Chapter 2
Data Acquisition

As noted in Chapter 1, remotely sensed data are collected by a diverse array of passive and active sensors mounted on aircraft (including airplanes, helicopters, and uninhabited aerial systems) or spacecraft (usually satellites). During the latter half of the twentieth century, large-scale space programs such as National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) were primarily responsible for the development of new remote sensing technologies. Such programs remain key sources of technological innovations, but the expansion of commercial remote sensing has contributed greatly to the proliferation of sensors that provide high-quality data for a variety of applications. The main goal of this chapter is to provide an overview of the types of sensors currently available to analysts, including details about the data they acquire and some of their potential applications. Prior to this discussion, we first introduce the concept of *resolution* in remote sensing. One common definition of resolution is the ability to discern individual objects or features in a captured image or in the "real world." In this context, it is related to the concept of *scale* as used by cartographers: a large-scale map—whether constructed from remote sensing imagery or other geospatial data sources—shows more details than a small-scale map, thus making it possible to discern smaller objects or finer features. Nevertheless, the term resolution also relates to several other aspects of remotely sensed data. We illustrate these aspects with examples of commonly used satellite sensors and imagery.

2.1 Data Resolution

When we talk about "remotely sensed data," we are usually referring to digital images (i.e., two-dimensional arrays of pixels). These data are typically described by four types of resolution: *spatial, spectral, temporal,* and *radiometric*. *Spatial resolution,* which corresponds most closely to the definition of resolution provided in the preceding paragraph, is a measure of the clarity or fineness of detail of an image. For digital images, this translates to the ground area captured by a single

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image pixel; because pixels are typically square, resolution is generally expressed as the side length of a pixel. *Spectral resolution,* represented by the width of the wavelength interval and/or the number of spectral channels (or *bands*) captured by a sensor, defines the storage of recorded electromagnetic energy and the sensor's ability to detect wavelength differences between objects or areas of interest. The amount of time it takes for a sensor to revisit or reimage a particular geographic location is referred to as its *temporal resolution*. Finally, the sensitivity of a sensor to incoming electromagnetic energy (i.e., the smallest differences in intensity that the sensor can detect) is known as its *radiometric resolution*. This metric is usually expressed in terms of binary bit-depth (Jensen 2005), which refers to the number of tonal levels at which data for a given spectral band are recorded by a particular sensor. Digital images, like other forms of digital data, are stored as bits (i.e., 0 s and 1 s), so a sensor's bit-depth defines the number of unique values, on a binary scale, at which the incoming data can be stored for a pixel. This number is equal to 2^n, where n is the stated bit-depth. For example, a bit-depth of 3 means that incoming data can be stored as one of the eight unique values: 000, 001, 010, 011, 100, 101, 110, and 111. The binary bit-depth of most contemporary sensors is at least 8-bit, meaning that image pixels have at least 256 (0–255) possible values.

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

Spatial Resolution The ability to discern spatial structure is an important element of any remote sensing analysis. It is only in recent years that satellite imagery has supplanted aerial photography as the primary image data source for analyses such as the classification of urban land use (Barr and Barnsley 2000). In an urban landscape, surface features such as roads, office buildings, parks, and residential neighborhoods comprise a mosaic, where many small constituent units or pieces are interspersed by a few large ones. Roads and buildings are typically some of the smallest of these units. When viewed from above (e.g., from an airplane), the net visual effect of these units is an aggregate patchwork of various land uses and cover types, but the degree of patchwork detail portrayed by a remotely sensed image, and thus the level of specificity at which it can be classified, depends on its spatial resolution (Fig. 2.3). For example, a 30-m pixel (i.e., the spatial resolution provided by several sensors listed in Table 2.1) stores one digital number per spectral band of

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

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

Table 2.1 (continued)

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

Table 2.1 (continued)

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

Table 2.1 (continued)

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

Table 2.1 (continued)

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

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

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

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

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

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

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

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

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

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

Table 2.1 (continued)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

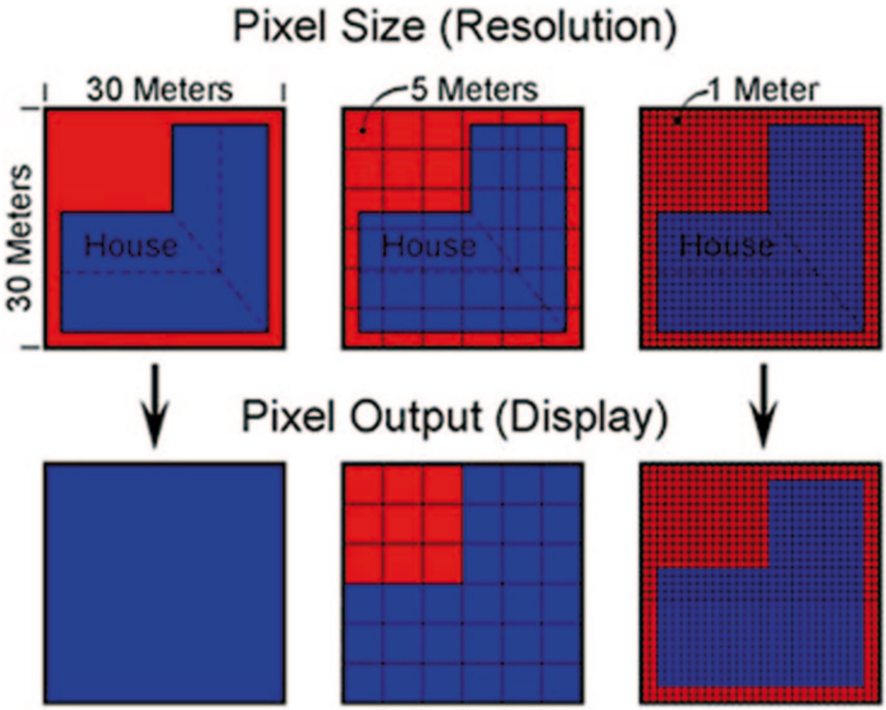

Fig. 2.1 An illustration of spatial resolution as it relates to pixel size. (Image courtesy of the EU Science Education through Earth Observation for High Schools (SEOS) Project and Satellite Imaging Corporation. (Source: www.seos-project.eu/modules))

information for any landscape feature smaller than 900 m^2. The pixel could, in fact, accommodate 6 one-story square houses, each having a 1500 ft^2 (139 m^2) footprint. In contrast, an Advanced Very High Resolution Radiometer (AVHRR) pixel, with its 1100-m resolution (see Table 2.1), could incorporate more than 8700 of these houses, if arranged regularly. Increases in spatial resolution have been a persistent trend in sensor innovation. Within a decade of the 1986 launch of the first SPOT satellite, whose 10-m panchromatic spatial resolution opened up new land cover mapping possibilities, space agencies in Japan, India, and Europe had produced satellites with finer spatial resolutions than any of the first five Landsat satellites. The latest generation of commercial satellite ventures, including Pléiades 1A and 1B, as well as WorldView-2 and WorldView-3, all provide spatial resolutions of 1 m or less.

Figure 2.1 is an illustration of the spatial resolution of a house as related to pixel size. The size of a pixel determines its spatial resolution (Khorram et al. 2012a, b), which in turn determines the degree of recognizable detail in an image. A practical example of four spatial resolutions of the same area is shown in Fig. 2.2, while Fig. 2.3 is a comparative example of Landsat ETM+ (30-m resolution) and QuickBird (fused at 0.8-m) images of Paris, France. Figure 2.3 demonstrates that the

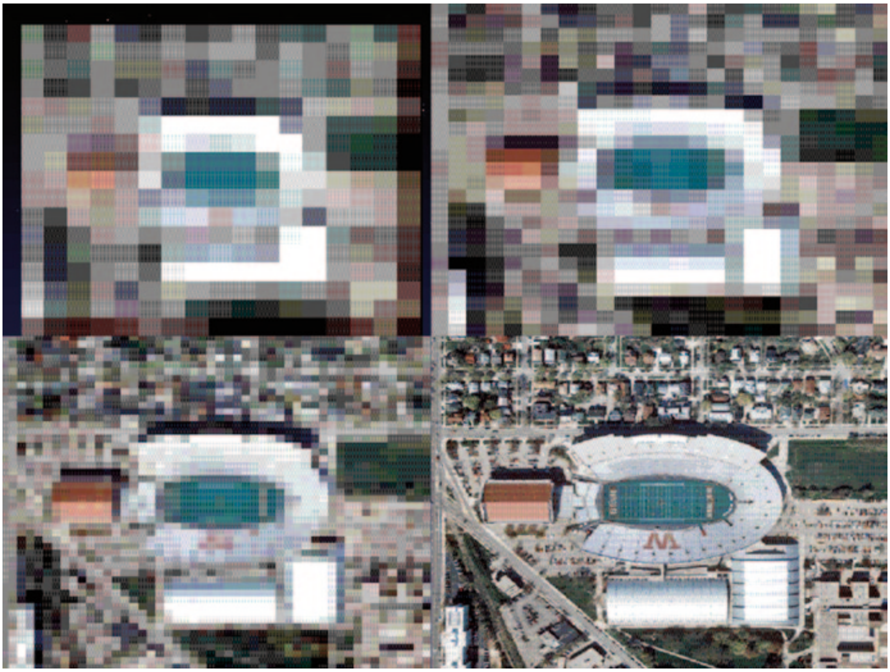

Fig. 2.2 Example images showing the University of Wisconsin stadium at different spatial resolutions: 30 m *(top left),* 20 m *(top right),* 10 m *(bottom left),* and 1 m *(bottom right)*

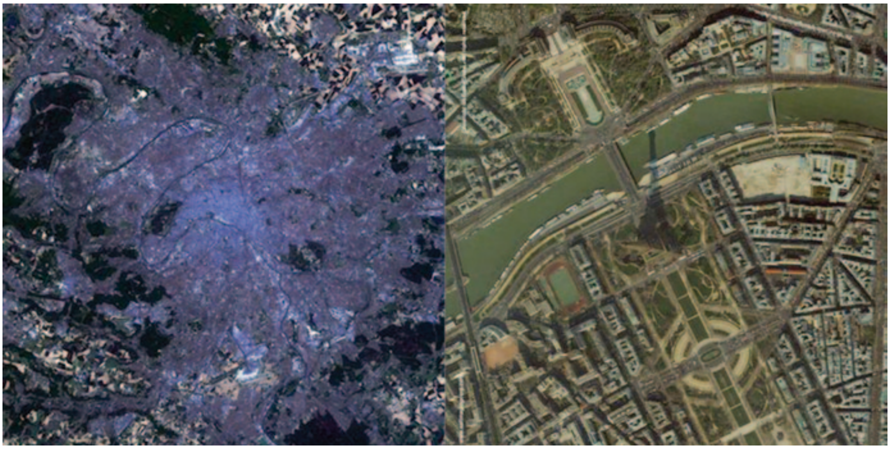

Fig. 2.3 Comparison of Landsat ETM+ *(left)* and QuickBird *(right)* images of Paris, France. (Image courtesy of the EU Science Education through Earth Observation for High Schools (SEOS) Project, Landsat, and GeoEye (now DigitalGlobe))

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