Advances in the use of Ground Based Radar for Disaster Recovery Risk Management

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Key words: Radar, GPR, Interferometry, Synthetic Aperture Radar

SUMMARY

At the beginning of the 20th century, radio waves were first used to detect the presence of objects but it was not until the 1940’s that radar, an acronym for RAdio Detection And Ranging, was used routinely for detecting the presence of aircraft and naval ships. Radar now has a broad range of highly diverse applications including air traffic control, astronomy, air-defence systems, speed calculation, navigation (air, sea and space), collision avoidance, surveillance and meteorology.

More recent uses of ground based radar include ground-penetrating radar (GPR) for geological and civil infrastructure investigations, and interferometry and synthetic aperture radar for remote monitoring of the movement of structures and landscapes. The use of ground based radar therefore lends itself to applications in disaster recovery risk management.

For example, GPR is now used routinely to determine railway ballast, road pavement and concrete substructure condition but can also be used to determine the extent of damage to this infrastructure after flood events, cyclones or earthquakes. Other novel applications of GPR is it’s use for real time detection of people trapped under rubble and to determine if there is movement.

Interferometric radar is used to detect sub-millimetre movement and provide vibration analysis of civil infrastructure, such as bridges, buildings, tunnels, and dam walls and therefore can determine whether these structures are performing according to their design specifications both during and after disaster events. It can also be used to monitor active volcanic cones to determine whether they are inflating prior to eruption. Other systems combine interferometry and synthetic aperture radar to monitor slope movement for landslide prediction and also to measure land subsidence after earthquake activity.

Frequency Modulated Continuous Wave (FMCW) radar is also used to detect obstacles blocking track at level crossings, overpasses and tunnel entrances and exits. Their primary aim is to ensure collision avoidance in high risk zones by providing real time alarming and video feeds to control centres to continuously monitor these zones. Again, this type of system lends potentially itself to monitoring infrastructure immediately following natural disasters.

This paper looks at recent innovations in ground based radar technology and potential applications to disaster recovery risk management.

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1. INTRODUCTION

Radar (RAdio Detection And Ranging) can determine the range to an object by measuring the time it takes for the radar signal to reach the target and return to the radar but it can also be used to define the size, shape and movement of targets. This paper describes some types of ground based radar and their application in assisting with disaster recovery and reducing the level of risk exposure through detailed analysis of infrastructure assets and geographical features prior to, and after disaster events.

2. SOME TYPES OF GROUND BASED RADAR

2.1 Interferometric Radar

The IBIS FS radar (See 2.1.3) developed by Italian company, IDS (Ingegneria Dei Sistemi), uses two radar techniques to simultaneously detect the position and movement of multiple targets at varying distances within its line of site and these are:

- The Stepped Frequency Continuous Wave (SF-CW) technique to resolve the positions of different targets
- Interferometry to very accurately measure movement of each target by examining the change in phase of the return signal from measurements taken at different times.

A brief description of these techniques follows.

2.1.1 Stepped Frequency Continuous Wave Technique (Barnes et al., 2011), (Taylor, 2001)

The principle of this technique is that the radar steps through a range of frequencies of the bandwidth, from low to high frequencies, at up to 200 times per second (200Hz). The real and imaginary components of the signal are analyzed in the frequency domain. The phase and amplitude information of the signal is retrieved by Inverse Discrete Fourier Transform (IDFT) (Palombo et al, 2011) and an amplitude versus range profile of the radio echoes is constructed for 0.5m bins forming a one dimensional map called a range profile which shows reflected amplitudes with respect to the range from the radar sensor. Figure 1 demonstrates this concept. Note that a Frequency Modulated Continuous Wave (FM-CW) radar works in a similar way to a Stepped Frequency Continuous Wave radar except that instead of stepping between frequencies at a particular step size, the radar moves through the range of frequencies linearly. IDS also use this type of technology in interferometric radars.

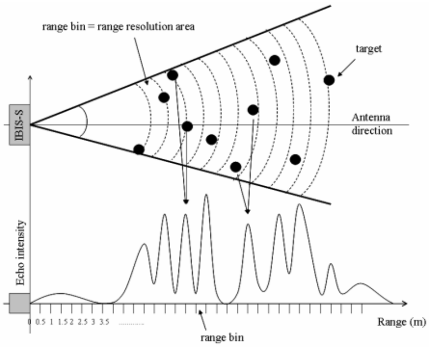


Figure 1. The range profile shows the intensity in dB of the signal reflected back from each object in the transmitted wave path back to the receiver of the radar as a function of each objects distance from the radar.

The sampling frequency controls the maximum frequency measurable by the system with the Nyquist frequency, or maximum detectable frequency, being approximately half of the sampling frequency. The frequency that can be sampled is controlled by the distance from the structure, as for radar waves travelling further to a reflector, the sensor must wait longer to receive the return signal. In practice this means that reflectors at a range of 1km can only be sampled at 20Hz, whilst closer reflectors can be sampled at 200Hz. The sampling rate does not affect the accuracy of measured deflections as this is determined by the wavelength of the radar waves.

The IBIS FS radar has a minimum range resolution of 0.5 metres meaning that only objects with separation greater than this can be resolved as separate objects i.e. they must be at least 1 range bin apart. Objects within the same range bin cannot be resolved as separate objects.

2.1.2 The Differential Interferometry Technique (Henderson and Lewis, 1998)

Once the measurement data has been assigned to range bins and the peaks selected for the targets of most interest, the deflection of the targets is measured using differential interferometry. The phase of the returned radar waves from each target is measured during consecutive samples with the phase of the return signal calculated using the formula:

$$d_p \propto \frac{\lambda}{4\pi}\Delta\varphi$$

Where d_p is the radial displacement, λ is the wave length, and φ the phase change. Figure 2 illustrates the concept.

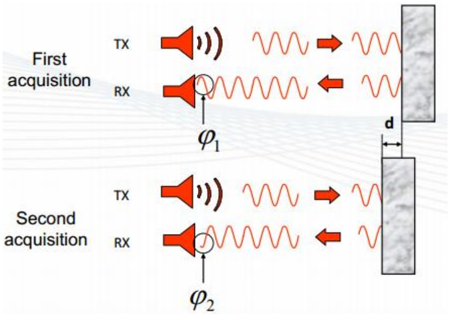


Figure 2. Interferometry concept

The displacement measured is along line of sight so to calculate vertical or horizontal deflection, the geometry of the scenario needs to be calculated. In the example shown in Figure 3, the vertical component of the deflection of the bridge is calculated as:

$$d_p = d \sin(\alpha).$$

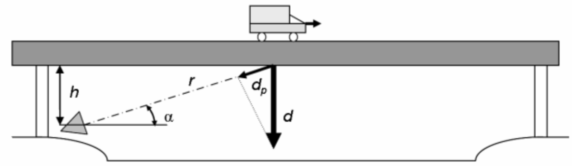


Figure 3. Vertical displacement calculation

In order to calculate deflections (i.e. vertical or horizontal) the alignment of the system to the structure is important. Where the vertical component is required, the alignment must be along the length of the structure and in most cases this would be from beneath the structure. To measure horizontal movement, the alignment would be from the side of the structure. Where both components are required, two systems would need to be synchronised wirelessly.

2.1.3 System Description and Specification

The system consists of a sensor, power supply and control unit and has two horn antennas for transmission and reception of the radar signal (See Figure 4). The sensor generates a tune-able sine wave with central frequency of 16.75GHz and with a bandwidth of 300MHz. The radar is classified as a Ku – band, according to standard radar-frequency letter band nomenclature from IEEE Standard 521-1984 (Bernardini et al, 2007).

The sensor is supported on a tripod with a fully rotatable head allowing it to be placed easily at any required angle. Communication between the radar sensor and the control unit is through a standard USB interface. The data logger is a standard laptop running Windows 7 with dedicated software to configure, store, process and view the data. The power supply is a commercially available 12V which can power the system for 8 hours in the field.

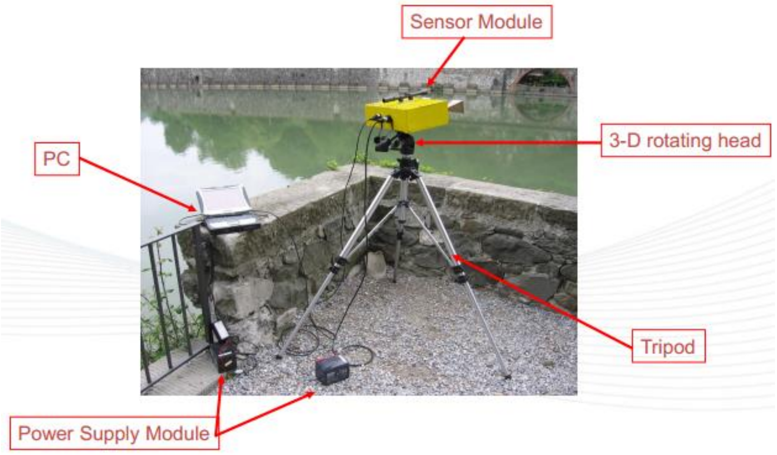


Figure 4. IBIS FS system setup

2.1.4 System Accuracy Calibration

The following test provides a comparison between IBIS-FS and a high-performance Leica TCA2300 Total Station in measuring a target displacement. Figure 5 shows a corner reflector with attached micrometre set at a distance of 33 metres from the radar and total station. The following movements were made using the micrometre:

- 3 x 1mm step towards IBIS-FS and -3mm back
- 2 x 0.5mm step towards IBIS-FS and -1mm back
- 5 x 0.1mm step towards IBIS-FS and -0.5mm back

The results in Figure 6 clearly show that sub-millimetre measurements are more accurately measured by the radar compared to the total station as the total station shows drift for sub-millimetre measurements whereas the radar does not.

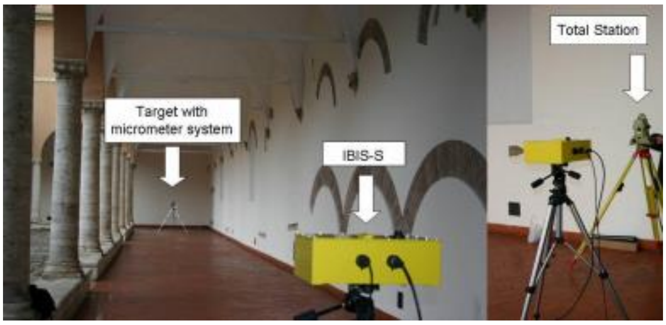


Figure 5 IBIS FS and Total station accuracy test

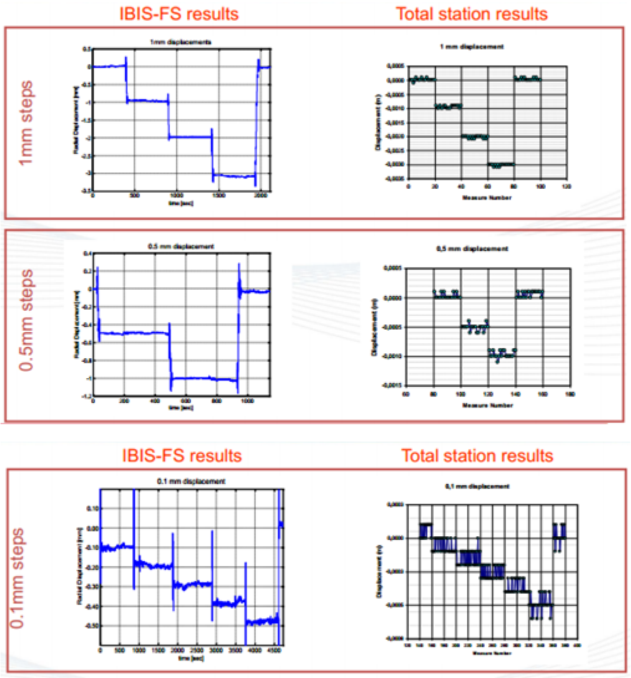


Figure 6 The results show that sub-millimetre measurements are more accurately measured by the radar than the total station

2.2 Ground Based Interferometric Synthetic Aperture Radar (GBinSAR)

Synthetic Aperture Radar (SAR) is the standard radar used for satellite radars as they require the highest possible angular resolution for focusing on the earth from space (Pieraccini, 2013)). Since the 1990's, satellites have been able to exploit the phase information of images to detect ground displacement. For the last 10 or so years, the same technique has been exploited by ground based systems to successfully monitor near real time slope displacement to facilitate slope failure prediction. The synthetic aperture for ground based systems is realized by moving a microwave interferometer along a linear length of rail as in Figure 7a. This enables the system to achieve cross range resolution from the SAR plus the range resolution from the FMCW radar allowing the surveyed area to be segmented into pixels whose dimensions vary with distance from the radar (See Figure 7b). Sub-millimetre movement from any pixel can then be measured through the interferometric technique. The range of the IBIS FL/FM radar is 4 km.

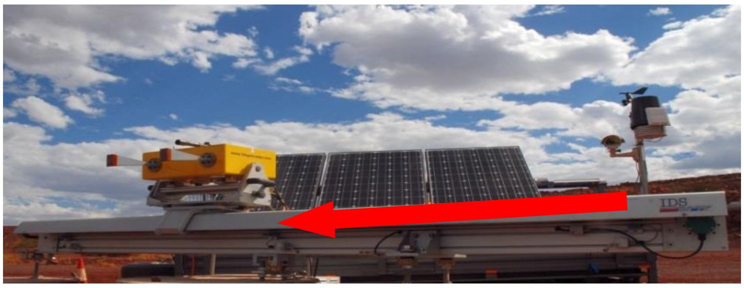


Figure 7a Example of IBIS FL/FM ground based interferometric synthetic aperture radar

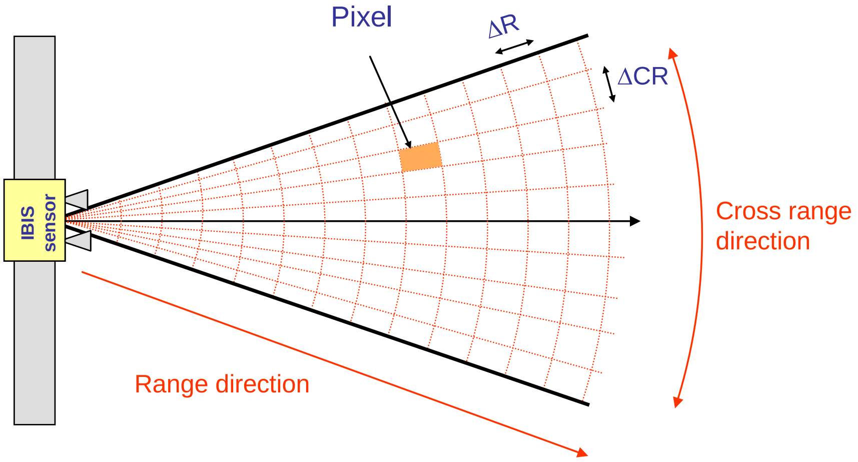


Figure 7b Range Resolution is achieved through the interferometric technique and cross range resolution acheived throught the SAR technique to produce pixels with pixel size varying with distance.

2.3 Ground Penetrating Radar

Ground penetrating radar (GPR) is a high resolution electromagnetic technique designed primarily to investigate the shallow subsurface of the earth and uses the principal of scattering of high frequency electromagnetic waves (typically from 10 MHz to 3,000 MHz) to locate buried objects (Daniels, 2000). Ground Penetrating Radar is one of the highest resolution geophysical techniques available and this makes it ideal to position underground objects located in complex geometries, for example, underneath urban environments. One of GPR’s features is that it can be used to detect any material buried within the shallow subsurface providing there is a contrast between the electromagnetic properties of the object and the surrounding material within which it is buried.

The EM wave is radiated from a transmitting antenna and travels through the material at a velocity which is determined primarily by the electrical properties of the material. The wave spreads out and travels downward until it hits an object which has different electrical properties from surrounding medium, gets scattered by the object and is detected by a receiving antenna, some part of the wave also continues travelling downward. The reflected part of the wave is captured by the receiver antennas and recorded digitally

Typically, these systems are hand pushed over an area with utilities showing up as hyperbolic features in a 2-dimensional cross section image of the subsurface called radargrams (See Figure 8) and linear features such as changes in lithology showing up as linear features (See Figure 9).

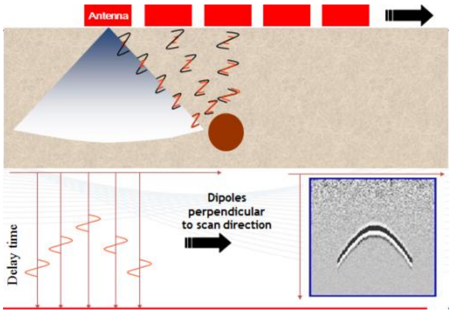


Figure 8 Radargrams are displayed as Distance (x-axis) versus Time (y-axis) plots and as such when an antenna approaches an object such as a pipe, the time for the signal to transmit, reach the pipe and return to the receiving antenna is called the two way time. This time reduces as the antenna approaches the pipe (as the pipe becomes closer) and increases when it moves away from the pipe. Hence, hyperbolic features are seen in the radargram for pipe like features.

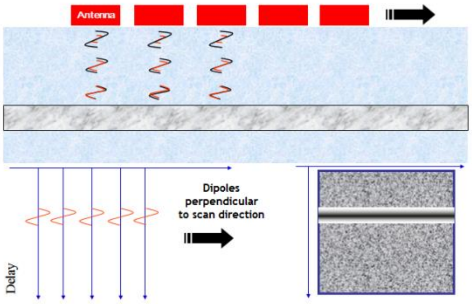
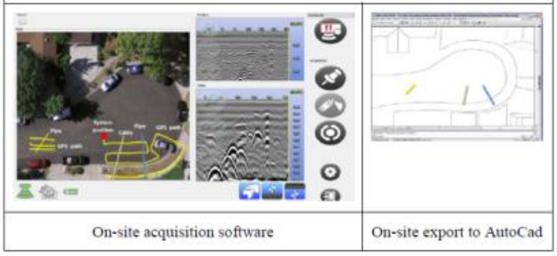


Figure 9 Linear features such as lithology show up in the radargram as a true representation of the lithology

Figure 10 shows an example of one of these systems designed by IDS, the Opera Duo, which has many useful features such as automatic delivery of CAD drawings, GPS tracking with Google Earth and dual frequency antennas for finding both deep and shallow buried utilities.

Opera Duo Dual Frequency GPR system



On-site acquisition software

On-site export to AutoCad

Figure 10 Shows the Opera Duo GPR system and software

3. ADVANCES IN THE USE OF GROUND BASED RADAR FOR DISASTER RECOVERY RISK MANAGEMENT

3.1 Interferometric Radar

3.1.1 Structural Integrity of buildings and bridges (real time)

The interferometric radar detailed in this paper has been used successfully to monitor sub-millimetre displacement and vibration characteristics in real time of many civil structures such as bridges, buildings and wind turbines. An example of the accuracy of the system when compared to accelerometers can be seen from a test undertaken of the Capriate Bridge, a reinforced concrete bridge crossing the Adda River 50km North East of Milan, Italy. The testing and analysis is courtesy of Gentile and Bernardini, 2008.

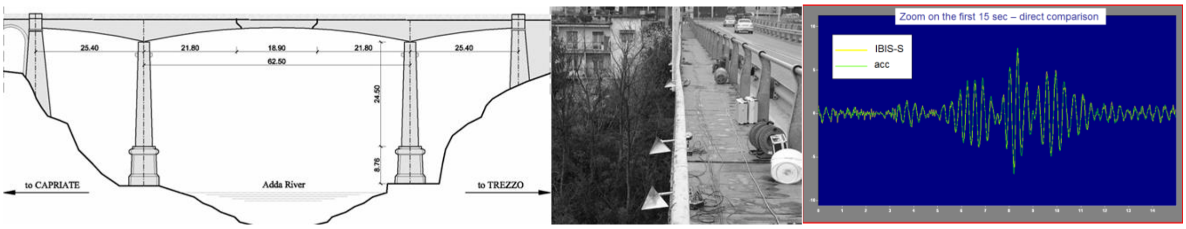


Figure 11 From left to right: i) bridge style and dimensions ii) accelerometers and corner reflectors for radar are placed in identical positions so direct comparative measurements can be made iii) velocity – time histories from the accelerometers and interferometric radar measurements overlay precisely

Figure 11 shows from left to right, the bridge surveyed, the corner cubes and accelerometer placement and the excellent agreement between the interferometric radar and the accelerometer results. The corner cube reflectors were used to reflect transmitted radar waves back to the receiving interferometric radar and WR-731A accelerometer sensors were placed in positions adjacent to the corner reflectors. The velocity time histories recorded by the WR-731A sensors were then directly compared to those derived from the displacements obtained by the radar. Resonant frequencies and modal shapes of the bridge were then calculated from the radar and accelerometers and the results were seen to be extremely similar. Please see (Gentile and Bernardini, 2008) and (Bernardini et al, 2008) for a detailed analysis of these results.

Along with vertical displacements and resonant frequencies of various points on structures, analysis of the modal shape of the entire structure can also be undertaken to determine if the bridge is performing as expected during disaster events such as earthquakes, flooding or extreme high winds.

Analysis of the structure can also be undertaken post disaster event to understand if there has been damage to the structure through analysis of variations between measurements before and after disaster events. Please see https://www.idscorporation.com/georadar/more-information/case-studies/interferometric-radar-ibis-case-studies?start=10 for more case study examples.

3.1.2 Volcano monitoring

Interferometric radar can be used to provide prior warning of impending volcanic eruption and has been used to successfully measure the displacement of the volcanic cone prior to, during and after eruptions. Professor Maurizio Ripepe from the University of Florence and IDS undertook measurements of Stromboli volcano in Italy which frequently erupts on a daily basis. The radar was placed at a distance of 400m from the volcano summit and measured the inflation of the volcano cone prior to eruption and the deflation following the eruption. The radar measurements were compared to seismometer and tiltmeter sensor measurement placed at various locations on the volcano and there was good correlation between these measurements and this can be seen in Figure 12. In this figure the radar displacement is negative during inflation and positive during deflation as it measures displacement in the line of sight of the radar. An obvious major advantage of using the radar is that no access to the volcano is required.

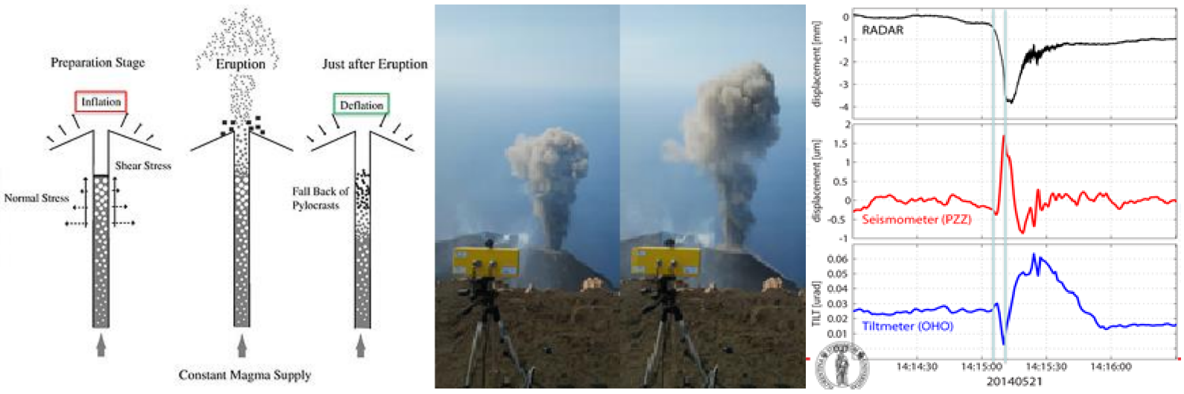


Figure 12 From left to right: i) typical inflation, eruption and deflation cycle of a Stromboli type eruption (Nishimura, T., 2009) ii) Radar view of eruption iii) Displacement – Time histories of the radar, seismometer and tiltmeter are in congruence

3.2 Ground Based Interferometric Synthetic Aperture Radar (GBinSAR)

GBinSAR's long range capability and very high accuracy displacement measurement, 0.1mm accuracy up to a range of 4km, makes it ideally suited for monitoring the stability of large slopes. Slope monitoring can be undertaken 24/7 and be used to measure the effects to slopes of disaster events such as heavy rain and earthquake activity.

3.2.1 Slope Stability Monitoring

There are many examples of the use of this technology for slope stability monitoring. For simplicity, one case study has been used as an example here but more can be found at the web address provided in Section 3.1.1.

Figure 13 shows an example from the Frank Slide on Turtle Mountain in Alberta, Canada where in 1903 over 80 Million tonnes of rock slid down the mountain burying part of the Frank Mining town and killing an estimated 60-90 people. The area is constantly moving even today.
The GBinSAR system was positioned approximately 1km from the site so that the whole slide could be illuminated by the radar. A 2D displacement-time map was generated and overlaid onto a

digital terrain model. This map is generated by many pixels, where the size of each pixel is a function of the distance of the radar from the slope. From the displacement-time map, individual pixels can be chosen and a full displacement-time graph of each pixel generated for the entire acquisition period. Over a 1 month acquisition period, it was noticed that some parts of these slope moved by over 180mm. By monitoring the acceleration of movement, it is possible to use an inverse velocity tool to calculate an estimated time of failure and critical alarm thresholds can be set to warn of this failure. Figure 13 provides a short summary of the monitoring with results.

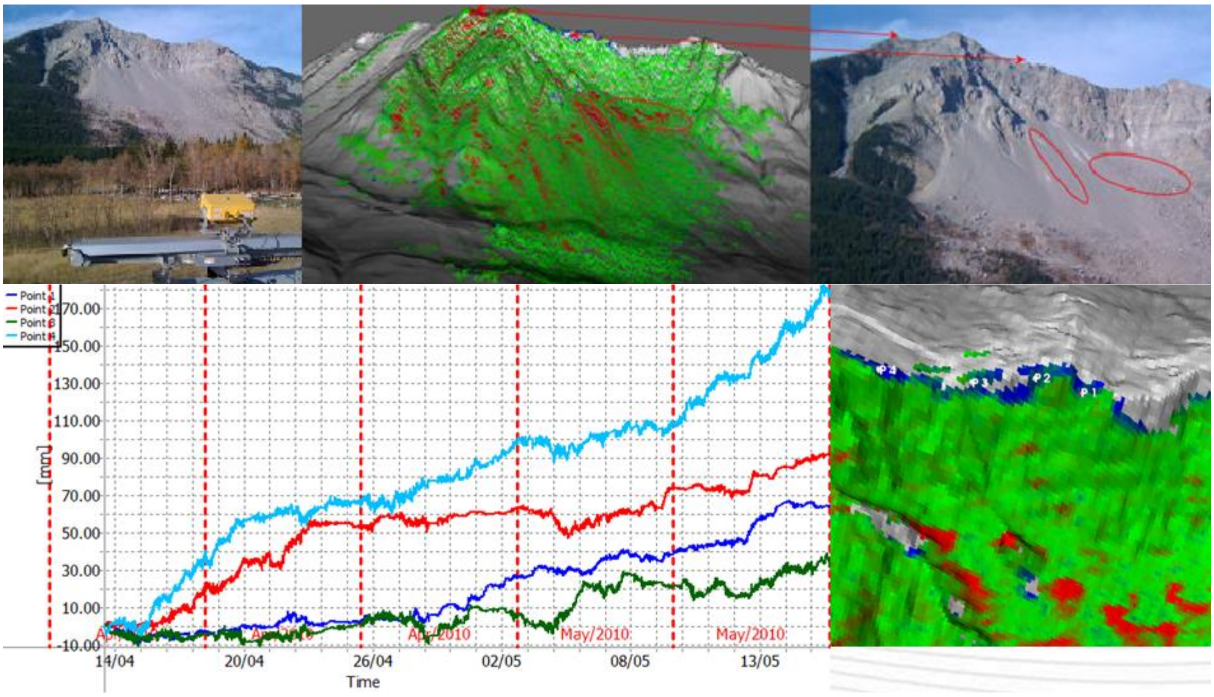


Figure 13 From left to right: i) GBinSAR setup on site ii) Displacement-Time map overlaid on DTM iii) Close up of slide with ellipses indicating areas of high displacement iv) Displacement – Time graphs of 4 points on the slope v) the 4 points (P1-P4) on the slope where the displacement – time graphs were generated from

3.2.2 Avalanche Monitoring

GeoPraevent (www.geopraevent.ch) used the IDS GBinSAR system IBIS FL to capture a detailed history of the movement of the Weissmies glacier in Switzerland. This glacier was reported to have produced several small ice avalanches in the summer of 2014. The measuring station was located approximately 3,200 metres above sea level with temperatures regularly below -20°C and winds exceeding 150km/hr. Geopraevent were able to show precursors of an avalanche 2 days prior to failure.

Figure 14 shows close up images of the avalanche area and a video of the captured avalanche can be seen at https://www.youtube.com/watch?v=VmC_-ww7F_Q&feature=youtu.be
The figure shows a 2D displacement-time map generated and overlaid onto a digital terrain model. This clearly shows displacement toward the radar of more than 200mm/day (highlighted in red) of

the area just above the avalanche area. A spatial coherence map was used to track the path of the avalanche itself.

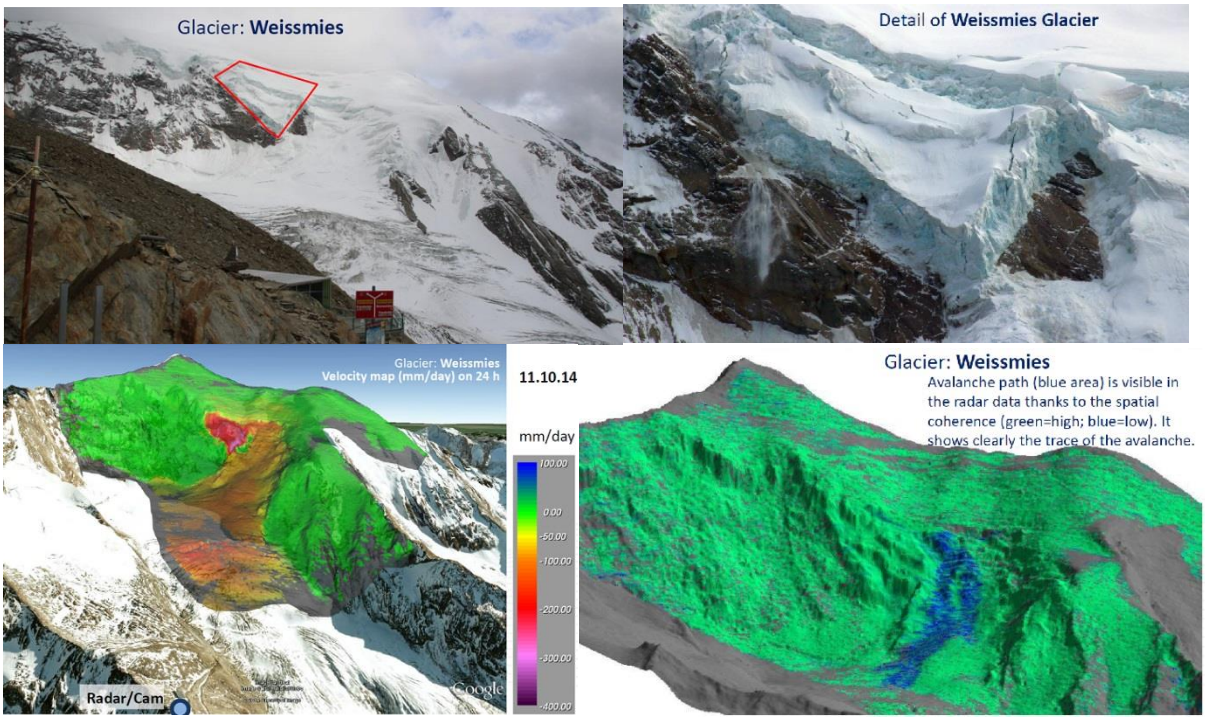


Figure 14 From left to right: i) avalanche catalyst area ii) close-up of avalanche area iii) displacement - time map overlain onto DTM showing greater than 200mm/day movement toward the radar from the avalanche area iv) Spatial coherence map overlain on DTM showing the avalanche path

3.2.3 Railway level Crossing Obstacle Detection and Avoidance

Frequency Modulated Continuous Wave (FM-CW) radar is also used for collision avoidance and obstacle detection on rail networks for example. These systems are installed close to the track infrastructure and are set to monitor set areas and warn train control whether obstacles are blocking track. Automated warnings can then be sent to the vehicle drivers, or for driverless networks, the trains themselves can be stopped directly from train control centres. These same types of radars can also be used for early warning rock fall detection devices warning of impending rock falls. Figure 18 shows and example of a track obstruction and the radar itself.

Figure 18 From right to left i) Rock fall obstructing track ii) Sirio system is setup at critical safety zones such as level crossings iii) the Sirio radar for obstacle detection

3.3 Ground Penetrating Radar

3.3.1 Real time utility locating after disaster events

Figure 15 From right to left i) massive array GPR system and mobile laser scanner towed behind a vehicle for network level mapping of utilities ii) Plan view radar tomography time slice of GPR data showing utilities under the ground

Massive array GPR systems combined with advanced laser scanning and stereoscopic imagery systems can now collect 30-40 hectares of data per day. These systems are specifically designed to map all below ground utility assets and relate this to all above ground utility assets such as fire hydrants, substations. The GPR data is available as plan view maps of utilities in real time (See figure 14). In disaster recovery situations, the position and condition of underground assets like power, water, gas and sewerage is vital. Having access to this information quickly during disaster recovery can assist with emergency planning operations and save lives.

3.3.2 Railway/Road Condition Assessment

GPR surveys can be undertaken soon after disaster events for risk mitigation. Rail and road data can be acquired at high speeds in excess of 100km/hr and can provide important information on road and railway ballast condition after severe storm events for example. Flooding can cause visible washouts but can also cause voiding and other damage which may be unseen on the track or road surface. GPR can be used in these areas to determine the true extent of damage to transport infrastructure and reduce the risk of future failures possibly associated with past flooding events. Figures 16 and 17 show the type of equipment and example resultant datasets generated from these types of GPR investigations.

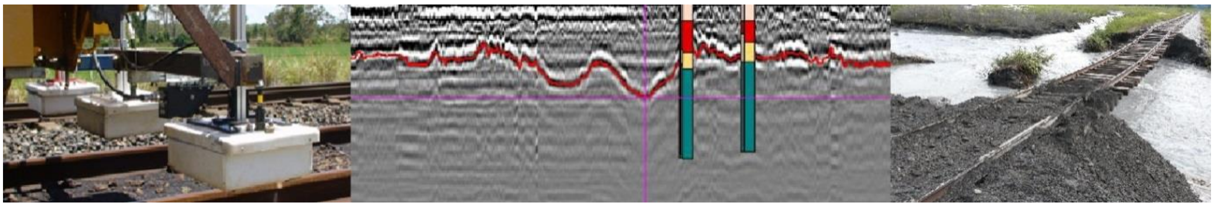


Figure 16 From right to left i) SafeRailSystem GPR for railway ballast condition assessment ii) GPR radargram showing cross section of deep ballast pocket caused by ballast washout and ballast replacement over many years iii) Severe example of complete ballast and formation washout

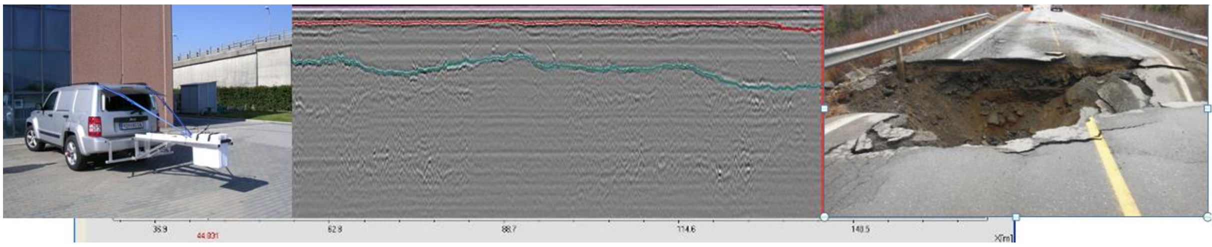


Figure 17 From right to left i) Hi-Pave GPR system for road condition assessment ii) GPR radargram showing variable asphalt thickness iii) Severe road washout caused by flooding event

3.3.3 Concrete scanning

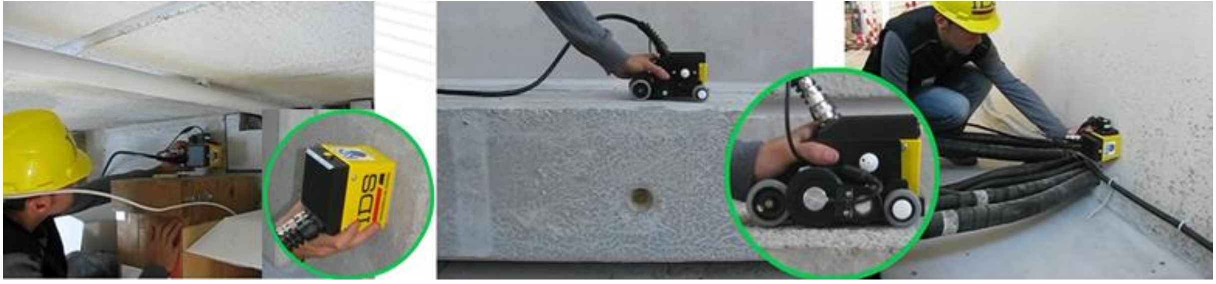


Figure 19 Concrete scanners can be used to assess the condition of concrete structures after major disaster event as a way of risk mitigation

Concrete scanners are ideal tools to investigate structural integrity of concrete structures prior to and after disaster events to ensure that the structural integrity of the asset is maintained. These systems can be used to locate the presence of defects such as voids, cracking and damaged reinforcing.

3.3.4 Through Wall Radar (TWR)

Figure 20 From right to left i) TWR can be used to locate people in smoke filled buildings ii) TWR has simple 2D display which shows person on a screen at a distance of up to 15 metres behind a wall iii) TWR can be used to detect breathing and heartbeat under buried rubble during disaster recovery operations

The IDS Though Wall Radar provides positional accuracy, wide coverage area, multi-target resolution and tracking and detection of stationary personnel through breathing and heart beat detection technology. This lends itself to detection of persons buried under debris or location of people in smoke filled environments. The system can see through various wall types and can detect moving people at a range of 15 metres, still people at a range of 8 metres, breathing at a range of 4 metres and heart beat up to a range of 2 metres. The system works wirelessly, is light weight with an ergonomic design and intuitive display.

4. CONCLUSIONS

There are many different types of radar and just a few of them have been discussed here. What is clear is that radar has many possible applications relating to disaster recovery risk management. From monitoring slopes and structures to determining the condition of infrastructure assets, to helping to locate people trapped in or under buildings, radar offers solutions to reduce risk after disaster events and can help to improve the efficiency and effectiveness of recovery efforts.

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BIOGRAPHICAL NOTES

Presenter Bio: Mark has 15 years experience as a Geophysicist and has worked as Business Development Manager for leading radar manufacturer IDS Australasia (Ingegneria Dei Sistemi) since 2013. Mark has focused on the integration of radar technology with other geophysical techniques for large scale infrastructure monitoring and maintenance optimization. He has managed several R&D groups in Australia and the UK using existing technology to develop new applications and business opportunities.

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