The current status of remote sensing for mapping and monitoring geological hazards

1Joyce, K.E., 2Samsonov, S., and 3Levick, S.R

1Research Institute for Environment and Livelihoods, Charles Darwin University, NT Australia
2European Center for Geodynamics and Seismology, Walferdange, Luxembourg
3GNS Science, Lower Hutt, New Zealand

EXECUTIVE SUMMARY

This report is designed to document the current status of remote sensing data types and image processing techniques that are commonly used for mapping and monitoring several geohazards known to be of significance in South Africa. In particular, it focuses on the use of optical imagery, LiDAR (light detection and ranging), and synthetic aperture RADAR. This document has been written in consultation with the South Africa Council for Geosciences, and is intended to be continually updated as the technology in this field progresses.
# Table of Contents

List of Tables iii  
List of Figures iv  

1. Introduction 1  
   1.1 Optical Remote Sensing 3  
   1.2 Synthetic Aperture RADAR 4  
   1.3 LiDAR 7  

2. Using Remote Sensing for Geohazard Assessment 8  
   2.1 Landslides and slope instability 9  
      2.1.1 Optical 9  
      2.1.2 Synthetic Aperture RADAR 11  
      2.1.3 LiDAR 12  
   2.2 Seismic hazard (natural or mining induced) 12  
      2.2.1 Optical 12  
      2.2.2 Synthetic Aperture RADAR 13  
      2.2.3 LiDAR 14  
   2.3 Deformation associated with mining activities and water abstraction 15  
      2.3.1 Synthetic Aperture RADAR 15  
      2.3.2 LiDAR 16  
   2.4 Sinkholes 16  
      2.4.1 Optical 16  
      2.4.2 Synthetic Aperture RADAR 17  
      2.4.3 LiDAR 17  
   2.5 Tsunami / Flooding 17  
      2.5.1 Optical 18  
      2.5.2 Synthetic Aperture RADAR 18  
      2.5.3 LiDAR 19  
   2.6 Coastal, beach, and terrestrial erosion 20  
      2.6.1 Optical 20  
      2.6.2 LiDAR 20  
   2.7 Problem soils (shrink/swell clays and acidic soils) 21  
      2.7.1 Optical 21  
   2.8 Geochemical hazards (both natural and anthropogenic) 21  
      2.8.1 Optical 21  
   2.9 Summary of data types and processing techniques 22  

3. Conclusions and Recommendations 26  
4. Acknowledgements 27  
5. References 27
LIST OF TABLES

Table 1: Summary of the characteristics of some sensors used in hazards mapping and monitoring (Joyce, et al. 2009a) .......................................................... 1

Table 2: Examples of potential information requirements from remotely sensed data .......................................................................................................................... 3

Table 3: Examples of potential sensors that may provide data associated with Table 2 .................................................................................................................. 4

Table 4: Important parameters required for SAR and InSAR analyses ................................................................................................................................. 6

Table 5: Potential application of remote sensing to geohazards. X – Data type can be used prior to event to map / measure / monitor precursor; O – Data type can be used post event to map / measure / monitor effect .................................................................................................................................................. 9

Table 6: Remotely sensed data types and image processing techniques for information extraction about geological hazards (adapted from Joyce et. al (2009a)) ........................................................................................................... 23
LIST OF FIGURES

Figure 1: Differences between full waveform and discrete return LiDAR (after Lefsky et al 2002a) 12

Figure 2: Landslide distribution based on analysis of SPOT-5 imagery after a major storm event in northern New Zealand. Landslide count is displayed as the number of landslides detected per 250 x 250 m grid cell (adapted from Joyce, et al. 2009b). Background images were acquired by Landsat ETM+ and shown for contextual purposes only. 14

Figure 3: Example of differential interferogram of M7.1 Darfield earthquake occurred on 4 September, 2010 in New Zealand (modified from Beavan et al (2010)). ALOS PALSAR images were acquired on 13 August and 28 September, 2011. Ground displacement between neighbouring fringes is about 12 cm. Background images were acquired by Landsat ETM+ and shown for contextual purposes only. 18

Figure 4: LiDAR derived hillshade view of a short section of the Greendale Fault, Canterbury New Zealand, revealing the rupture pattern. LiDAR data from NZ Aerial Mapping. The background image displays the InSAR imagery from Figure 3, and shows the difference in scale and detail of image acquisition. 19

Figure 5: Average rate of ground deformation for the Auckland Volcanic Field, New Zealand occurred during 2003-2007 from Small Baseline Subset Analysis (modified from Samsonov et al., (2010)). It was determined that subsidence is caused by withdrawal of ground water for irrigation and industrial needs. Background images were acquired by Landsat ETM+ and shown for contextual purposes only 20
1 INTRODUCTION

The use of remote sensing and spatial information is becoming increasingly prevalent for many different environmental applications. In particular the potential of remote sensing for providing information relating to geological hazard assessment is gaining momentum as data becomes more readily available, and awareness of the technology is enhanced in the community. Remote sensing remains the only way of providing broad scale assessments of environmental features and processes, such as information relating to vulnerability to geological hazards and/or damage assessment post event.

The purpose of this report is to review the current state of the art of remote sensing for mapping and monitoring a number of geological hazards known to be of significance in South Africa. The identified hazards of interest include landslides and slope instability; seismic hazard (natural or mining induced); deformation associated with mining and water abstraction; sinkholes; tsunami; erosion; problem soils; and geochemical hazards.

However it is first instructive to briefly introduce the reader to the broader field of remote sensing, including several technical concepts that will be presented throughout this document. In particular, the main types of remote sensing that will be reviewed are optical, synthetic aperture RADAR (SAR), and LiDAR (Light Detection and Ranging). Each of these data types may be acquired using airborne or satellite platforms, though the emphasis here will be preferentially on satellite data, due to the broad area coverage that it provides, and the relatively lower cost than airborne acquisitions. Some of the commonly used sensors that will also be mentioned throughout this document are listed in Table 1.

Table 1: Summary of the characteristics of some sensors used in hazards mapping and monitoring (Joyce, et al. 2009a)

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor</th>
<th>Swath (km)</th>
<th>Nadir spatial resolution (m)</th>
<th>Revisit capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne sensors</td>
<td>variable</td>
<td>Variable (dependent on flying height)</td>
<td>&gt; 0.1 (dependent on flying height)</td>
<td>Mobilised to order</td>
</tr>
<tr>
<td>Worldview</td>
<td>Panchromatic</td>
<td>16.4</td>
<td>0.46</td>
<td>1.1 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>16.4</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>Quickbird</td>
<td>Panchromatic</td>
<td>16.5</td>
<td>0.6</td>
<td>1.5 - 3 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>16.5</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Ikonos</td>
<td>Panchromatic</td>
<td>11</td>
<td>1</td>
<td>1.5 - 3 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>11</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>RapidEye</td>
<td>Multispectral</td>
<td>77 x 1500</td>
<td>6.5</td>
<td>1 day (5 satellites in constellation)</td>
</tr>
<tr>
<td>EO-1</td>
<td>ALI</td>
<td>60</td>
<td>30</td>
<td>16 days</td>
</tr>
<tr>
<td></td>
<td>Hyperion</td>
<td>7.5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Terra</td>
<td>ASTER*</td>
<td>60</td>
<td>15,30,90</td>
<td>4-16 days</td>
</tr>
<tr>
<td>Terra / Aqua</td>
<td>MODIS</td>
<td>2300</td>
<td>250, 500, 1000</td>
<td>At least twice daily for each satellite</td>
</tr>
<tr>
<td>ALOS</td>
<td>PRISM</td>
<td>35</td>
<td>4</td>
<td>Several times per year as per JAXA acquisition plan</td>
</tr>
<tr>
<td></td>
<td>AVNIR</td>
<td>70</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Platform</td>
<td>Sensor</td>
<td>Swath (km)</td>
<td>Nadir spatial resolution (m)</td>
<td>Revisit capability</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------</td>
<td>------------</td>
<td>-----------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>PALSAR</td>
<td>Fine</td>
<td>40-70</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ScanSAR)</td>
<td>250-350</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>SPOT-4</td>
<td>Panchromatic</td>
<td>60-80</td>
<td>10</td>
<td>11 times every 26 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>60-80</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>SPOT-5</td>
<td>Panchromatic</td>
<td>60-80</td>
<td>5</td>
<td>11 times every 26 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>60-80</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Kompats</td>
<td>Panchromatic</td>
<td>15</td>
<td>1</td>
<td>2 - 3 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>15</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Landsat-5</td>
<td>TM</td>
<td>185</td>
<td>30</td>
<td>Every 16 days</td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>185</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Landsat-7**</td>
<td>ETM+</td>
<td>185</td>
<td>15</td>
<td>Every 16 days</td>
</tr>
<tr>
<td></td>
<td>Panchromatic</td>
<td>185</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multispectral</td>
<td>185</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>NOAA</td>
<td>AVHRR</td>
<td>2399</td>
<td>1100</td>
<td>Several times per day</td>
</tr>
<tr>
<td>Envisat</td>
<td>MERIS</td>
<td>575</td>
<td>300</td>
<td>2 - 3 days</td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>Ultra-fine</td>
<td>20</td>
<td>3</td>
<td>24 days</td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>Fine</td>
<td>50</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>Quad-pol fine</td>
<td>25</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>Standard</td>
<td>100</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>Quad-pol standard</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>Wide</td>
<td>150</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>ScanSAR narrow</td>
<td>300</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>ScanSAR wide</td>
<td>500</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>Extended high</td>
<td>75</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/-2</td>
<td>Extended low</td>
<td>170</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>ERS-2</td>
<td></td>
<td>100</td>
<td>30</td>
<td>35 day repeat cycle</td>
</tr>
<tr>
<td>Envisat</td>
<td>ASAR standard</td>
<td>100</td>
<td>30</td>
<td>35 day repeat cycle</td>
</tr>
<tr>
<td></td>
<td>ASAR ScanSAR</td>
<td>405</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>Spotlight</td>
<td>10</td>
<td>1</td>
<td>11 day repeat cycle; 2.5 day revisit capability</td>
</tr>
<tr>
<td></td>
<td>Stripmap</td>
<td>30</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ScanSAR</td>
<td>100</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Cosmo-Skymed</td>
<td>Spotlight</td>
<td>10</td>
<td>&lt;1</td>
<td>4 days (constellation of 4 satellites each with a 16 day cycle)</td>
</tr>
<tr>
<td></td>
<td>Stripmap</td>
<td>40</td>
<td>3-15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ScanSAR</td>
<td>100-200</td>
<td>30-100</td>
<td></td>
</tr>
</tbody>
</table>


* ASTER SWIR detectors are no longer functioning, SWIR data acquired since April 2008 are not useable

** Landsat-7 nearing the end of its useful life; problems with scan line corrector resulting in data gaps

1.1 Optical Remote Sensing

The field of optical remote sensing has a wide ranging number of applications. It is also possible to consider optical remote sensing from a variety of scales. Environmental remote sensing typically refers to detailed field based measurements (e.g. field spectrometry); airborne imagery; and satellite imagery. Specifically the type of data acquired in optical remote sensing makes use of the visible, near infrared (NIR), and shortwave infrared (SWIR) parts of the electromagnetic radiation (EMR) spectrum. A sensor is termed ‘panchromatic’ if it acquires data in a single region or waveband of the spectrum. A ‘multispectral’ sensor will acquire several (up to ten) broad spectral bands, while a ‘hyperspectral’ sensor will acquire many more narrow bands.

Information obtained from features and processes on the land, water, and atmosphere make use of characteristic absorption and reflection of various wavelengths of light within the EMR spectrum. By understanding unique and characteristic absorption and reflection properties of features of interest, remote sensing affords identification of such features, leading then to mapping, monitoring, and management over broader scales. It is important to stress here that it is not possible to identify a feature in imagery without understanding or knowing its characteristic spectral and/or spatial properties, and there are some instances where this difficulty in identification will preclude the use of optical remote sensing entirely for a particular application. Recognition of this fact is crucial in ensuring that the technology is not ‘oversold’ to decision makers.

Remote sensing data types vary in the amount of detail that they can provide in terms of spatial, spectral, temporal, and radiometric information. Table 2 below provides examples of potential information that may be required at different spatial, spectral, and temporal scales. This is linked to Table 3, which gives examples of the sensors that are potentially capable of providing data at the different scales within these three dimensions. Additional potential sensors can also be cross referenced in Table 1. Note that there is a necessary trade-off when selecting an appropriate sensor for a particular application, that to achieve a high temporal resolution (for example), then either spectral or spatial resolution, or both, must be compromised and vice versa.

Table 2: Examples of potential information requirements from remotely sensed data

<table>
<thead>
<tr>
<th>Required Detail</th>
<th>Spatial</th>
<th>Spectral</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>National</td>
<td>Inundated areas from flooding</td>
<td>Annual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(i.e. distinction between water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>and land)</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Regional</td>
<td>Landcover types, exposed soil vs.</td>
<td>Seasonal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vegetation, vegetation density,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>moisture content</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Local</td>
<td>Mineral identification, soil</td>
<td>Daily</td>
</tr>
<tr>
<td></td>
<td></td>
<td>characteristics</td>
<td></td>
</tr>
</tbody>
</table>
Table 3: Examples of potential sensors that may provide data associated with Table 2

<table>
<thead>
<tr>
<th>Required Resolution</th>
<th>Spatial</th>
<th>Spectral</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>MODIS / AVHRR</td>
<td>Panchromatic sensor (available on many different satellites)</td>
<td>All sensors / platforms</td>
</tr>
<tr>
<td>Medium</td>
<td>SPOT, Landsat, ASTER</td>
<td>Multispectral – SPOT, Landsat, ASTER, Quickbird, IKONOS</td>
<td>Most sensors / platforms</td>
</tr>
<tr>
<td>High</td>
<td>Quickbird, IKONOS, Aerial photography, Worldview-2</td>
<td>Hyperspectral – Hymap, Hyperion</td>
<td>MODIS</td>
</tr>
</tbody>
</table>

Optical remote sensing differs fundamentally from SAR and LiDAR (to be discussed in subsequent sections), as it is most commonly a passive form of data collection as opposed to an active one. This means that the energy source is not provided by the sensor itself, but in this case the external source is the sun. Conversely, an active sensor both provides and records the energy.

1.2 Synthetic Aperture RADAR

Synthetic Aperture Radar (SAR) is an active air- or space-borne sensor that operates in a microwave diapason (wavelength ~2-25 cm). Since microwave radiation penetrates cloud coverage with minimal losses this sensor can be used in any weather and lighting conditions, for example, during a storm or at night (Elachi 1987). Radar data are acquired in long strips and focused to a Single Look Complex (SLC) format assuming synthetic aperture. The main advantage of SAR in comparison to a regular radar is a significant improvement in azimuth resolution (Hanssen 2001). Focused data in a Single Look Complex (SLC) format is in range-azimuth coordinate system and can be geocoded at later time. SLC data preserves phase information and can be used for the Synthetic Aperture Radar Interferometry (InSAR) processing. Various beam modes are supported by different sensors including spotlight, stripmap, and scansar.

SAR is a side looking sensor. Such configuration helps to avoid ambiguities in received signal. However, this geometry introduces distortions such as shadows, layover and foreshortening, which complicates visual interpretation of images. Data acquired over the same region with different incidence angles will appear different. It is practically impossible to perform computational analysis of two images acquired over the same area with two different incidence angles. Therefore, for multi-temporal analysis or for InSAR processing it is important to have data acquired with similar incidence angles.

During data acquisition, SAR sensors record in-phase and quadrature components reflected from the ground waves. This information then is converted to an amplitude and a phase. Amplitude information is usually utilized in a similar way to optical sensors, by looking at the magnitude of response and how that relates to different ground features. For example, it can be used for mapping ground changes and infrastructure damages by calculating a ratio or difference between multi-temporal images and then applying supervised or unsupervised classification (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.

Phase information is proportional to a travel time (or distance, assuming constant velocity) that takes for the wave to travel from the satellite to the ground and then back to the satellite. Therefore, phase can be used for measuring distances to
objects and in case of InSAR analysis for estimation of object motion. The limitation of this approach is the inability to unambiguously reconstruct travel time from the measured wrapped phase. The unwrapping methodology that attempts to reconstruct phase information has been developed and used in InSAR processing (e.g. Costantine (1998)).

Synthetic Aperture Radar Interferometry (InSAR) is a processing technique that uses two SAR images acquired by the same or similar sensors over the same area (Hanssen 2001, Massonnet and Feigl 1998, Rosen, et al. 2000). Along-track InSAR utilizes two images acquired simultaneously by two receiver antennas installed on one platform (airplane or satellite). In this case, one antenna emits a signal and both antennas record received echoes. Along-track InSAR is used for generation of Digital Elevation Models (DEM). Since both images are acquired practically simultaneous the effect of temporal decorrelation is minimal and phase can be unwrapped precisely. Using this technique, the Shuttle Radar Topography Mission (SRTM) of NASA in early 2000 acquired SAR data and produced a DEM for the entire world (Farr and Kobrick 2000, Rabus, et al. 2003). The 90 m resolution SRTM DEM is freely available (http://srtm.csi.cgiar.org/).

Across-track InSAR uses two images acquired at two different times. In this case, a DEM can be created as well but its quality will be reduced due to the effect of temporal and spatial decorrelation. The most common application of across-track InSAR is differential interferometry or DInSAR, as it was demonstrated for the first time in Massonet, et al. (1993). The goal of DInSAR is measuring movement of the ground over time caused by earthquakes and volcanic signals, subsidence due to extraction of groundwater, oil, or mining. This can be done by calculating an interferogram from two SAR images acquired at two different times and then subtracting the topographic phase recreated from an available DEM. The process of computing SAR differential interferograms consists of a few steps: image co-registration, interferogram formation, removal of earth curvature and topographic phases, filtering and phase unwrapping. The last step, interferometric phase unwrapping, can be complicated or even impossible if the level of coherence is low. The decorrelation effect, or lost of coherence between two SAR images depends on land cover, temporal and spatial baselines and SAR wavelength. Among the currently operational SAR systems, decorrelation is the most significant for X-band, moderate for C-band and minimal for L-band (Hanssen 2001).

There are a few factors limiting the accuracy of interferometry, such as temporal and spatial decorrelation, and atmospheric and topographic noise. The decorrelation effect is perhaps the largest limitation, which has been partially overcome by developing a Permanent Scatterers (PS) technique (Ferretti, et al. 2000, Ferretti, et al. 2001, Samsonov and Tiampo 2011). By using the PS approach it is possible to calculate linear deformation rates, and even to reconstruct non-linear time series of each permanent scatterer (Ferretti, et al. 2000). This technique works best when a dense network of permanent scatterers is found, which is not often the case for many regions. In areas of moderate to good coherence it is possible to apply a stacking technique (Samsonov 2010, Sandwell and Price 1998) that produces mean deformation rates and also the Small Baseline Subset (SBAS) technique that produces non-linear time series as well as linear deformation rates (Berardino, et al. 2002, Lanari, et al. 2004, Samsonov 2010, Samsonov, et al. 2011 in press). The SBAS technique works only on pixels that are coherent above a chosen threshold on all interferograms. In most favourable conditions, it is reasonable to expect precision equal to 1/4-1/2 of the satellite wavelength during the analysis of single interferogram. In case of PS or SBAS processing it is possible to achieve precision
better than a few mm of measuring displacements and a few mm/year of measuring deformation rates.

Modern SAR sensors are capable of acquiring data of more than one polarization. Some sensors can be programmed to acquire data of various but single polarizations (ENVISAT), and other sensors can acquire data of all four polarizations simultaneously (HH, VV, HV, and VH – where ‘H’ = horizontal, and ‘V’ = vertical) (e.g. Radarsat-2, TerraSAR-X, ALOS PALSAR). In the case of polarimetric data each polarization channel is stored in a separate file that can be processed individually. Some techniques such as polarimetric interferometry (PolInSAR) utilize all four polarization images simultaneously.

Polarimetric interferometry is a most recently developed application of SAR (Evans, et al. 1988, Lee and Pottier 2009). Using various polarimetric decompositions applied to polarimetric data it is possible to classify individual (or small subgroup of) scatterers based on their back-scattering properties. In the most basic form it is possible to subdivide all scatterers into three categories: single bounce (flat surface), double bounce (man-made structures, tree trunks), and volume scatterers (vegetation) (Freeman and Durden 1998). The more advanced polarimetric classification methods have been developed that allow estimation the density of vegetation, surface roughness, and many other parameters (Cloude and Pottier 1997, Lee and Pottier 2009, van Zyl 1989). However, it is important to remember that results of polarimetric analysis will depend on satellite wavelength and also incidence angle and sensor orientation (satellite heading).

Space-borne SAR sensors are capable of acquiring SAR data over the same area with regular intervals (20-40 days). However, due to storage, processing and downlink limitations of satellite only a fraction of the potential images is acquired. Acquisition of data by sensors owned by commercial organizations is usually guaranteed upon request by clients, but acquisition of data by sensors owned by the international space agencies can be missed due to higher priority requests taking precedence. Table 4 highlights some parameters that must be considered before ordering data. Often, the availability of historic data over a region of interest is the most significant limiting factor for selection of particular sensor.

Table 4: Important parameters required for SAR and InSAR analyses

<table>
<thead>
<tr>
<th>Important parameters</th>
<th>Description and Comments</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor wavelength</td>
<td>Critical parameter for many applications. Long wavelength data better penetrates vegetation, which is particularly important for InSAR over vegetated areas.</td>
<td>Bands: X (~3 cm), C (~6 cm), and L (~25 cm)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Choice of polarization depends on targets that are mapped. For InSAR processing cross-polarized images (HV and VH) are not suitable (except in special cases).</td>
<td>HH, VV, HV, and VH</td>
</tr>
<tr>
<td>Incidence angle</td>
<td>For InSAR or for multi-temporal analysis all images should be acquired with similar incidence angle. Large angles will increase travel distance through vegetation and effect of volume scattering.</td>
<td>20-50 degrees</td>
</tr>
<tr>
<td>Image resolution</td>
<td>Depending on application and coverage data with best resolution is preferred.</td>
<td>from 1x1 to 150x150 m</td>
</tr>
<tr>
<td>Image size</td>
<td>Inversely proportional to resolution due to</td>
<td>from 25x25 to</td>
</tr>
</tbody>
</table>
### Important parameters | Description and Comments | Example
--- | --- | ---
Processing level | Technical limitations of satellite and data downlink. Low resolution data has largest coverage. | 450x450 km
Critical baseline | RAW data can not be read by standard GIS software, SLC data is required for InSAR processing, geocoded data loses phase information (not suitable for InSAR) but preferred for GIS analysis. | RAW, SLC, geocoded

Critical baseline for ERS satellite is 1150 m.

The Complete InSAR manual was published by the European Space Agency (InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation, TM-19) and can be freely accessed at http://www.esa.int/esaPub/tm/tm19/TM-19_ptA.pdf (and also TM-19_ptB.pdf and TM-19_ptC.pdf).

### 1.3 LiDAR

Laser altimetry or LiDAR (light-detection and ranging) is an active remote sensing technique that can provide high resolution (< 1m) representations of the earth’s surface and it's above ground features. Lasers are well suited to ranging applications as high-energy pulses can be produced in short intervals, and short wavelength light can be highly collimated using small apertures (Wehr and Lohr 1999, Young 1986). LiDAR systems employ such lasers to measure the distance between the sensor and a target surface by calculating the elapsed time between the emission of a short-duration laser pulse and the return signal of that pulse (Bachman 1979). Laser pulses returned to a sensor are complex combinations of energy returned from surfaces at multiple distances, with the distant surface (ground) returned later in the reflected signal (Lefsky, et al. 1999). Such measurements enable the three-dimensional (3-D) representation of ground level, vegetation, power lines, buildings and other man-made features.

LiDAR systems differ primarily in terms of the nature of the laser pulse (Figure 1). Full waveform LiDAR operates at very high frequencies and can delineate the full above ground profile. Discrete return systems are more widely used and return ground elevation as well as the above ground height of the first layer of vegetation/man-made structures that the laser strikes. Discrete return LiDAR has been utilized extensively in forestry applications and has been shown to reliably return ground elevation and tree height data in forested systems (Lefsky, et al. 2002a, Lefsky, et al. 2002b). The vertical and horizontal accuracy of LiDAR is improving all the time and is a function of the sensor used, the type of aircraft (fixed-wing airplane or helicopter), the flying conditions (wind), and the altitude at which the aircraft operates. For environmental applications, LiDAR is mostly commonly operated from a fixed-wing aircraft at altitudes of 1000-2000 m, rendering elevation data at 0.5 m to 1 m spatial resolution. Because LiDAR is an active remote sensing technique and utilizes its own energy source, surveys can be conducted during the night and beneath high altitude cloud layers, conditions under which aerial photography and optical satellite imagery cannot be collected. Optech Inc. (Canada) and Leica Geosystems (Germany) are two of the leading manufacturers of LiDAR.
sensors (ALTM and ALS sensors respectively), with current models capable of operating at 70 kHz or higher. At a flying altitude of ~1000 m this translates to the generation of digital terrain models (DTMs) at 0.5 m spatial resolution with ~10 cm vertical accuracy. The commercial availability of such systems has therefore enabled high resolution digital terrain mapping across large spatial areas, with a number of benefits for geological hazard assessment.

Figure 1: Differences between full waveform and discrete return LiDAR (after Lefsky et al 2002a)

2 USING REMOTE SENSING FOR GEOHazard ASSESSMENT

With such a broad topic area, it is impossible to cover all potential geological hazards, all remote sensing data types, and all possible processing techniques. Instead, this report focuses on a number of pre-defined geohazards of relevance to South Africa, and provides a brief overview of assessment techniques that use optical, LiDAR, and/or InSAR remote sensing. It is acknowledged that there are other data types and techniques that could be used, however these are considered to be outside the scope of the current review.

Remote sensing can be used for geological hazard assessment in a range of different ways. In particular, it is noted that remote sensing can contribute to the assessment of likely risk of an event occurring, or in the assessment of damage post event. In this way, remote sensing can be linked explicitly to the different phases of the disaster management cycle (Joyce, et al. 2009c). In order to use remote sensing to help assess risk or vulnerability, it is necessary to identify either precursors to the event of interest, or specific related environmental characteristics that might make a particular location susceptible to that event. Post event damage assessment is potentially a more straightforward task. As the observation requirements will be different for both pre- and post-event assessment, the remote sensing data types and techniques will also be correspondingly different. Table 5 provides an indication of how the three main remote sensing data types (optical, LiDAR, and InSAR) may be used at the different assessment stages.
Table 5: Potential application of remote sensing to geohazards. X – Data type can be used prior to event to map / measure / monitor precursor; O – Data type can be used post event to map / measure / monitor effect

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Optical</th>
<th>LiDAR</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landslides and slope instability</td>
<td>X O</td>
<td>O</td>
<td>XO</td>
</tr>
<tr>
<td>Seismic hazard (natural or mining induced)</td>
<td>O O</td>
<td>O</td>
<td>XO</td>
</tr>
<tr>
<td>Deformation associated with mining and water abstraction</td>
<td>O O</td>
<td>X O</td>
<td>O</td>
</tr>
<tr>
<td>Sinkholes</td>
<td>O O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Tsunami</td>
<td>X O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Erosion</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Problem soils</td>
<td>X O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Geochemical hazards</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Although the above table identifies the potential for the different data types to be utilised in some aspect of assessment for each geohazard, successes reported for different methods are highly variable. Some areas can still be considered to be in the research domain, rather than operational, and there are many challenges still to be faced. The following sections outline how the different data types are currently used in pre- and/or post-hazard assessment, while directing the reader to the literature for further detail. Where the contribution of a particular data type is not considered to play a major role in the identification, mapping, or monitoring of a particular hazard, it is not written into that hazard’s subsection (e.g. optical data is not covered in §3.3 – deformation associated with mining and water extraction).

### 2.1 Landslides and slope instability

#### 2.1.1 Optical

Landslides can range in areal size from less than a square meter to millions of square meters. Additionally, they may be dispersed over a wide area. The combination of small spatial size and potentially large spatial extent provides a challenge for the selection of appropriate remotely sensed data and necessarily results in a compromise between spatial extent and spatial resolution. A sensor with moderate-high spatial resolution (e.g. SPOT) may cover a relatively large spatial extent, but will not adequately characterise small landslides. It may be possible to detect a landslide as small as half a pixel if the spectral contrast is high, however it is not possible to accurately define its size or shape (Nichol and Wong 2005b). Alternatively, very high spatial resolution satellites (e.g. Quickbird or Ikonos) or airborne imagery is costly and data intensive to acquire over large spatial extents. Ortho photography has demonstrated its utility for mapping landslides in detail, though IKONOS with pan-sharpening may provide equivalent if not superior results (Nichol and Wong 2005b).

There are several studies in the literature about landslide detection, but few attempt or demonstrate an automated, repeatable technique, and even fewer provide an accuracy statement for their mapping. Visual interpretation (with and without on-screen digitising of both two and three dimensional data) has been used in the past and is still proving to be a common and effective method of landslide mapping (Domakinis, et al. 2008, Kumar, et al. 2006, Nichol and Wong 2005a, Ostir, et al. 2003, Singhroy 1995, Singhroy, et al. 1998, Voigt, et al. 2007). In a study comparing various techniques for landslide mapping, Joyce et al. (2008) determined that manual digitising was indeed the most accurate method of identification, however was not appropriate for large area or wide spread landslide mapping due to its time intensive nature. Manual digitising techniques benefit from the analyst’s knowledge of the area, but cannot be automated. Figure 2 shows the spatial distribution of landslides in
northern New Zealand following a major storm event. Given the number of landslides detected, and their widespread nature, it is clear that manual mapping methods would be inappropriate and a more automated approach is required.

![Landslide distribution based on analysis of SPOT-5 imagery after a major storm event in northern New Zealand. Landslide count is displayed as the number of landslides detected per 250 x 250 m grid cell (Joyce, et al. 2009b). Background images were acquired by Landsat ETM+ and shown for contextual purposes only.](image)

**Figure 2:** Landslide distribution based on analysis of SPOT-5 imagery after a major storm event in northern New Zealand. Landslide count is displayed as the number of landslides detected per 250 x 250 m grid cell (Joyce, et al. 2009b). Background images were acquired by Landsat ETM+ and shown for contextual purposes only.

Of the more automated approaches, the techniques and data types used have been many and varied:

- Digital change detection using
  - Post-classification comparison in Hong Kong achieved an overall accuracy of 70% (Nichol and Wong 2005b);
  - Image differencing techniques appeared successful in Italy (Hervas, et al. 2003, Rosin and Hervas 2005), Taiwan (Cheng, et al. 2004), and New Zealand (Joyce, et al. 2008);
  - Change vector analysis was also used in Taiwan following NDVI calculation (Rau, et al. 2007);
  - Multivariate classification incorporating NDVI, principle component analysis (PCA) and independent component analysis (ICA) for high spatial resolution pansharpened imagery of both before and after event occurrence (Mondini, et al. 2011).
  - Unsupervised classification achieved 80% accuracy for landslides greater than 10 000m² on slopes greater than 5° in New Zealand (Dymond, et al. 2006).
  - Textural classification combined with principle components analysis of very high resolution airborne imagery achieved up to 90% overall accuracy (Whitworth, et al. 2005).
Perhaps the most promising results are offered by segmentation and object oriented approaches, where significant increases in accuracies are reported when compared to spectral classifiers (Barlow and Franklin 2007, Barlow, et al. 2006).

It is also possible to use remote sensing and other spatial data to provide information about many of the environmental characteristics known to increase landslide vulnerability. This in turn can help the development of landslide susceptibility maps and to improve understanding of landslide hazards in the landscape. The distribution of landslides with respect to geology, vegetation, and slope is clearly shown in Joyce and Dellow (2009).

2.1.2 Synthetic Aperture RADAR

The ability of SAR to image through cloud, and most rainfall events, makes it attractive for the reliable acquisition of imagery in the days following a storm induced landslide event, when information from remote sensing is likely to be highly valued for relief or assessment efforts. However, 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 land cover conditions on each date. Therefore, a difference-between-dates backscatter image might still show an overall brightness difference different from zero (i.e., 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 (Hilley, et al. 2004, Rott and Nagler 2006). In case of lower coherence it is possible to deploy corner reflectors that would appear as bright targets in the interferograms, however, significant presence of tropospheric noise in mountain regions affected by landsliding will degrease the accuracy of interferograms making phase unwrapping impossible and sometime produce false signals that can be identified only by ground truthing. It is important to remember that using DInSAR technique it is possible to detect only line-of-sight motion. This means that landsliding in direction parallel to the sensor azimuth is not detectable (usually north-south motion), as well as the motion that has horizontal and vertical components of similar magnitude but of opposite direction (in relation to line-of-sight). The most favorable imagining configuration of landsliding motion is on the back slope (slope opposing the satellite), however, this is only possible when the slope angle does not exceed incidence angle of the sensor, otherwise, the area becomes shadowed.
2.1.3 LiDAR

A map of slope failures is the primary element of landslide assessments as it is not possible to analyze the controls on mass movements, or their environmental and human consequences, without an accurate inventory of slope instability (McKean and Roering 2004). A high-resolution DTM is able to detect the divergence/convergence of areas related to both unchannelized and channelized processes with better detail than coarser DTMs (Tarolli, et al. 2010). As such, the use of LiDAR in understanding and mitigating the risks of landslides and slope instability has grown rapidly over the last ten years and is widely used to generate high quality DTMs for terrain analysis, map landslides and debris-flows, monitor mass movements, and refine surface flow models (Jaboyedoff, et al. 2010).

High resolution shaded relief maps, built from LiDAR derived DTMs, have proved extremely useful for the delineation of landslide morphological features (Ardizzone, et al. 2007, Corsini, et al. 2009, Eeckhaut, et al. 2007, Haugerud, et al. 2003). While the best mapping results are still achieved through manual digitization by expert users, significant progress has been made in automating the classification of landslides from high resolution DTMs. McKean and Roering (2004) developed an objective approach to mapping landslides from LiDAR data in Canterbury, New Zealand, through the analysis of power spectra which quantifies how roughness varies with scale. An expansion of this technique was successfully applied to coastal ranges of the Pacific North-western USA, where the automated technique achieved 82% classification accuracy (Booth, et al. 2009). Variogram analysis techniques have also shown potential in the Italian Alps (Trevisani, et al. 2009), while advances object-based image analysis techniques continues to improve morphometric classification accuracies (Blaschke 2010, Dragut and Blaschke 2006). Although landslide scars can often be mapped from aerial or satellite optical imagery, the real benefit of LiDAR in this regard emerges in forested systems where the ground surface is hidden from view yet high frequency lasers can still penetrate and map the underlying terrain (Reutebuch, et al. 2003).

While the detection and classification of past and present landslides is an important step in understanding the risk of slope failures, LiDAR data can further aid landslide susceptibility mapping and modeling by providing high quality slope parameter data. LiDAR derived terrain parameters have greatly improved results from slope stability models, such as SHALSTAB and TRIGRS (Casadei, et al. 2003, Dietrich, et al. 2001, Godt, et al. 2008), and as such have increased the reliability of derived hazard maps (Haneberg, et al. 2009). The same is true for rockfall models, whereby the increased accuracy and resolution of LiDAR-derived DTMs improves trajectory modeling and enables the testing of different kinetic energy profiles and rockfall trajectories (Agliardi and Crosta 2003, Jaboyedoff, et al. 2010, Lan, et al. 2010). LiDAR can play a further role in hazard assessment by helping to keep track of slow moving mass movements. Monitoring movements over time requires a time series of LiDAR data so that the resulting DTMs can be differenced to explore changes in morphological structure and volume over different time periods (Baldo, et al. 2009).

2.2 Seismic hazard (natural or mining induced)

2.2.1 Optical

The increasing availability of high-quality optical satellite images enables, in principle, the continuous monitoring of Earth’s surface changes (Leprince, et al. 2008). Optical satellite imagery and aerial photography can capture information on horizontal displacements in the earth’s surface, provided that pre- and post-event images are
available, and that both sets of images can be precisely ortho-rectified. A software package (COSI-Corr) was developed at California Institute of Technology to facilitate the precise co-registration of optical images and conduct sub-pixel correlation analyses (Leprince, et al. 2007a) Ayoub et al. (2009) used COSI-Corr to co-register and correlate multi-temporal images for the measurement of ground deformation following the 1992 Mw 7.3 and 1999 Mw 7.1 earthquakes in California. The principles for this technique have also been successfully applied with SPOT imagery (Barisin, et al. 2009, Leprince, et al. 2007b) and ASTER imagery (Avouac, et al. 2006) to measure horizontal ground displacements following seismic events. While useful in its own right, this technique can be coupled with synthetic aperture RADAR to measure both horizontal and vertical displacements (Barisin, et al. 2009).

2.2.2 Synthetic Aperture RADAR

Differential SAR interferometry is possibly one of the best techniques used for mapping ground deformation produced by earthquakes (i.e. post event). Differential interferometry (DInSAR) calculates the phase difference between two SAR images acquired over the same area at two different times (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 favorable conditions it is possible to achieve accuracy 1/4-1/2 of SAR wavelength. This accuracy is sufficient for mapping ground deformation of moderate earthquake (M5 and up) depending on the depth of the epicenter. Often DInSAR data is analyzed together with GPS data that has sparse spatial resolution but acquired frequently and other data from strain-meters, ground leveling, tilt-meters and so on.

When the goal is to map ground deformation caused by a single event such as an earthquake, two images acquired before and after the earthquake are required. In order to reduce decorrelation effect and sensitivity to residual topography it is recommended to select SAR images with smallest spatial (particularly perpendicular) and temporal baselines, and similar Doppler centroids. In case of vegetated land cover the sensor with longer wave length will produce more coherent results but with less precision since precision is inversely proportional to the sensor's wavelength. Deformation caused by earthquake in case of good coherence will be observed in areas where displacement between neighboring pixels does not exceed half of the sensor wavelength. If deformation gradient is larger than this critical value then phase unwrapping becomes impossible. Therefore, in order to map motion in the proximity of the ruptured area it is necessary to utilize data from sensors with longer wavelength (for example, L-band ALOS PALSAR). Another possibility is to employ offset tracking technique (Strozzi, et al. 2002). In this case offsets between highly coherent (or bright) coregistered pixels are measured directly, which then are converted to displacement map without need for phase unwrapping. The precision and coverage of offset tracking technique is significantly less than of standard DInSAR and depends on the accuracy of co-registration of two SAR images, but this technique is very valuable in case of large displacements and/or low coherence.

It is important to remember that magnitude of displacement produced by the earthquake can not be easily converted to damages caused by the earthquake. As an example, slow slip events produce deformation similar to earthquakes but do not cause any damages (McCaffrey, et al. 2008). On the other side, earthquakes that produce limited deformation can cause significant amount of damages. This was the case for the M7.1 Darfield earthquake (4 September 2010) that produced significant static displacements (Figure 3) but caused only minor damages (Beavan, et al. 2010).
and M6.3 Canterbury earthquake (22 February 2011) that produces significantly smaller static displacements but caused severe damages to Christchurch.

DInSAR can also successfully map inter-seismic and post-seismic deformation that are of smaller magnitude than co-seismic signals (Argus, et al. 2005, Fialko 2006) utilizing advanced processing strategies such as PS and SBAS described below.

![Figure 3: Example of a differential interferogram from the M7.1 Darfield earthquake which occurred on 4 September, 2010 in New Zealand (modified from Beavan et al. 2010)]. ALOS PALSAR images were acquired on 13 August and 28 September, 2011. Ground displacement between neighbouring fringes is about 12 cm. Background images were acquired by Landsat ETM+ and shown for contextual purposes only.

2.2.3 LiDAR

Understanding the spatial distribution and orientation of fault lines is fundamental to understanding seismic risk in a landscape. However, even in areas of known seismicity, these faults can be difficult to locate due to inaccessible terrain or their location being obscured by dense vegetation (Harding, et al. 2000). LiDAR is able to lift the vegetation mask off the land surface and provide a view of the terrain under even dense vegetation canopies (Reutebuch, et al. 2003), providing a useful tool for mapping fault line traces. Harding et al. (2000) demonstrated the ability of LiDAR to map terrain underlying forests of Puget Sound in Washington State, revealing geomorphic features associated with fault strands within the Seattle fault zone. These features included a previously unrecognized fault scarp, an uplifted marine wave-cut platform, and tiled sedimentary strata. Since then, the use of LiDAR for fault scarp mapping has gained much momentum and is being used across the globe to increase seismic insights (Arrowsmith and Zielke 2009, Cunningham, et al. 2006, Engelkemeir and Khan 2008, Haugerud, et al. 2003, Kondo, et al. 2008, Prentice, et al. 2010, Zielke, et al. 2010). In Canterbury, New Zealand, LiDAR was recently used to map the surface expression of the previously unknown Greendale Fault following the 2010 Mw 7.1 earthquake (Quigley, et al. 2010) (Figure 4).
Figure 4: LiDAR derived hillshade view of a short section of the Greendale Fault, Canterbury New Zealand, revealing the rupture pattern. LiDAR data were acquired by NZ Aerial Mapping. The background image displays the InSAR imagery from Figure 3, and shows the difference in scale and detail of image acquisition.

The application of LiDAR to seismic hazards extends beyond geomorphic feature mapping of historic events. As LiDAR data is becoming more widely used and increasingly available, so too is the potential of using time series LiDAR for assessing seismic induced changes to the land surface (Chen, et al. 2006a) and infrastructure (Li, et al. 2008, Rathje and Adams 2008).

2.3 Deformation associated with mining activities and water abstraction

2.3.1 Synthetic Aperture RADAR

Deformation due to ground water extraction and mining as well as inter-seismic and post-seismic signals are harder to measure because these deformations are usually much slower and often of the similar magnitude as various noises that affect DlnSAR measurements. In order to accurately measure a deformation signal, all sources of noise have to be estimated and if possible compensated for. In the case of good coherence, the noise caused by atmospheric disturbances mixed with residual orbital rams (caused by minor inaccuracies in estimation of platform orbit) is the single significant factor limiting the accuracy of interferograms. Strictly speaking it is impossible to distinguish atmospheric signal from a deformation signal in a single interferogram. This is because apparent displacements observed in interferograms are proportional to the travel time and velocity of electromagnetic waves, and velocity varies within the interferogram depending on the state of the atmosphere, in particularly the amount of water vapour in the troposphere and the amount of free electrons in the ionosphere. The ionospheric noise is particularly significant for long wavelength sensors and depends on the time of acquisition (day vs night) and the state of solar activity.

The practical way to improve precision of DlnSAR measurements is to employ statistical analysis and advanced processing techniques based on data redundancy. The best known approach is the Small Baseline Subset Algorithm (SBAS) that reconstructs a time series of deformation from set of coregistered interferograms (Berardino, et al. 2002). More advanced algorithms (e.g. Samsonov et al. (2011 in
press)) are designed to compensate for orbital ramps, residual topographic errors, and minimize atmospheric contribution by averaging large set of interferograms and multi-looking (spatial averaging).

In the case of lower coherence, it is possible to employ Persistent Scatterers (PS) interferometric analysis (Ferretti, et al. 2004, Ferretti, et al. 2001, Samsonov and Tiampo 2011). The processing methodology is similar to standard DInSAR but it is applied only to a few pixels that behave coherently over long period of time. Such pixels are selected based on amplitude dispersion, coherence or polarimetric properties. Finally, some techniques combine PS and SBAS approaches (e.g. StaMPS, (Hooper, et al. 2004)) into one processing scheme that in some cases produces better results than other techniques. The precision of measurements in advanced processing is proportional to the number of images and under favourable conditions can be very high (better than a few mm).

![Figure 5: Average rate of ground deformation for the Auckland Volcanic Field, New Zealand occurred during 2003-2007 from Small Baseline Subset Analysis (modified from Samsonov et al., (2010)). It was determined that subsidence is caused by withdrawal of ground water for irrigation and industrial needs. Background images were acquired by Landsat ETM+ and shown for contextual purposes only.]

2.3.2 LiDAR

Theoretically, airborne LiDAR has the potential to measure ground deformation associated with mining and water abstraction, though very few studies have utilized it for this purpose. The degree of deformation associated with water abstraction occurs on scales more relevant to SAR techniques which can derive millimeter accuracy under the right conditions. Furthermore, the costs of obtaining a long time series of airborne LiDAR are very high in comparison to SAR imagery.

2.4 Sinkholes

2.4.1 Optical

Fewer remote sensing related studies have been reported on sinkholes than many of the other geohazards discussed in this report. This may be due in part to the lack of success in using remote sensing for identifying these features and/or their precursors; the relatively small spatial extent of individual features, meaning that...
remote sensing is not necessarily required; or it genuinely being an area of research yet to be fully explored. Warren and Wielchowsky (1973) hinted on the potential for using airborne optical remote sensing and manual interpretation for identifying sinkholes, even citing the importance of colour infrared imagery for the benefits that the NIR band provides in vegetation analysis. However, they did not provide any quantitative results, and a long time has elapsed with curiously little further development in this field in the literature. Dinger et al. (2006) had mixed successes using aerial photography to identify sinkholes in an agricultural setting by assuming that vegetative stress could be used as a proxy for sinkhole location. This would seem to be a valid approach, but their findings were unconvincing.

2.4.2 Synthetic Aperture RADAR

SAR has experienced broader use for sinkhole subsidence analyses, given its ability to resolve subsidence at the millimeter scale under the right conditions. However, effective use of InSAR requires a spatially continuous deformation field, so if the sinking is spatially gradual, then it can be detected, however if it is spatially abrupt, i.e. a failure with sharp boundaries as is so often the case, then subsidence produced by sinkhole cannot be greater than half of the wavelength of the sensor used (2-10 cm) for it to be properly detected due to ambiguities in phase unwrapping. In addition, if the sinkhole is relatively small, it becomes difficult to detect using contemporary satellite systems based on their spatial resolution.

Also SAR can be used in a similar manner as an optical sensor - by comparing backscatter intensities before and after sinking (after should be lower, darker on the image). In some cases interferometric coherence can be lower due to changes in land cover caused by sinking, but it assumes that coherence before sinking was high, which is not always the case (for example, in densely vegetated or snow covered regions).

2.4.3 LiDAR

High resolution terrain models generated from LiDAR can be used to locate sinkholes and estimate subsidence rates (Gutiérrez, et al. 2008, Waltham, et al. 2005), however it has not been broadly applied for this purpose as rates of subsidence are often within the error limits of even low altitude and high density airborne LiDAR collections. Seale et al. (2008) and Vacher et al. (2008) found that LiDAR alone could not be considered a reliable technique for mapping sinkholes in urbanized covered karst in Florida, but results improved greatly when used in conjunction with aerial photography.

2.5 Tsunami / Flooding

Using remote sensing for mapping and monitoring tsunami related impacts or precursors has received considerably more attention in recent years following the Indian Ocean event in 2004. An increasing number of studies are also likely to emerge following the devastating and wide reaching impacts of the tsunami in March 2011 subsequent to the earthquake in Japan. In terms of post event surveillance, there is nothing in particular that is unique to a tsunami that wouldn’t be conducted for monitoring areas devastated by other forms of inundation such as cyclone induced flooding and associated destruction. As such, the post event ‘effect’ mapping discussed herein will not be isolate to tsunami related damage, but will consider flooding as all-encompassing.
2.5.1 Optical

Generally the most effective damage assessment relies on some form of multi-temporal analysis or change detection. Without knowledge of the baseline state of a particular location, it is near impossible to ascertain whether an observed feature is the result of an impact of sorts. For example, inland water should only be considered ‘flood’ if the baseline state of that location was once dry. As such, flooding and associated damage assessment techniques employ multi-date remote sensing data. The processing techniques can then range from post classification change detection, to multi-date classification (Roemer, et al. 2010), spectral index differencing (Kouchi and Yamazaki 2007, Yang, et al. 2007), or simple manual interpretation (Belward, et al. 2007, Kumar, et al. 2007, Wikantika, et al. 2007). Note that it is also possible to use SAR backscatter data in a similar way to optical data when employing these techniques (Bovolo and Bruzzone 2007). Note also that damage assessment of buildings and infrastructure using nadir imagery may not provide completely accurate information, as damage identification may be limited to determination of roof structural damage (for example). In actual fact, a building may be condemned without having roof damage, or conversely may still be structurally sound despite roof damage.

When considering pre-event techniques for detection, remote sensing can be used to observe wave height and direction of travel, and therefore may provide a means to guide evacuation and early warning if the source of the tsunami is far from the coast that it is likely to impact. Satellite altimetry (e.g. JASON / GRACE) offers the potential to capture wave height and direction information (Gower 2007), though is limited in the temporal domain. It can therefore only be useful if it captures data by chance. MISR has also shown promise for estimating wave speed and location (Garay and Diner 2007).

2.5.2 Synthetic Aperture RADAR

SAR would appear to be an ideal sensor for the detection of extensive flooded areas associated with tsunami, 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. For floods associated with storm events in high-slope areas, such as the February 2004 Manawatu floods in New Zealand (Fuller and Heerdegen 2005), the floodwater does not remain visible for longer than a few days as a target as such, although the devastating effects of such an event are clearly visible for a great deal longer than this.

SAR backscatter intensity and InSAR coherence can be successfully used together for mapping of regions affected by flooding. In Oberstalder 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 data and other GIS 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 both are 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.

2.5.3 LiDAR

Although tsunamis are triggered by instantaneous events that may not as yet have identifiable (and undebatable) precursors (e.g. tectonic plate movement, submarine ‘landslides’), it is possible to use remote sensing for identifying areas of hazard vulnerability using models of wave propagation and likely sources. The primary application of LiDAR to tsunami and flood hazard assessments is the provision of high resolution digital terrain data. A high quality DTM is invaluable in defining geomorphological features and modeling the flow of water through a landscape (Jones, et al. 2007, Marks and Bates 2000) as surface elevation constitutes one of the most important model boundary conditions (Schumann, et al. 2008). The accuracy and spatial resolution of LiDAR allow the identification of subtle topographic variations between adjacent flood compartments, and even when the effect on modeled hydrodynamics is minor, improved topographic parameterization is important in that it allows modelers to concentrate on the physical aspects of model performance (French 2003).

Schumann et al. (2008) illustrated the benefits of using LiDAR derived terrain data to predict water stages over contour and SRTM products, and Horritt and Bates (2001) found that predicted flood wave travel times are strongly dependent upon terrain model resolutions. Although the creation of bare earth models is the most common application of LiDAR to flood modeling, LiDAR data can also be used to model vegetation, building and other above ground features. As such, digital surface models (DSMs), which are derived from all of the LiDAR returns and not just the ground points, can be used to improve flow models by providing measures of flow friction and resistance (Mason, et al. 2003). Webster et al. (2004) highlighted the importance of accurate point cloud classification in the LiDAR processing chain, as the miss-classification of points into ‘ground’ and ‘non-ground’ classes can strongly impact flood model results. While LiDAR has some clear advantages in the realm of flood modeling, it’s important to note that the fusion of LiDAR with other forms of data can yield better results. Zwenzner and Voigt (2009), for example, illustrated how the combination of high resolution SAR data and a LiDAR derived DTM allowed the derivation of higher level flood parameters such as flood depth estimates.

The application of LiDAR to assessing and mitigating tsunami risk incorporates the exploration of historic events and aiding the modeling of future events. High resolution terrain models derived from LiDAR can reveal geomorphic features which provide insight into past and present events. For example, a LiDAR survey along the
Otago coastline of New Zealand revealed geomorphology consistent with a history of tsunami inundation (Goff, et al. 2009). High-resolution topographic data along coastlines, estuaries sand lagoon enable tsunami modelers to develop better hazard maps of potential tsunami inundation. Furthermore, the delineation of coastal vegetation and building structures from LiDAR returns facilitates the inclusion of advanced hydraulic parameters in coastal inundation models (Cheung, et al. 2011).

2.6 Coastal, beach, and terrestrial erosion

2.6.1 Optical

The factors involved in erosion susceptibility of a landscape are relatively well understood and include: ground cover (vegetation types or lack thereof); topographical factors (slope, aspect); climatic effects (wind, water, ice); and the physical characteristics of the weathered material itself (particle size, compaction, organic matter). Remote sensing can therefore be used to provide information about several of these factors, and combined with additional spatial data to create predictive models of potentially hazardous terrains (Krishna Bahadur 2009, Prasannakumar, et al. 2011). In particular, optical remote sensing is well recognised for provision of ground cover or vegetation information as is evidenced by the number of operational projects around the world that use satellite data for creating baseline landcover maps. The presence or absence of organic matter can be seen as an indicator of soil erosion, and it has also been shown to be effectively mapped using Landsat imagery and spectral unmixing techniques without the requirement for hyperspectral data (Hill and Schütt 2000). High resolution LiDAR imagery could also be combined with optical data to provide information relating to the topographical factors of a site (see below).

Many of the techniques for identifying that erosion has already occurred are similar to those already discussed for post-event landslide mapping (see §2.1.1). This is because under both scenarios, frequently the identifying factor is exposed soil or loss of vegetation. The use of Landsat data and multispectral indices still proves to be a simple and cost-effective way of identifying and mapping eroded landscapes (Chen and Gillieson 2009, Manyatsi and Ntshangase 2008). Alatorre and Beguería (2009) have also shown that supervised classification of Landsat imagery without the need for spectral indices is sufficient for identifying areas of erosion potential. However, as with landslide detection, it is not possible to solely use single date spectral information to determine if an area has been eroded or not – it is the change in the landscape that proves vital for this identification. Thus contextual knowledge and/or multi-temporal data are required to effectively identify the effects of erosion in the landscape.

2.6.2 LiDAR

High resolution DTMs derived from LiDAR can be utilized for the mapping and characterization of geomorphic features associated with and indicative of erosion processes (Anderson and Croft 2009, Ritchie, et al. 1994). If a time series of LiDAR data is collected, the resulting DTMs from multiple time periods can be differenced to calculate the volume of soil eroded from a system for that period. This approach was successfully employed along the Blue Earth River in Minnesota, where changes in the river bank were calculated between 2001 and 2002 to reveal a volumetric loss of over 280 000 m$^3$ (Thoma, et al. 2005).
2.7 Problem soils (shrink/swell clays and acidic soils)

2.7.1 Optical

It is known that certain types of clays are prone to shrinking and swelling as a result of moisture content (e.g. smectites), whilst others are not (illites and kaolinite). Necessary for effective remote sensing is the ability to detect differences in the spectral reflectance profiles between these different types of clays, as this permits mapping of potentially hazardous soils over a broad scale using satellite or airborne image data. It has been demonstrated that these spectral differences do exist, and are detectable using field spectrometer data in the range of 1800 – 2400 nm with a minimum spectral resolution of 10 nm, using derivative analysis (Goetz, et al. 2001). This foundation study was crucial in providing the spectral requirements necessary for future mapping endeavours.

Identification of problem soils is limited to optical analysis in areas devoid of (or with considerably low) vegetation or other ground cover (e.g. infrastructure) (Chabrillat and Goetz 2006). This is therefore severely restrictive in terms of an application, particularly if there is an area of interest that has already been settled and developed. On the positive side however, is that it is unlikely that the physical and chemical soil properties giving them a potentially hazardous nature will change over short periods of time. As such, the temporal resolution of imagery is irrelevant. This is particularly important, as one of the most useful data sets for soil and mineral analysis is ASTER, which unfortunately experienced degradation of the SWIR detectors, rendering all SWIR bands useless since April 2008. However, if the soil composition is time-independent, then it is possible to utilise older datasets to perform the required analysis. ASTER has proven useful for a two step identification of shrink-swell clays, firstly by mapping soil moisture, and then by following up with clay identification based on spectral libraries and supervised classification techniques (Bourguignon, et al. 2007). The strength of ASTER for soils and minerals mapping has always been with the five SWIR bands that it offered, which remains unmatched by any other multispectral satellite sensor.

Similar techniques were also employed using airborne hyperspectral data (HyMAP and AVIRIS), acknowledging the fact that clay soils have characteristic absorption features in their spectral profiles between 2200 nm and 2350 nm (Chabrillat, et al. 2002). The high spectral resolution nature of these datasets affords more detailed mapping, even down to a sub-pixel level, by estimating the abundances of identified materials (endmembers) within each pixel. Note that this study also reports a level of success in areas of up to 50 % vegetation cover, however the actual accuracy of clay soil detection is not reported. The disadvantage of this technique is that it requires the availability of high spectral resolution imagery, which is often extremely costly to both acquire and process.

2.8 Geochemical hazards (both natural and anthropogenic)

2.8.1 Optical

Using remote sensing for geochemical hazard assessment relies not on the identification of the hazardous element itself, but on the effect of that element in the local environment. This is because individual hazardous elements may not necessarily have a distinctive or unique surface expression. In this case, it is necessary to first establish causal relationships between the excessive presence (or indeed deficiency) of a particular element, and the surface expression of some sort of environmental change. The change is often related to the health or vitality of local vegetation. In Maya and Cloete (2011), a number of known hazardous elements are
detailed, along with their effects on vegetation. Effects such as leaf senescence, discolouration, or vegetation mortality, are all relatively easy observations to make when using optical imagery of an appropriate spatial scale with sufficient spectral resolution. Even using single band NIR data or a simple NDVI spectral transform has proven to be sensitive enough to detect vegetation health, related to Copper and Nickel (Rastmanesh, *et al.* 2010, Tommervik, *et al.* 1994).

### 2.9 Summary of data types and processing techniques

As is clear from the previous sections, there are a number of different techniques used for hazard assessment. These are dependent on the data sources and the specific application. A number of the potential processing techniques for geological hazard information extraction are summarised in Table 6, which also includes the advantages and disadvantages of each method.
<table>
<thead>
<tr>
<th>Data Type</th>
<th>Sensor Examples</th>
<th>Technique</th>
<th>Application</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral</td>
<td>Ikonos, Quickbird, SPOT,</td>
<td>Manual interpretation</td>
<td>Infrastructure and property damage due to flooding, earthquakes, landslides etc.</td>
<td>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</td>
<td>Can be subjective, time-consuming for widespread events, and non-repeateable</td>
</tr>
<tr>
<td>high to moderate</td>
<td>ASTER, ALOS</td>
<td>Spectral classification</td>
<td>Location and extent of flooding, landslides, identification of certain soil characteristics (e.g. clay)</td>
<td>Relatively rapid to apply over a large area</td>
<td>Non-unique spectral response values, may require additional manual editing, appropriate algorithm must be selected for optimal result</td>
</tr>
<tr>
<td>spatial resolution</td>
<td></td>
<td>Semivariogram analysis and other textural classifiers</td>
<td>Damage due to earthquakes; location of landslides</td>
<td>May be useful when spatial resolution is lower than desired</td>
<td>Only returns relative damage estimates</td>
</tr>
<tr>
<td>Image thresholding</td>
<td></td>
<td>Image differencing</td>
<td>Location and extent of flooding, landslides, volcanic debris, fire scars</td>
<td>Can be conducted on panchromatic data, band ratios or SAR backscatter imagery</td>
<td>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 (e.g., crop rotations); still need to determine a threshold of change</td>
</tr>
<tr>
<td>Data Type</td>
<td>Sensor Examples</td>
<td>Technique</td>
<td>Application</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>-----------</td>
<td>-------------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Post - classification change detection</td>
<td>- Location and extent of flooding, landslides, volcanic debris, fire scars</td>
<td>Does not require radiometric calibration between multiple images</td>
<td></td>
<td>Requires before and after imagery that is accurately co-registered, all changes will be identified regardless of their relevance to the particular natural hazard (e.g., crop rotations), requires classification to also be completed on 'before' image</td>
<td></td>
</tr>
<tr>
<td>DEM generation</td>
<td>DEM is used as a supplementary information in variety of studies</td>
<td>Photogrammetric methods can provide very high resolution DEMs in the absence of LiDAR</td>
<td></td>
<td>Stereo imaging is not automatically acquired so may not be available; DEM creation software is not standard in image processing packages - i.e., costs extra, derived elevation is based on vegetation rather than ground height, no data in cloudy areas</td>
<td></td>
</tr>
<tr>
<td>Coherence</td>
<td>Change detection due to landsliding, flooding, fire, etc.</td>
<td>Provides quantitative estimation of ground changes</td>
<td></td>
<td>Does not work well in densely vegetated regions, affected by seasonal changes, accuracy decreases with time</td>
<td></td>
</tr>
<tr>
<td>Backscatter intensity</td>
<td>Change detection due to landsliding, flooding, fire, etc.</td>
<td>Can be used in cloudy conditions, side-looking acquisition geometry is beneficial for certain applications</td>
<td></td>
<td>Quantitative analysis is complicated and varies significantly for different regions, may be difficult to interpret for non-experienced end-users</td>
<td></td>
</tr>
<tr>
<td>Interferometry/ DEM generation</td>
<td>DEM is used as supplementary information in variety of studies</td>
<td>Independent of weather conditions</td>
<td></td>
<td>Accuracy depends on acquisition geometry, wavelength and coherence, side-looking acquisition geometry creates distortion and shadowed areas</td>
<td></td>
</tr>
<tr>
<td>Differential interferometry</td>
<td>Surface deformation due to tectonic activity or ground water extraction; Velocity and extent of slow moving landslides</td>
<td>High precision, high resolution of some new sensors</td>
<td></td>
<td>Dependent on spatial baseline and DEM accuracy; cannot determine difference between vertical and horizontal components, high accuracy only available in areas without dense vegetation</td>
<td></td>
</tr>
<tr>
<td>Polarimetry</td>
<td>Land cover classification and</td>
<td>Ability to detect features that are not visible on optical images, side-</td>
<td></td>
<td>Dependent on type of land cover and seasonal changes</td>
<td></td>
</tr>
<tr>
<td>SAR</td>
<td>JERS-1, ERS-1/2, ENVISAT, ALOS PALSAR, TerraSAR-X, Radarsat-1/2, Cosmo-SkyMed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Type</td>
<td>Sensor Examples</td>
<td>Technique</td>
<td>Application</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
<td>--------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>DEM</td>
<td>PALSAR, LiDAR,</td>
<td>DTM differencing</td>
<td>Volume of landslide related earth movement, Fault locations and elevation displacement, tsunami and flood inundation zones</td>
<td>Provides quantitative estimation of volumetric depositions and ground change. Photogrammetric methods can provide very high resolution DEMs in the absence of LiDAR</td>
<td>Requires imagery both before and after event to be accurately co-registered. 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</td>
</tr>
<tr>
<td></td>
<td>TerraSAR-X, Ikonos, Quickbird, SPOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airborne LIDAR sensors, SEASAT</td>
<td>Manual interpretation</td>
<td>Very high horizontal and vertical resolution, can give accurate surface elevation (rather than tree heights)</td>
<td></td>
<td>Acquisition of LiDAR is expensive and takes a considerable amount of time to process</td>
</tr>
</tbody>
</table>
3 CONCLUSIONS AND RECOMMENDATIONS

This report has summarised a number of different remote sensing data types and processing techniques relevant to the identification, mapping, and monitoring of geological hazards. The hazards of interest were determined to be those of relevance to South Africa and were pre-defined as landslides and slope instability; seismic hazard (natural or mining induced); deformation associated with mining and water abstraction; sinkholes; tsunami; erosion; problem soils; and geochemical hazards. The remote sensing data types were limited to optical, LiDAR, and synthetic aperture RADAR (more specifically, InSAR techniques).

It was identified that geological hazard assessment can focus either in the period leading up to a hazard event occurring, or in the time that passes post-event. The remote sensing requirements will be very different for pre- and post-event assessment. In the case of the former, it is necessary to identify specific precursors or environmental features that render a particular location susceptible to a potential hazard, which can then be monitored and built into models for estimating vulnerability. In the case of the latter, the assessment focus on the will be on the effect of that hazard and the environmental change at the location of interest. It is therefore necessary to consider both the hazard type and assessment phase before making any decision on remote sensing requirements for data acquisition and processing.

Remote sensing has played a role in the assessment of each of the hazards identified, but its level of application and indeed provision of accuracy varies greatly. For example, InSAR is well recognised for the role it plays in assessment of deformation due to mining, water abstraction, or seismicity, and may be considered to be close to operational status. However in other fields it is either less effective, or further research should be conducted (e.g. erosion and sinkholes). The use of optical data for soil and mineral assessment has proven effective on many occasions in areas devoid of vegetation and thus holds great potential for identifying shrink/swell clays. In addition, a particular strength of optical remote sensing is in vegetation monitoring. Baseline information in landcover is well developed and operational globally. This is essential for modelling erosion and slope stability, while changes in vegetation health over time may be indicative of a sinkhole or geochemical hazard – both applications that could be areas of fruitful research in the future. Airborne LiDAR is particularly useful for providing highly detailed elevation data that can be used in relation to modelling a number of geological hazards including tsunami / flooding inundation, slope stability, erosion, and seismic hazards (fault identification), however it remains a high cost solution. Future research into the enhancing the utility of LiDAR could focus on determining the value of lower spatial resolution satellite systems.

It is clear that there is considerable scope for further revision of remote sensing data processing techniques in the field of geological hazard assessment. In particular, future research into the above named hazards should focus on the specific characteristics of the South African environment to ensure that the technologies used are relevant to the location and are the most appropriate for the facilities, infrastructure, and data available.
4 ACKNOWLEDGEMENTS

The South Africa Council of Geosciences is kindly acknowledged for their financial support in developing this document. In particular, Jeanine Engelbrecht was instrumental in conceiving the idea for the project and its implementation. Thank you to Charles Darwin University, GNS Science, and the European Center for Geodynamics and Seismology for providing in-kind support in the form of time to work on the project to each of the authors.

5 REFERENCES


Young M. (1986). Optics and lasers: including fibers and optical waveguides. Berlin: Springer