4 Urban Observing Sensors

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4.1 INTRODUCTION

Urban land cover (ULC) has a considerable impact on local, regional, and global environmental change, and has significant ecological, biophysical, social, and climatic effects (Seto and Shepherd, 2009; DeFries et al., 2010). These effects are further amplified by the temporal duration of urban changes that tend to last for decades and are often irreversible. Optical sensors on board various satellite platforms play a significant role in urban monitoring and assessment. Two representative examples are indicative of the importance of optical sensors. First, since 2009 after USGS made the Landsat archive freely available, a 60-fold increase was observed in data downloads (NASA, 2013). Second, in the last decade, there has been a strong interest from the commercial sector to launch satellite optical sensors. This interest is clearly driven by the constantly increasing demand for such products from governmental, military, nonprofit, and commercial sectors.
Remote sensing thermal infrared (TIR) data have been widely used to retrieve land surface temperature (LST) (Quattrochi and Luvall, 1999; Weng et al., 2004). A series of satellite and airborne sensors, such as HCMM, Landsat TM/ETM+, AVHRR, ASTER, TIMS, have been developed to collect TIR data from the Earth’s surface. In addition to LST measurements, these TIR sensors may also be utilized to obtain emissivity data of different surfaces with varied resolutions and accuracies. LST and emissivity data have been used in urban climate and environmental studies, mainly for analyzing LST patterns and their relationship with surface characteristics, assessing urban heat island (UHI), and relating LSTs with surface energy fluxes for characterizing landscape properties, patterns, and processes (Quattrochi and Luvall, 1999). Remotely sensed TIR data are a unique source of information to define surface heat islands, which are related to canopy layer heat islands. In situ data (in particular, permanent meteorological station data) offer high temporal resolution and long-term coverage but lack spatial details. Moving observations overcome this limitation to some extent but do not provide a synchronized view over a city. Only remotely sensed TIR data can provide a continuous and simultaneous view of a whole city, which is of prime importance for detailed investigation of urban surface temperature. Generally speaking, the application of TIR data has been limited in urban surface energy modeling (Voogt and Oke, 2003). Previous works have focused on the methods for estimating variables related to energy driving forces, soil moisture availability, and vegetation–soil interaction from satellite remote sensing data, but little has been done to estimate surface atmospheric parameters (Schmugge et al., 1998). These parameters are measured in the traditional way in the network of meteorological stations or in situ field measurements.

Traditional urban remote sensing studies did not make use of synthetic aperture radar (SAR) data, mainly because of issues in their interpretation. SAR sensors are active imaging systems that use runtime length and intensity of a transmitted microwave pulse for generating a consistent image. The appearance of objects and surfaces in radar images is dominated by geometric properties (imaging and object geometry, surface roughness) rather than by their chemical or biophysical characteristics (as in the case of optical data). In the geometrically highly structured urban landscape, the complex interaction of the radar pulse and the small-scale urban features leads to certain ambiguities in the received signal. Hence, especially for very high resolution (VHR) SAR, urban imagery lacks clarity. For example, there are distortions and shadow regions, which limit the capability for certain applications such as the exact delineation of buildings or other urban infrastructural elements. Moreover, the appearance of identical urban spots or objects might differ significantly depending on the imaging geometry of the data acquisition. Nevertheless, the basic phenomena affecting backscattering from man-made structures have been extensively discussed (Guida et al., 2008), with a focus not only on clearly defining mapping limitations but also on discovering very important applications, such as differential interferometry and persistent scatterers (Ferretti et al., 2001). The three-dimensional (3D) capabilities of SAR systems have also been analyzed with respect to urban areas to quantify flood risk, and their all-weather data availability is invaluable in managing catastrophic events, both at local and global scales. Therefore, notwithstanding the issues highlighted earlier, after the seminal paper
by Henderson and Xia in 2001, summarizing the relatively few achievements at that point, urban remote sensing using SAR has been flourishing, with applications from urban extent extraction (Gamba et al., 2011) to detailed ULC mapping (Hu and Ban, 2012), urban change detection (Bovolo and Bruzzone, 2005), and 3D building characterization (Soergel et al., 2009), including road network extraction (Hedman et al., 2010) and damage detection at both the block (Dell’Acqua et al., 2011) and the building levels (Bovolo et al., 2012).

4.2 OPTICAL SENSORS

4.2.1 COARSE SPATIAL RESOLUTION OPTICAL SENSORS

Regional, continental, and global changes in urban land cover/use have been monitored using optical data with coarse spatial resolution (>100 m), such as NOAA advanced very high resolution radiometer (AVHRR) and terra moderate resolution imaging spectroradiometer (MODIS). The AVHRR sensor was first launched by the satellite TIROS-N in November 1978 and then by the NOAA series, which started with NOAA-6 in June 1979 and continued with NOAA-7 through NOAA-19 between 1981 and 2009 (NOAA, 2013). All satellite series launched before 2001 have ended their missions while NOAA-15 through -19 are still in operation. The MODIS sensor on board the Terra satellite was launched in December 1999 as part of NASA’s Earth Observing System. It still acquires images although the life expectancy of Terra was designed for 6 years. AVHRR has five spectral bands targeting the wavelengths of red, NIR, and three TIR bands, with primary use of cloud, snow, ice, vegetation, cloud and surface temperature mapping, and land/water interface and hot target monitoring. MODIS has 36 spectral bands ranging from wavelengths of visible to shortwave and TIR, with primary use of land, cloud, vegetation, sediment, cloud and surface temperature mapping, chlorophyll, atmospheric properties, cloud fraction and height derivation, and forest fire and volcano monitoring. AVHRR acquires images of the entire Earth twice a day with a spatial resolution of approximately 1.1 km at the satellite nadir, while MODIS covers the entire surface of the Earth every 1–2 days with a spatial resolution of 250 m (bands 1–2), 500 m (bands 3–7), and 1 km (bands 8–36). Radiometric resolution is 10 bits for the AVHRR data and 12 bits for the MODIS data. The NOAA series are sun-synchronous, polar-orbiting satellites at 830–870 km above Earth, having 2500 km in swath width, while MODIS on board sun-synchronous, near-polar orbiting satellite acquires images at an altitude of 705 km at 10:30 a.m. local time in descending node (Terra) or 1:30 p.m. in ascending node (Aqua), and a swath width of 2330 km (NASA, 2013; NOAA, 2013).

It has been a challenge to apply the coarse-resolution remotely sensed data for urban observation and monitoring due to its limited spatial resolution (Schneider et al., 2003), yet it has proven useful for climatic studies due to its high temporal frequency and large spatial coverage (Gallo et al., 1993; Jonsson, 2004; Stathopoulou and Cartalis, 2009). Therefore, the effectiveness of urban studies has been dependent upon the fusion of AVHRR data with either finer spatial resolution images such as Landsat TM (Stathopoulou et al., 2004) or continuously observed meteorological (ground)
data (Bengang and Shu, 2000; Ji and Peters, 2004; Stathopoulou et al., 2006). A major advancement for using coarse-resolution data in urban observation was initiated by the launch of NASA’s Terra platform and specifically MODIS. The improved spectral resolution allows monitoring ecosystem processes across multiple scales (Stefanov and Netzband, 2005) and has resulted in a range of applications, including urban land use/land cover changes (Netzband and Stefanov, 2004; Clark et al., 2012), heat island studies (Schwarz et al., 2011), and vegetation phenology (Zhang et al., 2003). Another main application area has been in air quality monitoring to assess aerosol optical depth over urban areas (Hutchison et al., 2005) and to investigate particulate matter in aerosols during transboundary events, and again in combination with ground-based data (Engel-Cox et al., 2004; Alam et al., 2010, 2011).

Data fusion techniques can be applied to fusing coarse spatial resolution imagery with either finer spatial or spectral resolution remotely sensed data or both depending on the study objective. Alternative finer spatial resolution data are not limited to Landsat (Xu et al., 2006; Michishita et al., 2012a), ASTER (Xu et al., 2004), IKONOS (Xu et al., 2003), or aerial photographs (Wu et al., 2006). Finer spectral resolution data such as EO-1 Hyperion imagery with more than 200 bands (Xu and Gong, 2008) can also be combined with the coarse-resolution data in similar ways using spectral fusion models (Xu and Gong, 2007). Data fusion algorithms usually work on surface reflectance and NDVI that requires a smoothing procedure before the MODIS NDVI time series can be reconstructed for various applications (Jin and Xu, 2013). MODIS data that have been used to perform classification for urban areas resulted in confusion between urban and barren areas (Schneider et al., 2003). Few studies have attempted to develop algorithms that can optimize the potential of MODIS for urban area mapping (Schneider et al., 2009). Most of the studies that use MODIS data necessarily consider a combination with other image data or ancillary information. For example, Langer et al. (2007) fused MODIS and Landsat to monitor land cover changes, whereas Kasimu and Tateishi (2008) combined MODIS with population statistics and meteorological data for urban area mapping across the globe. It is concluded that although coarse-resolution data is advantageous because of frequent temporal acquisition and large spatial coverage for rapid large-scale observation and monitoring of urban areas, its ability to produce accurate information independently is limited. Therefore, these data sets produce robust results if combined with other data sources using appropriate fusion algorithms (Michishita et al., 2012b,c).

4.2.2 MEDIUM SPATIAL RESOLUTION OPTICAL SENSORS

There is strong demand for historical and current ULC information over large geographic areas. The Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors have spatial and spectral characteristics that are well suited for characterizing terrestrial ecosystem features, including the highly heterogeneous features of ULC. Landsat TM and ETM+ sensors that have spatial resolution of 30 m for visible, near-IR, and shortwave infrared (SWIR) bands provide consistent and repetitive observations that are suitable for monitoring dynamics of ULC. In addition, TM and ETM+ data have been systematically acquired for large portions of
the globe since the launch of Landsat 5 in 1984, and thus a rich archive is available for analysis. These data sets have been widely used to monitor ULC change at local and regional scales (Small, 2003; Maktav et al., 2005; Potere et al., 2009; Weng and Lu, 2009).

Urban extents and structures cannot be clearly determined by using discrete classification methods along with medium-resolution remote sensing data, in part because of highly heterogeneous features of ULC. Most urban areas, especially in single-house development areas, exhibit subpixel characteristics that mix impervious surface with other land covers (e.g., grass) in medium-resolution satellite imagery (Lu and Weng, 2004). However, by treating the urban landscape as a continuum such as percent impervious surface (PIS) while using modeling techniques to extract urban characteristics, the continuous field estimate of PIS derived from satellite data can serve as a surrogate to determine urban extent and infrastructure and to assess changes in the urban environment (Powell et al., 2007; Xian et al., 2008). The USGS National Land Cover Database (NLCD) has produced land cover and impervious surface products by using Landsat as the primary data source, and the PIS product has been used to assess the extent of urban development and associated ecological effects in the conterminous United States (Imhoff, 2010; Xian and Homer, 2010; Xian et al., 2011, 2012). Figure 4.1 shows the distribution of impervious surface in the conterminous United States in 2006. The figure further provides details of impervious surface change from 2001 to 2006 in two metropolitan areas: Los Angeles, California, and Atlanta, Georgia. The spatial patterns and new growths of ULC between the two times are displayed. The Landsat data continuity mission (LDCM) that was launched on February 11, 2013, will ensure the continued acquisition of Landsat-like data. LDCM will continue to provide valuable medium-resolution data and imagery that will be consistent with current standard Landsat data products.

Like Landsat, the SPOT (Système Pour l’Observation de la Terre) program initiated by the French government in the 1970s has been designed to provide long-term data continuity with successive improvements in sensor performance. SPOT-5 is a current popular choice for medium-resolution sensors. Launched on May 3, 2002, in addition to other sensors, SPOT-5 carries two high-resolution geometric (HRG) instruments with increased spatial resolution (compared to its predecessors) of 2.5 or 5 m in the panchromatic (0.48–0.71 μm); 10 m in the green (0.50–0.59 μm), red (0.61–0.68 μm), and near-IR (0.78–0.89 μm); and 20 m in the mid-IR (1.58–1.75 μm) bands. Images have an 8-bit radiometric resolution. The satellite flies in a sun-synchronous orbit with an altitude of 822 km, an inclination of 98.7°, and a 26-day repeat cycle. SPOT-5, due to its increased spatial resolution compared to Landsat (especially in the panchromatic band), has been extensively applied for ULC classification (e.g., Zhang et al., 2003) and building/settlement extraction in urban sprawl areas (e.g., Durieux et al., 2008; Rhinane et al., 2011). Meanwhile, SPOT-5 multispectral data at 10 m resolution were also employed in studies of suburban mapping and urban land use change detection (e.g., Deng et al., 2009; Yang and Wang, 2012). The SPOT-5 imagery was also used for urban road mapping (Couloigner et al., 1998). The latest addition to the SPOT family is SPOT-6, which was launched on September 9, 2012. SPOT-6 has an increased potential for urban-related applications due to the even higher spatial resolution.
FIGURE 4.1  (See color insert.) Impervious surface over the conterminous United States in 2006. The lower panels from left to right are the maps of 2001 impervious surface and 2006 new impervious surface in Los Angeles, California, and those in Atlanta, Georgia.
Another commonly used medium-resolution satellite sensor for urban studies is the advanced spaceborne thermal emission and reflection (ASTER) radiometer, which is being flown on the Terra platform since December 1999. ASTER consists of three instrument subsystems: visible and near-infrared (VNIR) with three spectral bands and stereoscopic band of 15 m resolution, SWIR with six spectral bands of 30 m resolution, and TIR with five spectral bands of 90 m resolution. Ground track repeat cycle is 16 days though observations are operated on demand. The 15 m spatial resolution of VNIR sensor makes ASTER data valuable in extracting urban objects (Small, 2005) and mapping impervious surface (Weng and Hu, 2008; Orenstein et al., 2011) and ULC (Zhu and Blumberg, 2002; Lu and Weng, 2006). The SWIR detectors are not functioning since April 2008 due to anomaly of SWIR detector temperatures.

Like other optical sensing systems, Landsat, SPOT, and ASTER have their limitations. They are highly restricted by weather conditions, such as clouds, haze, snow, and ice covers. Some approaches have been introduced to reduce these limitations. For example, the synergistic use of SPOT-5 multispectral imagery and SAR remote sensing data has been proposed to map impervious surfaces at the subpixel level, and notable improvements were achieved in comparison to using SPOT imagery exclusively (Leinenkugel et al., 2011). Similarly, the combination of ASTER data with other data sources can be a key technique for extending applications of ASTER data to urban areas around the world (e.g., Miyazaki et al., in press), where a large city is usually not captured within a single ASTER scene. Contextual analysis has also been demonstrated to be useful to enhance the classification process using medium-resolution satellite data (Luo and Mountrakis, 2010).

Another issue significantly affecting sensor popularity is data availability and cost. In ASTER’s case, the major limitation is the on-demand observation schedule, which limits spatial coverage. In SPOT’s case, the issue of data cost is prominent as the French government has not yet matched the free-of-charge policy for Landsat scenes. Decisions by the French government on data distribution policies will significantly affect the future popularity of SPOT sensors.

### 4.2.3 High Spatial Resolution Optical Sensors

A wide range of high resolution (HR) and VHR spatial sensors are available from governmental and commercial consortiums. Figure 4.2 lists known satellite platforms and sensors collecting optical (passive) image data with a spatial resolution equal to or finer than 10 m. The list includes more than 50 different platforms and sensors active for 2013 or planned for 2014. For spatial resolutions of 1 m or higher, only panchromatic sensors are currently available. Multispectral data are available only at 2 m pixel size or larger. Multispectral sensors with improved spatial resolution are planned for 2014 with GeoEye-2 and WorldView-3 satellites.

Due to their fine spatial resolution, HR/VHR input image data have been used for recognition and characterization of all basic components of human settlements, such as built-up structures or buildings (Shettigara et al., 1995; Lin and Nevatia, 1998;
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FIGURE 4.2
(See color insert.) Pixel size (meters) of current and planned high spatial resolution satellite sensors.

Downloaded by [Salman Qureshi] at 12:20 03 June 2014
Benediktsson et al., 2003; Unsalan and Boyer, 2004; Khoshelham et al., 2010; Sirmacek and Unsalan, 2011), roads (Zhu et al., 2005; Chaudhuri et al., 2012), and open spaces, including city squares, public and private gardens and parks, walking areas, parking lots, and the like. In particular, urban open spaces have mostly been addressed by analyzing urban vegetated areas (Nichol and Lee, 2005; Nichol and Wong, 2007), including by detection of individual tree crowns in urban areas (Ouyang et al., 2011; Ardila et al., 2012). At the maximum, HR/VHR resolution imagery allows for civilian usage, even for detection of targets having a smaller dimension than the standard settlement components. Such examples of urban analysis may include detection of cars and other vehicles (Gerhardinger et al., 2005; Leitloff et al., 2010), including the analysis of their direction and velocity (Pesaresi et al., 2008), and monitoring of human crowds in open spaces (Sirmacek and Reinartz, 2011; Schmidt and Hinz, 2011). Furthermore, VHR image data have been critical in the detection and monitoring of built-up structures that may be functional for disaster and crisis management operations. In particular, detection of damages in urban areas has taken place in earthquake and tsunami postdisaster damage assessment (Pesaresi et al., 2007; Chesnel et al., 2008; Ouzounis et al., 2011; Lu et al., 2012; Parape et al. 2012) and in postconflict damage and reconstruction assessment (Pagot and Pesaresi, 2008; Gueguen et al., 2009). Finally, the use of VHR image data has been demonstrated for the monitoring and analysis of informal and temporary settlements, which are usually not included in the standard land use/land cover classification schemes. In particular, slum and poor urban areas (Kit et al., 2012; Kohli et al., 2012) and refugee and internally displaced people (IDP) camps (Giada et al., 2003; Jenerowicz et al., 2011; Pesaresi and Gerhardinger, 2011) are special cases of temporary human settlements relevant in crisis management operations.

From the methodological point of view, three general image-processing approaches have been used to process satellite HR/VHR input data for the analysis of human settlements: (1) 2D monocular image-derived features and classification, (2) 3D processing of stereo pairs and derived features, and (3) multisource information fusion. Each approach has its own advantages and disadvantages. The “information fusion” approach has the key advantage of the possibility of combining the best results of 2D and 3D processing approaches and usually to increase accuracy and effectiveness (Baltsavias et al., 1995; Haala and Hahan, 1995). Moreover, the inclusion of external data sources such as digital cartography, cadastral data, socioeconomic surveys, and even social media can improve the automatic information extraction process. Despite the existence of various approaches, it is worth noting a methodological constant, that is, the increased importance of structural (texture, shape) and contextual (spatial relations) image descriptors in the inferential models for processing HR/VHR image data, when compared with the models using moderate-resolution image data. This is due to the fact that as spatial resolution improves, capturing sufficient energy to register an acceptable signal-to-noise ratio becomes more challenging, leading to limited spectral separability of urban targets, especially with shorter wave bands. This decrease of spectral separability encourages the inclusion of structural and contextual image descriptors in the image information extraction models. The importance of structural and contextual HR/VHR image analysis is also amplified by the fact that urban classification often includes more or less explicitly spatial
and contextual criteria in order to discriminate the relevant urban information, such as typically local densities of specific features, land cover heterogeneity measures, spatial pattern characteristics, and the sizes of built-up structures.

The key limitations concerning satellite VHR image data exploitation involve the following: commercial and confidentiality issues, high data volume, intrinsic spatial inconsistency, and limited spectral, temporal, and multitemporal archives. VHR image data are intrinsically spatially inconsistent: even accurate processing of stereo pairs cannot reach subpixel RMSE positional error, assuming a pixel size of 0.5 m. Because of the capacity to collect off-nadir image data from VHR platforms, the apparent displacement of image pixels increases further due to panoramic and parallax distortions. Unfortunately, these effects are more evident in above-ground urban targets as in the case of rooftops of buildings that are some of the key entities collected in remote sensing urban studies. In practice, these facts lead to an expected apparent displacement of the rooftops in the order of several tenths of pixels, assuming 0.5 m spatial resolution, tall buildings, and usual off-nadir data collection ranges. This fact has direct bearing in increasing the complexity of reference data collection and in decreasing the expected accuracy and repeatability of the image information retrieval tasks, especially in the frame of monitoring activities. In general, VHR multispectral sensors collect less number of bands than low- or medium-resolution sensors. This has a direct impact when applying inferential models based on spectral reflectance criteria. Moreover, image data input with spatial details of 1 m or more are available only in the panchromatic mode, which in VHR platforms is usually by summing VNIR bands. This has a direct impact when applying multispectral analysis to meter- and submeter-resolution input data. The majority of the available VHR platforms declare a nominal revisiting time in the range of 1–5 days. In some areas, because of the high probability of cloud cover, this may lead to several weeks (or even months) of unavailability of VHR data. VHR platforms are tasked only for specific commercial/governmental requests. Therefore, except for some places, usually no consistent multitemporal archived data is available for a specific area of interest, leading to a radical decrease in the multitemporal analysis capacity using VHR data.

Future perspectives include the increase of available spatial resolution in both panchromatic and multispectral sensors in the WorldView and GeoEye platforms. They reach 0.3 and 1.3 m, respectively, in the pan and multispectral modes. It is still unclear how and under which constraints these new data will be available for scientific use and for the general public. International commercial and security issues are directly proportional to the advances of the sensor and platform technologies, including the increasing spatial and spectral resolution and the increasing absolute pointing accuracy of the platforms. The de facto standard set by the US government limiting the pixel size of satellite sensors to 0.5 m for nonmilitary applications could be potentially revised in order to make the new image data available. The list of entities or users having access to VHR image data may also change accordingly. As a general trend, we can observe that legal and licensing barriers in both the input data and image-derived information products are becoming more influential as technology advances.
4.3 TIR SENSORS

4.3.1 COARSE-RESOLUTION TIR SENSORS

Several meteorological satellite missions have on board coarse spatial resolution TIR sensors and have by now acquired a considerable global archive of LST images over the last 40 years. According to their orbit, these are divided into two distinct groups, namely, geostationary missions (e.g., MSG-SEVIRI viewing Europe and Africa, GOES over America, Kalpana over India, Fengyun viewing China, and MTSAT observing East Asia) and low Earth orbiters like NOAA and Metop AVHRR. In the latter group, we may include Terra and Aqua MODIS, due to the similar TIR band characteristics and products, although Terra and Aqua are not weather satellites. These missions have been providing continuous monitoring of LST distribution at the spatial resolution ranging from 3 to 5 km for geostationary platforms to 1.1 km at nadir for low Earth orbiters. In most cases, service providers (e.g., NASA, ESA, EUMETSAT) distribute LST images as standard data products. The coarse spatial resolution of geostationary TIR imagery has prohibited their extensive use for urban studies; yet recently, scientific interest in these sensors has been revived as computational methods for sharpening these imagery to 1 km (Zákšek and Oštir, 2012; Keramitsoglou et al., 2013) or better (Bechtel et al., 2012) have become available.

A clear advantage of coarse-resolution sensors is their temporal resolution. The temporal measurement frequency of polar orbiting satellite systems at ~850 km is approximately two times per day, yet ordinarily a few acquisitions are available daily from similar sensors on board different platforms (see Table 4.1). The geostationary orbit TIR sensors provide images of the Earth’s disk from 36,000 km every 15–30 min, making them a unique means for capturing the diurnal variability of surface UHIs. The specific details of coarse-resolution TIR sensors are presented in Table 4.1.

LST from multispectral TIR imagery can be retrieved (Schmugge et al., 1998) either using a radiative transfer equation to correct the at-sensor radiance to surface radiance or by applying the split-window technique for sea surfaces to land surfaces, assuming that the emissivity in the channels used for the split window is similar (Dash et al., 2002). Land surface brightness temperatures are then calculated as a linear combination of the two channels. Jiménez-Muñoz and Sobrino (2008) provide a complete set of split-window coefficients that can be used to retrieve LST from TIR sensors on board the most popular coarse-resolution remote sensing satellites. Past studies of SUHI have been conducted primarily by using AVHRR or MODIS data (Kidder and Wu, 1987; Balling and Brazell, 1988; Roth et al. 1989; Gallo et al., 1993; Stathopoulos et al., 2004; Hung et al., 2006; Peng et al., 2012). Keramitsoglou et al. (2012) concluded that the spatial resolution of 1 km offered now by MODIS and AVHRR, and until April 2012 also by AATSR, is adequate for large-area urban temperature mapping and for observing the differences between daytime and nighttime patterns, although not acquired at the best overpass time to observe SUHI (Sobrino et al., 2011). Streutker (2002, 2003) used AVHRR data to quantify the SUHI of Houston, Texas, assuming an ellipsoid footprint to derive the SUHI parameters of intensity, spatial extent, orientation, and central location. Hung et al. (2006) adopted this method to measure the spatial extents and magnitudes of the
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Instrument Name Full</th>
<th>Instrument Agencies</th>
<th>Missions</th>
<th>Orbit</th>
<th>Spatial Resolution</th>
<th>Swath Width</th>
<th>Temporal Resolution</th>
<th>TIR Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR/3</td>
<td>Advanced very high resolution radiometer/3</td>
<td>NOAA</td>
<td>NOAA-15–19, Metop-B, Metop-A</td>
<td>Sun-synchronous at 705 km, inclination 98.6°–98.8°</td>
<td>1.1 km at nadir</td>
<td>~3000 km</td>
<td>Depending on the number of operational NOAA and Metop platforms; two images per platform</td>
<td>TIR: 10.3–11.3 µm, 11.5–12.5 µm</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate-resolution imaging spectroradiometer</td>
<td>NASA</td>
<td>Terra, Aqua</td>
<td>Sun-synchronous at ~850 km, inclination 98.2°</td>
<td>1 km at nadir</td>
<td>2330 km</td>
<td>Four images daily, two daytime and two nighttime</td>
<td>VIS-TIR: 36 bands in the range 0.4–14.4 µm, IR9.7 = 9.52–9.8 µm, IR10.8 = 10.3–11.3 µm, IR12.0 = 11.5–12.5 µm, IR13.4 = 12.9–13.9 µm, IR: 4 channels: 3.9 µm, 6.7 µm, 10.7 µm, and 13.3 µm</td>
</tr>
<tr>
<td>SEVIRI</td>
<td>Spinning-enhanced visible and infrared imager</td>
<td>EUMETSAT (ESA)</td>
<td>Meteosat second generation</td>
<td>Geostationary at 36,000 km viewing Europe and Africa</td>
<td>3–5 km</td>
<td>Full Earth disk</td>
<td>15 min</td>
<td>VIS-TIR: 0.5–12.5 µm (five channels)</td>
</tr>
<tr>
<td>Imager</td>
<td>Imager</td>
<td>NOAA</td>
<td>GOES-12, GOES-14, GOES-15, GOES-13 Fengyun-2</td>
<td>Geostationary at 36,000 km viewing America</td>
<td>10 km</td>
<td>Full Earth disk</td>
<td>15 min</td>
<td></td>
</tr>
<tr>
<td>IVISSR (FY-2)</td>
<td>Improved multispectral visible and infrared scan radiometer (five channels)</td>
<td>NRSCC (NSMC-CMA, CNSA, CAST)</td>
<td>Fengyun-2</td>
<td>Geostationary at 36,000 km viewing China</td>
<td>5 km</td>
<td>Full Earth disk</td>
<td>15 min</td>
<td></td>
</tr>
</tbody>
</table>

SUHIs for eight megacities in Asia using both daytime and nighttime MODIS data acquired over the period 2001–2003. Rajasekar and Weng (2009a) applied a non-parametric model by using fast Fourier transformation (FFT) to MODIS imagery for characterization of the SUHI over space, so as to derive SUHI magnitude and other parameters. Keramitsoglou et al. (2011) applied an object-based image analysis procedure to extract urban thermal patterns to more than 3000 MODIS images acquired from May until September from the years 2000 to 2009 for the Greater Athens Area, Greece, revealing the qualitative and quantitative characteristics of Athens’ SUHI retaining the original LST values, thus circumventing modeling.

Regarding the near future of sensors and satellite platforms, a number of relevant projects are under way. The European Space Agency (ESA) Sentinel-3 satellite is planned for launch from 2014, offering a sea and land surface temperature radiometer (SLSTR) with a 1 km resolution in the thermal channels and a daily revisit time. The geostationary GOES-R satellite is due in 2015, with a 2 km resolution in the thermal channels from a new advanced baseline imager (ABI). The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is due for launch in 2016, designed to replace NASA’s Aqua, Terra, and Aura satellites and offering the visible and infrared imagery radiometer suite (VIIRS) sensor for LST. Coupled with these large “traditional” missions, in the future there is likely to be an increase in “small satellites” (Sandau et al., 2010) that enable relatively quick and inexpensive missions, which could, for example, help to observe dynamic surface temperature patterns.

4.3.2 Medium-Resolution TIR Sensors

Currently, only a few spaceborne sensors with global imaging capacity can deliver medium-resolution TIR data required to address urban LST heterogeneity and to assess the UHI effect (Weng, 2009). The TM sensor on board Landsat 5 has been acquiring images of the Earth nearly continuously from July 16, 1982, to the present, with a single TIR band of 120 m resolution, and is thus long overdue. Figure 4.3 shows the mean annual surface temperature based on the ATC (annual temperature cycle)-modeled LST values of all available 115 Landsat-5 TM scenes (less than 30% cloud cover) between 2000 and 2010 in Los Angeles. Another TIR sensor that has global imaging capacity is with Landsat 7 ETM+ since April 15, 1999. The ETM+ provides an enhanced TIR band of 60 m resolution. Unfortunately, the scan-line-corrector on board Landsat 7 started malfunctioning after May 31, 2003, which caused a loss of approximately 25% of the data, mostly located between scan lines toward the scene edges. Although some gap-filling remedy methods can recover some of the data lost, the gap-filled data cannot match the quality of the original data. In addition, ASTER sensor flown on the Terra satellite collects five TIR bands with a ground resolution of 90 m. These multispectral infrared measurements can be converted into LST and emissivity products by using the ASTER temperature/emissivity separation algorithm (Gillespie et al., 1998). LST values calculated using this algorithm are expected to have an absolute accuracy of 1–4 K and relative accuracy of 0.3 K, and surface emissivity values an absolute accuracy of 0.05–0.1 and relative accuracy of 0.005 (TEWG, 1999). ASTER is an on-demand instrument, which means that data are only acquired over
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Landsat TM and ETM+ TIR data have been extensively utilized to derive LSTs and to study UHIs (e.g., Nichol, 1994; Weng, 2001, 2003; Weng et al., 2004) for American and Asian cities. With ASTER imagery, Lu and Weng (2006) estimated hot-object and cold-object fractions and biophysical variables using linear spectral mixture analysis and analyzed their relationship across various spatial aggregations. Rajasekar and Weng (2009b) applied association rule mining for exploring the relationship between urban LST and biophysical/social parameters. Moreover, the landscape ecology approach was employed to assess the interplay between LST and LULC.

FIGURE 4.3 (See color insert.) Mean annual surface temperature in Los Angeles determined by an unconstrained nonlinear optimization with the Levenberg–Marquardt minimization scheme. LST measurements of all available 115 Landsat-5 TM scenes between 2000 and 2010 were used for modeling by a sine function. (From Weng, Q. and P. Fu, Remote Sens. Environ., 2014, 140, 267.)

the requested locations. Terra satellite launched in December 1999 as part of NASA’s Earth Observing System has a life expectancy of 6 years and is now also overdue.
patterns in order to reach the optical scale for analysis (Liu and Weng, 2009). Because ASTER sensor collects both daytime and nighttime TIR images, analysis of LST spatial patterns has also been conducted for a diurnal contrast (Nichol, 2005).

Studies using satellite-derived LSTs have been termed surface temperature UHIs (Streutker, 2002). Moreover, satellite-derived LSTs are believed to correspond more closely with the canopy layer heat islands, although a precise transfer function between LST and the near-ground air temperature is not yet available (Nichol, 1994). Voogt and Oke (2003) criticized the slow progress in thermal remote sensing of urban areas, which has largely been limited to qualitative description of thermal patterns and simple correlations between LST and LULC types. Xiao et al. (2008) further noticed that little research has been done on the statistical relationship between LST and nonbiophysical factors. A key issue in the application of TIR data in urban climate studies is how to use LST measurements at the micro scale to characterize and quantify UHIs observed at the meso scale (Weng, 2009). Because medium-resolution sensors are typically associated with long-repeat-cycle satellites (16 days for both Landsat and Terra ASTER sensors), their TIR data are not readily useful for UHI monitoring. Bechtel (2012) found that it was feasible to extract mean annual surface temperature and yearly amplitude of surface temperature by modeling the ATC with Landsat data archive.

Looking into the near future, the LDCM may be the only option. It will have a TIR sensor acquiring data at 100 m resolution, but again with a low temporal resolution of 16 days (http://ldcm.nasa.gov/). The hyperspectral infrared imager (HyspIRI) has been defined as a mission with Tier 2 priority of the Decadal Survey (http://hyspiri.jpl.nasa.gov/). Its TIR imager is expected to provide seven bands between 7.5 and 12 μm and one band at 4 μm, all with 60 m resolution. The TIR sensor is intended for imaging global land and shallow water with a 5-day revisit at the equator (1-day and 1-night imaging). These improved capabilities would allow for a more accurate estimation of LST and emissivity and for deriving unprecedented information on biophysical characteristics, but HyspIRI has not yet set a definite time for launch due mainly to budget constraints.

4.4 SAR SENSORS

4.4.1 Coarse-Resolution SAR Sensors

SAR data in any ScanSAR mode are one of the most important sources of information for mapping purposes at the global level. The wide geographical coverage coupled with almost no blackout time mark SAR sensors as the best option for a number of land covers at the global level. For human settlements, the wide swath mode (WSM) data from the ASAR sensor on board ESA Envisat-1 are currently exploited in a semioperational way to globally map built-up arc extents (Gamba and Lisini, 2013). Table 4.2 provides ENVISAT ASAR sensor characteristics. Indeed, a global urban extraction of WSM data, with a spatial posting of 75 m per pixel, represents an excellent trade-off between detailed accuracy and computational load. They were collected as a sort of background mission whenever the satellite was not busy acquiring in a different mode. The number of acquisitions on the same area is thus variable.
from one year to the other, but in general the yearly coverage is guaranteed for the whole globe, with a few exceptions. The same methodology will presumably be applied with minor adaptation to data from future missions, such as ESA Sentinel-1.

### 4.4.2 Medium-Resolution SAR Sensors

The SAR sensors currently available have a spatial resolution in the range of 10–30 m, which has not been, until recently, considered useful for urban applications, or at least not very different from those (like urban extent extraction) equally achievable by coarse sensors. The main improvement that makes these systems useful for urban application is polarimetry, as it allows for the distinction among different scattering mechanisms. While this feature may be useful for mapping ULC, it is expected that very high-resolution SAR data can provide finer details of urban structures such as buildings and roads and thus further improve its application in urban analysis. In the following text, the characteristics of the RADARSAT-1 and -2 satellites are discussed.

Launched in November 1995 and December 2007, respectively, RADARSAT-1 and -2 are sophisticated Earth observation satellites developed by Canada to monitor environmental changes and the planet’s natural resources. The C-band SAR sensors on board these satellites are operational radar systems capable of timely delivery of large amounts of data for many applications, including urban, marine surveillance, ice monitoring, disaster management, environmental monitoring, resource management, and mapping, in Canada and worldwide. The RADARSAT SAR system characteristics are listed in Table 4.3. Polarimetric SAR data have increasingly been used for urban analysis (Niu and Ban, 2012). Moreover, by exploiting the multitemporal capability of medium-resolution SAR with no limitation due to weather conditions, these SAR data have also been considered for urban change analysis (Niu and Ban, 2013). Finally, several studies have also been undertaken on the fusion of SAR and optical data, showing improved ULC mapping over SAR or optical data alone (Gamba and

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**TABLE 4.2**

<table>
<thead>
<tr>
<th>Sensor</th>
<th><strong>ASAR</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>800 km altitude</td>
</tr>
<tr>
<td></td>
<td>35 days orbit repeat cycle</td>
</tr>
<tr>
<td></td>
<td>5–15 days revisit time (midlatitudes)</td>
</tr>
<tr>
<td>Range size</td>
<td>56–100 km (image and alternating polarization modes)</td>
</tr>
<tr>
<td></td>
<td>400 km (wide swath and global monitoring modes)</td>
</tr>
<tr>
<td>Geometric resolution</td>
<td>30 m (image and alternating polarization modes)</td>
</tr>
<tr>
<td></td>
<td>150 m (wide swath mode)</td>
</tr>
<tr>
<td></td>
<td>1 km (global monitoring mode)</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>1 channel 5.331 GHz (C-band)</td>
</tr>
<tr>
<td>Polarizations</td>
<td>HH or VV (single pol)</td>
</tr>
<tr>
<td></td>
<td>HH/VV or HH/HV or VV/VH (dual pol)</td>
</tr>
</tbody>
</table>
Houshmand, 2001; Ban et al., 2010; Ban and Jacob, 2013). The future is connected to the RADARSAT constellation. The three-satellite configuration will provide complete coverage of Canada’s and most of the world’s land and oceans, offering an average daily revisit as well as daily access to 95% of the world to Canadian and international users. The satellite launches are currently planned for 2018.

### TABLE 4.3
RADARSAT-1 and -2 Sensor Characteristics

<table>
<thead>
<tr>
<th>Sensor</th>
<th>RADARSAT-1</th>
<th>RADARSAT-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission lifetime</td>
<td>&gt;15 years</td>
<td>7 years</td>
</tr>
<tr>
<td>Orbit</td>
<td>793–821 km</td>
<td>798 km</td>
</tr>
<tr>
<td>Range size</td>
<td>45 km (fine beam)</td>
<td>Selective polarization:</td>
</tr>
<tr>
<td></td>
<td>100 km (standard beam)</td>
<td>50 km (fine beam)</td>
</tr>
<tr>
<td></td>
<td>75 km (high incidence)</td>
<td>100 km (standard beam)</td>
</tr>
<tr>
<td></td>
<td>170 km (low incidence)</td>
<td>75 km (high incidence)</td>
</tr>
<tr>
<td></td>
<td>150 km (wide)</td>
<td>170 km (low incidence)</td>
</tr>
<tr>
<td></td>
<td>300 km (ScanSAR narrow)</td>
<td>150 km (wide)</td>
</tr>
<tr>
<td></td>
<td>500 km (ScanSAR wide)</td>
<td>300 km (ScanSAR narrow)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 km (ScanSAR wide)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polarimetric:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 km (fine quad pol)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 km (standard quad pol)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Selective single polarization:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 km (ultrafine)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 km (SpotLight)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 km (multilook Fine)</td>
</tr>
<tr>
<td>Geometric resolution (m)</td>
<td>8 (fine beam)</td>
<td>Selective polarization:</td>
</tr>
<tr>
<td></td>
<td>30 (standard beam)</td>
<td>10 × 9 (fine beam)</td>
</tr>
<tr>
<td></td>
<td>18–27 (high incidence)</td>
<td>25 × 28 (standard beam)</td>
</tr>
<tr>
<td></td>
<td>30 (low incidence)</td>
<td>40 × 28 (high incidence)</td>
</tr>
<tr>
<td></td>
<td>30 (wide)</td>
<td>20 × 28 (low incidence)</td>
</tr>
<tr>
<td></td>
<td>50 m (ScanSAR narrow)</td>
<td>25 × 28 (wide)</td>
</tr>
<tr>
<td></td>
<td>100 m (ScanSAR wide)</td>
<td>50 × 50 (ScanSAR narrow)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 × 100 (ScanSAR wide)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polarimetric:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 × 9 (fine quad pol)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 × 28 (standard quad pol)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Selective single polarization:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 × 3 (ultrafine)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 × 1 (SpotLight)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 × 9 (multilook Fine)</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>1 channel</td>
<td>1 channel</td>
</tr>
<tr>
<td></td>
<td>Center frequency 5.3 GHz</td>
<td>Center frequency 5.405 GHz</td>
</tr>
<tr>
<td></td>
<td>(C-band), bandwidth: 30 MHz</td>
<td>(C-band), bandwidth: 100 MHz</td>
</tr>
<tr>
<td>Polarizations</td>
<td>HH</td>
<td>HH, VV, HV, VH</td>
</tr>
</tbody>
</table>
4.4.3 Fine-Resolution SAR Sensors

The last generation of SAR sensors has been developed to provide better spatial resolution characteristics, in the range of 1 m. This category of sensors has caused a boost in the use of SAR data in urban applications, especially connected to very detailed analysis (to the building level) of the urban environment. TerraSAR-X (TSX) and COSMO/SkyMed are examples of these systems. COSMO/SkyMed has been used for many applications, mainly related to risk mapping and interferometry (Ardizzone et al., 2012). In the following, a more detailed analysis of TSX is offered, because of its peculiar characteristics, connected to the twin TanDEM-X (TDX) mission.

The first German SAR satellite TSX was launched on June 15, 2007, in the context of a public–private partnership between the German Aerospace Center (DLR) and the EADS Astrium GmbH. Three years later, the TSX mission was amended by a second, almost identical X-band SAR satellite—TDX. For the TDX mission (TDM) (TSX Add-On for Digital Elevation Measurement), TSX and TDX are flying in an orbit at 514 km in a so-called helix formation with a typical distance of 250–500 m between the satellites. With this constellation, TDX is the first bistatic, spaceborne SAR mission. The primary mission is the generation of a consistent global digital elevation model with unprecedented accuracy. At the same time, TSX and TDX provide highly reconfigurable platforms for testing and demonstrating new SAR techniques and potential applications. TSX and TDX are scheduled for 5 years of operation, and they collect VHR data in three basic imaging modes—SpotLight (SL) and high-resolution SpotLight mode (HS), StripMap mode (SM), and ScanSAR mode (SC) (Roth et al., 2005). The characteristics of the imaging modes are listed in Table 4.4.

Due to the all-weather and day-and-night data acquisition capability of SAR sensors, the TDM allows to collect two global coverages of VHR images (SM mode) within a period of 3 years (2011–2013). With the unique spatial detail

<table>
<thead>
<tr>
<th>SENSOR CHARACTERISTICS</th>
<th>TSX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission lifetime</strong></td>
<td>2007–2013 (at least)</td>
</tr>
<tr>
<td><strong>Orbit</strong></td>
<td>514 km altitude</td>
</tr>
<tr>
<td><strong>Range size</strong></td>
<td>5–10 km (SpotLight mode)</td>
</tr>
<tr>
<td></td>
<td>30 km (StripMap mode single-polarized)</td>
</tr>
<tr>
<td></td>
<td>15 km (StripMap mode dual-polarized)</td>
</tr>
<tr>
<td></td>
<td>100 km (ScanSAR mode)</td>
</tr>
<tr>
<td><strong>Geometric resolution</strong></td>
<td>1 m (SpotLight mode)</td>
</tr>
<tr>
<td></td>
<td>3 m (StripMap mode)</td>
</tr>
<tr>
<td></td>
<td>16 m (ScanSAR mode)</td>
</tr>
<tr>
<td><strong>Spectral resolution</strong></td>
<td>1 channel 9.65 GHz (X-band)</td>
</tr>
<tr>
<td><strong>Polarizations</strong></td>
<td>HH or VV (single-polarized)</td>
</tr>
<tr>
<td></td>
<td>HH/VV or HH/HV or VV/VH (dual-polarized)</td>
</tr>
</tbody>
</table>
and temporal consistency of the data set in combination with the complementary characteristics of the VHR SAR data compared to medium- or high-resolution optical imagery used for urban analyses on a global scale so far, the TDM is predestined to substantially support the global mapping and future monitoring of human settlements. Hence, DLR’s German Remote Sensing Data Center (DFD) has developed a fully operational processing chain—the urban footprint processor (UFP)—for the delineation of built-up areas from the TDM SAR database (Esch et al., 2012). The goal is to provide a public domain global coverage of binary settlement masks showing a spatial resolution of 3 arcsec (~50–75 m)—the global urban footprint (GUF). The accuracies of the binary GUF settlement masks usually range between 70% and 95% depending on the complexity of the landscape and the significance of the built-up environment (size, height, density, arrangement of houses, vegetation cover, etc.). Figure 4.4 shows an example of the GUF mosaic for the region of Accra, Ghana.

![Figure 4.4](See color insert.) Optical data from Google Earth (a), TerraSAR-X amplitude image (b), calculated texture image (c), and urban footprint mask derived from combined classification of amplitude and texture (d).
With the two global coverages of VHR SAR imagery collected in 2011/2012 and 2012/2013, the TDM data set represents a suitable baseline for future analyses of global urban sprawl. Apart from classic postclassification change detection approaches, the calculation of long-term coherences might serve as an effective method to improve the intended GUF product and to provide an alternative method for the mapping and monitoring of urban sprawl. Moreover, the extraction of building structures and the estimation of building densities based on texture measures and the modeling of building volume on the building block level using the VHR DEM generated in the context of the TDM hold further potential (Esch et al., 2012). From an applied perspective, the combined analysis global SAR and optical data sets or the combination of settlement masks derived from these complementary sources are highly interesting.

4.5 NIGHTTIME LIGHTS

Nighttime lights are a class of satellite observations and derived products based on the detection of anthropogenic lighting present at the Earth’s surface. This style of product can only be produced using data from sensors that collect low-light imaging data in spectral bands covering emissions generated by electric lights. The standard “stable lights” product is a cloud-free composite that has been filtered to remove ephemeral fires and background noise. Nighttime lights are used to model the spatial distribution of variables that would be very difficult to measure in a globally consistent manner. Examples of nighttime lights–derived global grids include the spatial distribution of population (Doll, 2010; Sutton et al., 2010), economic activity (Ghosh et al., 2010), electrification rates (Elvidge et al., 2010), poverty mapping (Elvidge et al., 2009), density of constructed surfaces (Matsumura et al., 2009), food demand, stocks of steel and other metals (Takahashi et al., 2010), CO₂ emissions from fossil fuels (Rayner et al., 2009), and the ecological impact of artificial lighting (Aubrecht et al., 2008).

To date, there have been two systems flown capable of collecting global nighttime lights data. The original system is the Defense Meteorological Satellite Program (DMSP) operational linescan system (OLS). The more recently launched system is the Suomi National Polar Partnership (SNPP) VIIRS. In both cases, the low-light imaging was designed to serve the meteorological community, which has an interest in detecting moonlit clouds in the visible region to complement thermal observations.

The DMSP nighttime lights represent one of the most widely recognized global satellite data products and have proven valuable in a wide range of scientific applications. DMSP has flown low-light imaging sensors in polar orbits since the mid-1970s and has a digital archive that extends back to 1992. The OLS was designed to collect visible and TIR data, day and night, for use in observing weather systems and cloud cover. The “visible” band may be termed panchromatic, spanning the visible and near-infrared (NIR) from 0.5 to 0.9 µm. The DMSP low-light imaging is achieved using a photomultiplier tube. The global data are smoothed with five-by-five pixel averaging, which results in pixel footprints that are 5 km on a side at nadir and up to 8 km on a side at the edge of scan. The ground sample distance (GSD) is maintained at 2.7 km from nadir to edge of scan. Thus, there is substantial overlap between adjacent pixel footprints. The detection limit is estimated at 5E-10 Watts/cm²/sr.
The DMSP nighttime lights data have a set of well-known shortcomings (Elvidge et al., 2007): coarse spatial resolution, six-bit quantization, saturation on bright lights, lack of in-flight calibration, lack of spectral channels suitable for discrimination of thermal sources of lighting, and lack of low-light imaging spectral bands suitable for discriminating lighting types (Elvidge et al., 2010).

On October 28, 2011, NASA and NOAA launched the SNPP satellite carrying the first VIIRS. The VIIRS instrument includes a day/night band (DNB), which collects panchromatic (0.5–0.9 μm) low-light imaging data at night using a time delay and integration (TDI) charge-coupled device (CCD). The VIIRS instrument offers improvement in each of these shortcomings, except multispectral low-light imaging. The DNB pixel footprint is maintained at 742 m from nadir out to the edge of scan. Thus, the VIIRS DNB low-light imaging footprint is 45 times smaller than the DMSP-OLS footprint. The DNB data have a wide dynamic range, 14-bit quantization, and a detection limit estimated at 2E-10 Watts/cm²/sr, which makes it possible for the VIIRS to detect clouds, snow, and bright playa lake beds with exceedingly dim airglow illumination when no moonlight is present (Miller et al., 2012). The DNB has an in-flight calibration capability. In addition, the VIIRS collects data at night in a SWIR band that detects combustion sources, but not nighttime lights (Zhizhin et al., 2013). This makes it possible to distinguish thermal sources of light from electric lighting. All of this results in a far superior nighttime lights product when compared to DMSP products (Figure 4.5).

In 2012 and 2013, nighttime lights were collected by both DMSP and VIIRS, making it possible to cross-calibrate the nighttime light products generated by the two systems. There are two more DMSP satellites to be launched; however, it is anticipated that these will fly in dawn–dusk orbits that are ill-suited for global mapping of nighttime lights. The second VIIRS is under construction, and NASA/NOAA is planning the third. There are good prospects for a continuing series of VIIRS instruments. While VIIRS nighttime lights are expected to yield substantial

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**FIGURE 4.5** Comparison on DNB versus DMSP cloud-free composited nighttime lights of Guangzhou, China, in 2012.
advances in a range of science applications, there has yet to be a satellite mission dedicated to nighttime lights. Such a mission would likely have spatial resolution under 100 m and multispectral low-light imaging to enable discrimination of lighting types (Elvidge et al., 2007).

**ACRONYMS**

- **AATSR**: Advanced along track scanning radiometer
- **ABI**: Advanced baseline imager
- **AVHRR**: Advanced very high resolution radiometer
- **ESA**: European Space Agency
- **EUMETSAT**: European Meteorological Satellite Organisation
- **GOES**: Geostationary Operational Environmental Satellite
- **Metop**: Meteorological Operational Satellite Programme
- **MODIS**: Moderate-resolution imaging spectroradiometer
- **MSG**: Meteosat second generation
- **MTSAT**: Multifunction transport satellite
- **NASA**: National Aeronautics and Space Administration
- **NOAA**: National Oceanic and Atmospheric Administration
- **SEVIRI**: Spinning-enhanced visible and infrared imager
- **SLSTR**: Sea and land surface temperature radiometer

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Urban Observing Sensors


Urban Observing Sensors


