IBIS-M, an Innovative Radar for Monitoring Slopes in Open-Pit Mines

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Abstract
Slope monitoring in the surface mining industry has become routine practice, supporting mining staff in the management of geotechnical risks. Interferometric radar technology has emerged in the last ten years as a leading edge tool for this purpose. The success of interferometric radar technology is attributed to its ability to rapidly measure slope movements with sub-millimeter accuracy over wide areas in almost any weather condition, obviating the need to install artificial reflectors. As a result, slope monitoring radar is effectively used for the provision of alerts in the event of progressive movements that can potentially lead to mine slope failure. Slope stability monitoring radar is commonly used by prominent mining groups internationally. The first slope monitoring radar systems employed in the mining industry have been designed with parabolic dish antennas that are mechanically moved to achieve a full scan of the observed area. These designs presented several constraints, e.g. limited working distance, difficulties in historic data retention on the mine’s slope behaviour, limited spatial resolution, stability problems induced by strong wind, etc. IDS have overcome the above mentioned limitations with the introduction of an innovative radar system, known as IBIS-M. Owing to the unique radar technologies used in its design, IBIS-M is able to significantly improve the performance of slope monitoring radar by providing higher spatial resolution, longer working distances and faster acquisition time. The main technical features of the IBIS-M system are presented in this paper along with recent examples in different mining environments.

1 Introduction
Effective monitoring systems for both engineered and natural slopes is a critical component in risk management practices for urbanized areas threatened by active landslides, critical infrastructure management and mineral resources production. Radar interferometry is a well-known technology originally developed for satellite applications in order to retrieve ground displacements related to natural hazards and other physical phenomena such as land subsidence induced by oil, gas and water extraction, with a millimeter accuracy over wide areas (Rosen et al. 2000). In the last years, the same technology has been successfully implemented by using ground-based systems in order to overcome some of the limitations related to the satellite platform (e.g. low revisiting time of the available satellites and consequent temporal de-correlation of the radar signal and unwrapping problems, geometrical distortions induced by the almost vertical line of sight, etc.). Since the first scientific applications dated back to the early 2000, ground-based radar interferometry has been extensively exploited for slope monitoring, such as monitoring of landslides (Antonello et al., 2004; Corsini et al., 2006; Bozzano et al., 2008) and slope movements within open-pit mines (Noon, 2003, Harries et al., 2006). The most significant advantages of ground-based radar interferometry are related to the high accuracy of the measurements, the long-range capabilities of the technology, the limited impact of atmospheric artifacts on the measurement performances, the opportunistic character of the measurement (in most of the cases, the natural reflections
backscattered by the scenario are the measurement points) and the possibility to acquire simultaneously the response over a large number of points. As a result, slope monitoring radar is effectively used to get a better understanding of the spatial distribution of slope movements and for the provision of alerts in the event of progressive movements that can potentially lead to slope failure as well. Slope stability monitoring radar is today commonly used by prominent mining groups internationally, by civil protection authorities in developed countries and also by academics for the provision of high level consultancy to end users involved in landslide risk management.

Historically, radar systems employed in the mining industry have been designed with parabolic dish antennas that are mechanically moved to achieve a full scan of the observed area. These designs presented the following constraints:

- limited working distance from the target resulting in the need to move the radar frequently to cover the entire active wall
- consequent difficulties in historic data retention on the slope behavior
- limited spatial resolution owing to dish footprint size
- stability problems induced by strong wind
- potential reliability problems caused by numerous moving parts

The innovative radar system presented here by IDS, known as IBIS-M, has overcome most of the above mentioned limitations. Owing to the unique radar technologies used in its design and its high reliability connected to highest military standards used for its production, IBIS-M is able to significantly improve the performance of slope monitoring radar by providing higher spatial resolution, longer working distances and faster acquisition time. The main technical features of the IBIS-M system are presented in this paper along with some examples of the radar outcomes from different open pit mines.

2  IBIS-M

2.1  IBIS - Image by interferometric survey

IDS started to work on a ground-based interferometric radar in the late 90’s within a research project with local partners, among which one of IDS’s historical academic partner, the Electronic Engineering Department of the University of Firenze. The R&D project was originally aimed at developing an interferometric radar for the accurate measurement of displacement. In early 2007, after almost 7 years of research, prototyping and validation, IDS released the first generation of commercial products based on such an innovative technology. At that time the goal was to design robust, reliable and user-friendly interferometric radar in two different configurations, IBIS-S for structural applications (bridge static and dynamic testing, tower and building monitoring, etc.) and IBIS-L for landslide monitoring. In 2008 IDS started to approach the mining industry through a series of field trials with IBIS-L in open pit mines in Europe and Australia to understand the suitability of the technology to the specific needs of this market. In early 2009 IDS started the product development and validation through trials with selected users of a specific version of IBIS for mining, namely IBIS-M, officially released in early 2010. Today more than 30 IBIS-M units have been deployed in open pit mines located in 5 continents and 14 countries.

2.2  IBIS-M: Technical description

The slope monitoring radar for mining applications developed by IDS is composed by the following basic items:

- Radar unit, consisting of linear scanner, radar sensor and power supply module
- Rugged laptop housed inside the power supply module

As optional tools the system can be supplied with the following extra items:
- Radio Unit with integrated antenna to transfer the data from the radar to the mine dispatch
- High Resolution Industrial Ethernet Camera
- Diesel Generator
- Array of 4 photovoltaic modules
- Weather station

The system is supplied with two software, namely IBIS Controller, aimed at the set-up of the acquisition parameters and the diagnostic of the system, and IBIS Guardian for the data processing and output visualization. Guardian is devoted to the real time processing of radar data with automatic atmospheric corrections, and it is able to provide fully geo-referenced outputs, in terms of displacement maps and velocity maps with 3D interactive data handling (Figure 1). The software generate alarms based on the velocity data with user-defined levels and multiple alarm criteria on user defined zones. All the outputs of the software can be exported to the main common mine planning software.

![IBIS-M system components and output](image)

**Figure 1.** IBIS-M system with its main components (on the left) and a typical output of the Guardian software (on the right).

### 2.3 The innovation behind IBIS-M

The main technical differences between the IBIS-M system and the other slope stability radar available on the mining market are basically related to the type of employed radar technology and processing of the radar data. While the other slope monitoring radar are based on Real Aperture Radar (RAR) - a large parabolic antenna with a fine beam resulting in a small footprint on the ground and the consequent need to scan horizontally and vertically the slope to get a wide coverage of the observed area- IBIS-M is based on a Synthetic Aperture Radar (SAR). Spatial resolution of radar depends on the antenna beam width (inversely proportional to the antenna dimension) and decreases with the distance: to get radar imagery with high resolution (small resolution cell) is necessary to use large antennas. As there are practical constraints in enlarging the physical dimension of the antenna, SAR systems provides an alternative solution to get high resolution images using small antennas. They are based on two small horn antennas with a wide beam (usually 90° on the horizontal plane by 55° on the vertical plane) exploiting the movement of the physical antenna along a straight trajectory (linear scanner) to get a high resolution radar image of the observed scenario, thus simulating an acquisition with a physical antenna of the same dimension of the length of the synthetic aperture. By observing the same area from slightly different angles and then combining the backscattered signal coming from the different points along the path by means of
digital processing SAR system can obtain high resolution images. The cross-range or angular resolution provided by the Synthetic Aperture Radar is then combined with the range resolution, a function of the width of the used frequency band, to achieve a small resolution cell. The IBIS-M radar sensor also operates in a different frequency band with respect to the other slope monitoring radar, Ku band (17 GHz, corresponding to a wavelength of 2 cm) vs. X-band (9 GHz corresponding to a wavelength of 3 cm). The above mentioned differences results in higher performances for the IBIS-M system: a higher spatial resolution (e.g. a resolution cell of 0.5 m by 4.3m at 1 km of distance from the slope against a resolution cell of around 8.5 m by 8.5 m at the same distance with a 1.8 m wide parabolic dish), an higher accuracy in the displacement measurement thanks to the shorter wavelength of the employed radar signal(e.g. 0.1-0.2 mm along the radar line of sight in the first km from the slope and within 1 mm in the ranges of 2-4 km) and shorter acquisition time to get a full resolution image of the observed scenario (e.g. 5 minutes to cover an area of 5 km\(^2\) at 2 km of distance vs 10-15 min for real-aperture radar).

Moreover, limited moving parts of the radar and its very low power consumption make it able to dramatically reduce the use of the diesel generator relying mainly on solar power supply, resulting in a high reliability and high mechanical robustness. Finally, the use of small antennas instead of wide parabolic dishes eliminates completely the risk of wind-induced vibrations, particularly limiting in windy regions where it may result, depending on the wind speed, in noisy displacement measurements or in the need to turn off the radar to avoid damages to the system.

The other technical advances aboard of the IBIS-M radar are represented by the employed interferometric processing technique. The radar images acquired by the sensor are in fact automatically processed in real time using the state of the art of processing algorithms developed from satellite radar interferometry. The employed algorithms, developed along with one of the most important research center for satellite interferometry in the world, namely the Politecnico of Milano, allows through advanced statistics the selection of a grid of high quality pixels, namely Persistent Scatterers (PS), used to remove the atmospheric artefacts from the interferometric signal. Such an approach is based on the exploitation of the different spectral behaviour, through a time-space joint analysis, of the signal components related to displacements from the one related to atmospheric artefacts. In fact, phase artefacts generated by changes in the refraction index of the air (function of temperature, humidity and pressure) can be interpreted as false movements if not well addressed. Conventional approaches used for optical systems, such as robotic total stations and for other radar systems as well, based on the selection of points supposed to be stable and located at different ranges from the radar on which the atmospheric artefacts are estimated and then removed from all the pixels, do not work over long ranges or strong atmospheres. This is a result of the complexity of the spatial distribution of these effects and the consequent difficulties in modelling them with linear approaches. On the other hand, the algorithms developed for IBIS-M are based on the automatic estimation of the atmospheric artefacts over all the stable points contained in the radar image, identified through an automatic and iteratively updated classification, to achieve a closer and more complex model of these effects and remove them from the phase signal. Moreover, such a processing strategy does not imply the need for any atmospheric region selection done by the user (it can be difficult even for expert users to identify a priori stable points on the observed slope and furthermore a stable point can start to move after a while and vice versa). As a result, the advanced processing chain extends the operating range of the radar to far distances (up to 4 km vs 2-2.5 km of other radar) making possible to install the radar far from the production area (e.g. on the rim of the pit), leaving the radar unit installed permanently on the same position and obtaining a wide area coverage at the same time. Another significant added value of the system is represented by the possibility to stich data acquired in different time periods, through the “discontinuous” processing approach. By re-positioning the radar in the same location, thanks to a mechanical re-positioning kit, it is possible to combine data acquire in different monitoring sessions and to measure the cumulative displacement occurred between the time spanned by the two acquisitions.
3 IBIS-M in surface mining

In the surface mining industry, a comprehensive slope monitoring program, aimed at managing potential large-scale instabilities that involve multiple inter-ramp slope segments or the overall slope and able to detect at the same time local scale movements as well, should represent an integral part of every effective slope management system. This is a fundamental tool to reduce the uncertainties of the design stage of the pit and to maintain safe operating conditions for personnel and equipment. For this reason, a monitoring program should be established from the early days of the mine and maintained throughout the entire operating life of the pit.

Among all the parameters to be considered and included in an effective slope monitoring program, displacements, either surface or sub-surface components, play a crucial role. In fact, in open pit mines large failures are usually preceded by small scale slope movements, sometimes limited to few centimetres of total displacement and typically characterized by temporal evolutions ranging from several hours to several weeks. The capability of providing advanced notice over the whole slope of impending instability conditions, through the accurate and timely measurement of precursor to slope collapses clearly represents an outstanding benefit for the staff of the pit involved in the geotechnical risk management.

Thanks to the technical features of the slope monitoring radar IBIS-M described in the previous section, the system can be effectively used in the surface mining industry for different purposes.

The main reason to install an IBIS-M unit within an open pit is to get the real-time monitoring of wall movements. Early recognition of both large-scale and bench scale instability over almost all the pit walls, without the need of a priori knowledge of the moving areas (as it may happen with short range radar), allows to increase the knowledge of the slope behaviour. Covering wide segments of the pit from a single position and providing high accuracy even at very long ranges on a very fine grid of points, make possible the radar to map displacements potentially precursors of slope failures.

![Figure 2](image.png)

Figure 2. Example of installation of an IBIS-M unit in a coal mine, at a 2.4 km of maximum distance, and displacement map draped on a DTM of the mine.
The second type of use for an IBIS-M unit is critical monitoring, namely alarm generation for progressive movements based on the displacement/velocity measurement. The radar becomes a tool, to be combined with other sources of information, for aiding risk minimization thanks to the possibility to identify risk conditions and support the decision making process.

Finally, the possibility to have long term monitoring (months, years) of slope movements over very large portions of the pit allows the geotechnical staff of the mine to get a better understanding of the mechanism of large-scale instabilities and a better knowledge of the rock mass strength.

Figure 3. Geo-referenced cumulative displacement map (55 days) from an IBIS-M installation at Minera Escondida, Chile at a 2.5 km of maximum distance and time series of displacements (data courtesy of Minera Escondida Limited).

Figure 4. Installation of an IBIS-M unit at Minera Yanacocha, Peru (on the left) and example of geo-referenced velocity map draped on a DTM of the mine (data courtesy of Minera Yanacocha).
This type of use of the radar, mainly aimed at developing effective remedial plans, is also facilitated by the possibility to integrate the geo-referenced displacement maps generated by the radar with other geological/geotechnical layers importing them into mine planning software and GIS. Since the standard 3D view of Guardian is represented by displacement or velocity maps draped over a DTM of the pit, basic geomorphological analysis can be carried out. In addition, detailed monitoring, from both a spatial and temporal point of view, is a critical source of information for reliable calibration and validation of stability analysis models, to identify the mode of failure and the triggering mechanisms and to assess the performances of the implemented slope design.

Figure 5. Example of displacements measured by IBIS-M before a slope collapse. Two changes in the velocity are clearly identified before the exponential acceleration that led to the failure.

The wide spatial coverage provided by IBIS-M, combined with its very high spatial resolution, enables the radar system to cover the entire range of spatial scales of the typical slope instabilities within a pit (Figure 6). In fact, the high resolution in range direction (50 cm independently from the distance to the slope) enables the identification within a single bench of several pixels, allowing the detection of bench-scale failures, something not feasible using dish-based radar systems because of the lack of spatial resolution.

Multi-bench scale failures and inter-ramp scale failures, the typical instabilities measured with slope stability radar, can be measured by IBIS-M as well. In addition, the long range capabilities and the consequent wide spatial coverage and possibility to install the system far from the mine walls (e.g. on the opposite side of the pit) allows the radar to deal with overall slope failures, not easily measurable with conventional radar with lower working ranges.

By referring to the temporal scale of the typical instabilities within open pits, IBIS-M extends the use of slope monitoring radar from fast movements (from mm/day to few tens of cm/day), the typical deformation rates of interest for critical monitoring and the ranges covered by conventional radar, to very slow movements (from mm/month to mm/year). This can be achieved just thanks to long term installations or re-positioning of the radar unit. Through the combination of two specific processing done on different time scales, it is possible to track simultaneously fast and slow slope movements.
Thanks to the above mentioned characteristics IBIS-M has been deployed in several open pit mines around the world since its introduction into the mining industry in early 2010. To date the radar has been commissioned in mines in North America, South America, Europe, Africa, Oceania and Asia, by the most prominent mining groups, within variable geotechnical conditions including massive hard rock, intensely fractured rock and soft material, coal mines and metalliferous mines and with working distances ranging from few hundred meters to more than 3.5 km from the slope. The radar has detected movements and generated alarms in tens of cases on slope movements ranging from bench scale failures involving just a few tonnes of material to multi-bench failures with many millions of tonnes collapsed.

In Table 1 a summary of the most important technical features of the IBIS-M system and the corresponding benefits from a mining user point of view are listed.

4 Conclusions

IBIS-M, an innovative radar for slope monitoring within open pit mines has been introduced in the present paper. The main technical differences with respect to the radar based on parabolic antenna and their impact on the performances of the radar have been described. The use of a different radar technology and different processing techniques allows the proposed radar system to overcome some of the weakness of conventional slope stability radar. The improved performances are mainly related to the higher spatial resolution, the longer working distance from the slope, the faster acquisition time and the limited moving parts and power consumption. These features enable mining users to cover from a spatial point of view all the typical scales of slope instabilities, from bench scale to overall slope failures and to extend the range of monitored deformation rates to include also slow movements, previously poorly covered with conventional radar, thanks to the possibility to carry out with IBIS-M short-term monitoring sessions, but also long term monitoring.
Table 1. List of the main technical features of IBIS-M and of the corresponding user benefits.

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<tr>
<th>Technical features</th>
<th>User benefits</th>
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<tbody>
<tr>
<td>High Spatial Resolution</td>
<td>Smaller detectable area of failure</td>
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<td>Long operating distance</td>
<td>Limited use of personnel to operate the radar</td>
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<td></td>
<td>No need to move it during blasting</td>
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<td>Broad area coverage</td>
<td>Full picture of the slope allowing permanent installation and long term monitoring</td>
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<td>Advanced atmospherics estimation</td>
<td>Automatic atmospheric correction</td>
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<td></td>
<td>Reliable displacement data even at long ranges</td>
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<td>Fast time scan</td>
<td>HR images over the whole slope, without need to focus on subsets</td>
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<td>Re-positioning capabilities</td>
<td>Discontinuous monitoring</td>
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<td>Limited moving parts</td>
<td>Robust solution, high reliability</td>
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<td>Small antennas</td>
<td>No problems with strong wind</td>
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<td>Low power consumption</td>
<td>High service availability (reduced use of diesel generator)</td>
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<td>Scalable solution</td>
<td>Adaptable solution to user needs</td>
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5 References


