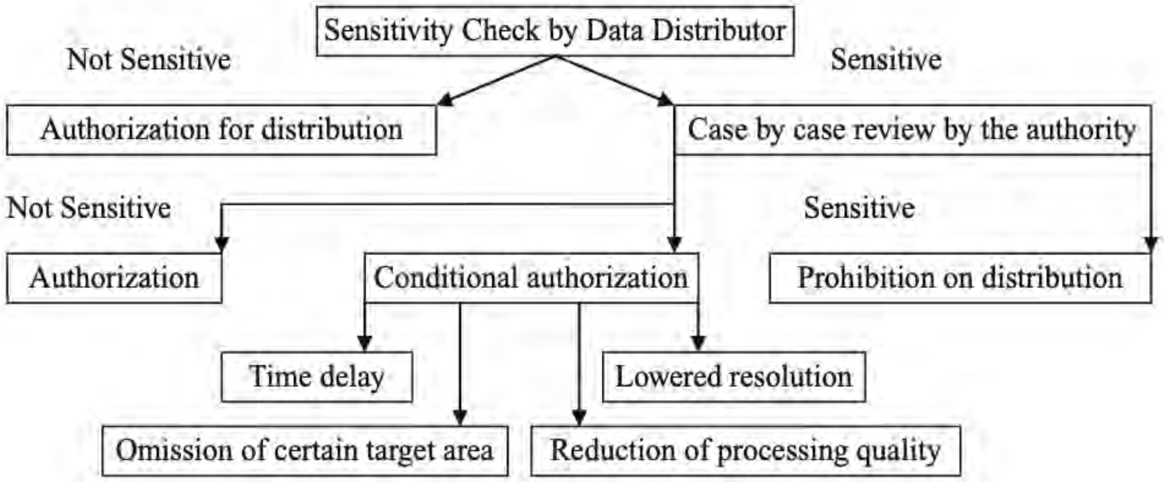


Figure:1 Flow of the Sensitivity Check and Resulting Actions

As is the case in Canada, the German government reserves its right of priority access to data in the event of an emergency. Data providers owe an obligation to prioritize in case of threat to German military and civilian forces in a foreign country or to foreign officers employed at German foreign embassies. These rights will be restricted to rare occasions of crisis.

Rules endorsed in the German Act on Satellite Data Security are enforced through sanctions. As to the form of sanctions, a three-tier penalty scheme is set depending on the type of offence. Offences can be categorized as either serious ones with heavier fines that may be replaced by sentence to imprisonment, or those that are less serious with lower fines. The highest fine of up to € 500,000 is imposed for offences such as: operating remote sensing system without permission; complying with a sensitive data request without permission; and distributing data without a permit. A fine of up to € 50,000 is imposed for offences such as failing to undertake the sensitivity check and conducting the check not using the designated procedure or conducting it incompletely. Any of the offences listed above in the first category may result in imprisonment up to five years instead of a fine. Finally, for those offences categorized as least serious, a fine of up to € 25,000 is imposed. Such offences include failing to provide the information requested by the authority as well as failing to report any changes that occurred after the issuance of license.

France: Unlike many other states, France does not have a specialized law for remote sensing as such, but the French Space Operations Act addressing general spacecraft control includes Title VII (Title VII : Space-based Data) devoted to the issues of remote sensing operations and data dissemination control. Remote sensing activities are addressed only by three articles – Articles 23 to 25 in Title VII of this law – and provisions are fairly general. The domestic French space law serves as an overall framework and is complemented by more detailed regulations in the form of decrees. The decree of 6 June 2009 supporting the applications of measures provided by Title VII of the French Space Operations Act389 effectuates the regulations of Title VII of French Space Operations Act, and articulates how rules are applied.

It is noteworthy that the part of French legislation addressing data control was developed separately by the Ministry of Defence, whilst the rest of the law was prepared by the Council of State, signifying the critical impact data collection and dissemination may have on national security. The scope of the legislation is limited to the natural or juridical person responsible for the programming of a remote sensing satellite or responsible for the collection of space-based remote sensing data. Therefore, mere data resellers and value added service providers that are not involved in the operation of the satellite or data collection are not covered under the legislation. Data from military spacecraft or data collected on behalf of the Ministry of Defence is excluded from the scope: it neither applies to activities of CNES nor to military applications. Title VII applies to data from panchromatic optical sensors, multi-spectral optical sensors, stereoscopic sensors, infrared, and radar sensors. A separate decree is to be adopted for further defining the data resolution, and the characteristics of precision.

Remote sensing data exploitation is subject to prior declaration to the Administrative Authority. It is clarified in the French Remote Sensing Decree, which states that the decree of 6 June 2009, which supports the applications of measures provided by Title VII of the French Space Operations Act, provides that the Administrative Authority is Secretary General for National Defence (SDGN). A declaration needs to be made at least two months prior to the starting of operations. In case the declaration is not in conformity with the regulations, or is incomplete, the authority asks the candidate to declare in a designated or complete manner.

Governmental control is exercised by declaration instead of through a license. Particular attention should be paid to French law adopting a system of a declaration. A declaration, which is a weaker form of a license, is closer to a notification than to an authorization. A declaration is a one-sided operation and implies that such a declaration will not be rejected – unlike the case of a license, which normally requires an application that is then granted or rejected upon review by the authority. No conditions to declare are articulated under the French Space Operations Act.

Title VII of the French Space Operations Act refers to possible restrictions on remote sensing actors to safeguard the national interest. Article 25 makes it clear that the Administrative Authority shall ensure that the primary operator of space-based remote sensing data does not interfere with the fundamental interests of the nation. Concrete measures of restriction are not specified, but there are historic incidents of suspension of data for a certain period, such as when France exercised the control of data dissemination by suspending Spot Image's data dissemination to Iraq during the Gulf War. In fact, a mechanism of control by the French government on commercial distribution has been operational via GIRSPOT, an inter-ministerial working group that reports on the specific cases that trigger the restrictive measures. GIRSPOT is composed of representatives of SDGN: the Ministry of Foreign Affairs, Ministry of Defence, Ministry of Space, and CNES. Upon the recommendation made by GIRSPOT, the Prime Minister has the responsibility to impose limitation on Spot Image. Since operations of GIRSPOT remain confidential and the legality of data control implemented in its framework was questioned, the need arose for a law to formally address the issue. Incorporating rules associated with satellite remote sensing into French law on space operation will codify and implement the operational regime already in place and, at the same time, will address the issue of shutter control in a more official and transparent manner.

Types of restrictions considered to be implemented include: the immediate suspension on data distribution for a limited period of time; the obligation to delay the data distribution, and the permanent prohibition of data dissemination for certain locations. It is envisaged that locations such as nuclear plants in France, the location of French troops abroad (e.g., the Ivory Coast), or the location of allied troops abroad (e.g., US Army troops in Iraq) are most likely to be the targets for restrictions.

Finally, the French Space Operations Act has a concrete enforcement mechanism imposing a € 200,000 fine against a person that distributes data without a declaration, as well as those who do not comply with data restriction regulations. This is a civil penalty with no distinction between an individual, and other person (e.g., juridical person). One can conclude at this point that the French Space Operations Act is intended primarily to ensure governmental control of remote sensing activities and subsequent data distribution, and has little provision for fostering the industry.

Overall, the remote sensing laws that exist at the domestic level serve as a regulatory regime for non-governmental as well as public-private remote sensing operations. With the exception of Canada, the respective laws are not applicable to national and military operations. One can conclude that the existing national laws addressing remote sensing perform primarily two functions:

1. to provide a regulatory regime to authorize and supervise remote sensing operations, and enforce associated regulations through a licensing frame- work; and
2. to codify and ensure enforcement of the government's right to interrupt services, and to have priority access to data.

The laws reflect the government's intention to regulate remote sensing activities, and to exercise control to ensure that a licensed operation does not harm the government's interests. The laws, however, are not intended to safeguard the right of the potential users or that of other parties affected.

Generally speaking, national remote sensing laws are not intended to serve the purpose of promoting remote sensing activities. Only the United States takes an active approach to realize that goal. The United States has kept pace with changing policies and regulations in line with the market evolution in the field of EO, and has attempted to maintain the competitiveness of national actors by adopting measures to foster the industry. Such a tendency is found to a minimal extent in other states. Certain elements of consideration for not hampering commercial business can be seen, however, to the extent of limiting restrictive measures by the governmental authority to the benefit of licensees. Examples include limiting the exercise of shutter control to only rare occasions; adopting a review process that is not overly lengthy; and government's willing- ness to pay for the transaction costs associated with priority access. The next section reviews the policies associated with remote sensing and analyses the general tendencies found in the existing remote sensing laws that also apply to such policies.

Whilst not established as a law, an increasing number of states adopt certain policies with respect to data dissemination. Driven by the needs that have emerged with the launch or planned launch of high performance remote sensing satellites and consequent data dissemination, states have moved to adopt, or consider framing, policies that endorse data- specific rules worldwide.

It is of particular importance to gain an understanding of the existing remote sensing policies of various states and to analyze their feature and impact on the data access environment. In theory, certain data policies exist for all satellites of different states currently in operation. The following part will look only at the policies implemented and exercised by state governments that significantly affect the actors; the discussion will focus on a state-by-state review of the policies and practices of China, India, and Russia.

China: The milestone from the standpoint of China's Earth Observation policy was the launch of Beijing-1, a high resolution satellite of 4 m in 2005. Beijing-1 forms a part of the Disaster Monitoring Constellation (Hereafter: DMC) that consists of satellites from several states/entities, whereby 32m data can be exchanged amongst the DMC partners. It is the policy of China not to provide its 4m resolution data of Chinese territory from the Beijing-1 satellite to users outside China. This practice is, in a way, de facto shutter control. Furthermore, the National Mapping Service has up-to-date maps available, but users who are not authorized by the Chinese government are only allowed to access up to 1: 1 million scale maps. Restrictions placed on a map scale for dissemination is relevant to remote sensing, as maps are often based upon or derived from satellite remote sensing data. This may serve as an impediment to open access to the satellite-derived maps and serves as a restriction on data availability on a global basis.

India: India has a comprehensive EO data policy. The Remote Sensing Data Policy established in 2001, fulfils a twofold purpose: 1) to establish a licensing mechanism; and 2) to establish guidelines to control the dissemination of remote sensing data.

With regard to licensing, India's policy requires a license and /or permission from the ministry in charge – the Department of Space – to operate remote sensing systems as well as to acquire /distribute remote sensing data within the country. The Department of Space assigns licensing operations to two entities: the National Remote Sensing Centre, and Antrix Corporation Limited, known as a commercial arm of the Department of Space. The National Remote Sensing Centre takes charge of the acquisition/distribution of remote sensing data within India410 whilst Antrix Corporation handles granting license for acquisition/distribution of IRS data outside of India.

With regard to guidelines for data dissemination, the policy is three-tier, depending on the resolution of data: 1) data lower than 5.8 m; 2) data between 5.8 m and 1 m; and 3) data higher than 1 m. The Remote Sensing Data Policy makes data lower than 5.8 m ground resolution available on a non-discriminatory basis and on an "as requested basis". Data between 5.8 m and 1 m resolution "can be distributed to users after screening and ensuring that the sensitive areas are excluded." Distribution of higher than 1 m differs by type of users. Whilst government users do not require further clearance, other users are subject to case-by -case review by an inter-agency High Resolution Image Clearance Committee (HRC), which makes decisions as to whether or not to grant such requests. The distribution of 1m resolution commercial imagery is kept under check through specific sales agreements containing non-disclosure clauses.

The Remote Sensing Data Policy does not provide a definition of sensitive areas; however, the examples of certain sensitive areas can be illustrated using an agreement concluded by the Indian government with a foreign operator in the past. Under a July 2000 agreement between the government of India and Space Imaging – a foreign private entity – sensitive Indian installations such as military bases and airfield will be blotted out of IKONOS images before their distribution in India. The conclusion of this agreement in

2000 signifies that a case-specific legal instrument was already adopted before the establishment of the Remote Sensing Data Policy that addresses guidelines for data dissemination in a general context. Furthermore, the National Remote Sensing Centre prohibits the dissemination of data concerning India's borders up to eighty kilometres inside the territory, including the states of Jammu and Kashmir. Whilst the Remote Sensing Data Policy does not provide for sanction measures such as fines, it is clearly characterised by rigid governmental control, and is closer to a law than a policy.

Russia: Russia went through phases of relaxing the restrictions on the resolution of available data whilst retaining the right of data refusal in the interests of national security. It was not until 1987 that the commercial images of 5 m high resolution were authorised for dissemination, and it was 1992 when Russia authorized the dissemination of 2m images. Russia started to distribute high resolution images acquired by its KVR-1000 panchromatic camera, which was initially designed for intelligence applications. Whilst restrictions may be imposed on data from specific locations of military sensitivity, in response to the evolution in marketing of commercial images Russia lowered the restriction on resolution to 1 m in 2000419 when the Russian Space Agency announced the commercial distribution of 1m spatial resolution space images taken by its KOMETA satellite system. Russia currently operates Resurs DK1, and imagery from Resurs DK1 and other remote sensing satellites is marketed on a commercial basis by SOVZOND JSC, a private firm established in 1992 to exploit the data.

Russia has placed restrictions on the map scale, just like China. The maps of a scale better than 1:200,000 are regarded by the state as confidential, and a combination of the Federal Security Service and Roskartografia, the National Mapping Agency of Russia, reviews and controls all cartography at map scales better than 1:200,000. The KOMETA images are used to produce 1: 50,000 scale topographic maps that are currently prohibited for civil commercial use. Again, this can serve as an impediment to access to data for public benefit purposes.

From the foregoing discussion, one can argue that 'control of the space object 'if applied to remote sensing satellites (i.e., data collection and dissemination), is much more specifically defined and implemented in the national framework addressing satellite remote sensing. As far as the remote sensing policies discussed in this Chapter are concerned, the tendency found in the analysis of law is only applicable to the first component; that is, to perform the function of a regulatory framework to authorize and supervise the domestic actors, as well as to ensure the rights of the government to interrupt the remote sensing operations. With regard to the remote sensing policies exercised at a national level, their aim is primarily to safeguard the national interests and they reflect little to no element of fostering the domestic industry.

Remote sensing actors are, to a greater or lesser extent, subject to restrictions imposed by governments in the national context. As conditions are mandatory on the licensed remote sensing operators, actors are forced to adhere to the provisions under the domestic regime, despite their possible inconsistency with the international regime. Indeed, if a government decides to exercise interruption of service, limitation on access to the data from any entity that is under the jurisdiction of that government is inevitable.

National legislation and policies relevant to remote sensing that exist today in different countries largely serve as restrictions, rather than to encourage a global data use or to bridge gaps that exist in the present international regime. They only clarify what can and cannot be done by national actors within the particular jurisdictions, and do not adequately complement the international regime by covering the issues not addressed therein.

Conclusion: The current legal framework surrounding remote sensing neither promotes nor regulates remote sensing activities sufficiently. International rules do not adequately address the critical issues associated with supply and use of data, whilst national legislation largely serves as a means for a government to exercise control on the activities of actors under its jurisdiction.

The inadequacy of the current international legal regime closely reflects the highly political background for, and drafting histories of, the existing international laws governing outer space. The Outer Space Treaty was a compromise of views of the early space powers, largely motivated by the justification of their interests, such as the non-appropriation of outer space and the protection of 'spy 'satellites; but the Treaty was not intended to generate practical rulemaking to realize the stimulation and regulation of space activities. The UN Remote Sensing Principles codified the views of states with sensing capabilities, mainly reflecting the viewpoint of the United States, which won the negotiation with a high degree of compromise by the developing nations. It was not that concrete rules – such as stating the liabilities arising from the dissemination of data – were never considered. Quite the contrary: various proposals to formulate concrete rules were not incorporated because the states failed to reach consensus. In certain respects, the ambiguities in the current regime were inevitable or, to some extent, even generated deliberately.

With respect to existing national laws and policies, these were primarily motivated by interests of respective states, and are characterized as regulating national actors through governmental control largely with regard to national security and foreign policy interests. Whilst certain rules are intended to minimise the negative impact of restrictive governmental measures on commercial operations, they would only benefit domestic actors, and not the global communities affected by remote sensing activities at large. The present international law regime on satellite remote sensing supports data applications for environmental protection and disaster management; however, the provisions dealing with data availability and pricing policy do not particularly promote the use of data for these applications. Furthermore, the current international legal regime fails to address important commercial and operational issues regarding use and application of data, such as data policy issues including intellectual property rights, guidelines for accuracy validation and data authentication, and liability issues. The uncertain legal environment currently pertaining to remote sensing from space restricts the widespread use and realization of the full benefits of this powerful tool.

The international legal regime is now at a turning point, as the environment surrounding remote sensing has changed since the formulation of the UN Remote Sensing Principles; this change has been particularly dramatically in the last few years. Today remote sensing has a more global presence, is used for a wide range of applications, and has further potential as a critical information tool. It is now time to regulate and promote remote sensing activities through an unambiguous legal framework. There is an urgent need for clarification of ambiguities and for studies of current practice, as well as a more comprehensive regime.

MODULE-V

REMOTE SENSING TECHNOLOGIES IN INDIA

MODULE-V: REMOTE SENSING TECHNOLOGIES IN INDIA

Indian Remote Sensing Sensor System: Current and Future Perspective: The Earth Observation (EO) satellites play a significant role in providing information in a spatial format and in determining, enhancing and monitoring the overall capacity of the earth. Satellite Observations over land, oceans, atmosphere, and during natural and human-induced hazards have become crucial for protecting the global environment, reducing disaster losses, and achieving sustainable development. Hence Earth Observation from Space has proved to be a game changer in providing valuable information on natural resources and environment at different scales. Indian Space Research Organization (ISRO), has made its mark in all facets of remote sensing and arguably has the most vibrant program, when it comes to civilian usage and outreach in general. Microwave and Electro Optical Remote Sensing programme has taken a great leap through development of remote sensing systems for both space-based and airborne remote sensing activity of ISRO.

Today, India has the world's largest constellation of electro optical remote sensing spaceborne systems in operation. Passive Microwave sensors developed at ISRO are aimed at providing atmospheric and oceanographic remote sensing data from space-based platforms. Active Microwave sensors are dedicated to imaging as well oceanographic applications. Imaging sensors, which witnessed a beginning in airborne application, have, over the period, graduated to space borne platforms. Indian Remote Sensing sensors provide space-based remote sensing data in a variety of spatial, spectral and temporal resolution meeting the needs of many applications of relevance to national development. The Indian earth observation satellites specifically designed to meet country's needs can ideally meet the global needs as well, in view of the similarity of situations in India and most parts of the developing world. This paper takes the reader through various phases of Indian Remote Sensing Sensors developed at ISRO by describing each sensor along with its functioning.

Indian Earth Observation Programme: The Indian Earth Observation (EO) Programme started with the experiment on detection of coconut root wilt disease from a helicopter-mounted multi-spectral camera system in 1970 has matured into a fully operational programme. It is self-reliant in every aspect of the technology and applications. It consists of space segment, ground segment, applications programme with particular emphasis on capacity building. The space segment deals with indigenous development of various types of sensors, spacecraft platforms and satellite launch vehicles. Setting up telemetry, tracking and command network of stations, data reception systems and generation of data products are important component of ground segment. Development of algorithms for retrieval of geophysical parameters and related utilization application are carried out for each satellite mission.

Indian EO program started from Bhaskara-1 satellite (June 1979) which had two types of sensor systems viz. television camera and microwave radiometer. Imageries of Bhaskara at 1 km spatial resolution helped in carrying out land use, forestry and geological studies. SAMIR payload measured brightness temperature in 19 GHz and 22 GHz for study of ocean-state, water vapor, liquid water content in the atmosphere, etc. Bhaskara-1 was followed by Bhaskara-2 (Nov. 1981) with improved SAMIR instrument. The first operational remote sensing satellite IRS-1A launched on March 17, 1988 had two types of payloads with Linear Imaging Self Scanned imaging (LISS-1 and LISS-II). IRS-1A mission was followed by IRS-1B and subsequently IRS-P2, IRS-1C, IRS-1D were flown with improvement as per user needs and requirements.

Currently, thirteen operational satellites are in Sun-synchronous orbit–RESOURCESAT-1, 2, 2A CARTOSAT-1, 2, 2A, 2B, RISAT-1 and 2, OCEANSAT-2, Megha-Tropiques, SARAL and SCATSAT-1, and four in Geostationary orbit- INSAT-3D, Kalpana & INSAT 3A, INSAT -3DR. Varieties of instruments have been flown onboard these satellites to provide necessary data in a diversified spatial, spectral and temporal resolutions to cater to different user requirements in the country and for global usage. The data from these satellites are used for several applications covering agriculture, hydrology, urban planning, rural development, mineral prospecting, environment, forestry, ocean resources and disaster management.

Evolution of the Indian Earth Observation (EO) Programme: In India, EO activities were initiated with the pioneering experiment on detection of coconut root-wilt disease carried out in 1970 using colour-infrared aerial photography obtained from a helicopter. This was the precursor to establishing operational remote sensing activity in the country. This was followed by many studies conducted using aerial data, and also data from the American Landsat series of satellites from 1972 onwards. The major experimental campaigns have been Agricultural Resources Inventory and Survey Experiment (ARISE), Mandya Crop Inventory Experiment, Land use Studies of Idukki area and Integrated Resources Survey of Panchmahals, Gujarat. These studies were carried out by ISRO in association with different collaborating agencies.

The Experimental Phase: Concurrently, pursuing the technological quest in satellite building, ISRO successfully developed and launched experimental satellites - Bhaskara-1 in 1979 and Bhaskara-2 in 1981. These satellites, carrying an optical payload providing data at 1 km spatial resolution in two spectral bands and a microwave radiometer, were aimed at getting hands-on experience in satellite building, telemetry and tele- command operations, data reception and processing. The optical payload on board these satellites was slow a scan vidicon camera with capability to collect images in 0.54 to 0.66 and 0.75 to 0.85 micrometre bands, and passive microwave radiometer having 19, 22, 31 GHz channels.

The optical and microwave data collected from the Bhaskara I & II experimental satellites during 1976-82 provided valuable experience and insight into a number of aspects, such as sensor system definition and development, conceptualisation and implementation of a space platform, data reception and processing, data interpretation and utilization, and integration of remotely sensed data with conventional datasets for natural resources management. The capability to build operational satellites for remote sensing became clearly visible with the successful completion of the Bhaskara programme. Around this time, in 1978, a Joint Experiment Programme (JEP) was launched with intensive test sites in the country, for ground verification of space data, in close collaboration with user agencies; this lead to improved understanding of user requirements.

With this background, the Indian Space Programme leaped into development of national operational satellite-based remote sensing system in the 80s to ensure generation of spatial and temporal information on vital natural resources sectors such as Agriculture, Land, Water, Forestry and Geology. A unique institutional framework called 'National Natural Resources Management System '(NNRMS) was established in 1985 under the aegis of the union Planning Commission to steer the remote sensing applications in the country. The NNRMS framework helped in optimal integration of remote sensing inputs with conventional data; and, realised in a highly cost and time effective manner.

The Operational Era: Having gained experience through the foregoing, and in the quest to address the national developmental needs, the satellite based remote sensing system got firmly established in the country with the launch of the first operational Indian Remote Sensing Satellite - IRS-1A in March 1988. This was followed by the launch of IRS-1B in August 1991. IRS-1A and 1B satellites were identical, and carried two types of cameras - LISS-I & II, with spatial resolutions of 72.5 and 36.25 m, respectively. IRS- P2 satellite with only LISS-II camera was added to this constellation by an indigenous launch in 1994. Both the LISS-I and LISS-II cameras ('LISS 'meaning Linear Imaging Self-Scanner) provided highly useful data for a variety of natural resource management related studies. With a large number of field-based campaigns carried out, predominantly over agricultural regions, for accuracy assessment; the need for improving the spatial resolution of remote sensing data was felt. As follow-on to the IRS-1A & 1B satellites, IRS 1C & 1D missions were planned with improved payloads such as a panchromatic (PAN) camera, LISS-III camera and a Wide Field Sensor (WiFS). The PAN camera operated in the 0.50 to 0.75 micrometre range with spatial resolution of ~5.8 m and a swath of ~70 km. The PAN camera was also the highest spatial resolution imager among the civilian space-based systems in the world at the time of launch of the IRS-1C satellite in 1995. Following, the four-band multi-spectral camera LISS-I/ LISS-II was modified into a four band multi-spectral LISS-III camera with inclusion of Short Wave Infra-Red (SWIR) band in place of blue band. Need for detection of moisture-stress in crops and snow-cloud discrimination were the driving forces for inclusion of the SWIR band. The spatial resolution of LISS-III was 23.5 m in green, red and NIR bands, and 70 m in SWIR band. IRS-1C incorporated enhanced capabilities in terms of spatial resolution, spectral bands, stereoscopic imaging, wider swath/ coverage and better revisit capability. The unique capabilities of IRS-1C were harnessed for a range of newer applications in different thematic areas. IRS-1D, identical to IRS-1C, was launched in September 1997, to maintain continuity of data services to the on-going projects and also to cater to newer initiatives.

While the availability of data from the operational remote sensing satellites starting from IRS-1A to IRS-1C/ 1D facilitated applications in the areas of agriculture, water resources, forestry, land use, coastal zone and cartography from regional scale to national scale; strong need was felt to design sensors for ocean observations, cartography and improved land applications. The IRS-P3 satellite, launched in March 1996, provided good experience in studying the ocean colour using data from the MOS sensor, and helped in formulating the sensor specifications for IRS-P4 satellite, also known as Oceansat-1. The IRS-P4 (Oceansat-1), launched in May 1999, was the first Indian satellite with Ocean Colour Monitor (OCM) and Microwave Radiometer for ocean applications. The Oceansat-2, launched in 2009, carried a modified OCM and a Ku band Scatterometer to enable ocean wind vector measurements. It also carried a Radio Occultation Sounder instrument to make profile measurements of humidity and temperature. Of most recent, in February 2013, the SARAL, a joint ISRO-CNES satellite mission with Argos and a Ka-band altimeter for measurement of sea surface height and study of oceanic circulation, was launched.

In order to ensure the mission continuity for focussed on land observation, IRS P6/ Resourcesat-1 was developed and launched in 2003 with three cameras - LISS-IV, LISS-III and Advanced Wide Field Sensor (AWiFS). To utilize the full dynamic range of spectral data, a ten-bit radiometry was incorporated, particularly in the AWiFS sensor, which made the image features appear sharper. The Cartosat-1, launched in 2005, carrying a PAN camera with 2.5 m spatial resolution, was a state-of-the-art along-track stereo mission. Both Resourcesat-1 and Cartosat-1 provided valuable data, and have been much acclaimed missions globally. Many international ground stations have received data from these two satellites.

In the applications front, many national scale projects were initiated; to name a few, monitoring acreage and production forecasting of different crops at national level, snow cover monitoring of the entire Himalayas, coastal zone mapping/ monitoring, preparation of groundwater prospects maps, periodic land use/ cover mapping, and so on. Data from Cartosat-1 was used for generation of Digital Elevation/ Surface Models at 8 m posting for the entire country. Further, an important project called 'Space-based Information Support for Decentralized Planning '(SIS-DP) was initiated, to provide high-resolution thematic maps for facilitating planning at Panchayat level. The AWiFs data was extensively used by USA, and in Europe for crop monitoring.

Considering the importance of studying the earth system process in general, and to study the water cycle and energy exchanges in the tropics, the joint ISRO-CNES mission, 'Megha-Tropiques 'satellite was launched in 2011. This satellite carried a conical-scanning microwave radiometer (MADRAS), multi-channel microwave humidity sounder (SAPHIR) and a radiation budget instrument (SCARAB). Megha- Tropiques formed a part of the Global Precipitation Measurement (GPM) satellite series - for carrying out rainfall measurements and related research as well as operational applications in the tropical region.

Focussing further on newer domains of space technology applications, and considering the hurdles faced by cloud cover in optical remote sensing, especially during the monsoon season; Imaging RADAR was considered necessary for the country. Accordingly, a C-band Synthetic Aperture Radar (SAR) was flown on board the Radar Imaging Satellite-1 (RISAT-1), in April 2012, for resource monitoring - particularly during the Kharif (June-September) season, flood monitoring and disaster management related applications.

On meteorology front too ISRO has made significant progress by way of building geostationary satellites for the purpose. 'Kalpana 'was the first in the series of exclusive meteorological satellites built by ISRO, launched in September 2002. Kalpana carried a Very High Resolution Radiometer (VHRR) with water vapour and thermal channels with 8 km resolution, and visible channel with 2 km resolution. Following this, INSAT-3A, a multipurpose satellite was launched in April 2004 for providing telecommunications, television broadcasting, meteorological and search and rescue services. For meteorological observation in particular, INSAT–3A carried a three-channel Very High Resolution Radiometer (VHRR) and a Charge Coupled Device (CCD) camera operating in visible and SWIR bands at 1 km spatial resolution. To ensure enhanced meteorological observations, monitoring of land and ocean surfaces, generating vertical profile of the atmosphere in terms of temperature and humidity for weather forecasting and disaster warning, the 'INSAT-3D 'was launched in July 2013 with improved 6-channel Imager and 19- channel Atmospheric Sounder.

Data from these satellites is regularly received, processed and disseminated to users for operational applications. India is one of the few countries, which have end-to-end operational space programme, that are able to integrate the products and services emanating from space assets to address the developmental needs of the country. The Indian Space Programme, with INSAT, IRS and IRNSS (Indian Regional Navigation Satellite System - heading to become an operational constellation soon); the globally sought- after indigenous launchers - the PSLV and GSLV; and the host of illustrious applications and services; is one of the most cost-effective Space Programmes in the world, with a unique societal outreach.

Electro Optical Remote Sensing Sensors: Presently, India is having the world's largest constellation of Electro Optical (EO) remote sensing satellites in operation (Fig. 1). It provides space-based remote sensing data in a variety of spatial, spectral and temporal resolutions, meeting the needs of many applications of relevance to national development. The Indian earth observation satellites specifically designed to meet country's needs is also useful in many global applications.

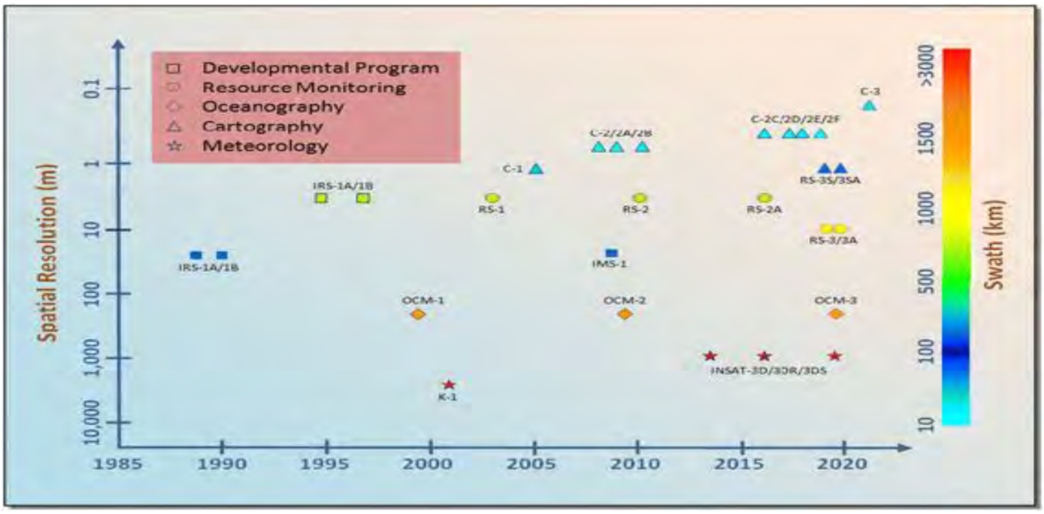


Fig:1 Electro optical remote sensing program of ISRO

Resource Monitoring: Resourcesat-1 was launched in 2003 and it changed the way agriculture was monitored and studied in India. The result has been incessant requirement of continuity of service for the series. In April, 2011, Resourcesat-2 was launched followed by Resourcesat-2A in December, 2017. The series has turned out to be one of its kind, having three tier imaging capability with LISS-4 (5.8 m), LISS-3* (23 m), AWiFS-A&B (56 m) (Figs. 2, 3). All the payloads are multispectral with SWIR bands in LISS-3* and AWiFS. This is probably the most widely accepted and popular program among the user community, world over, for its wide ranging applications covering Agriculture, Urban mapping, Forest management etc.

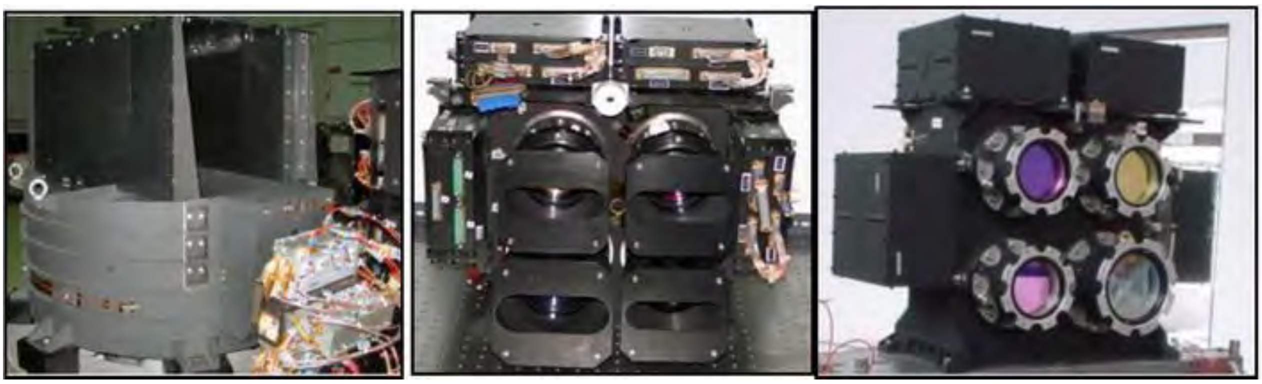


Fig. 2: LISS-4, LISS-3 and AWiFS cameras of resourcesat-2

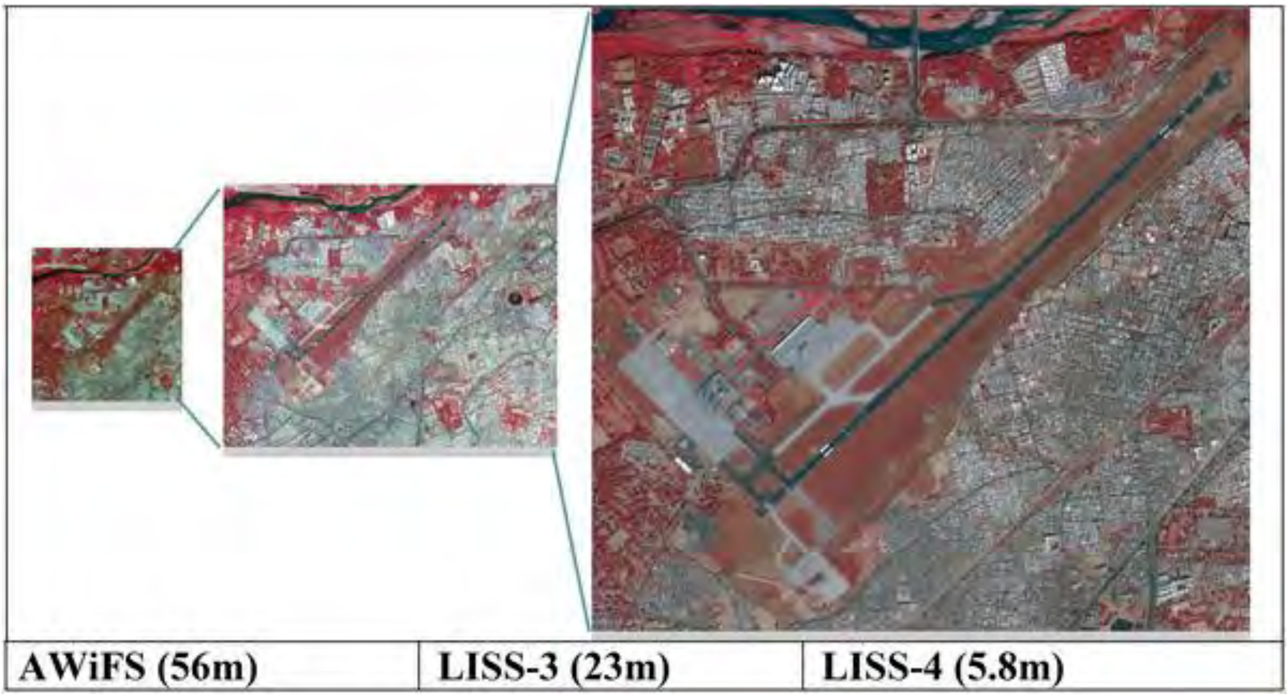


Fig. 3: Three tier imaging by resourcesat-2A, AWiFS (56 m), LISS-3 (23 m), LISS-4 (5.8 m)

Resourcesat-3 and Resourcesat-3S series of satellites, planned to fly together will be the next big step up. It will retain all the capabilities with enhancement in all aspects of observation. Resourcesat-3 will bring in a set of sensors to cover 925 km swath with a spatial resolution of 20 m in VNIR and SWIR spectrum. This will ensure a revisit in 4 days. Additionally, the satellite also will have capability to observe 280kms from designated altitude with 10 m discriminability. Entire 925 km will also be imaged by a VNIR hyperspectral imager to improve the overall product quality. Resourcesat-3S, with multi-view panchromatic stereoscopic capability having high spatial resolution of 1.25 m will facilitate generation of fused products of great utility.

Designed and developed specifically to meet Meteorological needs, INSAT-3D and 3DR (Fig. 4) together from geostationary orbit, cover the entire Indian landmass and beyond, every 15 min. 1 km in Visible and SWIR bands, and 4kms in Thermal Infrared complement the low earth imaging capability. Geostationary orbit provides constant monitoring and beyond Resourcesat-2A, high repetivity sensor would be continued on Geostationary platform as Geo Imaging Satellite (GISAT) mission. This will provide multiple day acquisition capability and shall overcome many limitations posed by AWiFS availability. Since geostationary satellites have longer life, GISAT will assure moderately high spatial resolution (50 m VNIR Multispectral, 320 m VNIR Hyperspectral, 190 m SWIR Hyperspectral and 1 km TIR) coverage over India for more than a decade.

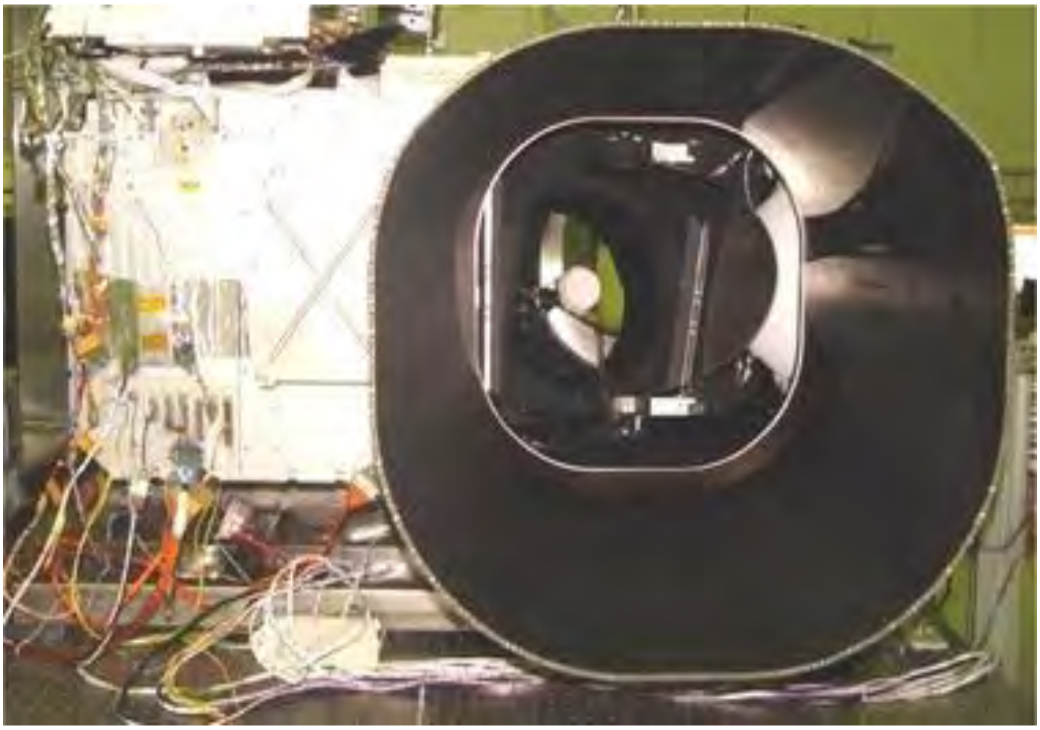


Fig.4: Imager camera (INSAT-3DR)

Oceanography: Specific attention was given to realize a sensor to meet the requirements related to study of oceans. Oceansat-1 was the first satellite built primarily for ocean applications. It was launched on 26th May, 1999 on-board PSLV-C2. The main mission objective of Oceansat-1 was to gather data for oceanography, land (vegetation dynamics) and atmospheric applications. OCM-1 provided data with two day repetivity, essential for systematic coverage of the huge oceanic resources. The camera aided in determination of chlorophyll concentration, detection and monitoring of phytoplankton blooms and obtain data on atmospheric aerosols and suspended sediments in water.

Continuity in service was ensured with development and launch of follow-on satellite Oceansat-2 on 23rd September, 2009. The OCM-2 payload on board Oceansat-2 satellite is shown in Fig. 5.

Oceansat-3 is planned as next in the series. It will consist of two payloads, OCM-3 having 13 narrow VNIR spectral bands and Sea Surface Temperature Monitor (SSTM-1) having 2 bands in Thermal Infrared region. Configurations for both the payloads have been finalized and the subsystems are in various stages of development.

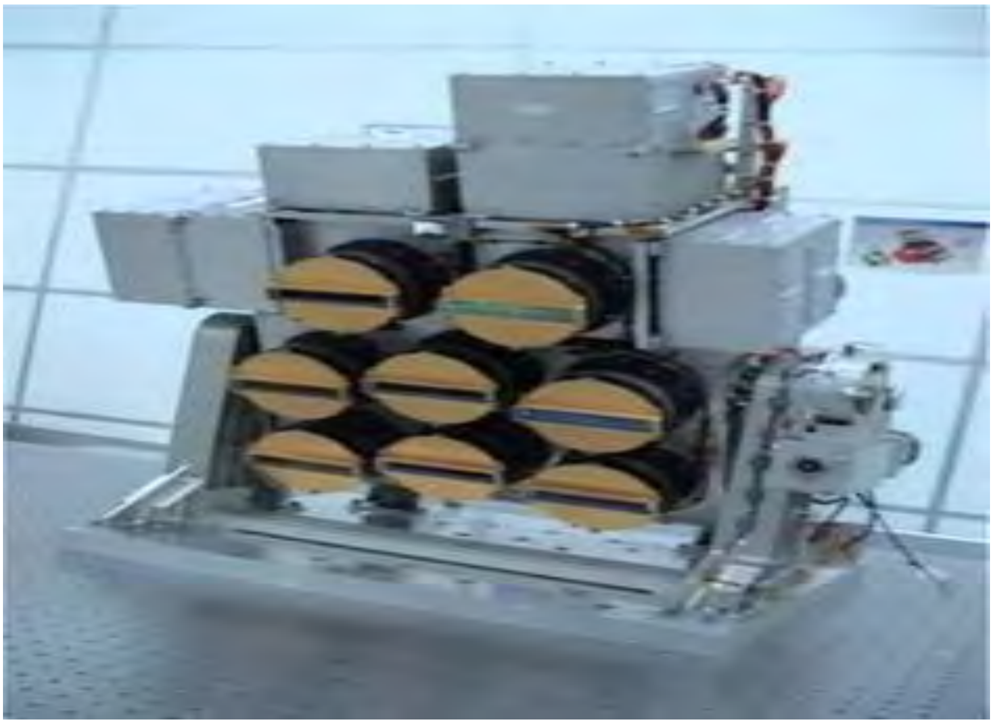


Fig.5: OCM-2 payload

High Resolution Observation: Since 1995, with launch of IRS-1C, ISRO has continuously provided High resolution images for various applications like Urban mapping, Cartography and Surveillance. From a spatial resolution of 5.8 m in IRS-1C, the capability has been contnuously improved to 2.5 m in Cartosat-1 to 1 m in Cartosat-2.

Presently, Cartosat-2S payload launched in June, 2016 offers spatial resolution of 0.63 m Panchroamtic and 1.57 m VNIR (Fig. 6) multicspectral capability with an operational life of 5 years.

In the field of High resolution imaging, next major jump will be realization of Cartosat-3 series. It will be a highly agile, advanced satellite having imaging capability with a very high spatial resolution of 0.25 m in panchromatic and 1 m in multi spectral bands. The spacecraft platform has many new technologies supporting the mission to manage and handle high data rates, agile enough to obtain more spots and strip images during a pass. This series will also have MWIR imaging capability to meet specific user requirements.

Fig.6: Cartosat-2S image of rome

To meet the ever increasing demands, HRSat series will be unique in the sense that it will provide not only high resolution imagery of 1 m, but will also have LWIR channels to cater to day and night monitoring requirements. Moreover, such three satellites will be launched together to offer specific viewing capability. The payload weight in this series will be less than 100 kg.

Small Satellite Platforms: ISRO also has taken up experimental missions that are aimed towards demonstration of technologies before they are taken up in regular missions. These missions are undertaken in small satellite platforms to reduce cost, time and associated risks. In order to facilitate systematic development, ISRO has developed standardized spacecraft bus for small satellite platforms. These fall under broad categories of 400 kg class, 100 kg class and 10 kg class of satellites.

In this category, IMS-1 satellite (100 kg class) was launched in 2008. It carried highly miniaturized multispectral camera MX-T. It had a four band imaging system that provided performance at par with LISS-2 camera of IRS-1A/1B. The weight of the MX-T camera (Fig. 7) was only 5 kg compared to LISS-2 weight of 150 kg. It also carried a compact imaging spectrometer HySI-T. This instrument provided measurement of reflected spectrum in the visible and near infrared wavelength in 64 contiguous bands. The weight of HySI-T was only 3 kg.

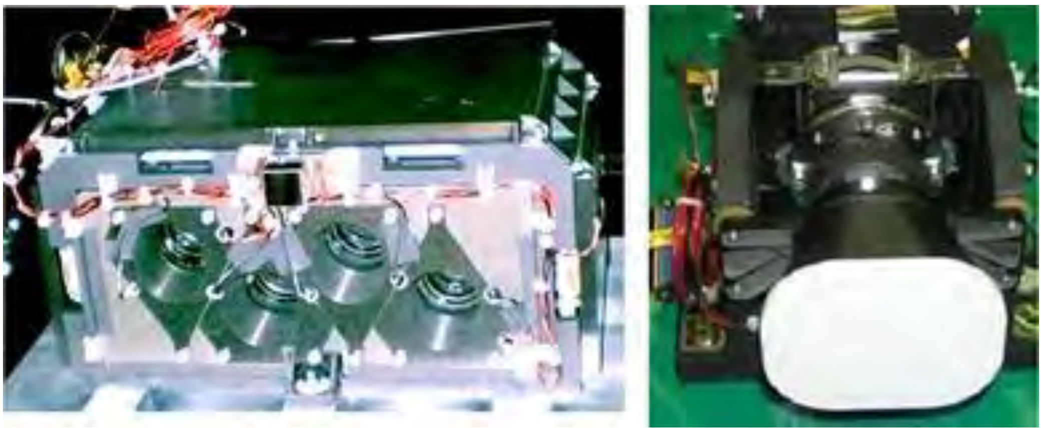


Fig.7: Mx-T and HySI-T cameras on-board IMS-1

Airborne Electro Optical Sensors: In addition to providing a wide spectrum of imaging options from space, ISRO has built specific sensors to meet the exclusive requirements of high resolution and hyperspectral imaging from aerial platform as well. The present suit of sensors comprises multi-view (Fig. 8) panchromatic (ATMC), VNIR multispectral (NMx) and VNIR hyperspectral (AIMS) instruments. Both panchromatic and multispectral sensor generate imageries with approximately 30 cm spatial resolution from an altitude of 6 km. The hyperspectral sensor offers a spectral resolution of 2.5 nm.

Fig.8: NMx colour composite

Microwave Remote Sensing Sensors: Microwave Remote Sensing (MRS) programme of ISRO has seen the development of both active as well as passive remote sensing systems for space and airborne remote sensing activities. Passive sensors (Radiometers) are aimed at providing atmospheric and oceanographic remote sensing data from space-based platforms, whereas Active sensors (SAR, Scatterometer, Altimeter) are dedicated for land as well oceanographic applications. Synthetic Aperture Radar (SAR) Imaging System, which witnessed a beginning in experimental airborne applications, have, over the period, graduated into operational spaceborne missions. The evolution of MRS programme also resulted into development of various sophisticated key technologies required for this programme.

Atmospheric and Oceanographic Sensors: Both passive and active microwave remote sensing instruments have been/are being developed to meet the requirements of atmospheric and oceanographic applications. From the modest beginning of development of SAMIR payloads for Bhaskara series of satellites for scientific understanding, payloads like MSMR and Scatterometers are designed for providing operational services. At the same time, ISRO initiated collaborative development of payloads, like Megha-Tropiques, with established space agencies, to consolidate expertise available in the development of complex technologies.

SAMIR Payload: Satellite Microwave Radiometer (SAMIR) ushered in microwave remote sensing technology. It was flown on Bhaskara-1 and -2 satellites in 1978 and 1981. SAMIR in Bhaskara-1 had 2 channels in 19.35 and 22.35 GHz. SAMIR payload in Bhaskara-2 had additional channel in 31 GHz. SAMIR provided the first glimpse of global water vapor and liquid water content with indigenous technology. Bhaskara was a spin stabilized satellite and this fact was effectively used to configure this vertically scanning radiometer. This radiometer was configured in Dicke configuration in which scan view of the open sky was used as cold calibration input. It provided a footprint of 150–250 km resolution with sensitivity of 1–2 K. Bhaskara satellites had two spinning modes namely around roll axis or pitch axis. In the first mode of spin, SAMIR provided a swath of 1500 from 777 km altitude. In second mode of spin, in every scan it provided single sample of measurement at Nadir.

MSMR onboard Oceansat-1: Multi-frequency Scanning Microwave Radiometer (MSMR) was the co-passenger payload along with Ocean Colour Monitor (OCM) onboard Oceansat-I (IRS-P4) satellite, ISRO's first satellite dedicated for oceanographic applications. The satellite has been launched on May 26, 1999. MSMR was a four-frequency, dual-polarised scanning microwave radiometer to measure brightness temperatures of the earth surface. This was used for deriving parameters like sea surface temperature, wind speed, water vapour content, etc. from the measured brightness temperatures. The system was designed for four frequencies viz., 6.6, 10.65, 18.0 & 21.0 GHz in order to cater to the above applications.

MSMR provided routinely 48 h global data product, in terms of Brightness Temperature, SST, Wind Speed, Water Vapor content and Cloud Liquid Water, on operational basis from National Remote Sensing Agency (NRSA), Hyderabad, India. The data was used for various experimental investigations like soil moisture, Antarctic ice study etc. Unfortunately, the payload was shutdown after two and half years of operation due to power starvation caused by partial failure of solar panel.

Ku-band Scatterometer On-Board Oceansat-II: Ku-band Scatterometer was being built by ISRO to gather information about the near surface winds over oceans at a global level. The scatterometer derived ocean surface wind field observations form a very important input to the global weather forecasting system. The scatterometer transmits a pulse through a dual polarized offset reflector antenna, spinning at the rate of 20.5 RPM around yaw axis. The vertical and horizontal beams are pointed at off nadir pointing of 49.4° and 42.6° respectively to cover a total swath of 1800 km with inner beam of 1400 km. All the regions within the inner beam coverage provide azimuthally divergent 4 measurements of radar cross section of capillary waves riding on the gravity waves of the sea. In the inner swath, wind direction can be measured unambiguously. However, in the outer swath, because of availability of only two measurements of radar cross section, wind direction is resolved with the help of auxiliary information like numerical model winds. It operates at 200 Hz, alternate pulses which are switched between V and H ports of the antenna. There is a provision of extensive on-board calibration of the system to provide improved accuracy in wind vector measurements.

OCEANSAT-2 Scatterometer (OSCAT) provided a global coverage of wind vector at 50 kmx50km as well as 25 × 25 km grid every 2 days with most of the earth covering daily. OSCAT proved to be an excellent instrument for oceanography. Widespread acceptance and usage of the OSCAT data by various international agencies like JPL, NOAA, KNMI, EUMETSAT and ECMWF for both research and operational purposes is a testimony to its quality and utility. OSCAT had developed snags in the transmitter subsystem system of primary chain and scan mechanism of the redundant (backup) chain during fag end of its design life period (around 4½ years from launch) forcing the ISRO to suspend its operation in April 2014. Scatterometer on OCEANSAT-2 was followed by dedicated scatterometer onboard SCATSAT-1 Mission in 2016. Various, Hydrological, Agricultural and Forestry applications are being carried out in SCATSAT-1 utilization program. ISRO will be launching OCEANSAT-3 & 3A missions with Ku-band pencil beam scatterometer in 2018/19-time frame.

Megha-Tropiques : In order to provide boost to climate research with high repetivity data over the tropical regions, a joint Indo-French collaboration resulted in Megha-Tropiques satellite with three payloads, namely MADRAS (Microwave Analysis And Detection of Rain And Atmospheric Structures)- Imaging microwave radiometer 18.7,23.8, 36.5, 89 to 157 GHz (5 Frequencies and 9 channels); SAPHIR (Sounder for Atmospheric Humidity Profiling (6 Channels around 183 GHz) and SCARAB (Scanner for Radiation Budget)-Broadband radiation measurement instrument in shortwave (< 4 mm) and long-wave (> 4 mm)

MADRAS was configured as total power radiometer with 65 cm diameter antenna to provide observation with resolution from 67 to 10 km over different frequency bands. It provided measurements over a swath of 1700 km at incidence angles ranging from 50°–55°. Megha-Tropiques was placed on an inclined orbit of 20° at 867 km altitude to provide repetitive coverage of equatorial region between 30°N and 30°S at every 6 h.

Planned MM Wave Sounder: Millimeter wave sounders exploit the atmospheric opacity to sense the atmospheric temperature and humidity profiles. Sounders have an amalgamation of channels at which the atmosphere is opaque for sounding purposes and at which the atmosphere is transparent for correction of the surface contamination. Already a programme to develop MM Wave sounder for measuring vertical profile of atmospheric temperature and humidity has been initiated. Two distinct sounders are being planned: (a) Temperature Sounding Unit (TSU) operating in oxygen absorption band in 50–60 GHz and (b) Humidity Sounding Unit (HSU) operating around 183 GHz. Both these units will operate in vertical scanning configuration.

Radar Based Imaging Sensors: ISRO mastered space based imaging capability two decades ago with the launch of IRS-1A on 17th March, 1988. Progressively, optical camera based imaging capability is in the path of continuous improvement both in terms of resolution and swath coverage till this date. In a programmatic approach, the scope of ISRO's remote sensing capability was extended to microwave bands after attaining successful grip over imaging technology in optical bands.

Synthetic Aperture Radar (SAR) was logical choice for Imaging Radars in microwave bands, considering its all weather and day-night capability. Further, radar response to geometric shape and distribution of features was realized to be complementary and supplementary to spectral reflectance based feature characterization available in optical imaging process. However, development of SAR needed mastering of both sophisticated radar technology and complex SAR processing algorithm. Since space borne SAR was highly cost intensive, airborne version of SAR was embarked upon as cost effective route of mastering SAR technology in all its nuances. Over the period, both airborne and space borne versions of SAR technology development have taken vibrant shape in ISRO towards harnessing their utilization potential. Summary of Airborne microwave imaging Radars is given in Table 1.

	SLAR	ASAR	DMSAR
Frequency	9.6 GHz (X-Band)	5.3 GHz (C-Band)	5.35 GHz (C-Band)
Polarisation	HH	VV/HH	VV/HH
Platform/Altitude	Dakota (2–3 km)	Beechcraft (8 km)	Beechcraft (8 km)
Pulsewidth/Chirp bandwidth	80/300 ns	20 µsec 25 MHz	20 µsec 22,575 37.5, 18.75 MHz
Resolution/Swath	50–100 m/5 km	6–8 m/25 km	<2 m/6 km 3 m/25 km 5 m/50 km 10 m/70 km
PRF	850 Hz	425–525 Hz	452 Hz
Peak power	25 kW	2 kW	8 kW
Antenna Length/Pattern	2 m/Cosine Weighted	1.3 m/Cosec2	1.3 m/Cosec2

Table 1 Summary specifications of airborne imaging radars developed in ISRO

Airborne Imaging Radar Development

X-Band Side Looking Airborne Radar (X-SLAR): Imaging Radar development was initiated modestly with development of Side Looking Airborne Radar (SLAR) in X-band. This SLAR was basically used for development of radar technology and it was in flying condition from 1985–1989. SLAR provided imaging over 2–5 km swath with 50 m-100 m resolution. Compared to today’s technology, its capability was primitive; but it acted as a test bed to test various new technologies like the radar itself, data recording system and on-board Quick Look Display (QLD) system. Further, the experience gained by experimenting with this system, acted as foundation for subsequent development of complex SAR technology.

ASAR (Airborne SAR) was the first proud foray of ISRO in SAR development (Fig. 9). The aim of this development was not only technology attainment but also demonstration of application potential. Consequently, this system was configured in C-band providing 6 m resolution over 25 km swath. Though the breadboard model was tested in 1992, the aircraft was lost in an accident in 1994. The development was continued in a new aircraft and the ASAR system was used for experimentation since 1997. For the first time, a modest narrow swath (2.5 km) Real Time Processor was demonstrated in this system.

The high point of this project was development of a sophisticated SAR processor involving motion sensing and compensation. In fact it had a novel two track motion compensation processor which added to the robustness of the system. This algorithm was implemented on a parallel processing system consisting of 8 Xeon processors. ASAR has been used to demonstrate flood mapping and monitoring operation in 2003–2004. ASAR experience provided the impetus for development of an improved version of C-band airborne SAR, DMSAR (SAR for Disaster Management), exclusively for flood monitoring activity. ASAR experience has demonstrated that for quick reaction to flood related emergency, airborne SAR system is more effective than its space borne counterpart. Spaceborne SARs, with their fixed orbital configuration, cannot ensure quick reaction to flood situation.

DMSAR–Airborne SAR for Disaster Management: DMSAR was developed with operational requirement for disaster monitoring. To aid flood monitoring and assessment of damage to infrastructure, four resolution modes were provided. DMSAR was test flown for the first time in Nov. 2005. It was calibrated completely and its effectiveness in flood assessment was evaluated in 2006. To support its high resolution and wide swath capability, the ASAR processing algorithm was significantly modified. A new algorithm called *Track Steering* algorithm was developed (under process of patenting) to process in high resolution modes. The DMSAR processor is available on three platforms:

A parallel machine with 32 Itanium processors; In house developed portable Near Real Time Processor (NRTP) built around 96 TS-101 processors and *GARUDA* computing grid provided by CDAC. Using this grid, DMSAR data can be processed simultaneously on an array of computing nodes available in academic and research institutions across India. Figure 10 shows the photograph of DMSAR in operation and also a sample of high resolution imagery obtained by it. Figure 10 depicts a typical flood region, mapped by DMSAR, over Dharbhanga, Bihar in 2007. Devastating breach of Koshi River in Nepal in September 2008 as captured by DMSAR is also seen in the Fig. 10. This breach resulted in change of Koshi river track leading to devastating flood of Bihar Plains.

Fig.9: ASAR system mounted in beechcraft and a sample of imagery obtained by ASAR

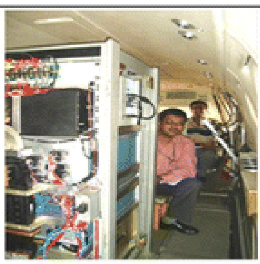
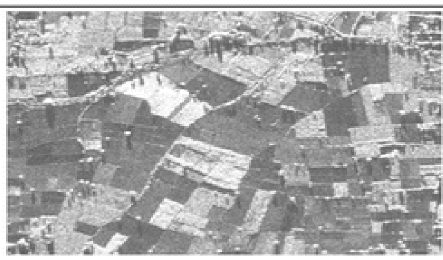
		
DMSAR system mounted in beechcraft	**High Resolution Imagery obtained by DMSAR**	**Koshi River breach imaged by DMSAR in 2008**

Fig.10: DMSAR system and its applications for flood assessment in Koshi, DMSAR system mounted in beechcraft, High Resolution Imagery obtained by DMSAR, Koshi River breach imaged by DMSAR in 2008

RISAT–Radar Imaging Satellite, ISRO's First SAR Satellite: India's first C-band spaceborne SAR onboard Radar Imaging Satellite-1 (RISAT-1) built by Space Applications Centre, launched on 26th April, 2012, has been extensively used by Indian and international users for various applications like agriculture, forestry, oceanography geology, cryosphere, disaster management support, land-use, etc.

RISAT-1 SAR (Fig. 11) is operated in the following basic imaging modes:

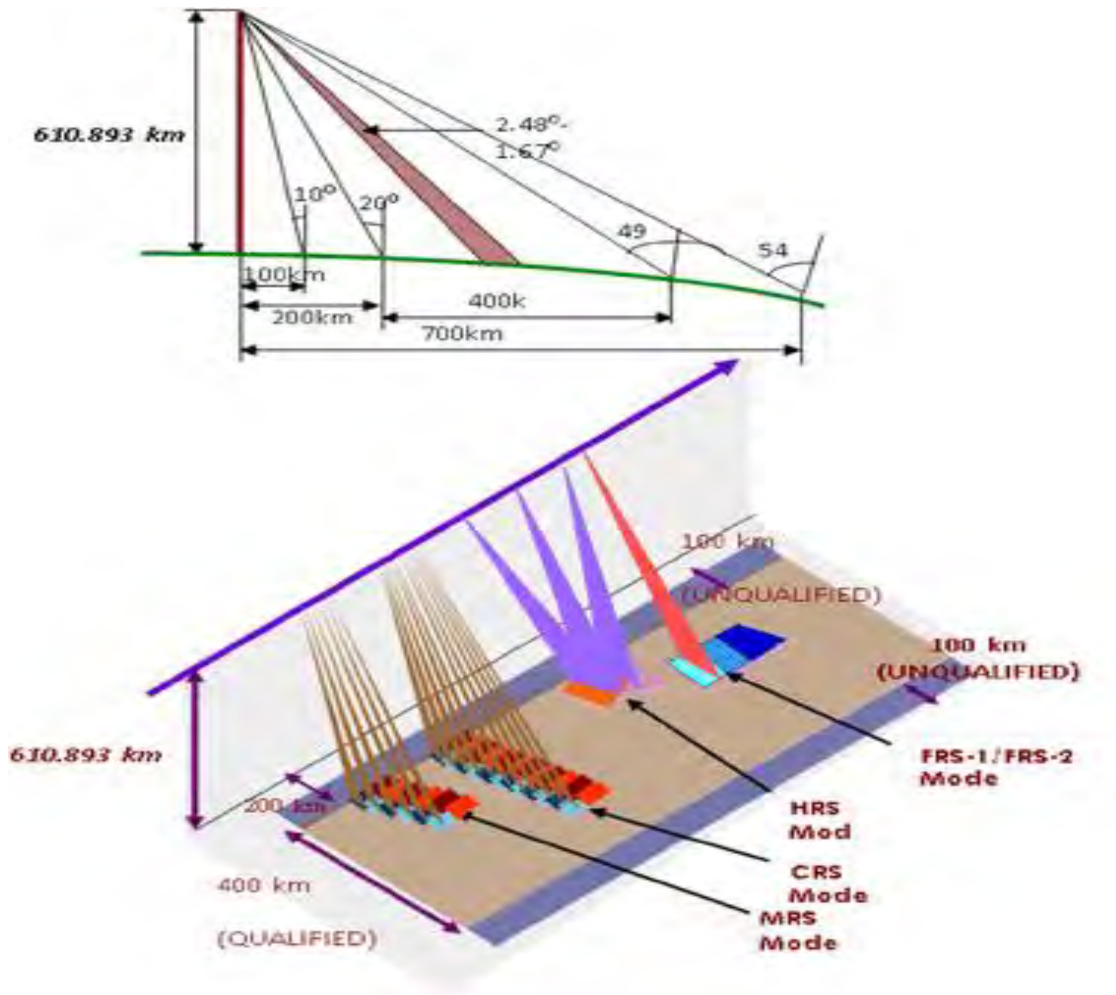


Fig.11:RISAT imaging modes

- *Fine resolution stripmap mode-1 (FRS-1)* It is based on conventional mode of SAR Stripmap imaging, providing 25 km swath (25 km) with 3-meter resolution.
- *Coarse resolution scan SAR mode (CRS)* This 12-beam ScanSAR mode provides 223 km swath with a resolution of 50 m.
- *Medium resolution scan SAR mode (MRS)* This is a 6-beam ScanSAR mode, similar to the CRS mode, providing a resolution of 25 m over a swath of 115 km.
- *Fine resolution stripmap mode-2 (FRS-2)* This mode has quad polarization capability. Philosophically, this mode is a hybrid stripmap and scanSAR.
- *High resolution sliding spotlight mode (HRS)* In the sliding spotlight mode, the antenna beam is oriented continuously to illuminate a particular 10 km × 100 km sliding spot on the ground, which can be imaged with 1 m resolution.
- *Circular polarimetric modes (C-HRS, C-FRS-1, C-FRS-2, CMRS, C-CRS)* All the modes mentioned above can be operated in hybrid-circular polarization.

There are several unique features of RISAT and the entire set of technologies associated with the payload is indigenous. RISAT-1 is the only C-band SAR in the world that is capable of giving 1 m resolution over 10 km x 100 km spot. It is the first SAR in the world with Hybrid polarimetry, which overcomes the constraint of restricted imaging below 35° incidence angle and allows RISAT-1 to operate at incidence angles as low as 12°. This feature helps the system develop new remote sensing application in soil moisture, glacier studies and better imaging in hilly regions.

RISAT-1 SAR images/data products are disseminated and utilized by the identified users on an operational basis mainly for Agriculture, Disaster Management and other ancillary applications related to oceanography, urban mapping, forest cover, etc. Hybrid Polarimetric SAR image generation from RISAT-1 SAR data is the other major capability utilized by interested scientists and researchers. Antrix, India has also entered into a major contract with M/s. Kongsberg Satellite Services (Ksat), Norway for RISAT-1 SAR direct data reception and SAR image generation at its Svalbard and Tromso stations, thereby confirming the good quality and international acceptability of RISAT-1 SAR data.

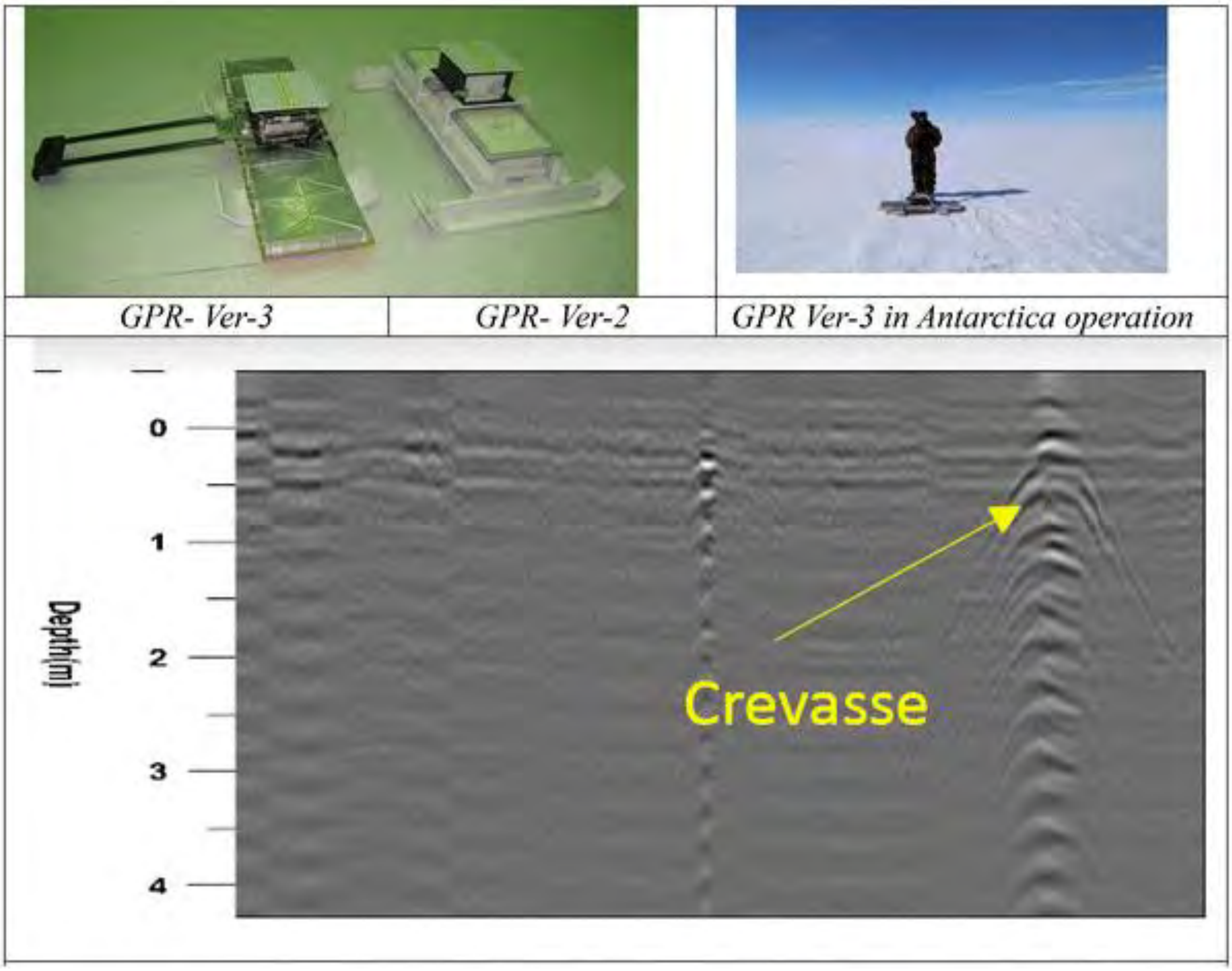
Apart from design and development of an active antenna based SAR system, the major achievement of RISAT project is extensive industrial partnership in developing critical technological elements needed for payload. This involved not only capacity building for production of space qualified hardware in the industry but also extensive qualification of production processes and training and sensitization of personnel involved. The TR module, along with all the MMICs associated with it, are designed and produced in India itself. Miniaturized pulsed EPC for powering TR module, featuring three different HMCs and planar transformer, has been a feat of Indian industry. Printed antenna aperture has been designed in ISRO and produced by Industry. The ASIC meant for controlling active array antenna elements, has been designed in-house.

ScatSAT-1: OSCAT, during its life time has demonstrated the importance and significance of the ocean wind vector data in weather modeling and prediction and laid the ground for continuation of the global ocean surface wind vector data acquisition. Based on this experience, SCATSAT-1 (Scatterometer Satellite) mission was planned as a dedicated mission to continue the global ocean wind vector data acquisition started by the OSCAT. SCATSAT-1 is configured on Indian Mini Satellite (IMS-2) Spacecraft bus of ISRO. Scatsat-1 is a Ku-band pencil-beam Scatterometer radar-only payload mission, has been launched in September 2016. The Scatterometer instrument onboard SCATSAT-1 is similar to the OSCAT flown onboard OCEANSAT-2.

Retention of major system levels specifications (altitude, scan geometry, look and incidence angles) has facilitated fast realization through the usage of hardware procured or designed for OSCAT. RF designs viz., Frequency Generator, TWTA, Front-End Switch Assembly (FESA), Receiver subsystem, have been retained while digital subsystem has been miniaturized by combining various functionalities like baseband chirp generation, radar Controller and Data acquisition and onboard processing into one subsystem. Major changes have been introduced to improve the overall instrument reliability factor through cross patching of the critical subsystems. Though the OSCAT has been designed primarily for capturing ocean surface wind vector data, it has been found that the scatterometry data has wide applications in sea ice and polar ice studies as demonstrated by both QuikScat and OSCAT.

Ground Penetration Radar: The design and development of a miniaturized ground penetration radar, operating at 250-750 MHz, has been taken up by SAC as a proof-of-concept prototype for geodetic applications on earth as well as future lunar and planetary missions, to derive information about land profile, geology and other potential subsurface resources. The frequency-stepping P-Band instrument uses a bow-tie antenna and is realized in a compact 8.4 W, 10 kg frame that is easy to use. The instrument makes use of miniature ruggedized (IP67 compliant) SSR of 64 MB (extendable to 512 MB) with UART recording interface and USB data-retrieval interface, specifically for GPR operations. Low-cost instrument has been realized which is ~ 20 times cheaper than commercial equivalent. Indian market is presently procuring GPRs from only foreign suppliers. Hence, this instrument presents a viable indigenous alternative, and is being offered for Technology Transfer.

This GPR has been a prime instrument for Antarctica snow studies (Indian Scientific Expedition to Antarctica, ISEA) over the past three years; the fourth expedition with this GPR is currently in progress. Snow and Ice profiles up to 14 m depth have been recorded at Antarctica (Fig. 12).



Follow-On Mission: RISAT-1A: To provide continuity of RISAT-1 mission, a follow-on mission called RISAT-1A has been already approved for launch by 2018-19 timeframe. Keeping in view the long lead times associated with the development of active-array electronics and other elements (like, antenna structure, spacecraft interfaces), no major changes have been planned in RISAT-1A configuration. Therefore, the system specifications of RISAT-1A are primarily the same as that of RISAT-1.

The improvements in RISAT-1A include configuration of full-polarimetric mode in lieu of quad-pol mode of RISAT-1 (termed Fine Resolution Stripmap-2, FRS-2; which basically operates with alternate bursts of H and V transmit pulses). Though the full polarimetric mode calls for high PRF (due to alternate H & V pulses) and compromises on swath, it allows extraction of the complete 4 × 4 Stokes 'matrix and is therefore, considered to be the gold-standard for polarimetric observations. Due to these factors, the full-polarimetric mode is an important inclusion in the RISAT-1A configuration. Hybrid polarimetry available with all the resolution modes of RISAT-1 will be retained in RISAT-1A as well. As a result, both the forms of polarimetry (hybrid and full-pol) will be available in RISAT-1A.

RISAT-1A will operate from a sun synchronous orbit at a nominal altitude of 536 km, same as that for RISAT-1. It will image from nominal 100 to 700 km off-nadir distance and corresponding look angles will vary from 10.5° to 50.6°.

Fig.12: GPRs and crevasse observed from Antarctica

RISAT-2A: RISAT-2A Active antenna based Synthetic Aperture Radar development is initiated with the objective of providing continuity to RISAT-2 mission requirements. RISAT-2 satellite was launched in April 2009 with mission life of 5 years. The SAR will operate in X-band with centre frequency 9.6 GHz with Single/Dual/Circular Polarization capability. It will offer multimode operation with high spatial resolution. The SAR will have a high resolution mode with spatial resolution of less than 0.4 m.

All the modes (StripMap, Spot, Fine Spot and Mosaic) are available in single polarization (HH/VV), dual polarization (HH + HV, VV + VH) and hybrid-circular polarimetry (transmit circular, receive linear). Swath coverage of 200 km to 650 km will be achieved by roll-tilting of the satellite.

In order to provide greater flexibility in the selection of the look angles for different applications and to increase the effective repeatability, a region on the ground may be accessed by different look angles ranging from 23.4° to 52.8° corresponding to off-nadir distances of 200 km and 650 km, respectively. This look angle variation is implemented by roll-tilting the satellite. Electronic beam scanning of ± 2° in elevation direction and ± 2° in azimuth direction is planned. SAR will operate with basic elevation beam limited swath of 6–10 km, over a total ground distance of 450 km, starting from an off nadir distance of 200 km and up to 650 km.

X-band MiniSAR: X-Band Miniaturized Synthetic Aperture Radar is developed with the objective of high spatial resolution imaging from an airborne platform. The SAR can operate in X-band, Single/Dual/Circular Polarization, with high spatial resolution. The system design is made such that it can accommodate altitude variation of 3 km to 10 km with on-board data storage. System can be fit in small aircrafts as it has small size and low weight.

L &S Airborne SAR: ISRO in collaboration with NASA & JPL is developing a Dual Frequency Sweep SAR (DFSS) in L and S bands. As part of this, Space Applications Centre (SAC), ISRO is realizing the S-SAR and Jet Propulsion Laboratory (JPL), NASA is developing the L-band SAR. In this process, a number of new technologies in digital and RF domains are being developed at SAC. As a pre-cursor to the space-borne SAR development, an airborne SAR in L& S band is being planned. For the airborne version, both L & S band SARs will be developed simultaneously by SAC itself, adhering to system design aspects of NISAR to the maximum extent possible. The sensor being developed is aimed to be operated in a Beech craft, currently available with NRSC, Hyderabad. The system is being designed to be operated at an altitude of 8 km with a platform velocity of 120 m/s. The centre frequencies are maintained at 3200 MHz for S-band SAR and 1250 MHz for L-band SAR, with bandwidth options of 25, 50 and 75 MHz, as in the case of NISAR. The sensor is being designed to operate in all the polarisation modes, viz. single, dual, compact, quasi-quad and full polarimetry.

L-Band SAR Satellite: Presently plans are afoot to build an L-band SAR as successor of RISAT (Fig. 13). Presently the pay load is in drawing board. This SAR will have scan SAR modes matching with RISAT. It will have stripmap mode of resolution 5 m and swath of 60 m. The interesting addition will be electronically steered spotlight mode providing 2.5 m resolution over 340 × 40 km spot. Compared to RISAT, it will have additional linear polarimetry mode apart from Hybrid polarimetry.

Fig.13: L-Band SAR imaging configuration

Like RISAT, the antenna will be based on active array technology to provide electronic steering in elevation and limited electronic steering in azimuth to support spotlight mode. The antenna size will be 10mx3 m, weighing 600 kg and the satellite is being planned for launch by PSLV.

L-band SAR pay load will also carry a demonstration model of Real Time Processor, for the first time, for processing the SAR raw data on the fly.

NISAR: NASA/JPL and ISRO have undertaken a collaborative programme for the joint development and launch of dual band NISAR science mission, based on JPL's patented SweepSAR concept, which helps achieve wider swath without compromising resolution (Fig. 14). NISAR will be a unique radar imaging satellite mission carrying together, JPL/NASA's L-band SweepSAR and ISRO's S-band SweepSAR. It will support 5-10 m resolution over > 225 km swath. The 12 m single reflector will serve both L- and S-band SweepSAR and will consist of 24 S-Band TR Module pairs for dual polarization operation. Payload level Baseline Design has been finalized and proof-of-the-concept development activities are underway related to various constituents like S-Band TR Integrated Module (TRiM) and RF Baseband & Digital hardware.

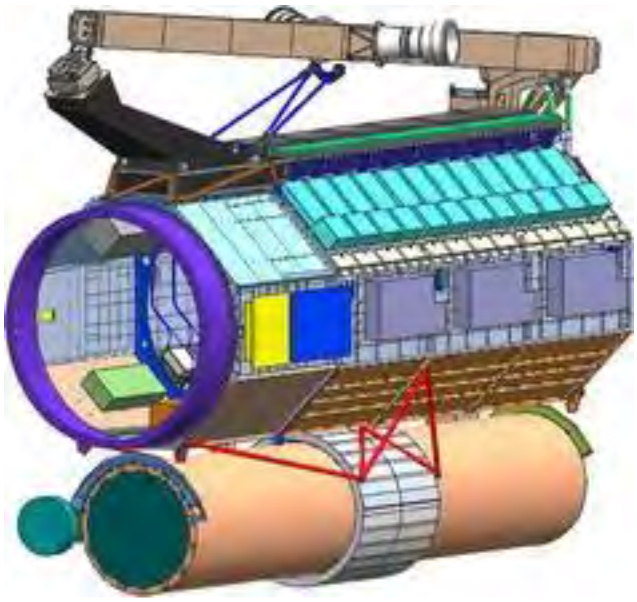


Fig.14:Schematic of NISAR payload

NISAR is optimized for studying hazards and global environmental change using advanced radar imaging that will provide an unprecedented, detailed view of Earth. The satellite is designed to observe and take measurements of the planet's most complex processes, including ecosystem disturbances, ice-sheet collapse, and natural hazards such as earthquakes, tsunamis, volcanoes and landslides. Scheduled to be launched in 2020, the mission will also monitor the country's agricultural biomass, snow and glacier studies in the Himalayas.

Terahertz Telecscope: The vision of the Terahertz technology development program is to bridge the so-called Terahertz "technology" gap that exists between the technologies at microwave and at infra-red and visible ends of the electromagnetic spectrum. The Terahertz gap spans over a large frequency range from mm-wave (up to 300 GHz) to sub-millimeter wave (300–750 GHz) and further to far infrared (25–350 µm). The technology is entirely different as one moves from one frequency regime to another— rom Schottky Barrier diodes to Superconductor-Insulator-Superconductor (SIS) to Bolometers and their associated stringent cooling requirements. Globally, astronomical observation has been the prime science driver for THz technology development for studying the evolution of the universe by spectroscopic and continuum observations in the ISM, the circumstellar discs, giant molecular clouds, proto-planetary discs, asteroids, and Young Stellar Objects of galaxies at different red shifts.

Continuing ISRO's thrust for building and indigenizing state-of-the-art technologies for various microwave/optical payloads, for realization of a multi-frequency mm-wave/sub-millimeter wave sensor covering frequency range up to 300 GHz, various critical technologies will be indigenously developed at SAC.

Earth Observations (EO) Applications in India - A few Examples: During the past decades, Indian Space Programme has made remarkable progress in building space infrastructure to accelerate various developmental processes, and harness the benefits of space for socio-economic development in the country. Since the early days of Remote Sensing with Landsat MSS data in the 70s, use of remote sensing for natural resources inventory & monitoring has come a long way in the country - graduating from demonstration phase to operational era, expanding scope to newer and newer areas over time. Today, remote sensing based actionable information/ products & services are supporting informed decision making in the country, in the areas of - food & water security, environment & eco-system management, cartography, ocean & atmospheric studies and disaster mitigation. The hallmark of the Indian EO programme is also the close cooperation between Government, Industry and Academia - forming a formidable EO triad.

In India, the space technology applications have helped in addressing the national developmental needs, and enabled creation of a comprehensive Spatial Data Infrastructure (SDI) as a national repository. Some examples of using such spatial data for management of natural resources, operationally, include: identifying environmentally degraded wastelands & reclaiming cultivable wastelands; identifying sources of drinking water - especially in hard-rock terrain, aw well as suitable sites/ zones for ground water recharge; watershed development in a holistic manner by linking livelihood system to soil & water conservation measures; irrigated/ command area management addressing issues like water-logging, salinity & alkalinity; assessment and forecasting of agricultural crop acreage & production; bio-diversity characterization at landscape level; and disaster management support for cyclone, flood, agricultural drought, landslides, forest-fire; etc. Following are some of the applications that highlight the use of EO data for societal benefits in the country.

Crop Forecasting:

In globalised world, agricultural statistics is key information for taking crucial decisions related food security. Towards this, Ministry of Agriculture has been supporting a remote sensing based nationwide project called pre-harvest Crop Acreage and Production Estimation (CAPE) for providing in-season crop statistics with reasonable accuracy. Based on the experience gained through CAPE; ISRO has developed methodology for Forecasting Agricultural Output using Space, Agro- meteorology and Land-based Observations (FASAL), combining remote sensing, meteorology and econometrics for providing multiple in-season crop forecasting. This is one of the operational applications developed using remote sensing to provide forecasts of major crops with reasonable good accuracy well before the harvest. The effort has contributed to reducing the gaps between crop production and post-harvest technology, pricing and policy decisions. ISRO has also transferred the methodology of FASAL and National Agricultural Drought Monitoring Assessment Project to Mahalanobis National Crop Forecast Centre (MNCFC) of Ministry of Agriculture. Currently, MNCFC operationally provides multiple pre-harvest production forecasts of 8 crops, viz., Rice (kharif & rabi), wheat, rapeseed & mustard, potato, jute, sugarcane, cotton and sorghum (rabi) at National/ State/ District levels. The Centre also assesses the progress and severity of drought in the country towards facilitating better management of agriculture in drought prone/ affected regions.

Disaster Management Support (DMS): DMS is another key application, which takes cognizance of the convergent technologies - satellite communication, satellite remote sensing and meteorology, towards timely delivery of operational products and services for disaster mitigation, during different phases of the disaster event. The unique capabilities of satellites providing comprehensive, synoptic and multi-temporal coverage of large areas at regular intervals with quick turnaround time has been valuable in disaster mitigation efforts. The sections below give the highlights of a few specific case studies.

Uttarakhand Flash Floods: Unprecedented heavy rainfall in parts of Uttarakhand during 16-17 June 2013 had led to flash floods and debris-flow, causing enormous destruction to life and property. Pre and post-flood satellite images were analysed and information on: (i) extent of damage to structures, roads, settlements etc., (ii) formation of new channels upstream of Kedarnath, and (iii) flow of debris from northern and north-eastern sides were provided to concerned State and Central Government Agencies in a timely manner for planning relief to the affected. Post disasters, about 2400 landslides were mapped in the disaster-affected area for implementing long-term mitigation measures.

Based on request from the State, 12 mobile satellite phones were provided to local administration in Uttarakhand for deployment in deep interior locations. About 1000 phone calls were made during the initial critical ten days. Five transportable satellite terminals (one mobile van and four fixed terminals) were established on crash basis, in the affected area, to facilitate videoconference, data & voice transfer for coordinating the rescue and relief activities.

Tropical Cyclone 'Phailin': Severe tropical cyclone Phailin (9-12 Oct 2013), a significant severe weather system, which hit the Odisha coast on 12 October 2013, was monitored extensively using India's advanced weather satellite INSAT-3D. The damage to human loss due to the cyclone "Phailin" in Bay of Bengal and the States of Odisha, Jharkhand and Bihar was minimized due to satellite based timely early warning, and constant tracking of the cyclonic system.

High-resolution images and the sounder data from the satellite provided information on detailed structure of clouds near the centre of the tropical cyclone, cloud properties, rainfall distribution, etc., which helped in assessment of likely damage that could be caused due to the cyclonic winds. The track and intensity of the cyclone, as predicted, were disseminated through the MOSDAC website of ISRO.

Immediately after the cyclone hit, the State Government of Odisha was updated on the inundation due to floods in different rivers - at every 12 hours for the first three days, and then on daily basis; based on this, the State Administration could plan and implement the evacuation activities resulting in a very low casualty of human lives.

National Drinking Water Mission: In the last two decades, significant changes have taken place in the country in using groundwater for irrigation. Currently, about 60% of irrigated agriculture depends on groundwater sources; and close to 90% of rural domestic water supply is from groundwater. Remote Sensing data has proved its immense potential in identification of potable groundwater sources in terms of prospective locales, depth to water table & yield; and also, in identifying suitable zones/ sites for constructing recharge structures.

The project has been carried out in phases to cover the entire country; and the Groundwater Prospects Maps have been provided to respective State Agencies for using them in conjunction with hydro-geological and geophysical investigations for selecting suitable sites for drilling wells around needy habitations. The maps have also been used for locating site-specific recharge structures based on nature of underlying aquifer, site conditions, availability of water for recharge, etc.

Using these maps, over 300,000 bore wells have been drilled, across the country, with 90-95 % success rate; and over 9,000 recharge structures have been constructed.

Apart from these, a few States are using these maps in MGNREGA and Watershed Development Programmes of Ministry of Rural Development. In Gajra sub-watershed of Durg District, Chattisgarh, the Public Health Engineering Department (PHED) has constructed over 100 recharge structures of various types, such as percolation tank, stop dam, check dam, nala bund, etc.). Subsequently, it has been reported that, during 2002-2010, the water table in the area has come-up by 15 m on an average, and, at some places, even by 20 m.

Space-based Information Support for Decentralized Planning (SIS-DP): Reliable information on land & water resources and their optimal management is vital in developmental planning. State level information repository comprising of natural resource database at 1:10,000 scale, coupled with stakeholder datasets and field- level information, helps in strengthening decentralized planning and decision making at grassroots level. In this regard, the recent initiative on 'Space based Information Support for Decentralized Planning '(SIS-DP) plays an important role in empowering the local bodies to prepare the action plans through a coordinated approach. For the 5 priority States (Andhra Pradesh, Assam, Haryana, Kerala and West Bengal), cadastral maps are also being integrated with the natural resources database. Taking advantage of the Information & Communication Technology (ICT), the information would be disseminated to grassroots through ISRO's Bhuvan Panchayat Geoportal.

Enhancing Area under Agriculture: About 16% of the country is characterized by wastelands, both cultivable and non- cultivable; and, reclamation of such lands is a must for enhancing agricultural productivity, improving ecology, and non-agricultural uses as well. Mapping and monitoring of wastelands for entire country has been carried out using remote sensing data at the behest of Ministry of Rural Development for planning and implementing various reclamation activities. The remote sensing based mapping and monitoring of wastelands has provided the estimate that the total wasteland area in the country is 46.72 mha (2009). Based on this information, Ministry of Rural Development has been planning and implementing wasteland development activities across the country. These efforts have also helped in diversification and intensification of agricultural activities especially in rain-fed areas.

Watershed Development: Watershed Development Programme is one of the major initiatives in the country towards conservation of soil & water in the rain-fed areas for enhancing agricultural production, providing livelihood security to rural people, besides halting the depletion of the natural resources. Space applications have been adapted to respond to integrated development of land and water resources, and assess/ monitor the improvements of the treated watershed.

The Integrated Mission for Sustainable Development (IMSD), carried out for 25% of country's geographical area, has significantly contributed towards implementing soil & water conservation measures in drought-prone and rain-fed areas. National Watershed Development Programme for Rainfed Areas (NWDPRA), watershed development activities in 100 watersheds spread across three States viz., Andhra Pradesh (19), Uttar Pradesh (45) and Rajasthan (36), are being monitored using temporal satellite data (pre, first mid-term, second mid-term & post-treatment periods).

The Sujala Watershed Development Programme was implemented in 738 watersheds falling in 38 taluks distributed across seven drought-prone districts of Karnataka covering 5.12 lakh ha and encompassing about 1270 villages and 400,000 households. The project was assisted by World Bank to draw developmental plans at micro-watershed level using satellite data. Sujala was a community driven, participatory, holistic and integrated programme towards improving the production potential of degraded lands through land & water conservation measures and maximize the returns from per unit of land.

Combining of geospatial and conventional methods has resulted in arriving at a comprehensive Monitoring & Evaluation System to provide the up-to-date information at field level for tracking the project progress, outcome and impacts. The evidence-based monitoring and evaluation using top-down remote sensing and bottom-up participatory approach has helped decision makers to apply corrective measures and make appropriate policy changes, which resulted in positive impacts on the environment and socio-economic conditions. As outcome, various visible impacts were observed on ground, viz., improvement in cropping intensity by 12%, decrease in fallow lands by 10-15%; increase in irrigated crops by 8-14%; and improvement in crop yield by 6-15%. The project has received recognitions both at national and international levels, and become a role model in adopting innovations in the rural livelihood and watershed development programmes.

India-Water Resources Information Syastem (WRIS): India-WRIS WebGIS provides a 'single window 'solution for comprehensive, authoritative and consistent data & information on India's water resources along with allied natural resources in a standardized national GIS framework (WGS-84 datum and LCC projection), with tools to search, access, visualize, understand and analyze the data for assessment, monitoring, planning, development, and finally, Integrated Water Resources Management (IWRM). 'Watershed Atlas of India 'has been prepared using detailed-scale drainage network at 1:50,000 scale, Digital Elevation Model (DEM) and other ancillary data.

There are 27 basins, 101 sub-basins and 4566 watersheds in the country. The atlas depicts distribution of watersheds in basins and sub-basins along with their major water resource assets, hydrological observatories, terrain characteristics and rainfall variability, and land use/ land cover. It would serve as baseline information for water resources development and management in the country.

India-WRIS WebGIS Version 4.0 has been released. The portal contains 12 major information systems, 35 sub information systems, 95 spatial layers and a large number of attributes (> 700) with 5-100 years data of the country. The portal also provides 'Automatic Map 'and 'Report Generation 'facility. Based on the National Map Policy (2005) and data dissemination guidelines of Central Water Commission (CWC), the public domain version has been developed, which complies with both. The mapping of country level base layers like river network, canal network, water bodies, location of towns/ villages, road and railway network has been completed using recent IRS-P6 LISS-IV & Cartosat-1 merged data. The Version also contains 6 modules for data visualization and analysis viz., WRIS Info Discovery, WRIS Explorer, WRIS Connect, Share Success Story, Water Resources Planning & Management and Input Data Builder. Further, the newer software features added in this version include interactive mobile application, interactive live screen, text and data sharing tool and 2D-3D linked view. India-WRIS would be institutionalized at CWC following the establishment of National Water Informatics Centre (NWIC).

Web-enabled Information Systems: ISRO/ DOS has developed many Web-enabled Geospatial Information Systems viz., NNRMS Portal/ Natural Resource Data Base (NRDB) to visualize the spatial datasets generated under NNRMS programme; 'Bhuvan ' for Indian Earth Observation Data Visualization; MOSDAC for Oceanography and meteorology data; BIS for Biodiversity Information; India-WRIS for water resources information; etc., to provide information services in the public domain. The ISRO data portal called "http://dataportal.isro.gov.in" provides unified access of all these databases to the user community. The services under ISRO data portal are organized under the category of Satellite Images, Land & Water, Ocean & Meteorology, Disaster Services and Planetary Science.

Future Perspectives in EO Applications: The future agenda of space applications is to further spread its wings to address developmental imperatives in various core sectors of the society with synergistic use of advanced communication, earth observation and navigation satellites; and, catalysing development of innovative applications and services towards sustainable development of natural resources, location-based services and smart governance for better decision-making, protection of environment & ecosystem, improved weather forecasting and near-real time support to disaster management.

The strategy of Indian EO programme is to ensure continuity and enhanced services to operational workhorse missions; plan newer missions by adapting and assimilating advances in technologies meeting user needs; innovative technology development both for on-board and ground systems for future missions; develop actionable EO products and services and address issues on access, affordability, timely delivery, user-friendly format and style; and work towards capacity building in user agencies and decision making bodies.

Future Scenarios in EO systems: Currently available data from various EO systems are operationally used in many national level resource monitoring programs but still many gap areas exists in observations as well applications and it need to be addressed in future. Need of high spatial resolution imaging is growing for infrastructure development including risk mapping and providing real time support for natural and human induced disasters. Multi crop inventory and detection of crop disease and pest require high revisit measurements at high spatial resolution with hyper spectral technology. The cartographic and urban/rural planning is an important thrust area. The Cartosat data has immense potential in this field. There is further need for high resolution mapping for preparation of rural development plans and creation of land information system, land parcel mapping at 1: 1000 to 1: 4000 scale cartographic maps.

It is proposed that Cartographic series be continued with launch of a very high spatial resolution camera on board Cartosat-3. LISS_III sensor would be modified into LISS-III-WS (Wide Swath) having swath around 925 km and revisit capability better than AWiFS in future Resourcesat-3/3A mission. New configuration in Resourcesat-3/3A will help in overcoming spatial resolution limitation of AWiFS. Resourcesat-3S, with multi-view panchromatic stereoscopic capability having high spatial resolution of 1.25 m will facilitate generation of fused products of great utility.

Vegetation stress, disease and pest detection using hyper spectral techniques such as red edge shift and mineral targeting are some of the important applications, which would require hyperspectral spectrometer on board IRS satellites on operational basis.

The cloud cover remains a major hurdle in optical remote sensing during monsoon season. Imaging RADAR applications are being served through RISAT-1 satellite. The C- band SAR sensor onboard the RISAT-1 satellite is found to be very useful for resource monitoring and disaster monitoring. Follow on mission with features similar to RISAT-1 (C-band and multi-polarization) with multi resolution capability is planned for service continuity. The L-band SAR is suggested on RISAT-3 mission for applications supporting soil moisture, crop and forest type discrimination. In addition, RISAT-1A (C band) and RISAT-2A(X band) are planned to meet needs of monitoring disaster situations. NISAR (L and S band), the NASA ISRO joint mission is optimized for studying hazards and global environmental change using advanced radar imaging that will provide an unprecedented, detailed view of Earth. Geostationary orbit provides constant surveillance, and 1 km imaging capability in visible and Near Infra red region already exists on INSAT 3A and additional channels available on INSAT-3D. Beyond Resourcesat-2/2A, high repetivity sensor with moderate spatial resolution would be continued on geostationary platform as a GISAT. This will provide multiple/day acquisition capability and overcome all limitations posed on current AWiFS data availability. Terahertz Telescope will start a new phase in our understanding of universe.

The Indian Remote Sensing satellite series from IRS-1A to IRS-P6/IRS-P5/Cartosat-2/2A/2B/2C/2D, Resourcesat-2/2A, RISAT-1/2, Oceansat-2, SCATSAT-1, Megha Tropiques, SARAL and sensors onboard-INSAT series of satellites like INSAT-3D/3DR have established space technology for operational applications related to areas of societal benefits. The missions planned in near future viz. Cartosat-3/3A, Oceansat-3/3A, INSAT-3DS*, GISAT-1, RISAT-1A/2A, NISAR shall enhance utility of EO data in meeting needs of societal benefit areas. Institutional framework for ensuring utilization of EO data is in place. Capacity building at different levels including decision makers is organized. Indian EO data is available to global users through the international ground stations set up and capacity building is extended to countries in the Asia–Pacific region. Continuity of EO missions with enhanced capability has been ensured. Road ahead for the EO programme has been visualized. Thus, Indian Earth Observation Programme is complementing GEOSS and adding to the remote sensing infrastructure in the world.

IRS Satellites: History, Characteristics and Applications: Since inception, The Department of Space (DOS) has the vision to harness space technology for national development, while pursuing space science research and planetary exploration. To actualize this vision the DOS has evolved and focused on four distinct fields –

(i) to develop indigenous capability for launching vehicles and the development and operationalisation of Polar Satellite Launch Vehicle (PSLV) and development of Geo-synchronous Satellite Launch Vehicle (GSLV) are significant achievements in this field;

(ii) the multi-purpose Indian National Satellite (INSAT) programme for the telecommunication, broadcasting, development of education and meteorology etc;

(iii) the Indian Remote Sensing Satellite (IRS) programme for observation of earth surface features for various developmental purposes, and

(iv) Research, Training and advancement in Space Sciences and Technologies for better acquisition and processing of remotely sensed digital data and to convert it into information for the socio -economic benefit of the country.

India's first indigenously designed and developed experimental satellite the Aryabhata (named after the famous ancient astronomer and mathematician) was successfully launched by a Soviet Kosmos-3M rocket on April 19, 1975 from Kapustin Yar. Starting from Bhaskara-I, the First Experimental Earth Observation Remote Sensing Satellite built in India and launched from Vostok, Russia (former USSR), in 1979 to the latest Cartosat 2 Series satellite launched (by indigenous launch vehicle PSLV) in 2018 a variety of sensors are operating in visible, infrared, thermal and microwave spectral regions, including hyper-spectral sensors to acquire digital data at spatial resolutions ranging from 1 km to a meter have been built and launched indigenously along with satellites of developed nations. Indian Space Research Organisation (ISRO) on 15 February 2017 in a single launch successfully fixed 104 satellites in orbits; out of these 3 satellites were Indian and rest were of the developed countries mainly the USA. Within a limited time period indigenous PSLV and GSLV have established huge number of IRS and INSAT series satellites in orbits. The facilities to receive and process the remotely sensed data have been established in different parts of India along with various international ground stations.

The focus of the present article is the Indian Remote Sensing Satellite (IRS) series along with sensor characteristics and applications. In the early experimental phase, Bhaskara-1(June 7, 1979) and Bhaskara-2 (November 20, 1981) provided data for land applications on the basis of two types of sensor systems – (i) television camera with spatial resolution of 1 km operated in visible and near infrared bands and (ii) Satellite Microwave Radiometer (SAMIR) for oceanic and atmospheric applications. Following the success of this experimental phase, India initiated an indigenous Indian Remote Sensing Satellite (IRS) programme to support national and sub national economies in the areas of agriculture, soils, water resources (surface and ground), forestry and ecology, geology and mineral resources, cartography, rural and urban development, marine fisheries, watershed and coastal management.

The IRS-1A was launched as first indigenous trendsetting operational remote sensing satellite on March 17, 1988 into a Sun-synchronous Polar Orbit (SSPO) by Vostok launch vehicle from Baikonur, former USSR. It was followed by the IRS-1B, an identical satellite, launched by same vehicle and from the same place on August 29, 1991. The IRS-1A/1B satellite sensors Linear Imaging Self-Scanning (LISS-I and LISS-II) operated in visible and near-infrared (NIR) bands with spatial resolutions of 72.5 m and 36.25 m respectively. IRS -P2 satellite was launched (after the failure of IRS-P1 mission on September 20, 1993) by indigenous launch vehicle PSLV-D2 (P series is named after PSLV) on October 15, 1994 with only LISS-II sensor. LISS-I and LISS-II sensors provided useful data for applications in the fields of land use land cover mapping, agriculture, forestry, hydrology, pedology, oceanography, geology, natural resource management, disaster monitoring, and cartography. To further improve the quality of data IRS-1C and 1D, identical satellites, were launched with three sensors – LISS-III, PAN (panchromatic) camera and a Wide Field Sensor (WiFS) with spatial resolutions of 23.5 m, 5.8 m and 188 m, respectively. In addition to fulfilling the general requirements, theme based IRS missions, for applications like natural resource management (RESOURCESAT series and RISAT series), ocean and atmospheric studies (OCEANSAT series, Megha- Tropiques and SARAL) and large scale mapping i.e.

detailed mapping applications (CARTOSAT series) have been introduced and well established (Table 1).

Table 1. History of Indian Remote Sensing (IRS) Satellites and Major Applications

Sl. No.	Name	Launch Date	Status	Applications
1	IRS-1A	17 March 1988	Mission completed in 1992	Land Use Land Cover Mapping, Agriculture, Forestry, Hydrology, Soil Classification, Coastal Wetland Mapping, Natural Resources (especially identification of potential groundwater locations), Disaster Monitoring, Cartography, etc.
2	IRS-1B	29 August 1991	Mission completed in 2001	
3	IRS-P1 (Also IE)	20 September 1993	Crashed, due to launch failure of PSLV	Mission failed
4	IRS-P2	15 October 1994	Mission completed in 1997	Land, Oceanographic and Atmospheric applications.
5	IRS-P3	21 March 1996	Mission completed in 2004	Technology Evaluation and Scientific Methodology Studies
6	IRS-1C	28 December 1995	Mission completed in 2007	Land and water resources management. Applications in forestry, agriculture, environment, soil characteristics, wasteland identification, flood and drought monitoring, ocean resource development, mineral exploration, land use and monitoring of underground and surface water resources.
7	IRS 1D	29 September 1997	Mission Completed in 2010	
8	IRS-P4 (Oceansat- 1)	27 May 1999	Mission Completed in 2010	Ocean- and atmosphere-related applications
9	Technology Experiment Satellite (TE S)	22 October 2001	Mission completed	Experimental satellite to demonstrate and validate the technologies
10	IRS P6 (Resourcesa t-1)	17 October 2003	In Service	Integrated land and water resources management

11	IRS P5 (Cartosat 1)	5 May 2005	In Service	First Indian Satellite (IRS P5) designed with capability to have stereo images;
12	IRS P7 (Cartosat 2)	10 January 2007	In Service	Digital Elevation Model (DEM); Geo-engineering (mapping) applications
13	Cartosat 2A	28 April 2008	In Service	Digital Elevation Model (DEM); Geo-engineering (mapping) applications
14	IMS1	28 April 2008	In Service	To provide remotely sensed data to students and scientists in developing counties,
15	Oceansat-2	23 September	In Service	Ocean- and atmosphere-related applications
16	Cartosat-2B	12 July 2010	In Service	Geo-engineering (mapping) applications
17	Resourcesat -2	20 April 2011	In Service	Integrated land and water resources management
18	Megha-Tropiques	12 October	In Service	To understand the tropical weather and climate and associated energy and moisture budget
19	RISAT-1	26 April 2012	In Service	In agriculture, especially paddy monitoring in Kharif season (sensor has cloud)
20	SARAL	25 February 2013	In Service	Marine meteorology and sea state forecasting seasonal forecasting climate
21	Resourcesat -2A	07 December 2016	In Service	Integrated land and water resources management
22	Cartosat-2D	15 February 2017	In Service	Cartographic applications, urban and rural applications, coastal land use and regulation, utility management like road network monitoring, water distribution and creation of land use maps. Change detection to bring out geographical and manmade features and various other Land Information System (LIS) as well as Geographical Information System (GIS) applications.
23	Cartosat-2E	23 June 2017	In Service	
24	Cartosat-2F	12 January 2018	In Service	

25	RISAT-2B	22 May 2019	In Service	
26	Cartosat-3	27 November 2019	In Service	
27	RISAT-2BR1	11 December 2019	In Service	

Characteristics of IRS Satellites: The quality of data acquired by earth surface observation satellites depends on the sensors used in the satellites. The four major characteristic features of sensors are spatial resolution, spectral resolution, radiometric resolution and temporal resolution. Resolution is defined as the ability of the sensor system to render the information at the smallest discretely separable quantity in terms of distance (spatial), wavelength band of electromagnetic spectrum (spectral), radiation quantity (radiometric) and revisit frequency (temporal). In the identical satellites IRS-1A and 1B the Linear Imaging Self-Scanning Sensor (LISS-I and LISS-IIA/B) of two multispectral cameras were used. Each LISS camera consists of the collecting optics, imaging detectors, in-flight calibration system, the processing electronics and data formatting electronics. LISS uses linear array detectors (CCD – charged-couple-devices). These sensors operated in the visible and near-infrared (NIR) bands. In IRS-P2 satellite LISS-IIM (Linear Imaging Self-Scanning System-II Modified) sensor was used. It operated in push broom scanning mode as linear CCD line detector in four spectral bands in VNIR (Visible and near - infrared) bands.

IRS-1C/ID, the identical twin satellites, used LISS-III, PAN (Panchromatic camera) and WiFS (Wide Field Sensor) camera sensors operating in pushbroom scanning mode using solid state charge-coupled-device detectors. PAN (Panchromatic camera) is a push broom imager with a very high spatial resolution of 5.8 m. LISS-III sensor operates in VNIR and SWIR bands with a spatial resolution of 23.5 m and 70.5 m, respectively. WiFS camera provides two spectral bands in the VNIR range with spatial resolution of 188 m and temporal resolution of 5 days. The experimental earth observation satellite IRS-P3 used WiFS and MOS (Multispectral Optoelectronic Scanner) and IXAE (Indian X-ray Astronomy Experiment) experimental sensors. The payload in IRS-P4 or Oceansat-1 includes OCM (Ocean Color Monitor) and MSMR (Multi-frequency Scanning Microwave Radiometer). OCM is a solid- state radiometer with high radiometric sensitivity (12 bit quantization level), which provides multi-spectral imagery with narrow spectral widths in eight bands in VNIR range. MSMR is a dual-polarized four-frequency radiometer measuring microwave brightness temperature. Cartosat-1 or IRS-P5 has PAN-F (Panchromatic Forward-pointing camera) and PAN-A (Panchromatic After- pointing camera) cameras to obtain two-line stereo configuration for terrain modeling.

Each camera operates in spectral band of 0.5 to 0.85 μm, a spatial or geometric resolution of 2.5 m, a swath width of 30 km for stereo imagery, and data quantization or radiometric resolution of 10 bits. The Cartosat-1 data products are to two types – standard product which is radiometrically corrected and georeferenced and precision product which is ortho rectified product. ResourceSat-1 or IRS-P6 carries three sensors – LISS-III, LISS-IV and AWiFS (Advanced Wide Field Sensor) and all are push broom scanners using linear arrays of CCDs. LISS-III camera is identical to the one used in IRS-1C/1D. The LISS-IV is multispectral high-resolution three band push broom camera in VNIR bands with a spatial resolution of 5.8 m. It can be operated in multispectral mode i.e. data collected in 3 bands and mono mode i.e. data collected in single selected band corresponding to a swath of 70 km. AWiFS is a wide - angle medium resolution (56 m nadir and 70 m at swath edge) camera. The wide swath 804 km of this WiFS heritage sensor provides temporal resolution or revisit frequency of five-day.

Applications of IRS satellites: In 1982 the Planning Commission of India had recognized necessity and significance of establishing a National Natural Resource Management System (NNRMS) to efficiently manage the natural resources by applying remote sensing techniques in conjunction with traditional techniques. Planning Committee of NNRMS (PC-NNRMS) sets guidelines for earth observation based systematic inventory of the country's natural resources and oversees the progress of remote sensing applications for natural resources management in the country. PC-NNRMS in 1984 constituted six Standing Committees on – (i) Agriculture and Soil; (ii) Bio-resources and Environment; (iii) Geology and Mineral Resources; (iv) Ocean Resources; (v) Remote Sensing Technology and Training and (vi) Water Resources ; and in 1997 three more were constituted on (vii) Rural Development; (viii) Urban and (ix) Cartography. The themes of these Standing Committees themselves represent the major fields of applications of information acquired from earth observation satellite IRS series. The main applications of IRS series satellites are listed in brief in the following section.

Applications in Agriculture and Soil: The agricultural applications of IRS satellite series are following: - (i) Cropping pattern mapping; (ii) Pre- harvest crop area, production and yield estimation; (iii) Condition assessment; (iii) Monitoring command areas; (iv) Compliance monitoring (farming practices) e.g. crop stubble burning; (v) Identification of suitable sites for different agricultural practices; (vi) Mapping of soil characteristics; (vii) Mapping of soil management practices; (viii) Mapping of saline soils and monitoring of land reclamation; (ix) Inventorying and categorization of wastelands; and (x) Identification of fishery prospects.

Applications in Bio-resources and Environment: The applications of IRS satellite series in forestry, b iodiversity and ecosystem sustainability are following: - (i) Mapping of forest cover, types, density and species inventory; (ii) Measurement of biophysical conditions of forest strands; (iii) Social forestry and agroforestry mapping; (iv) Biomass estimati on; (v) Afforestation and deforestation assessment; (vi) Forest fire surveillance; (vii) Forest health and vigor monitoring; (viii) Detailed survey and inventory of the existing bio-resources; (ix) Environmental impact assessment including pollution (land, water and air); (x) Mapping and monitoring of tiger reserves, elephant corridors, biosphere reserves, mangroves and coral reefs; (xi) Assessment of fuel wood and timber resources; and (xii) Environmental hazard related studies like zonation and damage assessment (floods, drought, cyclone, landslide, volcano, earthquake etc.).

Applications in Geology and Mineral Resources: Geological applications of IRS series satellites include the following: - (i) mapping of surfacial deposits and bedrock; (ii) Lithological and structural mapping; (iii) Mineral prospecting and exploration; and (iv) Geo - hazard mapping, monitoring and zonation.

Applications in Oceanography : The applications of IRS series satellites, especially Oceansat-1 and Oceansat-2, include the following: - (i) Identification of potential fishery zones; (ii) Phytoplankton abundance and habitat assessment; (iii) Observation of marine pollution and sedimentation and its impact; and (iv) Assessment of sediment dynamics, tidal fluctuations, sea level changes and coastal circulations.

Applications in Water Resources: The applications of IRS series satellite data products in water resource include the following: - (i) Mapping of surface water bodies; (ii) Identification of potential ground water resources; (iii) Wetland mapping and monitoring; (iv) Snow pack and glacial monitoring; (v) Ice thickness measurements; (vi) Rivers, watersheds and ice lake monitoring and modelling; (vii) Flood mapping and monitoring; (viii) Monitoring reservoir extends over seasons and irrigation scheduling and flood management; and (ix) Snowmelt runoff forecasting.

Applications in Urban Sector: The applications of IRS satellites data products in urban sector are following: - (i) Mapping and Land Use Land Cover classification; (ii) Urban sprawl analysis; (iii) Identification of illegal encroachment, and constructions; (iv) Property tax assessment and estimations; (v) Transport and urban planning; (vi) Mapping of utilities and services; (vii) Population estimation; (viii) Slum detection and monitoring; and (ix) Site suitability analysis

Applications in Cartography: Mapping constitutes an integral component of the process of resource management and mapped information is the common product of analysis of remotely sensed data from IRS series satellites. The Cartosat series is especially oriented towards geo-engineering mapping and DTM (Digital Terrain Modelling) or DEM (Digital Elevation Modelling). Natural as well as manmade features such as transportation networks, settlements and administrative boundaries are represented spatially with respect to geo-referenced data and integrated with attribute information or non-spatial in GIS (Geographical Information System). Baseline, thematic and 2D and 3D topographical maps are essential for planning, evaluation and monitoring, for civilian and military reconnaissance and land use planning.

Conclusion: Since inception the IRS satellite series is oriented towards societal benefits and its ultimate objective is sustainable development of India. To address this goal it is applications driven and has greatly diversified in applications, that too in a limited time period. The information derived from remotely sensed data is an essential component of the National Natural Resources Management System (NNRMS). The Indian Remote Sensing (IRS) satellite program is to support national and sub national economies in the areas of agriculture, soils, water resources (surface and ground), forestry and ecology, geology and mineral resources, cartography, rural and urban development, marine fisheries, watersheds, coastal and disaster management.

MODULE-VI

DATA POLICY, IPR, DATA RELIABILITY AND EMERGING TRENDS IN REMOTE SENSING TECHNOLOGIES

MODULE-VI: DATA POLICY, IPR, DATA RELIABILITY AND EMERGING TRENDS IN REMOTE SENSING TECHNOLOGIES

Introduction: Today there is a need for a large amount of reliable data to enable a variety of environmental assessments, as well as for large-scale and site-specific disaster monitoring. However, the need is not satisfied fully because the current legal framework does not address the issues sufficiently: for example, how data is accessed, charged, distributed, and used; and how the authenticity and accuracy of data is verified.

As illustrated earlier, there are no guidelines for the data policies. The only Principle related to data policy is Principle XII of the UN Remote Sensing Principles that addresses issues in a limited fashion: "As soon as the primary data and the processed data become available, Sensed States shall have access to the data on a non-discriminatory basis and on reasonable cost terms." This Principle deals with the data availability regarding both sensed states and other states that wish to access to the data, and both are treated equally in terms of conditions for access. The provision limits the scope of data availability to only sensing states, sensed states, and other states interested in the data. Furthermore, it does not serve as a basis to allow free access to data for public benefit service, particularly for disaster relief.

The only provision concerning the pricing policy, viz. 'reasonable cost terms', is ambiguous and open to different interpretations: it could mean either extremes of marginal costs, or a commercial price, insofar as it is reasonable for the particular image in question. It in no way serves as a general guideline for the price setting expected for the different types of data or a variety of uses by the different data generators. Although Principles X and XI encourage the disclosure of information for environmental protection and disaster management, it does not state in what terms data are supplied in such cases; therefore, it does not serve as a legal basis to allow favourable treatment for such uses. The Principles are far from sufficient to govern the supply and use of data currently taking place world-wide.

The UN Remote Sensing Principles are completely silent as to the rights of data generators, such as intellectual property rights or the conditions for the use of the data. The conditions of the applicability of the intellectual property rights are not spelled out (e.g., the categorisation of different types of products subject for protection and the rights associated with each of them). There are no provisions regarding the accuracy, integrity, and reliability of data, or how data should be validated and authenticated. Hence, the UN Remote Sensing Principles do not serve as a guideline that governs the activities of data suppliers; neither do they provide any expectations for the data recipients in dealing with the data.

At this time, access, distribution, and use of remote sensing data are governed largely by the varying policies set by an individual supplier and the implementation of any data validation also depends on the respective entity. Under the current environment, none of the interests of stakeholders are safeguarded properly. The rights associated with the data are not guaranteed to data suppliers; users may face limited access to the data as well as having low confidence in the data because of the uncertainties regarding its accuracy and authenticity. The current legal regime neither fosters easy access to data for the benefit of users, nor offers suitable protection of the different types of data to the appropriate parties in the data supplier chain.

There is an urgent need to consider new regulations in line with the current situation. A balance of interests of the different stakeholders needs to be achieved, the integrity of the data must be ensured, and the guidelines for the assessment of reliability of the resulting information products must be established. The aim of this Chapter is to reveal the reality associated with data policies, data accuracy, and authenticity validation – analysing the tendency for each, to identify gaps to be filled and then to propose improvements.

Data Policy Associated with Satellite Images and Derived Products: The recent trend in the field of remote sensing saw the proliferation of data use and growth of the data market. Nowadays it is a minority of governmental space agencies that are keeping their data for internal use and/or giving out the data at marginal cost, but most of the time significant capacity is allotted for distribution of data on a commercial basis. With the emergence of different funding models for satellites and numerous satellite-based programmes based on varying forms of cooperation, the issues of data policy have gained more and more attention. It is critical not only for users but for all remote sensing stake-holders to understand precisely what data policy is and its impact on accessibility and utility of data by users.

Data policies determine the rights and obligations for data providers and recipients. Effective data policies are essential to ensure that the right information can be made available to those who need it, in the right form and at the right time. Ideally, data policy should be established in a manner that users can enjoy the full benefits of data whilst suppliers can retain and exercise rights associated with data.

As discussed earlier, whilst government may have an overall framework to implement the law and policies to exercise control on domestic actors – particularly as to data dissemination – data policies are usually set independently for each satellite. A variety of data policies that exist worldwide have differing impact on accessibility to the data and the utilisation of the data, all of which affect the interests of the data suppliers, end-users, and the third parties.

Access Policies: Existing data policies, adopted by the different entities in terms of access and pricing, can primarily be categorised to two types. The clear distinction is made between governmental agencies and commercial entities that operate satellites and generate data/products. As far as the governmental agencies are concerned, they appear to be further categorised into: those entities, most notably those of the United States, which adopt an open access policy; and those – particularly European entities – that tend to have more regulated access.

Open access commonly allows users to access the data freely at least at marginal cost irrespective of the types of users and the purpose for which the data is utilised. For instance, Orthorectified Landsat Data is available free-of-charge via FTP. NASA makes QuickSCAT data and MODIS data available free of charge for scientific and educational use, with virtually no restrictions. This type of access policy is reflective of US federal policy, applying the concept of freedom of information for the data collected at the federal level or using federal funds, and consequently, no government copyright is claimed and no fee is charged for the spatial data.

On the other hand, space agencies, including ESA, and the Canadian Space Agency, adopt two (or multiple) tier systems encompassing different categories of users. ENVISAT distinguishes between category 1 and 2 uses: category-1 is for research and application development use; category-2 is for other uses, including operational and commercial use. For ERS, there are five categories: (A) internal use; (B) research and demonstration use; (C) national meteorological services belonging to WMO members; (D) those organizations of participating states engaged in operational services for public utility; and (E) commercial use.

The private entities operating remote sensing systems such as GeoEye and Digital Globe primarily distribute their data on a commercial basis. The commercial data generators only hold a single category of commercial users, unless a special arrangement is made so that the data is supplied free-of-charge for disaster relief in certain cases, such as within the framework of the Disaster Charter.

Finally, there is access policy based on the programme rather than based on each satellite or its owner. The DMC Consortium has a unique data policy. Part of the data capacity of each satellite in the constellation is reserved for national governmental use by the owner of the individual satellite and there is a collective commitment to supply data for disaster relief purposes, whilst the remaining capacity of the satellites is released to the commercial market. Within the total capacity of the DMC, approximately 5% to 10% of the data capacity is provided free of charge to disaster relief agencies. Each partner determines how the rest of the capacities are allocated – such as its own national use or commercial sale released onto the market place through the commercial distributor, Disaster Monitoring Constellation International Imaging (DMCii).

As discussed earlier, entities are subject to constraints imposed by the government through national legislation and policies, including shutter controls and priority access. Entities that fall under the jurisdiction of the United States, Canada, Germany, and France (amongst others) need to adhere strictly to the obligations they owe under the laws of the respective state. Other states, such as India and China, have framed specific policies that place restrictions on data dissemination in terms of spatial resolution. Consequently, users may be inevitably restricted by law and/or policy in accessing data under the framework of any of these states. In the near future, these types of restrictions may extend to other states in consideration of the launch or planned launch of their high resolution satellites.

The access policies of divergent entities are not uniform; however, analysis highlights the trend in clear distinction between public and commercial use. For governmental agencies, data access for public benefit purposes is reserved as just one category amongst many others, whereas for commercial entities it is a special arrangement. That means that the same data can be distributed both for the public good and for use in commercial products. For those governmental agencies that adopt more than one category of users, the distinction is made not by a type of data, but by a purpose for which the data is used, or the nature of the data recipients. Indeed, it is a common practice now that data from governmental space agencies are distributed on a commercial basis and vice versa: data from commercial entities is being supplied as a public service in support of disaster relief. In such cases, the policies and conditions for supply are not necessarily clear to the external parties. If easier access for the purposes of public benefit is to be achieved, it is necessary to establish a clear overall policy for public service applications.

Pricing Policies: Generally speaking, the pricing policies for different satellites and their derived products are non-uniform. The different access policies examined in the previous section are directly linked to variable pricing. A fundamental distinction is made between those entities operating under an open access policy adopting free or marginal cost pricing, and those entities operating under regulated access with cost recovery pricing.

***Pricing for Open Access*:** For the open access policy, which is typically adopted by US governmental suppliers, the price is set at a marginal cost. The marginal cost is regarded as "the price that recovers the costs incurred in providing data beyond the costs of the basic ground infrastructure." For instance, NASA adopts a 'cost of fulfilling user request ' mechanism for Landsat; it implies that all marginal costs that are necessary to fulfil the request of the user – which may include the programming, the satellite, and/or the retrieval of the data from the archive – are charged. The Landsat data is set at a marginal cost, where the cost of fulfilling the user request is assessed as approximately US$ 600 per scene16 for newly collected data, and US$ 25-50 for archived data. Furthermore, NASA's ASTER data was made available free of charge until August 2002; currently, the charge is approximately US$ 55 per scene.

Pricing for Regulated Access: The regulated access pricing environment is further categorized into (A) the pricing for entities that adopt categories of users and/or uses, and (B) commercial entities that basically have one single commercial user. Amongst those having more than one category of users, only data regarded as for public use – including internal, educational, and humanitarian use – are distributed under preferential conditions, either with a price waiver or distributed at a marginal cost. For example, ERS of ESA distinguishes between category 1 and 2 use: category 1 is for research and application development use, and category 2 is for other uses, including operational and commercial use. The marginal cost, referred to as 'at or near the cost of reproduction 'is applied to category 1.

When a governmental space agency creates a commercial use data category, the data will then be distributed on a commercial basis. Governmental space agencies do not distribute data themselves but delegate to authorized entities to market the data. More often than not, more than one supplier undertakes the data sale, most notably to cover the distribution in different regions. An increasing number of data distributors is independent from the governmental space agency that originates the data.

Private commercial data generators operate satellites and distribute their data on a commercial basis. The data generators of very high resolution satellites, such as GeoEye's Orbview, sell their data at a full commercial price; for instance, data with spatial resolution of 60 cm costs US$ 10 per square km. The examples make it clear that open access and regulated access, particularly by commercial entities, present a striking contrast in pricing models.

Finally, price waiver arrangements adopted by certain data generators for public benefit warrant a brief discussion here. In operational programmes using remote sensing, the participating data generators often compromises their individual access and pricing policy. Under the Disaster Charter, data from differ- ent systems are supplied free of charge, compromising the data policy of each system to the benefit of all potential afflicted states, provided that they follow the designated process. Such arrangements are increasingly adopted for a coordinated service.

GMES aims to provide integrated information services for monitoring the environment through contributions from different sources to the benefit of users in both public and private sectors. Precise data policy has not been defined for GMES, but a certain harmonization will be achieved, ensuring a user-friendly service and cost effective access to the standardised data. It is envisaged that a considerable part of GMES information should be available free of charge. Indeed, all EUMETSAT data and products will be made available free of charge to the pre-operational services of GMES, provided that every GMES user contacts EUMETSAT directly to receive the data/products and signs a simple license. First, however, a balance must be established between non-discriminatory access and the incentive for investment in satellite development and its financial sustainability.

Observation of Factors Determining Pricing: The factors affecting price settings for divergent satellite images and derived products merit close analysis. Obviously, the quality and characteristics of the data determine the pricing of both the data and derived products. Such factors as spatial resolution, image size, different levels of processing, and added value all contribute to varying prices associated with each product. Naturally, the data is more expensive if it has higher spatial resolution, if its image coverage is wide, and if it has value-added attributes – for instance, a product in the form of a digital elevation model – and if it is newly tasked data, in contrast to archived data.

The complexities of the pricing of satellite images often lie in the factors external to their quality and type of data; specifically in broader dimensions such as national policies, the type of data generator, and the financing for build- ing and operating the satellites. National policies, as previously mentioned, affect the overall pricing extensively, with the difference between the govern- mental US providers and European providers being particularly notable. The funding source is also a major pricing factor. The fundamental distinction is whether the satellite is financed fully or partially by public funding, or financed solely by private funding.

In short, various factors determining the access policy and pricing of satellite remote sensing products are so complex that it is not feasible to achieve a single access policy with a uniform price setting for all. What can be feasible, however, is to establish a common access and pricing policy for public benefit services, as already achieved under the Disaster Charter and the DMC.

Common access and pricing policy for the benefit of users is increasingly recognized and implemented to foster environmental protection, in addition to emergency response. In Europe, public access to environmental information is specifically written into a Directive. As discussed previously, the Directive on Access to Environmental Information establishes the right of any requestor to access environmental information held by or for public authorities at reasonable cost and without having to state his/her interest. The Environmental Directive contains basic data policy for broad categories of environmental information defined as "any information in written, visual, aural, electronic or any other material from." It is important to note that the Directive is applicable to environmental information insofar as the information is held by or on behalf of public authorities: a) government, other public administration; b) any natural or legal person performing public administrative functions under national law; and c) having public responsibilities or functions or providing public services. This language reflects the approach that allows public access to the environmental information on the basis of the content; that is, information on the environment itself, rather than on how the information is produced. The language of the Environmental Directive covers EO data produced by private entities as long as it is used for a public service related to environmental operations.

The Environmental Directive sets a timeframe for access to be: "as soon as possible or at the latest, within one month after the receipt of the public authority of the request" and sets forth a systematic mechanism to ensure easier access to environmental information. The Directive has a solid enforcement mechanism whereby when an applicant's request for information has not been processed properly by the public authorities, that applicant has the right to review both administrative and legal procedures. The Directive is thus a powerful instrument that has a significant impact on the access to satellite data for environmental purposes.

There is a movement within the European Community to establish a common infrastructure for spatial information, and data policy issues are amongst the considerations. The initiative commonly referred to as INSPIRE, became a Directive and was adopted by the European Commission on 14 March 2007. The scope of INSPIRE is limited to Europe for the purpose of environmental applications and covers "any data with a direct or indirect reference to a specific location or geographical area," which includes satellite data and products. It is important to note that INSPIRE is applicable primarily to spatial data held by public authorities for its use by those authorities in executing public tasks; however, it can also be applied to persons other than public authorities if they request it, thus extending its applicability to individuals and private entities. INSPIRE clearly establishes the pricing policy as follows: (1) the availability of the spatial data sets to public authorities at marginal costs; (2) availability of network services, and the data sets specifically to fulfil the reporting obligations under Community legislation relating to the environment, free of charge. The INSPIRE Directive is a major step toward a common access and pricing policy and toward establishing mechanisms for data sharing and coordination at a regional level; it can also serve as a catalyst for creating an operational satellite-derived information service on a global basis, particularly through GMES. It is imperative to facilitate data access on a global level beyond the existing frameworks for both disaster management and protection of the environment.

Distribution Agreements and Conditions Associated with the Use of Data: The practice of most data generators is that data supply and use is regulated through contractual agreements. They do not just release their data in an uncontrolled manner, but retain control over the data and products after distribution to the users. The contractual agreements between providers and users are valid only amongst the contracting parties. In practice, the majority of data generators provide data in a form of license agreements. In most cases, the pricing levels set for products are the fees for granting a license to use the products – just as in the case of software products. In the license issued to users upon distribution of data, data distributors set a variety of conditions associated with the data.

Concept of License Agreement: The term license originates in licentia, a Latin word meaning 'permission 'and 'agreement.'42 License is defined as "a permission, usually revocable, to commit some act that would otherwise be unlawful." A license permits a third party to conduct certain activities and exercise privileges associated with products which would be illegal without the license. A license associated with satellite data and products clarifies and enforces the rights of data suppliers and controls the activities of data recipients, thus serving as a means to implement and enforce the terms and conditions associated with products. A license normally involves a fee, but, theoretically, the license agreement exists even in the case of free of charge licenses. The supply of data under the Disaster Charter is a good example of free of charge license-based distribution with attached conditions.

Rights and Obligations with Regard to Licenses: A major obligation of a licensee is to pay a license fee (also referred to as a royalty) to a licensor in return for permission to obtain rights that belong to the licensor. In case of satellite images, there is a distinction between a license fee and a royalty: a license fee is when users pay for access to the data, whereas royalty is a fee paid to the owner/ operator of a satellite by distributors and value added resellers upon the sale of products. For instance, the individual DMC satellite owners receive royalties for use of their copyright from DMCii when the data from their satellites are sold by DMCii and the customers actually make payment. Spot Image charges a royalty fee to the value-added resellers upon the subsequent sale of value-added products rather, than when the data is sold for the first time. In case of ESA's ERS data, a royalty is not applicable only when products for further distribution have been modified significantly so that the resulting products do not retain the original pattern. According to ESA personnel, whether or not products retain the original pattern is determined on a basis of 'reversibility'; that is, whether resulting products can be re-constituted and reformatted back to the original data.

In general, a license gives rise to implicit obligations of a licensor not to prohibit a licensee from using the associated intellectual property rights. On the other hand, a licensee is constrained by a set of obligations imposed by a licensor. Licenses are issued under conditions set by the licensor. Such requirements are imposed as conditions for use in a license agreement. Licenses are classified into those that are exclusive, where the use of the intellectual property granted under the license is valid solely for the specific licensee; and those that are non- exclusive, where rights given under the license are also granted to those other than the licensee. In general, licenses for satellite images are non-exclusive and non-transferable.

Conditions Associated with the Use of Data: This section examines the typical obligations expected of a licensee in a license agreement with the satellite remote sensing data generators in terms of conditions associated with the data. Licensing conditions are commonly specified as either permitted activities or prohibited activities. Although licensing conditions vary in detail from one data generator to another, the overall tendency clearly indicates the intention of data generators to retain certain control over the data.

Permitted activities include: the reproduction of products and use of the products for internal use; permission for subcontractors to use products on behalf of the licensee; and the generation of derived and value-added products. Prohibited activities include: further distribution of products to a third party; sales of products; and sub-licensing without notification. In any case, the commercial resale of the data is prohibited unless the licensee is an authorized value- added reseller. Prohibited activities vary with the individual supplier and affect the degree of pervasiveness and utility of the data.

Some entities are very restrictive as to the further distribution and the treatment of the data, whilst others are less restrictive. In the case of Digital Globe, end-users can share the data with affiliated entities by means of a joint project and only if they agree to be bound by the conditions of the license and shared products may not be retained by affiliated entities after the completion of the project. On the other hand, IRS data can be disseminated for non-commercial purposes insofar as they are in a non-downloadable format.

A single use is typically permitted under a standard license. Overall, data generators restrict the further distribution and sharing of data with external parties. This is clear from the higher charges levied by data generators in the case of multiple users sharing the same data. This serves as an impediment to the effective implementation of programmes related to environmental protection and disaster management, as they benefit extensively from data sharing, e.g., sharing the data under the different projects requiring overlapping data-sets. As identified by the preamble of the INSPIRE Directive, it should be possible to combine data with other sources; to share data between several users and applications; for data collected at one level of public authority to be shared between other public authorities; to make finding data availability easy; and to make data available under conditions which do not unduly restrict their extensive use. Under an operational programme such as the Disaster Charter – although each partner provides the data free of charge – the intellectual property rights and restrictions associated with data that are set by each partner, such as prohibition on further distribution to the third party, are not waived.

Indeed, according to non-disclosure agreements, the ownership is retained and copyright is claimed by the data generator; further distribution of data to the third party is prohibited. Under the INSPIRE Directive, the intellectual property rights associated with data remain with data suppliers; therefore, despite certain frameworks that have included steps for the establishment of a common access and pricing policy for public service, the challenge remains to improve the restrictive conditions associated with the data and facilitate effective data sharing for the benefit of the public. These conditions need to be relaxed so as to enhance the exploitability of data, as well as to allow effective data sharing amongst relevant communities for public service purposes.

Many conditions associated with the data provided in the distribution agreements are the result of efforts by the data generators to protect their intellectual property rights. The conditions associated with data and intellectual property rights are interrelated and inseparable. In order to understand the control and restriction imposed on the data recipients in terms of intellectual property, and to examine the legitimacy of claimed rights as well as to consider suitable protection for satellite images and derived products, it is necessary to further explore the issues of intellectual property rights.

Intellectual Property Rights Associated with Satellite Images: Data generators attempt to seek protection for their products, which are the results of significant financial investment, and their technical achievements. In fact, it is common that the ownership of data remains with the data generators and copyright is claimed by a majority of data generators – with some exceptions, such as Landsat 7. Despite this widespread practice of claiming such rights, it is doubtful as to whether those rights are actually safeguarded. Although access and pricing policies can be exercised largely at the discretion of entities on a contractual basis, absolute security of intellectual property rights depends upon whether the legal regime permits such practices. It is hence necessary to explore and clarify the intellectual property regime, to determine how the rules may be applied to satellite images, and to identify the gaps between the regime and the current practices of the data generators.

Examination of the Current Legal Framework for Intellectual Property Rights : Intellectual property rights protect businesses wishing to exploit them. Historically, the need for copyright protection arose from the large amount of pirated copies of world renowned books by Dickens and Victor Hugo. Victor Hugo, having incurred losses because his works such as “Les Miserables” had been extensively printed and circulated at a low price in Belgium and Germany, established a union to appeal for the importance of copyright. This union led to the creation of the Berne Convention for the Protection of Literary and Artistic Works of 1886, which is the oldest treaty and primary source of international law regarding intellectual property rights. The aim of the Convention is to provide international protection for works of literature, science, or art and to establish an overall framework to harmonize the varying rules on intellectual property. It has established the rules for the protection of work without registration, a mechanism for mutual protection, and independent protection. Although it has created an overall framework, the Berne Convention leaves the implementation and enforcement to the national laws.

The Universal Copyright Convention (UCC) of 195270 is a compromise of the Berne Convention. The UCC is complex, and originally was not accepted by many states for signature. The main features include a provision with respect to artistic works from a given country that must carry a copyright notice to secure protection in other UCC countries – the internationally recognised © copyright symbol – and it has concrete provisions with regard to certain measures, such as requiring a license for translation rights.

A global agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS Agreement) of 1994, which follows the trend of recognizing works as equivalent to trade goods, obliges over 120 states to implement the protection provided. In contrast to the Berne Convention, which was intended to provide protection for persons, TRIPS Agreement was intended to set rules between governments. It provides international protection for different kinds of artistic works, including computer programs, satellite broadcasting, and databases. Although TRIPS does not mention databases specifically, the compilations of data or other material, which constitute intellectual creations by reason of the selection or arrangement of their contents, shall be protected as such.

The Copyright Treaty of the World Intellectual Property Organisation (WIPO) covers the internet environment and emerged as an extension of the Berne Convention to deal with computer programs, compilation of data, and the right to communicate with the public. States signatories to the Berne Convention can choose whether they wish to adhere to the WIPO Copyright Treaty or not. This Treaty serves as a significant bridge from the Berne Convention protecting primarily literary and artistic works to database law. Article 5 of the WIPO Copyright Treaty is applicable specifically to compilations of data; as a result of this Treaty the European Community adopted the Council Directive on the legal protection of databases of 199679 to achieve a European-wide database law. Amongst the relevant treaties, this section will focus primarily on the Berne Convention and EC Database Directive in analysing the protection for satellite images through examination of the protections for literary and artistic works, and the protection for databases.

The Analysis of Protection for Literary and Artistic Works: Intellectual property can be broadly categorised into two types: (1) protection for artistic and literary works such as copyright; and (2) protection for industrial property such as designs, patent, and trademarks. This Chapter will only examine the first category, as it is relevant to satellite images and their derived products. The fundamental concepts of protection for literary and artistic works include the concept of copyright and author's rights, the conditions for application, the measure for exercise of rights, and the consequences for infringement.

It is important to understand the two distinct types of rights recognized for the protection of literary and artistic works. One is an economic right, which is typical of copyright; the other is an author's right known as droit d'auteur, which is characterized as a legal or moral right or claim.

An author is given opportunities to profit from trading economic rights from reproduction, public performance, and broadcasting rights, to rental rights. Authors profit from their work through selling and licensing these rights, whereas moral rights provide the author with a continuing control over the work, despite its exploitation. The moral right allows an author to claim paternity of the work independent of any economic right, and to object to distortions, mutilations, and other modifications in relation to the work. Under the moral rights doctrine, the author alone decides when the work is ready for release and how it may be exploited; the work must be properly credited and it must not be modified contrary to the author's wishes – at least not in ways prejudicial to the author's honour or reputation.

The term 'copyright 'originally meant a 'right to copy 'the literary works of another, to encourage the publication of a diversity of written works. Copyright is a property right, which may be bought or sold. It protects creativity in literary and artistic works that involve original expressions. Although the Convention does not introduce 'copyright ' specifically, it establishes that an author has exclusive rights over work he created.

Copyright is a measure against unauthorised reproduction, distribution, use, and sale of one's creative expressions.

There are certain conditions to be fulfilled in order for the work to benefit from copyright protection. The most fundamental specific limits to copyright applicability is that copyright is applicable to expressions and not to ideas and methods and neither protects facts, bibliographical citations, nor headlines. As to more detailed conditions, copyright requirements mandated under the domestic law need to be fulfilled. This section provides an analysis of the trend in domestic laws with regards to the conditions for protection.

Sterling states that "The individual who produces a work by his or her creative activity is normally regarded as the initial beneficiary of the copyright or author's right in the work."90 The Berne Convention does not define 'author'; however, it implies a natural person, that is, a human being, and does not refer to a juridical person, which is an entity, such as a corporation, created by law and given certain legal rights and duties of a human being. The existing domestic law must be referenced with regard to the definition of author.

It is interesting to look at the definitional differences between the civil law system and common law system on 'author 'and the concept of a 'creator'. The initial ownership or right is given either to the individual who produces a work or to the legal entity responsible for its production, such as an employer. In the common law system, the general trend is that the employer is the first owner of the copyright when the work is made for hire. UK Copyright Act 1988, for instance, states that "Where a literary, dramatic, musical or artistic work is made by an employee in the course of his employment, his employer is the first owner of any copyright in the work subject to any agreement to the contrary." Likewise, in the US, Section 201(b) of the Title 17 of the United Code stipulates that "In the case of a work made for hire, the employer or other person for whom the work was prepared is considered the author for purposes of this title, and, unless the parties have expressly agreed otherwise in a written instrument signed by them, owns all of the rights comprised in the copyright."

On the other hand, in civil law jurisdictions, when an employee creates a work in the course of his employment, he is the initial owner of the author's right; nevertheless, contractual provisions, whether expressed or implied, can transfer or license the economic rights associated with the work to the employer.

The Berne Convention does not explicitly state that originality and intellectual creation are required in order for a work to be protected under copyright; however, most domestic legal systems require works to involve certain degrees of originality and creativity as distinctive human intervention in order to merit protection. The application of such conditions and the interpretation of the terms vary by jurisdiction.

Generally, the civil law countries take the conditions of creativity and intellectual creation into significant account. In contrast, originality is not linked very closely to creativity in common law countries. For instance, in the British tradition 'originality 'has been treated as a low threshold: in most cases the traditional approach has been to refer to "skill, judgement and labour" in assessing the originality. The basic concept is that the work must be the result of the investment of individual skill, judgement, or labour. Skill and judgement imply the application of a personal choice and some intellectual contribution, whilst mere labour does not. In practice, the element of labour alone does not appear to meet the condition for protection; in fact, it was demonstrated in the case of *Cramp v. Smythson*, that not only must the work not be a copy of previous work, but judgement has to be original based on individual skill.

The well-known US Supreme Court case, *Feist Publications Inc. v. Rural Telephone Service*, which concerned the alleged copyright infringement on use of a white page listing, demonstrated that the copyright protection for factual compilations is not granted if no originality is involved. This case clearly illustrates that copyright does not protect facts, and that works within the scope of protection need to be a product of intellectual activity – not merely a product of time, labour, and money invested.

The application of the conditions for protection varies, but the protection seems to require certain degrees of intellectual input with the involvement of subjective choices. Following this rule, there is doubt as to whether satellite data without human intellectual contribution, such as the raw data derived from a system where an operator makes no intellectual choice in taking such imagery (e.g., a decision on the best angle for image acquisition), merit copyright protection – even when the minimum standards of creativity requirements are applied.

Infringement of the creator's rights occurs when reproduction, communication, display, or distribution of works to the public is done without the transfer of right or permission with respect to the protected subject matters. The analysis under this Chapter will focus on the case of reproduction.

The consequence of infringement is that "the infringing copies of a work shall be liable to seizure in any member States where the work enjoys legal protection" and "the seizure shall take place in accordance with the legislation of each country." The consequences of infringement may result in litigation and/or involve compensation by the infringing parties subject to the respective national legislation. The concrete remedies for infringement depend upon domestic legislation.

The majority of disputes concerning copyright are settled out of court; however, when an infringement action is brought, the magnitude of consequences can be serious. For instance, the UK Automobile Association was fined 20 million pounds in 2001 after copying maps of Ordnance Survey, the National Mapping Agency of the United Kingdom. Any person that is involved in the supply and use of satellite data faces such risks. The copyrights and associated entitlement are unaddressed anywhere, and consequences for infringement may be detrimental to all parties concerned.

The Analysis of Protection for Database: As has been discussed, time, labour, and money invested to create works do not count as elements toward copyright protection; but these elements are subject for protection under the database category. This part examines the concept of database protection, conditions for protection, and infringement.

The EC Database Directive protects databases on two grounds: the protection based on copyright for databases that constitutes the author's own intellectual creation in terms of the selection and arrangement of their contents, and the protection on the basis of sui generis right, which protects the contents of the database. *Sui generis* means "of its own kind" in Latin and the term is used to describe a regime designated to protect right that fall outside the traditional doctrines such as copyright. The right of *sui generi*s is clearly contrasted from the copyright, which protects the "form" or how the data- base is presented. *Sui generis* applies "irrespective of the eligibility of that database for protection by copyright or by other rights." Thus it can be interpreted that a creative database may enjoy protection in terms of both copyright and sui generis rights. The extraction right permits authors to conduct or authorize acts including reproduction and distribution of the contents; this right prevents the unauthorized retrieval and use of all or substantial parts of database.

Unlike copyright, protection on the basis of the *sui generis* right does not require intellectual creation but only requires that substantial qualitative or quantitative investment be made in obtaining, verifying, or presenting the contents. Time and money invested in making a database are solid grounds for protection under the *sui generis* right.

The database right applies to "a collection of independent works, data or other materials arranged in a systematic or methodical way and individually accessible by electronic or other means." The natural person or group of natural persons who created the base, or the legal person designated as the right holder by legislation, can be the database right holder. This is more explicit than the regime of protection for literary and artistic works under the Berne Convention, which infers that the natural persons or a group of natural persons are primarily the beneficiary of such right. In these ways, database protection, in theory, is more readily applicable to satellite images and derived products than copyright.

There have been a number of cases that involve database rights. The first French case-law application *sui generis* over a database concerned a telephone directory. It was held that the unauthorised down-loading of the France Télécom electronic directory by a third party for the purposes of creating an inverse directory was an infringement of the sui generis right.

In the case of *British Horseracing Board (BHB) v. William Hill* the BHB objected to William Hill, a bookmaker, using information in its Internet betting service derived from horse race meetings conducted by BHB. William Hill extracted data without obtaining a licence from Satellite Information Services Ltd. licensed by the BHB to transmit much of the Board's data to its subscribers. William Hill used the information on the Internet betting site and the court found that, as William Hill had downloaded a substantial amount of data, they had therefore infringed database rights. This case is highly relevant to satellite images, as many of them are downloadable from the Internet. A third party can easily infringe the rights of the satellite data generator; therefore, the rights associated with the products should be clarified.

Applying Rules of Intellectual Property Rights to Satellite Remote Sensing Data: As far as the protection of the satellite data is concerned, although certain characteristics of the author's right, such as prohibition on modification, are inherent in the license itself, the primary purpose is to get economic benefits associated with the products. Economic rights are claimed by the data generators, most notably in the form of copyright.

The clarification of the differences between the regimes for copyright and database rights shows that database rights, by nature, are a more suitable basis for the protection of satellite images. However, depending on their characteristics, some data may be protected under copyright law. The following sections closely examine how different types of satellite data would fit under the regime of copyright and database right, respectively.

The Copyright Protection for Satellite Images: With regard to the protection of satellite images, three types of data should be considered: 1) raw data, 2) processed data, and 3) analysed information, value-added products, and derived products. Applying copyright protection to digital information is not an uncommon practice nowadays, since the scope of its applicability has widened in accordance with increased variety of works. Initially intended primarily for protection of literary and artistic works, many media have been recognized and now subject to copyright protection. This section explores how copyright law applies to raw data, processed data, and analysed information.

Primary data (often referred as raw data) is defined under the UN Remote Sensing Principles as "the data that are acquired by remote sensors borne by a space object and that are transmitted or delivered to the ground from space by telemetry in the form of electromagnetic signals, by photographic film, magnetic tape or any other means." Raw data from satellite imagery is simply a reflection of Earth phenomena; in other words, mere representation of facts. Theoretically, raw data does not precisely fit within the regime of copyright protection since human intervention is involved to a minimal extent. The development and operation of a satellite involves significant investment of time and money; however, it is questionable as to whether or not the raw data derived from such systems can be regarded as original expression.

If they are to be protected at all under copyright, the elements that would count toward protection can be found in how the satellite image is taken and the degree of creativity involved in the process of data collection. It seems difficult to find creativity in the operation of data collection alone from a sensor, such as Landsat, since it is continuously taking imagery simply of nadir, whereas with Spot images can be taken from different angles requested through human intervention. In this regard, it is more justifiable to argue that raw data from the Spot satellites involves subjective judgement and thus merits protection under copyright.

Processed data are defined under the Principles as "the product resulting from the processing of the primary data needed to make them useable." It is more difficult in this instance to deny copyright applicability. Processed data is generated after data handling operations such as standardization, classification, visualization, editing, and correction of data. If no creativity is involved in these data handling operations, processed data does not have the element of creativity and vice versa. Thus, it can be argued that if the processing is done only by machine, then it is difficult to justify copyright protection for the result- ing processed data. On the other hand, if the processing is done manually by an individual making subjective choices and judgements, then the resulting data involves an intellectual contribution and, consequently, is likely to merit copyright protection.

One aspect of creativity which could be found in data handling operations is a colour assignment of an image. An image can be colour assigned in different ways to produce different images. The fundamental difference lies between true colour and false colour images. Multi-band remote sensing images do not have the visual spectrum, but in order to see these in a colour monitor, one needs to assign red, blue, and green to bands outside the visual spectrum. The decisions to assign certain colours to produce the particular image can be considered to involve a certain degree of creativity, although the subsequent application is generally fully automatic and may indeed be based on accepted classifications requiring no individual input to a specific satellite image.

Processed satellite data is perhaps most closely analogous to photos, in the sense that it is capturing facts but may involve certain degrees of choice or creativity. Article 2(1) of the Berne Convention states that "literary and artistic works shall include every production in the literary, scientific and artistic domain, whatever may be the method or form of its expression, such as (...) photographic works to which are assimilated works expressed by a process analogous to photography."128 Therefore, photographs are, in general, within the scope of copyright protection; however, the degree of creativity is a critical element with respect to photographs, and a photograph without creativity is not protected.

The fact that photographs without originality are not protected under copyright law is well illustrated in the case of *Bridgeman Art Library Ltd. v. Corel Corporation*. In this case, the plaintiff claimed copyright regarding photographic transparencies incorporating photographs of paintings in the public domain; however, the defendant denied that the photographs concerned were protected by copyright. It was decided that no copyright in drawings, which were merely copies, is recognised even if skilfully made of previous drawings. The plaintiff appealed, but ultimately – relying on the US case of *Batlin and Son Inc. v. Snyder* – the Court concluded that the photographs were not original.

Analysed information is defined as “the information resulting from the interpretation of processed data, inputs of data, and knowledge from another source.” Derived products or value-added products are also considered to be analyzed information. There are different types of analyzed information including digital elevation models, maps, satellite data combined with metadata, population data, vector data, and navigation data. As previously discussed, satellite imagery is increasingly provided to end-users in a format that is ready to support decision-making such as maps of affected areas.

Whatever the form of value-added products derived from satellite data, they seem to fall into the category of protected work under Article 2 of the Berne Convention, as they include “illustrations, maps, plans, sketches and three- dimensional works relative to geography, topography, architecture or science.” Indeed, a map, which is a typical form of analysed information, is within the scope; however, not all maps are protected. Whether a particular map is protected or not hinges on both its originality and the intellectual activities involved in producing it.

A map was considered to be protected under copyright in the case of *Compagnie des Courtiers v. Cellier des Halles,* where a map of wines of France was held to be original, in part because of the choice of disposition of evaluations, typography, and colours. Protection for maps on the basis of copyright is applicable to digital maps as well.

Mason v. Montgomery Data Inc. concerned real estate tract maps showing the location, tract size and shape, deeds, abstract numbers, acreage, and tract ownership, along with other topographical features. The US Court of Appeals for the Fifth Circuit held that maps created by independent mapmakers meet the standard of creativity necessary for copyright protection on the ground of “selection of sources, interpretation of those sources and skill and judgement in depicting information.”

In *Kern River Gas Trans. Co. v. Coastal Corp*, the plaintiff mapped proposed gas transmission lines on 1:24,000 scale US Geological Survey topographic maps. The court held that the map was not protected by copyright, as the mapping of transmission lines created the only effective way of expressing the idea of the location of the pipeline. Karjala argues that a map should be copyright protected when it is the product of its maker’s intellectual effort – that is, when it is not copied from another map. Whether a particular work merits protection hinges on the intellectual activities involved to produce maps; thus, non-original maps are not protected.
Another important issue is the copyright of analysed information in terms of joint authorship. As previously noted, it is possible that more than one author is involved in analysing and producing information, such as maps, based on satellite images. The satellite images are often processed, interpreted, and analyzed by more than one person who belong either to the same organisation or who belong to different organisations. In such cases, it is important to clarify the nature of the joint authorship and how the total benefits are shared amongst the authors.

The Berne Convention provides recognition for joint authors in Article 7 bis; however, it is silent as to how the work of each author is assessed and how the benefits of each author are allocated as a result of being a joint author. Hence, determination of what joint authorship entails has to be made by consulting the national laws that contain more concrete provisions. A work of joint authorship means either that the separate contributions to the work are indistinguishable in some cases, or in other cases the term may be used generally to describe works with more than one author.

Joint work is recognized amongst European jurisdictions. Article 8(1) of the 1965 German Copyright Law stipulates that "if more than one person has created a work together, and their respective contributions cannot be separately exploited, they are joint authors of the work." Section 10(1), Chapter I of the 1988 UK Copyright, Designs, and Patents Act provides that "a work of joint authorship means a work produced by the collaboration of two or more authors in which the contribution of each author is not distinct from that of the other author or authors." Whilst what 'joint 'means is not defined, this provision infers that contributions by each party are not distinguishable from one another in terms of type and degree of each contribution. The German and UK laws seem to be inadequate to address a satellite product, which is, by nature, the result of contributions of different kinds and of unequal degrees, which may be exploited separately.

On the other hand, the 1992 French Intellectual Property Code144 recognizes joint work where contributions are of different types, with differing degrees, and can be separately exploitable. The Code recognizes three types of joint works: work of collaboration, composite work, and collective work. Work of collaboration means a work in the creation of which several individuals ('plus- ieurs personnes physiques') have participated. Composite work means a new work in which a pre-existing work is incorporated without the collaboration of the author of the earlier work. Collective work means a work created on the initiative of an individual or a legal person, who edits it, publishes it, and divulges it under his/its direction and name, and in which the personal contribution of several authors participating in its elaboration merge in the ensemble for which the work is conceived, it being not possible to attribute to each of the contributors a distinct right on the work as a whole.

Different types of joint works could lead to various interpretations amongst the concerned parties, and these differences have given rise to litigation. The French Intellectual Property Code appears to contain language that could be suitably applied to differentiate amongst the many types of value-added satellite-derived products. Applying the Code, a map constructed from two different satellites may be associated with a work of collaboration. On the other hand, satellite-derived products, in which the data generator and information extractor are different, can either be composite work or collective work.

It is critical to establish categories for the different types of joint work associated with satellite images and their derived products and to clarify what each of them involve. This highly relevant issue will be examined more thoroughly later in this part.

The Database Protection for Satellite Images: The right of *sui generis* can be applied to all types of satellite products – raw data, processed data, and analysed information – all of which may also be protected simultaneously under copyright. Such application is possible according to Recital 17 of the EC Directive, which reads that "(...) whereas the database covers collections of independent works, data or other materials which are systematically or methodically arranged and can be individually accessed." Since a satellite image is a set of geographically located measurements, it is considered to meet the condition of autonomy of elements because its measurements are not only individually accessible, but are also independent of the other in the file. Since the right of *sui generis* is applicable to non-electronic databases, it is also applicable to printed satellite images.

The database rights regime is much more concrete as to joint work than to the copyright regime. Article 4(3) provides that "In respect of a database created by a group of natural persons jointly, the exclusive rights shall be owned jointly." Therefore, in the case of a product made using the data from more than one satellite, a claim for the raw data on the basis of the right of *sui generis* will be shared jointly amongst the data generators.

It is possible to have different entities holding the copyright and database rights for satellite-derived products when the data generation and the information extraction have been done by different entities.

The Practice of the EO Data Generator with Regard to Copyright and Database Right and Identification of Gaps and Problems: Currently, the majority of data generators, whether they are governmental agencies or private entities, explicitly claim copyright in their distribution con- tracts/licensing agreements. It is common practice that the copyright notice © followed by the name of the data generator is included along with the image. If the owner and suppliers are different, the copyright holders of data, rather than the suppliers of the data, are normally the owners of the satellites (e.g., CNES holds the copyright for Spot data from Spot 1 to Spot 5 even if Spot Image distributes it).

The current practice of claims over intellectual property rights of satellite data and derived products has both problems and gaps that can be highlighted through further analysis. There are discrepancies between the legal regime and practice, and varying practices in exercising and enforcing intellectual property rights create uncertainties and confusion, most notably: 1) problems related to varying domestic laws; 2) protection for value added products; 3) the issues of joint authorship; and 4) the lack of universal applicability of database rights.

The Litigation over Copyright Infringement: Varying domestic laws applicable for the protection of satellite data152 can be a source of dispute. In the past, the problem concerning authorship of work has resulted in litigation related to satellite images. The dispute concerned published processed Meteosat data marketed by an ESA distributor in Germany without a copyright notice. Following the action brought by the distributor along with ESA, it was held that, according to German law, only a natural person could be recognised as an author of work; however, ESA could not prove before the court which employee was the author of the image, so the case was dismissed. This case invokes the need to understand the differences in the intellectual property regimes under different jurisdictions and the necessity to make suitable arrangements in case of copyright infringement of a cross border nature.

Protection for Value Added Products and Issues of Joint Authorship: A problem exists as to the types of products for which copyright is claimed. The practice is not uniform. Most data generators claim copyright over their products, irrespective of the type of data. Others do not claim copyright for the resulting products if they are modified to the extent that the original image is no longer identifiable. For instance, the Advanced Land Observation Satellite (ALOS) distinguishes between products retaining original patterns and those which do not, and copyright is not claimed for the latter, in which copyright is held by the persons who conducted the value-adding operations.

Who has copyright over a value-added product is a subject for debate. It is useful to approach the issue by applying the definition of three types of joint work from the French Intellectual Property Code discussed above. The joint authorship in terms of work of collaboration is adopted for a map made of data collected from distinct satellites. In this case, there are no critical problems because authors of collaborative works exercise their rights under the French Intellectual Property Code either by common accord or by separately exploiting their personal contribution. The question arises as to the issue of joint author- ship of two types of value-added products: collective work and composite work, respectively.

Copyrights of value-added products are largely held by the data generators, with a credit given to value-added entities as far as products delivered within the Disaster Charter are concerned. Examples of how the intellectual activity of the value-adding operation is credited include the statements: "image processing and information extraction by ...", "analysis and map created by ...", or "image processing, map created by ….", which describe the specific contributions made by the various value-added entities. However, there are generally no joint copyright notices.

The copyright practice on value-added products from collective work generates a situation in which value-adding entities are not in a position to exercise rights independently and to pursue claims in case of copyright infringement of the derived products to which they contributed. The rights of the entities that provide added value are secured only through the satellite data generator's goodwill. It appears that the legitimate rights that should be enjoyed by those entities that add value by conducting analysis and information extraction through intellectual contribution cannot be exercised because they are not even recognized.

The practice of collective work seems to be common amongst data generators, and is to be differentiated from the relatively minor practice involving composite work on value-added products where the value-adding reseller, on the basis of raw data, processes and extracts information to publish new work under its direction. In this case, copyright associated with pre-existing work is held by the data generator and such right can be exercised through a royalty paid by the value-adding reseller to the data generator or by exercising database rights with respect to the users of value-added products.

Following the conventional rules on copyright, the copyright should be claimed by the person who has conducted the value-adding process in trans- forming the raw data into useful knowledge, rather than the data generator who has invested in the development and operation of the satellite. It is necessary to clarify the resulting benefits relating to three different categories of joint works: 1) work of two or more data generators; 2) collective work published under a single data generator; and 3) composite work published under a value-adding reseller.

Non-Universal Applicability of Database Rights: The non-universal applicability of database rights also creates a problem. Currently, protection on the basis of *sui generis* or extraction right is limited to certain jurisdictions. The EC Database Directive is applicable only within the European Community and to its nationals. Some legal systems, apart from that of the European Community, also recognize database rights – including Japan– but others do not. For instance, the United States has not introduced the *sui generis* right into its national copyright system and, accordingly, satellite images are not protected under the US database rights. Data generators can refer to the inherence of their extraction right in their distribution agreement, but enforcement hinges on jurisdiction. Assertion of the extraction right is likely to serve as a safety net in case of court decisions against protection on the basis of copyright within jurisdictions that recognizes database rights.

The foregoing examination of the legal framework of intellectual property rights and the practice of EO data generators demonstrates that there is a gap between the goal of the data generators seeking protection for all types of data and what protection is actually available to them under present law. Furthermore, there are inconsistencies in practice amongst different data generators that create uncertainties and confusion, particularly with regard to copyrights for value- added products; this harms concerned parties, including data suppliers, users, and third parties. Considering the international nature of data generation and sale, the clarification of the rules on how intellectual property rights apply to satellite images is critical and there is an evident need for a common regime that provides that clarification.

Issues of Data Reliability: Data Authentication and Accuracy Validation: The section explores the issues of data reliability and mechanisms for data authentication and validation. Digital geographic information data quality has been defined in ISO standard 8402 as "the totality of features and characteristics of a product or services that bear upon its ability to satisfy stated or implied needs." This definition is limited: although it implies the ability of the final product to satisfy the need, it does not establish clear criteria as to how to verify whether the final product actually meets the specific user needs. Furthermore, it applies only to Geographical Information Systems (GIS); that is, digital maps or digital components of maps such as roads, cities, and lakes. The definition does not apply to satellite-generated raw images or processed images unless some cartographic layers are derived from the satellite image; then the definition applies.

The accuracy of the final product depends on two components: the quality of the original data, and the quality of the image processing used to obtain the final result. The quality of the original satellite image dramatically affects the subsequent decision possibilities. Generally, satellite image data is processed and the user(s) rely on the results to make decisions or take actions. Therefore, the ability to satisfy user needs hinge largely on the authenticity and accuracy of the data and those of data processing. The authenticity and accuracy of the data and those of data processing affect decision-making to such an extent that, if the image provider has not fully disclosed details regarding the image fidelity and potential errors, and/or the processing methodology is not described precisely, users must use the image with caution or discard it completely.

Satellite data generators and distributors do not provide any measurements for the accuracy of standard products. In some cases, if specifically requested, they might provide their best knowledge about the conditions of the satellite when the image was taken. There is no mechanism that enables the objective assessment of data in order to identify or measure its quality.

Data Authenticity and Accuracy: The issues relating to data quality can be categorised into: 1) authenticity, and 2) accuracy. The first category addresses data fidelity; that is, whether the satellite data is authentic and that there has been no manipulation involved of which the user may be unaware, such as intentional or unintentional modification and/or misinterpretation of the original data. For verification purposes, it is important to be able to trace the complete history of the data from the original source to the final product delivered to the user, including the image acquisition, the subsequent processing, and analysis that has been conducted at different stages.

The second category addresses how accurately the data reflects the actual phenomena on the ground. There are several methods to enhance the accuracy of the data during processing stages such as geometric and radiometric correction, calibration, and ground truth measurements. All these methods depend also on the accuracy of the auxiliary data used to process the satellite image. In this way, the assessment of the overall quality of data is complex and it is necessary to look closely at all aspects – authenticity of data, accuracy of data, and an analysis of what needs to be done to ensure data authenticity and accuracy.

The Authenticity of Data **:** In the aforementioned ICJ dispute resolution between Cameroon and Nigeria, the satellite images used in court generated confusion due to the conflicting interpretations of the image. In this case, Cameroon is alleged to have misinterpreted the image; however, in absence of a definitive mechanism for data authentication, it may be difficult for a court or other third party to judge.

It should be noted that the possibility of data manipulation exists in satellite images primarily because of its modifiable format, such as JPEG. If the processing is not documented, it might become extremely difficult, if not impossible, to notice if any processing was applied; consequently, experts should reject cases where there is any doubt of an artificial artefact created by image processing. In such cases, the original imagery should be requested from the satellite provider and compared to processed imagery to verify whether the original image contained such artefacts or not.

It is necessary to ensure that the processed and/or interpreted satellite data reflects the reality of what is on the ground using the method of ground truth – that is, to compare image data to real features and materials on the ground to verify the accuracy of interpretation. Certain laws of evidence and environmental laws require data authentication for verification use. It is necessary to be able to establish clearly the authenticity of images, as well as to identify those images that may have been manipulated and/or misrepresented.

The DIC of Delaware case illustrated that lack of information on the submitted photograph – including date, place, and the party responsible for defects – hampered its admissibility as evidence. In order to conduct data authentication, thorough disclosure of information on the data is crucial. Information providing the context of the data is referred to as metadata, which is complementary information such as name of the author, when the work is made, copyright information, methodologies for image processing applied to image, and software packages used.

Generally, the practice of satellite data providers is to include fundamental metadata information – such as the position of the satellite, geographical location of the centre of the satellite image, date of image capture, copyright, satellite description, and sensors description – in the data file.

Some metadata information is included in the contract/license and only available to data recipients. These data concern, for example, the distribution information and content of the information, such as technical specifications. Often, advanced products are provided with more comprehensive metadata; however, not all metadata information is available currently, particularly for standard products. Most notably, the quality of the data processing methods is not available. Metadata defined by the EC INSPIRE Directive includes "quality and validity of spatial data sets," but does not explain further how they are determined and applied. Such information is critical for verification use and, in the future, a common standard should be provided for this.

The Accuracy of Data: Article 1(8) of the Environmental Directive refers to 'accuracy 'in addressing the quality of environmental information, but does not explain this term in further detail. Before getting into the detailed discussion of accuracy, some attention should be given to the scope of satellite imagery as a suitable verification tool: the capability of satellite imagery in terms of the level of information that it can provide. If the court is interested to know whether an oil spill occurred on a certain date and time, remote sensing can assist. On the other hand, if the need is to measure such an oil slick at sub-metre precision, then satellite images have limitations and cannot be used alone to provide such accuracy. In fact, the use of data for verification purposes needs to be treated with caution. Today, satellite images can be used in court cases when the disputed point is within the level of accuracy that the satellite can provide with certainty. If the disputed matter requires accuracy at a very precise level, the imagery may not be completely reliable.

The question of accuracy is obviously whether the data contains errors. Potential errors may be caused not only from deliberate manipulation or negligence, but by the inevitable uncertainties inherent in satellite remote sensing techniques, inaccuracies, ground data used, and associated image processing activities. Indeed, the original remote sensing data has potential exposures to errors which may arise in the course of the chain of remote sensing operations. Potential errors may exist in each step of the data chain: data acquisition, storage, transformation, and use.

The following discussion focuses on the errors that occur in the phases of data transformation and use. In these phases, errors may occur in image interpretation because of ambiguous interpretation of surface features.

The image processing of remote sensing data is a relatively new technology with uncertainties, and both the experience and knowledge of the image interpreter affects the image analysis. For instance, oil slicks that appear dark on a radar image can be mistaken for the dark spots that result from wind, oceanographic and current effects, or weather conditions, and much will depend on the expertise of an interpreter to distinguish such differences. Subjective judgement is inevitably involved in the interpretation of images and it is essential that the standards for interpretation are clarified. Therefore, when the data are interpreted by another entity (possibly a subcontractor), it is necessary to quantify the levels of confidence in such interpretations and make them available to the ultimate user.

Currently, a parameter of validation of data accuracies is available to users in the form of technical adjustments conducted in pre-processing and ground verification. Pre-processing operations such as geometric and radiometric correction and calibration correct the data for distortions or degradations resulting from the image acquisition. Usually there is already some pre-processing on board the satellite. Using ground truth verification, it is possible to provide the data with a considerable degree of accuracy, thus enabling an overall improvement of accuracy from a technical perspective; nevertheless, human error is not adequately addressed.

Data accuracy is indicated in two components, namely, 1) maximum magnitude of error in metres, and 2) probability of occurrence of such an error. For example, Spot Image provides highly accurate digital elevation model products with their absolute horizontal accuracy within 30m and absolute vertical accuracy within 20 m; these accuracies are provided with a 90% confidence level. This indicates that 9 out of 10 products are accurate and, if they are not accurate, the errors are less than 30 m for vertical dimension and 20 m for horizontal dimension. These are the main criteria that can be relied upon in distinguishing more accurate images from those that are less accurate; however, the accuracy and fidelity of the processing procedures is not assessed for each product.

There are no objective assessments for all the processes of data handling activities from the raw data to final products. It is important to clarify the data handling processes so that accuracy is ensured in a uniform manner.

***What Needs to be Done to Ensure Data Authenticity and Accuracy*:** As previously discussed, currently basic metadata and pre-processing information is available. What is not readily available is full comprehensive metadata, particularly relating to the quality of information, data authenticity, and accuracy of data handling activities. Currently, it is difficult to determine the precise degree of data fidelity and accuracy because there is no systematic means to identify modifications and errors, and locate the sources thereof. The difficulty in the identification of where and how the errors occur lies largely in the changeable format and unrecorded history of data handling activities, which is not executed in a systematic way.

The fidelity and accuracy of the data processing procedures need to be ensured at the different stages of data handling activities, including data acquisition, pre-processing, processing, and interpretation. The fidelity and accuracy of the data processing procedures should be complemented by comprehensive information on the data/products at each stage. Instead of random availability of different types of metadata, metadata for disclosure should follow certain standards; for this, metadata endorsed by INSPIRE as well as the ISO standard on metadata of digital data – ISO 19115 – should be referenced. In accordance with these standards, depending on the applications, mandatory elements need to be set and must be available to users as well as to the concerned parties in the supply chains.

The determination of fidelity requires the recording of activities involved in product generation and the tracing of all subsequent processes, specifying by whom, when, and how processing is conducted. Recording such information in an unchangeable format would serve as an effective mean to avoid data manipulation and misrepresentation, and would enhance user confidence in data. The validation must enable the maintenance of data integrity and minimize the possibility of the data to be discredited by a court.

Issues of Traceability: Traceability is defined as the ability to follow activities associated with products through specified stages of processing and distribution. Traceability refers to the completeness of information for each step involved in the chain of production, and is used mainly in the context of food traceability, which is defined by Codex, the agency established by the FAO and WHO as follows: "to follow movement of food through specified stages of production, and processing." Since the term 'traceability 'is not yet adopted widely in the context of satellite images, it is practical to approach this topic by drawing an analogy with the existing traceability systems applied to other products – most notably, agricultural products.

The Consideration of Adopting Traceability for Satellite Images**:** Traceability in the verification of each process in a chain of processes from generation to distribution of products is applied extensively to various food products. The European Union generated a list of foods that must be subject to traceability: starting from beef (with the outbreak of bovine spongiform encephalopathy around 2000), a number of agricultural products, such as genetically modified foods and eggs, have been added to the list. The purpose of introducing traceability is to manage risks, to ensure reliability, and to disclose information.

There are two elements required in order for products to be verified: specification of a product and documentation of the history of the product; that is, how the product goes through various processes at different stages. Authentication requires the documenting of all major processes as well as proof that the documentation is reliable. Although it is not necessary to impose an obligation for all remote sensing data to follow such comprehensive traceability guidelines, they can serve as a concrete model. The most critical point is the ability to ensure the image is free from errors or without manipulation. Just as with agricultural products, if traceability is applied to satellite products, then higher reliability and quality can be achieved. Tracing of process requires assigning identification numbers to every product. A number of satellite data have identification numbers; thus the traceability of satellite images is already at a pre-operational stage. Now the question is: how can traceability be implemented in practice?

***How to Implement Tracing Satellite Products*:** The reasons for implementing a traceability requirement for satellite images are to achieve a uniform and objective approach and to establish a mechanism in assessing data authenticity and fidelity. Such implementation requires a methodology that would permit provision of metadata and recording of data history, such as how the data is generated and the degree of confidence in interpretation of images. Methods for traceability can range from documents, labels, marks and databases, to bar codes. For satellite images, an electronic authenticity tool is appropriate. Such a tool should fulfil several functions. First, the electronic authenticity tool should facilitate integration and disclosure of metadata and other relevant information that is currently available under different locations or is not available at all. Second, the tool should convey the information recorded at each stage of data acquisition and data handling activities. Third, the electronic authenticity tool should connect the information contained therein to a central database where the authorized agency can identify the avail- able information sources and ascertain the quality of each product. For implementation, two different periods for tracing are required for satellite images: pre-data supply and post-supply data.

As noted above, traceability before product distribution is already adopted for food products. A traceability system using a bar-code is common practice. By accessing a bar-code, consumers can get information such as who made the product and the history before its delivery to a consumer. Toshiba Tec uses three-step traceability for two-dimensional bar codes: the first step is to request the providers of the primary materials to disclose who the generators are and how the product is made – such as the use of a pesticide, and additives involved in production – and information is compiled into the database and then materials are labelled with bar codes. The second step is to make a database of processed food in the same way; and the final step is to build the infrastructure for disclosing all the information on the products to the consumers. Similar steps can be adopted for satellite-derived products combining multiple sets of data. Such a method allows the recording and integration of: 1) a set of metadata from a single source; and 2) more than one set of metadata from different sources.

Whilst traceability after sale is not necessary for food products, for satellite images, traceability after data supply may be critical. For example, data is supplied to a state representative that uses the data as evidence for a boundary dispute, and the court needs to know whether the data has remained free of manipulation after data supply. The method of traceability should also serve as a means for a data supplier to retain control after data distribution. It should permit the data generator such as a space agency to follow what happens to the data after distribution and to be able to prevent unauthorized reproduction and data manipulation. For this purpose, a digital watermark is a potential electronic authenticity tool. A digital watermark is a technique which allows an individual to add hidden copyright notices or other verification messages to digital audio, video, or image signals and documents without disturbing the information contained therein. Through the use of a digital watermark, information such as intellectual property rights can be imbedded, and the history of reproduction and possible manipulation can be traced. Such an electronic authenticity tool can serve to protect the interests of both the pro- vider and recipient of the data in the way that copyright protection is enforced for data providers. Ensuring data fidelity creates a disincentive for piracy and misuse, and also improves user confidence.

The need for verifying the accuracy and authenticity of data is urgent. In order to assess the quality of data objectively, transparency is required. In order to achieve transparency of processes before the final product, it is necessary for processing wholesalers and information extractors to: 1) document the data history, 2) indicate the level of certainty in interpretation and analysis, coupled with uncertainties and errors that may be involved; and 3) to provide the comprehensive metadata information at each stage. Ensuring the quality of data requires establishing common principles for the authentication and validation of data accuracy, as well as for traceability guidelines. Then, principles need to be implemented through use of the suggested electronic authenticity tool. Achieving the above described transparency measures using a suitable electronic authenticity tool will all contribute substantially to better data management. Consequently, the recommendation enables more effective assessment of the environment as well as response to disasters.

Conclusion: Improvements in the areas of data policies and data verification are urgent because satellite data is becoming an increasingly crucial source of information for disaster management and environmental protection applications, both of which require a large number of reliable data sets. Today, scattered data policies are an impediment to the full utilization and wide-spread use of data for public benefit purposes, and it is necessary to establish a clear regime with an exclusive set of rules to ensure availability, exploitability, and reliability.

Although the findings of this part show difficulty in unifying all the existing data policies, they infer the possibility for establishing a common data policy designed for public benefit service. Certain harmonization should be achieved as to access and pricing policies for the purposes of humanitarian aid and environmental protection. Data used for such public benefit pro- grammes should enjoy special treatment to relax the conditions usually placed on data. With respect to pricing, data should be available for urgent disaster response free of charge and for other non-urgent public uses at the cost of reproduction.

The improved regime to be proposed should serve to clarify current uncertainties involved in data use, specifically, intellectual property rights and lack of guidelines for data authentication and accuracy validation. It is recommended that data supply in both the public benefit service and commercial service categories come under a common intellectual property rights regime and data authentication mechanism. With regards to a common intellectual property rights regime, there are three primary recommendations:

1. Ownership of all types of satellite data will rest with the data generator, but protection on the basis of copyright will depend upon types of EO data.

2. Joint authorship for value-added products should be clarified.
3. The names of the persons who conduct data handling operations should be documented.

With respect to the first recommendation, manually processed data and value- added products that involve intellectual activity should be protected by copyright, whereas the raw data should be protected by database rights or merely credited without legal protection in those jurisdictions where such right is not recognized. Concerning the second recommendation, products generated by more than one individual or entity should be subject to protection under copyright when intellectual input is involved by each party, irrespective of types and degrees of contribution by each:

A. Value-added products of works of collaboration should be protected by copyright, then each data generator and associated rights share the associated rights equally.

B. For value-added products of collective work, copyright should be held by the data generator but a copyright notice should be provided that includes the name of the value-adding entity instead of simply crediting the entity.

C. For value-added products of composite work, copyright should be held by the value-adding reseller with database rights or credit given to the data generator.

D. For B and C, and other complex cases, intellectual rights should be determined on a case by case basis through the contractual agreements.

In any case, the names of individuals who conducted each operation should be documented. In case of copyright infringement, entities should be able to identify the originators of specific products. The responsibility and bene- fits of joint work should be allocated in accordance with the percentage of work obtained from each contributor to the final work, if necessary under the contract.

In order to enhance the reliability of data for verification, it is recommended that the metadata of all satellite images should adhere to common standards such as ISO, and mandatory elements for disclosure should be established for certain verification uses. Clear distinction should be made between authenticated and unauthenticated products, as well as between information with verified accuracy and that which has not been verified. The authenticated and verified products should be traceable with a suitable method.

For products verified as both authentic and accurate, the following principles should be applied:

1. Finished products at each data handling operation should be saved in a format that cannot be modified further after the completion of each processing stage, and/or upon distribution to users.

2. The names of persons who conducted processing and value-adding activities should be recorded and referred to if necessary.

3. Comprehensive metadata as well as the degree of certainties in the processing and analysis of images should be made available to all parties through the supply chain to end-users.

4. Proof of data authentication and verification should be marked clearly with a common symbol that should be used for all the authenticated and verified products.

The products with validated accuracy should be authenticated and their accuracies should be assessed objectively by a checklist including:

1. pre-processing information, such as whether the sensor is calibrated and the data is geometrically and radiometric corrected;

2. whether the products have been through ground truth verification or compared with other datasets for the same location; and

3. whether the final products are verified by external parties.

This way, the standards and qualities expected of the different products are set objectively.

Future Challenges and Perspective of Remote Sensing Technology: Earth-observing satellites are increasing in space and remote sensing data are under- going an explosive growth. These satellites will produce large volume of remote sensing data and will give rise to complexity and diversity in high-dimensional characteristics of data. However, it will be extremely difficult for various end users and advance user communities to efficiently use such traditional remote sensing data sets. At the same time, data processing and distribution will be a new challenge. It will also become difficult for user community to maintain the increasing volume of data and to build and launch hardware into space. Large volume of data, complex data formats, different map projections, applications of GIS, communication capability and processing time are crucial issues for the wide use of remote sensing data. Therefore, real-time remote sensing data in different formats will help users in analysing future earth-observing satellite systems. Preprocessing, data format conversing, open GIS applications and real-time data processing will help in better utilization of future earth- observing satellite systems.

Remote sensing technology has a wide range of scope from agriculture to urban and geosciences to disaster management. The study of plant characteristics in the agricultural field through the crop reflectance at various stages of growth is assessed to estimate the crop acreage and yield forecasting. It also studies about the identification of crops and landholding size through high-resolution data. Conventional visual interpretation method of land use and land cover classification has given way to high-tech machine learning tools. Remote sensing technology is widely used for planning and management of forest resources. The technology has proved useful in assessing forest biomass, deforestation, forest fragmentation, spatial distribution of tree species, classification of forest, etc. Landsat, SPOT, Sentinel and IRS data are extensively used in forest resource assessment and management. Very high spatial resolution data are used for classification and identification of built-up area in urban studies. Satellite sensors like IKONOS and QuickBird with high spatial resolution (<1 m) are used for cadastral mapping and urban planning. However, the growth of urban built-up, urban agglomeration and urban sprawl can be assessed using moderate resolution data acquired through Landsat, Sentinel and IRS sensors.

Hyperspectral images are widely used by geologists for identification of rocks and minerals. However, multispectral images are also used for detection and identification of geological structures and rock formation with the help of image interpretation keys. Geostationary satellite data is preferred for studying extreme weather events and cyclone due to its constant monitoring. MODIS and Landsat 8 sensors having coastal and aerosol spectral band are used for aerosol optical depth. Remote sensing data along with geographical information system (GIS) has also proved significant tools for disaster management. Digital elevation model (DEM) is extensively used to analyse the slope instability and occurrence of landslide. Remote sensing data are also used for mapping the past and current occurrence of landslide and analysing its trend and patterns. Weather and climate variability analysis, climate change analysis, natural hazards mapping and vulnerability assessment are being efficiently carried out with the help of remote sensing and GIS techniques. Earthquake mapping and flood mapping are also carried out by remote sensing data. Multispectral, hyperspectral and DEM are utilized for micro-zonation mapping of earthquake-prone areas, while microwave data along with DEM are extensively used for assessment of flood inundation.

Remote sensing technology is experiencing shift from optical and multispectral to hyperspectral remote sensing mainly due to limited spectral bands. Hyperspectral remote sensing or imaging spectroscopy has invited the attention of researchers since the last decade or so. First sensor of imaging spectrometer (Hyperion) was launched into orbit in 2000. Subsequently, access to such data became easier due to availability of various imaging spectrometer sensors, namely, HyMap, DAIS and AVIRIS. These sensors record spectral signature with hundreds or thousands of elements from a pixel in a targeted area. Hyperspectral remote sensing improves the capability of object identification in extremely harsh conditions due to the availability of large number of spectral bands. However, unmanned aerial vehicles (UAVs) are used nowadays for monitoring and collecting of data for small areas. Flexibility to sensor selection in UAVs has made it easy to collect data as per requirement.

The main challenges for remote sensing technology are preprocessing and validation. Various remote sensing data products are available for site-specific researches, but their resolutions varied from each other. For example, the assessment of forest fire needs high spatial and temporal resolution data. This is not possible for one sensor to provide both high resolutions, for example, if MODIS data is utilized for assessing forest fire, it will provide high temporal resolution of 1 day but will yield poor spatial resolution. Similarly, real-time flood assessment needs high temporal and spectral resolution data for bypassing cloud cover and detecting water spread. Hyperspectral remote sensing data with high spectral resolution will hold promising key to the solution to the future challenges of remote sensing technology. This will reduce the time of image processing for various spectral bands. However, hyperspectral remote sensing data will also need to be specifically enhanced for spatial resolution for providing better results. Hyperspectral image needs large storage and heavy processing configuration which will be a hurdle for digital image processing. Finally, remote sensing model validation is a complex task for researchers. There are large numbers of models based on remote sensing data applied by the researchers in various fields. All mathematical models don't have compatibility with all sensors, and these also don't work in all geographical locations. Therefore, validation of model is essential with in situ data. The on-ground data can also be utilized for model improvement through its integration with remote sensing data. This will improve the accuracy of results carried out by remote sensing data.

Future Advances in Hardware and Software of Remote Sensing Technologies: In the past, space-borne remote sensing instruments were primarily designed around a small, carefully-selected number of wavelength ranges due to resource constraints on system configurations. However, public–private partnerships are becoming the standard for satellite construction and operation. These partnerships are bringing innovation while reducing the cost of satellite systems. The coming decades are likely to see innovation in satellite construction and operation. These may include innovative approaches to refractive and reflective optics; larger antenna and mirror structures; use of compact Fourier transform and grating spectrometers to allow for the reductions in overall size and mass of optical instruments; more efficient cooling systems that will allow the extensions of these size benefits far into the infrared region of the electromagnetic spectrum; and the development of solar power and solid-state radio frequency amplifiers.

These technological innovations should improve the spatial resolution of satellites in low-Earth orbit (LEO) and allow for the inclusion of multispectral and hyperspectral, Radio Detection and Ranging (RADAR), Light Detection and Ranging (LiDAR), and Synthetic Aperture Radar (SAR) measurements from geostationary orbits (GEO). They may even allow tunable (i.e., with custom selection of desired wavelengths) imaging systems to become commonplace, allowing for much greater flexibility in spectral and spatial domains (Hartley 2003). An example of this sort of innovation is the hyperspectral data being acquired by the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS). It is expected that these high-spectral-resolution sensors, with improved spatial resolution, will be regularly placed on future Earth-orbiting satellites (U.S. Congress, Office of

Technology Assessment (OTA) 1993), building on early successes such as the Hyperion sensor.

These technological advances may also allow for the development of sensors with apertures of several meters from LEO and GEO, allowing for differential ab- sorption LiDAR (DIAL) and laser Doppler wind measurement sensors from space. Also, further development of the terrestrial laser scanners (TLS) and airborne laser scanners (ALS) is expected. The development of larger antenna mirror and structures may allow the placement of satellites at what are known as the Lagrange points, L1 and L2, which are located one and a half million kilometers from Earth on the Earth–Sun line. Because they will be operating in a nearly disturbance-free environment, sensors placed at the Lagrange points may be able to make highly precise measurements.

Some of these advances are already evident in the current generation of commercial satellites such as GeoEye-1 (data of 41 cm GSD), WorldView-2 (providing data of 46 cm GSD), and new satellites from India, Europe, China, Japan, Russia, Brazil, and other countries. In addition, in the coming years, several commercial providers expect to launch satellites with 1 m resolution or better. For example, the Indian Cartosat-3 is planned to collect imagery at 25 cm resolution. These higher resolution data will allow for new applications of remotely sensed data. An example that could impact everyday life for most people is the detection of automobiles with some level of uncertainty (depending on their size) with 1 m resolution imagery, whereas 50 cm resolution allows for the delineation of vehicle windshields. Automobile side mirrors can be detected only with 30 cm imagery, clearing a path for automated computer vision techniques permitting car model identification. It is also worth noting that yellow lines in the parking area appear clearer at 30 cm resolution, while they are barely visible at 1 m resolution. Finally, these newer classes of satellites will have high-performance camera control systems capable of rapid re-targeting, allowing the collection of dozens of images over a single target, each with a unique angular perspective.

Beyond innovation in traditional satellite technology, a range of new platforms for the acquisition of targeted remotely sensed data are being developed. These include nanosatellites, microsatellites, and uninhabited aerial vehicles (UAVs). These miniaturized platforms have three advantages as compared to larger systems. First, manufacturing, launching, and operating costs are less than larger satellites. This facilitates "risk taking" during design and encourages technical innovation. Second, small satellites can be developed in only a few years or months. Shortening the time to launch adds resilience and flexibility to the satellite systems, allowing for nimble response to emerging issues such as the need for a deeper understanding of global climate change. The current systems have a 10-year development cycle from conception to launch. Third, operating only a small number of instruments per satellite allows orbits to be optimized for a particular set of measurements. The growing popularity of UAVs and ongoing commercial exploration of their use by companies such as Amazon, UPS, and Federal Express (FedEx), along with the fact there is currently no need to have a pilot's license to fly one in the US (FAA), suggest continued growth and innovation.

These advances and continued decrease in the size of sensor electronics will come with and likely drive further increases in processing speed for both programmable and general-purpose processors as well as storage density and onboard re- cording capacity. By the time today's technologies are fully exploited, innovative new technologies, such as quantum and biological computing, will likely be realized. The ultimate result will be, for all practical purposes, unlimited computing power on orbit within the sensor itself.

Paralleling advances in hardware will be advances in algorithm to process the data. One key area of innovation is the development of parallel processing algorithms for remotely sensed data. Currently, parallel processing strategies for remotely sensed data are in their infancy. Those that have been implemented have assumed homogeneity in the underlying computing architecture (e.g., a dedicated cluster of workstations with identical specifications, connected by a homogeneous communication network). However, today we are beginning to see the emergence of both heterogeneous, distributed computer networks, built simply on local (user) computing resources and innovative heterogeneous parallel algorithms for extracting information from high-dimensional remotely sensed data. Plaza (2006) provides an example of the promise of these algorithms for the processing of hyperspectral imagery.

Overall, advances in remote sensing and associated technologies are already providing more focused agricultural and natural resources inventory and monitoring, quicker and more efficient emergency response, more accurate map products, improved navigation, and better geospatial information and derived products for the general public and professionals in a wide variety of fields.

Open, Social, and Timely: The rapidly developing and growing industry of commercial remote sensing along with expanded free access to governmental remotely sensed data has already made high-quality digital imagery widely available, leading to a substantial web-based market potential for remote sensing in media. Remote sensing data have allowed television, Internet, and print news media around the world to deliver more timely information. The Internet offers a unique medium to educate potential customers and to sell remote sensing data to them. News agencies, web sites, and a host of other visual media services will continue to benefit from the advances in remote sensing and continue to use remotely sensed data to provide current, relevant, and near-real-time information regarding events around the world. The widely-used Google Earth platform is an example of such applications.

Widespread access to remotely sensed data has made it integral and influential in our daily lives. Historically, NGOs and other entities who advocated for policy development (relating to economic, environmental, social, and other issues) have limited access to remotely sensed information because the technical expertise required to process satellite imagery was restricted to government agencies. The abundance of open-access satellite imagery and image processing capacity has resulted in near- ly unlimited capacity outside government. This movement is being further stimulated by the availability of web-based information systems, such as Google Earth and Google Maps, which provide users easy access to satellite imagery of your own backyard and beyond. These days, researchers, along with NGOs and the general public are applying remote sensing to mobilize support for situations requiring policy development—a process that has been called satellite imagery activism. The rise in satellite imagery activism has created its own set of challenges. These include issues such as who pays for infrastructure, training, and administration; whether to control data access; how to include the private sec- tor; and whether problems of collective action will continue to hamper the effort.

Government agencies have already begun to respond to these challenges by assembling, processing, and providing information at broad scales to a broad community of users. For instance, the US Geological Survey (USGS) realigned its science programs to better address relevant issues, concerns, and challenges to societies. New mission areas include Climate and Land Use Change, which is currently developing a science strategy that will guide USGS prioritization for research in the 2020s, and aid in the USGS developing methods to explain how changes in land use, cover, condition, and management alter climate, impact natural systems, and affect human health and welfare. This change in focus will allow USGS to take a leadership role in advancing science, leading to better understand (1) the interactions between the natural and physical environments (e.g., contaminants and pathogen exposure) and (2) the concept of One Health—the cohesive study of wildlife, human, ecosystem, and agricultural health.

For example, remote sensing is currently influencing research regarding climate, earth surface processes, and ecosystems across space and time through its contributions to the strategic goals of global climate change studies, including the US Climate Change Science Program. Remote sensing has guided other scientific research strategies and the linkages to other mission areas, including ecosystems and environmental health.

The application of remote sensing data is suggestive of its real-time nature. Once we begin to think of remote sensing in terms of more real-time (or near real-time) applications, then the scope of activities and applications may change significantly, opening the door to new possibilities and new realities for using spatial information. Data are already turned into information and will increasingly become knowledge. Remote sensing will become more valuable and we will become more reliant upon it.

We are already seeing this transformation with radio-frequency identification (RFID) tags, global positioning system (GPS) trackers, cell phones, and arrays of satellites. For example, DigitalGlobe's constellation of satellites has intraday revisit anywhere across the globe and it is capable of collecting over three million square kilometers of imagery every day. The company's archive has complete coverage of most nations and urban areas have imagery as recent as three months old.

In addition, the integration of mobile technology with real-time remotely sensed geospatial data is already supporting the development of decision support tools for a variety of environmental, disaster warning, and emergency monitoring and management applications such as wildland fire risk and damage assessment, large-scale drought conditions and impacts, irrigation and water allocation systems, flooding risks and damage assessments, earthquake, tsunami, and public health as well as infrastructure development of maintenance. For example, certain health issues are now benefiting from advances in information technology and numerous smart de- vices can now collect remotely sensed data to characterize the environmental and landscape causes for such problems. Sensors and scanners are being integrated into the mobile devices for continuous health assistance and disease attack prevention. Scientists are developing system framework for modeling and analyzing individual exposure to environmental triggers of asthma attacks. Finally, air quality indices, for example, are now monitored regionally in real time and available as "apps" for mobile devices such as Android and iPhone.

Beyond the use of real-time data, many of these applications are using remotely sensed crowd-sourced data. Much of these crowd-sourced data are often based on volunteer services that may be coupled with the mobile apps using smart mobile de- vices for collecting and transferring information. Currently, remote sensed data are being integrated with crowd-sourced data in agriculture to allow for the collection, distribution, and exchanges of data to farmers for drought, fertilizing, irrigation, and disease control (Amy J. Harris, NASA Ames Research Center). We expect this combination will be used more frequently in the future for disaster management practices by the remote sensing practitioners without having to be present in the disaster area for deploying the proper systems and allocating more relevant and timely resources for risk assessment and damage prevention or control.

While promising, the technologies described above are only the tip of the iceberg. If Martin Wikelski has his way, the International Space Station will one day keep a close eye on thousands of our planet's bats, songbirds, dragonflies, rodents, and other small creatures. A specialist in animal movements, the ecologist at the Max Planck Institute for Ornithology in Radolfzell, Germany, has for a decade pursued what a collaborator once dubbed a "ridiculous idea": a new space-based system to track animals too small to be monitored globally with current instruments. Wikelski and his colleagues have begun testing whether a new animal tag can eventually communicate with the International Space Station.

In an era of global land-use, land-cover, and climate change, a space-based way to track animals would revolutionize the study of animal movement and the field of conservation biology. As described by Ropert-Coudert and Wilson (2005), bio- logging is the use of data-recording units to acquire huge, multivariate datasets about the behavior of animals moving freely in their natural environment. This approach allows scientists to study wild animals in the field, behaving normally, with approximately the same degree of rigor as laboratory studies. A future space-based system along with advances involving higher data resolutions, faster data process- ing, and free access to data would allow scientists and policy makers to better understand the biotic and abiotic factors affecting behavior of mobile species as well as development of effective management plans.

Inter-disciplinarity and Big Data: Remote sensing is providing a platform for building vital bridges between scientific disciplines, pushing the frontiers of big data, and advancing science diplomacy.

Recent work on cropland mapping is an excellent example of the application of ongoing advances in remote sensing to provide accurate and reliable crop maps and statistics at local, regional, and global scales. Given that about one in eight people in the world suffer from chronic hunger, impacting their abilities to have an active and healthy life (FAO 2011), timely and accurate information on crop inventory, health condition, and yield estimation can be invaluable in helping to combat these problems. Remote sensing also provides a means to practice precision agriculture, which optimizes resources both within and across fields. In addition to agriculture, hyperspectral imagery and a thermal infrared scanner are currently being used to monitor a variety of environmental, ecological, and geological features at a wide range of wavelengths (e.g., over 200 bands of data). Specific applications include monitoring deforestation; water resources; disaster management such as hurricanes, tsunamis, earthquakes, urban and wildland fires as well as ecosystem management.

Remote sensed data underlies the rise of "Big Data." Moderate- to high-resolution remote sensing data available from multiple satellite systems such as Landsat, SPOT, MODIS, VIIRS, IRS, ERS, JERS along with airborne and satellite hyperspectral data such as AVIRIS, HyspIRI, Hyperion, PRISM, and HICO, and airborne UAV-based data such as UAVSAR when combined with vast amount of ground- based and crowd-sourced data over large areas have given birth to the explosive growth of remotely sensed information leading to the "Big Data" concept. Factors contributing to this massive growth include open access to land cover data (e.g., Landsat, MODIS, VIIRS); open access to vast and frequently collected meteorological data (e.g., GOES, Meteosat, Meteor); open access to field-based data collected by many government agencies and researchers; open access to other large-scale datasets such as digital elevation models (DEM); and organized approaches to collection and preprocessing of some of these datasets such as NASA NEX.

Despite the enormous computational power, the cluster-based high-performance computing (HPC) systems still remain considerably challenged with remotely sensed "Big Data" issues. These issues include the difficulties in storing massive and complex data, intensive irregular data access patterns, managing remotely sensed "Big Data" on multilevel memory hierarchy, optimal scheduling of large amount of interdependent tasks as well as the efficient programming for these vast databases. There is no doubt that the existing techniques and systems are limited in their ability to solve remotely sensed "Big Data" problems completely.

Finally in terms of enhancing scientific diplomacy, remote sensing has been at the heart of activities organized by the American Association for the Advancement of Science (AAAS) Center for Science Diplomacy. The Center has been instrumental in advancing scientific engagement as an essential element of foreign policy and of building vital bridges between societies. For example, during December 2014, AAAS organized a delegation to Havana, meeting with Cuban colleagues to dis- cuss opportunities for joint research on coral reefs, hurricane dynamics, and other areas of common concern, and in February 2015, an AAAS-led group traveled to Myanmar, the second time in as many years, to meet with government ministries and scientific NGOs to discuss health science, forestry, education, and the role of science in public policy.

Concluding Thoughts:

Several trends are expected to continue far into the future. These include the following:

- Miniaturization and integration of electronics
- Further development of UAV-based data acquisition systems
- Increases in computational power such as heterogeneous parallel computing, cloud computing, and quantum and biological computing
- Progress in large apertures and larger antennas
- Increases in transmitter power for active systems
- Miniaturization of optics
- Increase in storage technology
- Development of small satellites
- Advances in screen technology and mobile computing
- Increases in tunable systems and flexible frequencies
- Advances in techniques for processing "Big Data"

Ultimately, sizes of observing platforms will be dictated solely by the physics of their parts. Despite the established utility of remote sensing technology in a wide variety of applications, the state of the US and the global economy and the burden of an increasing federal deficit in the US and major European countries will force decision makers to seek ways to reduce the costs of remote sensing systems. This may cause challenges for the growth of remote sensing technology. These challenges can best be met through the combined efforts of the international scientific and user communities.

Despite the short-term economic pressures on the development of new sensors, payloads, and platforms, along with the international issues involved in acquisition and distribution of remotely sensed data, we are optimistic about the future of remote sensing. In addition to the rapid growth in the technological aspects of acquiring and processing remotely sensed data, the remote sensing community is a direct beneficiary of an ever-advancing state of the art through broad collaborative efforts between developers and user communities such as biologists, engineers, social scientists, the public health and legal communities, media, urban planners, and environmental resource managers. The opportunities to use remote sensing are limitless.