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REMOTE SENSING OF HUMAN SETTLEMENTS

edited by
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Chapter

12

New and Emerging Instruments and Some Emerging Trends for Remote Sensing of Human Settlements

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12.1 INTRODUCTION

As presented throughout this volume, many characteristics of human settlements are measurable via remotely sensed imagery. This chapter begins with an outline of the current and planned satellite platforms and sensors that are capable of addressing questions relating to human settlement characterization. Specifically, the following discussion focuses on a subset of sensors and platforms that provide terrestrial or very-near terrestrial measurements appropriate for analyzing settlement characteristics or the effects of settlement occupation and development. The first part of the chapter emphasizes space-based instruments and platforms and their potential to contribute to sensing of human settlements. This emphasis derives from the more synoptic perspective of the satellite-based systems, and the generally broader applications possible with these systems.

The chapter concludes with a special study illustrating the integration of advanced satellite and airborne data, including their resolution specifications, and some comparative techniques for data fusion. These data selection and processing techniques are merely suggestive of the many methods of remote sensing of human settlements currently being developed in various facilities around the world.

12.2 SATELLITE SENSORS AND HUMAN SETTLEMENT

To provide a foundation for sensor-specific information, it is first necessary to identify broad categories of settlement characteristics to which a specific sensor should be able to make a contribution. These categories include settlement extent, change, settlement-related environmental effects, and infrastructure. While not an exhaustive list, these categories encompass a broad range of settlement characteristics that in total provide a reasonable benchmark against which the capabilities of specific sensors can be measured.

The sensors discussed represent a continuation of trends in instrument development begun in the mid-1990s; therefore this sensor-focused discussion begins with a summary of the trends in current platforms that provide a foundation for the sensors and platforms that are planned for near-term or long-term launch. Table 12-1 summarizes systems utilizing new or innovative technologies. The table is arranged chronologically by launch date (right-hand column). In the first column, platforms (to the left) and the associated sensors (underneath and to the right in the first column) are shown, followed by the country or countries of origin, spatial resolution, sensor type, spectral characteristics, revisit cycle, and the footprint (image size or swath width). A new generation of high spatial resolution sensors is now operational, such as *Ikonos* (1-m panchromatic and 4-m multispectral [MSS]) launched in 1999, followed by a series of others including *EROS-A1* (1-m and 1.8-m panchromatic), *QuickBird-2* (0.6-m panchromatic and 2.4-m MSS), *OrbView-3* (1-m panchromatic and 4-m MSS), *SPOT-5* (2.5-m and 5-m panchromatic), and *CartoSat-1* (2.5-m panchromatic stereo). In addition there are several sensors designed for special purposes, to be discussed subsequently. The second part of Table 12-1 identifies platforms and sensors nearing scheduled launch date through 2007. Existing or follow-on systems not reflecting major changes in technology or specifications are not included, e.g. *Landsat*, *SPOT 1-4*, and *Radarsat 1*. The discussion concludes with a prospective look at how current trends in sensor design relate to general questions of settlement characterization, and whether there are any identifiable gaps in the planned sensor constellation that would impact remote sensing applications to settlement analysis.

12.2.1 Settlement Characteristics Observable from Space-based Sensors

The primary benefit of applying spaceborne observational technologies to the characterization and analysis of settlements is the recurrent synoptic view provided by these systems. Recurrence is important in the identification of temporal trends in settlement size and character, both in terms of non-repetitive changes through time, and periodic changes occurring at a variety of temporal scales such as seasons and years. The synoptic nature of remotely sensed imagery allows for the simultaneous characterization of large areas of the landscape, providing broad-scale "snapshots" of conditions over a large region at a specific time. Settlement characteristics discernable through the analysis of individual and sequential imagery include the following: the spatial extent and character of human settlements; changes in the nature and characteristics of settlements; environmental effects associated with and resulting from human settlements; and infrastructure of human settlements. Table 12-2 shows the applicability of several sensors toward the four categories.

Measuring the extent of human settlements via remotely sensed data allows for the derivation of multiple variables important in characterizing settlement dynamics. For example, the areal extent of a given settlement may allow for population estimation in the absence of census data or between census data collection periods. Likewise, comparison of the extent of multiple settlements may provide for the systematic comparison of settlements in terms of population or population density. More detailed definition of settlement components (e.g., building types, land use) and the measurement of the extent of those components within a settlement provide a means for characterizing regions within a settlement (e.g., urban, suburban, residential, commercial, etc.). The high spatial resolution satellites, such as *Ikonos*, *EROS-A1*, *QuickBird*, and *OrbView-3*, provide imagery useful for identifying and delineating individual structures and cover types, and isolating areas of settlement change. Remotely sensed imagery with a wide variety of resolutions and multiple spectral bands can very easily be used to identify the extent of settlements, both through automated classification schemes and manual extraction.

Change detection and characterization is also easily accomplished through the application of remotely sensed imagery. The collection of a series of images over a given settlement adds a temporal dimension to remotely sensed data. Analysis of change through time

Table 12-1 Sensor system characteristics.

Platform/ Sensor	Country	Resolution (m)	Sensor Type[1]	Spectral Characteristics[2]	Revisit Cycle (Days)	Footprint (Image Size or Swath in km)	Launch Date
IKONOS	US	1, 4	Pan, MSS	VIS, NIR	1-3	11 x 11	Sep, 1999
CBERS-1	China/ Brazil				26*		Oct, 1999
WFI		260	WFI	2 band, Red, NIR	5	890	
CCD Camera		20	Pan, MSS	5 band, Pan, VNIR	3	113	
IR-MSS		80, 160	Pan, MSS	4 band: VNIR, SWIR, TIR	26	120	
Terra	US						Dec, 1999
MODIS		250, 500, 1000	MSS	36 bands: VIS to TIR	1-2	10 x 2,330	
ASTER		15, 30, 90	MSS	14 bands: VNIR, SWIR, TIR	4-16	60	
MISR		250-275	MISR	9 cameras (4 bands ea.), VIS, NIR	9	360 x 20,000	
CERES		20 km	Pan	3 bands: UV-VIS, TIR, UV-FIR	1	Limb to Limb	
MTI	US	5 20		VIS, NIR MIR, TIR	7-21	12 x 12	Mar, 2000
EROS-A1	Israel/US	1, 1.8	Pan	VIS, NIR	1.8 - 4	12.7	Dec, 2000
QuickBird 2	US	0.6, 2.4	Pan, MSS	VIS, NIR	1 - 3.5	16.5 x 16.5	Oct, 2001
Proba	ESA						Oct, 2001
CHRIS		25	Compact High Resolution Imaging Spectrometer	62 band VNIR	N/A	18.6	
HRC		10	High Resolution Camera	Pan	N/A	N/A	
EnviSat	ESA						Feb, 2002
ASAR		30 to 1000	SAR	5 mode		5 to 400	
MERIS		300 to 1200	ocean color spectrometer	15 band, VIS to NIR	3	1,150	
MWR		20 km	microwave radiometer	2 channel	N/A	20	
AATSR		1 x 1 km	Sea surface temperature scanning radiometer	2 VIS, 4 TIR	N/A	N/A	
Aqua	US						May, 2002
AMSR/E		5-56 km	Passive Microwave Radiometer	12 channel/6 Frequencies	1	1445	
MODIS		250, 500, 1000	MSS	36 bands: VIS to TIR	1-2	10 x 2,330	
AMSU		40.5 km	microwave	15 band	1	1,690	
AIRS		2.3 km, 13.5 km	MSS, Hyper	4 band: VIS/NIR; 2378 MIR to TIR	1	1,650	
HSB		13.5 km	microwave	4 bands	1	1,650	
SPOT-5	France	2.5 & 5 Pan, 10 MSS, 20 SWIR	Pan, MSS, SWIR	Pan, 3 band MSS, 1 band SWIR	26 Days*	60 x 60	May, 2002
ADEOS II	Japan						Dec, 2002
AMSR		5, 60	microwave radiometer	14 band	4	1,600	
GLI		1 km, 250 m		23 bands: VNIR, 6 bands: SWIR, 7 bands: in MIR and TIR	4	12 x 1,600	
POLDER		7000 x 6000	radiometer and polarimeter	8 bands: VNIR	4	1694 x 1644	
ICESat	US						Jan, 2003
GLAS		70	Laser Altimeter	3 lasers in visible and infrared	183	N/A	
OrbView 3	US	1, 4	Pan, MSS	Pan, 3 band VNIR	<3 days	8	Jun, 2003

ResourceSat (IRS-P6)	India	6	MSS	3 band VNIR		25	Oct, 2003
		23	MSS	4 band		140	
		80	WFI			1400	
CBERS-2	China/ Brazil				26		Oct, 2003
WFI		250	WFI	2 band, Red, NIR	5	890	
CCD Camera		20	Pan, MSS	5 band, PAN, VNIR	3	113	
IR-MSS		78, 156	Pan, MSS	4 band: VNIR, SWIR, TIR	26	120	
AC		125/250		Atmospheric Corrector		185	
Aura	US						Mar, 2004
OMI		13 x 13 km, 13 x 24 km 13 x 48 km	Hyper	740 bands: UV to VIS	1		
TES		530 x 5300		TIR		5.3 x 8.5	
CartoSat (IRS-P5)	India	2.5	Pan	VIS			May, 2005

What's on the Drawing Board

Platform/ Sensor	Country	Resolution (m)	Sensor Type[1]	Spectral Characteristics[2]	Revisit Cycle (Days)	Footprint (Image Size or swath in km)	Launch Date
EROS-B series	Israel/US	0.8	Pan, MSS	VIS, NIR	1.8 - 4 days	13	?
Radarsat 2	Canada	3-100	radar	C-band	24	20-500	2005
ALOS-1	Japan				46*		Sep, 2005
PRISM		2.5	Pan	VIS		35	
AVNIR-2		10	MSS	VIS, NIR		70	
PALSAR		10 - 100	radar	L-band		250-350	
IKONOS-X	US	0.5, 2.0	Pan, MSS	VIS, NIR	N/A	N/A	?
WorldView	US	0.5, 2.0	Pan, MSS	VIS, NIR	N/A	NA	2006
LANDSAT Next	US	Undetermined	Undetermined	Undetermined	Undetermine d	Undetermine d	?
OrbView-5	US	0.41, 1.64	Pan, MSS	VIS, NIR	N/A	NA	2007

Explanation of Sensor Types and Spectral Characteristics for Table 12-1
* more frequently with off-nadir pointing

[1]Sensor Type:
- Pan - panchromatic (single broad-spectrum band)
- MISR - Multi-angle Imaging SpectroRadiometer
- MSS - multispectral (multiple broad spectral bands)
- Hyper - hyperspectral (many narrow contiguous spectral bands)
- SAR - synthetic aperture radar
- WFI - Wide Field Imager

[2]Spectral Characteristics:
- UV - Ultraviolet (.01-.4μm)
- VIS - visible (.4-.7μm)
- NIR - near infrared (.7-1.5μm)
- SWIR - short wave infrared (1.5-3μm)
- MIR - middle infrared (3.0-8.0μm)
- TIR - thermal infrared (8.0-15.0μm)
- VNIR - visible and near infrared
- IR - infrared

N/A - Not applicable, such as resolution or footprint of an atmospheric limb analyzer that does not view the solid Earth
-or-
the data are not available.

Explanation of Acronyms used in Table 12-1

Platform/ Sensor	Acronym Description
IKONOS	-----
CBERS-1	China-Brazil Earth Resources Satellite
WFI	Wide Field Imager
CCD Camera	High Resolution CCD Camera
IR-MSS	Infrared Multispectral Scanner
Terra	
MODIS	Moderate Resolution Imaging Spectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
MISR	Multi-angle Imaging SpectroRadiometer
CERES	Clouds and the Earth's Radiant Energy System
MTI	Multispectral Thermal Imager
EROS-A1	-----
QuickBird 2	-----
PROBA	Project for On-Board Autonomy
CHRIS	Compact High Resolution Imaging Spectrometer
HRC	High Resolution Camera
EnviSat	
ASAR	Advanced Synthetic Aperture Radar
MERIS	MEdium Resolution Imaging Spectrometer
MWR	Microwave Sounder
AATSR	Advanced Along-Track Scanning Radiometer
Aqua	-----
AMSR/E	Advanced Microwave Scanning Radiometer - EOS
MODIS	Moderate Resolution Imaging Spectroradiometer
AMSU	Advanced Microwave Sounding Unit
AIRS	Atmospheric Infrared Sounder
HSB	Humidity Sounder for Brazil
SPOT-5	Satellite Probatoire d'Observation de la Terre
ADEOS II	Advanced Earth Observing Satellite
AMSR	Advanced Microwave Scanning Radiometer
GLI	Global Imager
POLDER	Polarization and Directionality of the Earth's Reflectances
ICESat	Ice, Cloud, and Land Elevation Satellite
GLAS	Geoscience Laser Altimeter System
OrbView 3	-----
ResourceSat (IRS-P6)	-----
CBERS-2	China-Brazil Earth Resources Satellite
WFI	Wide Field Imager
CCD Camera	High Resolution CCD Camera
IR-MSS	Infrared Multispectral Scanner
AC	Atmospheric Corrector
Aura	-----
OMI	Ozone Monitoring Instrument
TES	Tropospheric Emission Spectrometer
CartoSat (IRS-P5)	-----

What's on the Drawing Board

Platform/ Sensor	
EROS-B series	-----
Radarsat 2	-----
ALOS-1	Advanced Land Observing Satellite
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2
PALSAR	Phased Array type L-band Synthetic Aperture Radar
IKONOS-X	-----
WorldView	-----
LANDSAT Next	-----
OrbView-5	-----

Table 12-2 Sensors and application areas in the assessment of human settlements.

Platform/ Sensor	Resolution (m)	Purpose	Applicable Uses in the Assessment of Human Settlements: Extent	Change	Infrastructure	Environment
IKONOS	1, 4	High Res Imaging	✓	✓	✓	✓
CBERS-1						
WFI	260	Earth observation				✓
CCD Camera	20	Earth observation	✓	✓	✓	✓
IR-MSS	80, 160	Earth observation	✓	✓		✓
Terra		eos-am.gsfc.nasa.gov				
MODIS	250, 500, 1000	Environmental				✓
ASTER	15, 30, 90	Geology/vegetation	✓	✓	✓	✓
MISR	250-275	Aerosols				✓
CERES	20 km	Clouds, radiant energy, land cover				✓
MTI	5	Demonstrate advanced multispectral and thermal imaging for detection of weapons of mass destruction	✓	✓	✓	✓
	20		✓	✓	✓	✓
EROS-A1	1, 1.8	High Res Imaging	✓	✓	✓	✓
QuickBird 2	0.6, 2.4	High Res Imaging	✓	✓	✓	✓
Proba						
CHRIS	25	Technology validation for future imaging spectrometer missions. Precision farming, regional yield forecasting, forestry	✓	✓	✓	✓
HRC	10	High Res Imaging	✓	✓	✓	✓
EnviSat						
ASAR	30 to 1000	SAR designed to provide continuity with ERS-1/-2, earth observation	✓	✓		✓
MERIS	300 to 1200	Measurement of sea color, chlorophyll, and suspended sediments				✓
MWR	20 km	Atmospheric water vapor and cloud water content, soil moisture				✓
AATSR	1 x 1 km	Sea surface temperature, continuity with ERS-1/-2				✓
Aqua						
AMSR/E	5-56 km	Precipitation, sea surface temperatures, ice concentrations, snow water equivalent, surface wetness, wind speed, atmospheric cloud water, and water vapor.				✓
MODIS	250, 500, 1000	Environmental				✓
AMSU	40.5 km	Atmospheric temperature profiles, clouds; assist calibration of AIRS				✓
AIRS	2.3 km, 13.5 km	Cloud cover radiance, ice concentration, snow cover, surface temperatures				✓
HSB	13.5 km	Water vapor profiles, clouds, rain intensities; assist calibration of AIRS				✓
SPOT-5	2.5 & 5 in Pan, 10 MSS, 20 SWIR	Earth observation	✓	✓	✓	✓
ADEOS II						
AMSR	5, 60	Water vapor, precipitation, sea surface temperature, sea surface wind, sea ice	✓	✓	✓	✓
GLI	1 km, 250 m	Surface temperature, vegetation distribution, and ice distribution, global circulation of carbon, monitoring cloud, snow, ice and sea surface temperature				✓
POLDER	7000 x 6000	Spectral characteristics of solar light reflected by aerosols, clouds, oceans and land surfaces	✓	✓		✓
ICESat		Elevation changes in ice sheets, ground, clouds, and sea ice thickness				
GLAS	70		✓	✓	✓	✓
OrbView 3	1	High Res imaging	✓	✓	✓	✓
	4		✓	✓	✓	✓
ResourceSat (IRS-P6)	6	Agricultural and vegetation	✓	✓	✓	✓
	23		✓	✓	✓	✓
	80		✓	✓		✓

CBERS-2 WFI	250	Earth observation	√	√		√
CCD Camera	20	Earth observation	√	√		√
IR-MSS	78, 156	Earth observation	√	√	√	√
AC	125/250	Atmospheric correction of images				√
Aura OMI	13 x 13 km, 13 x 24 km 13 x 48 km	Atmospheric ozone chemistry and climate				√
TES	530 x 5300	Long term variations in quantity, distribution and mixing in troposphere	√	√	√	√
CartoSat (IRS-P5)	2.5	Cartography, terrain modeling, cadastral applications	√	√	√	√

What's on the Drawing Board

Platform/ Sensor	Resolution (m)	Purpose	Applicable Uses in the Assessment of Human Settlements: Extent	Change	Infrastructure	Environment
EROS-B series	0.8	High Res imaging	√	√	√	√
Radarsat 2	3-100	Ice monitoring, structural geology, earth observation	√	√	√	√
ALOS-1						
PRISM	2.5	Terrain data, elevation	√			
AVNIR-2	10	Land cover, land use	√	√	√	√
PALSAR	10 - 100	Earth observation	√	√	√	√
IKONOS-X	0.5, 2.0	High res imaging	√	√	√	√
WorldView	0.5, 2.0	High res imaging	√	√	√	√
LANDSAT Next		Earth observation, continuity with previous Landsat systems	√	√	√	√
OrbView-5	0.41, 1.64	High res imaging	√	√	√	√

Explanation of Acronyms used in Table 12-2

Platform/ Sensor	Acronym Description
IKONOS	-----
CBERS-1	China-Brazil Earth Resources Satellite
WFI	Wide Field Imager
CCD Camera	High Resolution CCD Camera
IR-MSS	Infrared Multispectral Scanner
Terra	
MODIS	Moderate Resolution Imaging Spectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
MISR	Multi-angle Imaging SpectroRadiometer
CERES	Clouds and the Earth's Radiant Energy System
MTI	Multispectral Thermal Imager
EROS-A1	-----
QuickBird 2	-----
PROBA	Project for On-Board Autonomy
CHRIS	Compact High Resolution Imaging Spectrometer
HRC	High Resolution Camera
EnviSat	
ASAR	Advanced Synthetic Aperture Radar
MERIS	MEdium Resolution Imaging Spectrometer
MWR	Microwave Sounder
AATSR	Advanced Along-Track Scanning Radiometer
Aqua	-----
AMSR/E	Advanced Microwave Scanning Radiometer - EOS
MODIS	Moderate Resolution Imaging Spectroradiometer
AMSU	Advanced Microwave Sounding Unit
AIRS	Atmospheric Infrared Sounder
HSB	Humidity Sounder for Brazil
SPOT-5	Satellite Probatoire d'Observation de la Terre
ADEOS II	Advanced Earth Observing Satellite
AMSR	Advanced Microwave Scanning Radiometer
GLI	Global Imager
POLDER	Polarization and Directionality of the Earth's Reflectances
ICESat	Ice, Cloud, and Land Elevation Satellite
GLAS	Geoscience Laser Altimeter System
OrbView 3	-----
ResourceSat (IRS-P6)	-----
CBERS-2	China-Brazil Earth Resources Satellite
WFI	Wide Field Imager
CCD Camera	High Resolution CCD Camera
IR-MSS	Infrared Multispectral Scanner
AC	Atmospheric Corrector
Aura	-----
OMI	Ozone Monitoring Instrument
TES	Tropospheric Emission Spectrometer
CartoSat (IRS-P5)	-----

What's on the Drawing Board

Platform/ Sensor	
EROS-B series	-----
Radarsat 2	-----
ALOS-1	Advanced Land Observing Satellite
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2
PALSAR	Phased Array type L-band Synthetic Aperture Radar
IKONOS-X	-----
WorldView	-----
LANDSAT Next	-----
OrbView-5	-----

may indicate cyclic patterns (e.g., diurnal, seasonal), in addition to directional change without apparent cycles. In particular, changes from image to image may be precisely measured and linked to processes such as settlement expansion or contraction, localized environmental modification, conversion of settlement areas from one use to another, or natural processes such as desertification and impacts from flooding or volcanism. The specific spectra and resolutions required to perform change detection are dependent upon the specific attributes being measured, and just as importantly the spatial scale of those changes. For example, changes in the distribution of parks and other green space within a settlement would most efficiently be identified using one set of spectral bands, while measuring changes in the distribution of parking areas would optimally use a different set of spectral bands. Likewise the MODIS instrument might be a useful, fast, and inexpensive means of detecting generalized change in settlements, whereas details at the individual building level would require one of the high spatial resolution sensors, such as *Ikonos*, *EROS-A1*, *QuickBird*, or *OrbView-3*. An additional factor to consider is the significant data processing and storage costs of high-resolution imagery for an analysis covering a large region.

Like change detection, the identification and characterization of settlement-associated environmental effects requires an application of specific spectral and resolution characteristics. The spectral characteristics of settlement emissions such as light, heat, and pollution each require sensors with different spectral sensitivity, while also requiring spatial resolutions appropriate to the spatial scale of the emissions measured (cf. MODIS, ASTER, CHRIS, *ResourceSat*). Likewise the measurement of landscape modifications such as deforestation, erosion, fire, mining, and agriculture imposes spectral and resolution requirements specific to each environmental modification and the specific needs of an analysis.

Finally, the application of remote sensing technologies to the identification and characterization of infrastructure may yield valuable data in regions where settlement growth and change are occurring at high rates. In general, infrastructure identification and characterization requires moderate- to high-resolution imagery (e.g., *Ikonos*, *EROS-A1*, *QuickBird*, *OrbView-3*, *SPOT-5* and *CartoSat-1*) due to small feature sizes. Typical infrastructure elements that may be assessed using remotely sensed data include transportation features such as roads, highways and rail systems; communications features such as radio and cell-phone towers, telephone lines, and emergency warning sirens and horns; and utility features including pipelines and transmission lines.

In general, a wide variety of settlement characteristics can be enumerated using remotely sensed imagery, with the specific spectral and resolution requirements for a particular application being defined by the specific aspect of the settlement being measured. The following section provides a summary of planned sensors and platforms with additional information about their applicability to analysis of the settlement characteristics outlined above.

Significant enhancements to our ability to monitor and analyze human settlements can be expected from systems currently on the drawing board or under development. Improved spatial resolution with enhanced spectral and revisit capabilities are seen in systems such as *EROS-B*, *WorldView* and *OrbView-5*. These and the other systems listed in Table 12-2 are well suited to address each of the four areas of extent, change detection, environmental monitoring, and infrastructure assessment discussed above.

12.2.2 Detecting Human Settlements from Space

The assessment of human settlements from space for numerous purposes and at a variety of scales has been addressed throughout this manual. The future of the remote characterization of human settlements and their impacts is bright, with a wide range of systems operational or awaiting launch, and others under development, and a cadre of future systems on the drawing board. We will make explicit the assumptions that guide this optimistic characterization, as pertains to the near-term future of the remote sensing of human settlements.

In view of the sensible settlement characteristics outlined above and described in the previous sections, the systems of most interest in observing human settlements can be divided into two groups. The first group consists of terrestrial sensors having medium to high spatial resolution, that sense multiple spectral bands in the visible to thermal infrared wavelengths, and have moderate to low revisit frequency. These systems are for the most part operational. The second group represents systems incorporating technological advances that improve the spectral, spatial, and/or temporal resolution of interest in the sensing of human settlements. Several of the existing Earth observation systems fall into this category but for the most part represent incremental improvements on earlier systems, e.g., orbital adjustments to the *QuickBird* satellite improved its spatial resolution. Enhancements in the spatial resolution of radar systems, such as seen in *Radarsat-2,* further improve our ability to monitor settlements by providing radar imagery at previously unavailable resolutions.

The inclusion of satellite sensor systems in the tables provided is based upon the explicit assumption that sensors of interest for understanding human settlements must have one or more of the following capabilities: assessment of changes in the spatial extent of settlements; the ability to detect changes in the nature and character of settlements and settlement infrastructure; and the ability to characterize localized environmental effects of human settlements (cf. *CBERS-1* and *2*, ASTER, *EROS-A1*, CHRIS, HRC, and the *Ikonos, OrbView*, and *QuickBird* series sensors). Some of the platforms listed in Table 12-1 (e.g., *Terra, Aqua, Aura*) support additional sensors not included in the table, but they do not meet the capability requirements listed above. The assessment of these characteristics can be accomplished over a wide range of spatial, spectral, and temporal resolutions that are reflected in the systems included in the table. Suggested areas of application to sensing of human settlements are also noted in Table 12-1.

12.2.3 Current and Future Sensors

Current and planned satellite sensor systems show a broad range of spatial, spectral, and temporal resolutions well suited to address the varied requirements of sensing of human settlements. The recent trend toward finer spatial resolution has continued to serve the longstanding need for settlement details such as buildings and infrastructure. Meanwhile, the rise of hyperspectral sensors such as airborne AVIRIS, with its 224-channel spectral resolution and spatial resolution at 10 m or better, continues to benefit investigations related to human settlements where detailed environmental information is sought.

Sensing of human settlements is not restricted to the direct imaging or sensing of settlements themselves, but includes the impacts of those settlements on the Earth's biotic, hydrologic, and atmospheric systems as well. Of the 49 sensor systems summarized here, 31, or 63%, have a spatial resolution finer than 100 m, 27 of which provide data at 30 m or better. Thirteen systems have a spatial resolution ranging from 100 to 1,000 m, and an additional 11 sensing systems have spatial resolution in excess of 1 km, with the coarsest having a spatial resolution of 13 x 48 km. Many of these systems serve broad-scale environmental concerns related to urban and industrial development, as well as the agricultural infrastructure required to support human settlements.

Sensing of human settlements is not restricted to observation only in the spatial domain. Spectral characterization of settlements and their impacts plays an increasingly important role in understanding the nature of human settlements and their effects on the environment. Advances in hyperspectral and thermal sensors are seen in five sensors (MODIS, CHRIS, AIRS, GLI, IR-MSS and OMI) that use many small contiguous bands capable of providing continuous spectra of materials and features commonly or exclusively found in human settlements. The expansion of thermal imaging is particularly promising as the thermal signatures of settlements and their components are identified and defined. Eleven of the systems include at least one thermal band (e.g., IR-MSS [*CBERS-1* and *2*], ASTER, AATSR, AIRS, GLI, TES), with six sensors having two or more bands in the thermal infrared region of the spectrum (MODIS [*Terra* and *Aqua*], ASTER, MTI, AATSR, GLI). The thermal characterization of human settlements can serve as an important indicator of population, economic activity and comparative wealth—areas that have traditionally been difficult to assess using remotely sensed data.

12.2.4 Future Opportunities and Issues

An examination of existing and planned sensors finds that the technologies show an evolutionary change in capabilities that extends and improves existing technologies without introducing revolutionary change. This is particularly evident in the increasing spatial, temporal, and spectral resolutions of the new and planned systems. These improved resolutions will contribute to an enhanced ability to plan, characterize, monitor, and assess settlements, and to assess and respond to natural and human-caused disasters affecting human settlements. Increasing pressures to assess and monitor the built environment at higher resolutions will drive further advances in sensor design and capabilities.

In the near-term, remote sensing of human settlements will remain focused on predominantly passive sensors that measure visible and near-infrared wavelengths, but will increasingly move into sensing of the thermal portion of the electromagnetic (EM) spectrum. For most applications, these wavelengths will continue to serve archaeology well. The increased spatial and spectral resolution of new and planned systems will contribute to the utility of these systems by providing high-resolution information in a familiar and readily interpretable form. Active sensors such as those of the Radarsat and ERS systems will continue to provide information on settlements at varying spatial and temporal resolutions. These data allow the assessment of settlement growth and environmental impacts, particularly in urban areas, as well as measurements of settlement-related environmental impacts.

The fusion of disparate data sets that capitalize on information from different sensors is a valuable and potentially important area of research for the sensing of human settlements. The fusion of radar and visible and near-infrared sensors, for example, provides an opportunity to further explore the nature and character of human settlements. High-resolution *Radarsat 2* data fused with the high spatial resolution imagery from *Ikonos*, *QuickBird*, or *OrbView-3*, for example, can provide important information on post-disaster settlement conditions by capitalizing on the spectral and reflectance characteristics of undamaged and damaged structures.

An increasingly important EM component of modern human settlements that is currently largely unexplored is the variety of longer wavelength emissions generated by human activities. These emissions, ranging from the microwave to radio wave segments of the EM spectrum, provide an important addition to the currently available systems. Concentrations of such emissions from radio and television transmitters, cellular telephones, generating plants, and power grids are generally associated with settlements and provide indirect measures of population, economic development, and activity. Measurements of the interaction of these emissions with the natural and built environments are potentially an important area of development for sensing of human settlements. Other revolutionary technologies such as active sensor systems capable of remote chemical identification will likely have a significant impact on our ability to monitor settlements in new ways. Chemical signatures of settlements are a largely unexplored area that is ripe for investigation. The potential of chemical sensing systems is substantial, allowing the characterization of productivity through monitoring of the release of chemicals from manufacturing, to estimates of population from measures of atmospheric methane, and assessment of environmental health through the measurement of biological metabolites. This technology, however, is in the development stage and is unlikely to see implementation on a space-based system in the near future.

Satellite and sensor systems are increasingly international and multinational endeavors. Along with this trend, important questions concerning data accessibility and security have arisen. With this multi-nationalization of satellites and sensors comes an increased issue of access to global data that provides the context for all human settlements. To ensure accessibility, international agreements and distribution systems must be developed to protect intellectual property rights, while ensuring the availability of data and information necessary for life in the ever-more crowded settlements on Earth.

There is a growing consciousness of the linkage between urbanization/industrialization and global atmospheric and oceanic dynamics. Remote sensing research and applications are vital to the understanding of these processes. This is a multi-scale issue in which urban land use, vehicular transportation, thermal properties, and chemical constituents in air and water are intertwined at micro-, meso-, and macro-scales. As current and new sensors are further developed and applied, new databases may be established linking human settlements as discrete entities to the larger patterns and processes of weather, air quality, global warming, deforestation, energy development, and other environmental phenomena in constant flux. Growing human settlements, with their voracious appetites to consume global resources and propensity to expel waste, are prime movers in the global environmental picture. Remote sensing linkages at all scales are fundamental to understanding and dealing with these issues. The new and emerging instruments will assist in this effort as the scientific and technical communities pursue the problem.

12.3 SELECTED STUDY OF NEW DEVELOPMENTS AND TRENDS

Urban analysts and planners have longed for the day when spatial resolutions of digital remote imagery could rival the fidelity of the familiar aerial photograph, and that day has come. This section will demonstrate that not only is visualization on a par with conventional photography, but that unlike photography, the data is planimetric and to scale, ready for a GIS database. While the focus here is on spatial fidelity, through hyperspectral imagery environmental nuances of human settlements may likewise be determined and mapped. AVIRIS data, for example, through a neural network classifier has been shown to faithfully characterize environmental conditions of the Pasadena, California, area (Ridd et al. 1992). Through the combination of high-resolution spatial and spectral instruments, human settlements are now on a new frontier of detailed analysis.

12.3.1 Introduction

Due to the high spatial resolution requirements for urban information systems, aerial photography has been used as standard imaging input. However the advent of new satellites with resolutions of 1 m or better (e.g., *Ikonos*, *QuickBird*, *OrbView-3*) and digital airborne scanners with excellent geometric fidelity and high spatial resolutions in the cm range (e.g., HRSC, ADS, DMC) challenges the analog airphoto techniques. These airborne and spaceborne high-resolution sensors offer an advanced potential for generating and updating GIS databases, especially for urban areas. Moreover, digital airborne stereo sensors are capable of producing digital surface models (DSMs) by automated techniques. Coupled with differential GPS and inertial navigation systems (INS), these sensors generate georeferenced ultra high-resolution multispectral image data with the corresponding DSM.

Another source of three-dimensional information for city modeling is laser scanning (lidar) sensors which produce accurate height information of high and very high resolution. This section presents an overview of the new sensor developments and examples of integrated processing.

Highest resolution for all sensors is obtained in the panchromatic mode, whereas the multispectral information is acquired at lower resolutions. The ratio between the panchromatic and the multispectral resolution is usually in the order of 1:2 to 1:8. Especially for vegetation analyses and urban sprawl quantification, multispectral information is a requirement. To obtain multispectral image data with high spatial resolution, multispectral and panchromatic images have to be merged (pansharpened). Image transforms such as the Intensity-Hue-Saturation (IHS) or Principal Component (PC) transforms are widely used to fuse panchromatic images of high spatial resolution with multispectral images of lower resolution (Pohl and van Genderen 1998). These techniques create multispectral images of higher spatial resolution, but usually at the cost of losing some of the original color or spectral characteristics of the input image data. Section 12.3.4.2 presents a new method for image fusion that is based on the standard IHS transform combined with filtering in the Fourier domain (Ehlers 2004b). This method preserves the spectral characteristics of the lower resolution images. Using this fusion method, multispectral images can be pansharpened without changing their spectral characteristics.

12.3.2 Very High-resolution Satellite Systems

The advent of commercial very high-resolution satellite programs has opened new application fields for space-based remote sensing. Satellite data offer, for the first time, the potential for large-scale applications such as urban planning and environmental monitoring at the highest level of detail (Ehlers et al. 2003; Möller 2003). Spatial resolutions of 0.60–1.00 m (panchromatic) and 2.5–4 m (multispectral) have begun to challenge aerial photography.

Companies such as DigitalGlobe, Space Imaging, and OrbImage promise extremely fast processing. Data can be delivered within days (or even hours if downloading via internet is possible). Tiltable cameras offer short revisit periods of 2–3 days and across-track as well as along-track stereo capabilities. *Ikonos* was launched in September 1999, the first commercial very high-resolution satellite in orbit (see Table 12-3). Figure 12-1 shows a pansharpened multispectral QuickBird image at 70-cm resolution. The potential of these sensors for urban application is demonstrated by individual buildings that are clearly discernible in the image.

12.3.3 Ultra High-resolution Digital Airborne Sensors

After a long period of development, we now see the emergence of operational digital camera systems which challenge aerial frame cameras. Advanced technologies such as GPS-coupled navigation systems and advanced digital sensors have overcome the strongest impediment of aircraft scanners—the lack of geometric stability. Public and private research has concentrated on the development of digital line array or matrix scanners that will serve as successors to the "classical" air cameras. Companies such as Leica Geosystems, Zeiss Imaging (Z/I), and Vexcel offer commercial systems, and research centers such as the German Space Center (DLR) fly their own prototypes. Such systems have to establish their

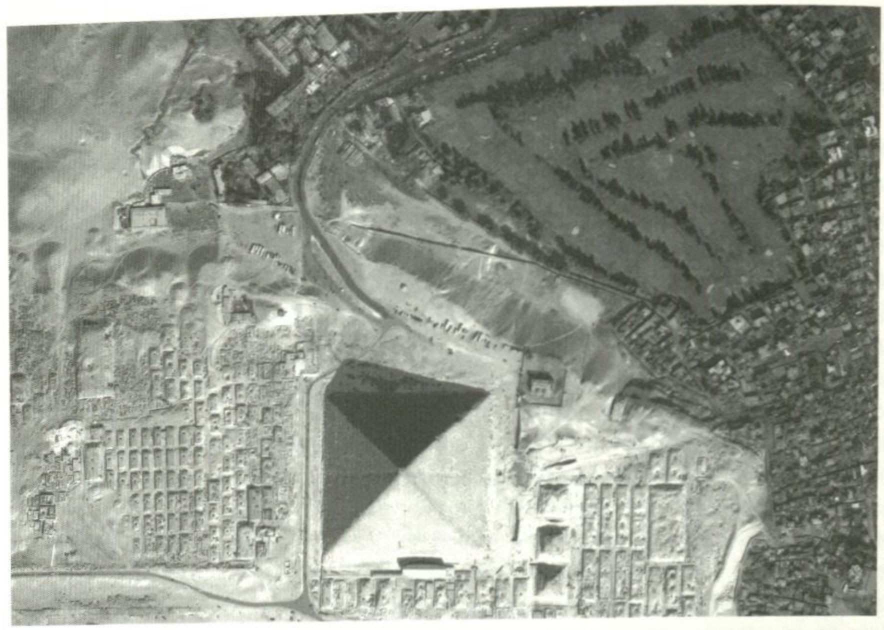

Figure 12-1 Pansharpened multispectral QuickBird image with 70-cm resolution (top) with enlarged subset (bottom). Courtesy: Manfred Ehlers. Data courtesy of and © 2000 DigitalGlobe Incorporated, Longmont CO USA 80501-6700. See color plates.

Table 12-3 Selected satellite missions of very high resolution (after Ehlers 2004a).

Company	*Space Imaging*		*DigitalGlobe*		*Orbimage*		*ImageSat International*
System	Ikonos launch 9/99		QuickBird launch 11/01		OrbView-3 launch 6/03		EROS A1 launch 12/00
URL	www.spaceimaging.com		www.digitalglobe.com		www.orbimage.com		www.imagesatintl.com/
Mode	Pan 11 bit	Multispectral 11 bit	Pan 11 bit	Multispectral 11 bit	Pan 11 bit	Multispectral 11 bit	Pan 11 bit
Geometric Resolution	1 m	4 m	0.61 m	2.44 m	1 m	4 m	1.8 m (hypersampling 1 m)
Spectral Resolution (nm)	525-929	445-516 (B) 506-595 (G) 632-698 (R) 767-853 (NIR)	450-900	450-520 (B) 520-600 (G) 630-690 (R) 760-900 (NIR)	450-900	450-520 (B) 520-600 (G) 630-690 (R) 760-900 (NIR)	500-900
Scale for Applications			1 : 5 000 – 1 : 25 000				
Swath Width	11 km		16.5 km		8 km		13.5 km
Image Scene Size	11 x 11 km^2		16.5 x 16.5 km^2 strip: 16.5 x 165 km^2		8 x 8 km^2		13.5 x 13.5 km^2 vector scene: 13.5 x 40 km^2
Orbit Altitude	681 km		450 km		470 km		480 km
Inclination	98.1 sun synchronous		97.2 sun synchronous		97 sun synchronous		97.3 sun synchronous

Figure 12-2 Three-dimensional perspective view of a subset of the nature protection area Heuckenlock near Hamburg, Germany, captured by the German Space Agency's High Resolution Stereo Camera HRSC-AX. The image has a ground resolution of 25 cm. The perspective view is a computer-generated drape of the RGB image data over the 50-cm resolution digital surface model (DSM) also generated by the HRSC-AX. Courtesy: Manfred Ehlers. See color plates.

market somewhere between the satellite image-user seeking higher resolution and the airphoto-user seeking digital input and GIS compatibility. Consequently, airborne scanner systems have to offer stereo capability and multispectral recording (Figure 12-2).

12.3.3.1 TECHNICAL PARAMETERS OF ULTRA HIGH-RESOLUTION AIRBORNE SYSTEMS

Two different technologies are being employed to accomplish an airborne digital recording system. Z/I and Vexcel make use of two-dimensional arrays and a set of coupled nadir-looking lenses to emulate a standard frame camera's central perspective (Dörstel 2003; Leberl and Gruber 2003). Leica Geosystems and the DLR employ triplet scanner technology with one-dimensional line arrays arranged in fore-, nadir-, and aft-looking modes (Fricker

Table 12-4 Selected digital airborne sensors (after Ehlers 2005; Schiewe 2005).

Sensor	*HRSC-AX*	*DSS*	*ADS 40*	*UltraCam-D*	*DMC*
Company	DLR	Applanix (Emerge)	Leica Geosystems	Vexcel Corp.	Z/I Imaging
URL	www.dlr.de	www.emergedss.com	www.gis.leica-geosystems.com/	www.vexcel.com	www.ziimaging.com
Sensor Type	Line CCD	Area CCD	Line CCD	Area CCD	Area CCD
Introduction	2000	2004	2000	2003	2002
Focal Length	151 mm	55 mm (color & CIR) 35 mm (only color)	62.7 mm	100 mm (28 mm multispectral)	120 mm (25 mm multispectral)
Field-of-view	29°	37° x 55.4°	64°	55° x 37°	74° x 44°
# CCD- Lines /-Matrix Camera	9	1	7	9	8
# CCDs across track	12 172	4077	2 x 12 000 (pan) 12 000 (ms)	11 500 (pan) 4008 (ms.)	13 824 (pan) 3 000 (msl)
# CCDs along track	-	4092	-	7 500 (pan) 2 672 (ms)	7 680 (pan) 2 000 (ms)
Sensor Size	6.5 μm	9 μm	6.5 μm	9 μm	12 μm
Radiometric Resolution	12 bit	12 bit	12 bit	> 12 bit	12 bit
Spectral Resolution (nm)	520–760 (pan) 450–510 (blue) 530–576 (green) 642–682 (red) 770-814 (NIR)	RGB Mode 400-500 (blue) 500-600 (green) 600-680 (red) CIR Mode 510-600 (green) 600-720 (nor/NIR) 720-920 (NIR)	465-680 (pan) 428-492 (blue) 533-587 (green) 608-662 (red) 703-757 (NIR) or 833-887 (NIR opt.)	390-690 (pan) 390-470 (blue) 420-580 (green) 620-690 (red) 690-900 (NIR)	400-580 (pan) 400-580 (blue) 500-650 (green) 590-675 (red) 675-850 (NIR)
Readout Frequency	1640 lines/s	0.25 images/s	800 lines/s	0.75 images/s	0.5 images/s
Largest Application Scale	1:500	1:1,000	1:500	1:150	1:150
Stabilization	Zeiss T-AS platform	Own platform	LH platform	Not specified	Zeiss T-AS platform
Data Recording	High speed recorded	80 GB exchangeable hard disk	MM40 mass storage	SCU (> 1 TB)	RAID disk system
Georeferencing	Applanix POS/DG with GPS and INS	Applanix POS IMU with GPS and INS	Applanix POS IMU with GPS and INS	Not specified	POS Z/I 510 navigation system with GPS and INS
Estim. Costs incl. Pos. system	-	$ 425,000	$1,200,000	$ 700,000	$1,600,000

Table 12-5 Selected lidar systems with optional imaging sensors (after Ehlers 2005; Schiewe 2005).

System	*FALCON*	*ALTM 3033, 3070*		*ALS 50*
Company	TopoSys	Optech		Leica Geosystems
URL	www.toposys.de	www.optech.ca		www.gis.leica-geosystems.com
Recording Principle	Glasfiber Array	Rotating mirror		Rotating mirror
Multiple Reflections	Max. 2 echoes	Max. 4 echoes		Max. 4 echoes
Image Sensor	Line scanner (pixel size 0.5 m)	DSS		ADS 40
Spectral Resolution in nm	450-490 (blue) 500-580 (green) 580-660 (red) 770-890 (NIR)	RGB Mode 400-500 (blue) 500-600 (green) 600-680 (red)	CIR Mode 510-600 (green) 600-720 (red/NIR) 720-920 (NIR)	465-680 (pan) 428-492 (blue) 533-587 (green) 608-662 (red) 703-757 (NIR) or 833-887 (NIR opt.)
Pulse Frequency	83 kHz	up to 70 kHz		up to 83 kHz
Scanning Frequency	653 Hz	70 Hz		412.33 x FOV-0.6548 (max. 51°)
Max. Flying Height	1600 m	3000 m		4000 m
Scan Angle (FOV)	± 7°	± 0... 25°		± 10... 37.5°
Swath Width (h=1000 m)	245 m	930 m		1530 m
Resolution	0.02 m	0.01 m		0.01 m
Vertical Accuracy	± 0.15 m	± 0.15 m (h=1200 m)		± 0.15 m ... ± 0.50 m
Horizontal Accuracy	-	± 0.50 m (h=1000 m)		± 0.15 m ... ± 0.75 m

et al. 2000; Hoffmann and Lehmann 2000). The advantage of a two-dimensional matrix camera is that all standard photogrammetric techniques can be used in a digital environment. The advantage of a stereo triplet solution is that photogrammetric preprocessing (i.e., digital surface model [DSM] and orthoimage generation) is performed before the user receives the data, thus alleviating the need to utilize sophisticated software at the user's organization. The image data are provided in the required coordinate system and can be easily integrated into an existing GIS database. The suitability of each approach largely depends on the user demands and the price-performance ratios of the respective systems. Table 12-4 presents five selected ultra high-resolution airborne digital camera systems.

The advantages of digital cameras are widely understood—no film, no photo processing, no scanning, better radiometric quality through direct sensing, and direct integration into GIS and image processing systems. The disadvantages of digital scanners, most notable being geometric distortions and monoscopic imaging mode, no longer exist due to the stereo capabilities of the new sensors and the use of integrated inertial navigation systems (INS) and differential GPS technology during image acquisition.

12.3.3.2 MULTI-SENSOR SYSTEMS

The progress of GPS and INS for direct orientation is also responsible for the development of operational laser scanning or lidar systems (Lemmens 2004). The simultaneous use of lidar and imaging technology creates multi-sensor systems that produce accurate DSMs and image data at the same time. Table 12-5 presents a selection of multi-sensor systems which have been increasingly used in Europe.

The acquisition of elevation data can be achieved by different techniques. For area CCD sensors, such as DMC or Ultracam, standard digital photogrammetric techniques (stereocorrelation) can be employed to create digital elevation models (DEMs) from overlapping frame images (see, for example, Spiller 2000). The line CCD sensors, such as ADS or HRSC, make use of a triplet along-track stereo geometry for three-dimensional information extraction that requires specific software for preprocessing (see, for example, Fricker et al. 2000; Ehlers et al. 2003). Figure 12-3 provides a comparison of three ultra high-resolution airborne sensors at different resolutions.

Combined laser scanners and imaging sensors create a very accurate and dense DSM which can be easily co-registered with the image data. All techniques allow the creation of orthophotos that can be readily interfaced with GIS and digital map data. Figure 12-4 demonstrates the geometric differences between the central perspective for the area CCD (left) and the line CCD cameras (right). The differences in elevation determination for stereocorrelation and lidar sensors are presented in Figure 12-5. The higher density and the direct distance measurements of the laser scanners produce more accurate digital surface models with sharper edges. Window-based correlation, on the other hand, tends to create "hills" in areas of distinct discontinuities (i.e., house walls, trees, etc.). For further information consult Schiewe and Ehlers (2004).

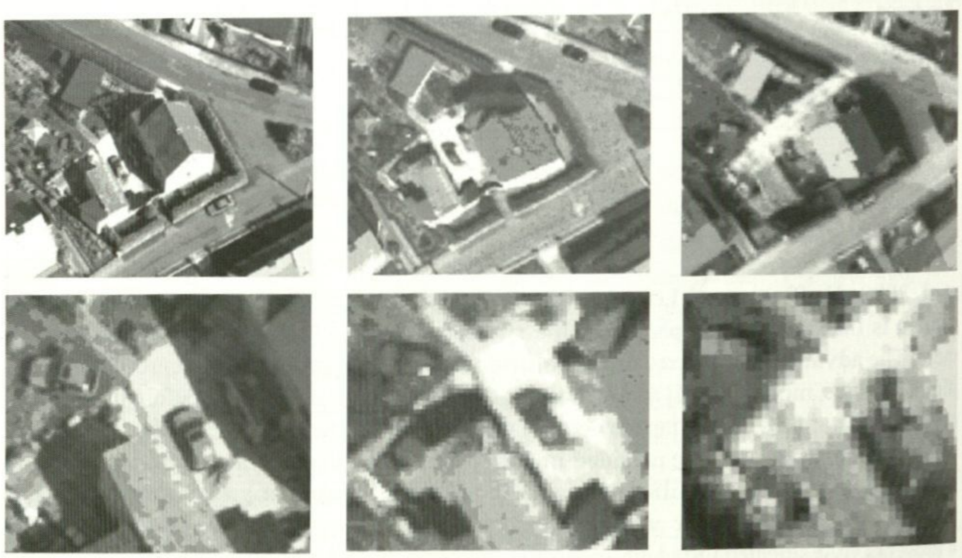

Figure 12-3 Comparison of ultra high-resolution airborne sensors (from left to right): DMC (10-cm pixel size), ADS 40 (25-cm pixel size), and Falcon (50-cm pixel size). The image subsets are 50-m resolution (top) and 20-m resolution (bottom). Courtesy: Manfred Ehlers. See color plates.

Figure 12-4 Comparison of the different recording geometries: central perspective DMC (left) and the line scanner ADS (right) with central perspective distortion only in cross-track direction. Digital cadastral data (houses) are overlaid for better clarification. Courtesy: Manfred Ehlers. See color plates.

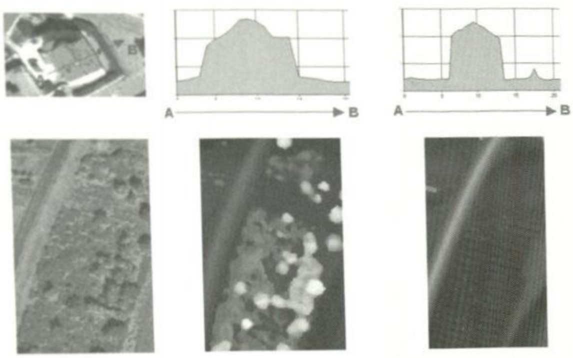

Figure 12-5 Comparison of elevation models from ADS image data (left) and Falcon lidar data. The lidar DSM (right) shows a better edge preservation than image-based correlation for the ADS 40 (center). The other advantage of laser scanners is the ability to use "last echoes" for retrieving ground elevation, even under trees (bottom). Courtesy: Manfred Ehlers.

12.3.4 Image Fusion

In a special issue on data fusion of the International Journal of Geographical Information Science (IJGIS), Edwards and Jeansoulin state that

> data fusion is a complex process with a wide range of issues that must be addressed. In addition, data fusion exists in different forms in different scientific communities. Hence, for example, the term is used by the image community to embrace the problem of sensor fusion, where images from different sensors are combined. The term is also used by the database community for parts of the interoperability problem. The logic community uses the term for knowledge fusion. (Edwards and Jeansoulin 2004)

Consequently, it comes as no surprise that several definitions for data fusion can be found in the literature. Pohl and van Genderen (1998) proposed "image fusion is the combination of two or more different images to form a new image by using a certain algorithm." Mangolini (1994) extended data fusion to information in general and also refers to quality. He defined data fusion as "a set of methods, tools and means using data coming from various sources of different nature, in order to increase the quality (in a broad sense) of the

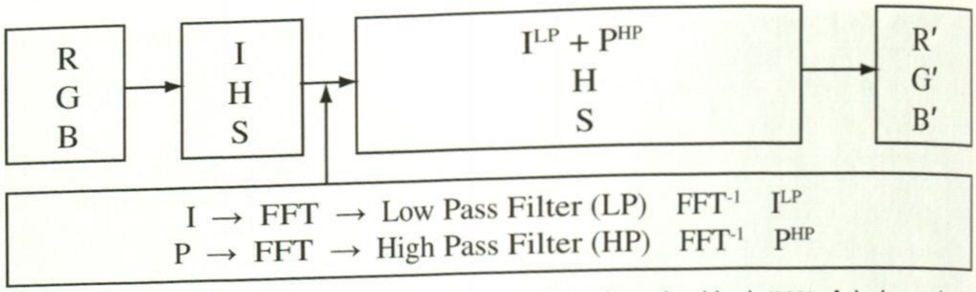

Figure 12-6 FFT-based filter fusion using a standard IHS transform. Three selected bands (RGB) of the low-resolution multispectral image are transformed into the IHS domain. The intensity component and the high-resolution panchromatic image are transformed into the Fourier domain using a two-dimensional Fast Fourier Transform (FFT). The power spectra of both images are used to design the appropriate low-pass filter (LP) for the intensity component and high-pass filter (HP) for the high-resolution panchromatic image. An inverse FFT transforms both components back into the spatial domain. The low-pass filtered intensity (I^{LP}) and the high-pass filtered panchromatic band (P^{HP}) are added and matched to the original intensity histogram. At the end, an inverse IHS transform converts the fused image back into the RGB domain (after Ehlers 2004b). Courtesy: Manfred Ehlers.

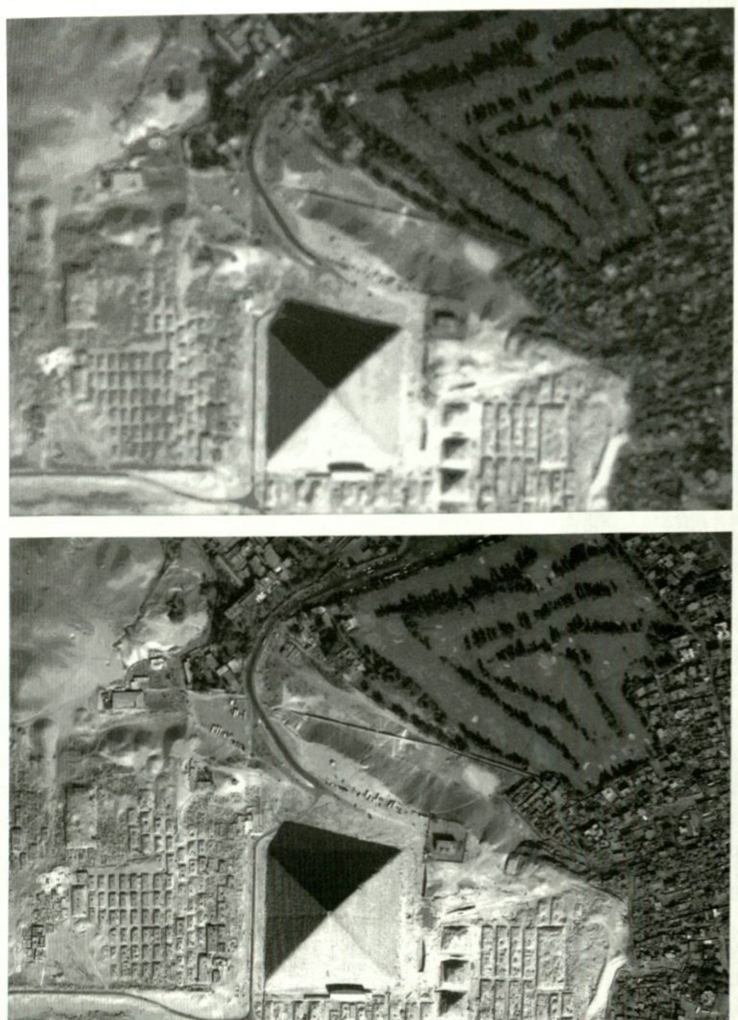

Figure 12-7 QuickBird multispectral image (Bands 4, 3, 2) resampled to 70-cm pixel size to match its panchromatic image mode (bottom). Courtesy: Manfred Ehlers. Data courtesy of and © 2000 DigitalGlobe Incorporated, Longmont CO USA 80501-6700. See color plates.

requested information." Wald (1999) defined "data fusion as a formal framework in which are expressed means and tools for the alliance of data originating from different sources. It aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application."

In the imaging community, fusion techniques are used to merge high spatial resolution panchromatic images into multispectral images of lower spatial resolution. These techniques are designed to produce images which present the "best of both worlds"—high spatial resolution combined with high spectral resolution.

12.3.4.1 FUSION TECHNIQUES

Fusion techniques for remotely sensed data (image fusion) can be classified into three levels: pixel level (ikonic), feature level (symbolic), and knowledge or decision level (Pohl and van Genderen 1998). Of highest relevance for remote sensing data are techniques for ikonic image fusion to merge panchromatic images of high spatial resolution with multispectral data of lower resolution (see Cliche et al. 1985; Welch and Ehlers 1987; Zhang 2002). However, existing techniques hardly satisfy conditions for successful fusion of the new-generation high-resolution satellite images such as *Ikonos*, *Landsat-7*, *SPOT-5*, and *QuickBird*, or ultra high-resolution airborne data (Zhang 2002). All of the new-generation satellites and almost all airborne sensors provide high-resolution information only in their panchromatic mode, whereas the multispectral images are of lower spatial resolution. The ratios between high-resolution panchromatic and low-resolution multispectral images vary between 1:2 and 1:8 (Ehlers 2004b). To produce high-resolution multispectral data sets (as are required for urban remote sensing), the panchromatic information has to be merged with the multispectral images. The most significant problem with image fusion techniques is the color distortion of the fused image.

12.3.4.2 SPECTRAL-CHARACTERISTICS-PRESERVING IMAGE FUSION (EHLERS FUSION)

The principal idea behind a spectral-characteristics-preserving image fusion is that the high-resolution image has to sharpen the multispectral image without adding new information to

Figure 12-8 Pansharpened QuickBird image using the Ehlers fusion. Courtesy: Manfred Ehlers. Data courtesy of and © 2000 DigitalGlobe Incorporated, Longmont CO USA 80501-6700. See color plates.

the spectral components. As a basic image fusion technique, we make use of the Intensity-Hue-Saturation (IHS) transform. This technique is extended to include more than the standard three bands (red, green, blue color transform) from color theory. In addition, filter functions for the multispectral and panchromatic images are developed. The filters are designed in a way that the effect of color change from the high-resolution component is minimized. The ideal fusion function adds the high-resolution spatial components of the panchromatic image (i.e., edges, object changes) but disregards its actual gray values. For a thorough analysis of the information distribution along the spatial frequencies of an image, use is made of Fourier transform theory (FFT) (Gonzalez and Woods 2001). An overview flowchart of the method is presented in Figure 12-6 (see Ehlers 2004b for complete description). Results of the FFT-based fusion are shown in Figures 12-7 to 12-9.

The positive results for the new technique have been confirmed for a number of image data sets. Even for multi-sensor and multi-temporal image fusion, the FFT-based technique preserves the spectral characteristics of the multispectral images, while keeping the spatial resolution of the panchromatic images. This is reflected by the correlation coefficient for the multispectral bands before and after fusion. The Ehlers fusion achieved a correlation coefficient of 0.994 (Table 12-6), far superior to all other methods.

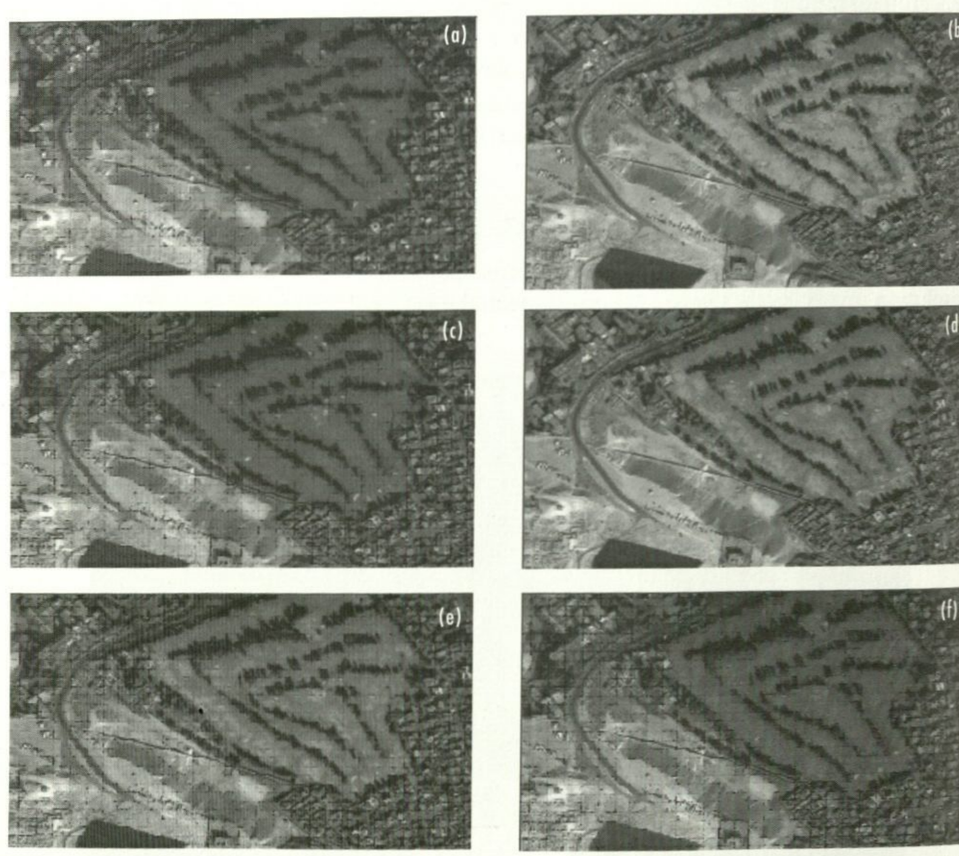

Figure 12-9 Comparison of standard pansharpening techniques with the Ehlers fusion: all methods show significant color changes when compared to the original unsharpened image (a). The employed methods were Brovey transform (b), HIS transform (c), multiplicative fusion (d), and Principal Component transform (e). The Ehlers fusion (f) shows almost no change in spectral characteristics. Courtesy: Manfred Ehlers. Data courtesy of and © 2000 DigitalGlobe Incorporated, Longmont CO USA 80501-6700. See color plates.

Table 12-6 Correlation coefficient between the multispectral bands of the original and the pansharpened image.

Pansharpening Method	*Correlation Coefficient with Original Bands*
IHS	0.762
Brovey	0.816
Principal Component	0.850
Multiplicative	0.932
Ehlers	0.994

12.4 CONCLUSION

The development of remote sensing systems capable of very high and ultra high resolution has matured over the last few years. The new airborne digital camera systems have the potential to finally end the reign of analog cameras when it comes to image acquisition for large-scale applications. The new very high- and ultra high-resolution sensors offer a tremendous potential for urban applications. In particular, the three-dimensional capability of the airborne sensors is a great advantage for applications such as city modeling. Image fusion for pansharpening is essential for image analysis, since almost all sensors have the highest resolution only for their panchromatic mode. FFT-based filtering prior to the application of an IHS transform produces fused images of improved spatial resolution without changing the spectral characteristics.

Now the focus has to shift to the development of new automated procedures to adequately deal with the spatial complexity of the current image data (Blaschke and Strobl 2001; Schiewe 2005). During a workshop on "Remote Sensing for GIS," emphasis was placed on the automated information extraction from very high-resolution remote sensing data (see Blaschke 2002). It is our firm belief that new sensors require new processing techniques, which in return offer new application fields. New possibilities for application will eventually lead to new demands on sensor developments so that the cycle of innovations can continue (Fig. 12-10).

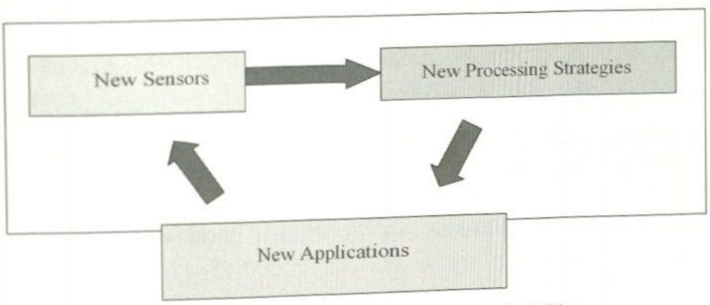

Figure 12-10 Idealized causal development in remote sensing. Courtesy: Manfred Ehlers.

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Chapter

13

A View to the Future

Authors: Stanley A. Morain and Wayne Mooneyhan

"For I dipt into the future far as the human eye could see
Saw the vision of the world and all the wonder that would be."

Alfred Lord Tennyson (*Locksley Hall*, 1842)

13.1 PHILOSOPHICAL NOTIONS

Humans represent the only species whose global distribution can be predicted largely by their settlement patterns. Human populations build structures of various materials for shelter and pursue numerous activities to sustain themselves. The major elements of these patterns are detectable through the optical, thermal, and microwave emissions collected by sensors that can be used to characterize the nature of settlements. This assertion is well illustrated by the pattern of global "nightlights" imaged by the Defense Mapping Satellite Program (Figure 13-1). Microwave emissions from radio and television transmitters, cellular telephones, ships and airplanes, emergency service providers, police radios, and similar sources are being used to better understand operations within population centers, as well as to locate and rescue individuals who have become lost, stranded, or otherwise separated from their kin.

We too-often think of "human settlements" as simply places where people live, work, conduct business, and socialize. As individuals, we are seldom conscious that the support for these activities (often referred to as our "quality of life") requires resources far removed from where we work and live, and as a consequence our cloistered existence in the settlement has impacts we cannot even see. Whereas other social animals (ants, termites, birds) build temporary nests, sedentary humans build permanent, ever-expanding, artificial ecosystems that consume the natural systems where they occur. They are, moreover, supported by massive quantities of still other, more remote resources that energize and power the system. The butcher, the baker and the candlestick maker all need different supporting resources, and these costs impact the entire biological skin of the Earth. Therefore understanding human settlements means more than just describing the places where people live. It means understanding how these built-up places, as ecosystems, fit into and alter the natural order at local, regional, and global scales. We should realize human settlements are living, pulsating places created out of an organic and inorganic world, and they are *not* immune to the consequences of their own existence.