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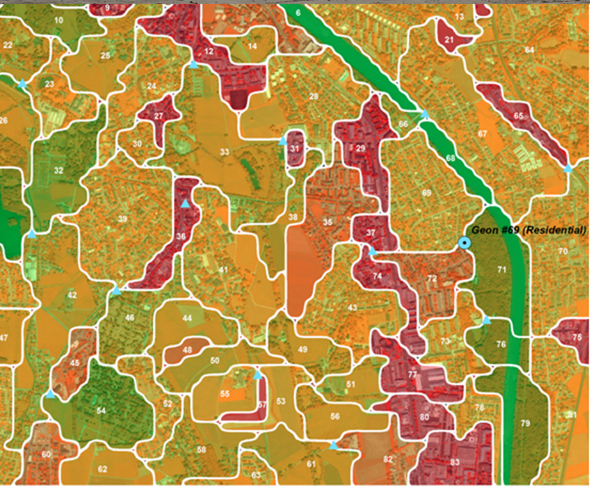
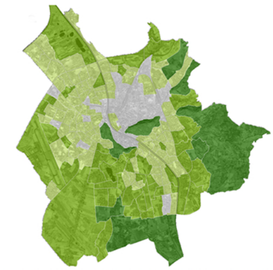
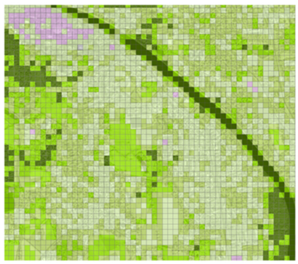
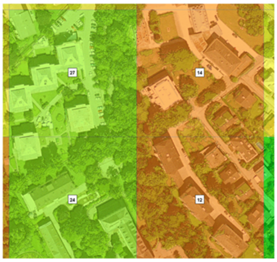
Urban Remote Sensing

Second Edition









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Remote Sensing Applications

Series Editor

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Preface

EARTH OBSERVATION FOR A SUSTAINABLE EARTH

Earth observation (EO) technology, in conjunction with in situ data collection, has been used to observe, monitor, measure, and model many of the components that comprise natural and human ecosystem cycles (Weng 2012a). Driven by societal needs and improvement in sensor technology and image processing techniques, we have witnessed a great increase in research and development, technology transfer, and engineering activities worldwide since the turn into the twenty-first century. Commercial satellites acquire imagery at spatial resolutions previously only possible to aerial platforms, but these satellites have advantages over aerial imageries including their capacity for synoptic coverage, shorter revisit time, and capability to produce stereo image pairs conveniently for high-accuracy 3D mapping thanks to their flexible pointing mechanism (Weng 2012b). Hyperspectral imaging affords the potential for detailed identification of materials and better estimates of their abundance in the Earth's surface, enabling the use of remote sensing data collection to replace data collection that was formerly limited to laboratory testing or expensive field surveys (Weng 2012b). While LiDAR technology provides high-accuracy height and other geometric information for urban structures and vegetation, radar technology has been re-invented since the 1990s due greatly to the increase of spaceborne radar programs (Weng 2012b). These technologies are not isolated at all. In fact, their integrated uses with more established aerial photography and multispectral remote sensing techniques have been the main stream of current remote sensing research and applications (Weng 2012b). With these recent advances, techniques of and data sets from remote sensing and EO have become an essential tool for understanding the Earth, monitoring of the world's natural resources and environments, managing exposures to natural and man-made risks and disasters, and helping the sustainability and productivity of natural and human ecosystems (Weng 2012b).

The 2002 World Summit on Sustainable Development in Johannesburg highlighted the urgent need for coordinated observation relating to the state of the Earth. The First Earth Observation Summit in Washington, D.C., in 2003 adopted a declaration to establish the ad hoc intergovernmental Group on Earth Observations (ad hoc GEO) to draft a 10-Year Implementation Plan. Since 2003, GEO has been working to strengthen the cooperation and coordination among global observing systems and research programs for integrated global observations. The GEO process has outlined a framework document calling for Global Earth Observation System of Systems (GEOSS) and defined nine areas of societal benefits (http://www.earthobservations.org/about_geo.shtml). On September 25, 2015, the United Nations adopted a set of sustainable development goals (SDGs), each of which has specific targets to be achieved over the next 15 years (United Nations Development Programme 2015). These goals represent the UN's response to numerous societal challenges and efforts to build a sustainable Earth. Through large-scale, repetitive acquisition of the Earth surface image data, remote sensing can provide essential information and knowledge to supplement statistical analyses in the assessment of indicators toward the attainment of the SDGs. Because EO offers an indispensable tool to measure and monitor progresses toward SDGs, in the recently developed “GEO Strategic Plan 2016–2025: Implementing GEOSS,” GEO has determined to develop a concerted direction with the SDGs (Group on Earth Observations 2015). To address the current state of remote sensing knowledge for sustainable development and management, Weng (2016) published an edited volume in this same book series entitled “Remote Sensing for Sustainability,” which intended to contribute to the GEO’s Strategic Plan by addressing and exemplifying a number of societal benefit areas using remote sensing data sets, methods, and techniques for sustainable development.

ADDRESSING THE NEEDS IN DEVELOPING COUNTRIES

GEO includes in its work plan a “Global Urban Observation and Information” (GUOI) Initiative since 2012. The leaders of this initiative set the following goals for the 2012–2015 period: (1) improving the coordination of urban observations, monitoring, forecasting, and assessment initiatives worldwide; (2) supporting the development of a global urban observation and analysis system; (3) producing up-to-date information on the status and development of the urban system—from a local to a global scale; (4) filling existing gaps in the integration of global urban observation with data that characterize urban ecosystems, environment, air quality and carbon emission, indicators of population density, environmental quality, quality of life, and the patterns of human environmental and infectious diseases; and (5) developing innovative techniques in support of effective and sustainable urban development. These goals have been extended and expanded for the GEO Work Programme of 2017–2019 (Weng et al. 2014). The goals support GEO’s objectives on Sustainable Urban Development well, which advocate the value of EOs, engage communities, and deliver data and information by assisting in the development of resilient cities and assessment of urban footprints. By accomplishing these objectives, GEO hopes to make cities and human settlements inclusive, safe, resilient, and sustainable through identifying economic externalities; managing environmental, climate, and disaster risks; and building capacity to participate, plan, and manage based on objective information regarding urban development. The GUOI Initiative, in particular, supports the development of urban resilience (including coastal resilience) by supplying objective data and information on the footprints of global urbanization and cities, developing indicators for sustainable cities (supporting UN’s SDGs), and developing innovative methods and techniques in support of effective management of urban environment, ecosystems, natural resources, and other assets, and the mitigation of adverse impacts caused by urbanization.

A major strategic shift of the GUOI Initiative for the 2017–2019 period is to extend urban mapping methods and EO data sets and technologies to developing countries. There are several activities in connection with this strategic focus. First, the GUOI team initiated a joint project of “Impervious Surface Mapping in Tropical and Subtropical Cities (ISMiTSC),” aiming at providing EO technologies and data sets to Asia, Africa, and South America. A preliminary research has been conducted in selected cities in the three continents with data support from German Aerospace Center (DLR) and research collaboration between Chinese University of Hong Kong, Indiana State University, and DLR, with a grant support from Hong Kong Research Grants Council (2016–2017). Preliminary result was published via a book entitled *Remote Sensing of Impervious Surfaces in Tropical and Subtropical Areas* (Zhang et al. 2015). Since most developing countries are located in tropical and subtropical regions, continuing urbanization in these regions has important implications in biodiversity, rainforest ecosystem, and global climate change (Weng 2015). Optical remote sensing faces more environmental challenges than it does in a temperate zone, due to frequent cloudy and rainy days and complex hydrological systems in association with strong seasonal change in water surface area, vegetation phenology, and morphological and species complexity (Weng 2015). To fully utilize long-term archives of medium-resolution satellite imagery, researchers have developed new algorithms and methods to overcome these limitations (Fu and Weng 2016; Zhang and Weng 2016).

Second, to facilitate online and off-line learning and knowledge sharing, a website has been created for sharing computer codes, algorithms, systems, products, and publications that support remote sensing observations and applications, digital image processing, and the extraction of geophysical and biophysical information. It is our hope that through co-learning, sharing, and collaborating, an e-community can be built among researchers, practitioners, teachers, and students worldwide, which is named Remote Sensing E-community for Digital imaGe procESsing (RS-EDGES, http://rs-edges.net/).

Finally, we strive to train and to educate students and young researchers worldwide to become tomorrow's leaders in EO technologies by disseminating GUOI ideas and goals and sharing outcomes of various activities through annual symposium, summer school, joint field works, and publications. Since 2012, the GUOI team has held annual workshops/symposia in conjunction with various international conferences. The GUOI symposia were held in conjunction with the conference series IEEE-sponsored EORSA in Shanghai, Changsha, and Guangzhou, China, respectively, and with IEEE/ISPRS jointly sponsored JURSE conference series in Sao Paulo, Brazil, and Lausanne, Switzerland. In 2014, the International Workshop on Global Urban Observation and Monitoring from Space was held in Athens, Greece, sponsored by the European Space Agency. Furthermore, during annual conferences of the American Association of Geographers, there was an annual Global Urban Observation Symposium with multiple sessions (Chicago, Illinois, 2015; San Francisco, California, 2016; and Boston, Massachusetts, 2017). Additional GUOI sessions were also organized in 2016 both in the IEEE IGARSS conference in Beijing, China, and in the ISPRS Congress in Prague, Czech Republic. A joint field work on current land use and land cover (LULC) and urban morphology was conducted in the Pearl River Delta (PRD), China, from January 4 to 8, 2016. The 5-day field campaign was made possible by grants from the Research Grants Council of Hong Kong and Natural Science Foundation of China. The field work was directed by Prof. Qihao Weng, Indiana State University, joined by researchers and graduate students from Chinese University of Hong Kong, Wuhan University, and South China Normal University. The joint field campaign aimed to obtain up-to-date "ground truth" data on all LULC types in PRD and to verify the accuracy of LULC maps that were derived from satellite imagery, especially on urban impervious surfaces in the delta region (see Zhang et al. 2017 for details).

SYNOPSIS OF THE BOOK

To meet the growing interests in applications of remote sensing technology to urban and suburban areas, Drs. Weng and Quattrochi assembled a team of experts to edit a book on Urban Remote Sensing in 2006. That book, for the first time, systematically examined various aspects of the field. Since its inception, the book had been used as a textbook in many universities and also served as a reference book for researchers in academia, governmental, and commercial sectors. When the acquisition editor at CRC Press expressed a strong interest for us to publish a second edition, we thought it would almost be impossible to update any chapter. Remote sensing technology in general has changed significantly since then, so has urban remote sensing. Thus, we decide to edit a new volume, instead of updating the 2006 volume. In addition to Drs. Weng and Quattrochi, Dr. Paolo Gamba (University of Pavia, Italy) was invited to be a co-editor.

The second edition reflects new developments in satellite sensors, image processing methods and techniques, and wider applications of urban remote sensing in order to meet societal and economic challenges. This book is divided into four sections. Section I focuses on data, sensors, and systems considerations and algorithms for urban feature extraction; Section II illustrates applications in assessing and modeling urban landscape compositions, patterns, and structures; Section III presents methods for monitoring, analyzing, and modeling urban growth; and Section IV demonstrates urban planning and socioeconomic applications. For each section, we are particularly interested in addressing the following issues:

- Methods for upscaling urban feature extraction to the global scale (Section I)
- New methods in mapping and detecting urban landscape features and structures (Section II)
- Mapping and monitoring urbanization in developing countries (Section III)
- Urban sustainability and environmental issues (Section IV)

Section I includes three chapters concerning methods and algorithms for extracting urban extents that may be applied globally. Chapter 1 introduces the generation of global urban footprint (GUF) based on data from TerraSAR-X and TanDEM-X at a spatial resolution of 12 m. GUF aims at deriving a GUF map with automation. Chapter 2 presents an experimental development of an on-demand system for human settlement mapping using the Landsat archive. The system was implemented with automated algorithms of satellite data selection for user's preference and human settlement mapping using a machine learning–based method called Learning with Local and Global Consistency. In Chapter 3, a novel morphological building index (MBI) and its improved versions are introduced. MBI utilized the spectral–spatial properties of buildings (e.g., contrast, size, and directionality) by a set of morphological operators (e.g., top-hat by reconstruction, granulometry, and directionality) and can be applied in a large area of complex building patterns.

Section II introduces novel methods for mapping and detecting urban features and structures. Very high resolution (VHR) satellite images provide an ideal data for building mapping. However, these images lack the height information and are usually acquired off-nadir. These limitations pose challenges for mapping buildings in off-nadir VHR satellite images. Chapter 4 identifies the challenges associated with building detection from off-nadir VHR images based on stereo 3D information and presents a few solutions through a case study. In Chapter 5, two recent projects—the World Urban Database and Portal Tools (WUDAPT) and the Global Human Settlement Layer (GHSL) project—are compared to find their agreement on mapping built-up and built density. WUDAPT uses the Local Climate Zone (LCZ) scheme, a generic typology of urban structures, and supervised classification, while GHSL-LABEL is derived from physical characteristics of settlements such as vegetation cover and building height. The result of cross-comparison proved useful to identify both doubtful LCZ maps and areas of low confidence within the maps. Chapter 6 explores the use of off-nadir satellite images for urban change detection. Close-to-nadir satellite images are commonly used in previous studies to avoid the mis-registration caused by image relief displacements. To use off-nadir images, a change detection procedure is presented in this chapter that uses the Patch-Wise Co-Registration method to overcome the mis-registration problem and integrates other methods to enable accurate change detection using images taken from different sensors and platforms.

Over the past decade, remote sensing technology has been increasingly employed for developing countries for mapping and monitoring urbanization and associated environmental changes. Section III illustrates a few cases of this direction of application. Chapter 7 analyzes urban growth in four megacities in India to understand land use changes over the past three decades and associated environmental deterioration. Further, this chapter models future land uses to examine different scenarios of urban growth and their implications for sustainable development. Chapter 8 continues to examine urbanization in Asia, but focuses on Vietnam. Urbanization is a major trend in the Asia-Pacific region where many cities are threatened by natural hazards such as urban flooding, typhoon, tsunami, and sea-level rise. In Chapter 8, an annual impervious surface map was generated for the greater Hanoi area by using time series Landsat imagery from 1988 to 2015. The rapid but uneven increase in impervious surfaces over time shows agreement with major events of economic transitions in Vietnam. In Chapter 9, the derivation of impervious surfaces in a desert environment is explored. The authors applied spectral mixture analysis and a machine learning method to map the subpixel distribution of urban impervious surfaces in Dubai, United Arab Emirates. The main sources of errors in the estimations were found to relate to the spectral confusion of impervious surfaces with dark sand and certain types of desert plants. Chapter 10 intends to extract urban densities and to model urban sprawl in several cities in Argentina, South America. The methodology consisted of extracting urban density classes using spectral mixture signatures and applying a predictive simulation (LanduseSIM) for a 30-year period to reveal the process of sprawl in the nation.

The last part of the book, Section IV, examines case studies of urban planning and socioeconomic applications of remote sensing technology. Chapter 11 reports on the evolution of different methodologies used to develop HEAT Scores as urban energy consumption metrics. HEAT Scores are defined for each house using high-resolution thermal infrared imagery obtained from the Thermal Airborne Broadband Imager (TABI-1800) and are developed as a part of the HEAT (Heat Energy Assessment Technologies) research project, initially developed as a public GeoWeb service designed to help residents improve their home energy efficiency and reduce greenhouse gas emissions. This project was conducted on 9000+ houses in 12 communities in the southwest region of Calgary, Alberta, Canada. In Chapter 12, a study was conducted to study the interplay between air pollution (as estimated from remotely sensed data) and clinical records, and to find out the relationship among black particulate concentration, micro- and macrovascular disease onsets, and hospitalization tracks. Experimental results show that effective connections between the estimated air quality and the clinical data behavior can be accurately derived by the methods for data mining over large-scale heterogeneous records. In the last chapter of this book, Chapter 13, EO satellite data and spatial analysis coupled with qualitative survey-based assessments are used to tackle the challenges of urban green planning and monitoring in the city of Salzburg, Austria, in the frame of a longer-term monitoring endeavor using VHR satellite data in 5-year intervals.

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We thank all the contributors for making this endeavor possible. Furthermore, we offer our deepest appreciation to all the reviewers who have taken precious time from their busy schedules to review the chapters submitted to this book. Finally, we are indebted to our families for their love and support. It is our hope that the publication of this book will provide fresh stimulation to students, researchers, and practitioners to conduct more in-depth studies on urban remote sensing, and will open up new opportunities for EO technology transfer and data services to developing countries. The realization of the societal and economic benefits of EO technology and sustaining of the Earth requires cooperation between developed and developing countries through such a framework as GEO.

The reviewers of the chapters for this book are as follows (in alphabetical order): Raid Al-Tahir, Christoph Aubrecht, Gang Chen, Xuefei Hu, Xiuping Jia, Alexander Keul, Kourosh Khoshelham, Wenzhi Liao, Linlin Lu, Hiroyuki Miyazaki, María Teresa Camacho Olmedo, Tonny J. Oyana, Dale A. Quattrochi, Stevan Savic, Yang Shao, Limin Yang, Nithiyanandam Yogeswaran, and Hongsheng Zhang.

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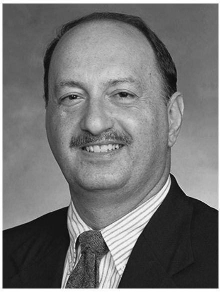
Editors

Qihao Weng, PhD, is the director of the Center for Urban and Environmental Change and a professor of Remote Sensing and GIS at Indiana State University, and worked as a Senior Fellow at the National Aeronautics and Space Administration from December 2008 to December 2009. He earned his PhD in geography from the University of Georgia in 1999. Dr. Weng is currently the Lead of Group on Earth Observation (GEO) Global Urban Observation and Information Initiative and serves as editor-in-chief of *ISPRS Journal of Photogrammetry and Remote Sensing* and the series editor of Taylor & Francis Series in Remote Sensing Applications. He has been the organizer and program committee chair of the biennial IEEE/ISPRS/GEO-sponsored International Workshop on Earth Observation and Remote Sensing Applications conference series since 2008; he was a national director of the American Society for Photogrammetry and Remote Sensing from 2007 to 2010 and a panelist of U.S. DOE's Cool Roofs Roadmap and Strategy in 2010.

In 2008, Dr. Weng received a prestigious NASA senior fellowship. He received the Outstanding Contributions Award in Remote Sensing in 2011 from the American Association of Geographers in 2011 as well as the Willard and Ruby S. Miller Award in 2015 for his outstanding contributions to geography. In 2005 at Indiana State University, he was selected as a Lilly Foundation Faculty Fellow, and in the following year, he also received the Theodore Dreiser Distinguished Research Award. In addition, he was the recipient of the 2010 Erdas Award for Best Scientific Paper in Remote Sensing (first place) and the 1999 Robert E. Altenhofen Memorial Scholarship Award, which were both awarded by the American Society for Photogrammetry and Remote Sensing. He was also awarded the Best Student-Authored Paper Award by the International Geographic Information Foundation in 1998. Dr. Weng has been invited to give more than 90 talks by organizations and conferences held in the United States, Canada, China, Brazil, Greece, UAE, and Hong Kong, and is honored with distinguished/chair/guest professorship at 11 top universities in China, which includes Peking University.

Dr. Weng's research focuses on remote sensing applications to urban environmental and ecological systems, land use and land cover changes, urbanization impacts, environmental modeling, and human–environment interactions. Through a serial invention of innovative algorithms, techniques, methods, and theories for urban remote sensing, he focuses research efforts on fostering the understanding of remote sensing in geographical applications and narrowing down the gap between geography and landscape ecology. Dr. Weng is the author of 206 articles (journal articles, chapters, and others) and 10 books. According to Google Scholar, as of July 2017, his SCI citation reached 11,568 (H-index of 49), and 28 of his publications had more than 100 citations each. Dr. Weng's research has been supported by funding agencies that include NSF, NASA, USGS, USAID, NOAA, National Geographic Society, European Space Agency, and Indiana Department of Natural Resources.



Dale Quattrochi, PhD, is a senior research scientist with the NASA Marshall Space Flight Center in Huntsville, Alabama, and has more than 26 years of experience in the field of Earth science remote sensing research and applications. Dr. Quattrochi's research interests focus on the application of thermal remote sensing data for analysis of heating and cooling patterns across the diverse urban landscape as they affect the overall local and regional environment. He is also conducting research on the applications of geospatial statistical techniques, such as fractal analysis, to multiscale remote sensing data.

Dr. Quattrochi is the recipient of numerous awards including the NASA Exceptional Scientific Achievement Medal, NASA's highest science award, which he received for his research on urban heat islands and remote sensing. He is also a recipient of the Ohio University College of Arts and Science, Distinguished Alumni Award. Dr. Quattrochi is the co-editor of two books: *Scale in Remote Sensing and GIS* (with Michael Goodchild) published in 1997 by CRC/Lewis Publishers and *Thermal Remote Sensing in Land Surface Processes* (with Jeffrey Luvall) published in 2004 by CRC Press. He earned his PhD degree from the University of Utah, his MS degree from the University of Tennessee, and his BS degree from Ohio University, all in geography.

Paolo Gamba, PhD, (SM'00, F'13) is professor of telecommunications at the University of Pavia, Italy, where he leads the Telecommunications and Remote Sensing Laboratory and serves as deputy coordinator of the PhD School in Electronics and Computer Science. He earned his Laurea degree in electronic engineering (cum laude) from the University of Pavia, Italy, in 1989, and his PhD in electronic engineering from the same university in 1993.

He served as editor-in-chief of the *IEEE Geoscience and Remote Sensing Letters* from 2009 to 2013, and as chair of the Data Fusion Committee of the IEEE Geoscience and Remote Sensing Society from October 2005 to May 2009. Currently, he serves as GRSS executive vice president.

Dr. Gamba has been the organizer and technical chair of the biennial GRSS/ISPRS Joint Workshops on "Remote Sensing and Data Fusion over Urban Areas" since 2001. He also served as technical co-chair of the 2010 and 2015 IGARSS conferences in Honolulu (Hawaii) and Milan (Italy), respectively.

Dr. Gamba has been the guest editor of special issues of *IEEE Transactions on Geoscience and Remote Sensing*, *IEEE Journal of Selected Topics in Remote Sensing Applications*, *ISPRS Journal of Photogrammetry and Remote Sensing*, and *International Journal of Information Fusion and Pattern Recognition Letters* on the following topics: urban remote sensing, remote sensing for disaster management, and pattern recognition in remote sensing applications.

He has been invited to give keynote lectures and tutorials on several occasions about urban remote sensing, data fusion, and EO data for exposure and risks. He published more than 130 papers in international peer-review journals and presented more than 250 research works in workshops and conferences.

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Section I

Data, Sensors, and Systems Considerations and Algorithms for Urban Feature Extraction

1 The Global Urban Footprint

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CONTENTS

1.1 INTRODUCTION

One of the most urgent present and future challenges is global urbanization. The real dimension of this phenomenon is still not completely understood. Particularly, precise worldwide information on the location and distribution of human settlements in urban and in rural areas is lacking. This chapter presents the Global Urban Footprint (GUF), which aims to close this information gap. The GUF is an inventory of human presence on Earth in the form of a raster map (Esch et al. 2017) that reflects the human settlements pattern in a thus far unique spatial resolution of 12 m.

In 1950, the urban population was only half the size of the rural population. In 2008, for the first time, the urban population became larger than the rural population. This observation, commonly known as the global urban transition (UN 2014), indicates that the majority of people on Earth inhabit some kind of urban environment. Various publications and reports on the vast urbanization (Birch and Wachter 2011; UN 2001, 2004, 2006) have made it clear that cities play a primary role as drivers of all social, economic, and environmental systems. Currently, there is considerable evidence that global urbanization affects the entire spectrum of human and natural systems, in particular with respect to energy, water, food, biodiversity, climate, or human health (Grimm et al. 2008; Kaufmann et al. 2007; Moore et al. 2003; Tilman et al. 2011; Zhou et al. 2004). However, many fundamental questions about the spatial dimension of urbanization could still not be answered to satisfaction: Which proportion of the global land surface is covered with built-up area? What is the ratio between urban and rural settlements area? How many cities are on Earth? Many studies agree that estimations of the effects of human presence on Earth are strongly biased (Potere and Schneider 2007; Potere et al. 2009) and that the dynamics of urban growth and its economic and social effects are poorly understood (Batty 2008). The lack of a shared definition of urban as opposed to rural areas as well as a missing spatially detailed and up-to-date inventory of the entirety of urban and rural settlements on Earth further complicates such analysis. This data gap is now closed by the GUF, which is described in this chapter.

1.2 GENERATING THE GUF

1.2.1 Global Urban Mapping Using Earth Observation

Earth observation (EO) imagery certainly represents an effective approach to overcome the lack of objective spatial information on the structure and spatiotemporal development of human settlements on Earth (Esch et al. 2010). The global classification of human settlements is a very specific topic in urban remote sensing because of the necessary trade-off between spatial resolution of the available EO data and ability to collect a global coverage within a reasonable period of time. A comprehensive overview of the available EO-based and EO-supported global geo-information layers on human settlements is provided by Potere et al. (2009), Gamba and Herold (2009), and Ban et al. (2015a). As they report, the majority of these data sets are generated from medium-resolution optical EO data, as, for instance, the largely established MODIS 500 (Schneider et al. 2010) and GlobCover 2009 (Bontemps et al. 2011) land cover maps with a spatial resolution of 500 and 300 m, respectively. However, their capabilities to accurately detect and delineate small and scattered villages and towns are quite limited.

More recent initiatives aim to provide spatially more accurate human settlement layers based on high-resolution EO data. NASA, for example, released in 2013 a new global nighttime light product derived from imagery of the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi NPP satellite (NASA 2012). The European Joint Research Center (JRC) with the Global Human Settlements Layer (GHSL) presented a procedure for an automatic extraction of built-up areas by analyzing global Landsat coverage for several time steps (Pesaresi et al. 2016). Wieland and Pittore (2016) also proposed a method based on object-based analysis and SVM to classify urban large areas from Landsat 8. Miyazaki et al. (2013) propose a method based on the integrated analysis of ASTER satellite images and geographic information system (GIS) data to produce a new global high-resolution settlement mask. By means of Envisat-ASAR radar imagery, Gamba and Lisini (2012) and Ban et al. (2015b) derived a built-up area layer that aims at improving the GlobCover 2009 urban class.

1.2.2 From TanDEM-X Imagery to GUF

In 2007 and 2010, the German Aerospace Center (DLR) launched the EO radar satellites TerraSAR-X and TanDEM-X, respectively (Krieger et al. 2007; Werninghaus

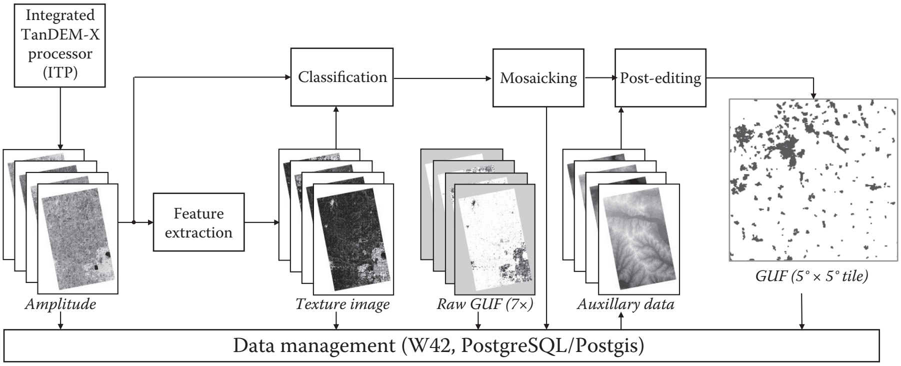

FIGURE 1.1 Urban footprint processor (UFP) processing environment to generate the GUF.

and Buckreuss 2010). Because the two missions collect a global coverage of very high resolution SAR imagery within a comparably short period, they are optimal to support global environmental monitoring activities. Encouraged by the promising outcomes of previous studies (Esch et al. 2010, 2011), DLR's German Remote Sensing Data Center (DFD) started the internal GUF initiative. The goal of this activity was the development of a fully automated processing framework to produce a worldwide map of human settlements in a thus far unique spatial detail by analyzing a global coverage of TerraSAR-X and TanDEM-X images collected in the context of the TanDEM-X mission (Esch et al. 2012).

The production of the GUF layer is based on the Urban Footprint Processor (UFP). This is a fully automatic, generic, and autonomous processing environment, orchestrating an extensive suite of processing and analysis modules. This system ensures an effective processing of the 182,249 TerraSAR-X and TanDEM-X single look complex (SSC) image products mostly collected in 2011 and 2012 (93%) in Stripmap mode with 3 m ground resolution. To fill data gaps, single scenes collected in 2013 and 2014 were included as well. Figure 1.1 provides a schematic overview on the UFP processing environment. The UFP consists of five main technical modules covering functionalities for data management, feature extraction, unsupervised classification, mosaicking, and automatic post-editing.

1.2.2.1 Feature Extraction

Esch et al. (2011) demonstrated that built-up areas show a characteristic small-scale heterogeneity of local backscatter in TSX Stripmap images that can efficiently be used to delineate built-up areas. This effect is related to the specific properties of SAR data for built environments that exhibit strong scattering due to double bounce effects and direct backscattering from the vertical structures (e.g., buildings, bridges, traffic signs). At the same time, shadow effects occur on those sides of vertical structures that are facing away from the incoming radar beams. To define this local image heterogeneity, or texture, the UFP calculates the speckle divergence feature defined as the ratio between the local standard deviation and local mean of the backscatter computed in a defined local neighborhood. A detailed description of the feature extraction algorithm is provided in Esch et al. (2013b).

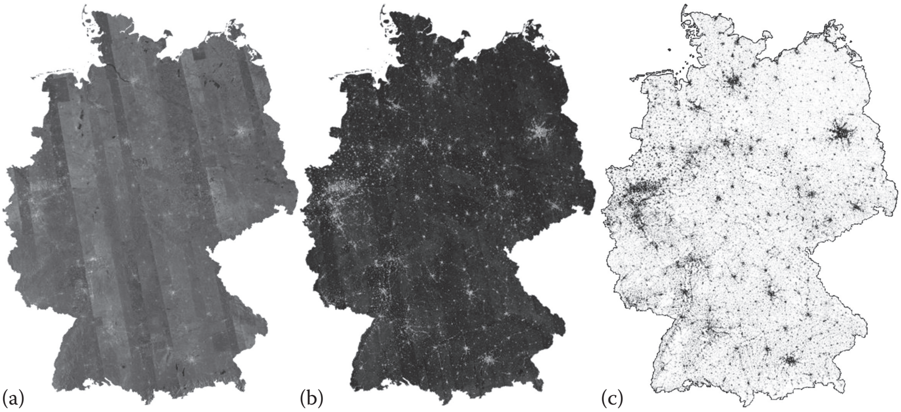

FIGURE 1.2 Backscattering amplitude (a), speckle divergence or texture image (b), and GUF (c).

Figure 1.2 shows TSX Stripmap amplitude data, the speckle divergence texture image derived from the amplitude data and the resulting GUF layer for the area of Germany next to each other. In the amplitude data (Figure 1.2a), urban areas show high values represented by bright gray tones, but other land cover types do so as well. The high-texture regions appearing as bright spots in the speckle divergence image (Figure 1.2b) show the urban areas in Germany very distinctively. Since the high local image heterogeneity originates from intense backscatter plus shadow effects around vertical structures, the texture directly relates to the presence of buildings or any structure with a distinct vertical component. This characteristic is used to derive the GUF (Figure 1.2c).

1.2.2.2 Unsupervised Classification

The classification step combines the analysis of the amplitude and the speckle divergence images. For that purpose, an unsupervised classification method based on advanced Support Vector Data Description (SVDD) one-class classification was implemented as described in detail in Esch et al. (2013b). The result of the classification procedure is a binary raster layer assigning the class built-up area and, for all regions not assigned to this class, the category non–built-up. The implemented classification method proved to be very robust, although over- or underestimation of a built-up area might still occur when scenes show very specific land cover distributions—for instance, in the case of scenes covering a coastline and mostly showing water with only few areas representing land surface. Such specific land cover configurations lead to extreme distributions of the amplitude and texture statistics of the corresponding images, which finally hinders the proper definition of accurate classification settings. To compensate for the resulting deviations between the GUF masks, a total of six additional GUF raw versions with systematically altered classification settings—that can be considered as confidence levels—are generated. Three versions are based on constantly stricter thresholds compared to the automatically defined version (leading to the assignment of less built-up area) and three versions with more relaxed settings compared to the original definition (thus showing an increased amount of potential built-up regions).

1.2.2.3 Mosaicking

The individual GUF raw masks in their original image geometry were merged to tiles of 5° × 5° geographical latitude and longitude for each of the seven GUF confidence levels, to provide more manageable working units for the post-editing procedure. As a result, 1,284,743 GUF masks (182,249 masks for each of the seven confidence levels) were reduced to 8309 GUF tiles (1187 masks for each of the seven confidence levels). The chosen tile size presents a reasonable trade-off between file size, number of tiles, and practicability in terms of data and file handling. The conformity of the merge is also retained as a quality measure. During the mosaicking, all multiple GUF accounts in the overlapping areas of neighboring scenes were aggregated by means of a majority vote for each single pixel and each separate GUF versions 1–7. As a result, each tile comprises seven GUF bands in the geometric resolution of 0.4 arc seconds (arcsec) (~12 m), or approaching the poles, in correspondingly lower longitudinal resolutions (e.g., north of 50°N up to 60°N in 0.6 arcsec).

1.2.2.4 Automated Postprocessing

The final stage of the GUF production is postprocessing. This highly automated procedure consists of two steps. First, image segmentation is conducted, which transfers all clusters of connected pixels classified as built-up in each of the seven GUF raw raster layers (confidence levels) into individual image objects. Second, the appropriate local GUF confidence level is selected and all GUF segments from the resulting collection that most likely represent false alarms are removed. For this second, rule-based step, auxiliary data, such as relief and water masks, are used. The postprocessing and the auxiliary data are described in detail in Esch et al. (2017).

1.3 THE GUF DATA SET

Figure 1.3 shows four urban footprints of Tokyo, Cairo, Minneapolis, and Ho Chi Minh City. Tokyo is a very densely built megacity with about 36 million people. Also, the center of the mega region of Cairo (estimated 80 million people, with estimated 24 million in Cairo City) is very densely built. The urban footprint of the whole Egyptian mega region follows the Nile and its delta. The urbanization of the Tokyo area is shaped by the surrounding mountains. Compared to these two megacities, Minneapolis (USA) is quite small. Together with its twin city Saint Paul, it has a dense urban core and extensive residential areas with many parks. The surroundings of Minneapolis are characterized by medium-sized cities along the main streets and single farms in between.

Ho Chi Minh City in Vietnam is a megacity with around 7 million people. In the north east, there is a mangrove area that is almost uninhabited. The people live, apart from in the city core, mainly along the many rivers and canals in the region, resulting in a characteristic settlement pattern.

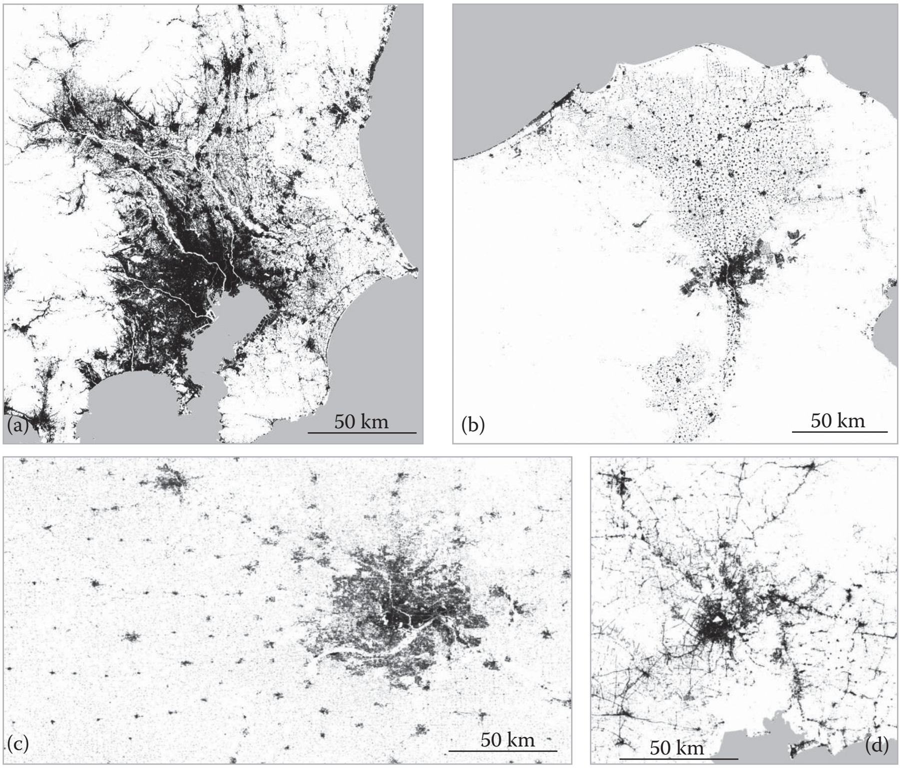

FIGURE 1.3 Urban footprints of (a) Tokyo (Japan), (b) Cairo (Egypt), (c) Minneapolis (USA), and (d) Ho Chi Minh City (Vietnam).

Because of the high spatial detail, not only (mega) cities but also rural areas with far fewer inhabitants can be studied with the GUF. Figure 1.4 shows four "rural" regions around the world. The name "rural" is actually not really appropriate, because built-up areas cover still a large part of the area in some of these regions. Each region has its own pattern of villages and/or single houses. The analysis of settlement patterns and structures provides unique and exciting insights regarding the roots of historic and cultural origin of settlements and man-made landscapes.

The GUF layer is provided as binary raster data sets in 8-bit, LZW-compressed GeoTiff format with a value of 255 indicating a built-up area, a value of 0 representing all non–built-up areas, and no data assigned by the value 128. The projection is geographic coordinates (Lat, Lon). The geometric resolution of the original GUF data is 0.4 arcsec, which corresponds to 12 m near the equator, while the GUF layer for any nonscientific/noncommercial use shows a reduced resolution of 2.8 arcsec (84 m near the equator). Toward the poles, the spatial resolution decreases to 0.6 arcsec between 50° and 60°N/S, 0.8 arcsec from 60° to 70°N/S, and 1.2 arcsec in areas >80°N/S. The generalized GUF version in 2.8 arcsec is directly derived from the 0.4-arcsec version by assigning a value of 255 (=built-up) to all pixels whose coverage contains a proportion of >25% GUF area as defined by the original 0.4-arcsec data.

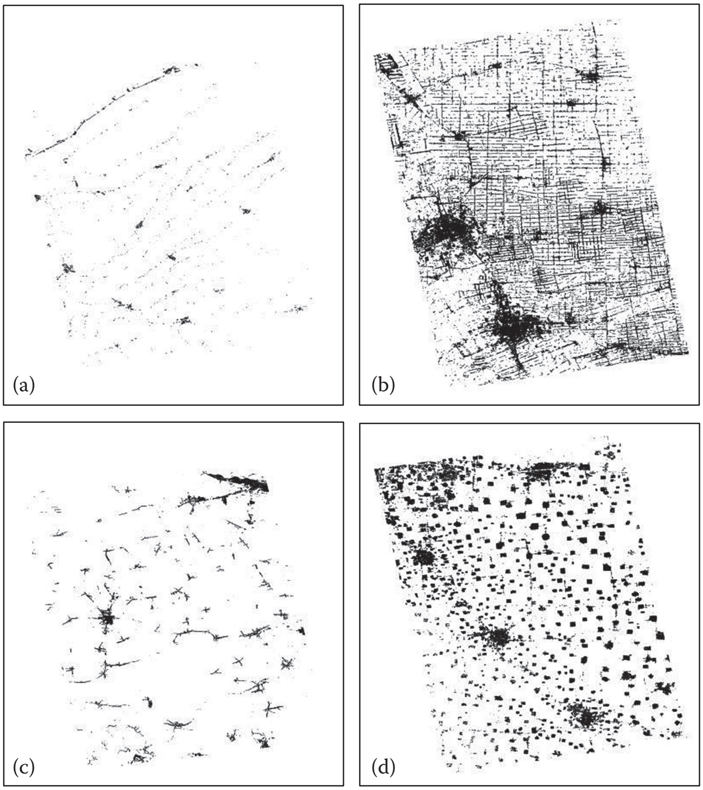

FIGURE 1.4 Footprints of the built-up areas in "rural" regions: (a) Saint-Henri/Saint-Gervais, Quebec, Canada; (b) Hai'an, Jiangsu, China; (c) Diakowar, Osijek-Baranja, Croatia; (d) Zhaoxian, Hebei, China.

On a regional scale, the thematic accuracy and the strengths and weaknesses of the GUF layer have already been documented in detail by comparisons to ground truth data in several studies and projects such as those presented by Esch et al. (2013a), Felbier et al. (2014), Gessner et al. (2015), and Klotz et al. (2016), who conducted a detailed multi-scale cross-comparison between the GUF layer and existing low-resolution (MOD500, GlobCover) and high-resolution (GHSL-SPOT2.5m) human settlement data derived from EO imagery. A statistical comparison of MOD500, GlobCover, GHSL, and GUF at the local and global scale is discussed in Esch et al. (2017).

Figure 1.5 shows the GUF of three cities in comparison to MOD500, GlobCover, and the FTS European Soil Sealing Layer (ESS). Figure 1.5a and b shows that the GUF displays a high level of detail, even with 2.8″ spatial resolution. Especially in the surroundings of New Delhi and Montreal, the GUF could identify much more settlements in comparison to MOD500 and GlobCover, respectively. This can be mainly attributed to the higher spatial resolution of the GUF. Figure 1.5c shows the GUF in comparison to the high-resolution (20 m) ESS. The similarity is very high. However, the ESS only covers the EU member states. Other regions such as Africa or Asia

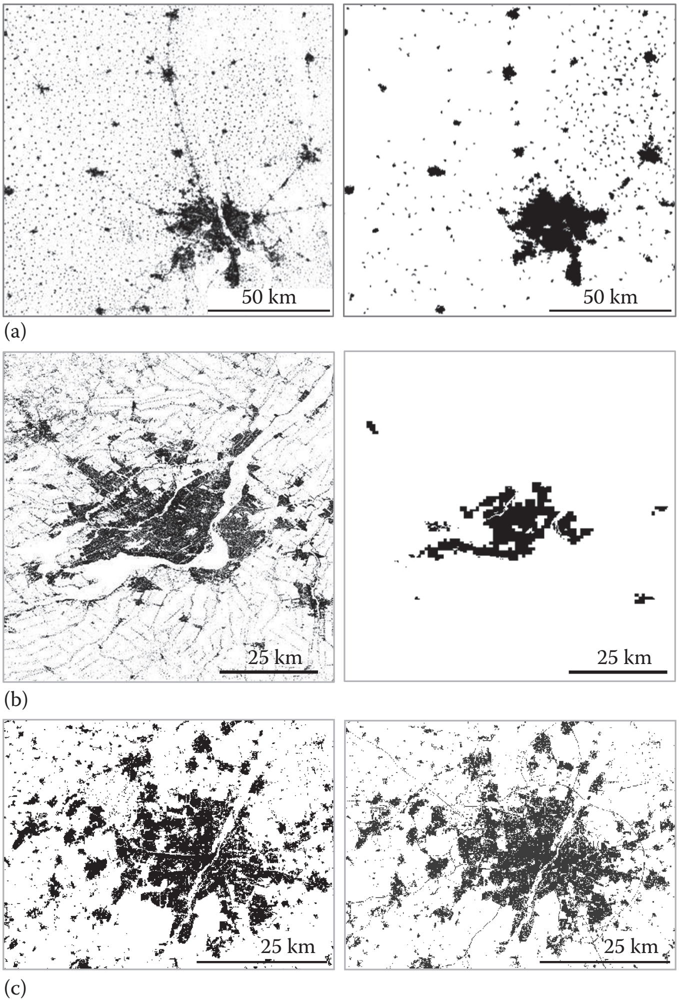

FIGURE 1.5 Comparison of the GUF (2.8″) on the left to other urban layers: (a) GUF New Delhi (India) compared to MODIS 500; (b) GUF of Montreal (Canada) compared to GlobCover2009; (c) GUF of Munich (Germany) compared to FTS European Soil Sealing.

often lack such detailed large area data sets. The ESS also shows roads, which are, by definition, not included in the GUF because roads do not have vertical structures.

1.4 ANALYZING URBAN FOOTPRINTS

With the GUF data set, for the first time, urban footprints from all over the world can be analyzed in comparison. The different cities in Figure 1.3 allow questions to the total area of the city, or the urbanization of the surroundings, to be answered. And the urban footprints in Figure 1.4 allow a comparison of the urbanization of

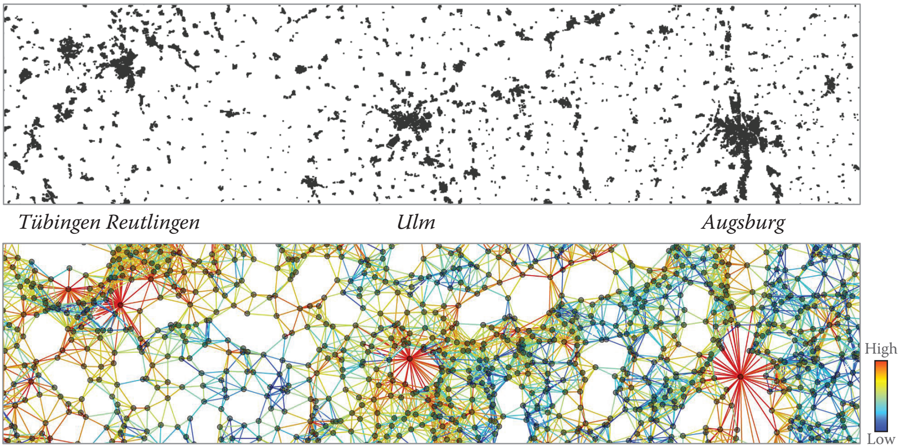

FIGURE 1.6 Settlement analysis of Tübingen, Reutlingen, Ulm, and Augsburg in southern Germany. Top: GUF settlement mask as input. Bottom: local significance measure.

rural areas. Even more interesting analysis can be carried out if additional data are used. For example, in combination with population data, population density can be calculated. Additional historical data sets show urban growth.

The binary GUF map can also be used to derive various spatial metrics, for example, on the compactness or dispersion of the settlements. Figure 1.6 shows the result of a network analysis based on the GUF. The urban areas were segmented, nodes were assigned, and the edges between the nodes were calculated. Subsequent derived statistics allow the visualization of various network characteristics, such as the connectivity and centrality of urban settlements within a region. In Figure 1.6, the local connectivity is shown. This measure characterizing the connection between the nodes combines the size of the two connected nodes with the distance between them (Esch et al. 2014). Thus, the connection (arcs) between two large urban areas (nodes) that are close together receives the highest local significance (colored red). When visualizing this network measure, the urban centers (here Tübingen, Reutlingen, Ulm, and Augsburg) are highlighted in red, whereas the areas with small dispersed settlements become blue.

1.5 SUMMARY AND OUTLOOK

With 12-m pixel spacing, the GUF data represent a precise inventory of both large urban agglomerations and the dispersed small-scale built-up areas in rural regions. It allows detailed quantitative and qualitative analyses and comparisons of settlement properties and patterns from the local municipal level up to the global scale. Urban areas over the whole globe are mapped with the same, comparable method. In this context, the GUF layer also benefits from the fact that the global input data could be collected within just 2 years. The GUF data set can help to acquire a better understanding of the urbanization phenomenon and to respond appropriately to future challenges related to sprawling cities, population explosion, poverty reduction, economic growth, climate change and carbon emissions, and the loss to biodiversity.