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A review of the status of satellite remote sensing and image processing techniques for mapping natural hazards and disasters

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Abstract: In the event of a natural disaster, remote sensing is a valuable source of spatial information and its utility has been proven on many occasions around the world. However, there are many different types of hazards experienced worldwide on an annual basis and their remote sensing solutions are equally varied. This paper addresses a number of data types and image processing techniques used to map and monitor earthquakes, faulting, volcanic activity, landslides, flooding, and wildfire, and the damages associated with each. Remote sensing is currently used operationally for some monitoring programs, though there are also difficulties associated with the rapid acquisition of data and provision of a robust product to emergency services as an end-user. The current status of remote sensing as a rapid-response data source is discussed, and some perspectives given on emerging airborne and satellite technologies.

Key words: image processing, natural hazards, optical, remote sensing, SAR, thermal.

I Natural hazards and disasters

The use of remote sensing within the domain of natural hazards and disasters has become increasingly common, due in part to increased awareness of environmental issues such as climate change, but also to the increase in geospatial technologies and the ability to provide up-to-date imagery to the public through the media and internet. As technology is enhanced, demand and expectations increase for near-real-time monitoring and visual images to be relayed to emergency services and the public in the event of a natural disaster. Recent improvements to earth monitoring satellites are paving the way to supply the demand. Techniques needed to exploit the available data effectively and rapidly must be developed concurrently, to ensure the best possible intelligence is reaching emergency services and decision-makers in a timely manner.

A comprehensive review of remote sensing for some natural hazards was completed by Tralli *et al*. (2005), and Gillespie *et al*. (2007)

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reviewed natural hazard prediction and assessment by remote sensing, with a focus on the types of sensors available. The research presented in this paper complements these works by directing attention to the manner in which the mapping was achieved with respect to different image processing techniques. Further, we also report on the reality of remotely sensed image acquisition and processing requirements with the view that timely intelligence and information extraction is critical in an emergency response to a hazard or disaster situation.

For reference, the details of a number of satellites and sensors that are commonly used or have the potential for hazards mapping are collated in Table 1.

The four phases of the disaster management cycle include reduction (mitigation), readiness (preparedness), response and recovery (Cartwright, 2005). Remote sensing has a role to play in each of these phases, though this paper focuses primarily on its contribution to the response phase. Several different types of natural hazards and disasters are presented in the following sections to determine the commonly used image processing techniques (summarized in Table 2), their advantages and disadvantages, and to review the reality of applying them in a rapid-response environment.

Through this review it became apparent that many mapping operations are still using manual interpretation techniques to achieve

Table 1 Summary of the characteristics of some sensors used in hazards mapping and monitoring

Satellite	Sensor	Swath (km)	Nadir spatial resolution (m)	Revisit capability
Airborne sensors	variable	variable	> 0.1	Mobilized to order
	CASI	variable	1–2	
	Hymap	100–225	2–10	
Worldview	Panchromatic	16.4	0.46	1.1 days
	Multispectral	16.4	1.85	
Quickbird	Panchromatic	16.5	0.6	1.5–3 days
	Multispectral	16.5	2.4	
Ikonos	Panchromatic	11	1	1.5–3 days
	Multispectral	11	4	
RapidEye^	Multispectral	77 x 1500	6.5	1 day
EO-1	ALI	60	30	Every 16 days
	Hyperion	7.5	30	
Terra	ASTER	60	15,30,90	4–16 days
Terra / Aqua	MODIS	2300	250, 500, 1000	At least twice daily for each satellite
ALOS	PRISM	35	4	Several times per year as per JAXA acquisition plan
	AVNIR	70	10	
	PALSAR (Fine)	40–70	10	
	PALSAR (ScanSAR)	250–350	100	
SPOT-4	Panchromatic	60–80	10	11 times every 26 days
	Multispectral	60–80	20	

(*Continued*)

Table 1 *Continued*

Satellite	Sensor	Swath (km)	Nadir spatial resolution (m)	Revisit capability
SPOT-5	Panchromatic	60–80	5	11 times every 26 days
	Multispectral	60–80	10	
Kompsat	Panchromatic	15	1	2–3 days
	Multispectral	15	1	
Landsat-5	TM Multispectral	185	30	Every 16 days
	TM Thermal	185	120	
Landsat-7*	ETM+ Panchromatic	185	15	Every 16 days
	ETM+ Multispectral	185	30	
	ETM+ Thermal	185	60	
NOAA	AVHRR	2399	1100	Several times per day
Envisat	MERIS	575	300	2–3 days
Radarsat-2	Ultra-fine	20	3	Every few days
Radarsat-1/-2	Fine	50	8	
Radarsat-2	Quad-pol fine	25	8	
Radarsat-1/-2	Standard	100	25	
Radarsat-2	Quad-pol standard	25	25	
Radarsat-1	Wide	150	30	
Radarsat-1/-2	ScanSAR narrow	300	50	
Radarsat-1/-2	ScanSAR wide	500	100	
Radarsat-1/-2	Extended high	75	25	
Radarsat-1	Extended low	170	35	
ERS-2		100	30	35-day repeat cycle
Envisat	ASAR standard	100	30	36-day repeat cycle
	ASAR ScanSAR	405	1000	
TerraSAR-X	Spotlight	10	1	11-day repeat cycle; 2.5-day revisit capability
	Stripmap	30	3	
	ScanSAR	100	18	
Cosmo-Skymed^	Spotlight	10	<1	~37 hours
	Stripmap	40	3–15	
	ScanSAR	100-200	30–100	

*Landsat-7 nearing the end of its useful life; problems with scan line corrector resulting in data gaps
^Figures quoted for one satellite in constellation

high accuracy, but are disadvantaged by speed of reproduction. It is considerably faster and more sustainable to have automatically implemented algorithms for hazard detection and monitoring. Several programs already exist globally for providing near-real-time information to monitor thermal 'hotspots' associated with volcanic activity or fire (for example, see University of Hawai'i and Geoscience Australia). Ultimately it would be useful to have similar automated methods and algorithms in place for the acquisition and processing of imagery and provision of geospatial information about other hazard events. To achieve this goal, robust techniques need to be developed and thoroughly tested in an operational environment. The following sections document the testing of various methods for scientific and monitoring purposes, while examples of some current operational programs, of the role of remote sensing in rapid response systems, and of emerging developments are given in later parts of the paper.

II Earthquakes and faulting

There are several aspects involved in the detection of earthquakes, faulting, and damages associated with each. DInSAR (Differential Interferometric Synthetic Aperture Radar) is generally accepted as the best method for earthquake associated deformation mapping; LiDAR (Light Detection and Ranging) provides the highest resolution DEM available for fault interpretation; and very high resolution optical data will provide the best imagery for damage assessment of buildings and infrastructure.

1 Optical detection of earthquakes and faulting

The technique of choice in the use of remote sensing for fault mapping with optical data is manual interpretation, regardless of the data source (Fu *et al.*, 2004; 2005; Walker, 2006; Walker *et al.*, 2007). Frequently, the effects of earthquake activity and faulting are not manifested in spectral variations within image data, but in topographical changes. Image interpretation therefore relies on the expertise of the analyst, rather than spectral classifiers. It is possible that this field could benefit from the use of filters specifically designed to detect linear features. Note that fault detection is more of an exercise in preparedness than rapid response.

A number of different techniques have been reported in the literature to map the extent of earthquake damage, particularly in urban areas. Image differencing of multidate spectral ratios demonstrated better results than synthetic aperture radar (SAR) in Turkey and Iran, though a combination of optical and SAR coherence was reported to give the most accurate result (Stramondo *et al.*, 2006). Sertel *et al.* (2007) used semivariogram analysis of SPOT panchromatic imagery obtained both before and after the Izmit earthquake in Turkey. This technique demonstrated the possibility of mapping earthquake severity based on changes in the shape of semivariograms, although further research was suggested before the relationship to a quantifiable amount of damage could be determined. It may also be of use where the spatial resolution of the image data is sufficient to detect textural changes, though insufficient to detect specific damages. See also section IV for details of landslide mapping as a result of earthquake damage.

2 Thermal and microwave detection of earthquakes and faulting

As an alternative to mapping earthquake damage, several studies have sought to characterize short-term temperature increases immediately prior to earthquakes. While the detection of thermal anomalies has thus far been conducted retrospectively, refinement of this technique and routine investigation may hold information key to earthquake prediction and warnings. A 'normal' temperature for a region can be calculated using a time series of image data and an image of interest compared with this to determine areas of anomaly (Choudhury *et al.*, 2006). This technique, as well as the split-window method, can be used with various multiband thermal sensors. Temperature anomalies have been observed over both land and sea in this manner (Ouzounov *et al.*, 2006).

Recently, attempts were undertaken to measure the microwave signal produced by rock failures during earthquakes with passive microwave sensors such as Advanced Microwave Scanning Radiometer for Earth Observation System (AMSR-E) aboard the satellite Aqua. Some initial results are promising (Takano and Maeda, 2009) but more work needs to be done in this direction.

3 SAR detection of earthquakes and faulting

High resolution Synthetic Aperture Radar (SAR) intensity data is used for mapping ground changes and infrastructure damages

Table 2 Remotely sensed data types and image processing techniques for information extraction about natural hazards

Data type	Sensor examples	Technique	Application	Advantages	Disadvantages
Multispectral high to moderate resolution	Ikonos, Quickbird, SPOT, ASTER, ALOS	Manual interpretation	Infrastructure and property damage due to flooding, earthquakes, landslides, etc	Benefits from analyst's knowledge of the area in addition to other interpretation cues such as context, site, association, shape, size; immediate vector output file	Can be subjective, time-consuming for widespread events, and non-repeatable
		Spectral classification	Location and extent of flooding, landslides, volcanic debris, fire scars	Relatively rapid to apply over a large area	Non-unique spectral response values, may require additional manual editing, appropriate algorithm must be selected for optimal result
		Semivariogram analysis and other textural classifiers	Damage due to earthquakes; location of landslides	May be useful when spatial resolution is lower than desired	Only returns relative damage estimates
		Image thresholding (including band ratios)	Location and extent of flooding, landslides, volcanic debris, fire scars	Simple and rapid to apply, band ratios reduce illumination variability, can be applied with panchromatic data	Determination of threshold values may be subjective
		Image differencing	Location and extent of flooding, landslides, volcanic debris, fire scars	Can be conducted on panchromatic data, band ratios or SAR backscatter imagery	Requires before and after imagery that is accurately co-registered and radiometrically balanced, only takes the spectral information from a single band (though this may be a ratio combination), all changes will be identified regardless of their relevance to the particular natural hazard (eg, crop rotations); still need to determine a threshold of change

(*Continued*)

Table 2 *Continued*

Data type	Sensor examples	Technique	Application	Advantages	Disadvantages
		Post-classification change detection	Location and extent of flooding, landslides, volcanic debris, fire scars	Does not require radiometric calibration between multiple images	Requires before and after imagery that is accurately co-registered, all changes will be identified regardless of their relevance to the particular natural hazard (eg, crop rotations), requires classification to also be completed on ‘before’ image
		DEM generation	DEM is used as a supplementary information in variety of studies	Photogrammetric methods can provide very high resolution DEMs in the absence of LiDAR	Stereo imaging is not automatically acquired so may not be available; DEM creation software is not standard in image processing packages – ie, costs extra, derived elevation is based on vegetation rather than ground height, no data in cloudy areas
SWIR	GOES, TOMS, MODIS, ASTER	Split window	Height, extent and volume of volcanic ash clouds	Commonly used and well tested	Relatively low spatial resolution of thermal sensors. Unable to derive sub-pixel components
Thermal	ASTER, MODIS, AVHRR	Split window	Crater lake temperatures, lava flow, precursor to earthquake activity, temperature and size of fire hotspots	Commonly used and well tested	Relatively low spatial resolution of thermal sensors. Unable to derive subpixel components
		Dual band	Crater lake temperatures, lava flow, precursor to earthquake activity, temperature and size of fire hotspots	Can derive subpixel components	Assumes only two thermal components
UV or thermal	GOES, TOMS, MODIS, ASTER	Absorption in UV or TIR	Height, extent and volume of SO_2 and other gas emissions	Commonly used and well tested	Low spatial resolution of geostationary satellites, requires very high temporal resolution to monitor changes

SAR	JERS-1, ERS-1/2, ENVISAT, ALOS PALSAR, TerraSAR-X, Radarsat-1/2, Cosmo-SkyMed	Coherence	Change detection due to landsliding, flooding, fire, etc	Provides quantitative estimation of ground changes	Does not work well in densely vegetated regions, affected by seasonal changes, accuracy decreases with time
		Backscatter intensity	Change detection due to landsliding, flooding, fire, etc	Can be used in cloudy conditions, side-looking acquisition geometry is beneficial for certain applications	Quantitative analysis is complicated and varies significantly for different regions, may be difficult to interpret for non-experienced end-users
		Interferometry/ DEM generation	DEM is used as supplementary information in variety of studies	Independent of weather conditions	Accuracy depends on acquisition geometry, wave-length and coherence, side-looking acquisition geometry creates distortion and shadowed areas
		Differential interferometry	Surface deformation due to volcanic or tectonic activity; velocity and extent of slow moving landslides	High precision, high resolution of some new sensors	Dependent on spatial baseline and DEM accuracy; cannot determine difference between vertical and horizontal components, high accuracy only available in areas without dense vegetation
		Polarimetry	Land-cover classification and change detection	Ability to detect features that are not visible on optical images, side-looking acquisition geometry	Dependent on type of land cover and seasonal changes
DEM	PALSAR, LiDAR, TerraSAR-X	DTM differencing	Volume of landslide related earth movement, fault locations and elevation displacement	Provides quantitative estimation of volumetric depositions and ground change	Requires imagery both before and after event to be accurately co-registered
	Ikonos, Quickbird, SPOT			Photogrammetric methods can provide very high resolution DEMs in the absence of LiDAR	Stereo imaging is not automatically acquired so may not be available; DEM creation software is not standard in image processing packages – ie, costs extra, derived elevation is based on vegetation rather than ground height, no data in cloudy areas
	Airborne LIDAR sensors, SEASAT	Manual interpretation		Very high horizontal and vertical resolution, can give accurate surface elevation (rather than tree heights)	Acquisition of LiDAR is expensive and takes a considerable amount of time to process

by calculating a ratio or difference between multitemporal images and then applying supervised or unsupervised classification in the same way as is done with optical data (Matsuoka and Yamazaki, 2005). The main limitation of this approach is a significant variability of backscatter intensity for different regions, lack of quantitative estimations and dependence on incidence angle.

A few modern SAR satellites such as TerraSAR-X, Radarsat-2 and ALOS PALSAR are capable of providing data of various polarizations simultaneously. Phase shift and intensity difference between images of various polarizations are dependent on land cover and, therefore, can be successfully used for its classification (Czuchlewski *et al.*, 2003). For example, due to side-looking acquisition geometry, urban constructions often produce distinct signal caused by the double bounce mechanism (Guillaso *et al.*, 2005) and this pattern changes when buildings are damaged by an earthquake. For this particular case and many other applications, SAR polarimetry will produce valuable results and complement optical observations.

Differential SAR interferometry is possibly one of the best techniques used for mapping ground deformation produced by earthquakes. Differential interferometry (DInSAR) calculates the phase difference between SAR images acquired before and after an event or some other period when deformation has occurred (Massonnet and Feigl, 1998; Rosen *et al.*, 2000). The accuracy of this technique depends on data type and its quality: wave-band, perpendicular and temporal baselines, ground conditions (such as vegetation and snow coverage), tropospheric and ionospheric noise. In the most favourable conditions it is possible to achieve accuracy better than one quarter of SAR wavelength, about 0.5–1 cm for X-band, 1–2 cm for C-band, and 2–3 cm for L-band. This accuracy is sufficient for mapping ground deformation of a moderate earthquake (M5 and up) depending on the depth of the epicentre.

The success of DInSAR depends on the degree of phase correlation between the various scenes, which in turn depends on the relative timing and geometry of the various scenes, as well as decorrelation due to the atmosphere, the relative accuracy of the orbit knowledge, and the precise conditions of image acquisition. Decorrelation occurs when surface conditions are significantly different between two acquisitions, or when they appear different in case of large spatial baselines. The effect of decorrelation is less significant for L-band than for C- and X-band. In early SAR satellites, images that might otherwise be suitable for InSAR or DInSAR were sometimes incoherent due to lack of yaw steering, although this is not a significant issue for SAR satellites at the time of writing. Various techniques have been developed in order to minimize atmospheric noise (stacking; Small Baseline Subeset – SBAS; Permanent Scatterers – PS) but usually atmospheric noise is not a problem for earthquake mapping because of a large magnitude of coseismic signal. However, in close proximity to a fault, displacements are too large and interferometric phase cannot be reconstructed due to ambiguity in phase unwrapping (Hanssen, 2001).

4 LiDAR detection of faulting

Airborne LiDAR surveys are increasingly useful for mapping surface expressions of faulting. The extremely high vertical and horizontal resolution is ideal for observing previously undetected faults. Cunningham *et al.* (2006) demonstrated the utility of mapping active faults after applying a tree removal algorithm to the derived digital elevation model (DEM). Subsequent analysis was completed manually by visual interpretation. Manual interpretation was also used in New Zealand to extend the length of known faults and identify and map new fault scarps (Begg and Mouslpoulou, 2007). Topographical profiles were used to assist analysis and quantify vertical deformations. However, this technique of hazard mapping and monitoring is not appropriate for providing information in a rapid-response emergency situation due to the time it takes to acquire and process the data to a point where it can be manually interpreted.

III Volcanic activity

Detection and monitoring of volcanic activity spans a number of different data types and processing methods. Thermal anomalies are commonly detected by comparing a location with its background or average temperature; volcanic deposits are best detected with optical data, often using the normalized difference vegetation index (NDVI) for spectral enhancement; the split-window method is used for detecting ash composition within clouds; and InSAR is best for volcanic deformations.

1 Optical detection of volcanic activity

A variety of sensors are available to provide data suitable for debris mapping, with a preference noted towards the higher spatial resolution satellites such as SPOT, Landsat and ASTER (Kerle *et al.*, 2003; Joyce *et al.*, 2008c). The use of additional spatial information such as pre-event images has been considered important for accurate detection of the deposit and vital for damage assessment. Quickbird and IKONOS could be used for this application, dependent on the extent of debris – and financial constraints on the project. Lower spatial resolution satellites such as AVHRR have been found to be inadequate (Kerle *et al.*, 2003). ASTER has the added advantage of providing data that can be used to develop a DEM of the region, which can be useful in volumetric analysis of debris deposits (Huggel *et al.*, 2008).

Few methods of automatic detection of volcanic debris using remote sensing have been reported in the literature, and it appears that the favoured technique is manual digitization. However, the normalized difference vegetation index (NDVI) is commonly used for its ability to enhance the difference between volcanic deposits and surrounding vegetated areas (Castro and Carranza, 2005; Harris *et al.*, 2006). The NDVI can also be combined with a threshold value to delineate the deposit. Other techniques that have been used to aid visual interpretation of changes due to volcanic activity include a multiband display incorporating different input dates (Calomarde, 1998; Castro and Carranza, 2005), principal components analysis, and image subtraction (Torres *et al.*, 2004).

2 Thermal detection of volcanic activity

Of the more common applications, thermal monitoring of crater lake temperatures, lava, and thermal anomalies have been conducted since the 1980s, initially using the thermal sensor on board the Landsat series of sensors (Francis, 1989; Oppenheimer, 1996; Kaneko, 1998; Kaneko and Wooster, 1999; 2005; Donegan and Flynn, 2004; Harris *et al.*, 2004). The number of thermal applications has since increased with the development of more sophisticated techniques such as subpixel analysis with multiband thermal sensors like ASTER (Pieri and Abrams, 2004; 2005; Lombardo and Buongiorno, 2006), MODIS (Wright and Flynn, 2003; Wright *et al.*, 2004; 2005) and AVHRR (Mouginis-Mark *et al.*, 1994; Carn and Oppenheimer, 2000; Patrick *et al.*, 2005). The dual-band method is commonly applied to derive subpixel-level thermal anomalies, though is considered an oversimplification of reality as it assumes that only two features of different temperatures exist within a pixel, whereas realistically there may be up to seven components (Wright and Flynn, 2003). Alerts for thermal anomalies observed on a global scale are available freely on the internet, utilizing both MODIS and GOES image data (Wright and Flynn, 2003; Wright *et al.*, 2004; Rothery *et al.*, 2005). These need to be viewed with caution, however, as the alerts are not sensitive to merely warm features (eg, minor crater lake heating), and will also be triggered by other non-volcanic sources of heat such as a bushfire (Rothery *et al.*, 2005).

Remote sensing is commonly used to monitor ash clouds and volcanic gaseous emissions (SO_2) from both explosive and non explosive eruptions. Large-scale eruptions can eject gases and ash into the stratosphere, which may be monitored using geostationary satellites that measure absorption in the UV, SWIR and TIR wavelengths (eg, TOMS, GOES). However, they often lack the spatial resolution and radiometric sensitivity to monitor smaller fluctuations in volcanic activity. Such plumes may be monitored with higher resolution using ASTER (Realmuto *et al.*, 1997; Pieri and Abrams, 2004; Pugnaghi *et al.*, 2006), though temporal variability monitoring is compromised with the less frequent overpasses of this sensor. SO_2 is measured using diagnostic absorption features in either the UV or TIR region of the spectrum. Ash composition is commonly measured using the 'split-window' technique, and requires subtraction of the reflectance in one SWIR or TIR band from another (Prata, 1989). This technique allows distinction between volcanic ash clouds and those of meteorological origin, based on threshold values (Dean *et al.*, 2004; Tupper *et al.*, 2004; Gu *et al.*, 2005). Ash monitoring is considered operational and useful for aviation and warnings to volcanic ash advisory centres (VAACs).

3 SAR detection of volcanic activity

SAR has successfully been used for mapping volcanic deformations (Berardino *et al.*, 2002; Kwoun *et al.*, 2006) as well as for monitoring of pyroclastic flows and lahars (Terunuma *et al.*, 2005). It is particularly useful in eruptions where there is a lot of smoke obscuring the target and preventing the effective use of optical data. Three products derived from SAR data are usually used: SAR backscatter intensity, InSAR coherence, and DInSAR interferometry.

Various ground conditions (eg, roughness, soil moisture, slope) affect intensity of reflection. Therefore, calculating a difference or a ratio of intensity images from before and after the event should produce an image where changes caused by pyroclastic flows or lahars are easily observable. However, Terunuma *et al.* (2005) showed that changes of intensity signal are not clearly observed for either C- or L-band SAR sensors. But coherence calculated for the pair of images before and after an event was significantly lower in regions where pyroclastic flows or lahars had occurred. However, estimation of coherence variation is only possible in regions with a high initial degree of coherence, ie, those not covered by dense vegetation or snow, and not being eroded too quickly.

SAR interferometry can be used to derive DEMs before and after an eruption. By subtracting these models it is possible to observe large-scale deformations caused by lahars or pyroclastic flows. Alternatively, differential interferometry can estimate deformation with subcentimetre accuracy caused by thermal and pressure sources underlying the surface. By monitoring volcanoes over a long period it is possible to reconstruct temporal patterns of deformation using SBAS (Berardino *et al.*, 2002) or permanent scatterers techniques (Ferreti *et al.*, 2001; Hooper *et al.*, 2004).

IV Landslides

It is possible to use both SAR and optical data for landslide detection, but it appears that optical data provides better results, most likely due to spatial resolution and sensor look angle. It can, however, suffer from misclassification with other areas of bare groud. Multitemporal analysis is preferable and spectral enhancement is often required. SAR data would be most useful in the event of storm-induced landsliding, where cloud cover impeded optical acquisition. InSAR could be useful for measuring the rate of slow-moving landslides. Difficulties can arise with SAR data in areas of high slopes due to layover and shadowing effects.

1 Optical detection of landslides

Visual interpretation, with and without on-screen digitizing of both two- and three-dimensional data, has been commonly used in the past and is still an effective method of landslide mapping (Singhroy, 1995; Singhroy *et al.*, 1998; Ostir *et al.*, 2003; Nichol and Wong, 2005a; Kumar *et al.*, 2006; Voigt *et al.*, 2007). Orthophotography in particular has demonstrated its utility for mapping landslides in detail and IKONOS with pan-sharpening has been suggested to be of equivalent if not superior use (Nichol and Wong, 2005b). Manual techniques benefit from the analyst's knowledge of the area, though they cannot be automated, and are impracticably time-consuming when mapping widespread numerous landslides. Some emerging studies are attempting to use more automated extraction techniques, utilizing band ratios (Cheng *et al.*, 2004; Rau *et al.*, 2007) and unsupervised (Dymond *et al.*, 2006) and supervised classification (Nichol and Wong, 2005b; Joyce *et al.*, 2008a; 2008b) to reduce the level of manual interpretation, while still providing reasonably high accuracy levels (up to 80%). In a study to test the most accurate method for mapping landslides with SPOT-5 imagery, it was determined that the spectral angle mapper (SAM) supervised classification and NDVI thresholding were the most accurate semi-automated techniques compared with the results achieved with parallelepiped, minimum distance to means, principal components, and multitemporal image differencing (Joyce *et al.*, 2008a; 2008b). This study also noted that manual digitizing produced a higher accuracy than any of the aforementioned techniques, but was considerably more time-consuming for a widespread event.

Multitemporal image analysis is a valuable technique that can be used if imagery is available both before and after a landsliding event. This is perhaps the most promising option for rapid response. The process applied then relies on digital change detection – a number of methods of which are available (Singh, 1989; Jensen, 1996). An overall accuracy of approximately 70% was achieved using the postclassification comparison technique for landslide detection in Hong Kong (Nichol and Wong, 2005b). While apparently effective, and commonly used in other areas of interest, this method is not documented frequently in landslide detection literature. An alternative technique requires multidate image differencing, as demonstrated with SPOT imagery in Taiwan (Cheng *et al.*, 2004), using an infrared and red band ratio, image differencing, and thresholding. The results were later confined to slopes greater than 22° to reduce misclassification due to human-induced change. Image differencing has also proven effective using panchromatic data for landslide mapping in Italy (Hervas *et al.*, 2003; Rosin and Hervas, 2005), though while the authors report success an accuracy assessment is not given. Less success was reported when using SPOT-5 data in New Zealand, and difficulties with this technique were associated with cloud cover affecting the radiometric calibration between the two dates (Joyce *et al.*, 2008a; 2008b). This technique is also heavily reliant on accurate co-registration between images.

Unsupervised classification without change detection was used by Dymond *et al.* (2006) with SPOT-5 data for mapping the combined erosion scar and debris of a landslide. The classification was restricted to slopes greater than 5° in an effort to reduce misclassification of 'bright' pixels that may otherwise be areas of bare ground. While 80% accuracy was reported, only landslides greater than 10 000 m^2 were checked, and an independent data set was not used for verification. Given the spatial resolution of SPOT (10 m), it is possible that there were many undetected small landslides that were not represented in this accuracy statement. Due to the high contrast of landslides with background features, subpixel identification is possible, though accurate boundary delineation is not (Nichol and Wong, 2005b).

An alternative option to the use of spectral classifiers with optical data is to include textural layers (Whitworth *et al.*, 2005). The image roughness with respect to its surrounds caused by landslide debris and shadow effects can add additional information as a layer in a classification. A principal components layer can also be used to assist distinction between land-cover types that appear similar in the textural layer (Whitworth *et al.*, 2005).

The calculation of change in a DEM surface is one of the more frequently used techniques for landslide detection and monitoring using remotely sensed data (Kaab, 2002; Ostir *et al.*, 2003; Singhroy and Molch, 2004; Casson *et al.*, 2005; Chen *et al.*, 2006; Nichol *et al.*, 2006; Tsutsui *et al.*, 2007). This technique is only useful for large landslides with considerable vertical change in the topography. The stereo viewing capability of several contemporary sensors (SPOT, Ikonos, Quickbird) makes this a viable technique for acquiring imagery for the use of change detection and potentially for rapid response. In addition, the very high spatial resolution of the panchromatic stereo imagery from the Ikonos and Quickbird satellite sensors produce very detailed elevation models that are considerably more cost-effective than the equivalent areal coverage of airborne LiDAR or SAR. The technique of DEM differencing also allows volumetric calculation of erosion and debris. However, stereo imaging is not automatically acquired with all sensors and may not be available for the specific area of interest, especially as rapid response type imagery. In addition, DEM extraction tools do not come as standard with image processing software, thus require separate add-on modules or software to create (eg, Leica photogrammetry suite, DEM extraction tool in ENVI).

2 *SAR detection of landslides*

As with optical remote sensing, there is no distinct backscatter signature that can uniquely be associated with the mixed targets in a landslide. Instead, it is necessary to either use expert interpreter knowledge on a single scene, or estimate the backscatter difference from a pre- and post-landslide event, and apply some threshold of change (Belliss *et al.*, 1998).

While detecting backscatter difference is theoretically a straightforward task, there are some complications involved. First, if the images have slightly different viewing positions or different ground local incidence angles, then the scenes will exhibit an apparent change in brightness due to the difference in local incidence angle. This topographic difference can be corrected, provided a good DEM is available (Pairman *et al.*, 1997). Second, the inherent radar brightness of a target depends to a certain extent on surface environmental conditions on each date. Therefore, a difference-between-dates backscatter image might still show an overall brightness difference different from zero (ie, false positive). This effect is exacerbated with shorter wavelengths. Finally, unless the pre- and post-landslide images tightly embrace the times of the landslide event, the difference-between-dates backscatter image will tend to falsely detect landslides that are simply due to land-cover change – a problem that is similarly recognized with optical imagery.

Differential interferometry is used to measure velocities and extent of slow-moving landslides. In Rott and Nagler (2006) ERS SAR was used to map a landslide that is moving with 2.4 cm per year velocity. Unfortunately, such a high accuracy is only possible in regions not covered by dense vegetation that are coherent for extended periods of time.

V Flooding

Flooding is readily apparent in both optical and SAR data, providing there is knowledge of water body location prior to the event. The use of SAR is preferable due to the likelihood of associated cloud cover. Simple techniques of image thresholding are easy to implement.

1 *Optical detection of flooding*

Mapping and monitoring water inundation can be a challenging process for passive remote sensing due to the often coincident cloud cover, and the fact that water is generally not visible under a closed vegetation canopy. The utility of high temporal resolution sensors such as AVHRR is realized by Sandholt *et al*. (2003), who state that although the spatial resolution is coarser than many other satellite sensors the frequent revisit time offers a greater probability of obtaining cloud-free imagery. They used linear spectral unmixing with thermal imagery to determine inundated areas, but were faced with the difficulty of selecting pure endmembers. Alternatively, they also tested supervised maximum likelihood and ISODATA clustering classifications with the higher spatial resolution Landsat ETM+, concluding that no technique is necessarily better than the other, rather that each has its advantages and disadvantages depending on the flooding extent, cloud cover and temporal variability.

Manual analysis of MISR imagery was completed to determine quantitative characteristics of the 2004 tsunami development along the eastern coast of India (Garay and Diner, 2007). This provided information about wave propagation and behaviour, but was not used to estimate the extent of damage.

Potentially one of the most useful studies for rapid-response flood mapping was conducted to create on-board satellite processing algorithms for Hyperion imagery (Ip *et al*., 2006). The algorithm utilizes three narrow spectral bands for a classification and is then compared to a base scene to extract flood detail rather than just wet regions (eg, rivers, lakes). However, Hyperion has limited global coverage, and obtains imagery in relatively small segments that would be useful for localized flooding but not necessarily large events.

The extreme flooding events associated with several tropical storms in recent years (Hurricane Katrina, Cyclone Nargis) have been successfully and rapidly mapped using a variety of sensors to take advantage of differences in spatial and temporal resolution. Geoscience Australia is actively acquiring imagery of flooding events in Australia and attempting to develop semi-automated techniques for extracting inundated areas (Lymburner *et al*., 2008; Thankappan *et al*., 2008). Flooding events of 2007 and 2008 were successfully mapped using Landsat-5 TM and ALOS AVNIR-2.

2 SAR detection of flooding

SAR would appear to be an ideal sensor for the detection of extensive flooded areas, since the backscatter signature of water is so distinctive compared with that of vegetation (Lewis *et al*., 1998). Spectacular examples of the use of SAR include the April 1997 Red River flood near Winnipeg, Canada (Bonn and Dixon, 2005), and the Mississippi flood of 1993 (Nazarenko *et al*., 1995). The basic underlying assumption in these cases is that the floodwater remains visible for a sufficiently long period of time to allow for acquisition of imagery and subsequent delineation of the flood boundary, which was certainly the case in these two major flood events.

SAR backscatter intensity and InSAR coherence can be successfully used together for mapping of regions affected by flooding. In Oberstadler *et al*. (1997) it was shown that flooded areas appear darker on ERS SAR intensity images and, therefore, comparing two images before and during flooding it is possible to map flooded areas with a high degree of accuracy. By combining SAR with other geospatial data such as DEMs, it is also possible to estimate the depth of water in flooded regions. InSAR coherence can also be used for the same purposes (Geudtner *et al*., 1996). This technique maps coherence of a SAR pair of images acquired before and during flooding and comparing it to a pair of SAR images that are both acquired before flooding. Areas affected by flooding have significantly lower coherence than dry areas and by subtracting both coherence maps it is possible to identify these areas easily.

One of the unique features of SAR is the ability to detect areas of flooding under closed-canopy vegetation. Areas of flooded vegetation show with enhanced backscatter, due to the corner-reflector effect formed from the vegetation and the smooth water surface. The effect is wavelength- and vegetation-dependent, with short-wavelength (X- and C-band) sensitive to flooding under grasses (MacDonald *et al.*, 1980), mid-wavelength (S-band) sensitive to flooding under reed and brush vegetation (Lewis *et al*, 1998), and long-wavelength (L- and P-band) sensitive to flooding under trees (Imhoff *et al.*, 1987). This phenomenon has been long known with wavelengths as short as K-band (Waite and MacDonald, 1971), and has been explained by a comprehensive model (Ormsby *et al.*, 1985). As in the case of the SAR detection of landslides above, successful detection of flooded areas under vegetation requires some visual interpretation experience, or the assistance of a scene gathered before the flooding in order to make a comparison.

VI Wildfire

Monitoring fires using remote sensing is done in one of two ways: applications are based on either near-real-time monitoring of the fire itself and/or smoke, or on mapping the extent and severity of burnt areas. MODIS and AVHRR are the most commonly used data types for this application due to their high temporal resolution. The use of their NIR wavelengths also allows for some penetration through smoke to view the fire scar.

1 Optical detection of wildfire

Mapping and monitoring of fire scars can use similar methods to those described for landslides, as the characteristic of these features is cleared vegetation. However, while landsliding results in exposed soils appearing as brighter features than their surrounds, burnt vegetation and organic matter in soils generally results in optically darker scar features in imagery due to the presence of ash. The degree of difference in reflectance values between burnt and unburnt surfaces is dependent on the type of vegetation.

Satellite-based remote sensing has been used to extract information about the combustion completeness and also the fraction of an area that contains burns, through developing regression models with *in situ* information (Roy and Landman, 2005). While texture was considered to vary with burn scars in low spatial resolution (1 km) imagery, the isodata spectral classifier produced higher accuracy levels for detection of scars in savannas. Band ratios and normalized indices are considered to provide better separation between burnt and non-burnt areas than individual spectral bands, particularly when combining wavelengths in the SWIR region of the spectrum (Trigg *et al.*, 2005). Other ratios, such as the normalized difference vegetation index (NDVI) and the normalized burn ratio (NBR), were found to be less effective (Trigg *et al.*, 2005; Hoy, 2007). Unsupervised classification has also been successfully used to delineate large scar areas in mosaicked AVHRR imagery. Most recently, the bushfires in Victoria, Australia (February 2009), have been captured by optical sensors like MODIS, ASTER, Hyperion and ALI. It is too soon to report on automated or semi-automated techniques for extraction of the burn extent.

2 Thermal detection of wildfire

As with estimating hotspots due to volcanic activity, the MODIS sensor is often used. Two techniques are commonly cited for derivation of surface temperatures and hotspots. The dual-band technique derives the temperature of two components and their portions within a pixel (Dozier, 1981), though problems with the oversimplification of this technique were explored by Giglio and Kendall (2001). As an alternative, the split-window technique has proven useful as a basis for global monitoring of fires, through detecting changes from a specified background value. However, it is unable to derive subpixel components. These methods are similar to those used for detection of thermal-based volcanic activity. Thermal differences have also been noticed between burnt and unburnt areas, thus temperature can also be used to map and monitor fire scars.

3 SAR detection of wildfire

Synthetic aperture radar has been successfully used for identification of burnt areas over the boreal forest of Alaska, Canada (Bourgeau-Chavez and Kasischke, 2002), and Siberia (Ranson *et al.*, 2003) as well as over the tropical rain forest of Indonesia (Siegert *et al.*, 1995) and semi-arid Mediterranean forest (Gimeno and San-Miguel-Ayanz, 2004). In these studies it was shown that the intensity of SAR backscatter signal was noticeably different between predominantly undisturbed and fire-disturbed forest. This was due to an increase in soil moisture, increased surface roughness exposed to the incoming microwave radiation, and damage to the vegetation canopy by fire.

In Gimeno and San-Miguel-Ayanz (2004), various SAR products with different resolution and various incidence angles were tested and novice incidence-angle normalization was introduced. It was also shown that acquisitions with low incidence angle are the most successful in identification of burnt areas in hilly regions. In Couturier *et al.* (2001) the relationship between SAR backscatter intensity and fire-related Daily Drought Index (DDI) was investigated over rain forest of Indonesia. A strong correlation between these two characteristics was observed, which suggested that SAR data can be successfully used not only for identification of burnt areas but also as a proxy for the susceptibility of forest to burn.

VII Operationally active hazard monitoring programs using remotely sensed imagery

Various programs are becoming available and more accessible for serving both imagery and information with respect to hazards and disasters. The USGS hosts a Hazards Data Distribution System (HDDS), where it is possible to download pre- and post-event imagery from recent hazard events. It is also possible to retrieve baseline imagery from other areas in the United States through this interface. However, this is not an online operational portal for analysed imagery.

The University of Hawaii operates two websites for near-real-time monitoring of thermal hotspots. The first site contains GOES imagery of selected sites in the Western Hemisphere that is updated every 15 minutes, displaying combinations of visible, mid-infrared and thermal radiation. The second, more interactive site is based on MODIS imagery and displays hotspots as determined by a threshold in thermal values (Wright *et al.*, 2004). The user can select a particular area of interest and retrieve a text file containing the location of the hotspot.

Geoscience Australia has a similar hotspot identifying GIS interface based on MODIS and AVHRR thermal imagery. This covers Australia, New Zealand and the South Pacific. Again, a threshold is used to identify locations hotter than a 'background' value. The University of Maryland hosts a global fire mapper that is linked to a system to provide email alerts of fires within a specified area of interest. The option is also available at several of these sites to export the current hotspots to Google Earth for near-real-time viewing by emergency responders. Due to the underlying data, each of these applications experiences difficulties in detecting hotspots in areas of high cloud and/or smoke.

To ensure safe navigation and monitor possible climatic impact, NOAA records global historical volcanic eruptions, tracks volcanic ash eruptions affecting the United States, issues volcanic ash advisories, and provides ash cloud forecasts. The USGS Volcano Hazards CAP Alert provides daily updates of volcanic activity for sites identified as requiring a watching brief (for example, see http://volcano.wr.usgs.gov/cap/cap_display.php?releaseid=3886).

In the Asia/Pacific region, Sentinel Asia is an on-demand network of information delivery websites, largely using free-to-air satellite imagery, developed to provide online information in near-real-time. Based upon the Australian bushfire tracking system, Sentinel Hotspots, and supported by the Japanese Government via the Japan Aerospace Exploration Agency (JAXA), Sentinel Asia can detect and then monitor natural disasters in the region (Kaku *et al*., 2006). Thus far, it has been activated a number of times by several countries and contains information on a various events such as the cyclone and flooding in Myanmar and earthquake damage in China (May 2008), as well as other flooding events throughout Asia and the bushfires in Australia (February 2009).

The International Charter 'Space and Major Disasters' has a membership of several international space agencies and space system operators and aims to provide remotely sensed imagery and data to member countries affected by a disaster. In January and February 2009 alone, the charter was activated eight times for an earthquake and landslides (Costa Rica); floods (USA, Morocco, Argentina, Namibia); fires (Australia); a hurricane (France); and volcanic eruption (Chile). The type of imagery acquired will be specific to the scale, location and type of hazard and could be a combination of optical and SAR. There does not appear to be a standard for image processing, and this may depend on the organization enlisted for project management. The service is provided free to member organizations.

VIII Remote sensing for providing rapid response information

Remote sensing satellites have frequently been used to contribute to disaster management. The most common, best understood, and operational of these uses is that of weather satellites for cyclones, storms and, in some cases, flash floods. These systems have certain clear advantages. For instance, there are many orbiting and geostationary satellite services available, and coverage of almost any part of the world is available in small timescales ranging from hours to a few days. Further, imagery from these satellites is relatively cheap or freely available, and the scale of the events roughly matches the resolution of the satellite imagery. Spatial resolution, image extent and spectral characteristics play a large role in determining whether or not a particular sensor or data type is capable of detecting individual hazards, irrespective of the ability to acquire or process these data (see Table 3, derived from similar work in coastal environments – CRSSIS, 2006). Many of these data types have been discussed in previous sections with specific examples.

There are a number of other provisos on the ability of a satellite sensor to monitor a disaster. Where imagery cannot be recorded on board the satellite, and where there is no local receiving station coverage or where a local receiving station is not licensed for a particular satellite, data cannot be collected. For many parts of the world, medium to high resolution remote sensing satellites will only acquire data *after the satellite has been programmed to do so.* In these circumstances, coverage of the affected area is likely to be delayed and possibly missed. However, when major disasters unfold, most satellite operators will schedule imagery collection, even without confirmed programming requests, either on humanitarian grounds or in the hope of data sales.

In a country with national reception capabilities, programming satellite acquisition may not be required but data acquisition will still depend upon satellite orbit constraints, For example, when the World Trade Center in New York was attacked, the French SPOT satellite was the first able to acquire imagery, on 11 September, just hours after the event. The American Ikonos satellite collected imagery the following day (Huyck and Adams, 2002). In this situation, the satellites were the only platforms capable of acquiring early imagery since there was an air traffic ban in force over the USA that was not lifted until 13 September. From then on, aircraft-mounted sensors were able to provide daily multispectral imagery, thermal imagery, photographs, hyperspectral imagery, and LiDAR. Some time later, some aerial photographs were converted to three-dimensional information by use of proprietary software from Pictometery, which can make all angles of a structure visible and measurable. Such images would have been useful for assessing hazards, eg, overhanging debris, during the clean-up (Huyck and Adams, 2002).

There are still many countries that do not have access to direct reception stations within their territory for medium to high spatial resolution imagery. In an emergency, commercial satellite services can be tasked to collect data. Depending upon the position of the particular satellite within its orbit, the time interval between an urgent data programming request and the first acquisition attempt could be as short as 24 hours or as long as several days. As a general rule, satellite services more commonly used for emergencies are better at rapid response. A prime example of such a satellite service is Radarsat, which can typically schedule a data acquisition at very short notice and then supply the data to the data requester within hours of a successful acquisition. Other optical commercial satellite services could accept a programming request at similar short notice. Successful data acquisition would then rely predominantly upon orbital constraints plus, for optical satellites, cloud-free conditions over the area of need.

IX Emerging systems

Every year, more earth observation satellites are launched than go out of commission. Currently, both Radarsat and SPOT have two satellites in orbit, and many other services with one satellite are planning a replacement and/or a second vehicle. Just as there are constellations of communications satellites to allow continual coverage, a number of national/international initiatives are in the process of launching constellations of satellites to enable daily or more frequent observation of anywhere in the world. One of the main drivers/justifications of these services is national security and this includes hazard monitoring. Systems that are under way include Cosmo-Skymed, a constellation of two X-band SAR satellites and two optical satellites phased at 90 degrees from one another. Another constellation under way is one developed by Surrey Satellite Technology (SST) and known as the Disaster Monitoring Constellation (DMC). This is a series of micro-satellites carrying multispectral sensors, each of which will be owned by individual countries/partners that will cooperate in data acquisition and distribution in the event of a disaster. When complete, the constellation should enable daily data coverage at the equator and hourly at higher latitudes (da Silva Curiel *et al.*, 2005).

The German satellite TerraSAR-X (launched in June 2007) is capable of acquiring imagery with up to 1 m spatial resolution. Again the literature on processing and applications of this sensor is limited, but the sensor is expected to be another useful option for disaster monitoring. TanDEM-X is scheduled for launch in 2009 and will fly in orbit close to TerraSAR-X, allowing the generation of high resolution DEMs that could potentially be used for change analysis, particularly with respect to volumetric analysis of landslide-related earth movement. Also German, the RapidEye constellation of five satellites launched in August 2008 boasts a daily revisit time with a 6.5 m pixel size. Their online kiosk is also designed for rapid access to data. The combination of high spatial and temporal resolution in optical sensors holds great potential for disaster monitoring.

In addition to satellite platforms, the high level of flexibility afforded by some airborne platforms is proving to be of real utility for disaster mapping and monitoring. With state of the art GPS and IMU (inertial measurement units) on board, it is possible to

Table 3 Utility of various data types for providing information about natural hazards

Spectral		Visible – NIR				SWIR			Hyperspectral			Thermal		SAR		LiDAR
Spatial (very high = <5 m; high = 5–20 m; medium = 20–250 m; coarse = >250 m)		Very high	High	Medium	Coarse	High	Medium	Coarse	Very high	Medium	Coarse	Medium	Coarse	Single polarization	Polarimetric	DEM
Sensor example		Quickbird, Ikonos	ASTER, SPOT, ALOS	Landsat	MODIS, AVHRR	ASTER, SPOT	Landsat	MODIS, AVHRR	CASI, Hymap	Hyperion	MODIS	ASTER, Landsat	MODIS, AVHRR	Radarsat-1, ERS-1/2	Radarsat-2, TerraSAR-X	Airborne Sensor
Volcano	Thermal anomaly – < 100°C	E	E	E	E	E	E	E	E	E	E	A	A	E	E	E
	Thermal anomaly – >100°C	E	E	E	E	B	B	B	B	B	B	A	A	E	E	E
	Thermal anomaly – >1000°C	B	B	B	B	B	B	B	B	B	B	A	A	E	E	E
	Lahar	B	A	A	E	E	E	E	B	B	E	B	E	B	D	B
	Ash clouds – detection	B	B	B	B	B	B	A	E *	B	B	B	B	E	E	E
	Ash clouds – quantification	E	E	E	E	B	B	A	E *	B	B	B	B	E	E	E
	Gas clouds – detection	B	B	B	B	B	B	B	E *	B	B	B	A	E	E	E
	Gas clouds – quantification	E	E	E	E	B	B	B	E *	B	B	B	A	E	E	E
	Deformation	E	E	E	E	E	E	E	E	E	E	E	E	A	D	A
	Debris	B	B	B	C	E	E	E	B	B	C	E	E	C	D	B
	Lava flow	B	B	B	C	B	B	C	B	B	C	B	B	C	D	B
	Pyroclastic flow	B	B	B	C	B	B	C	B	B	C	B	B	C	D	B

Earthquakes and faulting (see also fires, flooding and landslides)	Fault location	B	C	C	E	C	C	E	B	C	E	E	E	B	E	A
	Deformation	E	E	E	E	E	E	E	E	E	E	E	E	A	C	A
	Aftermath – building and property damage	B	B	B	C	E	E	E	B	B	C	E	E	C	C	B
Landslides	Scar + debris flow	B	A	B	C	E	E	E	B	B	E	E	E	C	D	B
	Isolate scar from debris flow	C	C	E	E	E	E	E	C	C	E	E	E	C	D	B
Flooding	Inundated area	A	A	B	C	B	B	C	B	B	C	B	C	A	A	B
	Aftermath – building and property damage	A	B	B	C	C	C	E	B	B	E	E	E	C	D	C
Wildfire	Fire front	B	B	B	B	B	B	A	B	B	B	B	A	E	E	E
	Aftermath – building and property damage	B	B	B	C	B	B	C	B	B	C	E	E	C	D	B
	Landscape scars	B	A	A	C	E	E	E	B	B	C	E	E	C	A	B

A: Clearly demonstrated to work using standard image processing systems and is openly available in the literature
B: Shown to work with experimental image data sets or over limited areas with very small pixels or over global scales with large pixels
C: If extent is bigger than several pixels
D: Not widely available in literature but theoretically should be a potential use
E: Not feasible
* Listed as not feasible because of aircraft restrictions on flying over volcanic ash/gas clouds, rather than sensor inability

achieve relatively accurate geopositioning for acquired imagery and to develop automated procedures for orthorectification. Onboard processing can also facilitate anomaly detection such as that used in fire mapping so that a useful product can be served to the end-user as a shapefile, image, or layer on Google Earth within minutes of capture (Ambrosia and Hinkley, 2008). Systems are being developed for both manned and unmanned vehicles that have the added advantage of being able to fly under clouds in some areas and can incorporate a variety of sensors including optical and thermal.

X Summary

The use of remote sensing for mapping and monitoring natural hazards has diversified in recent years owing to an increase in data availability and technological advances in their interpretation. Remote sensing has proven useful for a range of applications including the detection of earthquakes, faulting, volcanic activity, landslides, flooding, wildfire, and the damages associated with each. A number of options for processing different data types collected in response to each of these hazards have been reviewed, with the commonality being the strong preference for baseline data to be acquired and maintained pre-event. It has been noted on several occasions that damage assessment is not possible without an understanding of the initial-state environmental characteristics. Automated techniques are well established for identification of fire and volcanic activity associated with excessive heat, but the operationalization of mapping other hazard and disaster events requires more robust and generic techniques to be developed and implemented.

As the importance of good spatial data is becoming increasingly recognized, remote sensing in the field of hazard assessment and disaster management is likely to grow in the future. New earth observation satellites are continually being launched, recognizing the prospective market in disaster management, but the provision of acquired image data in a rapid response situation remains a challenge both technically and financially. There is also the potential for increased use of airborne platforms to provide the first level of image data in an emergency situation by acquiring, processing and serving imagery in near-real-time to the end-user.

It is not possible to recommend a single data type or processing solution that will work under all conditions. This is a broad field of applications where some techniques will work better under some circumstances than another. While manual interpretation of many data types for various applications provides a popular mapping solution, this is unlikely to be the way forward for rapid response and emergency events. SAR data and InSAR techniques, for example, are of considerable value for mapping flooding extent and earth deformations due to volcanic or tectonic activity, but are unable to detect thermal anomalies or concentrations of volcanic gaseous emissions. Optical data offers several advantages over SAR, but is inherently affected by cloud cover, smoke or haze at the time of satellite overpass. The flexibility provided by a multisensor, multiplatform approach is likely to give the most comprehensive coverage of a disaster event.

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