# Chapter 3

# Imagery Fundamentals

## Introduction

Imagery is collected by remote sensing systems managed by either public or private organizations. It is characterized by a complex set of variables, including

- collection characteristics: image spectral, radiometric, and spatial resolutions, viewing angle, temporal resolution, and extent; and
- organizational characteristics: image price and licensing and accessibility.

The choice of which imagery to use in a project will be determined by matching the project's requirements, budget, and schedule to the characteristics of available imagery. Making this choice requires understanding what factors influence image characteristics. This chapter provides the fundamentals of imagery by first introducing the components and features of remote sensing systems, and then showing how they combine to influence imagery collection characteristics. The chapter ends with a review of the organizational factors that also characterize imagery. The focus of this chapter is to provide an understanding of imagery that will allow the reader to 1) rigorously evaluate different types of imagery within the context of any geospatial application, and 2) derive the most value from the imagery chosen.

# Collection Characteristics

Image collection characteristics are affected by the remote sensing system used to collect the imagery. Remote sensing systems comprise *sensors* that capture data about objects from a distance, and *platforms* that support and transport sensors. For example, humans are remote sensing systems because our bodies, which are platforms, support and transport our sensors—our eyes, ears, and noses—which detect visual, audio, and olfactory data about objects from a distance. Our brains then identify/classify this remotely sensed data into information about the objects. This section explores sensors first, and then platforms. It concludes by discussing how sensors and platforms combine to determine imagery collection characteristics.

A platform is defined by the *Glossary of the Mapping Sciences* (ASCE, 1994) as "A vehicle holding a sensor." Platforms include satellites, piloted helicopters and fixed-wing aircraft, unmanned aerial systems (UASs), kites and balloons, and earth-based platforms such as traffic-light poles and boats. Sensors are defined as devices or organisms that respond to stimuli. *Remote sensors* reside on platforms and respond "to a stimulus without being in contact with the source of the stimulus" (ASCE, 1994). Examples of remote sensing systems include our eyes, ears, and noses; the camera in your phone; a video camera recording traffic or ATM activity; sensors on satellites; and cameras on UASs, helicopters, or airplanes.

Imagery is acquired from terrestrial, aircraft, marine, and satellite platforms equipped with either analog (film) or digital sensors that measure and record electromagnetic energy.[1] Because humans rely overwhelmingly on our eyes to perceive and understand our surroundings, most remote sensing systems capture imagery that extends our ability to see by measuring the electromagnetic energy reflected or emitted from an object. Electromagnetic energy is of interest because different types of objects reflect and emit different intensities and wavelengths of electromagnetic energy, as shown in figure 3.1. Therefore, measurements of electromagnetic energy can be used to identify features on the imagery and to differentiate diverse classes of objects from one another to make a map.

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[1] Most remote sensing systems record electromagnetic energy, but some, such as sonar systems, record sound waves.

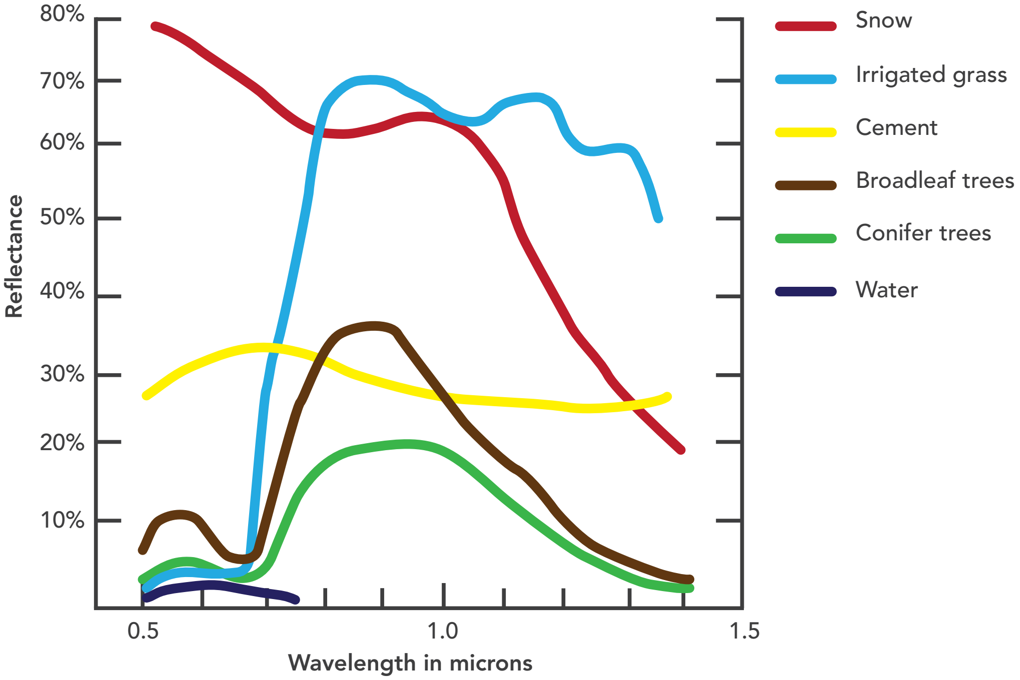


**Figure 3.1.** Comparison of example percent reflectance of different types of objects across the electromagnetic spectrum (esriurl.com/IG31)

The type of sensor used to capture energy determines which portions of the electromagnetic spectrum the sensor can measure (the imagery's spectral resolution) and how finely it can discriminate between different levels of energy (its radiometric resolution). The type of platform employed influences where the sensor can travel, which will affect the temporal resolution of the imagery. The remote sensing system—the combination of the sensor and the platform—impacts the detail perceivable by the system, the imagery's spatial resolution, the viewing angle of the imagery, and the extent of landscape viewable in each image.

## Sensors

This section provides an understanding of remote sensors by examining their components and explaining how different sensors work. As mentioned in chapter 1, a wide variety of remote sensors have been developed over the last century. Starting with glass-plate cameras and evolving into complex active and passive digital systems, remote sensors have allowed us to "see" the world from a superior viewpoint.

All remote sensors are composed of the following components, as shown in figure 3.2:

- Devices that capture either electromagnetic energy or sound, either chemically, electronically, or biologically. The devices may be imaging surfaces (used mostly in electro-optical imaging) or antennas (used in the creation of radar and sonar images).
- Lenses that focus the electromagnetic energy onto the imaging surface.
- Openings that manage the amount of electromagnetic energy reaching the imaging surface.
- Bodies that hold the other components relative to one another.

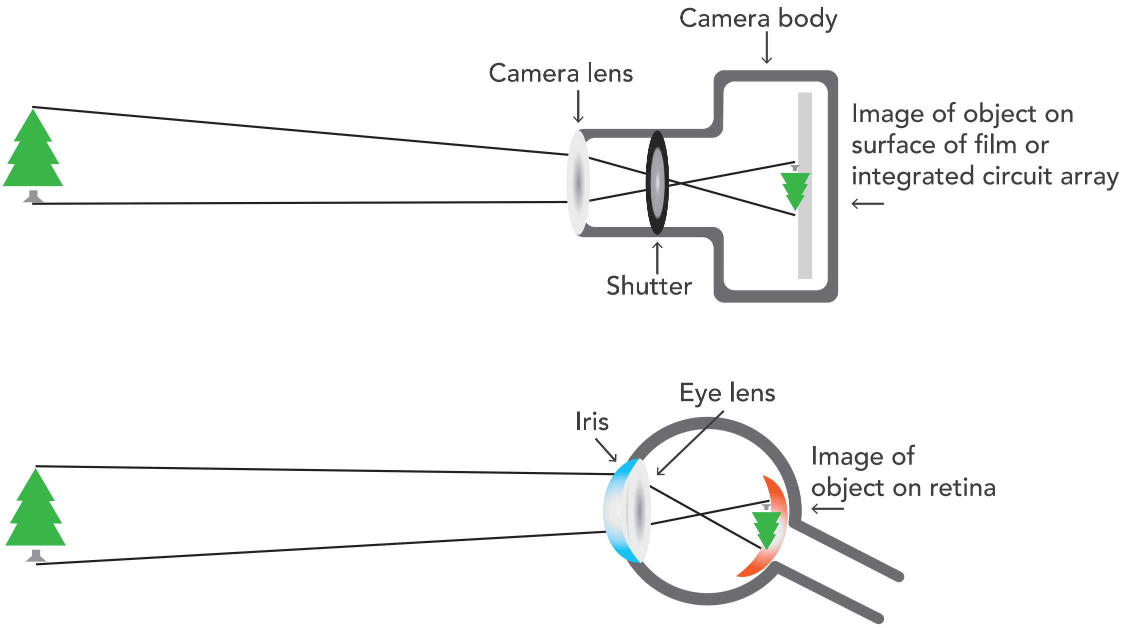


**Figure 3.2.** The similar components of the human eye and a remote sensor

Our eyes, cameras, and the most advanced passive and active digital sensors fundamentally all work the same way. Electromagnetic energy passes through the opening of the sensor body where it reaches a lens that focuses the energy onto the imaging surface. Our brains turn the data captured by our retinas into information. Similarly, we convert remotely sensed image data into information through either manual interpretation or semi-automated image classification.

## Imaging Surfaces

Imaging surfaces measure the electromagnetic energy that is captured by digital sensors such as a charged coupled device (CCD) or a complementary metal-oxide-semiconductor (CMOS) array. The wavelengths of energy measured are determined by either filters or dispersing elements placed between the sensor opening and the imaging surface. The energy is generated either passively by a source (such as the sun) other than the sensor, or actively by the sensor.

### *The Electromagnetic Spectrum*

Most remote sensing imaging surfaces work by responding to photons of electromagnetic energy. Electromagnetic energy is caused by the phenomenon of photons freeing electrons from atoms. Termed the photoelectric effect, it was first conceptualized by Albert Einstein, earning him the Nobel Prize in physics in 1921.

Electromagnetic energy occurs in many forms, including gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves. It is characterized by three important variables: 1) speed, 2) wavelength, and 3) frequency. The speed of electromagnetic energy is a constant of 186,000 miles/second, or $3 \times 10^8$ meters/second, which is the speed of light. Wavelength is the distance between the same two points on consecutive waves and is commonly depicted as the distance from the peak of one wave to the peak of the next, as shown in figure 3.3. Frequency is the number of wavelengths per unit time.

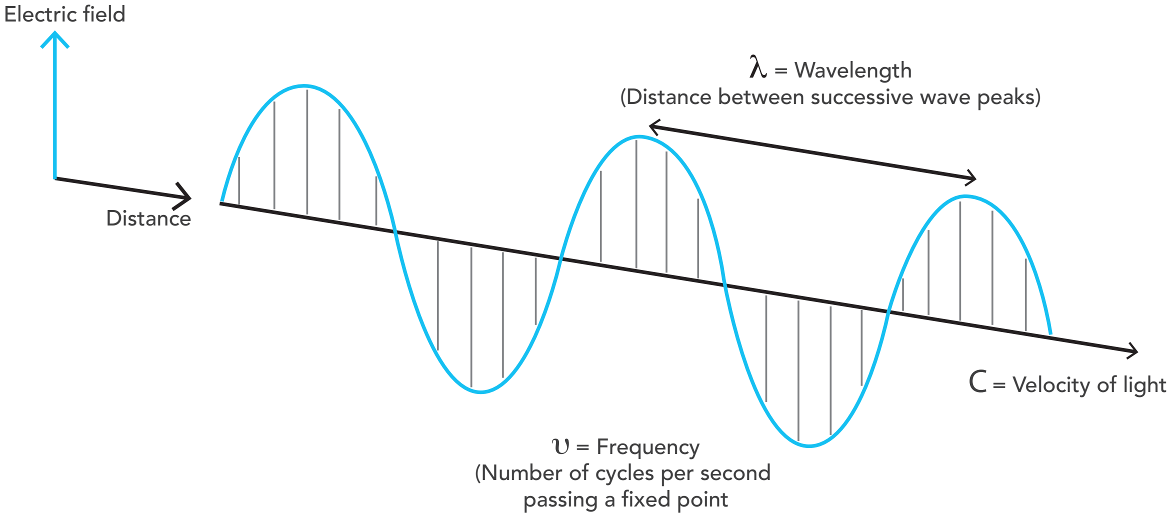


**Figure 3.3.** Diagram demonstrating the concepts of electromagnetic wavelength and frequency

The relationship between wavelength, wave speed, and frequency is expressed as

$$\textit{Wave Speed} = \textit{Wavelength} \times \textit{Frequency}\ .$$

Because electromagnetic energy travels at the constant speed of light, when wavelengths increase, frequencies decrease, and vice-versa (i.e., they are inversely proportional to each other). Photons with shorter wavelengths carry more energy than those with longer wavelengths. Remote sensing systems capture electromagnetic energy emitted or reflected from objects above 0 degrees Kelvin (absolute 0).

Electromagnetic energy is typically expressed as either wavelengths or frequencies. For most remote sensing applications, it is expressed in wavelengths. Some electrical engineering applications such as robotics and artificial intelligence express it in frequencies. The entire range of electromagnetic wavelengths or frequencies is called the electromagnetic spectrum and is shown in figure 3.4.

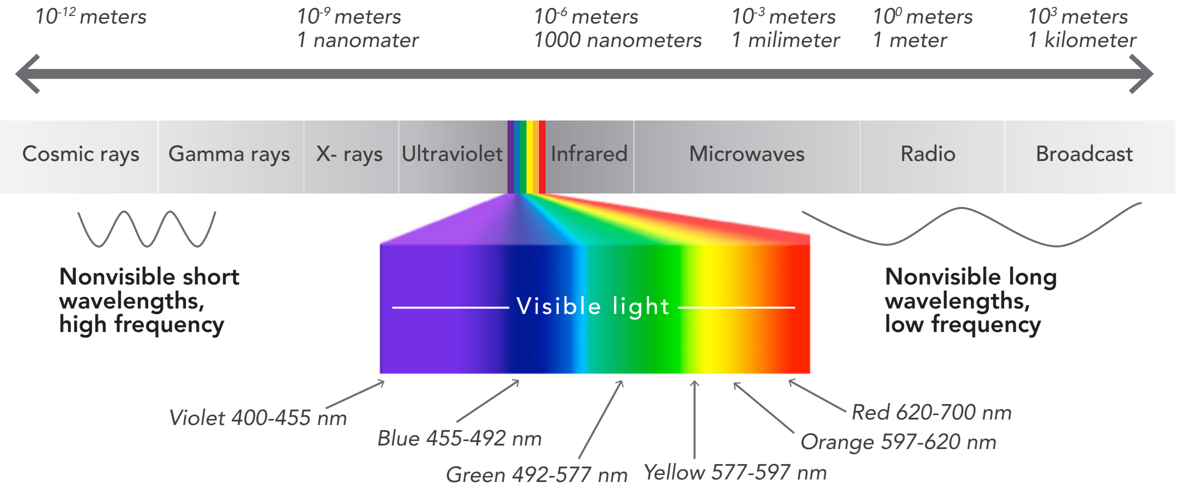


**Figure 3.4.** The electromagnetic spectrum

The most significant difference between our eyeballs and digital cameras is how the imaging surfaces react to the energy of photons. As shown in figure 3.4, the retinas in human eyes sense only the limited visible light portion of the electromagnetic spectrum. While able to capture more of the spectrum than human eyes, film is limited to wavelengths from 0.3 to 0.9 micrometers (i.e., the ultraviolet, visible, and near infrared). CCD or CMOS arrays in digital sensors are sensitive to electromagnetic wavelengths from 0.2 to 1400 micrometers. Because remote sensors extend our ability to measure more portions of the electromagnetic spectrum than our eyes can sense, remote sensors extend our ability to "see."

## *Film versus Digital Array Imaging Surfaces*

The imaging surfaces of our eyes are our retinas. Cameras once used only film, but now primarily use digital (CCD or CMOS) arrays. From its beginnings in the late 1800s to the 1990s, most remote sensing sensors relied on film to sense the electromagnetic energy being reflected or emitted from an object. Classifying the resulting photographs into information required manual interpretation of the photos. In the 1960s, digital sensors were developed to record electromagnetic energy as a database of numbers rather than a film image. This enabled the development of sensors that can sense electromagnetic energy across the range from ultraviolet to radio wavelengths. Now, most remote sensing systems use digital arrays instead of film. Because the values of the reflected and emitted energy are stored as an array of numbers, computers can be trained to turn the imagery data into map information by discovering correlations between variations in the landscape and variations in electromagnetic energy. While manual interpretation is still very important, objects that are spectrally distinct from one another can be readily mapped using computer algorithms.

The imaging surface of a digital camera is an array of photosensitive cells that capture energy from incoming photons. Each of these cells corresponds to a *pixel* in the resulting formed image. The pixels are arranged in rectangular columns and rows. Each pixel contains one to three photovoltaic cells or photosites, which use the ability of silicon semiconductors to translate electromagnetic photons into electrons. The higher the intensity of the energy reaching the cells during exposure, the higher the number of electrons accumulated. The number of electrons accumulated in the cell is recorded and then converted into a digital signal.

The size of the array and the size of each cell in the array affect the resolving power of the sensor. The larger the array, the more pixels captured in each image. Larger cells accumulate more electrons than smaller cells, allowing them to capture imagery in low-energy situations. However, the larger cells also result in a corresponding loss of spatial resolution across the image surface because fewer cells can occupy the surface.

## *Source of Energy: Active versus Passive Sensors*

Passive sensors collect electromagnetic energy generated by a source other than the sensor. Active sensors generate their own energy, and then measure the amount reflected back as well as the time lapse between energy generation and reception. Figure 3.5 illustrates the difference in how active and passive sensors operate.

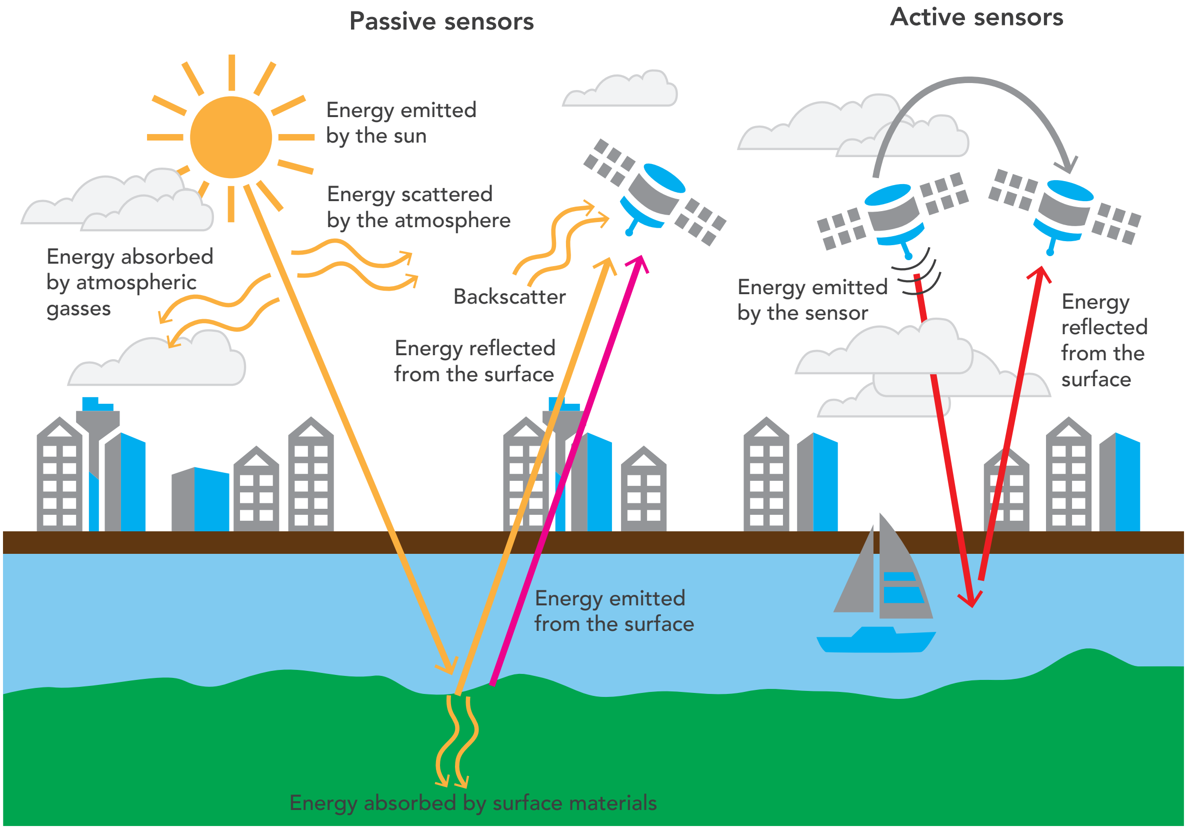


**Figure 3.5.** Comparison of how passive and active sensors operate

Most remote sensors are passive sensors, and the most pervasive source of passive electromagnetic energy is the sun, which radiates electromagnetic energy upon objects on the earth that either absorb/emit, transmit, or reflect the energy. Passive energy can also be directly emitted from the earth, as from the eruption of a volcano or a forest fire. Examples of passive remote sensors include film aerial cameras, multispectral digital cameras, and multispectral/hyperspectral scanners. Passive sensors are able to sense electromagnetic energy in wavelengths from ultraviolet through radio waves.

Passive sensors fall into three types: framing cameras, across-track scanners, and along-track scanners. Framing cameras either use film or matrixes of digital arrays (e.g., UltraCam airborne sensors, PlanetLabs satellite sensors). Each frame captures the portion of the earth visible in the sensor's field of view (FOV) during exposure. Often, the frames are captured with greater than 50 percent overlap, which enables stereo viewing. Each image of a stereo pair is taken from a slightly different perspective as the platform moves. When two overlapped images are viewed side by side, each eye automatically takes the perspective of each image, enabling us to now "see" the overlapped areas in three dimensions. With stereo frame imaging, not only can distances be measured from the aerial images, but so can elevations and the heights of vegetation and structures, discussed in detail in chapter 9.

Most across-track scanners (also called whisk broom scanners) move an oscillating mirror with a very small instantaneous field of view (IFOV) side to side as the platform moves. Each line of the image is built, pixel by pixel, as the mirror scans the landscape. Developed decades before the digital frame camera, across-track scanners were the first multispectral digital sensors and were used in multiple systems including the Landsats 1-7, GOES, AVHRR, and MODIS satellite sensors, and NASA's AVIRIS hyperspectral airborne system.

Along-track scanners (also called push broom scanners) rely on a linear array to sense entire lines of data simultaneously. Rather than mechanically building an image pixel by pixel or by groups of pixels, the along-track scanner builds an image line by line. Along-track scanners have higher spectral and radiometric resolution than across-track scanners because the sensor can spend more time (termed dwell time) over each area of ground being sensed. Like across-track scanners, along-track scanners often also use a dispersing element to split apart the incoming beam of electromagnetic energy into distinct portions of the electromagnetic spectrum to enable the collection of multispectral imagery. Developed 30 years ago, along-track scanners are a more recent development than across-track scanners. Many multispectral satellite systems (e.g., WorldView-3, Landsat 8) rely on along-track sensors, as do the Leica Airborne Digital Sensors.

Active sensors send out their own pulses of electromagnetic energy, and the sensor measures the echoes or returns of the energy as they are reflected by objects in the path of the pulse. For example, consumer cameras with flash attachments are active systems. Active remote sensors include lidar (light detection and ranging) systems, which generate laser pulses and sense electromagnetic energy in the ultraviolet to near-infrared regions of the spectrum, and radar (radio detection and ranging) systems, which generate and sense energy in the microwave range. An advantage of active systems is that they do not rely on the sun, so acquisitions can be made at times when the sun angle is low or at night. An additional advantage of radar systems is that the long wavelengths of microwaves can penetrate clouds, haze, and even light rain.

## *Wavelengths Sensed*

### Passive Sensors

Most images are collected by panchromatic or multispectral passive sensors that are able to sense electromagnetic energy in the visible through infrared portions of the electromagnetic spectrum. To separate different optical and midinfrared wavelengths from one another, passive remote sensors place filters or dispersing elements between the opening and the imaging surface to split different wavelengths or “bands” of the electromagnetic spectrum from one another. Filters are usually used with framing cameras and include the following:

- Employing a Bayer filter over the digital array, which restricts each pixel to one portion of the electromagnetic spectrum, but alternates pixels in the array to collect at different wavelengths. The computer then interpolates the values of the non-sensed wavelengths from the surrounding pixels to simulate their values for each frequency at each pixel. This is how consumer cameras and many of the high-resolution small satellite constellations (e.g., Planet Doves) collect multispectral imagery.
- Placing separate filters on multiple cameras, each filtered to accept energy from a distinct portion of the electromagnetic spectrum, allows each focal plane to be optimized for that portion of the spectrum. Many four-band (red, green, blue, and infrared) airborne image sensors (e.g., Microsoft Ultracam and Leica DMC sensors) use this approach, which requires that the images simultaneously captured with the separate cameras be coregistered to one another after capture.
- Placing a spinning filter wheel in front of one camera so that each exposure of the image surface is in one portion of the electromagnetic spectrum. This approach is very useful for fixed platforms, however it requires very complex postcollection registration for systems with moving platforms and is rarely used in remote sensing systems.

Alternatively, a dispersing/splitting element can be placed between the lens and a series of CCD arrays to split the incoming energy into its discrete portions of the electromagnetic spectrum. Many multispectral and most hyperspectral sensors employ dispersing/splitting elements (e.g., Leica Airborne Digital Sensors, NASA AVIRIS).

Figures 3.6 to 3.8 illustrate how Bayer filters, framing cameras, and dispersing elements are typically used to create multispectral images. In general, because pixel values are interpolated for two values out of every three, Bayer filters will always have lower spectral resolution than multiheaded frame cameras or systems using dispersing elements.

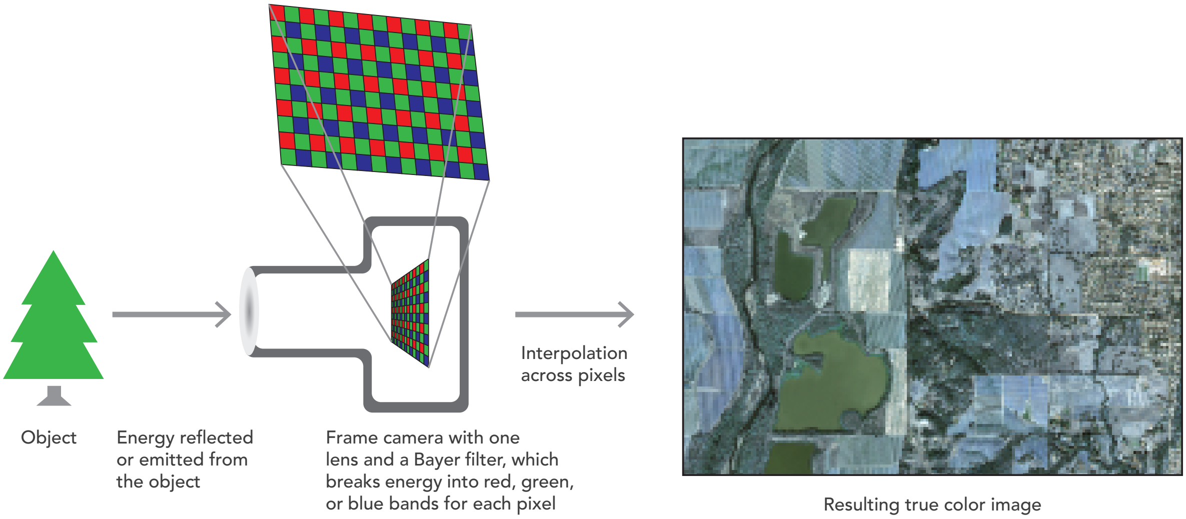


**Figure 3.6.** How a Bayer filter framing camera system works. While the figure shows a true color image, Bayer filters can also be used to collect in the near-infrared portions of the electromagnetic spectrum, resulting in infrared imagery.

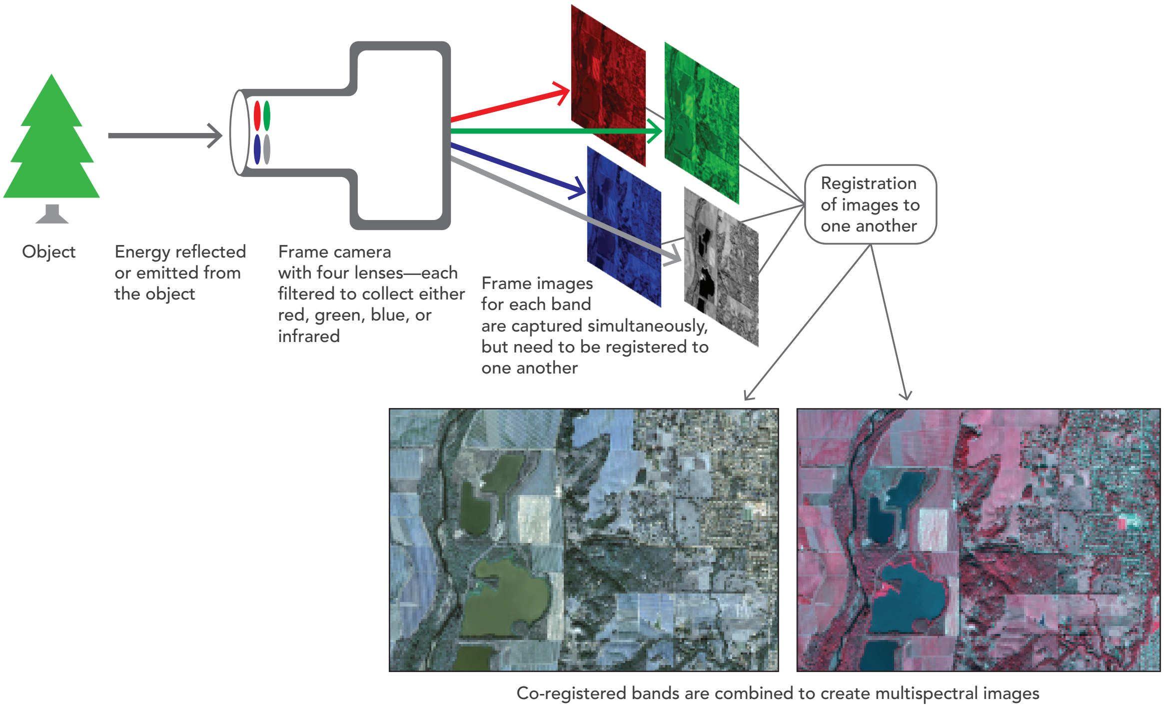


**Figure 3.7.** How a multilens multispectral framing camera system works

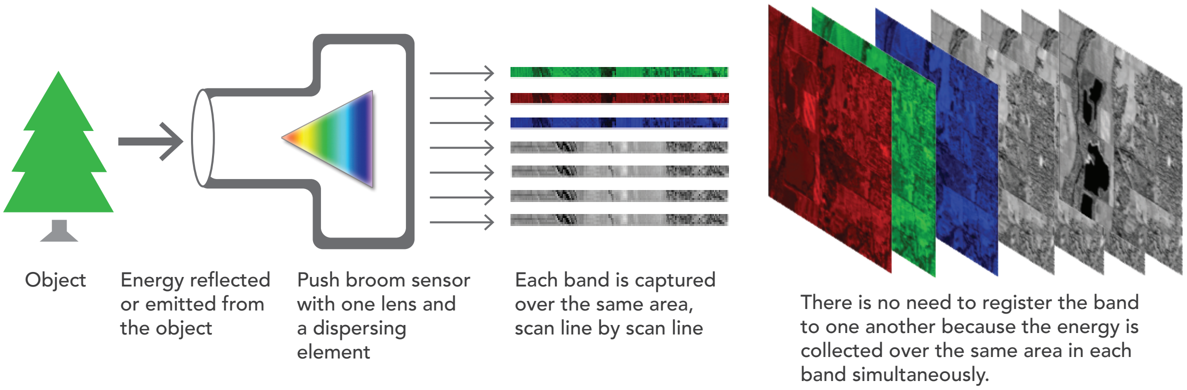


**Figure 3.8.** How a push broom multispectral scanner works with a dispersing element

## Active Sensors

The most common active remote sensors are lidar and radar systems. As mentioned earlier, all active instruments work similarly by transmitting electromagnetic energy that is bounced back to the sensor from the surface of the earth. Because active sensors generate their own energy, they can capture imagery at any time of the day or night.

Radar imagery is often used to create digital surface and digital elevation models over large regions, and to map sea or land cover in perpetually cloudy areas where optical imagery can't be effectively collected. Figure 3.9 shows an example of a radar image of Los Angeles, California. Radar imagery is collected over a variety of microwave bands, which are denoted by letters and measured in centimeters as follows: Ka, 0.75 to 1.1 cm; K, 1.1 to 1.67 cm; Ku, 1.67 to 2.4 cm; X, 2.4 to 3.75 cm; C, 3.75 to 7.5 cm; S, 7.5 to 15 cm; L, 15 to 30 cm; and P, 30 to 100 cm. Usually, radar imagery is collected in just one band, resulting in a single band image. Bands X, C, and L are the most common ranges used in remote sensing. Some radar systems are able to collect imagery in several bands, resulting in multispectral radar imagery.

Varying antenna lengths are required to create the radar signal at these different wavelengths. Because it is often not viable to have a long antenna on a platform moving through the air or space, the length of the antenna is extended electronically through a process called synthetic aperture radar.

Radar signals can also be transmitted and received in either horizontal or vertical polarizations or a combination of both. HH imagery is both transmitted and received in a horizontal polarization, and VV imagery is both transmitted and received in a vertical polarization (i.e., like-polarized). HV imagery is transmitted horizontally and received vertically, and VH imagery is transmitted vertically and received horizontally (i.e., cross-polarized). The different polarizations can be combined to create a multipolarized image, which is similar to a multispectral image as each polarization collects different data about the ground.

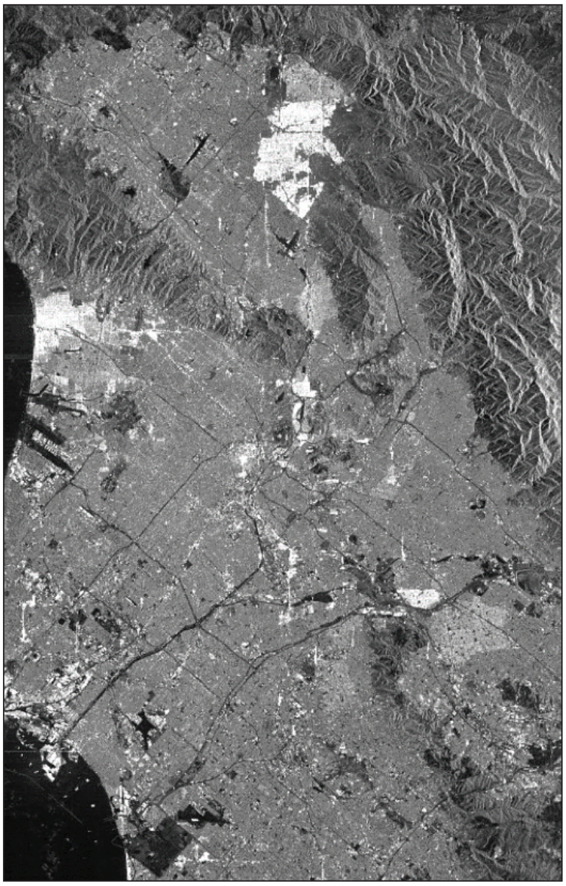


**Figure 3.9.** An example radar image captured over Los Angeles, California (esriurl.com/IG39).
Source: NASA

Over the last 20 years in much of the world, airborne lidar has surpassed photogrammetric methods for measuring the 3-dimensional world. Lidar imagery is used to develop digital elevation models (DEMs), digital terrain models (DTMs), digital surface models (DSMs), digital height models (DHMs), elevation contours, and other derived datasets (chapter 8 provides more detail on the creation of DEMs). Additionally, NASA uses low-spatial-resolution satellite lidar to monitor ice sheet mass balance and aerosol heights and has recently initiated the Global Ecosystem Dynamics Investigation (GEDI) mission, which will result in the first global, moderate-spatial-resolution, spaceborne topographic lidar (http://science.nasa.gov/missions/gedi/).

Lidar sensors emit discrete pulses of electromagnetic energy that illuminate a given spot on the earth for an instant (less than 1/100,000 of a second). The energy emitted can be of ultraviolet through near-infrared wavelengths (250 nm to 10 µm), which are much shorter than those of radar pulses. The pulses of light then bounce back and are recaptured by the lidar instrument where the durations of their paths are recorded and analyzed to extract elevation information. The number of returns per unit area for discrete return lidar can be much higher than the number of pulses sent earthward, because each pulse can have multiple (typically three to five) returns.

There are two types of airborne lidar: topographic and bathymetric. Topographic lidar uses an infrared laser to measure elevations across the surface of the earth. Bathymetric lidar employs green laser light to penetrate water and measure the depth of water bodies. In topographic lidar, pulses of light encounter porous objects, such as vegetation, which will have multiple returns. For example, as shown in figure 3.10, a selected single pulse from this discrete return airborne lidar system has three returns from branches and a fourth return (the final return) from the ground. DTMs are generated from the last returns, DSMs from the first returns (buildings must be removed using specialized algorithms), and DHMs from the difference between the digital surface model and the digital terrain model. Lidar returns collectively form a lidar "point cloud" consisting of millions to billions of points that each contain the point's latitude, longitude, and elevation.

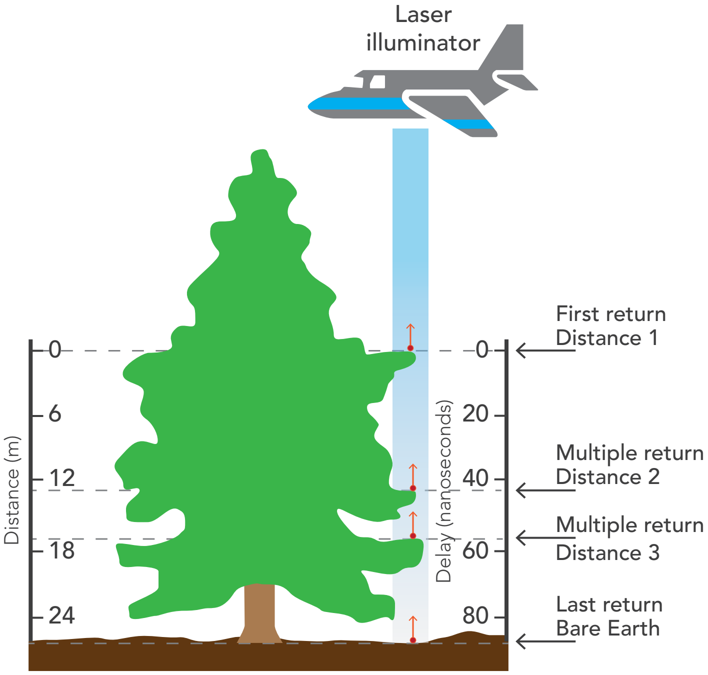
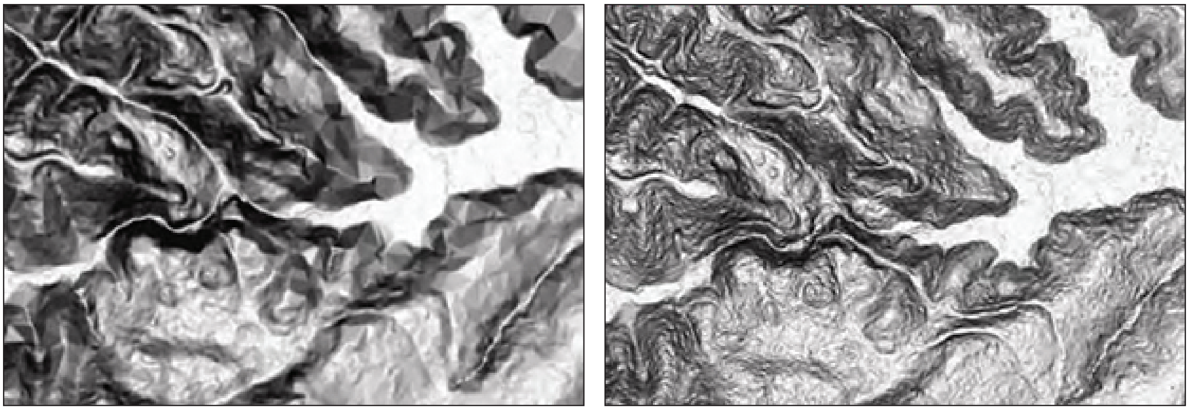


**Figure 3.10.** Illustration of the returns from a topographic lidar system. Source: Dr. Maggi Kelly

Lidar point density is measured by the average number of pulses sent downward from the aircraft per square meter of ground. As of this writing, "high density" airborne lidar is generally considered to have a point density of greater than eight points per square meter. In vegetated terrain, only a fraction of the pulses of light sent earthward by the lidar system penetrate all the way to the ground, and the number of ground returns decreases as the thickness of the vegetated canopy increases. The lack of ground returns in thickly vegetated areas can lead to inaccuracy in the digital terrain models derived from a lidar dataset. For this reason, the effective resolution of the digital terrain model and the digital height model depend on the point density of the lidar data. The higher the point density, the more ground returns and the higher the resolution of the derived DHM and DTM. It is recommended that lidar data be collected at a point density of at least eight pulses per square meter in project areas with dense forests. Eight pulses per square meter is the minimum point density that meets the US Geological Survey's (USGS) quality level 1 lidar data specification.[2] Figure 3.11 compares hillshades derived from a digital terrain models at USGS quality level 1 versus USGS quality level 2 lidar data, illustrating the enhanced detail and resolution gained by collecting lidar data at higher density.



1.2 pulses/m$^2$ (0.91 meter post spacing)

8.0 pulses/m$^2$ (0.35 meter post spacing)

**Figure 3.11.** Comparison of a hillshade derived from 1.2 pulses/m$^2$ lidar to one derived from eight pulses/m$^2$ lidar. Source: Quantum Geospatial, Inc.

There are two common types of airborne topographic lidar: discrete return and waveform. Discrete return lidar provides elevation values at the peak intensity of each return. Typically, a maximum of between three and five returns is possible where there is vegetation, but only one return will occur in open areas. Each of the multiple returns is stored as a point in the point cloud, with its associated latitude, longitude, and elevation.

Full waveform lidar—which is mostly still in the R&D phase—provides the entire "waveform" graph associated with a lidar pulse. Because it records the entire waveform of a lidar pulse's returns and not just three to five discrete peaks, waveform lidar requires 30 to 50 times the amount of data storage as discrete return lidar.

Historically, lidar systems have been able to transmit energy in only one wavelength. However, recent advancements in lidar technology allow for transmitting energy in multiple wavelengths, making multispectral lidar images possible (Teledyne Optech Titan

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[2] Hans Karl Heidemann, "Lidar Base Specification," ver. 1.2, November 2014, US Geological Survey Techniques and Methods, book 11, chap. B4, https://pubs.usgs.gov/tm/11b4/pdf/tm11-B4.pdf.

system). Additionally, new technologies such as Geiger-mode (Harris) and Single Photon (SigmaSpace/Hexagon) have been introduced that significantly improve the rate of data collection and resulting point density by increasing the sensitivity of the lidar sensors.

## Lenses

Objects emit or reflect electromagnetic energy at all angles. The angles between an object and an imaging surface change as the imaging surface moves closer to or farther from the object. The purpose of a lens in a camera or in an eyeball is to focus the electromagnetic energy being emitted or reflected from the objects being imaged onto the imaging surface. By moving the lens back and forth relative to the imaging surface, we can affect the angle of electromagnetic energy entering and exiting the lens, and thereby bring the objects of interest into focus.

Most remote sensing systems capture electromagnetic energy emitted or reflected from objects at a great distance from the sensor (i.e., at an effectively infinite distance), from hundreds of feet for a sensor in an aircraft to hundreds of miles for a sensor in a satellite. Because these distances approach infinity relative to the focal length, the lenses have a fixed focus.

The combination of the sensor's lens and the resolution of the imaging surface will determine the amount of detail the sensor is able to capture in each image—its resolving power. The resolution of a digital image is determined by the format size of the digital array of the imaging surface.

## Openings

The purpose of a sensor opening is to manage the photons of electromagnetic energy reaching the imaging surface. Too large an opening results in the imagery being saturated with photons, overexposing the imaging surface. Too small an opening results in not enough photons captured to create an image.

Our irises manage the amount of light reaching our retinas by expanding and shrinking to let more or less light onto our retinas. In a camera, the diameter of the opening that allows electromagnetic energy to reach the imaging surface is called the aperture, and the speed at which it opens and closes is called the shutter speed. Together, aperture and shutter speed control the exposure of the imaging surface to electromagnetic energy. In a digital camera, the CCD array is read and cleared after each exposure.

## Bodies

Remotely sensed imagery can be used for visualization—to obtain a relative concept of the relationship of objects to one another—or to measure distances, areas, and volumes. For either visualization or measurement, the geometry of the lenses, opening, and imagery surface within the camera body must be known. In addition, for measurement the location and rotation of the imagery surface when the image is captured must also be known.

# Sensor Summary

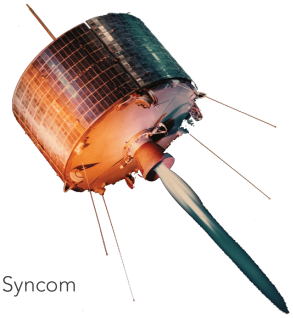
While remote sensor components share similarities with our eyes and consumer cameras, they differ in the following fundamental ways:

- Imaging surfaces must be absolutely flat to minimize any geometric distortion.
- The energy sensed may be passively received by the sensor from another source (commonly the sun) or actively created by the sensor and then received back by the sensor.
- Because most remotely sensed images are taken from high altitudes, their lenses are commonly designed for an infinite object distance; i.e., the lenses are fixed.
- Shutter speeds are usually extremely fast because most platforms are moving at high speeds.
- Remote sensor camera bodies must be able to withstand the extreme temperatures and vibrations encountered by the vehicle, boat, aircraft, or satellite platform. Additionally, for mapping purposes, the precise internal geometry of the sensor components within the body must be known as well as the location of the imaging surface when an image is collected so that the imagery can be accurately terrain corrected and georeferenced to the earth.

# Platforms

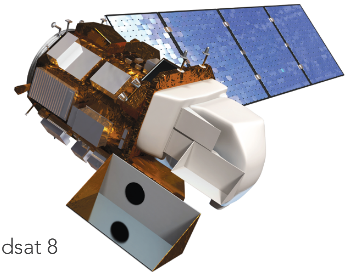
This section reviews remote sensing platforms by examining platform features. Seven major features distinguish platforms from one another: whether they are manned or unmanned, and their altitude, speed, stability, agility, and power.

# Different Types of Platforms



Syncom

**Geosynchronous—22,236 miles**
Satellites that match Earth's rotation appear stationary in the sky to ground observers. While most commonly used for communications, geosynchronous orbiting satellites like the hyperspectral GIFTS imager are also useful for monitoring changing phenomena such as weather conditions. NASA's Syncom, launched in the early 1960s, was the first successful "high flyer."

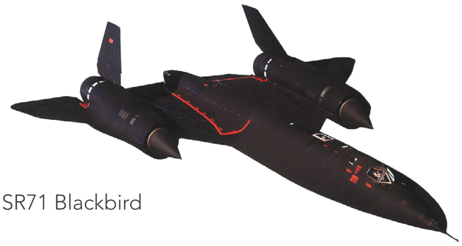


Landsat 8

**Sun synchronous—375-500 miles**
Satellites in this orbit keep the angle of sunlight on the surface of the earth as consistent as possible, which means that scientist can compare images from the same season over several years, as with Landsat imagery. This is the bread-and-butter zone for earth observing sensors.

Helios

**Atmospheric satellite—100,000 feet**
Also known as pseudo-satellites, these unmanned vehicles skim the highest edges of detectable atmosphere. NASA's experimental Helios craft measured solar flares before crashing in the Pacific Ocean near Kauai.



SR71 Blackbird

**Jet aircraft—90,000-30,000 feet**
Jet aircraft flying at 30,000 feet and higher can be flown over disaster areas in a very short time, making them a good platform for certain types of optical and multispectral image applications.

Cessna

Ultralight

US Navy Silver Fox

Helicopter

### General aviation aircraft—100-10,000 feet

Small aircraft able to fly at low speed and low altitude have long been the sweet spot for high-quality aerial and orthophotography. From Cessnas to ultralights to helicopters, these are the workhorse of optical imagery.

3DR Solo private drone

### Drones—100-500 feet

Drones are the new kid on the block. Their ability to fly low, hover, and be remotely controlled offer attractive advantages for aerial photography, with resolution down to sub-1 inch. Military UAVs can be either smaller drones or actual airplanes.

Smartphone

Handheld spectrometer

### Ground based/handheld—ground level

Increasingly, imagery taken at ground level is finding its way into GIS workflows. Things like Google Street View, HERE street-level imagery, and Mapillary; handheld multispectral imagers; and other terrestrial sensors are finding applications in areas like pipelines, security, tourism, real estate, natural resources, and entertainment.

Street-level mapping car

## Piloted or Unpiloted

Until recently, most satellite platforms were unpiloted, and most airborne platforms were piloted. However, with the advent of unmanned aerial vehicles, most airborne platforms are now unpiloted, but piloted aircraft still capture much larger areas than unpiloted platforms. While less used, piloted satellite platforms have been very important in remote sensing. Starting with the Apollo space mission in the late 1960s and continuing with the International Space Station today, piloted satellites have completed many successful remote sensing missions including NASA's Shuttle Radar Topography Mission, which generated global digital elevation models of the earth from 56 degrees south to 60 degrees north. In 2019, the International Space Station will deploy the GEDI lidar to produce a 3D map of the earth's forests.

Most of the areas captured by airborne platforms used for mapping today are flown over by a pilot residing in the platform. UASs are either autonomous or have a pilot operating them from the ground. Originally developed and used by the military, the use of UASs in civilian markets is exploding because of their low cost, their ability to collect imagery over inaccessible or dangerous areas, and their ability to fly low and slow, enabling the capture of high-resolution imagery over small areas that would be too expensive to capture with piloted aerial systems. Hobbyist use in the United States has skyrocketed since 2010, but commercial use was stalled because of cumbersome FAA regulations. In 2015, the FAA streamlined the process for gaining authorization to commercially operate UASs in the US, resulting in a 500 percent increase in applications in the first six months of 2015 over all of 2014 (Andelin and Andelin, 2015). Outside the United States, UAS use is also rapidly increasing with successful deployments to map archeological sites, establish property rights, monitor illegal resource extraction, and support disaster response (Pajares, 2015).

While civilian drones do not currently have the capacity to capture imagery over large areas, the use of UASs is likely to continue to rapidly expand and evolve. As stated in the primer *Drones and Aerial Observations*:

> *Technology will change. Faster processors will stitch together and georectify images more quickly. The acuity of photographic sensors will improve, as will the endurance and range of drones. Increasing levels of autonomy in both flight software and post-processing software will allow for the creation of cheap maps with increasingly less direct human intervention (Kakaes et al., 2015).*

## Altitude

Altitude is an object's height above sea level. The altitude of a remote sensing platform can vary between below sea level (in bathymetric projects) to more than 20,000 miles above sea level. Remote sensing platforms are classed into three types based on their range of distance from the earth:

1. Terrestrial and marine platforms, including elevated work platforms, mobile vehicles, buildings and towers, lampposts, buoys, boats, and humans.
2. Airborne platforms including UASs, fixed-wing aircraft, helicopters, and balloons.
3. Spaceborne platforms, which are either geostationary or orbit the earth.

Terrestrial platforms operate from beneath the ocean to the highest buildings on earth and may be fixed (e.g., ATM video cameras) or mobile (e.g., cars and boats). Airborne platforms fly within the earth's atmosphere up to an altitude of typically 9.5 miles (15.3 kilometers) and include fixed-wing aircraft, UASs, helicopters, and balloons. Fixed-wing aircraft are the most common type of remote sensing platform and are used by many private companies and governments for imaging purposes. High-altitude piloted aircraft platforms have pressurized cabins, enabling them to fly as high as 50,000 feet above sea level. Low-altitude piloted aircraft platforms operate at altitudes up to 30,000 feet (5.7 miles), but are generally used to collect data at lower elevations to gain higher spatial resolution. The hovering ability of helicopters (below 500 feet and up to 12,500 feet) allows them to collect imagery at lower speeds than fixed-wing aircraft. Balloons have a wide range of achievable altitudes, from as low as needed for a tethered balloon to around 20 km or more for a blimp. UASs can be fixed- or rotor-winged with altitudes ranging from very close to the ground to very high in the air.

At the highest altitudes, earth observation satellites carry remote sensors around the earth in orbit at altitudes ranging from 100 to over 22,000 miles above sea level. Maintaining orbital altitude is a constant requirement for satellites because of the earth's steady gravitational pull and atmospheric drag. Lower satellites must travel at higher velocities because they experience greater gravitational pull than satellites at higher altitudes. Thus, maintaining orbit requires a constant balance between gravity and the satellite's velocity. Satellites with fuel onboard maintain their orbital altitude by using the fuel to maintain their velocities. However, at some point all satellites fall back to earth and burn up in the atmosphere, usually in controlled descents.

## Speed

Speed is the rate of motion of an object expressed as the distance covered per unit of time. It determines the level of detail and amount of area (extent) a remote sensing system can collect. The altitude and speed flown while collecting remotely sensed data are also determined by the desired resolution and coverage, as well as the sensor being used (e.g., digital or film camera, lidar). Remote sensing platform speeds can range from stationary (zero velocity) to over 17,000 miles per hour. Most terrestrial platforms are stationary. Mobile terrestrial platforms such as cars and boats tend to travel at low speeds to enable the collection of very-high-spatial-resolution imagery. Fixed-wing UASs and aircraft typically fly at 55 to 650 miles per hour. Helicopters and rotor UASs, with their ability to hover, typically fly at 0 to 150 miles per hour. The speed at which a satellite travels in orbit is determined by its altitude. The lower the altitude, the faster the satellite must travel to remain in orbit and not fall to earth. Satellites in near-circular orbits have near-constant speeds, while satellites in highly elliptical orbits will speed up and slow down depending on the distance from the earth and direction of motion.

## Stability

Stability is the ability of an object to resist changes in position. Stability is an important feature of remote sensing platforms because platforms need to either maintain stability or precisely measure instability to ensure high-quality image capture and accurate registration of the image to the ground. The most stable platforms are fixed terrestrial platforms because they are structurally rigid and immobile, which also means that they have little or no agility. Satellite platforms are also relatively stable because they operate in the vacuum of space. Helicopters are less stable than fixed-wing aircraft because of the unequal lift and vibrations caused by the rotating blades. While balloons were an important platform in the early days of remote sensing, they are not widely used today because their flight is easily influenced by air currents and pressure changes resulting in minimal control of balloon flight path or position. Fixed-wing platforms are relatively stable airborne platforms. Because of this and their large range and speed, they remain the workhorse of airborne image collection.

Operating in the earth's atmosphere subjects aircraft to air pressure and wind variations that can result in changes in pitch, roll, and yaw (figure 3.11), causing a variety of displacements in the collected imagery. Pitch is rotation of the aircraft about the axis of the wings. Yaw is rotation about the axis that is perpendicular to the wings and directed at the nose and tail of the aircraft. Roll is rotation of the aircraft about the axis of the fuselage.

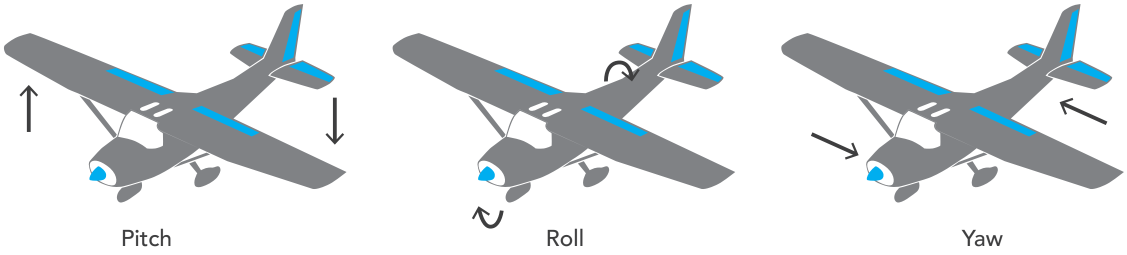


Figure 3.12. The effects of pitch, yaw, and roll on aircraft stability

Traditionally, aerial photography missions required the precise measurement of many ground control points in each photograph to establish the exact spatial position and orientation of the photograph relative to the ground at the moment the image was taken. In the late 1950s, a technique called bundle block adjustment was developed to reduce the number of expensive control points required. This was based on finding tie points between photographs and then solving least squares adjustment formulas. In the 1990s, the number of control points required was again reduced by the advent of accurate GPS positioning of the aircraft that effectively added control points in the air, further reducing the control required. The advent of lower-cost precise IMUs (inertial measurement units) has further reduced the number of control points required, so that for many applications sufficient accuracy can be achieved using only highly accurate GPS and IMU systems, which is referred to as direct georeferencing. These orientation parameters are used in image orthorectification (see chapter 6) to geometrically correct the images so that coordinates in the imagery accurately represent coordinates on the ground.

## Agility

Agility refers to the ability of the platform to change position and can be characterized by 1) reach or the ability of a platform to position itself over a target, which is sometimes referred to as field of regard; 2) dwell time, which is how long the platform can remain in the target area working; and 3) the ability to slew across the target area.

Fixed platforms such as a traffic-light pole above a street intersection have no agility. Satellites are tied to their orbits, which restricts their agility. However, some satellites are pointable (e.g., able to slew off nadir), which makes them much more agile than nonpointable satellites. This, coupled with their ability to quickly orbit the earth, provides them with a long-range reach around the globe, which is not available to aircraft.

Within their range, aircraft and fixed-wing UASs are more agile than satellites, and helicopters are more agile than fixed-wing aircraft. The hovering abilities of helicopters and rotor-winged UASs allow them to obtain more target specific data than fixed-wing aircraft can collect, and they can more easily reach targets in a congested airspace. Blimps and remote-controlled balloons have greater mobility than hot-air balloons because they have engines and are more maneuverable.

## Power

Power refers to the power source that runs the platform. The more powerful the engine or engines, the faster and higher the platform can travel and the greater payload it can carry. Satellites are propelled into space by launch vehicles to escape the earth's gravity. Afterward, they use electric power derived from solar panels for operation, and stored fuel for orbital maneuvering. Of critical importance is the amount of power remaining after launch for the sensor to operate. Size, weight, and power, coupled with communication bandwidth (the ability to offload the image from the focal plane) are the biggest drivers in satellite sensor design.

Fixed-wing aircraft are powered by piston engines, turbocharged piston engines, turboprops, or jet engines in single- or twin-engine configurations. High-altitude piloted aircraft platforms are usually powered by twin jet engines or turboprops. The high power of these aircraft and their ability to fly at high altitudes with large payloads results in large operational costs, but this can be offset by their broad spatial coverage abilities and fast data collection (Abdullah et al., 2004). Single-engine platforms are lighter and have fewer logistical concerns and lower operational costs, while twin-engine platforms offer more power and weight for larger payloads (Abdullah et al., 2004). Many low-altitude platforms employ a dual sensor configuration for collecting multiple types of data (e.g., lidar and optical), but aircraft with less powerful engines are less likely to be able to carry multiple sensors because the power requirements are too high and the combined payload becomes too heavy for the plane. However, over the last 10 years the weight, size, and power requirements of many sensors have rapidly decreased, making multiple sensor configurations more feasible.

# Collection Characteristics

The components of sensors and the features of platforms combine to determine the collection characteristics of an image: its spectral resolution, radiometric resolution, spatial resolution, viewing angle, temporal resolution, and extent. Table 3.1 provides definitions of commonly used categories of the three most important collection characteristics: spatial, spectral, and temporal resolution.

Table 3.1. Commonly used categories of imagery collection characteristics

| | Very high | High | Moderate | Low |
|---|---|---|---|---|
| Spatial resolution (ground length of one side of a pixel) | less than 1 meter | 1.1 to 5 meters | 5.1 to 30 meters | greater than 30 meters |
| Spectral resolution (number of bands) | greater than 50 bands (hyperspectral) | greater than 7 to 49 bands (superspectral) | 2 to 7 bands (multispectral) | 1 band (panchromatic) |
| Temporal resolution (minimum revisit period) | Once a day | Once a week | Once a month | Once a year |

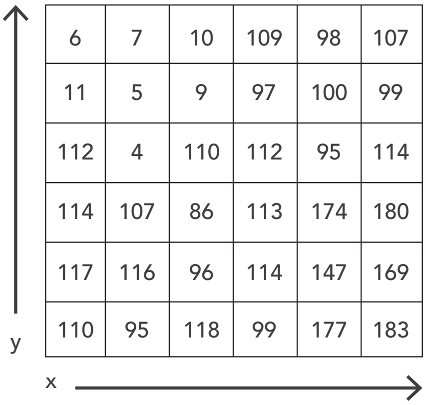
## Spectral Resolution

The spectral resolution of an image is determined by the sensor and refers to the following:

- The number of bands of the electromagnetic spectrum sensed by the sensor
- The wavelengths of the bands
- The widths of the bands

Panchromatic sensors capture only one spectrally wide band of data, and the resulting images are shades of gray, regardless of the portion of the spectrum sensed or the width of that portion. Panchromatic bands always cover more than one color of the electromagnetic spectrum. Multispectral sensors capture multiple bands across the electromagnetic spectrum. Hyperspectral sensors collect 50 or more narrow bands. Traditionally, multispectral bandwidths have been quite large (usually 50 to 400 micrometers), often covering an entire color (e.g., the red portion). Conversely, hyperspectral sensors measure the radiance or reflectance of an object in many narrow bands (usually 5 to 10 micrometers) across large portions of the spectrum, similar to imaging spectroscopy in a chemistry laboratory.

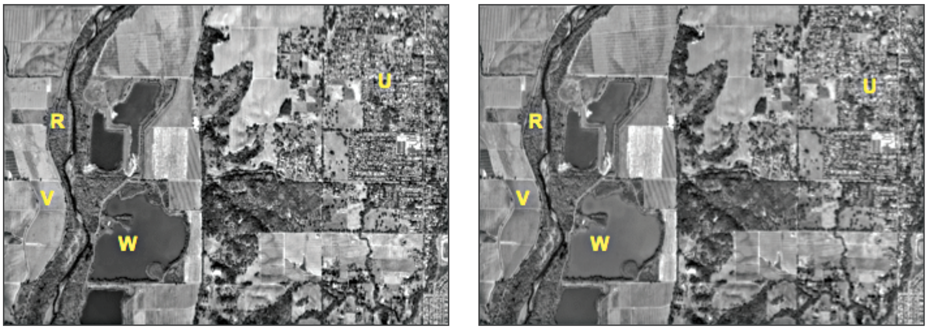
Film images are stored as negative or positive film or paper prints. Remotely sensed digital data files are stored in a raster or rectangular grid format. When imaging, each picture element, or pixel, collects a digital number (DN) corresponding to the intensity of the energy sensed at that pixel for each specific band of the electromagnetic spectrum. Panchromatic data is stored in a single raster file. Figure 3.13 shows example infrared DNs for a small area.



| | | | | | |
|---|---|---|---|---|---|
| 6 | 7 | 10 | 109 | 98 | 107 |
| 11 | 5 | 9 | 97 | 100 | 99 |
| 112 | 4 | 110 | 112 | 95 | 114 |
| 114 | 107 | 86 | 113 | 174 | 180 |
| 117 | 116 | 96 | 114 | 147 | 169 |
| 110 | 95 | 118 | 99 | 177 | 183 |

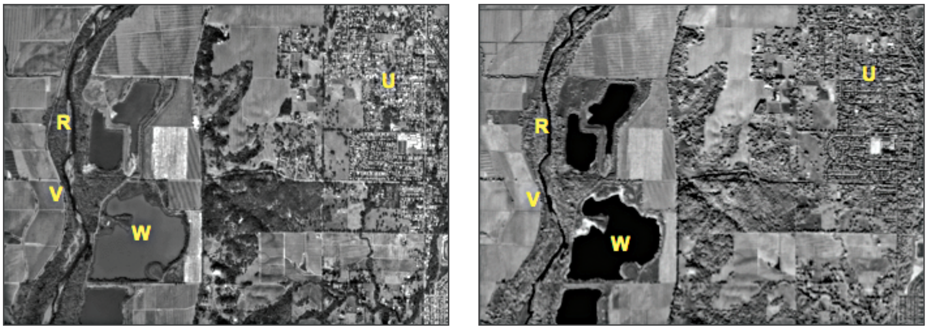
**Figure 3.13.** Example infrared digital number (DN) values

Multispectral images store each band as a separate raster. Each band is monochromatic, but when they are combined they can be displayed in color. Figure 3.14 shows four separate bands of airborne digital imagery collected over a portion of Sonoma County, California. Each band is monochromatic. Figure 3.15 combines the bands to create true color and color infrared displays.



Band 1 — Red portion of the spectrum

Band 2 — Green portion of the spectrum



Band 3 — Blue portion of the spectrum

Band 4 — Infrared portion of the spectrum

W = water V = vineyards R = riparian vegetation U = urban

**Figure 3.14.** Red, green, blue, and near infrared bands of airborne multispectral imagery captured over Sonoma County, California (esriurl.com/IG314)

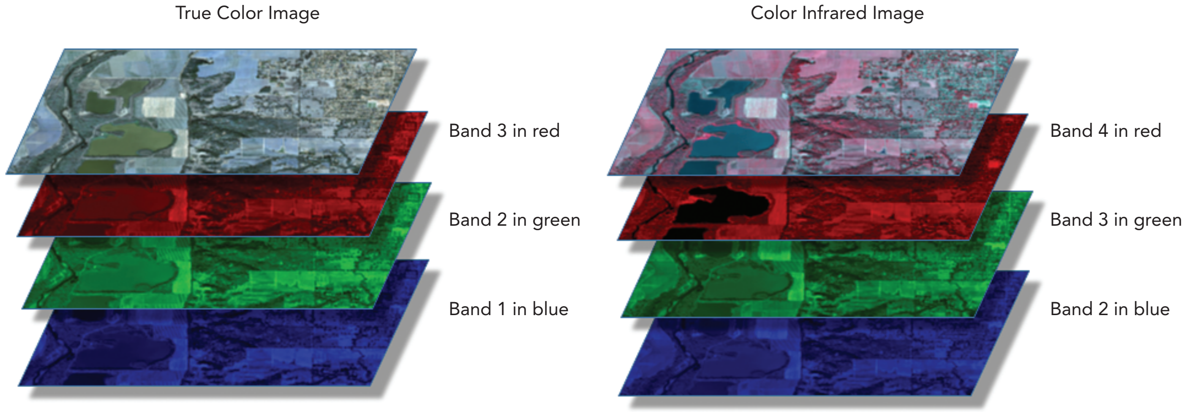


**Figure 3.15.** True color and infrared combination of bands of airborne multispectral imagery collected over Sonoma County, California (esriurl.com/IG315)

The bands shown in figures 3.14 and 3.15 are in the red, green, blue, and near-infrared portions of the electromagnetic spectrum. Each pixel of the imagery contains four numbers, one for the DN recorded in each of the four bands. Table 3.2 presents the range of DN values for each band of the different land-cover types depicted in figure 3.15.

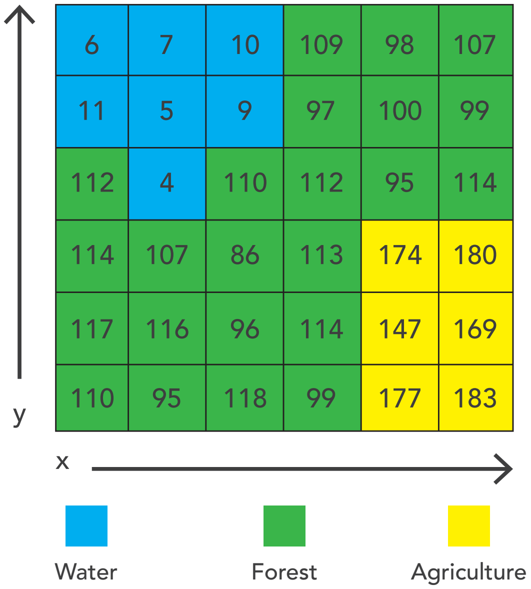
**Table 3.2.** Range of sample DN values

| Land-cover class | Water DNs | Riparian vegetation DNs | Vineyard DNs | Urban DNs |
|---|---|---|---|---|
| Band 1—blue | 12–98 | 17–77 | 95–133 | 148–183 |
| Band 2—green | 32–120 | 23–115 | 111–152 | 142–194 |
| Band 3—red | 29–65 | 23–56 | 65–91 | 93–198 |
| Band 4—infrared | 0–5 | 144–204 | 165–203 | 111–200 |

*Note:* The range of values are in each band of airborne multispectral imagery for different types of land cover in Sonoma County, California. This imagery's DN range is from 0 to 254.

Notice how water is significantly lower in the infrared band than are the other land-cover types. Also, urban has high values in all bands relative to the other classes. Riparian vegetation and water are similar in the red, green, and blue bands, but significantly different in the infrared band, indicating that without the infrared band it might be difficult to distinguish the greenish water from the green vegetation.

At this point, we can begin to see how variations in land-cover types can be related to variations in spectral responses, and it becomes straightforward to group the similar pixels of the image sample in figure 3.14 together into land-cover classes, as depicted in figure 3.16. Of course, it is never quite this straightforward to turn image data into map information, which is why chapters 7 to 9 thoroughly examine the methods and tools for image interpretation and classification.



| | | | | | |
|---|---|---|---|---|---|
| 6 | 7 | 10 | 109 | 98 | 107 |
| 11 | 5 | 9 | 97 | 100 | 99 |
| 112 | 4 | 110 | 112 | 95 | 114 |
| 114 | 107 | 86 | 113 | 174 | 180 |
| 117 | 116 | 96 | 114 | 147 | 169 |
| 110 | 95 | 118 | 99 | 177 | 183 |

**Figure 3.16.** Infrared DN values from figure 3.13 combined into land-cover classes

## Radiometric Resolution

Radiometric resolution is the minimum variation in electromagnetic energy that a sensor can detect, and therefore determines the information content of an image. Like spectral resolution, radiometric resolution is determined by the sensor.

In film systems, radiometric resolution is determined by the contrast of the film. Higher-contrast films will have higher radiometric resolutions than low-contrast films. In digital sensors, the potential range of DN values that can be recorded for each band determines the sensor's radiometric resolution. The larger the number of bits or intensities discernible by the sensor, the higher its radiometric resolution and the better the sensor can detect small differences in energy. In general, higher radiometric resolution increases the ability to more finely distinguish features on the imagery. Discerning objects within shadowed areas or extremely bright areas is particularly enhanced by higher radiometric resolution.

Digital data is built with binary machine code, therefore each bit location has only two possible values (one or zero, on or off), and radiometric resolution is measured as a power of 2. One-bit data would result in image pixels being either black or white, so no shades of gray would be possible. The first digital sensors were 6 bit, allowing 64 levels of intensity. More recent sensors such as Landsat 8, Sentinel-2, and WorldView-3 have 11- to 14-bit radiometric resolutions (for a range of from 2,048 to 16,384 levels of intensity).

The range of electromagnetic energy intensities that a sensor actually detects is termed its *dynamic range*. Specifically, dynamic range is defined as the ratio of the maximum intensity that can be measured by a device divided by the lowest intensity level discernible. It is important to note the difference between radiometric resolution and dynamic range. The radiometric resolution defines the *potential* range of values a digital remote sensing device can record. Dynamic range is calculated from the *actual* values of a particular image. Dynamic range is defined by the difference between the lowest detectable level and the brightest capturable level within one image. It is governed by the noise floor/minimal signal and the overflow level of the sensor cell.

The sensor used to originally capture an image determines the radiometric resolution of the image. Thus, scanning a film image to create a digital version results in a digital image with the radiometric resolution of the film sensor, not of the digital scanner, even though the radiometric resolution of the scanner may be better than that of the film image.

## Spatial Resolution

An image's spatial resolution is determined by the altitude of the platform, and the viewing angle, lens focal length, and resolving power of the sensor. Spatial resolution has two different definitions:

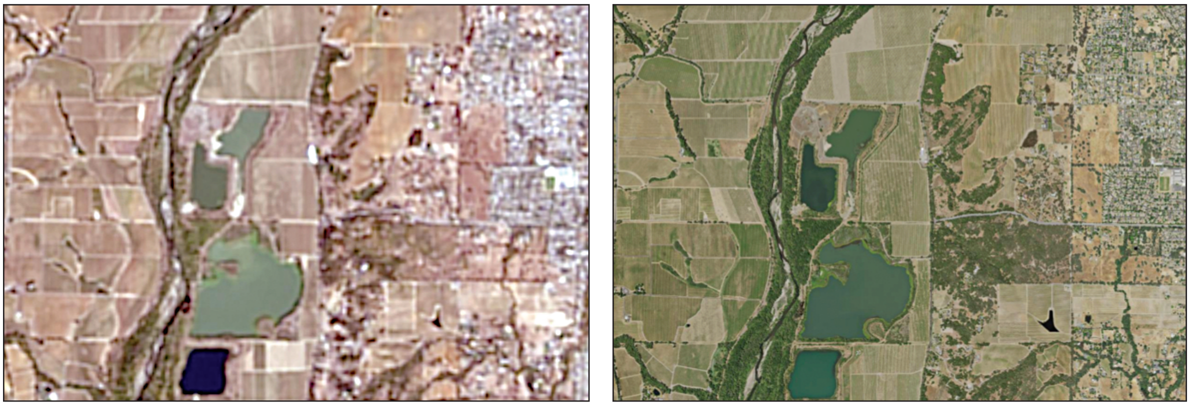
- The smallest spatial element on the ground that is discernible on the image captured by the remote sensing system. The definition of "discernible" can refer to the ability to detect an element as separate from another, or to both detect and label the different elements. This definition was commonly used when remotely sensed images were collected primarily on film.
- The smallest spatial unit on the ground that the sensor is able to image. This is the more common meaning and is the one relied upon by makers and users of digital remote sensing systems. Usually, it is expressed as the ground sample distance (GSD), which is the length on the ground of one side of a pixel.

GSD is a function of sensor pixel size, height above terrain, and focal length, as expressed in the following equation:

$$GSD = (\text{sensor pixel size} \times \text{height above terrain}) \,/\, (\text{focal length}) \quad .$$

The distance to ground is a function of platform altitude and sensor viewing angle. If focal length and sensor resolving power are held constant (as they are in most airborne systems), then the lower the altitude of the system, the smaller the GSD and the higher the spatial resolution of the resulting imagery. If focal length and distance to ground are held constant (as they are in satellite systems), then the higher the sensor resolving power, the higher the spatial resolution. If sensor resolving power and distance to ground are held constant, then the longer the focal length, the higher the spatial resolution of the sensor. Because the sensor and the altitude of satellite remote sensing systems are constant over the usable life of the system, their spatial resolutions are also fairly constant for each satellite system and change only when the viewing angle is changed.

Airborne systems have varying spatial resolutions depending on the sensor flown and the altitude of the aircraft platform. Spatial resolution is also affected by whether the sensor has a stabilized mount, a forward motion compensation unit, or both, which compensate for the forward motion of the aircraft and minimize the blur caused by the motion of the platform relative to the ground by moving the sensor in the reverse direction of that of the platform (and at the ground speed of the platform) during sensor exposure. Figure 3.17 compares the spatial resolution of 15-meter pan-sharpened Landsat imagery to that of airborne 1-meter National Agriculture Imagery Program (NAIP) imagery over a portion of Sonoma County, California. Figure 3.18 compares the NAIP imagery to 6-inch multispectral imagery over a subset of the same area.



True color pan-sharpened Landsat imagery. Pixel size = 15 meter.

True color NAIP airborne imagery. Pixel size = 1 meter.

**Figure 3.17.** Comparison of Landsat 15-meter pan-sharpened satellite imagery to 1-meter National Agriculture Imagery Program (NAIP) airborne imagery over a portion of Sonoma County, California. Color differences are due to sensor differences and the imagery being collected in different seasons. (esriurl.com/IG317)

True color NAIP airborne imagery. Pixel size = 1 meter. Spring 2015.

True color airborne imagery flown for the County of Sonoma. Pixel size = 6 inches. Fall 2013.

**Figure 3.18.** Comparison of 1-meter National Agriculture Imagery Program (NAIP) imagery to 6-inch airborne imagery over a subset of the area of figure 3.17. Color and shadow differences are due to sensor differences and the imagery being collected in different seasons. (esriurl.com/IG318)

The highest spatial resolution obtainable from a civilian satellite is WorldView-4's 30 centimeters (11.8 inches). High-resolution airborne multispectral sensors have spatial resolutions of 2 to 3 centimeters at an altitude of 500 feet (e.g., UltracamEagle). Because they can fly lower than piloted aircraft, UASs can obtain higher spatial resolutions than manned aircraft.

## Viewing Angle

Viewing angle is often used to refer to one or both of the following angles:

- *The maximum angle of the IFOV* of the sensor, from one edge of the sensor view to the other, as shown in figure 3.19. Traditional film-based aerial survey cameras often used wide-angle cameras with a 90-degree IFOV. When they took photographs vertically, the features at the edges of the frames were captured at an angle of about 45 degrees to vertical. With the advent of digital photography, many digital aerial survey cameras have a narrowed IFOV, and coverage is achieved by taking more images. Most satellite imagery is collected with an even narrower IFOV. For example, a vertical WorldView-3 scene captures a strip about 13.1 km wide from an altitude of 617 km, with an IFOV of about 1 degree.
- *The pointing angle of the sensor* as measured from directly beneath the sensor (0°, or nadir) to the center of the area on the ground being imaged. This angle is also

referred to as the elevation angle. Sensor viewing angles are categorized as vertical or oblique, with oblique being further divided into high oblique (images that include the horizon) and low oblique (images that do not include the horizon), as shown in figure 3.20.

Traditionally, with aircraft imagery, images captured with the sensor pointed at less than ± 0 to 3 degrees off nadir are considered vertical, and images collected at greater than ±3 degrees are considered oblique (Paine and Kiser, 2012). However, with the plethora of pointable high-resolution satellites, satellite companies tend to define images captured with a sensor viewing angle of ± 0 to 20 degrees as vertical images, and images collected with sensor angles greater than ±20 degrees as oblique.

Viewing angle is important because it affects the amount of area captured in an image, whether only the top of an object or its sides are visible, and the spatial resolution of the imagery. The larger the viewing angle from the sensor to the object, the longer the distance to the ground and the lower the spatial resolution of the pixels. For example, DigitalGlobe's WorldView-3's nadir spatial resolution of its panchromatic band is 0.31 meter on-nadir, and 0.34 meter at 20 degrees off nadir. The spatial resolution and scale within an oblique image change more rapidly than across a vertical image.

The primary advantage of a vertical image is that its scale and illumination are more constant throughout the image than those of an oblique image. While a vertical image's scale will be affected by terrain and the slightly off-nadir pixels at the edge of the frame or scan line, a vertical image will always have more uniform scale than an oblique image. As a result, measurements are easier and directions can be more easily determined, allowing the image to approximate a map and be used for navigation (as long as the impacts of topography are considered).

On the other hand, an oblique image will show the sides of an object instead of just the top, allowing for realistic 3D rendering. Because humans spend much of their time on the ground, an oblique view is more intuitive to us and we are easily able to judge distances to objects seen in an oblique view (Paine and Kiser, 2012). Much imagery for military surveillance applications was captured as oblique or nonvertical, providing the advantage of showing objects farther away and showing more of the sides of the features, which often provide significant details for interpretation.

The very first aerial photographs were mostly oblique. However, for 70 years vertical photographs became the basis for most maps because the geometrical relationship between the sensor and the ground is fairly straightforward to determine with vertical images. In addition, the scale and illumination of vertical images are relatively constant within the image, and stereo models can be easily created by overlapping vertical images. Usually, the photographs were collected with at least a 50-percent overlap to enable stereo viewing and photogrammetric measurements (see chapter 6 for more detail on photogrammetry). Similarly, since the first launch in 1972, all nine Landsat satellites were designed to collect vertical images, but the systems are incapable of stereo except over higher latitudes, where there is enough overlap to allow some stereo collection.

When a vertical object such as a building is viewed at nadir, the sides of the building are not visible; only the top of the building is visible. If that vertical object is not located directly below the sensor at nadir, then one or more sides of the object will be visible in the image; this is termed an off-nadir view, and the effect is called relief displacement. We can refer to the angle between the nadir and the ray of light between the sensor and the vertical object as the off-nadir angle. This angle can be the result of a ray being off the center of a vertical image, meaning that it is not the principal axis of the image, or it can be the result of a ray from an oblique image. In either case, you can see the side of the vertical object, and this view allows for height measurements as well as being the basis for parallax between two images, which provides stereo imagery. Parallax is the apparent displacement of the position of an object relative to a reference point due to a change in the point of observation. This off-nadir angle may be small across the image when the imagery is vertical and the IFOV is small. Larger off-nadir angles are seen when the imagery is captured as oblique imagery or if the camera has a large IFOV.

These geometric shifts due to sensor perspective and collection geometry enable some good things like stereo imagery, but they also lead to occlusion of objects and variation from image to image that adversely affect image classification and other automated processes if elevation is not modeled at a high fidelity.

The 1986 introduction of the French SPOT systems brought off-nadir pointability to civilian satellite image collection, allowing for the collection of off-nadir stereo pairs of imagery to support the creation of DEMs. Now, most very-high-spatial-resolution satellites and airborne systems are able to collect both nadir and off nadir to oblique imagery either through pointing the system as shown in figure 3.20 or through the use of multiple sensors on the platform, some collecting at nadir and others collecting off nadir, as shown in figure 3.21. Recently, with advances in photogrammetry and computing power, airborne and terrestrial oblique images have been used to created detailed and accurate 3D representations of the landscape.

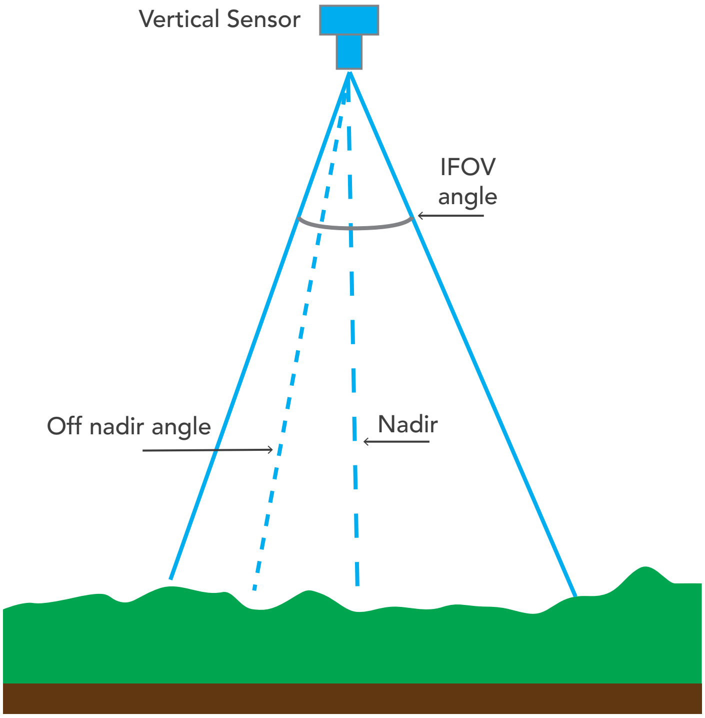


**Figure 3.19.** The concepts of the instantaneous field of view (IFOV), nadir, and off-nadir angles of a vertically pointed sensor

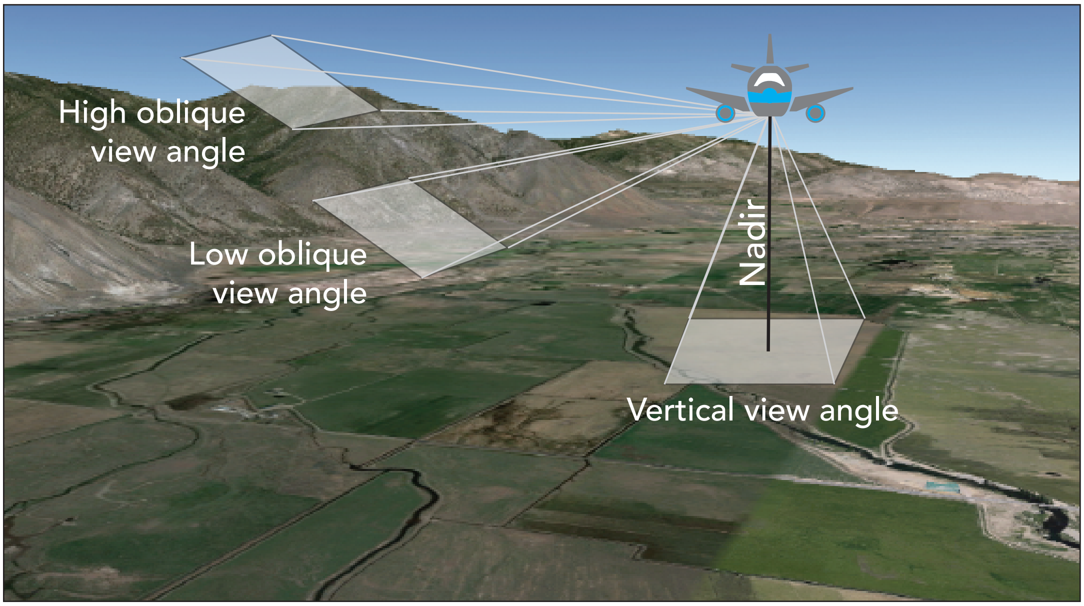


**Figure 3.20.** Examples of a framing camera's vertical, low-oblique, and high-oblique viewing angles

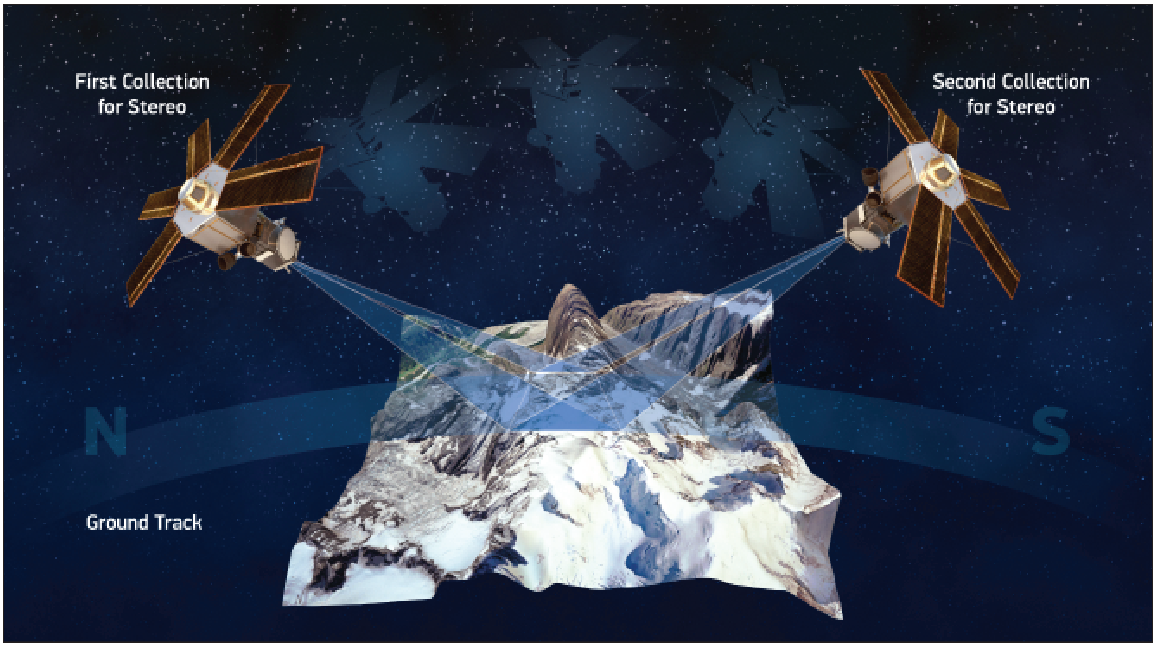


Figure 3.21. Diagram showing how pointable satellites can pitch from side to side during orbit to collect off-nadir stereo images. Source: DigitalGlobe

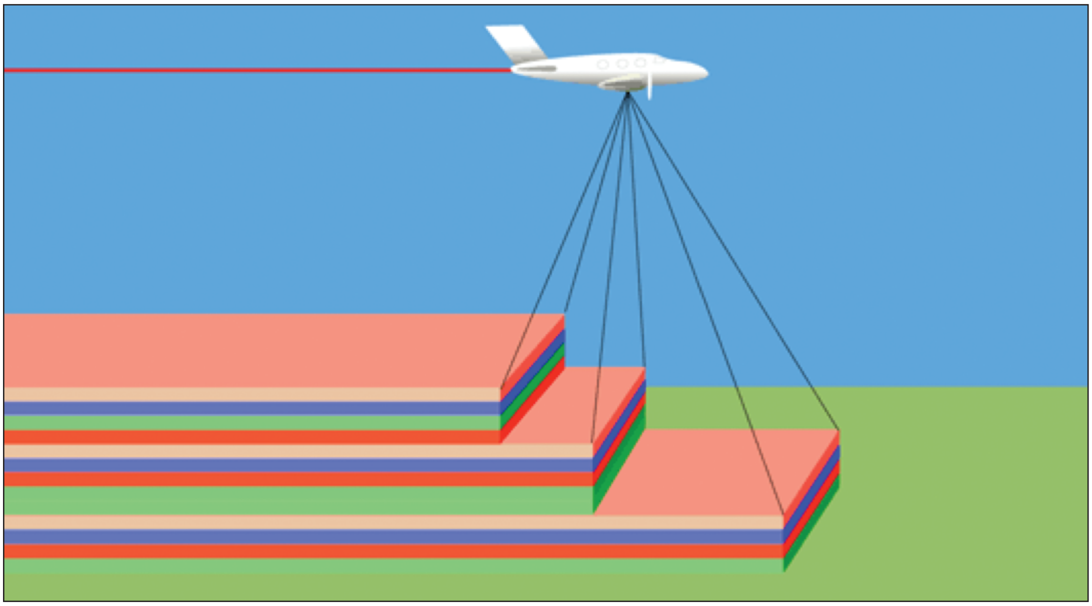


Figure 3.22. Conceptual diagram of an aircraft with a Leica ADS100 with three beam splitters: two tetrachroid beam splitters in forward and backward directions with multispectral red, green, blue, and near-infrared (RGBN) bands and one bi-tetrachroid beam splitter in nadir with multispectral red, green, blue, and near infrared bands with staggered green bands. Source: Hexagon

## Temporal Resolution

Temporal resolution is determined primarily by the platform and refers to the flexibility regarding the day, time of day, and time between capture of remote sensing images of the same feature by a sensor on the platform.

The highest temporal resolution will always be obtained with a geostationary system. Because weather is constantly changing and must be constantly monitored, many of our weather satellites are geostationary—that is, they rotate above the earth at the same speed as the earth allowing them to remain stationary over a particular region. To remain geostationary, they require an orbit of about 35,786 kilometers above ground, and as a result their spatial resolution is very low. Other examples of high temporal resolution geostationary systems are video cameras placed in banks, at many road intersections, and in high-risk areas such as subway stations and airports. Other applications for fixed platforms include continuous weather observation using a Doppler radar system or continuous spectral monitoring of a specific ground point (e.g., monitoring spectral characteristics of a specific farm crop). However, terrestrial platforms are not practical for most large mapping missions.

Airborne platforms usually offer higher temporal resolution than orbiting spaceborne platforms because orbiting platforms are restricted by their orbits, which determine how often and when a spaceborne platform will pass over a specific location on the earth. Conversely, airborne platforms can be flown at any time of day or night but may be restricted from flying over a specific area such as a war zone.

Because passive systems rely on the energy of the sun, they will always have lower temporal resolution than active systems, which can be flown at any time of the day or night. Because satellites are tied to their orbits, they will never have the temporal resolution of aircraft systems in countries where airspace is relatively unrestricted (as opposed to severely restricted airspace over countries such as Iraq or North Korea). Sun-synchronous satellites capture imagery during the same period every day, which reduces their versatility. Aircraft can often fly under clouds, and image collections can be specifically timed to tidal stages, crop calendars, or deciduous leaf conditions.

## Extent

The term extent is used to refer to the area on the ground that can be captured with each exposure of the sensor. It is often used relative to one mission or collection and is determined by the sensor size, its focal length, and its distance to ground. Many satellite systems collect imagery continually along their orbital paths. The area collected is, therefore, constrained by the width of the sensor's swath, but not by the strip length. The length of individual satellite scenes is arbitrary and is determined by the operator of the system. Most scenes are approximately square. For example, a Landsat scene is 170 by 183 kilometers.

The size and shape of a project area will affect what remote sensing systems are most suitable for imaging it. Because of their altitude, satellites can capture large areas in individual satellite scenes (e.g., a Landsat scene covers just over 12,000 square miles). However, satellite images are restricted to the satellite's orbital paths, making aircraft systems more effective in collecting linear or sinewy project areas (such as riparian areas, transmission lines, and coastlines) because aircraft are not tied to an orbit.

Helicopters are ideally suited to collect data over multiple distributed points because they are more agile than airplanes. They are also suitable for collecting data along corridors where frequent turning may be necessary. Fixed-wing aircraft are more suitable for collecting imagery over large areas because they can quickly collect large swaths of data. For extremely large areas, a high-altitude aircraft or satellites might be employed to maximize ground coverage.

For example, a riparian mapping project, following a long sinewy river with a required spatial resolution of 1 meter will probably be better accomplished with an airborne system than with a satellite system. The airborne platform can follow the path of the river and constrain its data collection to only the river area. Using data from a satellite system would require collecting multiple scenes, and then extracting the river areas from the larger scenes. More area and thus more data than required would be collected, which would increase the cost of the project.

An advantage that moderate-spatial-resolution, large extent satellite systems (e.g., Landsat and Sentinel) have over airborne collections is that the entire scene is captured at once with instantaneous sun illumination, vegetative condition, and atmospheric conditions fixed across the scene. Capturing the same area as a Landsat scene with an aircraft system would take several days, with the sun illumination, vegetation, and weather conditions changing throughout each day and from day to day. These variations can introduce confusion when the images are manually interpreted or classified to create maps.

High-spatial-resolution systems (both airborne and satellite) have a smaller extent than moderate- and low-spatial-resolution systems, but individual scenes can be mosaicked together to represent a larger area. Mosaicking is discussed in more detail in chapter 5.

# Organizational Characteristics

## Introduction

The choice of what imagery best meets a project's requirements will be determined not only by the imagery collection characteristics but also by the imagery's organizational characteristics. Organizational characteristics are determined by the organization(s) funding the imagery acquisition and distribution. Types of organizations include public agencies, private companies, and organizations with a combination of public and private funding. Organizational characteristics affect the imagery's accessibility and price to users. This section introduces and reviews imagery organizational characteristics—its pricing and licensing and its accessibility.

## Pricing and Licensing

Price is the amount a user pays to gain access to imagery. Licensing refers to the restrictions placed on the use of the imagery. Licensing and pricing are often linked. Much of the medium- and low-spatial-resolution remote sensing data collected is free and its use is unrestricted (i.e., the data is in the public domain). Other imagery, especially high-resolution satellite imagery, is either severely restricted by government policy or accessible only through the purchase of a license with associated restrictions on the user's ability to share the imagery with other users.

Because the primary demand for low- and moderate-spatial-resolution imagery is from the public sector, acquisition and distribution of much of the low- and moderate-spatial-resolution civilian satellite imagery acquired by the US government and the European Space Agency (ESA) is funded by taxpayers and available to most users at no charge with few or no use restrictions. As a result, NASA earth observation data, Landsat imagery, National Oceanic and Atmospheric Administration (NOAA) weather imagery, and the ESA's Sentinel imagery are all freely available to most users worldwide.

The collection of high-resolution airborne imagery in the United States is usually purchased as a service by government agencies from commercial providers. The agencies pay the provider to collect and process the imagery, with the agency retaining all or most rights to the imagery. Similar to the availability of low- and moderate-resolution satellite imagery, most high-resolution airborne imagery is made available by agencies to the public at no cost, although some charge user fees. The USDA NAIP collects high-resolution, 4-band multispectral imagery over one-third of the continental United States every year at 1-meter spatial resolution. The imagery is available to the public at no cost and with no user restrictions. Most of the NAIP commercial providers also offer the ability to "upgrade" the imagery to 30- centimeter spatial resolution on a paid subscription basis. The upgrades are available because the providers capture the imagery at the higher resolution and resample it to the lower resolution for the public domain product. The provider then makes the higher resolution product available through a licensing agreement that restricts the use of the imagery (i.e., the purchaser is restricted in some way from copying or sharing the imagery with other organizations). Besides NAIP, many states and local governments retain commercial firms to collect airborne high-resolution multispectral and lidar data over their jurisdictions. Usually, the imagery is made available to the public at low or no cost, and with few, if any, use restrictions. Private companies such as utility and forestry firms also contract with airborne providers to produce high-resolution imagery of their properties.

Until recently, high-spatial-resolution satellite imagery was either completely government funded with use severely restricted, or partly government funded, with use restricted by licensing. For example, the United States, Russia, China, India, and Israel all have constellations of satellites that are fully funded by their government agencies but whose imagery use is strictly restricted to security agencies.

The passage of the 1992 Land Remote Sensing Act made it possible for US commercial companies to build, launch, and operate satellite sensors able to collect high-resolution imagery globally. Although fully commercial, the first companies to launch high-resolution systems received large contracts from the National Geospatial Agency of the Department of Defense for imagery. As a result, the funding for the imagery is part government and part commercial. The commercial companies distribute the imagery through licensing agreements that restrict either the amount of time the imagery is available for use or the sharing of the imagery with other organizations. This quasi-public/private funding model for high-resolution satellite imagery with licensing restrictions has since been replicated by several companies (e.g., DigitalGlobe, Airbus, Planet, and DMC constellations).

## Access

Organizations make imagery available in a variety of ways. It can be delivered on a hard drive, downloaded from the web, or served as image services. Because imagery files are very large, access can be problematic and can affect the cost of working with imagery. Free imagery with no license restrictions can still be difficult to use if its access is cumbersome.

Before digital sensors, imagery was accessed as hard copy negatives and photographs. Reproduction of the negatives and photographs was very expensive and, as a result, access to them was limited. With the adoption of digital sensors, digital imagery was initially accessed from tape, and then from hard drives and CDs, and processed first on mainframe computers and then on desktop computers.

Until recently, the most efficient way to deliver and gain access to high-spatial-resolution imagery for analysis was still by shipping hard drives and then using on desktop machines or serving the imagery locally. With increases in Internet bandwidth, imagery is increasingly accessible by FTP download or direct access from cloud storage. In this way, imagery can be downloaded to desktop machines or directly used in the cloud infrastructure.

Over the last five years, several imagery providers and software companies have begun to host imagery in the cloud and offer direct visualization, analysis, and processing of the imagery. Most notable is Esri's Landsat services, which obtain Landsat imagery hosted on Amazon Web Services and provide access and on-the-fly processing of large collections of multitemporal multispectral Landsat imagery that is updated daily as imagery is acquired by the USGS. Google also hosts archives of Landsat imagery and provides processing to educational and research organizations.

## Case Study—the Effects of Price and Licensing on the Use of Landsat Imagery

The history of Landsat imagery is a good example of how organizational characteristics affect imagery use. Landsat satellite imagery is moderate resolution, multispectral, and funded by US taxpayers. NASA launched the first Landsat satellite in 1972. The spatial resolution was coarse (80 meters) and included only four bands (green, red, and two infrared bands). Technological barriers slowed the use of the imagery because the knowledge base was small, little image processing software existed, and the files were huge for that time, requiring mainframe computers. Most users were NASA or academic scientists and government agencies. Landsats 2 and 3 were similar to Landsat 1.

In 1979, the Landsat program was moved from NASA to NOAA. In 1982, Landsat 4 was launched and included a 30-meter resolution instrument that collected seven bands of imagery, adding two middle-infrared and one thermal band. A similar system, Landsat 5, soon followed in 1984. However, Congress passed the Land Remote Sensing Commercialization Act of 1984, which directed NOAA to migrate Landsat imagery distribution from the federal government to the private sector with the hope that revenue from imagery sales would support the continuation of the Landsat program. As a result, the cost of Landsat imagery increased from $2,800 per scene from NOAA to $6,000 per scene from the commercial company

EOSAT, and use of the imagery was license restricted. The demand for imagery sharply declined, as did Landsat research and innovation (Draeger et al., 1997).

In 1992, Congress passed the Land Remote Sensing Policy Act (Public Law 102-555), which ended Landsat commercialization by designating the USGS to take over distribution of Landsat 7 imagery when it was launched (Landsat 6 failed to reach orbit). The act required that imagery be priced at the cost of fulfilling user requests and have no licensing restrictions. Landsat 7 was successfully launched in April 1999, and the USGS initially set the price of a scene at $600. The lower price of Landsat 7 imagery forced the company distributing Landsat 4 and 5 data to match the price of Landsat 7 imagery. Unable to run Landsats 4 and 5 profitably, the company returned its rights to distribute Landsat 4 and 5 imagery to the federal government in 2002. The lower price and unrestricted licensing for all Landsat imagery resulted in a dramatic increase in the operational use of Landsat imagery, with government revenue from image sales growing from $4 million in 1999 to $11 million in 2002. However, access to the imagery was still cumbersome and slow, requiring the manual ordering and writing of CDs.

With improvements in the web and automation of the USGS distribution processes, the agency made Landsat imagery free and downloadable from the web in 2009. As a result, the use of Landsat imagery skyrocketed from 20,000 scenes to 2,000,000 scenes a year, and commercial companies such as Esri are hosting Landsat imagery and processing services, which further increases global access to the imagery.

## Summary—Practical Considerations

In this chapter, we have learned how imagery is differentiated by a combination of technical and organizational characteristics. An image's sensor and platform determine its technical characteristics—its spectral, radiometric, spatial, and temporal resolutions, as well as its viewing angle, and extent. In summary:

- Spectral resolution—Terrestrial, airborne, and satellite platforms can and do carry all types of sensors. Currently, panchromatic, multispectral, and hyperspectral sensors can be found on terrestrial, airborne, and satellite platforms, as are active and passive sensors.

- Radiometric resolution—Older sensors will often have lower radiometric resolution than newer sensors because newer sensors can take advantage of continual improvements in digital arrays, memory, and storage.
- Spatial resolution—Airborne systems are more commonly used to collect high-spatial-resolution imagery than spaceborne systems if the infrastructure to support aircraft is available and if the aircraft have access to airspace. If access to the air is limited, satellite systems or drones can be used to collect high-resolution imagery. Moderate-and low-spatial-resolution imagery is best captured from satellites.
- Temporal resolution—Geostationary systems offer the highest temporal resolution, but at either a lower spatial resolution (e.g., weather satellites) or a smaller extent (e.g., video cameras at ATM machines) than airborne or satellite systems. Airborne systems are more flexible than satellite systems and are limited only by aircraft access and fuel capacity. Additionally, cloud interference can be avoided by positioning airborne systems below the cloud ceiling or by timing flights to avoid cloud cover (e.g., flying after fog has burned off in a coastal area). However, the marginal cost of mobilization for each image is higher for airborne systems than for satellite systems.
- Extent—Depending on the resolving power of the sensor, high-altitude platforms will generally result in greater area imaged per exposure (i.e., larger extent), but at coarser spatial resolution than platforms operating at low altitudes. Airborne systems are usually more effective than satellite systems in collecting long and sinewy project areas.

Technical characteristics are not the only factors differentiating imagery types from one another. Often more important are the organizational characteristics, which will determine an image’s price, licensing, and accessibility. Choosing what imagery to use in a project requires making trade-offs between technical and organizational characteristics. In the next chapter, we will learn how to match imagery characteristics with user requirements to decide what type of imagery will best meet user needs.