Geospatial Information Technology for Emergency Response – Zlatanova & Li (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-42247-5

Satellite remote sensing for near-real time data collection

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ABSTRACT: Satellite remote sensing has been applied to a variety of emergency responses for predicting, monitoring and/or managing natural or man-made disasters locally, regionally and globally. It has demonstrated that satellite imagery is a great data source for quickly responding to different emergency events. However, due to technical limitations, satellite remote sensing still faces certain challenges in real-time data collection. This paper discusses current satellite remote sensing technologies, on-going international initiatives, and future developments for rapid data collection. General discussions and examples with respect to spatial, spectral and 3D capacities of satellite imagery vs. effectiveness of information interpretation for certain natural and man-made disasters will also be given, to provide an overall guideline for data selection for a given emergency event.

1 INTRODUCTION

The previous chapter provided a detailed overview of the utility of airborne remote sensing for the provision of near-real time information in an emergency situation. Here we discuss the contributions satellite-based sensors can make. As in the previous chapter, by 'near-real time' we mean approximately the first 72 hours after an event.

Although satellite-based Earth observation only began in the 1960s, much later than airborne remote sensing, it has proved to be an excellent information source for emergency response locally, regionally and globally, because of its special advantages – (i) synoptic (i.e. large area) coverage, (ii) frequent and repetitive collection of data of the Earth's surface, (iii) diverse spectral, spatial and potentially three dimensional information, and (iv) relatively low cost for per unit coverage.

Examples of using satellite remote sensing for emergency responses can be found in many publications, such as Metternicht et al. (2005) on landslides, Tralli et al. (2005) on earthquakes, floods, and other disasters, Kerle et al. (2003) on mudflows, and Doescher et al. (2005) on satellite data for emergency support. For quick responses to forest fires nation-wide, the Forest Service of the U.S. Department of Agriculture (USDA) publishes an Active Fire Map on the Web to show weekly updated fire locations in the US (USDA Forest Service, 2006).

However, due to technical limitations, a range of challenges still affect real-time collection of imagery of areas of interest. This paper discusses state-of-the-art satellite remote sensing technologies, on-going international initiatives, and future developments for rapid data collection of the Earth's surface, to give readers an overview of current status and future development trends.

Spatial, *spectral and temporal resolution* (*repeat cycle*), as well as *spatial coverage* and *2D and 3D capacity* are critical technical aspects for selecting remote sensing imagery for a given emergency event. Therefore, this paper provides general information and examples on these aspects with respect to current and future Earth observation satellites and relevant natural and man-made disasters.

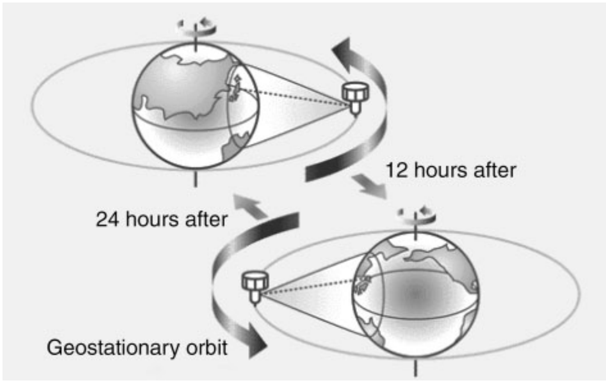


Figure 1. Geostationary orbit (courtesy of the National Space Agency of Japan (NASDA)).

2 SATELLITE ORBITS, SENSORS AND IMAGES

2.1 *Satellite orbits*

For different remote sensing missions, different satellites carrying a range of sensors have been launched. The satellites follow different *orbits* around the Earth, acquiring images of the Earth's surface. A particular satellite is usually launched into a special orbit such that the satellite 'circles' the Earth repeatedly. The time used for completing one circle is called *period*. The time interval needed to collect repeatedly images of the same area is called *repeat cycle.* Depending on the characteristics of an orbit and the pointing capability of a satellite, the repeat cycle ranges from several days to approximately one month. The three principal satellite orbit types are introduced below. The fundamental distinction is whether a satellite revolves around Earth's major or minor axis, i.e. around its poles or the equator.

(1) Geostationary orbits
A geostationary orbit allows a satellite to appear stationary with respect to the Earth's surface (Figure 1). When positioned at approximately 36,000 km above the Earth, the period of the satellite will be 24 hours. When the satellite orbit is parallel to the equator in the same direction as the Earth's rotation, the satellite will rotate at the same speed as the Earth, appearing stationary above the same longitudinal position.

Geostationary orbits enable a satellite to view the same area of the Earth at all times. Given its large distance to the Earth, the ground coverage is very large (hemispheric). They are commonly used by meteorological satellites, such as the GOES series of NOAA, and Europe's Meteosat Second Generation (MSG). The permanent position over the same location allows a very high temporal resolution; in theory continuous, in case of MSG images are acquired every 15 minutes. However, given the large altitude, this comes at a cost of low spatial resolution, typically on the order of 3–4 km. This is sufficient for meteorological applications, but of less value in a disaster situation. Exceptions are thermal anomalies such as extensive forest fires or magmatic activity at volcanoes. Even small intense heat sources, such as 900°C lava covering only some 90 m^2, would be detectable with MSG's Seviri Sensor (see section 4.3 from the previous chapter). However, it is worth noting that the hemispheric coverage is not uniform, with spatial resolution decreasing steadily towards the periphery of the observed areas.

(2) Near polar orbits
A near polar orbit is one which passes close to the two poles of the Earth, in order for a satellite to collect images covering nearly the entire Earth surface in a repeat cycle (Figure 2). Polar orbits are

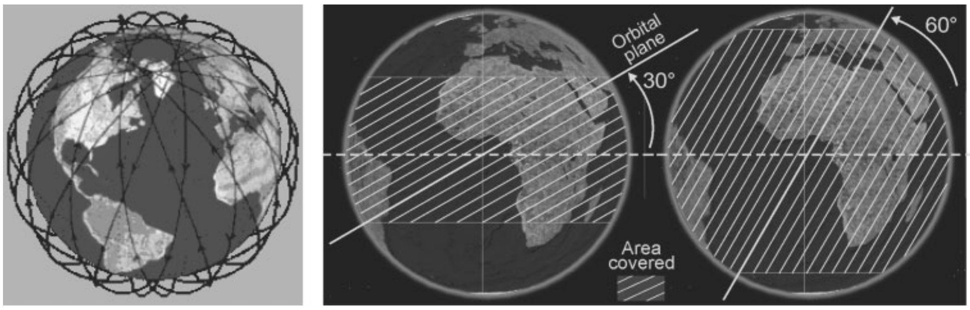


Figure 2. Near polar orbit (left; courtesy of www.newmediastudio.org/DataDiscovery), and illustration of the effect of orbit inclination on ground coverage (right).

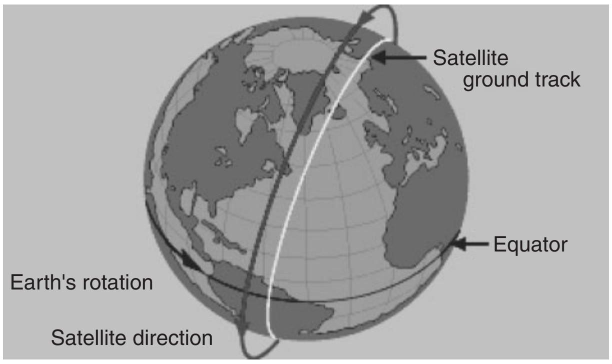


Figure 3. Sun synchronous orbit (courtesy of Centre for Remote Imaging, Sensing and Processing).

much closer to the surface than those of geostationary satellites, typically between 500 and 800 km. A single satellite then travels in its orbit, while the Earth beneath rotates. Thus, upon return to the same point in the orbital cycle, typically some 80–100 minutes later, an area further west is imaged. Given that the Earth underneath rotates at a speed of 15 degrees per hour, the observation strips will not be contiguous.

While the spatial resolution of a polar orbit satellite is higher, the temporal resolution is generally lower compared to a stationary satellite. The current Landsat satellites, for example, have a repeat visit of only 16 days. For immediate disaster response this is clearly only sufficient if the satellite happens to be at a suitable position.

The alternative for increasing the temporal resolution is to use (i) several satellites, (ii) pointable sensors or platforms, or (iii) to incline the orbit. In the latter case the area near the poles is not observed, but the inclined orbit allows faster returns. This will, for example, be used by the FUEGO/Forest Fire Earth Watch constellation, whose purpose is forest fire monitoring in Mediterranean areas.

(3) Sun synchronous orbits
A sun synchronous orbit, a special case of a near-polar orbit, is one which allows a satellite flying over the ground track (vertical projection of the orbit on the ground) at the same local sun time, to achieve the same solar illumination condition (except for seasonal variation) for a given location (Figure 3).

Earth observation satellites usually have a sun synchronous and near polar orbit. This allows the satellites to collect images covering the entire world at a similar sun illumination condition. In a disaster response situation this is of value if pre-event data exist, thus facilitating the detection of change related to the disaster. To perform such change detection, corresponding datasets have to be tied to the same reference system, which is typically done with accurate ground control points acquired by GPS in the field, or from topographic maps. In absence of those, the ephemeris data of the satellite itself can be used, although errors will be larger.

2.2 *Remote sensing satellites and sensors*

2.2.1 *General classification of sensors*

Approximately 80 civilian imaging and non-imaging remote sensing satellites are currently in polar and geostationary orbits (Kramer, 2002), providing data suitable for a variety of emergency responses. In addition, many new satellites or satellite constellations are being built or planned. The satellites carry *optical* sensors that collect images within the wavelength of visible and near infrared (NIR), shortwave infrared (SWIR), med-wave infrared (MWIR) or thermal infrared (TIR) – and *radar* sensors – collecting images in microwave ranges, also called synthetic aperture radar (SAR) images. The images collected by the sensors can be characterized by spectral resolution (wavelength bands), spatial resolution, spatial coverage (swath), and repeat cycle, thus the same assessment criteria as in airborne remote sensing apply (see Section 2 of the previous chapter).

Optical sensors can be categorized into four types according to the number of spectral bands (spectral resolution):

- monospectral or panchromatic (Pan) sensors: collecting single spectral band, grey-scale images;
- multispectral (MS) sensors: collecting images with several spectral bands, forming MS imagery;
- superspectral sensors: collecting images with tens of spectral bands; and
- hyperspectral sensors: collecting images with hundreds of spectral bands.

The number of bands determines how well different materials on the ground can be distinguished. For broad discrimination of features such as water or vegetation, a low number of bands (3–5) is sufficient. However, to detect more subtle differences, e.g. disease damage or invading species within vegetation, or chemical contamination of soil or other surfaces, hyperspectral data would be needed.

Radar or SAR sensors can be categorized according to the spectral bands and the polarization modes (see Section 4.4 of the previous chapter).

- Wavelength:
  - L-band (15–30 cm), S-band (8–15 cm), C-band (4–8 cm), X-band (2.5–4 cm) or K-band (1.7–2.5, 0.75–1.2 cm).
- Polarization:
  - Single polarization modes: VV, or HH, or HV polarization (H: horizontal; V: vertical).
  - Multiple polarization modes: combination of two or more polarization modes.

The explanations given in Section 4.4 of the previous chapter for different radar properties, such as the effect of different polarizations or incident angles, are also applicable here. Principle differences are the large coverage achieved by satellite-based radar systems, and the regular repeat visits that facilitate interferometric applications and change detection.

In terms of **spatial resolution**, satellite sensors can further be classified into:

- low resolution sensors: >approx. 100 m ground resolution;
- medium resolution sensors: approx. 10 m to 100 m; and
- high resolution sensor: approx. sub-meter to 10 m.

The generally inverse relationship between spatial resolution and coverage discussed for airborne sensors also applies to satellites, as does the need to select an appropriate image resolution for a given emergency type.

2.2.2 *Overview of optical satellites and sensors*

An overview of the currently operational and future optical remote sensing satellites with the specifications of the corresponding sensors and images is given in Table 1, sorted by launch year. More detailed information on all operational and defunct satellites and sensors can be found at http://www.itc.nl/research/products/sensordb/searchsat.aspx.

From Table 1 it can be seen that the spatial, spectral and temporal resolution (repeat cycle), as well as spatial coverage (swath) follow certain patterns, which can provide some guidance for selecting suitable satellite imagery for a given emergency response:

Spatial resolution:

- The highest spatial resolution is 0.6 m for panchromatic images taken by the BGIS200 sensor onboard QuickBird 2, followed by Ikonos Pan with 1 m ground resolution.
- The highest spatial resolution for multispectral images is 2.5 m, also taken by QuickBird 2, followed by Ikonos MS and some other MS images with 4 m spatial resolution.
- Most high resolution satellite sensors collect Pan and MS images simultaneously, such as QuickBird, Ikonos and KOMPSAT-2. The resolution of Pan is usually four times higher than that of MS.

Spectral resolution:

- Most satellites collect both Pan and MS images in the spectral range of visible and near infrared wavelength (VNIR).
- Most MS images are taken within the visible and near infrared wavelength (VNIR) and are recorded into 3 or 4 multispectral bands.
- Nearly half of the sensors provide MS images with the spectral range from visible up to shortwave infrared (SWIR). However, these imagers fall mainly in the medium resolution category (20 to 30 m).
- Only a few medium resolution sensors collect MS images up to thermal infrared (TIR).

Temporal resolution:

- The repeat cycle of a single polar orbiting satellite is usually 2 to 3 weeks.
- Some satellites with body pointing capacity can reach a repeat cycle of 3 to 5 days, by turning the satellite off nadir and collecting oblique images (e.g. QuickBird, Ikonos).
- Only a few satellite constellations reach a daily repeat cycle by collecting images using many satellites (e.g. RapidEye A–E, and the Disaster Monitoring Constellation, both five-satellite constellations), others, such as SPOT, come close.

Spatial coverage:

- Usually spatial resolution and coverage are inversely related.
- High resolution satellite images usually have a swath of 10 to 20 km on the ground.
- Medium resolution images have a broader swath from 30 to 600 km.

Although in practice data are typically chosen according to what is available, the more appropriate strategy is to select imagery based on their characteristics as they pertain to a disaster situation in question. The principal question to ask is the purpose of the data/derived information. Is it to (i) obtain a general overview of the event, (ii) to aid in immediate crisis response, (iii) to assess the potential for secondary disasters (further building collapse, landslides after heavy rainstorms, etc.), or (iv) to guide cleanup and reconstruction? Beyond these questions the nature of the events, as well as its physical consequences (type, size, distribution, extent, etc.) has to be understood. Lastly, some image-derived products require special processing equipment or expertise, which also needs to be available in time.

Table 1. Main parameters of currently operational and future optical satellite systems with medium to high spatial resolution (adopted from Metternicht et al., 2005 and Earth Observation Resources, 2006).

		Spatial resolution (meters) and (# bands)							
Optical satellite	Sensor	PAN	VNIR	SWIR	MWIR	TIR	Swath (km)	Repeat cycle (days)	Year launch
Landsat 5	MSS		80 (4)				185	16	1984
	TM		30 (4)	30 (2)		120 (1)			
SPOT 2	HRV	10	20 (3)				60 (80)	26	1990
IRS-P2	LISS-II		36.4 (4)				74	22	1994
IRS-1C	LISS-III		23.5 (3)	70.5 (1)			142	24	1995
	PAN	5.8					70	24	
	WiFS		188 (2)	188 (1)			774	5	
IRS-P3	WiFS		188 (2)	188 (1)			774	5	1996
IRS-1D	LISS-III		23.5 (3)	70.5 (1)			142	24	1997
	PAN	5.8					70	24	
	WiFS		188 (2)	188 (1)			774	5	
SPOT 4	HRVIR	10	20 (3)	20 (1)			60 (80)	26	1998
	Vegetation		1000 (3)	1000 (1)					
Landsat 7	ETM+	15	30 (4)	30 (2)		60 (1)	185	16	1999
CBERS 1 and 2	HRCC	20	20 (4)				113	26	1999 &
	IR-MSS	80			80 (2)	160 (1)	120	26	2003
	WFI		260 (2)				890	3 to 5	
Ikonos 2	OSA	1	4 (4)				11	3	1999
Terra	ASTER		15 (3)	30 (6)		90 (5)	60	16	1999
KOMPSAT-1	EOC	6.6					17	28	1999
	OSMI		1000 (6)						
EROS A1	PIC	1.9					14	2.5–4.5	2000
MTI	MTI		5 (4), 20 (3)	20 (3)	20 (2)	20 (3)	12		2000
Quickbird 2	BGIS 2000	0.6	2.5 (4)				16	3	2001
SPOT 5	HRG	2.5–5	10 (3)	20 (1)			60	26	2002
	HRS	10					120	26	
	Vegetation 2		1000 (3)	1000 (1)			2200	1	

IRS-P6	LISS-4	6	6 (3)			23.9 (70)	5	2003
(ResourceSat-1)	LISS-3		23.5 (3)	23.5 (1)		141	24	
	AWiFS		56 (3)	56 (1)		740		
DMC-AlSat1[a]	ESIS		32 (3)			600	4	2002
DMC-BILSAT-1[a]	PanCam	12				25 (300)	4	2003
	MSIS		28 (4)			55 (300)		
	COBAN		120 (4)					
DMC-NigeriaSat 1[a]	ESIS		32 (3)			600	4	2003
UK-DMC[a]	ESIS		32 (3)			600	4	2003
OrbView-3	OHRIS	1	4 (4)			8	3	2003
ROCSat-2/	RSI	2	8 (4)			24	14	2004
FormoSat-2								
KOMPSAT-2	MSC	1	4 (4)			15	28	2004
China DMC + 4[a]	ESIS		32 (3)			600	4	2005
(Beijing-1)	CMT	4				24 (800)		
IRS-P5	PAN-F	2.5				30	5	2005
(CartoSat-1)								
ALOS	PRISM	2.5				35 (70)	46	2005
	AVNIR-2		10 (4)			70		
RazakSat	MAC	2.5	5 (4)			20	13–15	2006
Resurs DK-1	ESI	1	3 (3)			28.3	N/A	2005
TopSat	RALCam1	2.5	5 (3)			25	4	2005
EROS B–C	PIC	0.7	2.8			11		2005–2008
RapidEye A–E[c]	REIS	6.5	6.5 (5)			78	1	2007
CBERS 3 and 4	MUX		20 (4)			120	26	2008 &
	PAN	5				60	1–26	2011
	ISR		40	40 (2)	80	120	26	
	WFI		73 (4)			866	5	
Plèiades[b]-1 and 2	HiRI	0.7	2.8 (4)			20	1–2	2008–2009

[a] DMC (Disaster Monitoring Constellation of 5 satellites) in sun-synchronic circular orbit, daily revisit cycle.
[b] Two-spacecraft constellation of CNES (Space Agency of France), with provision of stereo images.
[c] Five-satellite constellation.

2.2.3 *Overview of radar satellites and sensors*
Table 2 gives an overview of the current and future radar satellites and sensors with the specifications of individual images.

From Table 2 we can find that:

- The majority of radar satellites use C-band, while some use L- or X-band.
- The spatial resolution of most radar sensors is variable depending on the beam mode used (e.g. 1–100 m, 30–150 m, etc.), although it increases for modern systems.
- The spatial coverage (swath) of the sensors is also variable depending on the beam mode.
- Early radar satellites only have a single polarization mode, while new radar satellites tend to introduce multi-polarization modes.

This general information on radar remote sensing is also of use for users when considering radar data for emergency responses. For example, if high resolution is selected, the ground swath of image will be smaller; if radar data from an early satellite are used, multi-polarization will not be available.

2.2.4 *Spectral, spatial, stereo and orbit characteristics of selected satellites*
(1) Medium resolution optical satellites

Landsat 5 and 7
Landsat imagery has been a major source of optical images for regional and global observations in a variety of application areas, such as agriculture, forestry, geology, geography, land resources, water quality, oceanography, and global change. Table 3 presents the wavelength ranges of individual spectral bands and spatial characteristics of different Landsat sensors and orbit information of the satellites (Earth Observation Resources, 2006).

Landsat TM and ETM+ sensors have seven spectral bands and medium spatial resolution. Different spectral bands are sensitive to different materials of the Earth's surface. Therefore, different bands or band combinations will be suitable for different applications in emergency response. For example:

Band 1 (blue): coastal water mapping, soil/vegetation differentiation, deciduous/coniferous differentiation, chlorophyll absorption.
Band 2 (green): green reflectance, peak of healthy vegetation, plant vigor.
Band 3 (red): chlorophyll absorption, plant type discrimination.
Band 4 (NIR): biomass surveys, water body delineation.
Band 5 (SWIR): vegetation moisture measurement, snow/cloud differentiation.
Band 6 (TIR): plant heat stress, thermal mapping, soil mapping.
Band 7 (SWIR): hydrothermal mapping, geology.
The sensors on board of Landsat series do not have stereo capacity.

SPOT series
SPOT images are another frequently used information source from optical sensors for Earth observation and regional emergency response. Table 4 shows the wavelength ranges of individual spectral bands and spatial characteristics of different SPOT sensors and orbit information of the satellites (Earth Observation Resources, 2006).

SPOT sensors, compared to Landsat sensors, have a higher spatial resolution, but with fewer spectral bands. Due to the lack of a blue band in SPOT MS imagery, natural colour images are difficult to compose.

An advantage of SPOT is its capacity to collect panchromatic stereo images, which allows digital elevation models (DEMs) to be generated.

Table 2. Main characteristics of current and upcoming microwave satellites (Metternicht et al., 2005 and Earth Observation Resources, 2006).

Satellite	ERS-1	ERS-2	Radarsat-1	JERS-1	Envisat	Radarsat-2	Alos	TerraSAR-X	Cosmo/SkyMed[a]
Sensor	AMI	AMI	SAR	SAR	ASAR	SAR	PALSAR	TSX-1	SAR-2000
Space agency	ESA	ESA	RadarSat Int	NASDA	ESA	RadarSat Int	NASDA	DLR/Infoterra GmbH	ASI
Year of launch	1991	1995	1995	1992	2002	2006	2005	2006	2006
Out of service since	2000			1998					
Band	C	C	C	L	C	C	L	X	X
Wavelength (cm)	5.7	5.7	5.7	23.5	5.7	5.7	23.5	3	3
Polarization	VV	VV	HH	HH	HH/VV	All[b]	All	All	HH/VV
Incidence angle (°)	23	23	20–50	35	15–45	10–60	8–60	15–60	Variable
Resolution range (m)	26	26	10–100	18	30–150	3–100	7–100	1–16	1–100
Resolution azimuth (m)	28	28	9–100	18	30–150	3–100	7–100	1–16	1–100
Scene width (km)	100	100	45–500	75	56–400	50–500	40–350	5–100 (up to 350)	10–200 (up to 1300)
Repeat cycle (days)	35	35	24	44	35	24	2–46	2–11	5–16
Orbital elevation (km)	785	785	798	568	800	798	660	514	619

[a] Constellation of 4 satellites.
[b] All four polarization combinations HH, HV, VV and VH.

Table 3. Spectral bands and spatial parameters of Landsat sensors.

Satellite	Landsat 4 and -5	Landsat-4 and -5	Landsat-7
Orbit	Sun-synchronous polar orbit, altitude = 705 km, inclination = 98.2°, repeat cycle = 16 days, descending node at 9:30–10:00 AM (LS 4-5), 10:00–10:15 AM (LS 7)		
Sensor	MSS	TM	ETM+
Spectral bands (all bands in μm)	1) 0.5–0.6 2) 0.6–0.7 3) 0.7–0.8 4) 0.8–1.1	1) 0.45–0.52 VNIR 2) 0.52–0.60 VNIR 3) 0.63–0.69 VNIR 4) 0.76–0.90 VNIR 5) 1.55–1.75 SWIR 7) 2.08–2.35 SWIR 6) 10.4–12.5 TIR	P) 0.52–0.90 VNIR 1) 0.45–0.52 VNIR 2) 0.53–0.61 VNIR 3) 0.63–0.69 VNIR 4) 0.78–0.90 VNIR 5) 1.55–1.75 SWIR 7) 2.09–2.35 SWIR 6) 10.4–12.5 TIR
Swath width	185 km	185 km	185 km
Spatial resolution	80 m	30 m VNIR/SWIR 120 m TIR	15 m PAN 30 m VNIR/SWIR 60 m TIR
Radiometric resolution	6 bit	8 bit	9 bit (8 bit transmitted)

Table 4. Spectral bands and spatial parameters of SPOT sensors.

Satellite	SPOT-1,-2,-3	SPOT-4	SPOT-5
Orbit	Sun-synchronous polar orbit, altitude = 820 km, inclination = 98.8°, repeat cycle = 26 days, descending node at 10:30 AM		
Prime sensor	2 × HRV	2 × HRVIR	2 × HRG
Spectral bands PAN	PAN (0.51–0.73 μm)	PAN (0.61–0.68 μm) co-registered with B2	PA-1 (0.49–0.69 μm) PA-2 (0.49–0.69 μm)
Spectral bands MS	B_1 (0.50–0.59 μm) B_2 (0.61–0.68 μm) B_3 (0.79–0.89 μm)	B_1 (0.50–0.59 μm) B_2 (0.61–0.68 μm) B_3 (0.79–0.89 μm) SWIR (1.58–1.7 μm)	B_1 (0.49–0.61 μm) B_2 (0.61–0.68 μm) B_3 (0.78–0.89 μm) SWIR (1.58–1.7 μm),
Spatial resolution	10 m PAN 20 m MS	10 m PAN 20 m MS	5 m PA- and -2 10 m B_1, B_2 and B_3 20 m SWIR
Swath per sensor	60 km	60 km	60 km
Cross-track pointing	±27° about nadir	±27° about nadir	±27° about nadir (along-track/cross-track)
Radiometric resolution	8 bit	8 bit	8 bit

Terra Mission

ASTER is one of five sensors on board of the Terra satellite, launched in 1999. The sensor was build for collecting superspectral high-resolution imagery of the Earth's surface and clouds to better understand the physical processes affecting climate change (Yamaguchi et al., 1998; Yamaguchi et al., 1993). Table 5 gives detailed information on the spectral bands and spatial parameters of the ASTER sensor and orbit information of the satellite (Earth Observation Resources, 2006).

ASTER has 14 spectral bands with different ground resolutions from 15 m to 90 m. The main advantage of ASTER data is that the large number of bands allows substantially more detailed discrimination of different surface materials than Landsat TM/ETM+. A comparison of the spectral bands or ASTER and TM/ETM+ is provided in Table 6.

Table 5. Spectral bands and spatial parameters of ASTER sensor on board of Terra satellite.

Orbit	Sun-synchronous polar orbit, altitude = 705 km, inclination = 98.5°, repeat cycle = 15 days, descending node at 10:30 AM					
Parameter	Band No.	VNIR	Band No.	SWIR	Band No.	TIR
Spectral bands in μm	1	0.52–0.60	4	1.600–1.700	10	8.125–8.475
	2	0.63–0.69	5	2.145–2.185	11	8.475–8.825
	3N	0.76–0.86	6	2.185–2.225	12	8.925–9.275
	3B	0.76–0.86	7	2.235–2.285	13	10.25–10.95
	Stereoscopic viewing		8	2.295–2.365	14	10.95–11.65
	capability along-track		9	2.360–2.430		
Ground resolution	15 m		30 m		90 m	
Cross-track pointing	±24°		±8.55°		±8.55°	
Swath width	60 km		60 km		60 km	
Data quantization	8 bit		8 bit		12 bit	

Table 6. Spectral range comparison of ASTER and TM/ETM+ (Earth Observation Resources, 2006).

Sensor	ASTER		TM/ETM+ (Landsat 4/5)	
Wavelength Region	Band No.	Spectral Range (μm)	Band No.	Spectral Range (μm)
VNIR			1	0.45–0.52
	1	0.52–0.60	2	0.52–0.60
	2	0.63–0.69	3	0.63–0.69
	3	0.76–0.86	4	0.76–0.90
SWIR	4	1.60–1.70	5	1.55–1.75
	5	2.145–2.185	7	2.08–2.35
	6	2.185–2.225		
	7	2.235–2.285		
	8	2.295–2.365		
	9	2.360–2.430		
TIR	10	8.125–8.475	6	10.4–12.5
	11	8.475–8.825		
	12	8.925–9.275		
	13	10.25–10.95		
	14	10.95–11.65		

ASTER has two telescopes in the VNIR range, one nadir-looking with 3 spectral bands (1, 2 and 3N) and one backward-looking with a single band (3B). The band 3N (nadir) and 3B (backwards) are within the same spectral range, collecting along-track stereo images in NIR of nearly the same area on the ground as the satellite follows its orbit, thus allowing DEMs to be generated from a single ASTER data set. Such information is of use to study more voluminous landscape changes such as landslide scars (Figure 4).

(2) High resolution optical satellites

Ikonos and QuickBird

Ikonos-2, launched in 1999, was the first civilian high resolution optical satellite to reach a spatial resolution of 1 m. QuickBird-2, launched in 2001, surpassed this mark by acquiring data at a spatial resolution of 0.6 m. Both satellites collect Pan and MS images simultaneously at a resolution

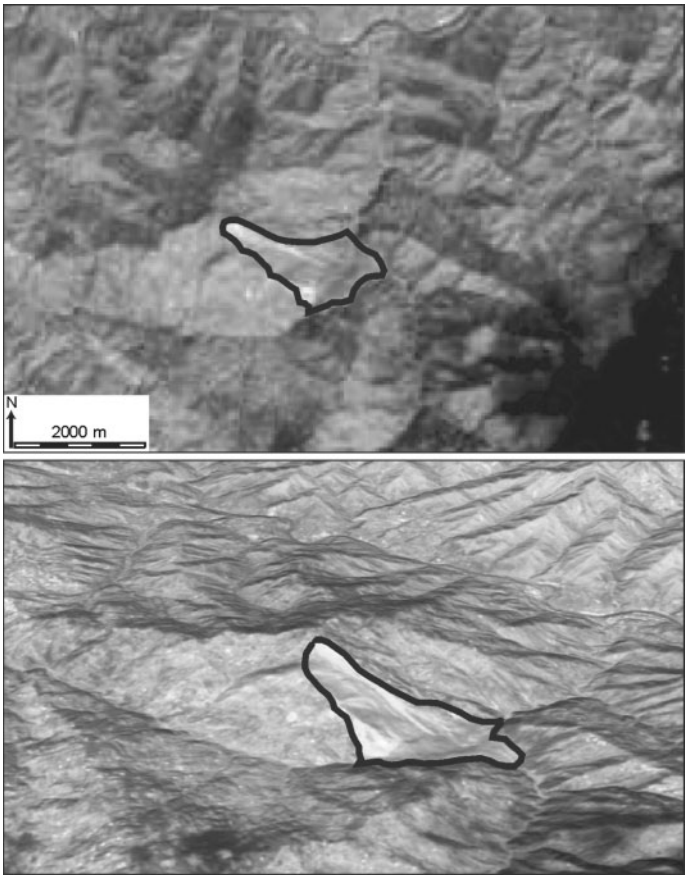


Figure 4. ASTER image of the 2005 Pakistan earthquake area with an identified landslide outlined (top), and draped over a DEM created from the dataset. Length of scar in maximum dimension is appr. 2.5 km. Note that landslide identification is substantially facilitated when displayed in colour. (From U.S./Japan ASTER Science Team).

ratio of 1 to 4. To date, QuickBird-2 is still the satellite which provides commercially available images with the highest spatial resolution. Table 7 gives the information on spectral bands, spatial resolutions, 3D capacity and orbit information of the two satellites (http://www.spaceimaging.com/ and http://www.digitalglobe.com/).

The spectral bands of the two satellites are identical, but the spatial resolution and ground coverage are different. The capacities of body pointing and stereo imaging along or across the track are the special characteristics of the both satellites, which allow for quicker acquisition of ground images and effective 3D information acquisition and extraction.

The detailed data acquired by modern high resolution satellites, which, in addition to Ikonos and Quickbird, also include the Indian Cartosat (2.5 m Pan), Orbview-3 (1 m Pan, 4 m MS), EROS-A/B (1.9/0.7 m), Proba's HRC (5 m) and others have profound benefits for emergency response applications. These data facilitate detailed damage assessment at a house-level (Saito et al., 2004), and those with body pointing capability also allow DEM generation. However, data from these sensors tend to be very expensive, and the area covered small (Figure 5). For example, it would take more than 260 Ikonos scenes to cover the area observed in a single Landsat TM image.

Table 7. Spectral, spatial and orbital information of Ikonos and QuickBird.

Satellite	Ikonos	QuickBird
Orbit	Sun-synchronous polar orbit, altitude = 682 km, inclination = 98.1°, repeat cycle = 14 days, revisit cycle = 1–3 days (for observations at 40° latitude or higher), descending node at 10:30 AM.	Sun-synchronous polar orbit, altitude = 450 km, inclination = 98°, revisit cycle = 1–3.5 days depending on latitude (30° off-nadir), descending node at 10:30 AM
Sensor	OSA	BGIS 2000
Spectral range PAN (μm)	0.45–0.90	0.45–0.90
Spectral range MS (μm)	0.45–0.52, 0.52–0.60, 0.63–0.69, 0.76–0.90	0.45–0.52, 0.52–0.60, 0.63–0.69, 0.76–0.90
Spatial resolution	1 m PAN (0.82 m at nadir) 4 m MS	0.6 m PAN (at nadir) 2.4 m MS
Pixel quantization	11 bits	11 bits
Off-nadir pointing angle	±30° in any direction	±30° in any direction
Stereo capability	Along-track/cross-track	Along-track/cross-track
Swath width	11 km × 11 km (single image)	16.5 km × 16.5 km (single scene)
Nominal strips	11 km × 100 km (length)	16.5 km × 225 km Area (mosaic patterns): 32 km × 32 km (typically) Stereo: 16.5 km × 16.5 km typically; in along-track direction (single pass)

(3) Radar satellites

RADARSAT-1 and 2

First launched in 1995, RADARSAT acquires radar (or SAR) images in the microwave region. Because of the special advantages of active radar sensors, as described in Section 4.4 in the previous chapter, all radar satellites can take images of the Earth's surface under any weather condition and during day and night. This special characteristic makes radar sensors important for emergency response under bad weather conditions.

Compared to optical sensors the number of spaceborne radar instruments is low. After a first short-lived experiment in 1978 (SEASAT, operational for 106 days), the only civilian systems launched were Europe's ERS-1 (1991–2000) and ERS-2 (1995–), Japan's JERS (1992–1998), the Russian Cosmos-1870 and Almaz series (intermittently from 1987–1992), and Canada's Radarsat-1. After a long gap, ASAR was launched aboard Europe's ENVISAT, and in late 2005 Japan's Daichi (previously called ALOS) was deployed. The new Radarsat-2 and Germany's TerraSar-X are scheduled for launch in 2007.

Notable development trends are an increase in spatial resolution (up to 1 m for TerraSar-X) and more polarization settings. The principal disaster applications of spaceborne imaging radar are flooding (Tralli et al., 2005) and oil spill detection (Brekke and Solberg, 2005). Additionally, the utility of radar data to detect structural post-seismic damage has been explored (Bignami et al., 2004; Arciniegas et al., in press). Remarkable success has been archived in mapping surface deformation on volcanoes, as well as following large earthquakes and landslides (e.g. Massonnet et al., 1995; Kimura and Yamaguchi, 2000). The capability to monitor ground deformation with interferometric techniques is one of the most important characteristics of SAR sensors, which can not be found in any optical remote sensing sensor.

Representative for other radar sensors, table 8 provides detailed information on RADARSAT-1 and -2 (Grenier et al., 2004; Earth Observation Resources, 2006).

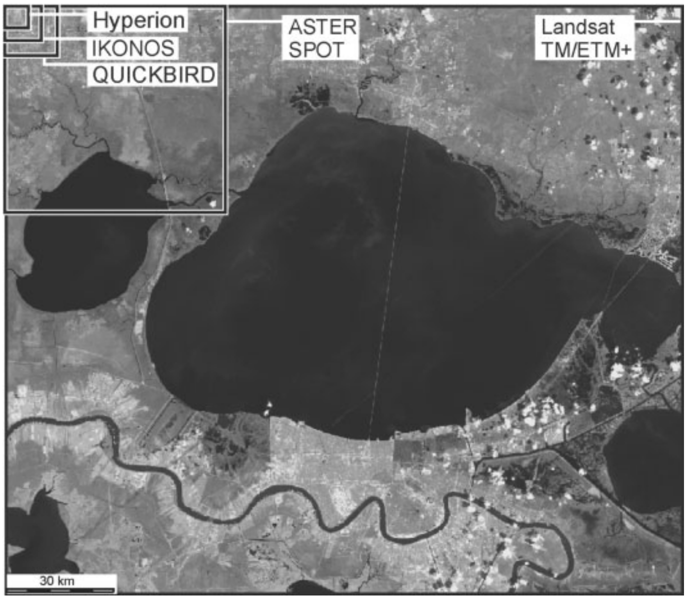


Figure 5. Ground coverage of a Landsat scene (185 × 172 km) of post-Katrina New Orleans, as well as of ASTER, SPOT, IKONOS, QUICKBIRD and Hyperion.

Table 8. SAR imaging modes of RADARSAT-1 and -2.

RADARSAT-1/2 modes (C-band, 5.5 cm center wavelength)						
Orbit	Sun-synchronous polar orbit, altitude = 798 km, inclination = 98.6°, repeat cycle = 24 days, ascending node at 6:00 PM					
	Beam modes	Nominal swath width	Incidence angles to left or right side	Nr. of looks Range × Azimuth	Spatial resolution (m)	Swath coverage left or right (km)
Selective polarization: Transmit H or V Receive H or V or (H and V)	Standard	100 km	20°–49°	1 × 4	25 × 28	250–750
	Wide	150 km	20°–45°	1 × 4	25 × 28	250–650
	Low incidence	170 km	10°–23°	1 × 4	40 × 28	125–300
	High incidence	70 km	50°–60°	1 × 4	20 × 28	750–1000
	Fine	50 km	37°–49°	1 × 1	10 × 9	525–750
	ScanSAR wide	500 km	20°–49°	4 × 4	100 × 100	250–750
	ScanSAR narrow	300 km	20°–46°	2 × 2	50 × 50	300–720
New RADARSAT-2 modes (beyond those offered by RADARSAT-1)						
Polarimetric: transmit H, V on alternate pulses	Standard Quad polarization	25 km	20°–41°	1 × 4	25 × 28	250–600
Receive H, V on any pulse	Fine Quad polarization	25 km	20°–41°	1 × 1	11 × 9	400–600
Selective single polarization Transmit H or V Receive H or V	Multi-look fine	50 km	30°–50°	2 × 2	11 × 9	400–750
	Ultra-fine	20 km	30°–40°	1 × 1	3 × 3	400–550

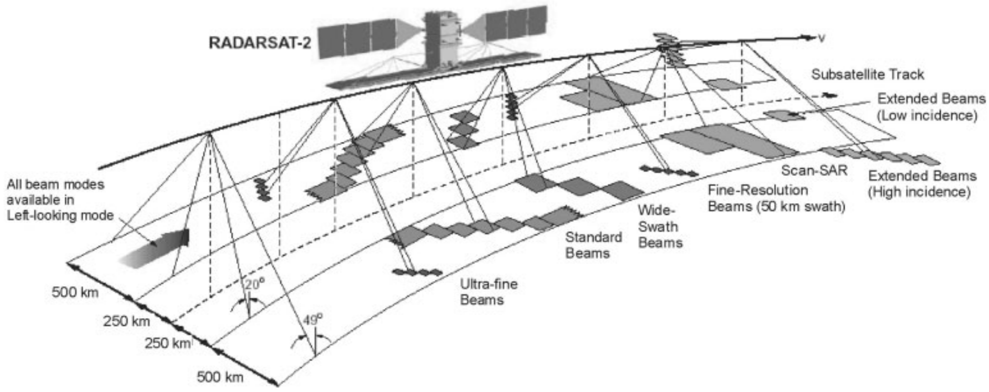


Figure 6. Overview of different beam modes and ground coverage of RADARSAT-2 (Source: MacDonald Dettwiler).

RADARSAT uses C-band with a center wavelength of 5.5 cm for image acquisition, which is also being used by other radar satellites (Table 2). RADARSAT has the capability to generate 3D information with two different techniques: (1) stereoscopic method for DEM generation; and (2) interferometric method for DEM generation or ground deformation monitoring.

- For the stereoscopic method, stereo images taken from two different directions or orbits (Figure 6) are required.
- For the interferometric method, microwave phase information collected from two different orbit paths is required.
  - For DEM generation, it is desired that the two paths are apart from each other with a certain distance to allow the calculation of height information.
  - For deformation monitoring or measurement, it is desired that the two paths are close to each other, whiles the images are taken at different times.

(4) General orbit characteristics
In terms of orbit characteristics of all the above described polar orbiters, it can be seen that

- most satellites follow a sun-synchronous near polar orbit with inclination angles about 98° (with the exception of specialised satellites with inclined orbits for higher temporal resolution and limited coverage in higher latitudes);
- the satellite altitudes range from 450 km to 820 km;
- the temporal resolution for areas at the equator are between 2 and 3 weeks, while for regions in high latitudes (closer to the poles) it is significantly shorter since orbits begin to overlap;
- the temporal resolution of a satellite with body pointing capacity (e.g. off nadir ±30°) can be reduced to 1 to 3 days depending on the latitude of the region; and
- optical satellites usually take images around 9:30 to 10:30 AM, while radar satellites do not, for example RADARSAT at 6:00 AM or 6:00 PM (dawn-dusk orbit), since no sun illumination is needed.

3 IMAGE PRODUCTS AND IMPACT OF SPATIAL AND SPECTRAL CHARACTERISTICS

3.1 *Image products*

Image products from different providers may vary from each other and the product names may be slightly different (e.g. Eurimage, 2006). But the essential products are generally the same both for optical and radar images.

Products from optical sensors can be divided into image products and image-derived products:

- Image products include:
  - raw image, geo-referenced image (referenced to a coordinate system), and ortho-rectified image (distortions related to elevation changes removed using a DEM, creating an image with map-like properties), which are categorized according to geometric corrections; and
  - Pan image, MS image, Pan-sharpened MS image, and stereo image, which are categorized according to spectral resolution, spatial resolution and stereo capability.
- Image derived products include:
  - image maps, thematic maps, DEMs, and 3D images, which need to be processed by the end users or by remote sensing service companies.

Products from radar sensors can also be divided into image products and image derived products:

- Image products include:
  - raw data (unprocessed radar signals);
  - single look complex (stored in slant range, corrected for satellite reception errors, latitude and longitude information included, good for interferometric applications);
  - precision image (north oriented, corrected using ground control points); and
  - ortho-image (terrain distortions removed using a DEM and ground control points GCPs).
- Image derived products:
  - radar image maps, polarization colour image maps, DEMs, interferograms for surface deformation measurements, etc. (see for example Henderson and Lewis, 1998, or Stimson, 1998).

As was explained in the previous chapter (Table 3), the availability of image-derived products, which may require substantial processing and expertise, is generally low for the first 3 days after a disaster. While in principle an airborne platform can be launched quickly and flexibly to acquire imagery, fast data collection with satellite-based sensors is only possible if (i) a satellite happens to be in an appropriate orbit position, (ii) the satellite body can be pointed sideways, (iii) a constellation of several satellites is used, (iv) the area in question is at a high latitude, or (iv) geostationary satellites are used (although those provide data with low spatial resolution).

The availability of optical data has grown substantially in recent years. With some 80 systems in orbit, the possibility of acquiring data in an emergency situation is high. However, the time required for collected data to be downlinked, processed and distributed is typically still on the order of several days. This is a problem addressed by the International Charter 'Space and Major Disasters' (discussed below).

3.2 *Impact of spatial resolution*

Spatial resolution is one of the most important criteria for selecting remote sensing data for responding a specific emergency event. Figure 7 gives an example of spatial resolution vs. object detail. In an image with 30 m resolution, such as MS images of Landsat TM or ETM+, only large area objects can be recognized. Streets or highways are just single lines in the image, if they appear at all. However, in a QuickBird Pan image with a spatial resolution of 0.7 m, individual cars and parking lines can be clearly seen, even people in an open area can be identified.

Figure 8 shows a series of degraded images of a volcanic mudflow area. While coarse (low resolution) imagery is sufficient for general features related to the main flow, any detailed analysis involving smaller features such as houses demands very high resolution.

For emergency response, therefore, medium resolution images such as Landsat are more appropriate for macroscopic monitoring of areas affected by a natural disaster, such as flooded areas along a river or coast, or damaged areas of a forest fire or landslide. Conversely, high resolution images from Ikonos or QuickBird are more appropriate for detailed investigations within areas damaged by a natural or man-made disaster, in urban areas, or to examine individual objects damaged or in

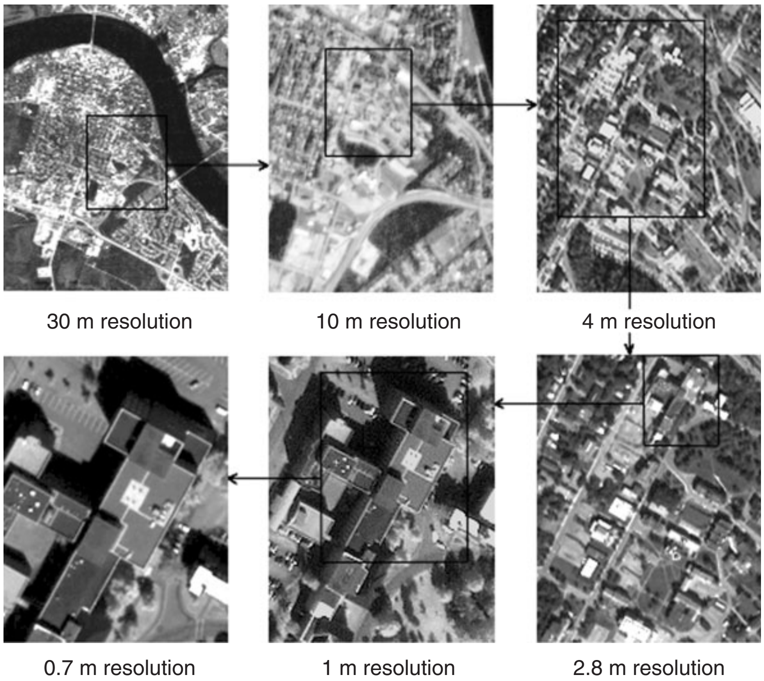


Figure 7. Spatial resolution vs. object detail showing in Landsat TM (30 m), SPOT Pan (10 m), Ikonos MS (4 m), QuickBird MS (2.8 m), Ikonos Pan (1 m) and QuickBird Pan (0.7 m) (courtesy of the city of Fredericton).

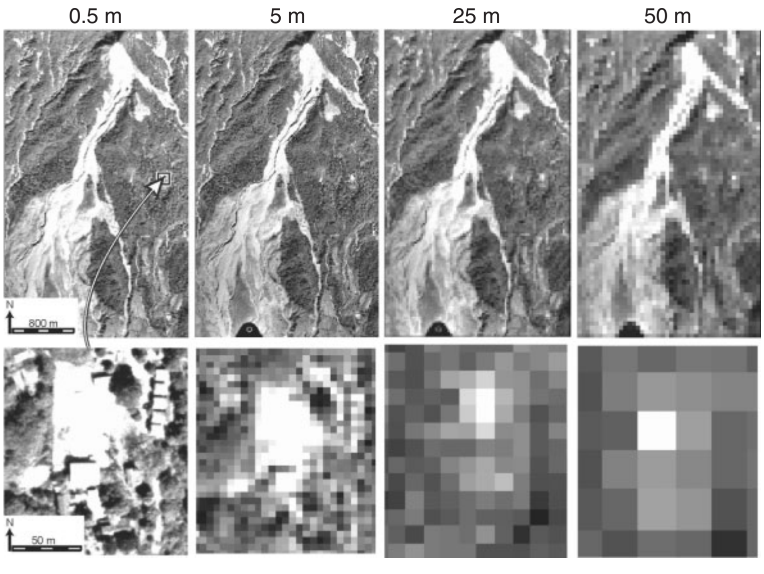


Figure 8. Images of varying spatial resolution of the 1998 Casita volcano (Nicaragua) mudflow. Note that for characteristics of the actual flow, such as boundaries or main channels, even a comparatively low resolution is sufficient. For smaller features such as buildings, however, as illustrated in the bottom row, the imagery's utility declines rapidly.

Figure 9. Natural colour image (left) and false colour composite (FCC) (right) of QuickBird 2.8 m MS data showing different landcovers on the campus of the University of New Brunswick. Note that in the original colour images, reproduced here in greyscale, buildings and paved areas are particularly apparent in the natural colour image (left), while vegetation is highlighted in red in the FCC image (right).

danger, such as buildings, houses, and other infrastructures. The rule of thumb is to use images as coarse as possible, but as detailed as necessary.

3.3 *Impact of spectral resolution (or spectral bands)*

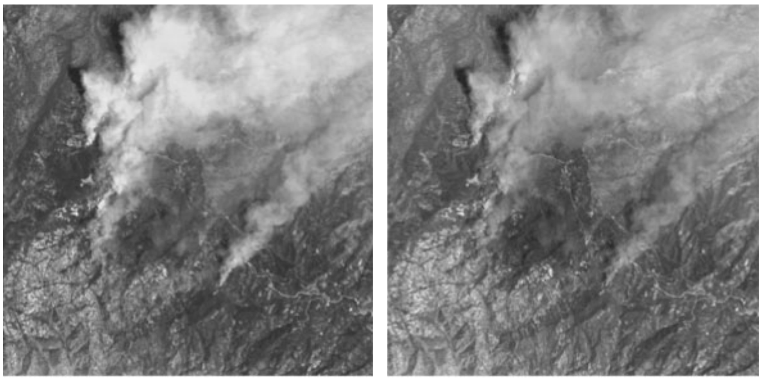
Multispectral information is also important in emergency response to identify objects of interest. Figure 9 shows two colour images from the same QuickBird MS data set, but one is composed of bands 1, 2, and 3 forming a natural colour image (Figure 9 left), the other of bands 2, 3, and 4 forming a standard false colour composite (FCC) (Figure 9 right). Buildings and paved areas stand out in the natural colour image, while trees and other vegetations show up clearly in the FCC.

Another example of the importance of spectral information can be seen in Figure 10. The smoke of the forest fire can be clearly seen in both the natural colour image (left) and the FCC image (right), but in slightly different colour. However, it is difficult to identify burned areas in the natural colour image because forest (dark green) and burned areas (black) appear in very close colours. In contrast, burned areas (black) can be clearly differentiated from the forest areas (red) in the FCC due to the reduced near infrared signal of destroyed vegetation.

In general, natural colour images may be more effective for investigations of man-made objects in urban areas, because of the diversity of man-made objects and similar object colours in both the image and the real world. However, false colour infrared images may be better for investigations of forest fire or water flooding, because of clear colour contrast between vegetation and non-vegetation (including burned areas) and between flooded and dry areas. Near-infrared imagery is particularly suited for the identification of water, which appears black. Proper spectral band selection is also important for effective monitoring/investigation of other emergency events. A band combination should be selected which can best differentiate the objects of interest from each other.

3.4 *Difference between optical and SAR images*

Optical images are usually easier to interpret than SAR images, a difference shown in Figure 11. The grey values of an optical image represent the magnitude of the spectral reflectance of individual objects, making them similar in appearance to normal photographic images. This makes optical



Natural colour Colour infrared

Figure 10. The difference of forest fire shown in a natural colour image (left) and a colour infrared image (right). Note that in the original colour images, forest appears dark green in the natural colour image but red in FCC image, while burned areas appear black in both images. (Source: DigitalGlobe).

Optical image, 9 m resolution Radar image, 9 m resolution

Figure 11. Difference between optical image (left, Ikonos pan resampled to 9 m) and radar image (right, RADARSAT-1 fine bean) (courtesy of the city of Fredericton).

images relatively easy to understand and interpret, although the unusual (near-) vertical viewing direction, as well as the low image scale, can also pose some problems. However, the amplitude or intensity values of a SAR image are a function of the roughness and moisture of the ground surface, as well as the radar type and incident angle used (see Section 4.4 of the previous chapter). Together with characteristic image distortions this can make for challenging image interpretation. An accurate interpretation of SAR images requires the operator to have the knowledge of the area of interest and knowledge of the principles of SAR imaging.

Normally, if optical images can be quickly acquired for an emergency area, they would be a more appropriate choice than radar due to their ease of interpretation. In case of bad weather conditions, however, as well as for specific damages such as oil spills, radar images are the only suitable option alternative for a quick response. In addition, radar images are good for certain special applications such as differentiation of flooded from dry areas and detecting ships in ice covered ocean (a challenge with optical images for typically white ships). For precise 3D measurements over larger areas, such as to detect ground deformation caused by an earthquake, interferometric SAR is uniquely suited.

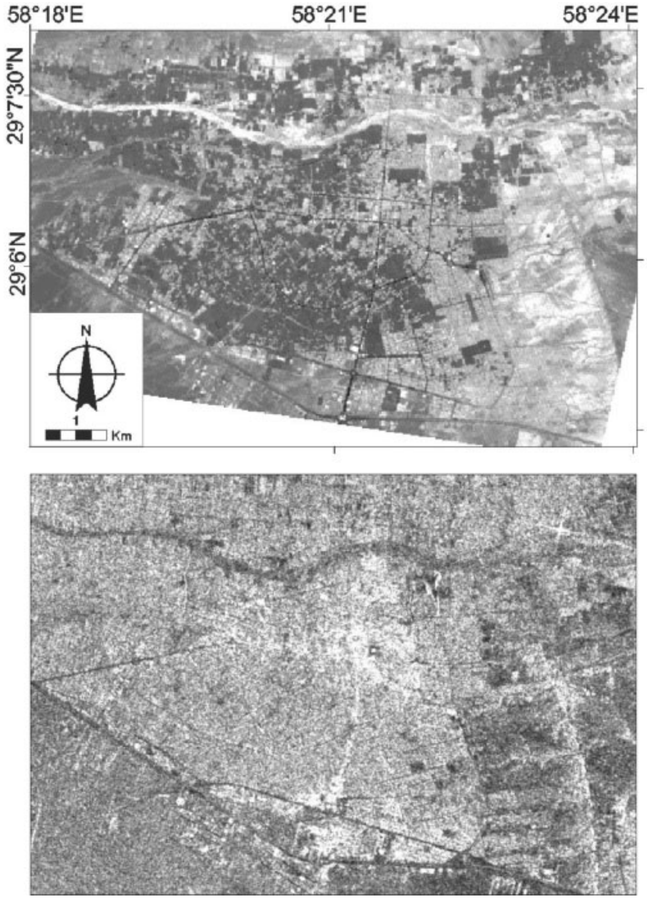


Figure 12. Pre- and post-earthquake ASTER (top) and ASAR radar (bottom) images, respectively, of the city of Bam, Iran. Note that in particular vegetation would appear very prominently in optical data such as ASTER if displayed in colour. In this greyscale reproduction vegetation corresponds to the dark patches.

Radar data have also been used for urban damage assessment. However, Figure 12 illustrates how different radar data can be. The figure shows an ASTER image (left) and an ENVISAT ASAR scene (right) of the Iranian city of Bam. The latter was acquired following the December 2004 earthquake. While the build-up and vegetated areas are easily distinguished in the optical data, such interpretation is difficult and still subject to active research for radar images (e.g. Arciniegas et al., in press).

3.5 *Impact of image fusion*

As discussed in section 2 (Table 1), most optical satellites simultaneously collect Pan and MS images at higher and lower spatial resolution, respectively. To obtain a high resolution MS image, image fusion is an important process, a technique to produce high resolution MS images by merging available high resolution Pan and low resolution MS Images. Many image fusion techniques have been developed to combine Pan and MS images for a high resolution pan-sharpened MS image. To date, the PCI Pansharp module produces the best Pan-MS fusion results among all commercially available software tools (Zhang, 2004; PCI, 2004; Gorin, 2005).

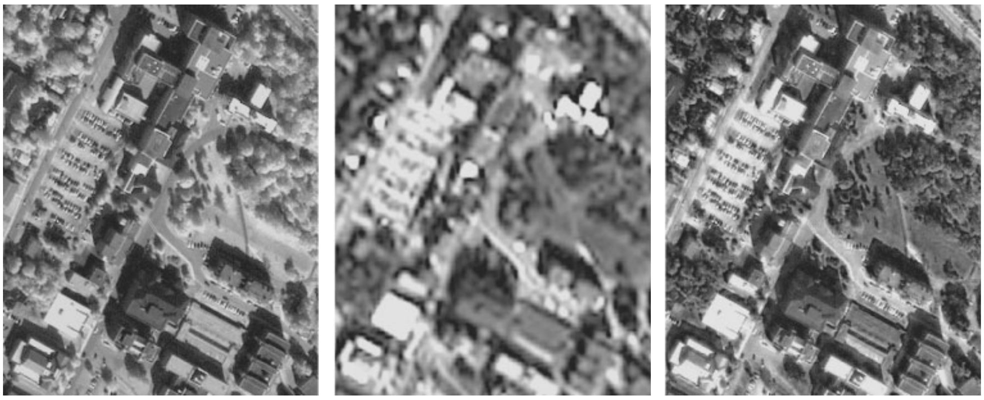


Figure 13. Spectral and spatial comparison between original Pan (left), original MS (middle), and pan-sharpened MS (right) images. Note that in the original colour images, the colour of the pan-sharpened MS (right) is almost identical to that of the Ikonos MS (middle) (engineering buildings and science buildings of the University of New Brunswick, image courtesy of the city of Fredericton).

Figure 13 illustrates the spatial and spectral differences between original Pan, original MS and pan-sharpened MS images from Ikonos-2. In the original Pan image (left) detailed information such as cars and trees can be clearly recognized, but due to the lack of spectral information it is not possible to identify their colours. On the other hand, the colours of cars and trees can be roughly seen in the original MS image (middle), but they cannot be clearly differentiated from each other due to the lack of spatial detail. However, in the pan-sharpened image (right), fused using the PCI Pansharp module, both colours and boundaries of individual cars and trees can be clearly seen. This example shows the importance of image fusion (or pan-sharpening) for detailed observation of the Earth's surface.

The impact of image fusion for detailed emergency investigation can also be seen in Figure 14, which shows a forest fire in southern California recorded by QuickBird on 27th October 2003. The left image is the original QuickBird MS image, 2.8 m, while the right one is the MS image after image fusion, 0.7 m. It is clear that the original MS image is not adequate for investigating individual houses in danger of the forest fire, but the fused image does provide much more adequate information for the investigation – individual family houses can be delineated and even cars in the area can be identified. Therefore, fused high resolution satellite MS images are a valuable information source for emergency response in residential areas or urban areas (also see Figure 15).

In addition to pan-sharpening, image fusion can also be used to integrate different data sources, such as GIS or map data with images, to support visual or quantitative analysis of change.

3.6 *Impact of body pointing*

Satellite body pointing is a relatively recent technique developed to increase the speed of image acquisition of areas of interest. It significantly enhances the agility of image acquisition and reduces the temporal resolution. Figure 15 shows two pan-sharpened Ikonos natural colour images of Manhattan before and after September 11, 2001. The right image was acquired on September 12th just one day after the man-made disaster. If body pointing technique had not been used to allow the satellite to take off-nadir images, it would not have been possible to observe the disaster site within such as short period, except with constellations of several satellites. However, it has to be remembered, the pointing of the satellite has to be specifically programmed. Such tasking is expensive, and may conflict with other observation priorities.

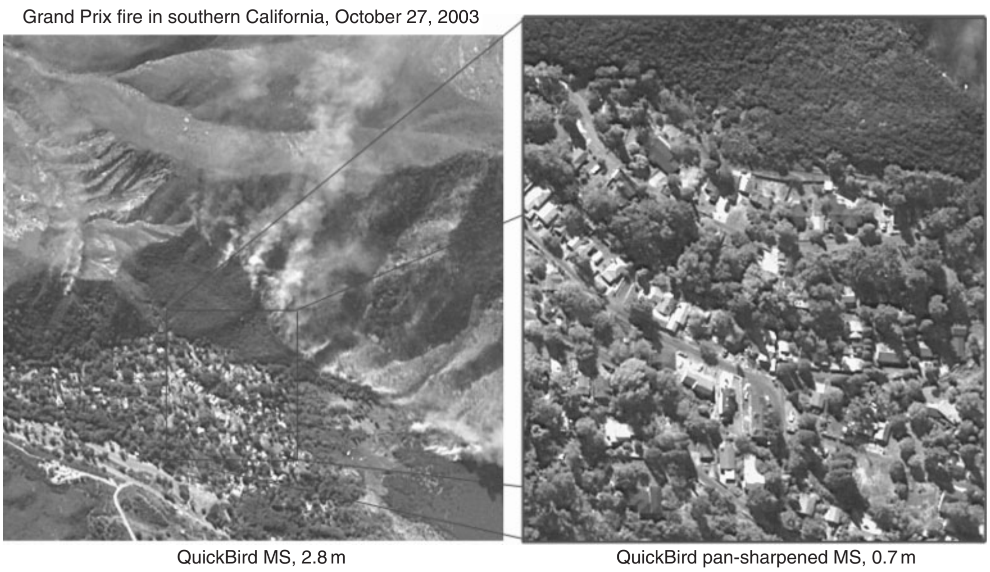


Figure 14. Difference of original natural colour image (left) and fused natural colour image (right) for investigating forest fire and residence in danger, both displayed at 1:1 scale. Original images were in colour. (Credit to DigitalGlobe).

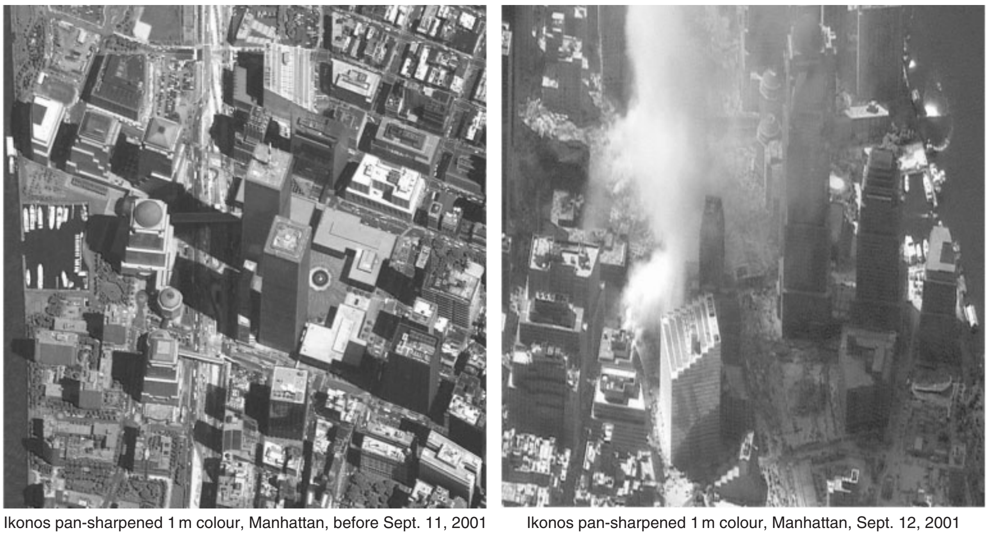


Figure 15. High resolution oblique images collected by Ikonos before and after the man-made disaster in New York on September 11th of 2001. Original images were in natural colour. (Credit to Space Imaging).

From the two pan-sharpened natural colour images in Figure 15 it can be seen that buildings, streets and trees are clearly recorded, and cars can be clearly recognized. In the right image the destruction of buildings and the impact to surrounding areas can be interpreted. Even the chaotic traffic jam on the surrounding streets can be seen. This demonstrates the usefulness of high resolution satellite images for urban emergency response.

However, due to the off-nadir viewing, which results in oblique imagery, many areas are occluded, i.e. blocked by taller buildings, making a comprehensive investigation of damages impossible. In particular precise mapping, as well as automated change detection based on pre-event data, suffer from such geometric distortion. Therefore, off-nadir pointing may also cause problems for emergency response, and should thus be avoided if possible.

4 CHALLENGES IN DATA AVAILABILITY

In the collection of remote sensing data for emergency response, one of the most challenging issues is to obtain image data of areas of interest within the 3 day emergency response window. From Tables 1 and 3–8 it can be seen that the normal repeat cycle of a single satellite is 2 to 3 weeks. If the satellite has the body pointing capabilities, the repeat cycle can be reduced to 3 to 5 days. However, in case of poor weather conditions etc., the actual time needed for collecting useful ground images often exceeds that time frame. On the other hand, oblique images taken by off-nadir pointing may not be suitable for many emergency events due to large blocked areas and geometric distortions. These limitations constrain the utility of using satellite remote sensing for emergency response. To overcome this limitation, some international initiatives have been proposed and developed, and joined by many countries and organizations to synergize the capacity of individual satellites and reduce the acquisition time.

There are technical solutions such as dedicated satellite constellations for disaster management, as well as more organisational approaches. The only currently operational satellite network solution is the Disaster Monitoring Constellation (DMC), which is described below. A constellation of 4 radar satellites, COSMO-Skymed, is being built by the Italian Space Agency, and is expected to be completed in 2008 (Metternich et al., 2005). The RapidEye constellation of 5 satellites, to be launched in 2007, also aims at supporting disaster response, although the principal focus is on agricultural remote sensing (http://www.rapideye.net/). For a list of other previously proposed constellations see Kerle and Oppenheimer, 2002.

4.1 *Disaster Monitoring Constellation (DMC)*

The Disaster Monitoring Constellation (DMC) is an international satellite program for rapid global response to natural or man-made disasters. DMC was initially proposed in 1996 and is led by Surrey Satellite Technology Ltd (SSTL), Surrey, UK. The objective of the constellation is daily global imaging capability by means of a network of five affordable micro-satellites, which collect medium resolution (28–32 m) images in 3 or 4 multispectral bands (corresponding to Landsat TM bands 2, 3, 4 and 1, 2, 3, 4, respectively) (Sweeting and Chen, 1996). As explained in section 2.2.2., such medium spatial resolution limits the utility of such data.

The DMC consortium consists of partners from Algeria, China, Nigeria, Turkey and the United Kingdom. Often involving engineers from these countries, SSTL built five low-cost Earth observation micro-satellites that were launched as the first Earth observation constellation (Table 9), and that provide daily images for global disaster monitoring (da Silva Curiel et al., 2005).

Already in March 2004, the first four DMC satellites, AlSAT-1, BILSAT-1, NigeriaSat-1 and UK-DMC, achieved the targeted orbit in the same orbit plane with a phase difference of 90° (Figure 16). This enables the DMC consortium to image anywhere on the Earth's surface with a revisit period of 24 hours (Earth Observation Resources, 2006). With the fifth satellite, Beijing-1, in orbit, the temporal resolution of the DMC constellation is even shorter. Another substantial strength of the DMC satellites is the large ground coverage in tiles up to 600 km wide (compare to figure 5).

4.2 *International Charter 'Space and Major Disasters'*

As detailed above, substantial space resources already exist, covering a wide range of technical specifications and hence specific utilities. This suggests that the best way forward may not be to

Table 9. The DMC satellite constellation for daily monitoring of global disasters.

Spacecraft	Spectral bands	Spatial resolution	Swath	Country	Launch date
AlSAT-1	MS (3)	32 m	600 km	Algeria	Nov. 28, 2002
BILSAT-1	MS (4)	28 m	55 km (300)	Turkey	Sept. 27, 2003
	Pan	12 m	25 km (300)		
NigeriaSat-1	MS (3)	32 m	600 km	Nigeria	Sept. 27, 2003
UK-DMCSat-1	MS (3)	32 m	600 km	UK	Sept. 27, 2003
Beijing-1	MS (3)	32 m	600 km	China	Oct. 27, 2005
(China-DMC+4)	Pan	4 m	24 km within a FOR of 800 km		

Constellation orbit: Sun-synchronous polar orbit, altitude = 686 km, inclination = 98°, equator crossing at 10:30

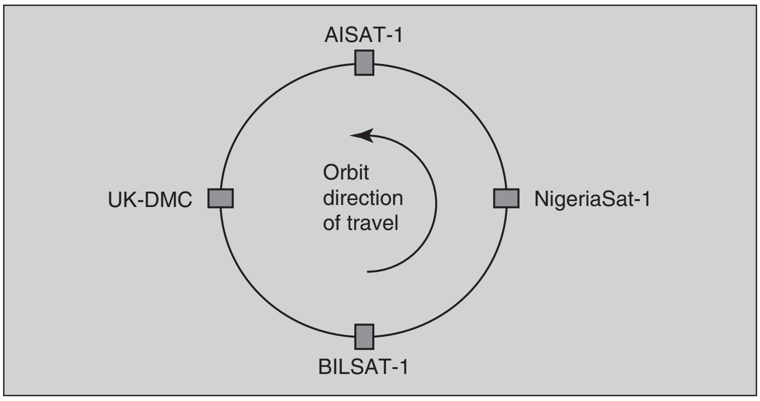


Figure 16. Orbit spacing of DMC satellite constellation for daily monitoring in 2004 (Earth Observation Resources, 2006).

equip every country with its own space technology, but rather to coordinate and optimise data acquisition by existing resources.

The International Charter 'Space and Major Disasters' is not a technical solution, but aims at improving the efficiency in the use of existing space technology during a disaster response phase. It was initiated by the European and French space agencies (ESA and CNES) after the UNISPACE III conference held in Vienna, Austria, in July 1999, and was declared formally operational on November 1, 2000. The objective of the Charter is to provide a unified system of space data acquisition and delivery for a rapid response to natural or man-made disasters. To date, the Canadian Space Agency (CSA), the National Oceanic and Atmospheric Administration (NOAA), the Indian Space Research Organization (ISRO), the Argentine Space Agency (CONAE), the Japan Aerospace Exploration Agency (JAXA), the United States Geological Survey (USGS), and the DMC-operator DMCII have joined the Charter (Table 10). Each member agency has committed resources to support the data collection of the Charter to improve the efficiency of data provision for emergency responses globally (disasterscharter.org).

To date the Charter has been activated more that 100 times, responding to a variety of natural and technological emergencies (see for example Bessis et al., 2004; www.disastercharter.org). Once the Charter is activated, the most suitable and most quickly available space resources of the participating partners are used to obtain imagery of the affected areas. These data are then

Table 10. The current members of the Charter and their space resources.

Member	Space resources
European Space Agency (ESA)	ERS, ENVISAT
Centre national d'études spatiales (CNES)	SPOT
Canadian Space Agency (CSA)	RADARSAT
Indian Space Research Organisation (ISRO)	IRS
National Oceanic and Atmospheric Administration (NOAA)	POES, GOES
Argentina's Comisión Nacional de Actividades Espaciales (CONAE)	SAC-C
Japan Aerospace Exploration Agency (JAXA)	ALOS
United States Geological Survey (USGS)	Landsat
DMC International Imaging (DMC)	
Centre National des Techniques Spatiales (Algeria)	ALSAT-1
National Space Research and Development (Nigeria)	NigeriaSat
Tübitak-BILTEN (Turkey)	BILSAT-1
BNSC and Surrey Satellite Technology Limited (UK)	UK-DMC
Beijing Landview Mapping Information Technology Ltd (China)	BEIJING-1

further processed by Charter partners, such as the German Space Agency (DLR), UNOSAT or SERTIT, who provide map products that are made available via the Global Disaster Alert and Coordination System (GDACS, http://www.gdacs.org/), ReliefWeb (http://www.reliefweb.int) or Reuters's AlertNet (http://www.alertnet.org/). Such organisational improvements are arguably of greater value than the mere launching of more satellites. Typically the time-consuming aspect is not the data acquisition itself, but rather the transfer, processing and dissemination of useful products to emergency response personnel in the field, a requirement well served by Charter-like activities.

5 FUTURE DEVELOPMENTS

In parallel to improvements in data management and organisation, new satellites are also being built, either with new capabilities or to replace old ones. Satellite remote sensing has reached a point where it is of critical importance to many disciplines, from meteorology to the enforcement of non-proliferation treaties. It is thus an increasingly dependable and predictable tool that must be part of disaster management and crisis response plans. The future developments of remote sensing technologies are directed mainly towards the higher spatial, spectral, and temporal resolution, as shown below. It addition it must be realised that imaging satellites are only one part of relevant space infrastructure. Equally important are communication and navigation systems. The vital GPS system is satellite-based, as are emergency communication points set up in disaster areas.

5.1 *Higher spatial resolution*

WorldView. After the remarkable success of QuickBird-2 for acquisition of the highest resolution satellite images, DigitalGlobe is now in the development of the next generation satellite, WorldView, with an even higher spatial resolution of 0.25 m (Pan) and 1 m (MS), and 8 MS bands within the VNIR range. However, for non-US government customers the imagery must be re-sampled to 50-cm. The satellite is planned to be launched in 2007 (DigitalGlobe, 2004).

OrbView-5. The company ORBIMAGE has also scheduled the launch of OrbView-5 for early 2007. The satellite will simultaneously acquire Pan images at 0.41 m resolution and MS images at 1.64 m. It will have the capacity of collecting more than 800,000 km^2 of imagery in a single day

Table 11. Future sensor development of the Pleiades program (after Earth Observation Resources, 2006).

Sensor	Resolution (m)	Swath width (km)	Nr. of bands	Revisit time (days)	Main applications
Wide field	2–5	40–100	3–4	3–7	Cartography, geology, agriculture, forest, hydrology
Optical HR	<=1	10–30	3–4	1–2	Cartography, risk, forest, geology
Superspectral	3–10	100–300	6–20	1–2	Agriculture, forest, geology
Hyperspectral	5–20	50–300	30–200	2–7	Geology
Thermal	1–40	100	TBD	<1	Forest fires, geology, ocean

and downlinking imagery in real-time to international ground station customers (ORBIMAGE, 2005).

TerraSar-X. This radar satellite will provide 1 m, 3 m and 16 m data in various polarization modes. In particular in spatial resolution this constitutes a substantial improvement over existing systems. Detailed studies such as urban damage assessment will benefit from the improvement (www.terrasar.de).

5.2 *Higher spectral resolution and response speed*

Pleiades-HR (High-Resolution Optical Imaging Constellation of CNES [French Space Agency]) is an example of the development towards higher spectral resolution and temporal resolution. A two-satellite constellation is planned for a higher repeat cycle. The planned first launch is in 2008 with the overall objectives for (Perret et al., 2002; Baudoin et al., 2001):

- high resolution panchromatic (0.7 m) and multispectral (2.8 m) imagery;
- a daily observation accessibility to any point on the Earth; and
- large coverage stereo imagery (up to 350 km × 20 km, or 150 km × 40 km).

Pleiades is a multi application, multi sensor and multi partnership program. The first generation will only carry an optical high-resolution imager (HiRI). Further sensor systems, such as wide-field, superspectral, hyperspectral and thermal (TIR) sensors, will be options for future Pleiades implementations to be launched after 2009 (Table 11).

6 OUTLOOK

Satellite remote sensing has demonstrated a tremendous potential in data collection for emergency response. Currently available satellite imagery has been applied to numerous applications in disaster prediction, investigation and/or management at global, regional and local scales. Due to technical limitations, it is still challenging to acquire quality imagery of emergency areas within a short time period (e.g. within 3 days). Therefore, the data have been mostly used for more detailed assessments of an event's aftermath and reconstruction, as well as in post-disaster scientific research. Unfortunately, bad weather conditions are often associated the natural disasters, causing further delay in the acquisition of suitable imagery and, hence, reduce the utility of satellite remote sensing for emergency response. Radar satellite images can overcome weather condition problems, although the nature of radar data limits their use to emergency aspects that entail characteristic changes in surface roughness or moisture (such as flooding), or to situations where subtle surface deformations occurred. In addition the number of operational radar sensors is very small.

The current limitations of satellite remote sensing for rapid data collection have been realized by the remote sensing community, including image providers and end users. To solve the existing problems and explore the potential of satellite remote sensing for emergency response, many international initiatives have been proposed, satellite constellations have been or are being constructed, new satellites with agile pointing capability have been developed and are being further improved, and new sensors with higher spatial or spectral resolution, or more polarization settings are under development. This will lead to faster data acquisition, and more diverse data types at higher resolutions (including multispectral, superspectral, hyherspectral, multipolorization and stereo images), which will significantly increase the utility of satellite remote sensing for emergency response. Currently the UN's Committee on the Peaceful Uses of Outer Space is also working on establishing an international space coordination body for disaster management that would link existing initiatives and mechanisms.

Importantly, there is increasing awareness of the need to integrate satellite infrastructure into a global observation strategies. To that end, groups such as the Committee on Earth Observation Satellites (CEOS) or the Integrated Global Observing Strategy (IGOS) seek to devise comprehensive and synergistic frameworks that maximise the benefit of existing and planned technology. Disaster management, including crisis response, features prominently in these efforts. An example is the Global Earth Observation System of Systems (GOESS), which is currently being developed, and for which the Global Monitoring for Environment and Security (GMES) is the European contribution. The processing of Charter data by DLR or SERTIT, as detailed above, is done under this umbrella.

Lastly, given the vast amounts of data being collected, some automation of image reception and processing is required. This is already being done successfully with lower resolution data, such as those collected by AVHRR (1.1 km resolution) and MODIS (250–1000 m resolution), to detect volcanic activity or forest fires automatically (see for example http://modis.higp.hawaii.edu/). Similar data mining approaches that comb large data sets (semi-)automatically can also be devised for other hazardous situations that allow disasters to be detected before of while they occur, and thus allowing a faster response.

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