APPLICATIONS OF GROUND-BASED RADAR TO MINE SLOPE MONITORING

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ABSTRACT

While less than 1% of reported mine accidents are associated with slope stability problems, slope failure accidents were responsible for about 15% of U.S. surface mine fatalities between 1995 and 2003. Small rockfalls, which may involve hand-sized rocks weighing only a few pounds, can cause fatal injuries to workers away from the protection of large machinery. Massive highwall failures containing a million cubic yards of material or more can be fatal even for heavy-equipment operators. As part of an ongoing study at the Spokane Research Laboratory, several remote sensing technologies are being evaluated as tools to assess slope stability and monitor slopes for hazards. An interferometric radar device capable of detecting very small displacements on slopes has been assembled and tested. Radar techniques can provide new tools to augment current methods for monitoring ground control hazards in mines.

INTRODUCTION

Unstable slopes are hazardous for miners who work on or beneath them, and large-scale failures have the potential to cause catastrophic loss of life. In the past 9 years (1995-2003), 42 miners have died in slope failure accidents at surface mines in the United States. These fatalities ranged from individual rocks, falling and striking exposed workers, to massive highwall failures that buried large-scale mining equipment. Some instability can be expected at any surface mining operation, but the unexpected movement of ground endangers lives and destroys property. Small rockfalls can cause fatal injuries to workers on foot, away from the protection of large machinery, but shovel operators and drillers suffered the greatest numbers of fatalities in massive highwall failures.

A research project was begun at the Spokane Research Laboratory, National Institute for Occupational Safety and Health (NIOSH) to improve the recognition of slope stability hazards at surface mines. A principal objective of the project is to improve the means for detecting conditions in open-pit mines that could lead to catastrophic slope failure. One approach taken was to assess the application of remote sensing technologies to mine slope safety. Three aspects of remote sensing technology –hyperspectral imaging, interferometric radar, and photographic image analysis –are being evaluated as tools to help recognize potential hazards at mine sites. These technologies have been developed mainly as airborne or satellite instruments, but in these configurations spatial resolution and sampling intervals are not sufficient for addressing local ground control problems in surface mines. Only recently have increased microprocessor speeds, data storage capacities, and signal processing capabilities led to the development of smaller, portable, ground-based systems. Adaptation of these technologies to simplified ground-based instruments could provide a cost-effective means to reduce injuries from the catastrophic failure of mine slopes.

This paper summarizes developments in the application of ground-based radar to slope stability monitoring and presents information on NIOSH-sponsored experiments recently completed. Field tests of a hyperspectral imager were conducted to assess its value for improving geologic maps of potentially unstable alteration zones on mine slopes (McHugh and others, 2001). Computerized monitoring methods using images from digital and video cameras are being assessed for application to mine slope surveillance (McHugh and Girard, 2002).

Factors that Limit Slope Stability

Mine slopes are designed with an engineered factor of safety to control the risk of injury and equipment damage from rock falls and slope failures. Geologic structures, rock mass properties, and hydrologic conditions are elements considered in designing a safe and efficient mining operation. The need to control costs commonly results in pit walls being made as steep as practical to minimize waste removal and surface disturbance, and to maximize ore recovery. However, steeper walls normally mean a greater potential for slope stability problems that need to be

accommodated. Blasting practices can be adapted to minimize unnecessary fracturing of the highwall. Groundwater, surface water, and precipitation runoff can be controlled to abate their deleterious affects on stability. Benches and berms are normally used to stop rocks before they can fall far enough to present a significant hazard. Mechanical rock fall catchment systems or secondary supports may used where feasible to stabilize slopes as needed in particular locations.

However, even carefully designed and constructed slopes may fail (figure 1) because of unidentified geologic structures, unexpected weather conditions, or seismic activity. For this reason, regular examination and systematic monitoring of slopes for early warning signs of failure are the most important means of protecting exposed mine workers.

Standard Highwall Monitoring

Conventional modern monitoring methods normally depend on visual inspections and regular benchmark surveys using reflecting prisms at specific locations. This may be augmented by detailed recording of movement at known problem sites by use of extensometers, tension-crack monitors, or other instruments. A comprehensive system may also register subsurface rock mass displacements, groundwater parameters, and blast vibration levels with additional instrumentation. Aside from visual inspection, these methods provide displacement information only for a single site, or at best for a discrete number of sites. If the monitored sites are too widely separated or if displacements occur between the sites, early indications of a slope failure might go unnoticed. In addition, these monitoring tools are difficult to implement at many quarries and surface coal mines where steep highwalls and lack of benches limit access to areas above the working floor. As mining progresses and monitoring different sections of the pit walls becomes necessary, relocating monitoring devices is not only costly and time consuming, but can also be dangerous on unstable slopes.

Point by point monitoring of every potential failure block on a mine slope is not practical, but a new generation of scanning laser range finders has partially addressed this under-sampling problem in detecting movement over large areas. These instruments can generate digital models of mine slopes without the use of reflector prisms. Displacements can be detected by comparing successive scans. Scanning lasers will likely prove a practical solution in some mine slope monitoring applications, but processing requirements and scan rates have so far made repeat pass intervals too great for effective, timely slope monitoring. In addition, the range and accuracy of these systems can be impaired by differences in the reflectivity of the rock, the angle of the rock face, weather, and other factors.

Figure 1 Highwall failure at a stone operation crushed this dozer, fatally injuing the operator (November 2002). Photograph courtesy of the Mine Safety and Health Administration**.**

Radar Displacement Monitoring

Radar has some advantages over other methods in its ability to cover large surface areas for true two-dimensional monitoring day and night in almost any weather condition; atmospheric dust or haze have little effect. Radar's active transmit/receive mode of operation provides an advantage over passive optical methods that depend on solar or other illumination.

Although radar technology has been widely used for the last 50 years, only in the last ten years have advancing computer capabilities provided the low-cost processing power needed for interferometric computations. The widespread adoption of modern wireless communications devices has resulted in practical integrated circuits for microwave frequencies that can be used in task-specific radar applications. A cooperative agreement was established between NIOSH and the

Center for Remote Sensing at Brigham Young University (BYU) to assess the feasibility of using interferometric radar to monitor mine slope stability using prototype equipment.

Airborne and Satellite Systems

One of the earliest and most spectacular applications of radar interferometry for change detection was accomplished at the site of the Landers earthquake of 1992 in the Mojave Desert of California (Massonet and others, 1993, 1994, Massonet, 1997). A sequence of ERS-1 radar satellite images of the Landers area from before and after the earthquake revealed interference fringes when topographic effects were removed by means of a digital elevation model. Each cycle of interference fringes corresponded to 28 mm of seismic movement. Interference patterns also revealed movement on smaller faults in the region including movement of 7 mm on a fault 100 km from the Landers quake. Similar applications of radar satellite data have been used to map and monitor landslides, ice movement, and volcano deformation (Fruneau and Achache, 1996), and subsidence caused by the extraction of ground water, oil and gas, or minerals (Carnec and others, 1996; Stow, 1996; Dixon, 1995). These pioneering studies have generated enormous interest in the Earth science community because they point to an entirely new way to study the surface of the Earth. Interferometry can also be used to measure ocean surface currents from moving aircraft by aligning the two antennas in the along-track (azimuth) direction, rather than cross-track. In this case, interferometry allows estimation of the Doppler shift induced by the moving ocean surface. Azimuth interferometry is sensitive to surface changes in the along-track/vertical plane.

Ground-Based Differential Radar

A slope monitoring radar to detect hazards needs a much shorter repeat time and greater spatial resolution than airborne and satellite systems can provide. Ground-based interferometric radar systems have been designed to monitor displacement of unstable slopes both in landslide-prone natural settings and at mine sites.

Briole (1999) described a real-time displacement sensor designed as a "microwave range-meter" for risk management applications in hazardous terrains. A prototype was built to test the concept with a goal to measure displacements at ranges to 10 km with an accuracy of 1 cm or less. The system uses microwave signals that are back-scattered from the illuminated surface over a few seconds and processed to generate a wide-band spectral analysis. Sequential pairs of observations are analyzed for inter-correlation from which is extracted the relative radial displacement of the surface over the time interval, as well as a coefficient of similarity for the two scenes. In 1997, Malassingne and others (2001) conducted field experiments using a static differential configuration to test its potential for use in monitoring active volcanoes. The system used a wide-band radar centered at 26 GHz (25-27 GHz). Short pulses of a few centimeters were transmitted, and return signals were processed to remove ambiguities of distance. Final accuracy was attained by analysis of phase data. Methods were developed to measure displacement both with and without corner reflectors. With corner reflectors, absolute distance can be measured to an accuracy of about 1 mm at a range of 1500 m with compensation for atmospheric effects. Differential measurements at that range had a typical accuracy of 0.1 mm. The rock fall area showed a substantial decorrelation over the 4 days of the experiment while the more stable slope showed a high degree of correlation throughout the period.

Experiments in the use of ground-based SAR interferometry to detect displacements associated with landslide motion were conducted by Tarchi and others (2003). The site of the experiments was the Tessina earth slide in the eastern Italian Alps. The radar system, called Linear SAR (LISA), consists of a continuous-wave stepped-frequency (CW-SF) radar with rail-mounted transmit and receive antennas. The instruments were mounted at a stable location facing the landslide area at an average distance of 500 m. The radar operated in the frequency band 16.70-16.78 GHz. The radar system configuration and slope geometry resulted in a range resolution of about 2 m and azimuth resolution of about 2 m at the center of the range. Differential interferometry for the system had a theoretical displacement resolution of about 0.5 mm along the radar line of sight, equivalent to a phase shift of about 20° at the frequencies used.

Bennett (2003) described a program at the University of Sheffield, UK, for investigating radar characteristics of soils and vegetation canopies, providing basic information for the use of radar in environmental applications. The outdoor component is a polarimetric ground-based synthetic aperture radar system, which can be deployed in remote field sites. The synthetic aperture is formed by mounting an antenna array on a 4 m-long linear scanner, which can be elevated to a height of 10 m on a hydraulic boom. Wide-band L, S, C or X band data are processed using SAR

and pulse synthesis techniques to create multi-polarimetric images of the target region over an area of as much as 2,000m^2.

A scanning radar system was designed by researchers at the University of Queensland, Australia (2002) specifically for monitoring mine slopes using differential interferometry. The system, known as the Slope Stability Radar (SSR), uses a real aperture 2° beam-width radar to scan a slope in both vertical (height) and horizontal (azimuth) directions. Scanning at a rate of 10°/second over a range of ±60° vertically and 340° horizontally, the system continuously monitors the slope face for deformations. The return signal phase is recorded for each pixel in the resulting image and phase unwrapping is used to remove the 2π ambiguity (Reeves and others, 1997, p. 123) A commercial trailer-mounted unit is available for lease (Ground Probe Pty Ltd) that features a 0.92 m diameter scanning parabolic dish antenna, mounting, controlling/data collecting computer, remote area power supply, warning siren and lights, CCD camera, communication links, and internet compatibility. Typical scan repeat time is 15 minutes. The system can operate at a range to 450 m from the target slope. Line of sight displacement can be measured to ±0.2 mm without the use of reflectors. In operation, the system produces an image showing spatial deformation relative to a reference image for the entire slope scanned. The displacement history of each point in the image can be plotted.

MINING HAZARDS RADAR

A radar system designed and assembled at Brigham Young University (BYU) was configured for a series of experiments to evaluate the approach for identifying small-scale displacements on mine slopes. The technology stems from research efforts at BYU to build a low-cost interferometric synthetic-aperture radar (InSAR) that can be deployed in a light-aircraft and operate at low altitudes (Lundgren and others, 2000). NIOSH funding facilitated field tests of a ground-based version of the radar system to detect and measure displacement on mine slopes. Such displacement measurements can be used to track mass movement of failing slopes in surface mines and possibly to warn of imminent catastrophic collapse. The ground-based approach has the distinct advantages of high resolution derived from a smaller radar footprint and a high sampling rate (repeat times in seconds) to provide real-time displacement detection.

Background

After developing a series of small, low-cost SAR systems in the mid-1990's, the design team at BYU began the development of a novel, non-SAR interferometric radar system designed to detect railroad track hazards due to rock falls. This system was designed to be very low-cost and short range (Waite, 2000). The intention was to adapt this system (by extending its range) to support experiments in highwall stability monitoring. As the track hazards system developed, the design proved to have inadequate long-term phase stability and could not be used for the proposed experiments. As a result, development was begun of a new prototype natural hazards radar system with an improved chirp transmitter and a fully coherent oscillator scheme to maximize the long-term stability. The original system has since been modified by a commercial firm for use as a road traffic monitoring system and is now being sold commercially.

At the same time, development was begun of an X-band interferometric SAR system (known as YINSAR) for operation in a small plane. When completed, YINSAR was successfully used in a multi-season experiment to collect interferometric data over a landslide in Colorado and an archeology site in Utah. Conclusion of the planned flight program allowed a reconfiguration of the hardware to support the mine slope monitoring experiments.

Theory and Methods

Experiments were designed to demonstrate that an interferometric radar signal resulting from small changes in a rock face is detectable in a mine environment. Interferometry is based on the difference in signal phase between two observations and thus requires a coherent (phase-preserving) measurement system. YINSAR uses two receive antennas separated by a baseline to receive the radar echo from the target surface. The antennas are offset in the cross-track (range) direction. The phase difference in the echo from each distance (range) bin measured at each antenna can be related via the geometry of the measurement to the height of the surface (Zebker and Goldstein, 1986).

Small surface movements on a mine highwall that are precursors to a failure may provide sufficient warning to enable men and machinery to be withdrawn to safety. Such movements may be less than a few cm, and thus require precision measurement systems. Radar interferometry offers the desired precision and can operate at night, through smoke and dust, without requiring reflectors on the highwall face and thereby avoiding the hazards workers would face installing reflectors on a potentially unstable highwall.

Detailed study of slope failure mechanisms would require a fine spatial resolution, but for safety monitoring the spatial resolution can be fairly coarse. Essentially, the radar measures the path length between the antennas and each resolved portion of the highwall face. Changes in the path length will be due to movement on the highwall face. This simple picture is complicated by a number of factors. Humidity variations in the intervening atmosphere can give rise to apparent path length changes. Any variations in the location of the microwave scattering centers within the resolution element due to moisture content, freezing, liquid water, snow, etc. can also give rise to path length changes. These effects vary with radar operating frequency and configuration. While the variation of microwave scattering center with environmental conditions is inherent to the problem, the effect can be ameliorated by the interferometry used and the operating frequency employed.

Two approaches to the application of radar interferometry for highwall monitoring can be distinguished based on the number, characteristics, and movement of the radar antennas. One approach uses a single, two-dimensional (2D) scanning antenna; the second uses dual receive antennas and one-dimensional (1D) scanning. Both approaches have advantages and disadvantages. The latter can be further separated into azimuth or range subclasses based on the relative orientation of the two antennas.

In the first approach, a single pencil-beam antenna is scanned in two dimensions over the highwall face (figure 2). At each scan location, a radar signal is transmitted and the radar echo received and processed. The radar signal phase recorded at each scan location is preserved. The face is repeatedly scanned in time. The phase measured at each location is compared to the phase of the previous scan (or a time average of previous scans). Difference in the phase between scans is related to face movement with an estimated correction based on weather conditions. This approach requires a high-precision 2D scanning system and an exceptionally phase-stable radar; both add to the expense of the system. This approach forms the basis of a monitoring system developed in Australia (University of Queensland, Australia, 2002).

The second approach, adopted in the design for these experiments, uses a fan-beam transmit antenna to illuminate the entire vertical face over a narrow horizontal distance. The face is scanned repeatedly in a horizontal (1D) sweep (figure 3). Two receive antennas are separated by a short baseline distance. The radar's range resolution enables vertical resolution of the face. The interferometric phase difference between the receive antennas (which is due to the small path length difference between the target and each antenna) is recorded for each scan position. Since the radar is stationary, the differential interferometric phase between scans can be easily computed. The differential phase is very sensitive to changes in the surface in the plane of the baseline orientation e.g., either azimuth (horizontal) or range (vertical). (Note that with three receive antennas, azimuth and range interferometry can be done simultaneously.) However, because the interferometric path length for a given scan is nearly the same, the atmospheric effects are similar for both channels and interference is minimized. Further, this approach does not have the stringent long-term phase stability requirements of the pencil-beam, 2D scan design, though two receivers

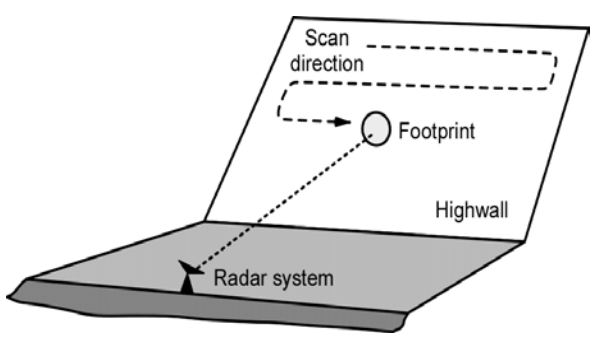

Figure 2. Two-dimensional scanning radar configuration.

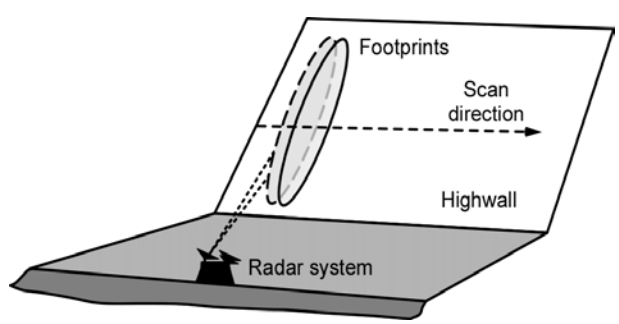

Figure 3. One-dimensional fan-beam scanning radar configuration.

and antennas are required. In addition, since scanning is in a single dimension the scanning system is less expensive than a 2D system.

Field Experiments

Slope monitoring experiments using the YINSAR apparatus were conducted at a sand and gravel operation near Provo, UT in January 2003 (figure 4). To simplify the tests, the system used a fixed antenna position, without the scanning configuration required to scan the full face as an operational system would. Due to battery power limitations and because the YINSAR hardware is unsuited for long-term outdoor deployment, data were collected only for short periods. The system operates at 9.9 GHz with a 200 MHz bandwidth, giving it a 60 cm range resolution. While a lower operating frequency would make the system less sensitive to environment-induced scattering center variations, the system was suitable for the proof of concept experiment. The final intermediate frequency is all-digital with the signal digitized at 500 MHz. The pulse repetition frequency is 1200 Hz while the pulse length is variable from 0.1 to 150 microseconds.

The system has separate receive and transmit antennas (bistatic). The antennas are slotted wave-guide fed horns with beamwidths of approximately 12° horizontal and 45° vertical. The two receive antennas were in a range interferometric layout with a 60 cm vertical separation (baseline) (figure 5). A phase change of 2π radians corresponds to 3 cm or more of surface change. The instrument was setup approximately 30 m from the base of a gravel slope. The slope was about 11 meters high and had an inclination of about 35°. A baseline test was an initial measurement of the undisturbed slope. Other tests showed the effect of throwing a softball-sized rock onto the slope, disturbing the surface and shifting a few other rocks, and included a person climbing up the slope and then descending.

Results and Analysis

Processed radar data for the tests are shown in figures 6-9. The two receive channel magnitudes (decibels) and phases (radians), as well as the range interferometric phase (radians), are shown as a function of slant range (distance from the radar) and time. The x-axis is distance (range), while the y-axis is time. The radar was not

Figure 4. Radar view of slope with man climbing; inset shows transmit antenna (left) and receive antennas (right).

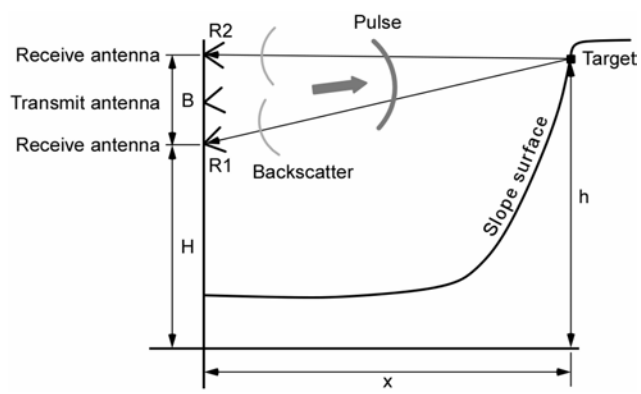

Figure 5. Geometry of two-antenna system for elevation modeling.

scanned as it would be to monitor the entire slope; the images represent a topographic slice along the radar beam from the bottom of the slope to the top over the footprint width of the beam (about 4 m). In figure 6, the vertical band near 0 m is the result of the radar interacting with itself, the ground and the truck; this can be ignored. The band between 20 m and 30 m is the face of the gravel

slope. Note that in the later figures, the radar self-interaction occurs at about 10 m and the slope face is between 30 m and 40 m as a result of a change in radar settings.

In the baseline interferometric image (figure 6, bottom), the slope is unchanged over the time of the scan as shown by the uniform vertical bands (with minor phase variations) –elapsed time goes from 0 seconds at the top of the image to more than 9 seconds near the bottom. The bands represent the static topography of the slope as shown by phase differences that result from the different path lengths for return signals to the two vertically separated receive antennas. The phase values here are unimportant but result from interaction of radar frequency and the angle of the slope across the range bins.

Figure 7 shows the radar response of a softball-sized rock striking halfway up the slope at about 6 seconds. The static profiles of the slope before and after the impact demonstrate the sensitivity of the radar to even very small changes in the surface. The difference in the profiles shows that a lasting change occurred on the slope.

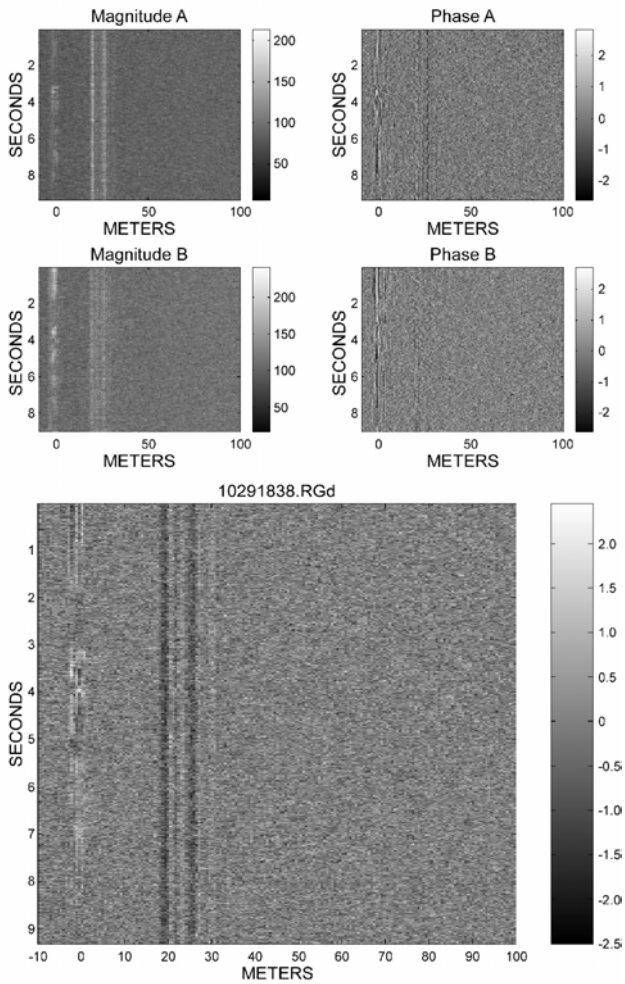

Figure 6. Baseline test with no displacement; magnitude and phase of each receive channel as a function of time (top), range interferometric phase showing self interference near 0 m and return from the slope at about 20 to 30 m (bottom).

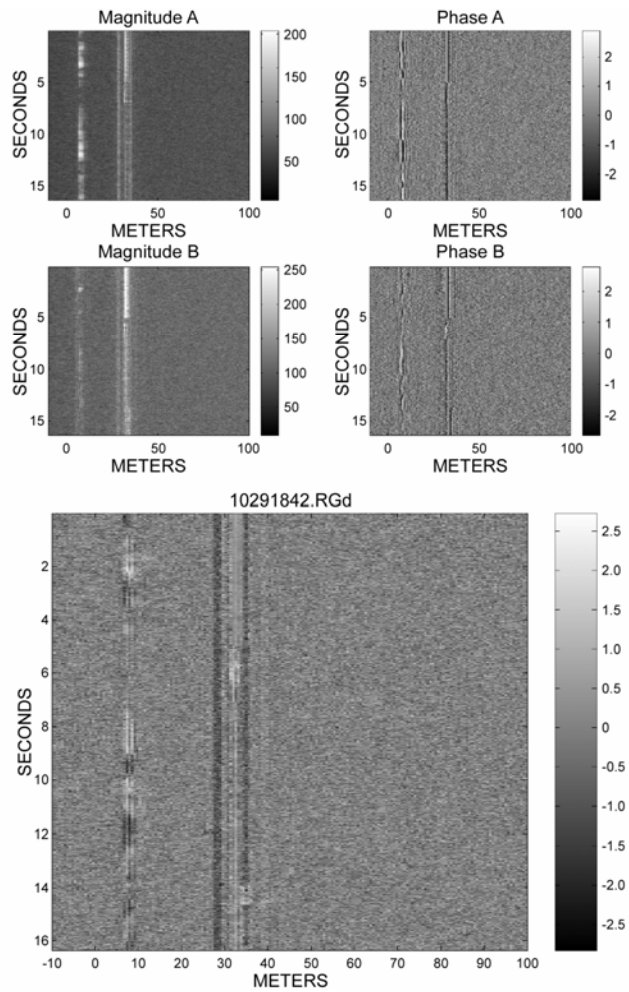

Figure 7. Rock thrown onto slope at about 6 seconds; magnitude and phase of each receive channel (top), range interferometric phase (bottom).

Figure 8 shows the progress of a man climbing the slope as the change in phase moves from nearer to greater range, from the left of the slope bands near the top of the image diagonally toward the right over a period of less than 20 seconds. Figure 9 shows the man descending the slope with the phase change moving closer to the

instrument (right to left diagonally) with time. Note the difference in static slope profiles that reveals the surface change before (e.g. 5 seconds) and after his passage (30 seconds).

A closer look at the interferometric phase plot for data shown in figure 9 provides a method for measuring the displacements detected during the test (figure 10). Image processing software (Envi 3.2) was used to quantify the phase scale and radar return data by resolving numeric values pixel by pixel. The value of the interferometric phase is shown in the scale at the right of figure 10, extending between approximately -3 and +3 radians and encompassing the range of gray-scale color values from 0 to 255. Each pixel in the image array has x and y coordinates and an associated data value (Dv) corresponding to this scale. For the interferometric phase at 0 radians Dv =127, at the middle of the color range. Lighter colors (higher Dv) have a limit of Dv=255 at a positive interferometric phase of $+\pi$ radians; darker colors (lower Dv) represent a negative a phase to Dv=0 at $-\pi$ radians. A Dv change of 42 represents a phase change of one radian, yielding the following relationship:

Phase (Φ, radians) = (Dv – 127)/42 and
Phase change ($\Delta\Phi$, radians) = ΔDv/42.

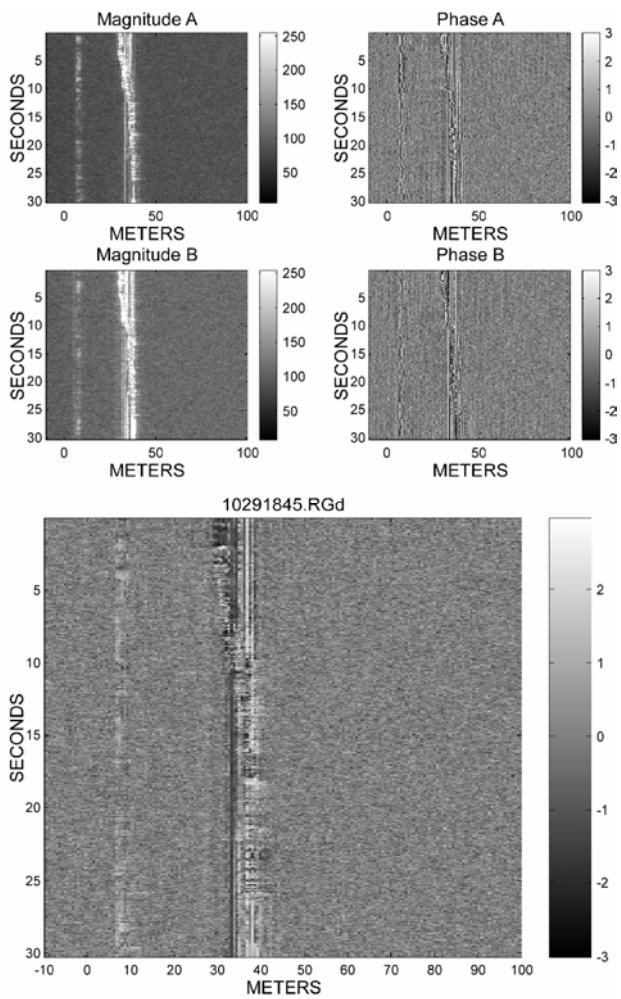

Figure 8. Man ascending slope; magnitude and phase of each receive channel (top), range interferometric phase (bottom).

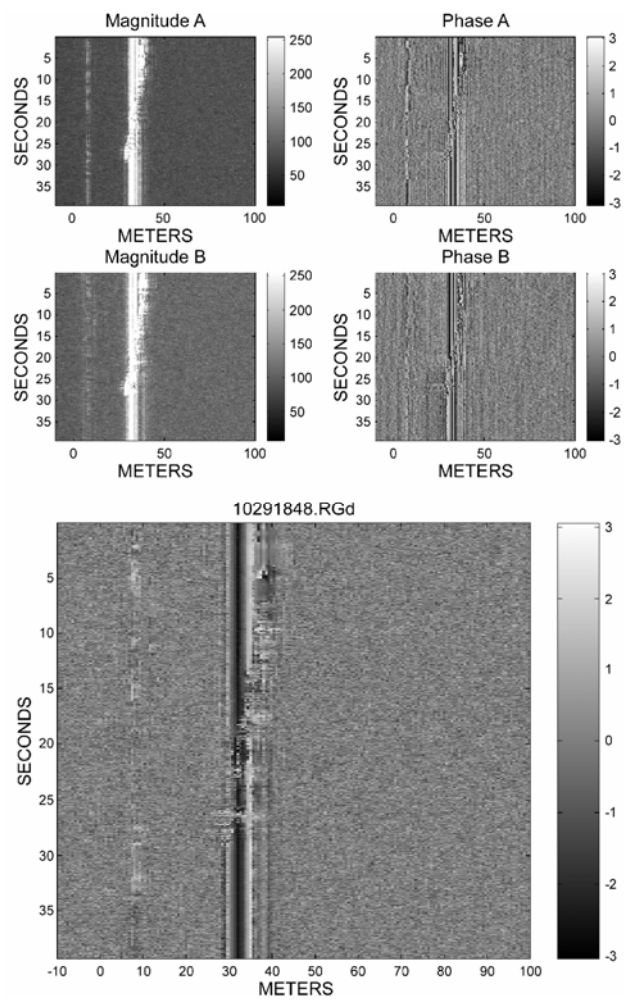

Figure 9. Man descending slope, magnitude and phase of each receive channel (top), range interferometric phase (bottom).

Phase data are plotted by range in horizontal bands every 0.05 seconds down the image (y axis). Range values (x axis) are grouped in segments averaging 4.3 pixels wide corresponding to the 60 cm instrument resolution.

A section of the radar image (box in figure 10) was enlarged to analyze incremental displacements on the slope. For the column of data at 32 meters (vertical line in figure 11), Dv were recorded over the interval from 13 seconds to 26 seconds and the difference between each succeeding pixel, sampled at 0.05 seconds, was computed. This difference represents the interferometric phase change over the sample increment.

For interferometric radar with separate transmit and receive antennas, displacement is related to phase change by the formula:

$\Delta d = (\Delta\Phi * \lambda)/2\pi$

where Δd is displacement (cm), $\Delta\Phi$ is phase change (radians), and λ is radar wavelength (cm). Wavelength of the 9.9 GHz INSAR radar is 3.03 cm. Displacement that occurred from one time increment to the next is computed by converting the Dv difference between pixels to phase change then using the above formula. For example, between 18.30 seconds and 18.35 seconds, Dv changed from 177 to 9 ($\Delta Dv = -168$), corresponding to a phase difference of -4.00 radians. From the equation, net displacement between those two pixels is:

$\Delta d = (-4.00*3.03) / 2\pi$ or

$\Delta d = -1.9$ cm.

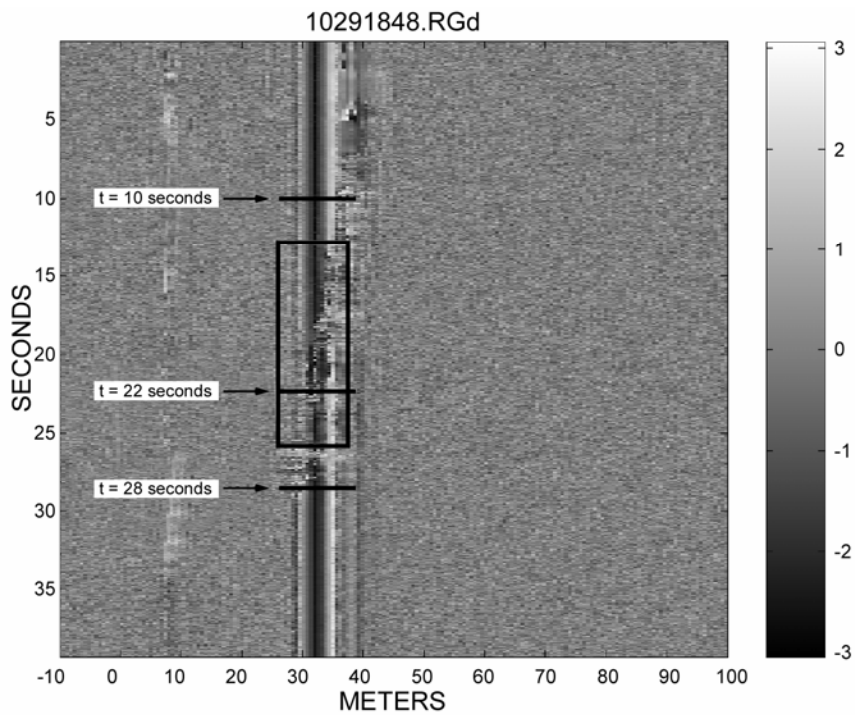

Figure 10. Range interferometric phase image showing data analysis segments.

Table 1 Summary statistics for segments of phase image shown in figure 10.

Test segment	Baseline Prior to Displacement (Before)	Active Displacement (During)	Stabilizing in new configuration (After)
Time interval, s	13.0 thru 17.45	17.50 thru 23.14	23.78 thru 25.59
Minimum, cm	-0.56841	-2.59195	-0.23873
Maximum, cm	0.30694	2.56922	0.32968
Range, cm	0.87535	5.16117	0.56841
Sample Variance, cm	0.01120	1.43829	0.01914
Standard Deviation, cm	0.10585	1.19929	0.13834
Count	83	107	35

Negative displacement denotes movement toward the instrument (downslope). Note that the observed phase corresponds to the average phase change over the illuminated resolution element on the slide face and thus represents an average displacement. While it is possible to relate the phase change in the image to the exact volume of material moved, our interest in this experiment is primarily in detecting change due to precursor movements of the slide face.

Apparent displacement for each successive time increment along the sample line is shown in figure 12. The trace shows an inactive interval prior to the slope disturbance ("before"), a period of change while the man descends the slope ("during"), and a restabilization of the slope following the traverse ("after"). Table 1 lists summary statistics for these intervals. Baseline data shows that the system configuration tested has about a 0.2 cm displacement resolution (two standard deviations above the mean) and a signal to noise ratio (variance) of 128. The 3 cm maximum possible displacement recorded by this method is determined by the radar wavelength and depends on accurate phase unwrapping. Measuring cumulative displacement across multiple time increments in this simple experiment is not possible because of inherent phase ambiguity in the data for this particular setup.

Phase data in the range direction allows comparison of the slope profiles during the test interval. The phase at each range increment from about 26 to 40 meters was computed from Dv for 0.1 second intervals at about times t=10 seconds, t=22 seconds, and t=28 seconds; before, during, and after the man traversed the slope, respectively (see figure 10). The results of the analysis are shown in figure 13. The "before" and "after" data show similar profiles, which can be thought of as baseline data; differences reflect a lasting change in the slope geometry caused by the man's passage. The "during" data show distinct interferometric phase shifts compared to baseline profiles as a result of active displacements in the radar footprint.

Implementation of a scanning mechanism for horizontal sweeps of the slope with the fan-shaped beam would provide

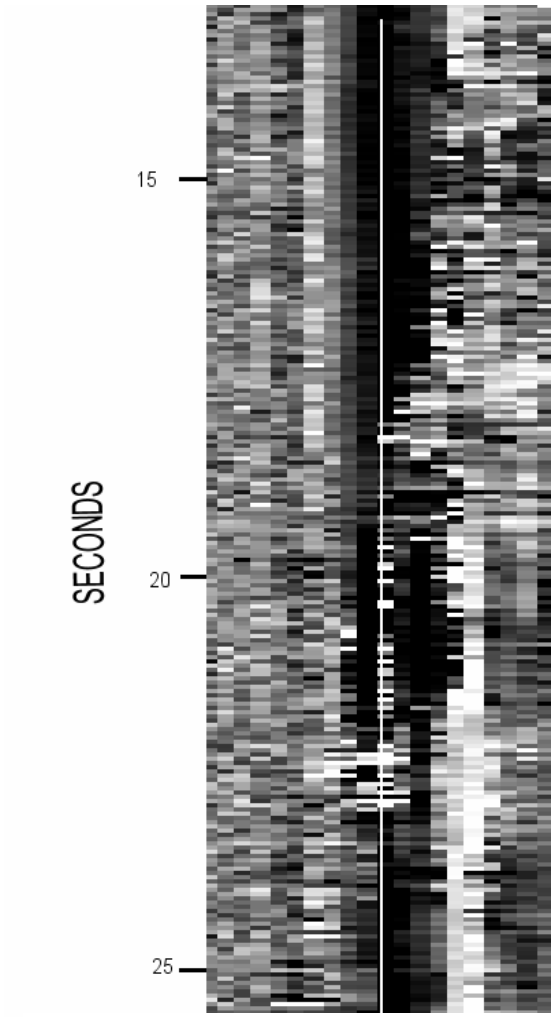

Figure 11. Interferometric phase image from 13 to 26 seconds showing data source at 32 m for time/displacement analysis (vertical line).

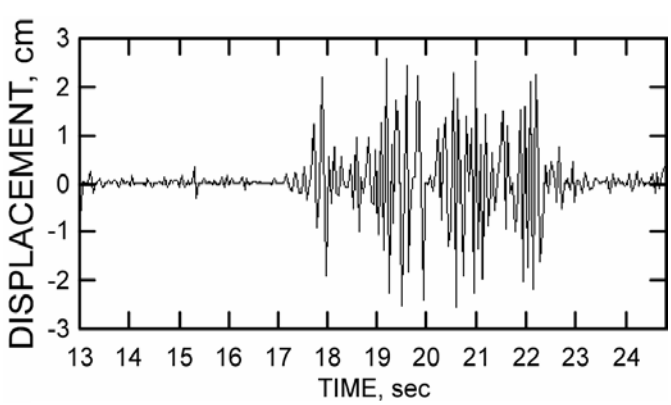

Figure 12. Displacements on the slope at a range of 32 m from the radar.

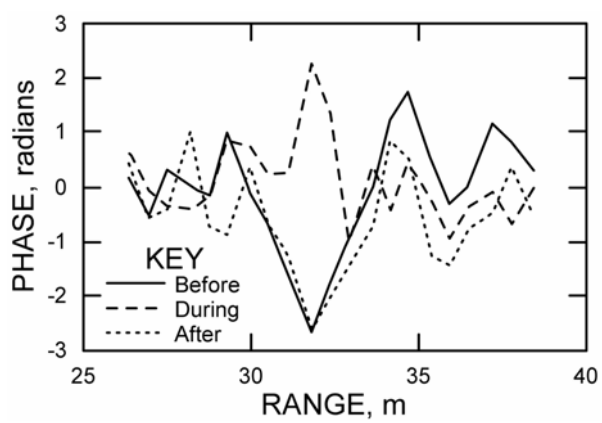

Figure 13. Phase profiles along range from the bottom to the top of the slope during three intervals.

three-dimensional data to assess the stability of the mine highwall. Processing would allow automated computation of displacements, velocities, and accelerations for each point on the slope. Data could be used to generate a two-dimensional image of the highwall to assist in analyzing failure mechanisms.

CONCLUSIONS

Ground-based interferometric radar has the potential of measuring displacements over large areas of mine high walls at unprecedented resolution. Prototype versions using the technology in a number of approaches have been introduced at several locations. Based on our simple experiments, range interferometry clearly has the desired sensitivity and thus is a viable approach for low-cost slope monitoring. Further development is required, however.

Design development to support longer-term experiments will need to address such issues as scanning rates, alarm detection thresholds, the effects of weather, and methods to prevent interference from ordinary mining operations (e.g., movement of equipment). In particular, the effects of weather on radar return from the surface are critical. Moisture on the rock face will likely change the scattering center that could be interpreted as changes on the monitored slope. Detection algorithms must be sufficiently sophisticated to provide reliable discrimination between changes in atmospheric conditions versus actual displacements. The radar's long-term phase stability and effects of events such as snow and ice accumulation on benches or water running down the highwall face need to be tested. Carefully conducted monitoring of real high wall faces with independently measured movement will be essential for ultimately validating this technology.

The objective for further work will be to develop a practical ground-based interferometric radar instrument for measuring small displacements on rock slopes as an aid to assessment of their stability. Such an instrument would be:

Robust and easily transportable
Simple enough to be operated by non-experts
Reasonably priced
Able to present displacement data on 2D or 3D images of the slope
Autonomous in operation where continuous monitoring is required
Able to measure displacements of less than 1 cm
Capable of a spatial resolution approaching 2 m
and, able to monitor rock slopes from a range of at least 1 km.

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