Using advanced InSAR techniques as a remote tool for mine site monitoring

D. Colombo* and B. MacDonald†
*TRE Srl, Milan, Italy
†TRE Canada Inc, Vancouver, Canada

Advanced Interferometric synthetic aperture radar (InSAR) techniques are capable of measuring and accurately characterizing ground deformation due to their unique capacity to provide dense point clouds of deformation measurements coupled with a history of movement over time. Recently, remote monitoring of ground deformation from radar satellites has become an operational tool for mines world-wide. While InSAR techniques have long been able to provide accurate deformation rates over a mine’s total surface assets, results were not available at a reporting frequency short enough to meet operational planning and monitoring needs. Satellite observations were limited to time intervals of 24, 35, or even 46 days. Now with 16-, 11-, 8-, and even 4-day revisit times of current modern satellites, the data collection cycle has vastly improved. The reporting time cycle has also improved with advanced InSAR techniques and tools that can process the increased data loads and provide critical deformation information to the geotechnical departments on operational planning time schedules.

This paper covers the advances made in the InSAR-derived products and services designed for the mining industry. Case studies presented include two African open pits monitored for surface changes due to mining operations, as well as deformation affecting waste piles and tailing dams. Subsidence due to underground coal excavation in Poland is being analysed. An example of monitoring surface infrastructure and tailings facilities over an active block cave operation is also presented.

Introduction

Currently, critical mine areas are monitored for geotechnical stability with the deployment of expensive ground-based monitoring equipment. The cost of equipment and management of the complex data from multiple systems limited full mine and mine infrastructure coverage. Interferometric synthetic aperture radar (InSAR) has always shown promise to provide full mine site monitoring, but the poor resolutions (10 and 20 m) and long repeat pass times (24-, 35-, and 46-day repeat) prevented this technique from becoming commonly applied in the mining industry. The availability of modern synthetic aperture radar (SAR) satellites, with revisit times down to 4 days and ground resolutions commonly down to 3 m, has brought InSAR technology to the forefront of mine site deformation monitoring.

Processing techniques have improved as well. Over the past two decades, InSAR techniques evolved from the use of differential interferograms (DInSAR) in the late 1990s (Massonnet et al., 1998; Carner et al., 2000) to persistent scatterers interferometry (PSI) in the early 2000s (Ferretti et al., 2001, Berardino et al., 2002; Werner et al., 2003; Costantini et al., 2008). PSI in fact overcomes limitations related to the atmospheric contributions affecting the standard DInSAR technique and allows millimetre precision to be reached. Compared to conventional surveying methods, PSI provides higher spatial resolution at lower cost, being particularly convenient for wide area monitoring. This is particularly true in urban and mining areas, where large number of reflecting features results in a dense distribution of measurement points (up to 1000 per km²). Recent advances have seen the merging of PSI algorithms with DS-InSAR algorithms, leading to very dense coverage of 10 000 points per km² (Ferretti et al., 2011). The theory of each InSAR technique is well explained in the cited references and will not be covered in this paper.

A brief technology overview is included here to highlight recent advances in SAR satellite capabilities and InSAR processing. We present three case studies that illustrate these advances and deformation products generated. The first case study is a historic review of surface deformation from longwall coal mining operations. The second case study is the active monitoring of the infrastructure, slurry dams, and waste piles at a diamond mining site. The third case study is the active monitoring of the subsidence zone over a block cave mining operation.
Technology evolution

Space segment

The last eight years saw a significant increase in the number of SAR radar satellites in orbit. While the first decade of the century was dominated by huge single-satellite operations (like ERS, ENVISAT, and Radarsat-1 and -2), we have now several constellations (multiple satellites occupying the same orbit) providing commercial SAR data services, including:

- Terrasar-X (TSX), from the German space agency (DLR), consisting of two satellites providing a new image every 11 days. A third satellite is planned to join this constellation in 2015.
- Cosmoskymed (CSK), from the Italian space agency (ASI), consisting of four satellites providing a new image every eight days. A new-generation Cosmoskymed constellation is already planned.

The constellation satellite approach provides imagery acquisition with a high reporting frequency (Figure 1) and redundancy to the data acquisition plan. These features are crucial to provide a reliable monitoring service to every mining facility. The higher spatial resolution – routinely 3 m but can achieve 1 m – provides improved definition of deformation rates and boundaries (Figure 2).

Figure 1 – Current satellite availability

Figure 2 – Recent improvement in SAR satellite resolution: (a) 20 m ENVISAT acquisition, (b) 3 m Terrasar-X acquisition
Processing techniques and services

While modern satellites provide improved spatial and temporal resolutions, InSAR processing techniques have also improved to exploit the full benefit of these robust data-sets. PSI techniques were refined throughout the last decade to provide the standard InSAR deformation monitoring services. Persistent scatterers (PS) provide strong return signals that are coherent over the longer revisit time of the older satellites. These PS are limited in distribution to more urban settings or rocky terrain (Figure 3). To better exploit diverse surface conditions, such as those found in and around mining operations a more complex scattering model was needed. Distributed scatterers (DS) are low-amplitude but coherent returns that are identified on a pixel-by-pixel basis. The better temporal and spatial resolution of the new satellites improved the signal-to-noise ratio to the point where these DS became a significant contributor to the deformation monitoring signal. Advanced processing that optimizes the PS and DS returns, such as SqueeSAR™, were developed to provide displacement information not only on man-made structures or exposed rocks, but on outcrops and thinly vegetated areas. Figure 4 (Mt Etna volcano), shows where a denser point cloud provides a clearer picture of the slope deformation with SqueeSAR processing. This advanced processing technique provides a major advantage when monitoring all assets at a mining site.

Figure 3 – First-generation PSI analysis of slope deformation on Mt Etna

Figure 4 – The High point density (PS and DS) from second-generation SqueeSar™ analysis

All measurements are acquired along the line of sight (LOS) from the satellite to the ground from a single viewing geometry. By collecting imagery from the ascending and descending orbits we can provide two viewing geometries for common points on the ground. The decomposition of this double geometry allows for the decomposition of the true
vertical and east-west vectors. Figure 5 illustrates how the LOS directions of imagery acquired along the ascending and descending geometries are modelled for the calculation of vertical and horizontal displacement measurements.

**Figure 5 – SqueeSAR™ 2D decomposition, geometric rationale**

### Mining case studies

Surface deformation in and around large mining operations is currently monitored with *in-situ* equipment and conventional survey techniques. These ground-based instruments do include radar applications, but only in the last 5 years has there been strong growth in the implementation of spaceborne InSAR monitoring due to the advances in satellite and processing technologies.

The case studies presented here will show the relevant findings on three different mining operations and the deformation information delivered to geotechnical engineers. The first case study is related to the heavy subsidence experienced from longwall coal mining operations. The second highlights motion detected over the surface assets of a large open-pit diamond operation in Africa. Finally, monitoring surface deformation over a block caving operation is the topic of the third case study.

#### Mining-induced subsidence over a coal mine in Poland

Surface subsidence can be very hazardous around shallow underground mining activities. Longwall coal mining can result in severe damage to urban structures and significantly affect surface infrastructure like roads and railways when not managed properly (Przyłucka *et al*., 2015). Subsidence is expected following the advance of the working face, and depending on the mining depth and the nature of the overburden this movement can be immediate and over a larger area than the footprint of the area worked in the seam. Such boundaries are usually defined by means of an angle of draw that extends upwards and outwards from the working face and which can vary from <10° to >60°. InSAR can measure the subsidence bowl to its furthest extents.

The results presented here refer to a longwall coal operation in southern Poland. The excavated coal layer is 2.5 m thick, 250 to 400 m long, and about 680 m deep. Historical subsidence has been measured (up to 27 m in 33 years), and these mining activities already affect an estimated subsidence region of nearly 300 km².

In order to study the rapid evolution of subsidence the in the area we exploited the Terrasar-X constellation, which is able to acquire a new image every 11 days. A new interferogram (a difference in phase between two subsequent acquisitions) over the area can be generated every 11 days. Such maps present fringes (i.e. wrapped phase signal presented in false-colour images) related to measured displacement.

Figure 6 shows some examples of such maps, and Table I contains acquisition dates of the interferogram pairs.

#### Table I. Interferograms dates

<table>
<thead>
<tr>
<th>Code</th>
<th>1st acq.</th>
<th>2nd acq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5 Jul. 11</td>
<td>16 Jul. 11</td>
</tr>
<tr>
<td>b</td>
<td>16 Jul. 11</td>
<td>27 Jul. 11</td>
</tr>
<tr>
<td>c</td>
<td>23 Oct. 11</td>
<td>03 Nov. 11</td>
</tr>
<tr>
<td>d</td>
<td>17 Dec. 11</td>
<td>28 Dec. 11</td>
</tr>
<tr>
<td>e</td>
<td>14 Mar. 12</td>
<td>25 Mar. 12</td>
</tr>
</tbody>
</table>
As the fringes represent surface displacement, a measurement of deformation can be calculated. Figure 6f shows the cumulative surface deformation observed. Extending this approach over the coal seam area yields the regional situation map represented in Figure 7.
While interferograms have been proficiently used to track subsidence bubbles to centimetre precision, SqueeSAR applied over the entire area will provide millimetre-precision displacements. Figure 8 shows the mapping extent and millimetre displacement measured from the SqueeSAR analysis.

**Monitoring surface assets around a diamond pit operation**

The pit slopes of a diamond mining operation can be quite steep due to the structure of the orebody and in order to minimize the cost of extracting the surrounding non-productive materials. As a result, the pit walls are well covered with robust and redundant monitoring networks, using the most advanced and up-to-date technologies. The rim of the pit and other surface assets, including waste piles, slurry pits, and tailings facilities, are not regularly monitored. Satellite-based InSAR monitoring provides a solution for monitoring such structures due to its intrinsic bird’s eye view,
Using advanced InSAR techniques as a remote tool for mine site monitoring

as illustrated in Figure 9. Figure 10 and Figure 11 show deformation measured on a waste pile southwest of the pit. Both vertical (up to 40 mm/a) and east-west deformation (approx. 25 mm/a westward) were measured, thereby accurately defining the limit of the unstable areas.

Figure 9 – Open pit deformation maps

Figure 10 – Waste piles, vertical deformation
Figure 12 shows the vertical deformation detected over the slurry dams. The northern deposit was not operating during the monitoring period, and the deformation measured is likely to be interpreted as compaction induced by evaporation. The southern deposit was in full operation, and is clearly identified by the cyan signature from the overlaid change detection map (Figure 12). Since the changes in surface conditions were detected within the basin, no further
InSAR deformation measurements have been available due to the corresponding de-correlation of the radar phase signal. Vertical displacement is clearly detected over some parts of the surrounding dam; a visit to the site verified that subsidence was occurring over the dam flanks.

The main focus of the project was over the waste piles. However, the InSAR response did provide some information from inside the pit highlighting a significant east-west displacement on the western wall. Geotechnical measurements from in-situ instrumentation confirmed these results.

**Monitoring surface conditions above a block caving operation**

The unstable surface subsidence induced by block caving quickly results in a prohibited access area where subsidence measurements can be difficult to obtain. Surface deformation rates and patterns within this zone can be key elements for monitoring the caving operations below. The InSAR monitoring provided here required no in-situ equipment and was the optimal surface deformation monitoring solution.

The block caving operation was approximately 600 m deep on a vertical 350 m mineralization zone. For this case study, TSX data was acquired regularly on an 11-day revisit schedule for the production of dynamic image-to-image D-InSAR products as well as the temporally coherent SqueeSAR products. An example D-InSAR interferogram and the unwrapped deformation map are shown in Figure 13. The precision of these products is down to the 1 cm level.

![Figure 13 – 11-day Interferogram (left) and unwrapped deformation map (right)](image)

![Figure 14 – SqueeSAR results over block cave zone (blue polygon)](image)
The motion velocity within the subsidence zone in Figure 14 is too large to be measured using SqueeSAR processing and therefore no data points are in this zone. To measure these higher displacement velocities we need to use our rapid motion tracking (RMT) processing.

RMT is a technique that maps displacement velocities well above the limit of any InSAR processing products. RMT provides measurements in the LOS (east-west) and azimuth (along the path of the satellite north-south) directions, allowing the capture of magnitude and vector information from a single acquisition geometry. Velocities greater than 1.5 m/month have been captured with the RMT technique over many mine operations. Figure 16 show the higher velocities captured in the caving zone with the RMT analysis.

Each RMT point has a temporal history similar to the SqueeSAR points but the rate of motion is much higher at -2290 mm/a, as shown in Figure 17. The profile in Figure 17 shows an increasing slope, indicating an accelerating rate of deformation as the block caving operation came into full production.
Using advanced InSAR techniques as a remote tool for mine site monitoring

Figure 17 – The profile of an accelerating deformation rate within the block cave zone as measured with RMT

With these techniques a full motion profile was monitored over all assets of a complex mining operation. The long-term millimeter- and metre-scale motions can now be captured in a single product by merging of the SqueeSAR and RMT technologies (Figure 18).

Figure 18 – SqueeSAR and RMT results representing millimetre- and metre-scale deformation rates in one product
Conclusion
Mining activities, whether open pit or underground, cause surface displacement. This deformation needs to be monitored to minimize any impact that can jeopardize mining activities. To increase safety at the mine site, geotechnical engineers use several instruments and techniques. InSAR and SqueeSAR™ are robust tools that enhance geohazard detection and displacement measurement. Through a fully remote approach (no sensor installed on site) and improved reporting frequency, InSAR technologies have demonstrated their ability to detect deformation over vast areas and major mining assets like waste piles and tailing dams world-wide.

References


The Author