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A novel radar-based system for underground mine wall stability monitoring

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Abstract

Ground collapse is a serious issue for underground mining, and currently there is a lack of remote sensing monitoring systems to perform real-time deformation monitoring. Extensometers can be used in several situations; however, this instrumentation obliges the user to work close to unstable areas, thus a remote monitoring system would offer noticeably improved safety conditions.

IDS GeoRadar, a provider of radar technology for slope monitoring in surface mining, recently developed an interferometric radar system for underground operations to monitor ground fall precursors and provide early warning in order to evacuate people and machinery at risk. This radar system is able to monitor slow deformations to produce preliminary risk assessment on potentially exposed instabilities in underground areas.

The new radar system is able to provide sub-millimetre displacement accuracy at a spatial resolution of tens of centimetres, with updated displacement information every 30 seconds.

In this paper, the system is described, along with performance test results and assessment of monitoring performances in real scenarios.

Keywords: *radar, interferometry, deformation, rockfall, stability, safety, monitoring, underground, mining*

1 Introduction

Underground mines represent one of the most difficult, tough and challenging environments for humans to work in. Although safety is considered one of the key issues, limitations in feasible technological solutions, cost, and the very nature of underground mining have restricted the development of a remote monitoring system to ensure full safety for the miners with respect to monitoring and prediction of ground collapses.

Mine Safety and Health Administration (2015) reports that in the years 2011–2015, 31% of fatalities in underground mines in the United States of America were related to fall of ground accidents, while only 13% of fatalities in surface mining were related to ground instabilities (Figure 1).

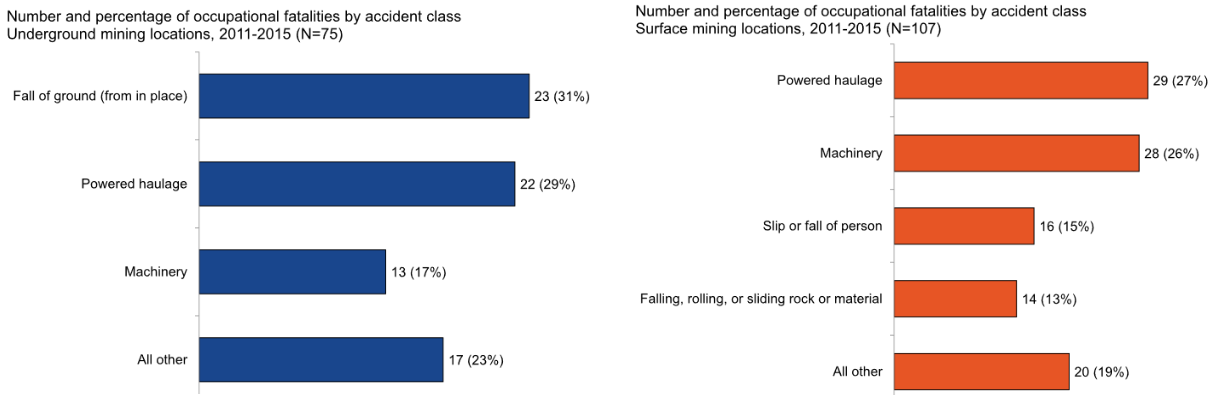

Figure 1 Occupational fatalities by accident class, 2011–2015 (Mine Safety and Health Administration 2015)

Also, in highly automated underground mines, where the human presence is reduced to the minimum, ground falls represent a major damage risk for the expensive machinery used and for the interruption of operations.

The use of monitoring systems to detect wall movements in surface mining has emerged in the last ten years as a standard work and safety practice. The development and optimisation of remote monitoring systems, with particular regard to interferometric radar technology, has greatly contributed to the anticipation of slope movements and contributed to the reduction of incidents and fatalities related to slope failures.

The same has not happened for underground mines, where deformation measurement is in most cases still devoted to contact sensors such as extensometers, strain gauges and fibre optic systems, which can provide only point information. To date, technological limitations have not allowed for the development of effective remote monitoring systems capable of providing accurate measurement of small deformations over extended, continuous spatial areas for the early detection of ground collapse in underground mines.

The new Hyper Definition Radar - Underground (HYDRA-U) radar system, designed by IDS GeoRadar, has been developed to address the need for a high-accuracy, portable and contactless monitoring system able to provide real-time information on surface deformations over large portions of underground openings. HYDRA-U has been tested in a real underground mining scenario to measure the radar performance in terms of spatial resolution and displacement measurement accuracy.

2 Deformation monitoring in underground

Ore extraction by an underground mining method involves the generation of different types of openings, with a considerable range of functions. Irrespective of the mining technique adopted for ore extraction, it is possible to specify four common objectives for rock mechanic engineers (Brady & Brown 2005):

- To ensure the overall stability of the complete mine structure adjacent to country rock.
- To protect the major service openings throughout their designed duty life.
- To provide secure access to safe working places in and around the centres of ore production.
- To preserve the mineable condition of unmined ore reserves.

The engineering mechanics problem posed in underground mining is the prediction of the performance of the excavation for improved support design and hazard assessment.

As reported by the Mines Occupational Safety and Health Advisory Board (1997):

> *"Ground control may be described as the ability to predict and influence the behaviour of rock in a mining environment, having due regard for the safety of the workforce and the required serviceability and design life of the openings. Successful ground control is an integral part of any well managed underground mining operation and is primarily concerned with rock stability and instability issues that result from mine development and the economic extraction of ore."*

Several studies evidenced the importance of monitoring unstable areas in order to assess the exposure to ground fall risks, such as Szwedzicki (2008) and Brink et al. (2008).

Geotechnical engineers make use of LIDAR (terrestrial laser scanners) mainly for mapping the underground openings. LIDAR can be used to monitor slow, long-term movements or convergence, and provide statistics about the volume, location and size of rock mass involved in fall of ground events, but it does not provide early warning on the onset of movements and the capability to set up alarms before the ground fall takes place (Kukutsch et al. 2015; Slaker 2015). Advanced laser systems can be mounted on machinery and provide change detection information of the scenario by performing rapid scans. The system, however, still faces the low accuracy of laser technology in the measurement of displacement (mm to cm) and can be configured mostly as post-event information.

Contact sensors include a variety of tools: extensometers, strain gauges, fibre optic systems and microseismic receivers (Kumar et al. 2011; Moffat et al. 2015; Maleki & McVey 1988). These sensors, although very accurate, pose the same limitations as in surface mining:

- Point-wise/localised information.
- Need to access the area for installation.
- Indirect measurement (microseismic).

The HYDRA-U system (Figure 2) is a remote sensing radar system able to monitor in real time, sub-millimetre deformations of the illuminated surface over wide areas and is able to trigger early-warning alerts in case of impending collapses. From a technical point of view, the measurement is performed by high-frequency interferometry radar working as a rotating synthetic aperture radar (ArcSAR), which provide a displacement heat map of the monitored scenario. The radar system is not intended to replace, but rather supplement, existing measurement technologies providing information in the following fields of application:

- Real-time stability monitoring of openings and provision of early warnings at the onset of impending collapses.
- Assess the performance of ground supports and reinforcements.

Figure 2 The HYDRA-U monitoring system

3 System description

HYDRA-U has been specifically developed for real-time monitoring of underground openings, aiming at improving safety of workers and reducing the risk of unexpected collapses.

The system can be divided into two main parts: the acquisition unit, and the supply and control unit (Figures 3 and 4).

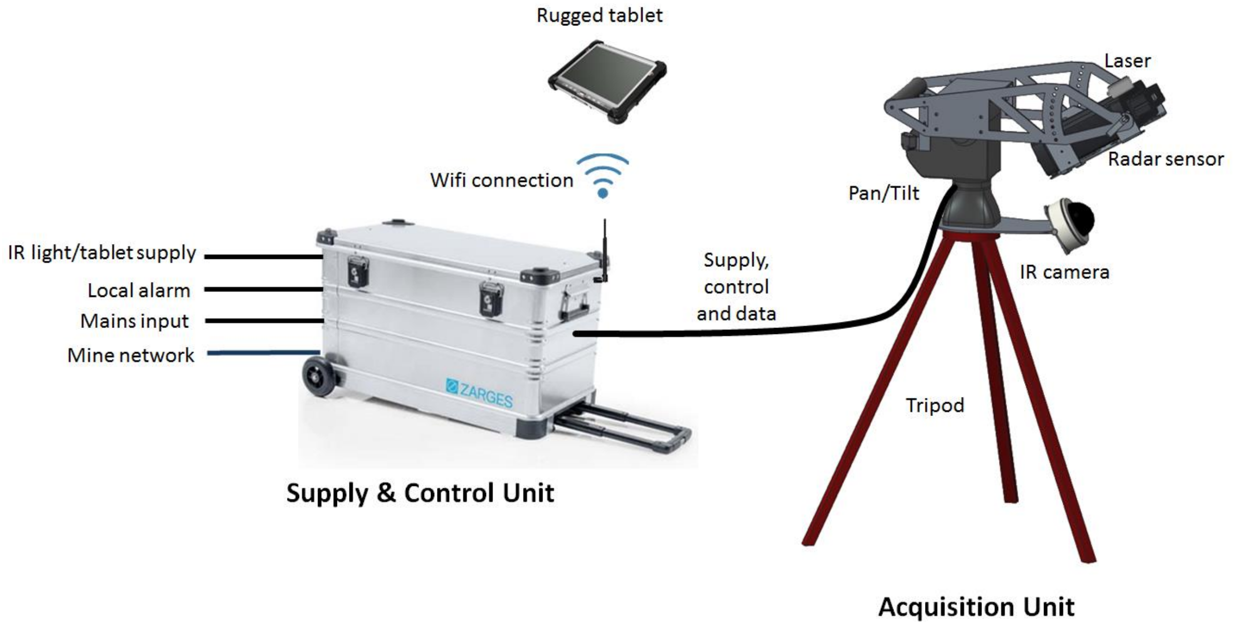

Figure 3 HYDRA-U system composition

Figure 4 HYDRA-U typical configuration in the underground environment

The acquisition unit consists of a pan/tilt module which rotates the radar sensor in order to perform the SAR acquisition, while an infrared camera continuously provides visual feedback of the monitored area, even under complete darkness. A laser unit is used to survey the 3D model of the monitored area, on which the heat map produced by the radar is overlaid.

The supply and control unit (IP65 rated) provides power to the acquisition unit, processes the radar data and provides the network interfaces to remotely control the system.

Both acquisition software (Controller) and processing software (Guardian) run on an industrial computer integrated inside the supply and control unit.

The real-time displacement/velocity heat maps can be visualised onsite on a rugged tablet in wireless connection, or remotely on a desktop PC.

The HYDRA-U system is designed to be transported by a single person. In transport mode, each box weighs less than 25 kg and all transport cases are equipped with off-road wheels.

HYDRA-U is a remote sensing monitoring system that does not need any reflectors or instruments to be placed on the rock face. With a maximum scan range of 200 m from the point of installation, it is possible to monitor portions of the openings that cannot be reached or made accessible to contact sensors.

The main technical features of the system include:

- Spatial coverage: horizontal field of view of 100° and vertical of 30°. Radar head can be tilted ±30° to extend the maximum reach of the system in the vertical alignment (Figure 5).
- Scan speed: a new acquisition is performed every 30 secs.
- Spatial resolution: monitored area is discretised in resolution cells of 0.20 × 0.12 m for distances up to 10 m from the radar and 0.20 × 0.60 m at 50 m.
- Accuracy: line-of-sight displacement with an accuracy better than 0.1 mm, providing an updated displacement heat map immediately after every acquisition.
- Survey: the 3D surface model of the monitored area is created by means of an integrated laser sensor with 1 cm accuracy on distance measurement.

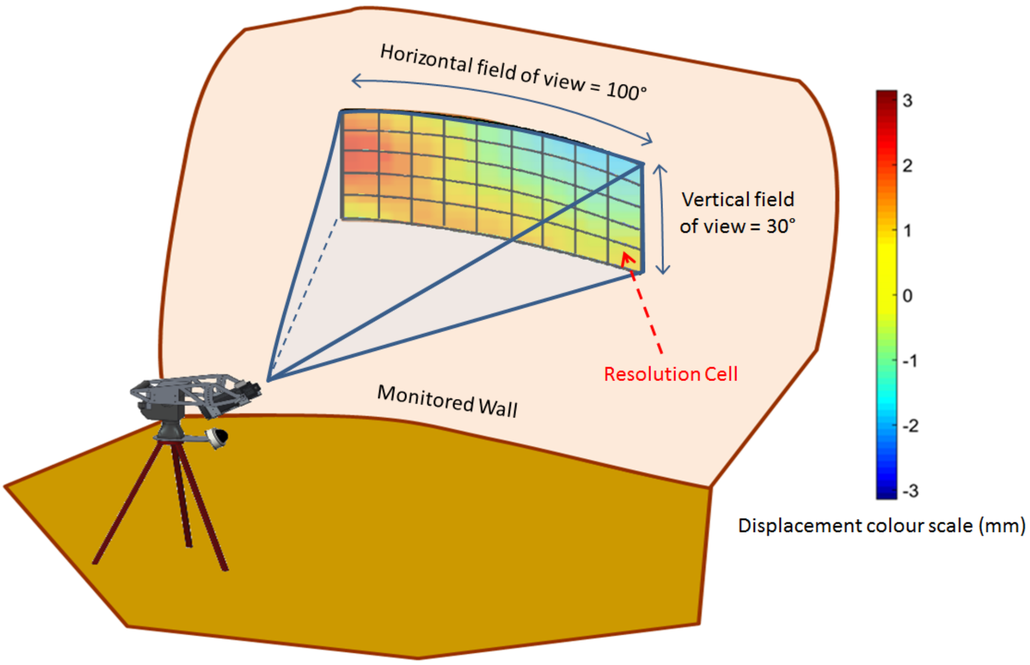

Figure 5 HYDRA-U field of view and resolution

After every acquisition (30 secs) updated information is visualised by means of an interactive heat map that can be customised to show displacement, velocity and acceleration (Figure 6). Time series graphs for specific points or areas on the map can be extracted and visualised in real time, side-by-side to the maps.

In order to help the interpretation and localisation of moving areas, the displacement heat map is draped onto the 3D model of the monitored surface surveyed by the integrated laser sensor.

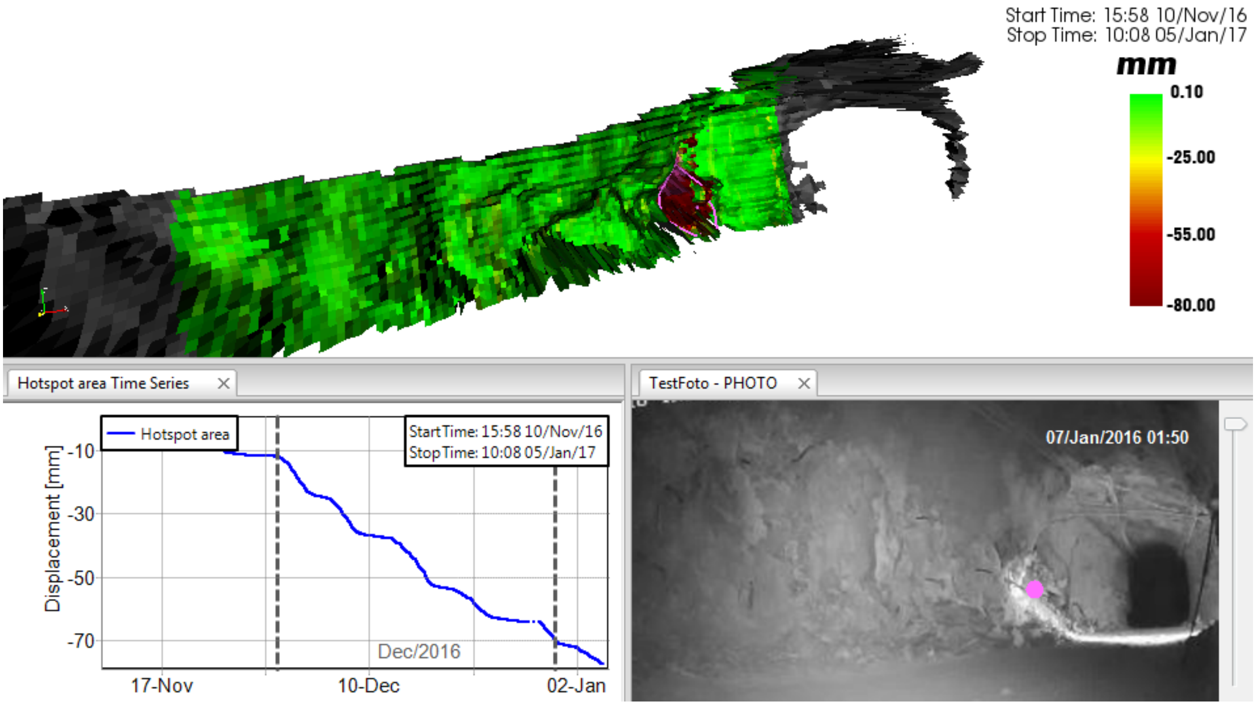

Figure 6 HYDRA-U displacement map: The radar displacement data are overlaid onto a 3D surface model produced by the integrated laser scanner

To have a real-time visualisation of the current level of hazard of the monitored area, alarms can be added into the project in the visualisation software. Alarms are set based on velocity thresholds, which can be unique for the entire scenario or area-defined, in order to consider different geotechnical/geological area or movement direction. Each alarm activates a specific pop-up on the local tablet where the real-time radar data is visualised; the alarm may also consist in the activation of a local audio/visual siren, in the transmission of a specific email message to a remote device or an SMS text message. The setting of alarms can be merged with the trigger action response plan (TARP) and create levels for geotechnical hazard and mine control.

3.1 Spatial resolution

The HYDRA-U system is designed to remotely measure displacements with sub-millimetre accuracy. Like any other radar system, HYDRA-U is an instrument able to detect the presence of objects and measure the relative distance between the apparatus and the object. HYDRA-U performs this task by emitting continuous radio waves with a variable frequency (LFMCW, linear frequency modulated continuous wave radar) and comparing the received echo frequency with the transmitted wave: the difference between the two frequencies is proportional to the two-way flight time from the apparatus to the target and so to the distance between them (Bernardini et al. 2007).

Range resolution, i.e. the ability to distinguish close targets along the line-of-sight of the radar, depends on the transmitted bandwidth, and for HYDRA-U this is equal to 0.20 m.

Cross-range resolution, i.e. the ability to distinguish close targets perpendicular to the line-of-sight of the radar, is obtained by means of the SAR technique. However, differently from other IDS GeoRadar systems for slope monitoring in open pit mines (IBIS) (Escobar et al. 2013; Farina et al. 2011; Mononen et al. 2016;

Ramsden et al. 2015), HYDRA-U uses the motion of the radar antenna over a circular trajectory to provide finer angular resolution than conventional beam-scanning radars. Signal processing of the successive recorded radar echoes combines the recordings of multiple antenna positions. This process forms the synthetic antenna aperture, and allows the radar to achieve a higher resolution than otherwise possible with a given physical real antenna.

The circular trajectory used for obtaining the synthetic aperture (often denoted as ArcSAR) permits a more compact design of the radar and a wider angle coverage with respect to the traditional linear SAR. These features prove particularly crucial in underground mine environments, where transportability and compactness of the system is a must, and where the reduced available distance between the system and the wall to be monitored requires a wide field of view.

The combination of range and cross-range resolution allows the creation of a bi-dimensional image, where each pixel is a measurement point providing real-time displacement information. The superposition of the range–cross-range image on the digital elevation model registered by the integrated laser sensor produce a 3D deformation map.

3.2 Deformation measurement

HYDRA-U measures the amplitude and the phase of the signals reflected by the monitored scenario; the amplitude provides information about the strength of the reflected signal, whereas the phase can be related to the relative movement of the target towards or away from the radar. The displacement magnitude is obtained with the interferometric technique, which relates the phase measurement difference that occurs between a first and a second acquisition (Figure 7) to the line-of-sight displacement of the monitored surface according to the following equation:

$$d = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1) \quad (1)$$

The accuracy on the displacement measure d depends on the accuracy on the phase measure φ and on the value of the transmitted signal wavelength λ. HYDRA-U is capable of providing displacement measurement with an accuracy better than 0.1 mm, by combining a very high phase measurement accuracy (< 0.1 radians) to a short wavelength (4 mm).

After any acquisition, HYDRA-U gives a displacement measure of any resolution cell within the field of view of the system.

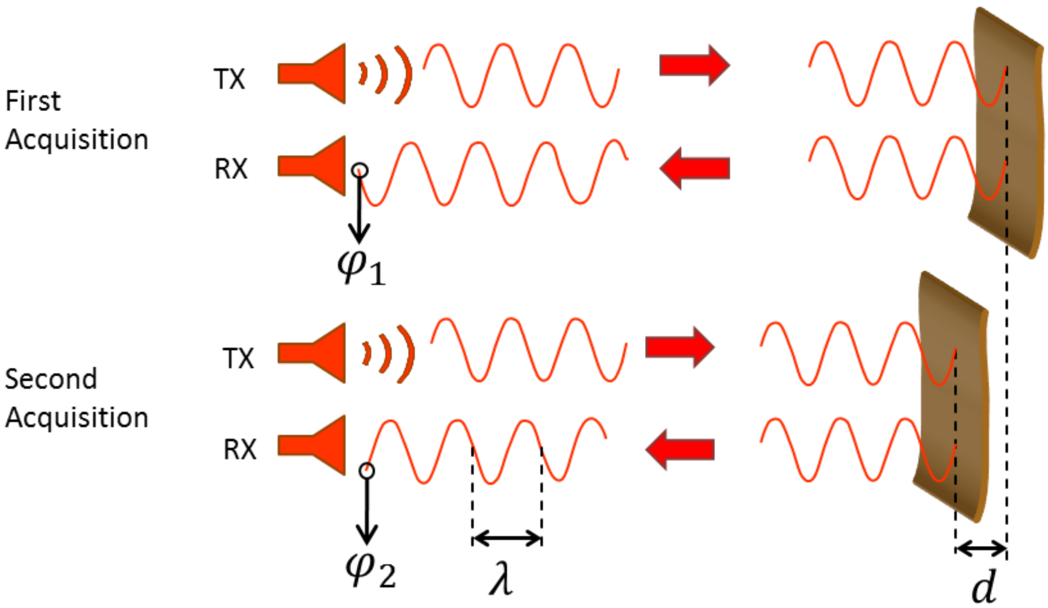

Figure 7 Displacement measurement using radar interferometry

4 Laboratory test

In order to verify the expected monitoring performance, two laboratory tests were performed using a metal corner reflector representing a point-wise target (Figure 8):

- Corner reflector resolution test: a corner reflector is used as point-wise target to measure the spatial resolution of the system.
- Corner displacement test: a corner reflector is moved by means of an electrical motor by known quantities to verify the accuracy of the radar displacement measurement.

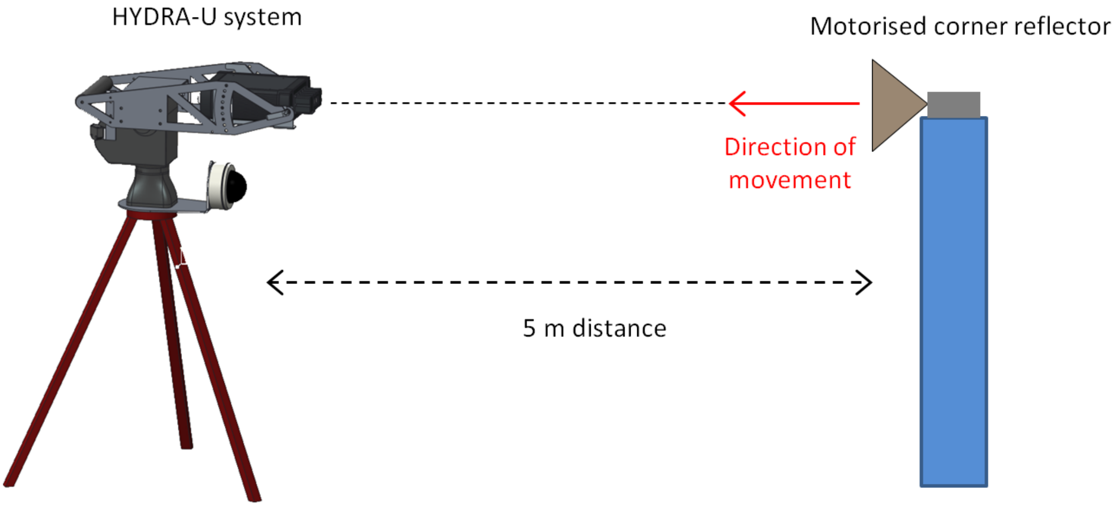

Figure 8 Laboratory test configuration

4.1 Data and results

The laboratory test data using the corner reflector provides information about the spatial resolution of the system. It is possible to retrieve these data by measuring the -3 dB width of the range and azimuth profile of the reconstructed corner reflector power map assuming that the reflector acts as a point-wise target.

As shown in Figures 9 and 10, the test confirmed range resolution of 0.20 m and azimuth resolution of 12 mrad.

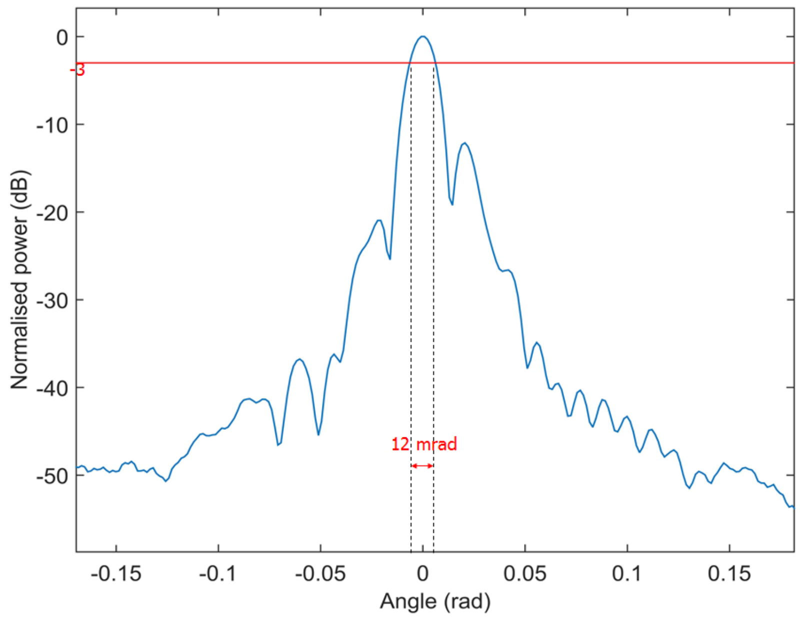

Figure 9 Azimuth profile of the corner reflector

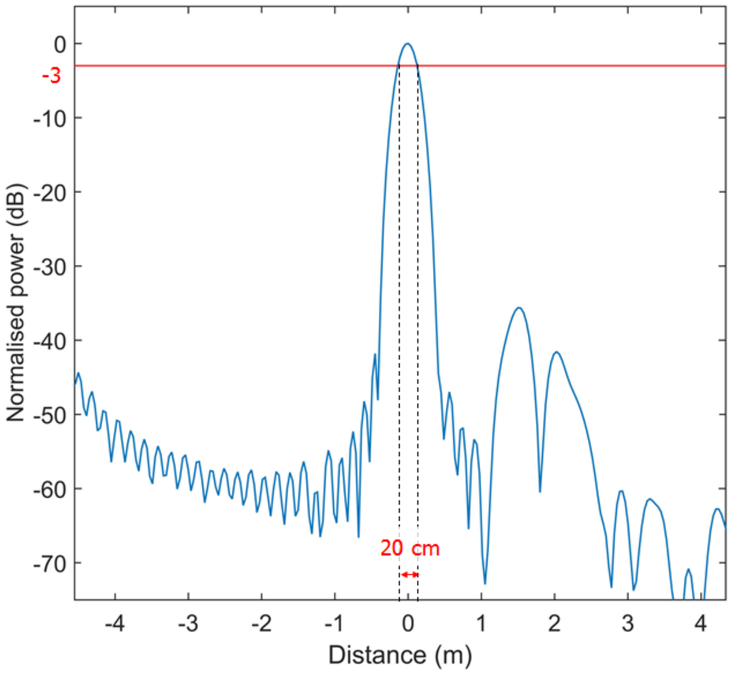

Figure 10 Range profile of the corner reflector

In the second test, the motorised corner reflector was moved in two different steps: ΔS_1 = 0.5 mm and ΔS_2 = 0.2 mm (Figure 11).

The HYDRA-U system continuously acquired data during the corner movement to measure the corner displacement. The measured data resulted in: ΔS_{1M} = 0.471 mm and ΔS_{2M} = 0.191 mm.

The displacement measurement accuracy can therefore be computed as the average error between radar-measured and expected displacement, thus providing an instrument accuracy of 0.019 mm.

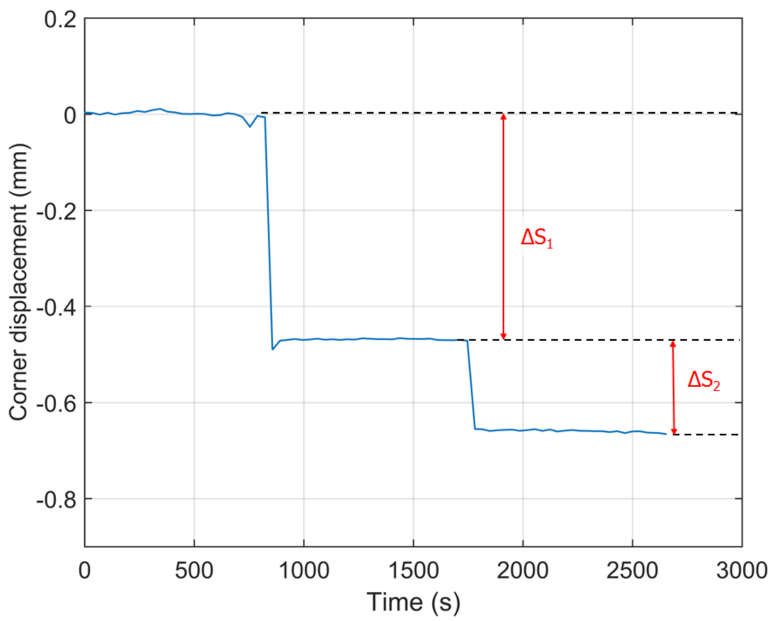

Figure 11 Radar-measured corner displacement

In summary, the laboratory test with corner reflector matched the radar capabilities of 12 mrad angular resolution, and 0.20 m range resolution. The displacement accuracy of the radar in a laboratory environment is in the order of 0.02 mm.

5 Field application

The system has been deployed in an underground mine to monitor a portion of a tunnel at the caving undercut level that had experienced several rockfalls.

With a granitic rock type in an underground mining environment, the amount of visual displacement is very minimal and limited to roof collapse or rockbursts, especially with a panel caving mining method. Installing contact monitoring systems in areas of concern can be difficult since access to the area is dangerous and sometimes even closed off to humans. The current underground mining industry standard is the visual inspection of tunnels and by the use of laser scanners, which do not allow for early warning detection of small displacements. The operational hazards increase when there are access points or infrastructure located near an unstable area. If an early warning monitoring system can be deployed, mine personnel can evacuate to a safe area when precursor displacement occurs and before a roof collapse closes access points and damages equipment.

5.1 Data and results

The tunnel, located at approximately 1 km below ground, is 4.5 m high and excavated in granitic rock. The radar system was installed with the central direction of view forming an angle of 40°, with respect to the vertical wall at approximately 4.3 m distance from the wall (Figure 12).

Before starting the radar acquisition, the 3D surface model of the monitored area was automatically surveyed by the HYDRA-U for subsequent overlay of radar heat maps.

From the first day of monitoring (10 November 2016), the HYDRA-U radar picked up a moving area that is shown as a red spot on the displacement heat map (Figure 13).

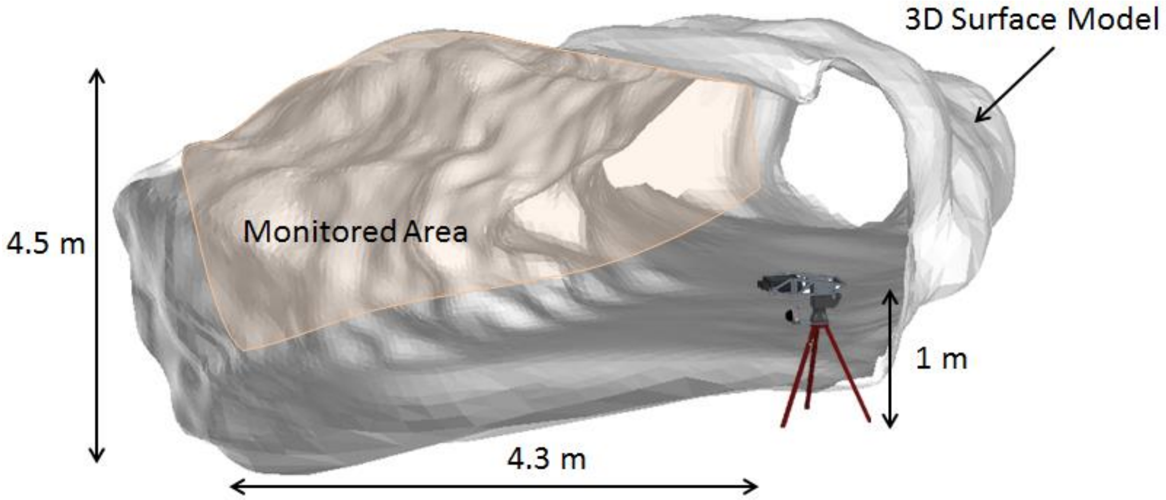

Figure 12 Field acquisition geometry

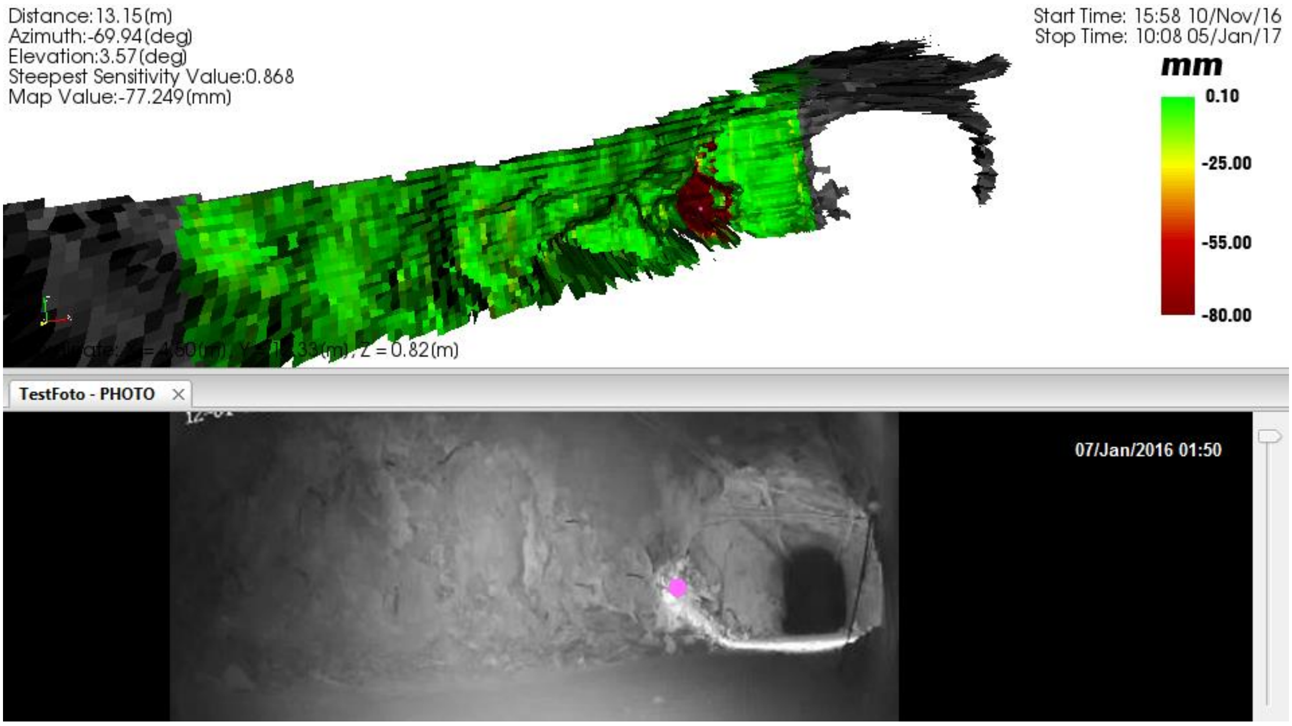

Figure 13 HYDRA-U displacement map. The radar displacement heat map is overlaid onto a 3D surface model produced by the integrated laser sensor

The moving area (Figure 14) shows a developing trend with marked accelerations and periods of relative steadiness. The whole portion of the rock face has undergone a total displacement of 77 mm over two months. Local engineers correlated the time intervals where the movement slowed with periods of no mining activity, while the movement constantly increases during normal working days. This relationship is evidence of the impact of the ore extraction process as a trigger for the movement in the unstable area.

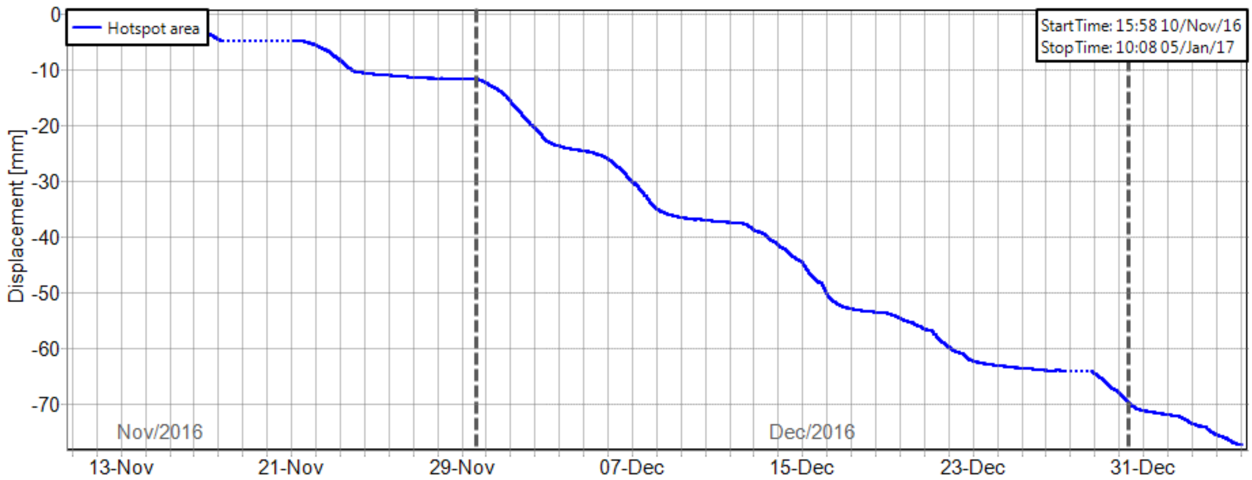

Figure 14 HYDRA-U underground displacement time series of the moving area (10 November 2016 to 5 January 2017)

Figure 15 shows the displacement data collected during 16 December 2016 from 1:00 pm to 3:00 pm, sub-millimetre displacement trends can be clearly detected in the time series.

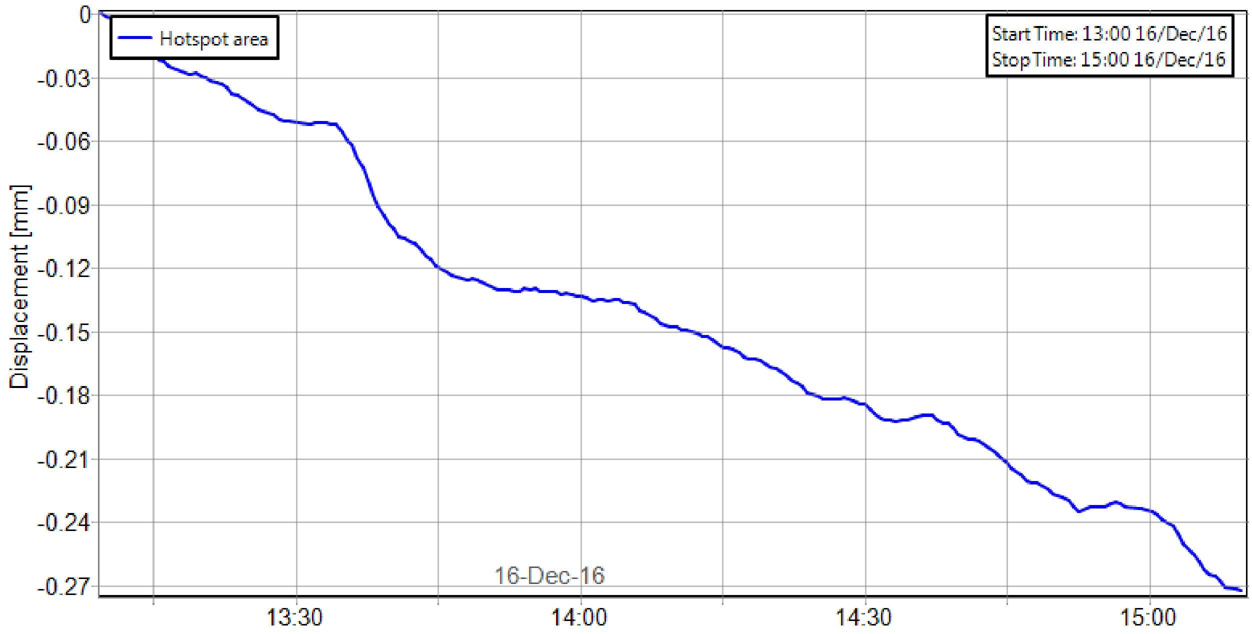

Figure 15 Detail of the displacement time series of the moving area (16 December 2016, from 1:00 pm to 3:00 pm)

6 Conclusion

The performance of the HYDRA-U radar system has been assessed by means of laboratory tests and an in situ monitoring campaign in an underground mining environment. The system was able to monitor in real-time the surface deformations of a vertical wall located in an underground access tunnel.

Thanks to new technological achievements, such as the use of interferometric millimetre wave technology, the synthetic aperture obtained along a circular scan, and the ability to autonomously reconstruct the geometry of the monitored scenario, HYDRA-U opens the perspective of bringing the radar technology, already extensively used in open pit mines, to underground mines for the early warning of wall instabilities.

Acknowledgement

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