Advanced InSAR Techniques for Mining Applications

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Abstract

InSAR (Interferometric synthetic aperture radar) is a remote sensing tool that can be used in several different types and stages of mining. The technique has developed rapidly in recent years and the most evolved algorithms are now capable of providing a high density of precise ground movement measurements over large areas. The most advanced approaches process a large number of radar images to determine displacement of natural or man-made targets called Permanent Scatterers. The use of multiple images allows for the application of statistical calculations to detect and remove atmospheric noise from displacement measurements, thereby increasing precision to within millimetres. SqueeSAR™, the most recent algorithm produced by TRE (Tele-Rilevamento Europa), has the unique capability to process signals from spatially distributed targets called Distributed Scatterers in addition to Permanent Scatterers, which greatly increases the density of measurement points in non-urban areas. In open pit mine applications InSAR can be used to monitor areas within and surrounding the pit, providing surface-displacement information that can be used to guide the development of the mine. Surface displacement over the Highland Valley Copper mine in British Columbia and slope instabilities in the nearby Thompson Canyon are presented. InSAR can also be used to measure ground subsidence occurring in areas of sub-surface mining. Examples from Rock Springs, Wyoming, are shown in which SqueeSAR™ was used to identify and delineate subsidence over underground mine shafts and guide remediation activities. Further applications of InSAR-based techniques include post-closure monitoring of mining sites, monitoring of tailing pond dams and the monitoring of waste pile stability.

1 Introduction

Interferometric Synthetic Aperture Radar (InSAR) is an approach that uses radar imagery to map surface topography or ground deformation occurring over time. This technology was introduced in the early 1990's, when the first research satellites were launched by the European Space Agency. While the earliest radar satellites were not specifically designed for InSAR, it was found that the information within repeat-pass radar images could be used to measure ground motion precisely and over large areas (e.g. Massonnet and Feigl, 1998; Burgmann et al. 2000). Initially used mainly for scientific investigations such as the study of ground motion associated with earthquakes, the number of applications has since grown steadily. With the recent launch of new satellites with improved characteristics specifically designed for InSAR, including shorter revisit times and higher resolutions, the monitoring capabilities of these systems have been substantially enhanced. Combined with the advent of next-generation data processing algorithms, the use of InSAR as a promising monitoring tool is being recognized in many new fields.

Advances in data-processing algorithms have allowed the amount of information extracted from radar datasets to increase by orders of magnitude in recent years (Prati et al. 2010). Beginning with simple differential interferometry in which two radar images are compared, a breakthrough in the field of InSAR was achieved with the development of Persistent Scatterer Interferometry, which involves the processing of entire stacks of images (Ferretti et al. 2000). The recently developed SqueeSAR™ algorithm utilizes sophisticated statistical data-
processing techniques to take full advantage of the information within radar datasets and represents the next generation of InSAR approaches (Ferretti et al. 2011).

The evolution of InSAR-based algorithms has extended the range of applications for this technology. From initial scientific studies on earthquakes and volcanoes, this technique has become an operational tool for oil and gas, mining, geothermal, transportation, civil engineering, groundwater, land management and urban planning applications. In the mining sector, InSAR is also gaining considerable interest (Colesanti et al. 2005). The combination of more frequent satellite passes with the recent improvements in data-processing algorithms is leading to solutions that provide timely and detailed surface deformation data for use in all stages of mining development and operation.

2 InSAR

2.1 Radar satellite characteristics

Radar satellites transmit microwave pulses to the ground surface and record characteristics of the returned signal. As these satellites are active systems that utilize microwave wavelengths, they can penetrate cloud cover and operate in day and night conditions. The most recent generation of satellites have characteristics that have led to significant improvements in the quality and quantity of data that can be extracted (Prati et al. 2010). The main advances in satellite technology have focused on higher site revisiting frequency and increased spatial resolution (Table 1). The revisiting time of radar satellites has decreased in several stages, from an initial repeat-pass frequency of 35 days down to 8 days with the COSMO-SkyMed constellation of satellites. The acquisition interval of the COSMO-SkyMed system is anticipated to further decrease to 4-day intervals in the near future, once the sixteen day orbits of the four satellites are fully synchronized. Satellite constellations have the added advantage of redundancy; the failure of one satellite does not compromise ongoing projects as the other satellites will continue acquiring data. Several future satellite missions are in various stages of development such as the European Space Agency's Sentinel satellites, the Canadian Space Agency's RADARSAT Constellation Mission and Government of Argentina's National Space Activities Commission SAOCOM series.

Table 1. Characteristics of radar satellites used for InSAR applications.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Acquisition mode</th>
<th>Wavelength (mm)</th>
<th>Pixel size (m)</th>
<th>Revisit frequency (days)</th>
<th>Year of launch</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS 1/2</td>
<td>Standard</td>
<td>56.6</td>
<td>20 x 5</td>
<td>35</td>
<td>1992</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Standard</td>
<td>56.6</td>
<td>20 x 5</td>
<td>35</td>
<td>2002</td>
</tr>
<tr>
<td>RADARSAT 1 &amp; 2</td>
<td>Standard</td>
<td>56.6</td>
<td>20 x 5</td>
<td>24</td>
<td>1995 &amp; 2007</td>
</tr>
<tr>
<td>RADARSAT 1 &amp; 2</td>
<td>Fine</td>
<td>56.6</td>
<td>7 x 5</td>
<td>24</td>
<td>1995 &amp; 2007</td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>Spotlight</td>
<td>56.6</td>
<td>3 x 1</td>
<td>24</td>
<td>2007</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>Stripmap</td>
<td>31</td>
<td>3 x 3</td>
<td>11</td>
<td>2007</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>Spotlight</td>
<td>31</td>
<td>1 x 1</td>
<td>11</td>
<td>2007</td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>Stripmap</td>
<td>31</td>
<td>3 x 3</td>
<td>8</td>
<td>2007</td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>Spotlight</td>
<td>31</td>
<td>1 x 1</td>
<td>8</td>
<td>2007</td>
</tr>
</tbody>
</table>
In terms of spatial resolution the improvements have also been significant. Pixel size has decreased from 100 m² for the first generation of satellites to less than 9 m² in standard acquisition modes belonging to the recently launched satellites. Spotlight modes, in which the exposure time of a targeted area to the satellite signal is lengthened, can be used to decrease pixel size even further, down to 1 m² or less. As radar images cover large spatial extents that can reach areas up to thousands of square kilometres in size, they can provide synoptic views of ground deformation over large sites while still measuring ground deformation precisely.

2.2 Radar interferometry

Radar sensors record the phase of both the transmitted and received signals in a radar image. When features on the ground move, the distance between the sensor and the ground changes, which produces a corresponding shift in the signal phase. This phase shift between image acquisitions is used to precisely determine ground movement. The amount of movement that can be quantified using interferometric approaches depends on the wavelength of the signal, the time between measurements and on the radar coherence of the area. Coherence is related to the stability of the phase values over space and time, and results cannot be obtained in areas of low coherence, where the phase values vary randomly between adjacent pixels. In general, InSAR is best suited for measuring relatively slow and regular movements.

Differences in the signal phase values recorded between successive radar images are represented with an interferogram. Interferograms are the basic building block for all forms of InSAR, including more advanced multi-image approaches. In basic Differential InSAR (DInSAR), single interferograms are used to generate deformation maps. However, this type of InSAR is limited by the lower accuracy of the deformation measurement (centimetre precision as compared to the millimetre precision of more advanced approaches). Furthermore, DInSAR can only measure linear motion, and information is lost in areas of marginal coherence.

Advanced forms of InSAR process a large number of radar images (multi-interferogram approaches) to determine the displacement of radar targets over time. These targets can be naturally occurring features such as rock outcrops, or man-made objects such as buildings and artificial reflectors (purposely installed radar targets). The processing of a long series of radar images allows the motion history of a radar target to be observed (including non-linear motion), and increases measurement precision to millimetre level. The recently released SqueeSAR™ algorithm presents the unique feature of processing weaker signals from spatially distributed targets covering several pixels, which significantly increases the density of measurement points in non-urban areas (Ferretti et al. 2011). In many cases these capabilities make it possible to avoid installing artificial reflectors at the site, making it ideal for the monitoring of remote, inaccessible or restricted-access sites.

2.2.1 PSInSAR™ and SqueeSAR™

The PSInSAR™ technique is a multi-interferogram approach that identifies targets on the ground from which surface motion is measured. These targets are referred to as Permanent or Persistent Scatterers (PS) and are dominant reflectors of the radar signal and produce strong signal returns in every interferogram of a long temporal series (Ferretti et al. 2000, Ferretti et al. 2007). This approach requires at least fifteen images in order to increase measurement precision to the millimetre level by applying advanced statistical algorithms to remove atmospheric noise and orbital effects from the data. It also allows non-linear motion to be measured and can extract information in areas where the DInSAR approach cannot. PS often correspond to relatively small objects located within individual pixels such as buildings, transmission towers, pipelines, or rock outcrops. Although PS-type approaches have numerous advantages over more primitive forms of InSAR they are constrained by the necessity to identify point-like radar targets on the ground.

The recent SqueeSAR™ algorithm was released with the objective of extending the application of InSAR to areas devoid of, or with a low density of PS targets. Compared to PS approaches, the SqueeSAR™ algorithm is capable of detecting and processing radar signals reflected from large homogeneous areas of ground surface (Ferretti et al. 2011). These are referred to as Distributed Scatterers (DS - Fig. 1). Distributed Scatterers have a minimum size of several pixels (i.e. hundreds to thousands of square meters) and typically correspond to fallow fields, rangeland, sparsely vegetated areas, scree or bare earth. As SqueeSAR™ also incorporates the
PSInSAR™ algorithm, both PS- and DS-type targets are identified. This new approach produces a higher density and an improved spatial distribution of radar targets compared to persistent scatterer approaches such as PSInSAR™. Data processing is computationally intensive as it involves several steps in which advanced statistical analyses are performed to identify radar targets and remove sources of error from the measurements (e.g. atmospheric artefacts, orbital errors).

![Figure 1. Identification of Permanent Scatterers (PS) and Distributed Scatterers (DS) with the SqueeSAR™ algorithm.](image)

### 2.2.2 Movement decomposition

The displacements measured by radar satellites are one-dimensional, and are called line-of-sight measurements. If an object on the ground is moving, the satellite will observe that the distance between itself and the object either increases or decreases, depending on the direction of movement. Line-of-sight measurements can be challenging to interpret since these measurements often contain both vertical and horizontal components of movement. However, by viewing the same area from different angles, such as from ascending (satellites travelling from South to North) and descending orbits (satellite travelling from North to South), information about multi-directional ground movement can be obtained. For instance, in areas where ascending and descending line-of-sight results both indicate movement away from the satellite, ground motion is primarily vertical. In contrast, line-of-sight results that show opposing movement patterns between ascending and descending datasets suggest that horizontal ground motion is present.

By acquiring two or more radar datasets that view the same area from an ascending and descending orbit, the line-of-sight measurements acquired from different look angles can decomposed into two- or even three-dimensional motion. This is accomplished by combing the line-of-sight measurements into a regular grid of points from which the true vertical and east-west horizontal vectors can be extrapolated using basic vector geometry. All radar satellites travel along a quasi-polar orbital path and most images are acquired with a right-looking viewing angle meaning the radar beam looks eastward or westward to acquire images. As a result, radar satellites are sensitive to movement in the East-West direction, but have limited sensitivity in the North-South direction. While movement decomposition can be extended to the North-South direction as well, the precision of these values is lower.
3 Mining applications

Recent advances in InSAR technology allow for frequently updated and detailed surface deformation data to provide valuable information at all stages of mining development and operation. During mineral exploration, deposit evaluation and site planning phases, InSAR can provide information to identify areas of unstable ground, landslides, active faults and areas of volcanic activity (Bonforte et al. 2011, Colesanti et al. 2003, Hilley et al. 2006, Massironi et al. 2009, Peltier et al. 2010). During mine construction, ground stability information can assist with the placement of access roads, mine infrastructure, tailings ponds and waste piles, as well as guide mitigation of unstable areas.

Throughout the operational phase of open pit mines, the ability to provide a synoptic overview of the entire mine site including the upper portions of the pit walls can provide information on movement dynamics over time. The areas adjacent to the open pit may be of particular interest for regular observation in order to identify potential instabilities that may impact nearby structures or equipment or provide precursor information on a possible pit wall collapse. For underground mining operations, subsidence occurring above the mine can be rapidly identified and delimited in detail. Displacement data can also be used to identify the potential activation or reactivation of faults in the area (Massironi et al. 2009).

Waste piles can also be monitored using advanced InSAR techniques, with measured deformation rates contributing to the identification and demarcation of unstable areas. Ground movement along tailing pond dams and levees can be rapidly characterized and used to identify potential threats to structural stability. Furthermore, vertical settlement can be readily distinguished from horizontal movement if a dual-orbit approach is used (Klemm et al. 2010). The identification of horizontal motion may be of particular interest as this type of movement can often pose a greater threat to safety and mine operations. In the mine closure and post-closure stages, waste piles and tailings ponds (including any covers), can be monitored remotely over the long term. Monitoring frequency can be adjusted according to necessity and may vary in time.

3.1 Open pit mines

The Highland Valley Copper mine is one of the largest open pit copper mines in the world. Located in central British Columbia, mine facilities operate continuously throughout the year and consist of the Highland mill and the Valley, Lornex and Highmont open pit mines. A RADARSAT-2 dataset was acquired over the Highland Valley Copper mine between January 2009 and April 2010 in the F4 beam mode, which has a viewing angle of approximately 45°. The SqueeSAR™ algorithm was applied to this dataset and over 37,000 measurement points were identified across the mine site and from the surrounding area (Fig. 2). More than 90% of the measurement points identified were of the Distributed Scatterer type, highlighting the advantages of using the SqueeSAR™ approach in this type of environment.

Destabilized portions of the pit wall are easily identifiable, as are areas of surface deformation surrounding the pit due to the high density of measurement points identified over mining operations (Fig. 3). The deformation shown in Figures 2 and 3 is along the satellite line-of-sight, meaning the negative and positive movements represent motion either towards (positive values) or away from (negative values) the sensor. As the RADARSAT-2 dataset used in this analysis was acquired from a descending orbit, surface displacement measurements were made relative to a westward-looking viewing angle. As it is unlikely that upward movement is occurring, and considering the 45° viewing angle, it is probable that areas in blue have a strong eastward component. Conversely, it is more difficult to determine whether negative measurements represent only vertical subsidence or whether a western component is also present.
Figure 2. Line-of-sight surface displacement results obtained from the SqueeSAR™ analysis over the Highland Valley Copper mine.

Figure 3. Line-of-sight surface displacement results obtained from the SqueeSAR™ analysis over an open pit within the Highland Valley Copper mine.
3.2 Slope monitoring

A series of slow-moving landslides are located within the Thompson Canyon in close proximity to the Highland Valley Copper mine in British Columbia, Canada. Monitoring of these instabilities is important due to their potential to damage infrastructure or disrupt service along two critical railway lines that run parallel to the Thompson River at the bottom of the canyon. Dual-pass radar datasets acquired from RADARSAT-2 satellite covering the period between January 2009 and April 2010 were used to measure ground displacement along a 50km stretch of the Thompson Canyon. The two datasets were processed using the SqueeSAR™ algorithm, which identified a density of 700 and 808 measurement points per square kilometre in the ascending and descending passes, respectively. The ability of the SqueeSAR™ approach to identify DS points was critical over this non-urban area, as the density would have decreased to 55 and 72 measurement points per square kilometre in the ascending and descending passes if a PS approach had been applied. As the two datasets acquired over this area were from different orbits, it was possible to combine the two one-dimensional measurements and use vector geometry to decompose the movement into its vertical and east-west horizontal components (Fig. 4).

Figure 4. An example of slope instability in the Thompson Canyon shown clockwise from top left: A) ascending orbit data; B) descending orbit data; C) East-West horizontal ground displacement; and D) vertical ground displacement. The black line running North-South represents the approximate location of the railroads.
The opposite colours of the measurement points in the top two panels (Fig. 4) derive from the different orbits from which the images were acquired. One image stack was acquired from an ascending orbit (Fig. 4A), in which the area is observed from the west, while the other was acquired from a descending orbit, in which the same area is imaged from the east (Fig. 4B). As discussed in section 2.2.2, the differences in movement observed between the two orbits are indicative of a strong horizontal component in the surface displacement. The decomposition of the movement is shown in the bottom panels of Figure 4 C and D, where it is apparent that the landslide is both subsiding and moving westward towards the river.

3.3 Underground mining

Underground coal mining in the area of Rock Springs, Wyoming started in the late 1860's (Karfakis and Topuz, 1991). Mining was of the room-and-pillar type, in which the pillars support the ceiling to prevent it from collapsing. Depth of the mined areas ranges from 15 - 122 m. Subsidence in the area began soon after the onset of mining and continues to this day, causing damage to buildings and other infrastructure. Various forms of InSAR have been used to measure subsidence at Rock Springs, making it an ideal site for demonstrating recent improvements in both radar satellite sensor technology and InSAR algorithms (Table 2). Three examples from this area are discussed below.

Table 2. Target count and density for PSInSAR™ and SqueeSAR™ analysis at Rock Springs mines.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Algorithm</th>
<th>Number of Points</th>
<th>Density (points/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS 1/2</td>
<td>PSInSAR™</td>
<td>11,363</td>
<td>176</td>
</tr>
<tr>
<td>ERS 1/2</td>
<td>SqueeSAR™</td>
<td>150,155</td>
<td>2,321</td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>SqueeSAR™</td>
<td>1,139,302</td>
<td>17,609</td>
</tr>
</tbody>
</table>

An archive dataset containing thirty-four images covering the period 1992 – 2000 acquired by the European Space Agency's ERS-1 and ERS-2 satellites were initially processed with PSInSAR™. A measurement point density of approximately 176 targets per square kilometre was achieved over the Rock Springs area (Fig. 5). While deformation trends are apparent in some areas, clear overall patterns of deformation are less obvious. Interpolation of the point cloud (Fig. 5B) assists data interpretation, but uncertainties remain.

In a subsequent step aimed at illustrating the advantages of identifying Distributed Scatterers in addition to Permanent Scatterers, the same satellite dataset was reprocessed with the new SqueeSAR™ approach (Fig. 5 and Fig. 6). The difference in the density of points is an order of magnitude higher, with 2,321 targets per square kilometre identified with the SqueeSAR™ algorithm (Table 2). The point cloud (Fig. 6A) is sufficient to delineate several areas of subsidence in this second example, including a linear subsidence trough running through the southern portion of the processed area. The spatial interpolation (Fig. 6B) of the point data provides a more accurate picture of deformation patterns compared to the previous interpolation (Fig. 5B), but presents only a marginal improvement from the point data results because of the high point density (Table 2).

Ongoing monitoring of the Rock Springs area is being carried out with the COSMO-SkyMed constellation of radar satellites (beam mode H4-04), which have higher temporal and spatial resolutions than the ERS data. Seventeen images were acquired between 19 May and 20 September 2010. When processed with the SqueeSAR™ algorithm, the COSMO-SkyMed dataset produced surface deformation measurements with a radar target density of 17,609 measurement points per square kilometre, representing an order of magnitude increase from the ERS-1/2 and SqueeSAR™ processing results (Table 2). Figure 7 shows the results of the SqueeSAR™ analysis applied to the COSMO-SkyMed imagery over Rock Springs. Both the deformation rates and spatial distribution have changed significantly compared to the earlier ERS-1/2 analyses. While it is possible that surface deformation patterns have changed between the two time periods covered by the ERS-1/2 and COSMO-
SkyMed datasets, knowledge of the area indicates that these differences are more likely the result of the much shorter period of time covered by the COSMO-SkyMed imagery (i.e. four months compared to eight years). The four-month rates are affected by seasonal changes in soil moisture content and fluctuations of the water table that produce intra-annual ground deformation variations that in the short term mask the longer term subsidence trends. Once the COSMO-SkyMed archive spans a period of one or two years these effects will be attenuated.

Figure 5. ERS-1/2 satellite data processed with the PSInSAR™ algorithm within the Rock Springs area: A) distribution of radar targets; and B) a surface deformation map produced from the interpolation of the point data.

4 Discussion

Several InSAR applications related to mining have been described in the previous paragraphs. However, before deciding whether InSAR can provide useful information at a specific site, there are several factors that need to be considered. In many cases rugged topography can be problematic for InSAR as the off-nadir angle at which the satellites image the ground can cause geometric distortions in the radar imagery (Burgman et al. 2000). Geometric errors are most often caused when portions of a slope face are compressed or completely hidden from the satellite. As a result, the identification of radar targets can be challenging in areas with steep slopes such as open pits or mountainous terrain. This aspect has been partially mitigated with newer satellite sensors as the angle of the radar sensor can be modified, meaning that the most appropriate angle can be chosen based on the slope orientation and gradient of a particular site. However, in extreme cases such as large, deep pits it is often possible to only extract information from the upper portions of the walls. It should also be noted that dense
vegetation and snow cover are not good reflectors of radar signals and inhibit the measurement of ground deformation. In these areas it is necessary to install artificial radar targets to be able to measure displacement.

The frequency with which ground deformation can be measured using InSAR is limited by the frequency with which the images are acquired and the data processing interval. In the case of image frequency constraints, it will soon be possible to acquire a new image from the same orbit every four days, meaning that the temporal sampling with which surface displacement can be measured will also be four days. Although this interval has decreased sharply from the 35 day revisiting time of the first space-borne sensors, satellite-based InSAR cannot be considered a continuous, real-time monitoring tool. Furthermore, advanced multi-image approaches such as SqueeSAR™ require enormous computational power that can only be provided by means of large parallel processors. Even the most advanced set-ups can take many hours or even days to complete data processing over extensive areas with large data stacks. As a result, data processing is often carried out at fixed intervals that are typically annual or semi-annual. With the advent of improved computing power and the increased standardization of procedures, this interval has been decreasing and will soon reach a point where processing can be carried out after every new image acquisition. This will bring satellite InSAR to the level of a near-real-time tool.

Satellite-based InSAR techniques have progressed significantly in recent years and can today be considered a viable tool in many mining operations. However, although InSAR is well-established in other fields, it is still relatively unknown in mining and will require more case studies and research to understand its true potential.

Figure 6. ERS-1/2 satellite data processed with the SqueeSAR™ algorithm within the Rock Springs area: A) distribution of radar targets; and B) a surface deformation map produced from the interpolation of the point data.
Figure 7. COSMO-SkyMed dataset processed with the SqueeSAR™ algorithm showing the distribution of radar targets within the Rock Springs area.

5 References


