Chapter 1

Introduction to Remote Sensing

Remote sensing is a field designed to enable people to look beyond the range of human vision. Whether it is over the horizon, beyond our limited range, or in a spectral range outside our perception, we are in search of information.[1] The focus in this text will be on imaging systems of interest for strategic, tactical, and military applications, as well as information of interest to those domains.

To begin, consider one of the first airborne remote-sensing images. Figure 1.1 shows a photograph by Gaspard-Félix Tournachon[2] (Tournachon was also known by his pseudonym, Nadar). He took this aerial photo of Paris in 1868 from the Hippodrome Balloon, tethered 1700 feet above the city. Contrast this image with the photo taken by astronauts on Apollo 17, roughly one hundred years later (Fig. 1.2).

Tournachon's picture is a fairly classic remote-sensing image—a representation from a specific place and time of an area of interest. What sorts of things can be learned from such an image? Where, for instance, are the streets? What buildings are there? What are the purposes of those buildings? Which buildings are still there today? These are the elements of information that people want to extract from such imagery.

The following material establishes a model for extracting information from remote-sensing data. The examples used here are also meant to illustrate the range of information that can be extracted from remote-sensing imagery, as well as some of the consequences of wavelength and resolution choices made with such systems.

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[1] The term "remote sensing" emerged as the imaging technology moved beyond film-based aerial photography. The initial impetus for the term is attributed to Evelyn Pruitt and Walter Bailey (ca 1960).

[2] Tournachon was a notable portrait photographer from 1854 to 1860. He made the first photographs with artificial light in 1861, descending into the Parisian sewers and catacombs with magnesium flares. He apparently was also an early experimenter in ballooning, even working with Jules Verne. http://www.getty.edu/art/collections/bio/a1622-1.html.

Figure 1.1 Gaspard-Félix Tournachon took his first aerial photographs in 1858, but those earlier images did not survive.[3] He applied for a patent for aerial surveying and photography in 1858. Curiously, there is no evidence of photography during the American Civil War, although balloons were used for reconnaissance by both sides. Image courtesy of the Brown University Library Center for Digital Scholarship.

1.1 Order of Battle

Remote-sensing data, *sans* analysis, have a fairly modest value. In general, the truly valuable component is information appropriate to making a decision. To the extent that one can obtain or understand what information can be derived from remote-sensing data, one can begin to address a question posed in the preface: What is remote sensing good for? To answer this question, a paradigm is introduced, called the "order of battle" (OOB). This term is largely associated with the counting of "things," but not entirely. Indeed, the levels of information should not be limited to simple "counting." Attention must also be paid to nonliteral forms of information.

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[3] Jensen, *Remote Sensing of the Environment*, page 62 (2000).

Figure 1.2 An image of earth (“The Blue Marble”), taken from near-geosynchronous orbit by Apollo 17 on December 7, 1972.

An OOB has a number of forms, depending on the area of interest:

- Air order of battle (AOB);
- Cyber order of battle (COB);
- Electronic order of battle (EOB);
- Ground order of battle (GOB), which includes logistics;
- Industrial order of battle (IOB);
- Naval order of battle (NOB);
- Missile order of battle (MOB); and
- Space order of battle (SOB).

What items characterize these OOB types? What sort of information is being considered? A GOB, for example, might consist of vehicles—their numbers, locations, and types. Sample types include armored (e.g., tanks), transport (trucks), and personnel (high-mobility, multipurpose, wheeled vehicles, or HMMWVs). After the types are established, further elements of information include operational status (fueled, hot, armed, etc.), capabilities, and armament (weapons). Other elements of a GOB are troops (numbers, arrangement, types, etc.), defenses (e.g., minefields, geography, missiles, chemical/biological, camouflage, and decoys), and infrastructure (such as roads and bridges). The following subsections provide OOB examples with images that range from historic systems to the most-advanced modern commercial systems.

1.1.1 Air order of battle

An air order of battle (AOB) focuses primarily on aircraft and airfields. A tabular approach to compiling salient elements of information is provided in Table 1.1; it is organized in increasing level of detail. There are several levels of detail that you will want to know about. Not all will be amenable to remote sensing, but the first step is to identify what you want to know. The next step is to determine which elements can be provided by available sensors. The first illustration uses an early Cold War system only recently declassified for public use.

Table 1.1 Air order of battle details.

Planes	Type	Fighter	Weapons	Air-to-Air
				Air-to-Ground
			Sensors	FLIR
				Radar
				Visible
				EW
		Bomber		
		Tanker		
		Transport	Civilian	
			Military	
		Trainer		
		EW		
		Reconnaissance		
	Number			
	Locations	Bunkers		
		Runway		
		Aprons		
Runways	Length			
	Composition	Material (asphalt, dirt, concrete)		
	Direction	Heading		
	Approach	Terrain		
		Lighting		
		Weather		
		Ground Controllers		
Logistics	Supply Lines / Lines of Communication			
Petroleum, Oil, and Lubrication (POL)	Fuel Tanks	Capacity		
		Type of Fuel		
		Fill Factor		
Pilots	Number			
	Ranks			
	Training			
	Experience			
Defenses	Weapons	AA Guns		
		AA Missiles		
	Radar	Frequency		
		Range		
		Location		
		Type		
	Locations	Field of View (FOV)		

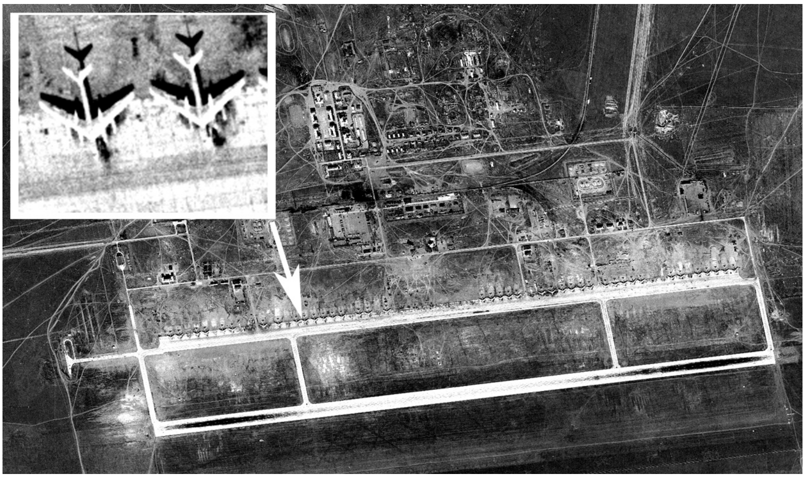

Figure 1.3 Image of the Dolon air base in Chagan, Kazakhstan (50° 32′ 30″ N, 079° 11′ 30″ E) taken by the Gambit (KH-7) system during Mission 4022 on October 4, 1965. The inset is a close-up of the Tupolev Tu-95 (Bear) bombers along the 4-km runway. North is up. The planes are 46 m in length, with a wingspan of 50 m. The spatial resolution in the scanned image is ~0.735 m per pixel. Image reference: DZB00402200056H012001; the film was scanned at a 7 μm pitch.[4]

An AOB is illustrated in Fig. 1.3; it is derived from one of the early satellite reconnaissance systems: the Gambit, or KH-7 film return system. Important elements such as the length and orientation (heading, roughly 90/270 here) of the runways are immediately apparent; the number of TU-95 aircraft can be counted easily, and the smaller aircraft are visible in the original image. The infrastructure is clearly defined. This illustration of the Dolon air base in the former Soviet Union reveals relatively little in the way of defenses (the base is far away from any border). As with a number of Soviet airfields, the runway has a curious checkerboard pattern. Soviet construction techniques involved large (pre-cast) concrete blocks, rather than the smoother, continuous surfaces of American runways.

1.1.2 Electronic order of battle

The electronic order of battle (EOB) is really the domain of the signals-intelligence (SIGINT) community, but imagery can contribute to the topic. Relevant subjects include defenses, such as surface-to-air missiles (SAMs) and radar installations. The technical details for radars are admittedly more the domain of SIGINT or electronic intelligence (ELINT) than imagery intelligence (IMINT) because the elements of information include frequencies, pulse-repetition frequency (PRF), scan type, and pulse width and mode. Regardless, the location and layout of radar provides a lot of information, particularly with

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[4] http://en.wikipedia.org/wiki/Tupolev_Tu-95.

Figure 1.4 This Gambit-1 image shows the Sary Shagan Hen House radar (centered at 46° 36′ 41″ N, 74° 31′ 22″ E). The image was taken on May 28, 1967. Similar images with a 1-m resolution date to 1964. These large Soviet radars were designed to watch for ballistic missiles and satellites. The 25-MW system was designed to monitor the south and west with two pairs of antenna, one transmitting and one receiving (bistatic). The image chip for two of the radar systems is overlaid on the full frame image for context. The original film was 9 inches wide (the vertical direction in this frame).

regard to access. The size of an antenna implies characteristics such as range. It might be possible to determine operational patterns. The radar types can be identified by comparison to known systems, e.g., air search, surface search, fire control, and target tracking. Networking and communications details, such as nodes or types (HF, microwave, fiber, etc.), or even the power source may be determined.

Figure 1.4 illustrates a famous Cold-War Russian system: the orientation of the Hen House radar is associated with its primary role of watching the horizon for ballistic missiles. Given the size and orientation of the radar, and some knowledge of the wavelength used, the resolution and FOV of the radar can be determined. "Moon Bounce" signals from this system were observed by the Naval Research Laboratory at the Chesapeake Bay facility, and in Palo Alto with the 150-ft. Stanford Dish. These observations allowed observers to measure the radar power.[5]

1.1.3 Space order of battle

The space order of battle (SOB) is a relatively new area, illustrated with images from much more recent commercial and civil systems. It includes two

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[5] CIA Center for the Study of Intelligence; Studies in Intelligence, series, series Volume 11, #2, pp. 59–66; Spring 1967; Moon Bounce Elint, Frank Eliot. https://www.cia.gov/library/center-for-the-study-of-intelligence/kent-csi/vol11no2/html/v11i2a05p_0001.htm.

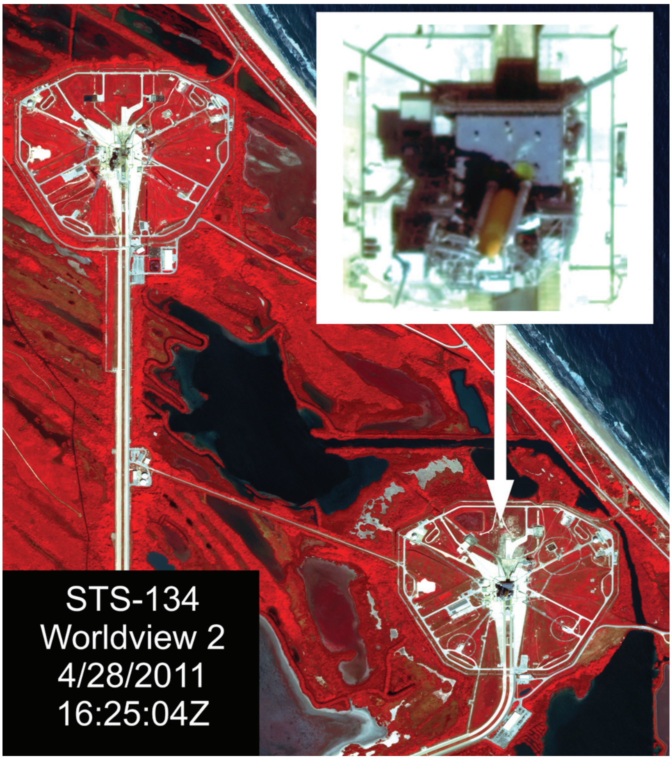

Figure 1.5 Worldview-2 image of STS-134 on the pad. North is up. This illustration uses the near-infrared, red, and green bands in a false-color representation similar to that obtained from infrared-color film in previous years. The vegetation appears bright red. Somewhat coincidentally, the red external tank on the shuttle maintains a fairly orange color. The color image has been "pan-sharpened" to the 0.6-m resolution of the panchromatic sensor that collected these data. Imagery reprinted courtesy of DigitalGlobe.

components: space and ground systems. Ground elements of interest include launchers (boosters), launch pads and other infrastructure, and communications ground sites. Figure 1.5 illustrates the ground component with an image of a shuttle being readied for launch. There is a characteristic pattern to the launch complex that is repeated nearby for the second shuttle launch complex.

Space elements of information that are important are communications systems (relay satellites), operational payloads, and satellite orbital data. Figure 1.6 illustrates satellite-to-satellite imaging (sat-squared, or Sat^2). This image was taken by the SPOT-5 satellite as the European Radar Satellite 2 (ERS-2) flew under the French earth-imaging system. Given the close range, the cross-track resolution is ~12.5 cm.

The image is distorted in the horizontal direction (along the orbital track) due to the unusual relative velocity of the radar satellite compared to the ground, and the image has been adjusted to remove that distortion. Solar

Figure 1.6 On June 3, 2002, SPOT-5 took this picture of the ERS-2 satellite at about 23:00 UTC over the Southern Hemisphere. ERS-2, 42 kilometers below, overtakes SPOT-5 from north-east to south-west at a relative velocity of ~81 m/s. Image reprinted with permission of the Centre National d'Études Spatiales (CNES).

arrays, radar antenna, and telemetry antenna are visible. Previously, SPOT-4 had imaged ERS-1 at a lower resolution; TerraSAR-X has shown a similar capability in radar imaging, as illustrated below in Section 1.2.5.

1.1.4 Naval order of battle

A naval order of battle (NOB) involves ships, of course. It is concerned with battle groups and their composition (types of ships, numbers, arrangement in the group, steaming direction, velocity, etc.), as well as ports (harbor characteristics, draft, piers, defenses, communication lines, and facilities) and the state of readiness of ships in a harbor. For individual ships, manpower, supplies, weapons, and sensors are important. In the case of carriers, what aircraft are aboard and how they are armed are all essential elements of information (EEI).

Figure 1.7 illustrates a little of what can be seen by viewing a Russian naval base. The submarines can be counted, and to some extent they can be identified by length and shape. There is some indication of readiness by looking at the ice: are the boats locked in, or is there a path to open water? Notice the level of activity on the docks around the submarines. In this case, things look pretty quiet.

This illustration was also chosen to emphasize the international nature of remote sensing today—this image came from an Israeli commercial system. (Higher-spatial-resolution illustrations from U.S. satellite and airborne systems are shown for aircraft carriers in Figs. 1.16, 1.18, and 1.20.)

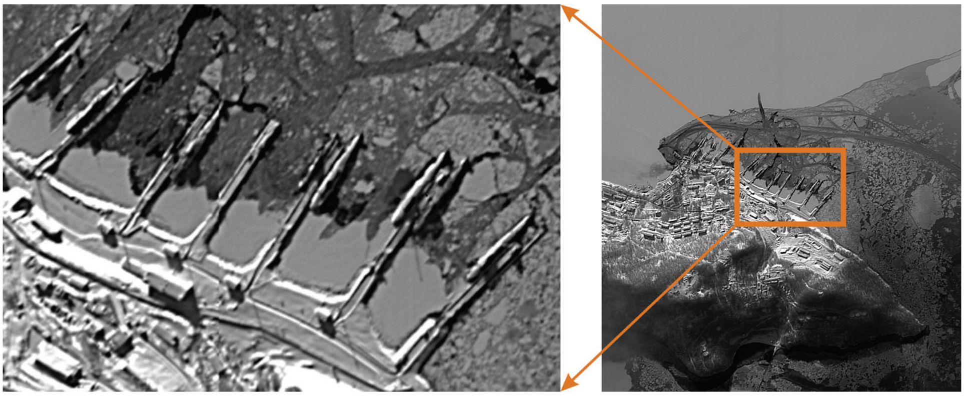

Figure 1.7 Image of Kamchatka Submarine Base, Russia, taken by Earth Resources Observation Satellite (EROS) on December 25, 2001 with a 1.8-m resolution.[6] Located on the far-eastern frontier of Russia and the former Soviet Union, this peninsula has always been of strategic importance. Kamchatka is home to the Pacific nuclear submarine fleet, housed across Avacha Bay from Petropavlovsk at the Rybachy base.

1.1.5 Industrial order of battle

The infrastructure of a country can be revealed by the pattern of lights at night. Historically, the Defense Meteorological Satellite Program (DMSP) provided intriguing nighttime imagery from the Operational Line-Scan system, a photomultiplier tube (OLS-PMT) sensor on the DMSP designed to see clouds at night. DMSP's low-light capability included the ability to see city lights, large fires (like those of oil wells and forests), and the aurora borealis, as well as less-obvious light sources, such as those produced by industrial activity. More recently the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the NASA/NOAA weather satellite Suomi NPP has provided much more detailed images of the earth at night (Fig. 1.8). The Suomi NPP was launched on October 28, 2011, and is redefining our ability to detect low-light-level activity on earth.

This image of Egypt and the Nile River reflects the distribution of energy (and people) in Egypt. Such data can be correlated to industrial output. Chris Elvidge at NOAA has done extensive work, for example, in tracking the de-industrialization of portions of the former Soviet Union following the dissolution of the country.[7] Figure 4.16 shows a global view developed from an ensemble of images like the one shown here.

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[6] http://www.imagesatintl.com/; image no longer posted.

[7] C. D. Elvidge et al., "Preliminary Results from Nighttime Lights Change Detection," Proceedings of the ISPRS joint conference: 3rd International Symposium Remote Sensing and Data Fusion Over Urban Areas (URBAN 2005) and the 5th International Symposium Remote Sensing of Urban Areas (URS 2005); Editors: M. Moeller, E. Wentz; International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences; XXXVI, 8/W27.

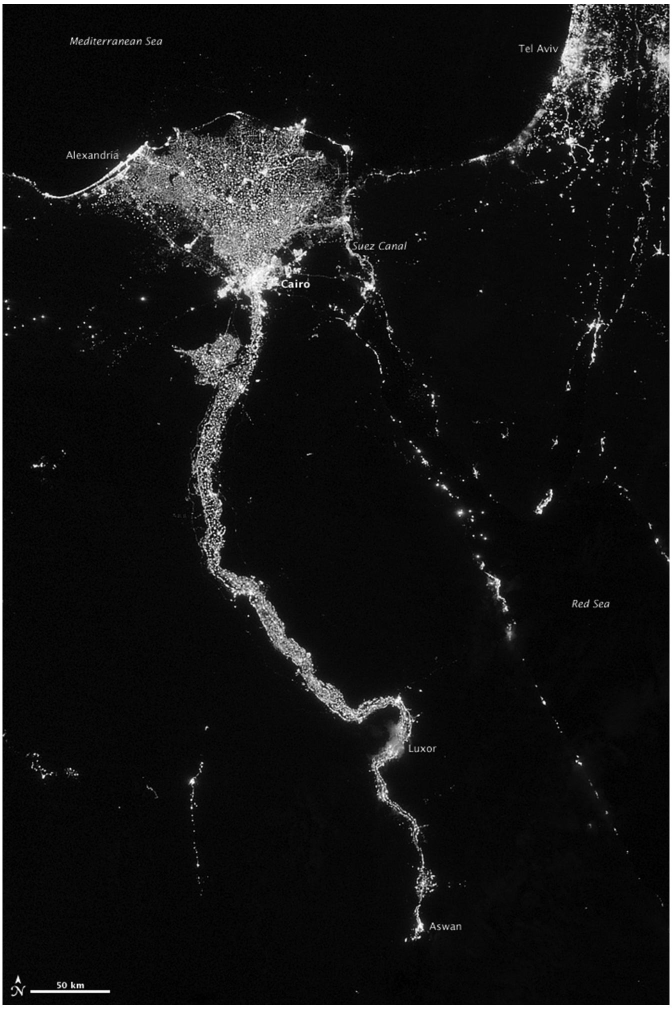

Figure 1.8 View of Egypt at night taken by the VIIRS aboard the Suomi National Polar-orbiting Partnership (NPP) satellite on October 13, 2012.

Later in this chapter, Figs. 1.16 and 1.19 illustrate a different element of IOB: lines of communication. The Coronado Bridge and associated roads appear at a higher spatial resolution. Figure 4.17 in this book shows port activity in a nighttime image, with roads made visible by cars and static light sources.

These illustrations of orders of battle provide an idea of the types of information that can be obtained. The following section briefly surveys the various forms of remote-sensing data available historically and today. Visible, infrared, LiDAR, and radar imagery are illustrated.

1.2 Technology Survey

The first section of this book took a quick look at the types of information that might be desired from imaging systems. This section examines imaging as a function of spatial resolution and mode, in part to develop an initial view of the tension between area coverage, temporal coverage, and resolution. This conflict was more obvious when most satellites imaged in a purely nadir view. Off-nadir imaging systems change the paradigm and greatly reduce the temporal gap traditionally implicit in high-spatial-resolution systems. Other illustrations are chosen to reflect the international character of current remote-sensing systems; they also highlight the variety of organizations involved with remote sensing—military and civil systems dominate, but there are also important private systems. The first concept covered here is (nearly) whole-earth visible imagery. The Apollo 17 image in Fig. 1.2 raises several important points, especially a vexing one for remote sensing: clouds. Do you see indications of intelligent life?

1.2.1 Imaging the whole earth: optical and infrared imaging

1.2.1.1 Geostationary Operational Environmental Satellite (GOES): whole-earth visible imaging

High-altitude satellites (such as weather satellites) image most of a hemisphere. The GOES-9 visible imager acquires an image of one hemisphere every 30 minutes, or the northern quad once every 15 minutes, with a spatial resolution of 1 km. Televised weather reports frequently show images from GOES satellites (like that shown in Fig. 1.9).

What value do such data have for the military? For one thing, cloud coverage is revealed. Clouds are a major concern in modern warfare because they directly affect the ability of pilots and autonomous weapons to locate targets. This whole-earth image also begins to illustrate the important tradeoffs between spatial resolution, frequency of coverage, and area of coverage. High-altitude satellites, such as geosynchronous[8] weather satellites, provide large-area coverage (more or less continuously) and produce an image every 15–30 minutes at a spatial resolution of 1 km.

1.2.1.2 GOES: whole-earth infrared imaging

A companion figure to the GOES visible image is shown in Fig. 1.10. Infrared images from the GOES weather satellite again show much of the western hemisphere. Per the weather-community convention, the gray scales are inverted: cold is brighter, dark is hotter, so that cold clouds will appear white. Images taken in three long-wave infrared (LWIR) wavelengths are combined in a false color image, as further developed in Chapter 8. This image was

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[8] Geosynchronous orbit (GEO) satellite orbits have a radius of 6.6 earth radii.

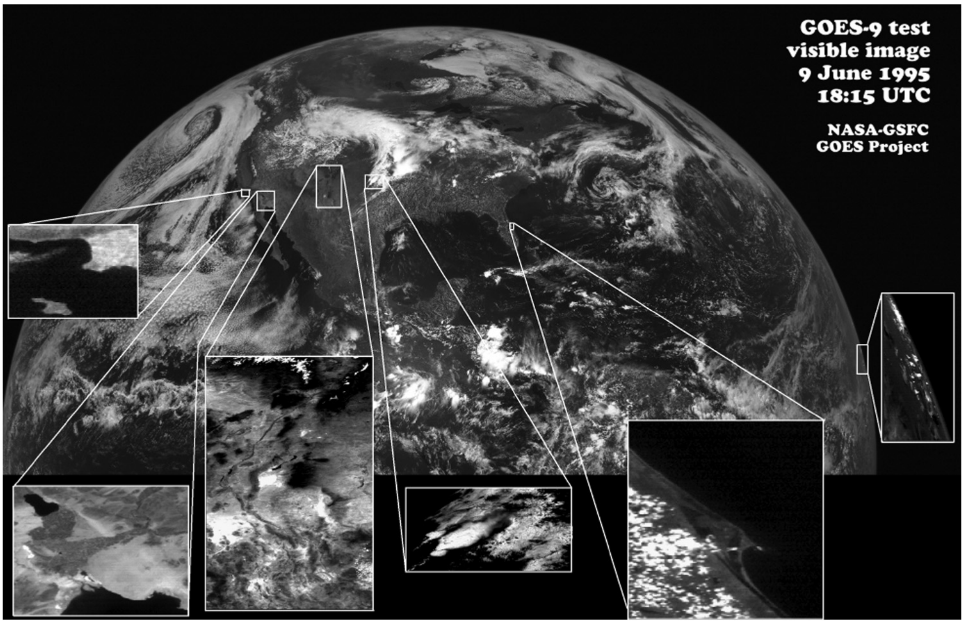

Figure 1.9 GOES-9 visible image taken on June 9, 1995 at 18:15 UTC. Image courtesy of NASA-Goddard Space Flight Center, with data from NOAA GOES.[9]

taken in daylight in the western hemisphere. The solid earth is hotter than the oceans during the day and thus appears dark, particularly over the western United States. The drier western states, with less vegetation, are hotter than the eastern side of the country.

The earth's atmosphere decreases monotonically in temperature with altitude within the troposphere (the region with weather), and the cloud temperatures vary along with the ambient atmosphere. The character of infrared emission varies in wavelength with temperature, so the apparent color of the clouds in this presentation reflects cloud temperatures and therefore height.

1.2.2 Earth resources systems: 30-m pixels

Classic earth resources satellites provide ground resolution at the 20–40-m pixel level. This is true for both optical and radar systems, illustrated here. These systems are typically designed to provide synoptic views of the earth at roughly two-week intervals—the period of time necessary to cover the earth at a 30-m resolution from low-earth orbit with technologies from the 1970–2000 time period.

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[9] http://goes.gsfc.nasa.gov/pub/goes/goes9.950609.1815.vis.gif.

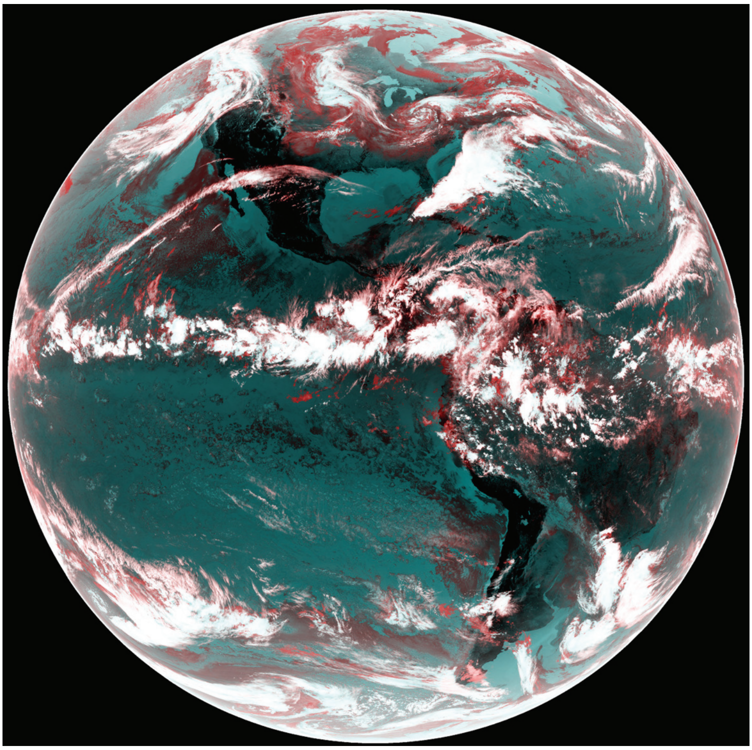

Figure 1.10 GOES-15 infrared imagery taken April 26, 2010 at 17:30 UTC. This is the "first light" image for the GOES-15 infrared sensors. The composite is made by using the 3.9-μm infrared channel (G, B) and the long-wave infrared channel at 11 μm (R). The cloud colors provide information about their height (which corresponds with temperature) and water content. Here, higher-altitude clouds are colder and appear white.[10] Related views are shown in Fig. 8.15.

1.2.2.1 Landsat 7 (30 m), San Diego

Multiple-wavelength (or multispectral) images are most commonly applied to earth resources. Landsat has been the flagship system for earth-resources studies for over four decades. The low-earth orbiting satellites image the whole earth once every sixteen days. The Enhanced Thematic Mapper Plus (ETM+) sensors provide 30-m-resolution imagery in seven spectral bands.[11] The image in Fig. 1.11 was taken from three visible-wavelength sensors and combined to make a "true" color image. The figures show one complete Landsat scene. Figure 1.12 shows a small segment covering San Diego

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[10] http://www.nasa.gov/mission_pages/GOES-P/news/infrared-image.html; http://goes.gsfc.nasa.gov/text/goes15results.html.

[11] Landsat 7 also offers a higher-resolution panchromatic image with 15-m pixels. The resolution for the long-wave infrared sensor on the ETM+ is only 60 m.

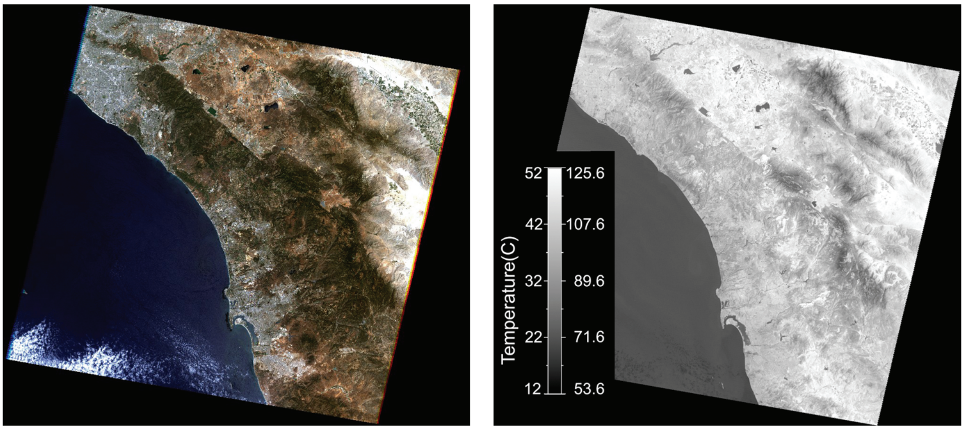

Figure 1.11 Landsat 7 image of San Diego taken June 14, 2001. The RGB "true color" image is on the left (30-m pixels), and the thermal infrared (LWIR) image is on the right. White is "hot" in this display. Temperatures are from 12–52 °C, or 53.6–125.6 °F.

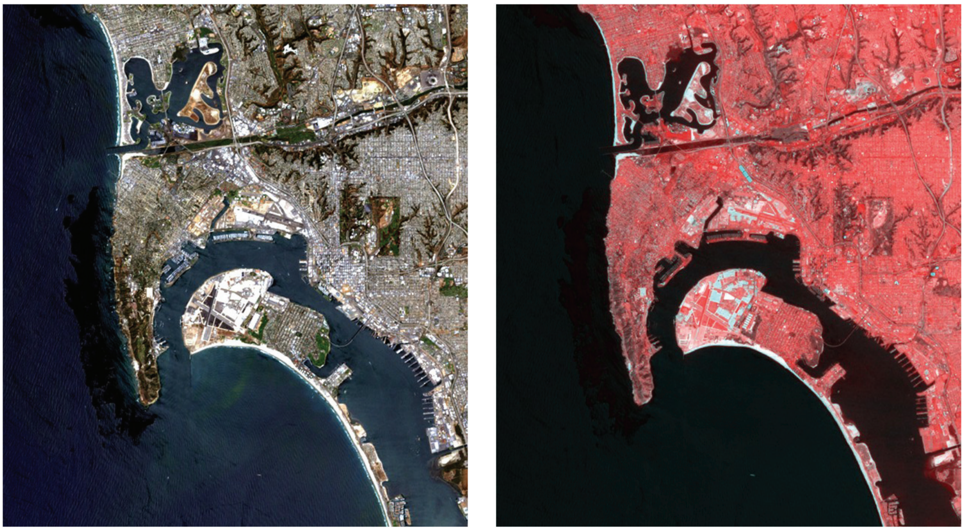

Figure 1.12 Landsat 7 image enlarged (acquired June 14, 2001 at 18:12:08.07Z), with the "true-color" image on the left and a Landsat thermal image on the right. The right image uses IR wavelengths bands 6 and 7; the red is 11 μm, and the green and blue are 2.2 μm.

harbor. Adjacent to the true color images in Figs. 1.11 and 1.12 are the corresponding LWIR images from Landsat. The 60-m-resolution sensor is the highest-spatial-resolution LWIR sensor flown to date on a civil or commercial system.

Figure 1.13 Landsat 7 panchromatic channel. The high-spatial-resolution channel for the Enhanced Thematic Mapper Plus (ETM+) has a 15-m resolution capability shown here. The Coronado Bridge starts to appear clearly. The golf course is bright because of this sensor's spectral response extends into the near-infrared (see Chapter 6).

In the visible sensor data, the Coronado Bridge is just visible crossing from San Diego to Coronado Island. Long linear features, such as bridges and roads, show up well in imagery even if they are narrow by comparison to the pixel size. Reflective infrared and thermal IR data from Landsat are shown encoded as an RGB triple on the right side of Fig. 1.12. The hot asphalt and city features are bright in the red (thermal) frequencies, whereas parks are green (cool, and highly reflective in short-wave IR).

Figure 1.13 shows the higher-spatial-resolution panchromatic channel from the ETM+ sensor. In comparison to an imager like GOES, the penalty paid for this high spatial resolution is a reduced field of view—nominally 185 km across for any image.

1.2.2.2 SSTL/DMC (30 m)

The previous illustrations were created by government systems. Beginning in the late 1990s, a remarkable change occurred as small satellite designs were flown with imaging systems. One of the most influential such systems started as an experimental effort at the University of Surrey. This effort spawned the commercial entity Surrey Satellite Technology Limited (SSTL,

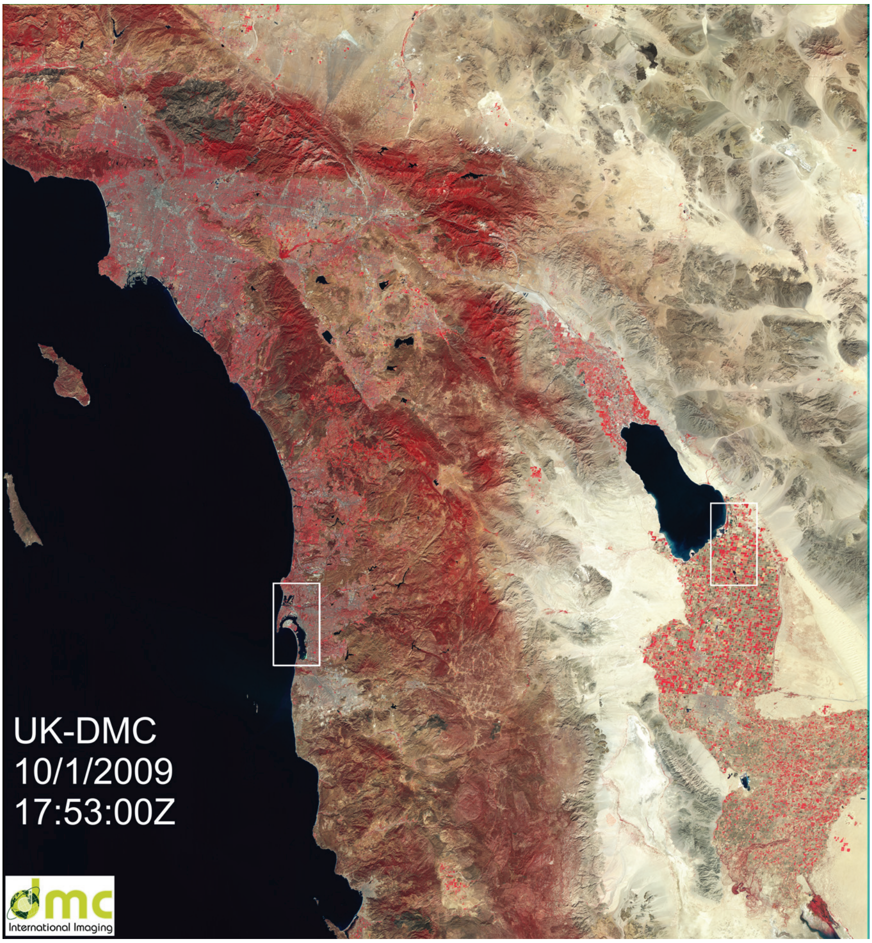

Figure 1.14 Full-frame image captured by the UK-DMC on October 1, 2009, at 17:53:00Z. The false-color "IR" image is 14400 × 15550 pixels and provides a 30-m ground sample distance (GSD). Regions that appear red have significant healthy vegetation. UK-DMC2 image, October 1, 2009 ©2016 DMCii, all rights reserved. Supplied by DMC International Imaging, U.K.

now part of Airbus).[12] SSTL has designed and flown a number of small satellites, selling many of them to countries without indigenous capabilities in this area.

Figure 1.14 shows an image of southern California and northern Mexico (Baja California), comparable to the Landsat system shown earlier in this chapter, though limited in bands (green, red, and near-infrared). This newer technology provides a much larger image area (3× in linear dimensions). The system is limited in bandwidth and collection rates, with revisit times of

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[12] Now called Airbus Defense and Space (2014).

Figure 1.15 Full-frame image captured by the UK-DMC on October 1, 2009 at 17:53:00Z. The false-color "IR" image is 14400 × 15550 pixels and provides a 30-m ground sample distance (GSD). Regions that appear red have significant healthy vegetation. UK-DMC2 image October 1, 2009, ©2016 DMCii, all rights reserved. Supplied by DMC International Imaging, U.K.

two weeks being the norm for such low-earth orbiting systems. Surrey addresses the revisit issue by providing their different customers a means to team up, formally in the Disaster Management Constellation (DMC). As the fleet grows, the revisit time drops to about a day for the ensemble of satellites.

Medium-resolution imaging systems like the DMC system are becoming practical for the support of agriculture. Figure 1.14 shows a checkerboard pattern of irrigated vegetation north and south of the Salton Sea in the middle-right portion of the image. Figure 1.15 shows a zoomed-in image of San Diego, emphasizing the similarity to the quality of the Landsat 7 data. The very bright red regions in this figure are golf courses (natural vegetation is not particularly healthy at this time of year in southern California).

The base system at this writing is focused on payloads with a 10-m resolution in the panchromatic band and 32-m resolution in the multispectral (e.g., color) bands. These robust systems cost about 10–20 million USD.

The main limitation in smaller systems is the telemetry bandwidth, which limits the overall coverage. Higher-bandwidth telemetry demands higher-power systems, and all such systems are considerably larger than the Surrey designs.

1.2.3 Higher resolution: 1–3-m ground sample distance

The launch of the IKONOS satellite in 1999 dramatically changed the world of remote sensing. For the first time, imagery comparable to that obtained from military systems was widely available to civilians. IKONOS offered 1-m-spatial-resolution panchromatic imagery, and 4-m-resolution multispectral (color) imagery. (See Fig. 4.10 for the first light image of Washington, D.C.) Since then, a fleet of high-resolution commercial systems have flown.

1.2.3.1 Worldview-3: San Diego and Coronado Island

The Worldview-3 (WV3) satellite appears to have the lead as the highest-spatial resolution systems in orbit at this point, with a 0.30-m panchromatic sensor resolution and a 1.2-m multispectral resolution. Figure 1.16 presents a color image of San Diego taken on September 6, 2014 by the Worldview-3 satellite. The color image has been pan-sharpened to a 1.2-m resolution. The Coronado Bridge (heretofore a rather tenuous, thin line in earlier illustrations) is now clearly defined, as are the many small watercraft in the harbor. Figure 1.16 includes an image chip from the panchromatic sensor of the carrier U.S.S. Midway, now a floating museum. The museum also appears in Figs. 1.18 and 1.20. There is a large collection of military aircraft on the deck. Referring back to the concepts of air and naval order of battle, it is clearly possible to count the aircraft and, in general, identify the type. Direct comparison between the Worldview satellites with systems described earlier is difficult: not only does the modern system have higher bandwidth but it also has the ability to look off-nadir (sideways), thus dramatically improving the revisit time. See if you can locate the word "Coronado" written in the sand adjacent to the Hotel del Coronado.

1.2.3.2 High-resolution airborne LiDAR

Figure 1.17 takes a close-up of Fig. 1.16 and changes modalities; laser scanner (or LiDAR) data are shown for a small patch around the Coronado hotel, including the raised sand "Coronado." The elevation is color coded with a rainbow scale: dark blue is ~2 m, and red is 25 m. The dunes are measured to be about 2 m above the base sand level (light blue/cyan against the dark blue background). The word "Coronado" is about 260 m across in length.[13]

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[13] A video shows how the dunes marker has been built up over the years, largely through the efforts of Armondo Morena, a San Diego city worker: https://www.youtube.com/watch?v=Ag5n_1CPQ7M.

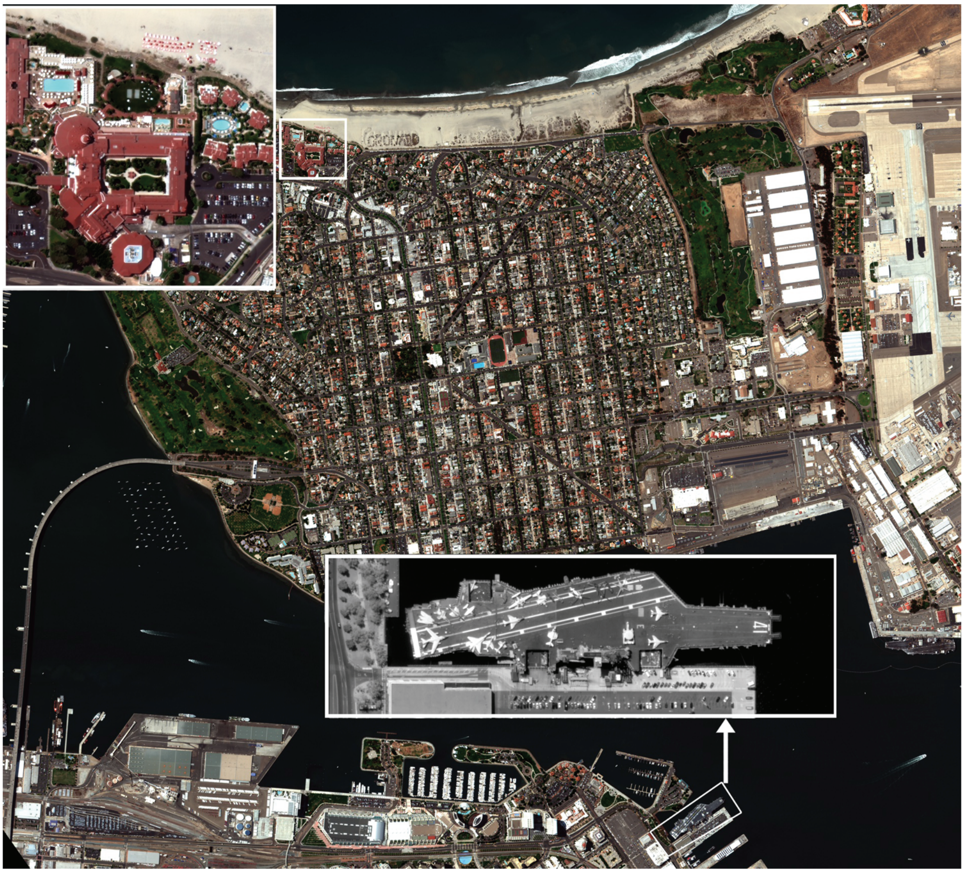


Figure 1.16 Worldview-3 image of Coronado Island, San Diego, California, 9/16/2014. North is approximately to the right, and the sun is to the upper left. The Hotel del Coronado is shown in the upper inset, and the carrier Midway is shown in the lower inset, using the higher-resolution panchromatic data (0.30-m GSD). Imagery reprinted courtesy of DigitalGlobe.

Laser scanners are extensively used for mapping and surveying, with point densities of 1–30 points/m^2 depending on the application. In the illustration here, the nominal point density is 3.5 pts/m^2, which is typical for mapping at the time of this image. The point density corresponds roughly to a ground resolution of 0.5–1.0 m.

1.2.4 High-resolution airborne imagery

Still-higher resolutions are possible, primarily from airborne platforms. Over the last few years, electronic cameras have begun to replace film cameras, but the illustration given here comes from a film system, which at the time (2004) gave the highest quality data. Figure 1.18 shows a flight over San Diego harbor using a film system, with resolution of better than 1 foot. The relatively

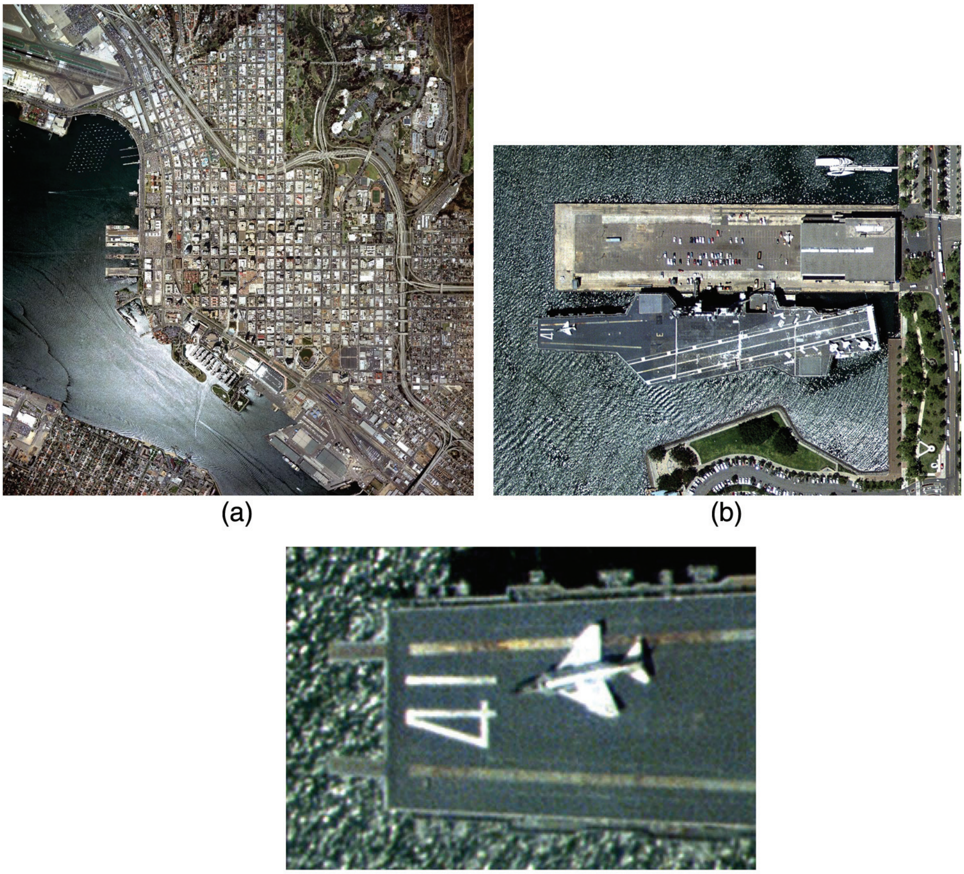
Figure 1.17 Image of Coronado Island, San Diego, California with LiDAR data from USGS. The sensor used was an Optech, Inc. Airborne Laser Terrain Mapper (ALTM) 1225. The LiDAR data were collected on March 24–25, 2006. The following settings were used for these flights: 25-kHz laser pulse rate, 26-Hz scanner rate, ±20° scan angle, 300–600-m AGL altitude, and 95–120-kts ground speed.

large image size (> 400 megapixels) is a consequence of the relatively large area being imaged at high resolution. Modern digital cameras used for airborne mapping are frequently operated to image at a 4–6-inch GSD.

1.2.5 Synthetic aperture radar (SAR)

Beginning with the launch of RADARSAT-2 at the end of 2007, a small fleet of high-spatial-resolution radar satellite systems have gone into orbit. RADARSAT-2 offers C-band (6-cm wavelength) imagery at resolutions of 1–3 m, whereas the German TerraSAR-X, Italian Cosmo SkyMed, and Israeli TecSAR systems offer a 1-m resolution or better in the X-band (3-cm wavelength). Figure 1.19 shows the RADARSAT-2 data for San Diego. Ships become fairly obvious at these spatial resolutions, and radar provides an important tool for maritime domain awareness. The carriers docked at Coronado Island are obvious at this resolution.

The concluding imagery examples come from the German TerraSAR-X satellite. Within the last year, the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, or DLR) has been licensed to collect data at a resolution as fine as 25 cm. Data from the San Diego area are shown here in Fig. 1.20. The overall observable area is reduced at this resolution (about 3 × 5 km), but the spatial resolution is remarkable. A subset of the data taken on August 24, 2015 at 01:50:58 Z (approximately dusk local time) are shown, with the U.S.S. Midway again illustrated at a higher magnification.



(a) (b)

(c)

Figure 1.18 The images shown here are from an aerial photograph taken over San Diego harbor in 2004: (a) the full frame, (b) a small chip from the 21,000- × 21,000-pixel image scanned from the film image, and (c) a further zoomed-in view of the 1.3-gigabyte file. The resolution is between 6 and 12 inches. Notice the glare on the water and how the wind-driven water waves show from above. The carrier is the U.S.S. Midway, part of an exhibit at the San Diego Maritime Museum.[14] Images reprinted with permission from Lenska Aerial Images.

In closing, let us return to space situational awareness, or Sat^2. Figure 1.21 shows a synthetic aperture radar image of the International Space Station (ISS) taken by the German TerraSAR-X system while the Space Shuttle Endeavor was docked. Smooth surfaces such as solar arrays tend to reflect energy away from the radar system and appear as though they are transparent (dark). Corners and edges provide most of the reflections.[15]

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[14] http://www.navsource.org/archives/02/41.htm.

[15] http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts123/multimedia/fd15/fd15_gallery.html; http://www.dlr.de/en/desktopdefault.aspx/tabid-6840/86_read-22539/.

Figure 1.19 RADARSAT-2 image collected at 3-m resolution on 5/5/2009. Polarization is HH. Elements of the scene are well captured by radar, others less so. The Coronado Bridge shows up clearly, as do the air fields due to their absence of reflection. Systems such as RADARSAT-2 have nearly daily access to mid-latitude and high-latitude targets. RADARSAT-2 data © Canadian Space Agency and MacDonald, Dettwiler and Associates Ltd, 2009, all rights reserved.

1.3 Three Axes

The sequence of images presented in this chapter illustrate a few of the different imaging modalities (visible, infrared, radar, LiDAR) and introduce the decline in area coverage that comes from increased spatial resolution. There is a basic conflict between resolution and field of view: image a larger area, and the result will (generally) have a lower spatial resolution. Going beyond the spatial dimension, there are, in practice, three dimensions associated with remote sensing imagery: spatial, spectral, and temporal. Figure 1.22 illustrates these three dimensions, which define competing requirements for design and operation. You can have high spatial resolution and global coverage but only at low temporal coverage (like Landsat, which provides decent pictures only once every 16 days or so). You can have high temporal coverage (like GOES, which processes once every 30 minutes), but then the spatial resolution is only 1 km. In order to achieve spectral coverage (multispectral or hyperspectral), the other dimensions will suffer a corresponding penalty.

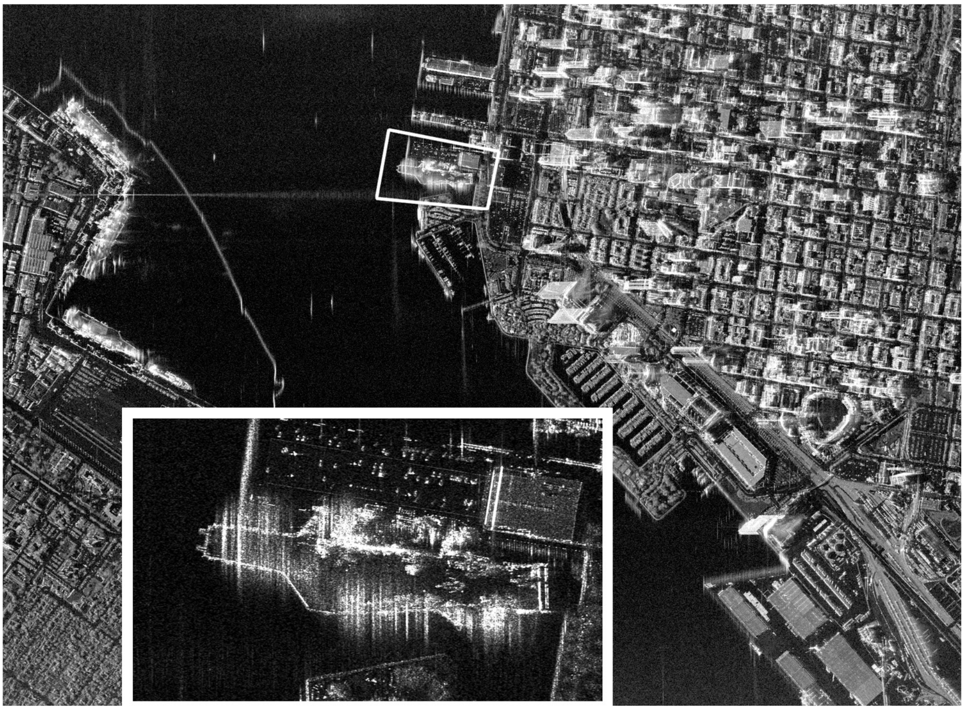

Figure 1.20 TerraSAR-X sub-meter imaging. The buildings have a peculiar look due to the specular reflection of energy back to the satellite. Visible here besides the U.S.S. Midway are three Nimitz-class carriers docked at North Island and the baseball stadium for the San Diego Padres. The small streaks in the water are from smaller boats moving rapidly through the scene. The resolution appears to be a bit better than 25 cm. By comparison to the WV3 and airborne illustrations presented earlier, the aircraft on the deck of the Midway appear to have vanished. In the inset image, cars are detectable in the parking lot to the north of the Midway.

A fourth axis, polarization, has been an important term for passive and active radar systems, and it has started to appear in the optical remote-sensing community as an additional dimension of information.

1.4 Resources

There are some classic and modern remote sensing textbooks to note:

- The classic text—*Fundamentals of Remote Sensing and Airphoto Interpretation*, by Thomas Eugene Avery and Graydon Lennis Berlin—is rather dated even in its 5th edition (1992), but it is still a great reference with many illustrations.
- *Remote Sensing of the Environment: An Earth Resource Perspective*, 2nd edition, published in 2006 by John R. Jensen, is an excellent book by one of the top people in remote sensing.

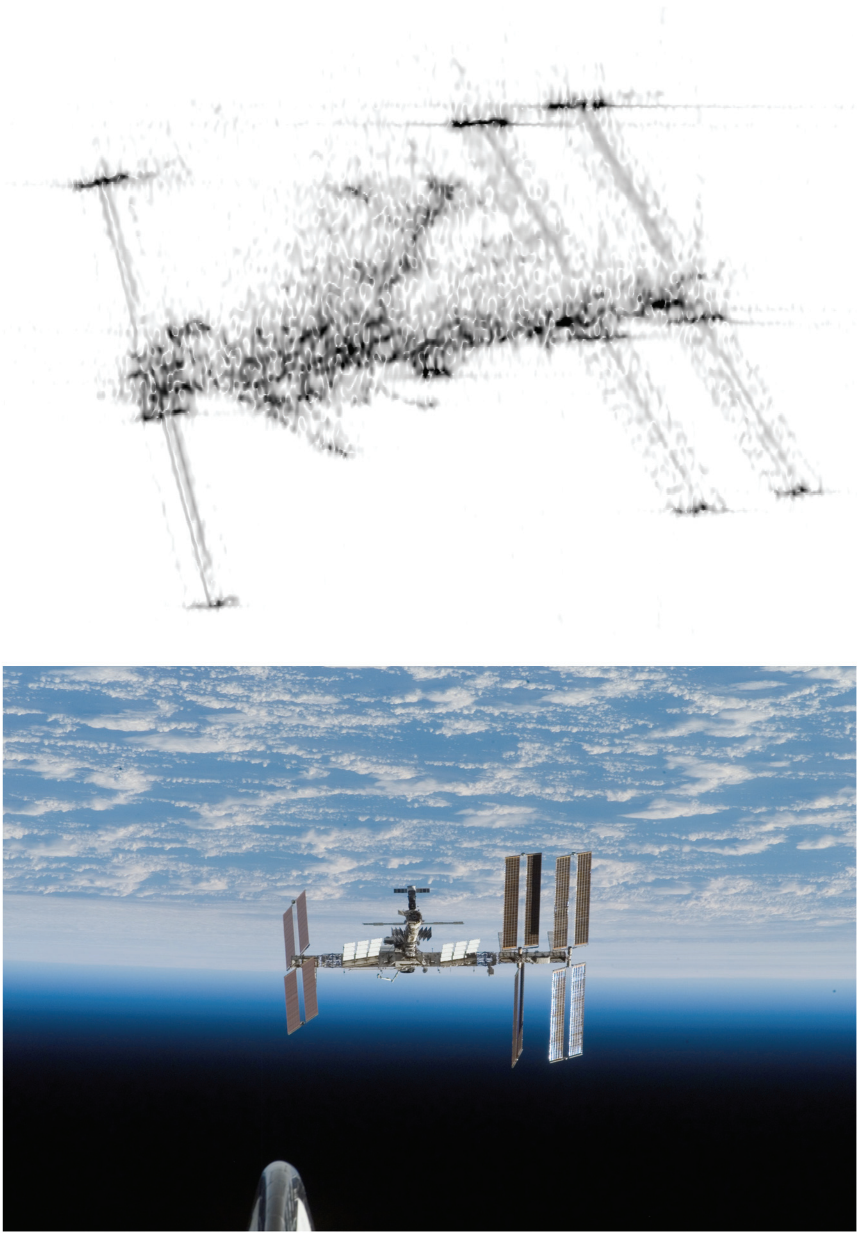

Figure 1.21 TerraSAR-X image of the International Space Station (ISS), collected on March 13, 2008 (~1325Z). TerraSAR-X passed the ISS at a distance of 195 km and at a relative speed of ~9.6 km/s. The resolution is about one meter, obtained in a 3-s exposure. The image grayscale is inverted (dark indicates stronger returns). The size of the ISS is roughly 110 m × 100 m × 30 m. The Space Shuttle Endeavour was docked at this time, so it is in the image. The lower image is taken from STS-123 as it departed on March 24. Reference NASA image S123E010155.[16]

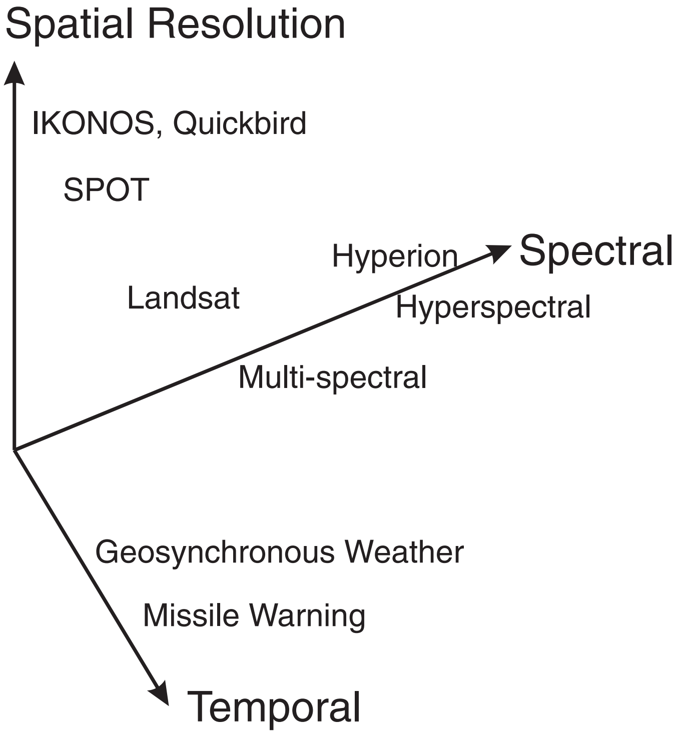

Figure 1.22 Three dimensions for remote sensing.

- *Introduction to the Physics and Techniques of Remote Sensing*, 2nd edition, published in 2006 by Charles Elachi and Jakob J. van Zyl, updates the classic 1987 textbook by one of the most influential radar scientists of the modern era.
- *Remote Sensing and Image Interpretation*, by Thomas M. Lillesand, Ralph W. Kiefer, and Jonathan W. Chipman (2007), is a classic text, now in the 6th edition.
- *Remote Sensing, Principles and* Interpretation, 3rd edition, is a fairly geology-oriented, but still excellent text by Floyd F. Sabins (2007).
- *Physical Principles of Remote Sensing*, by W. G. Rees, has a new (3rd) edition, published in 2013, that extends into geophysical topics not addressed here. Good physics extending beyond the level taught here.
- *Introduction to Remote Sensing*, by James B. Campbell, provides a good qualitative view of remote sensing, without equations. Now in its 5th edition (2011).

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16. TerraSAR-X image of the month: The International Space Station (ISS); news release dated: 4 March 2010. Image acquired 13 March 2008, image #SWE1-E1058981, http://www.dlr.de/en/desktopdefault.aspx/tabid-6215/10210_read-22539/10210_page-4/.

- By far the best book on the topic of data analysis is *Remote Sensing Digital Image Analysis: An Introduction*, by John A. Richards, 5th edition (2012).

1.5 Problems

1. List 5–10 elements of information that could be determined for NOB from imagery. Typical main elements are battle group, ships, submarines, ports, weather, personnel, C3, and medical.
2. What wavelengths of EM radiation are utilized in the images shown in this chapter? (This is really a review question, best answered after completing Chapter 2.)
3. Construct a table/graph showing the relationship between the ground resolution and area of coverage for the sensors shown in this chapter. (Also a review question.)
4. Compare the various images of San Diego Harbor. What are the differences in information content for the highest-resolution systems (e.g., IKONOS), the earth resources system (Landsat, visible, and IR), and the radar system. Which is best for lines of communication? Terrain categorization? Air order of battle? NOB?