Surface displacement monitoring: using satellite InSAR for mining and infrastructure planning

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Abstract

InSAR (Interferometric Synthetic Aperture Radar) uses satellite radar imagery to precisely measure ground deformation. TRE developed advanced techniques, PSInSAR\textsuperscript{TM} and subsequently SqueeSAR\textsuperscript{TM}, as a standard monitoring tools in a number of applications: natural hazards, geothermal, oil and gas, mining, urban and infrastructures monitoring.

Thanks to its capability in detecting millimeter level displacements over long periods and large areas, SqueeSAR\textsuperscript{TM} analysis can be considered complementary to conventional geological and geomorphological studies in displacement detection and monitoring, supporting also the effectiveness of landslide and subsidence inventories at regional scale.

In this presentation, we would like to present some results obtained in several sectors; as a matter of fact these data has been widely used by civil protection and planning authorities, but also by Oil and Gas and mining companies. In order to give consistency to these statements, after a brief introduction on the capabilities of the technology, a set of examples will be presented taking into account lots of different displacement phenomena.

Some examples over mining areas are presented. In the case of open pit, the greater attention would be put on the immediate surroundings of the pit and on the nearby facilities (tailing ponds and waste piles); on the other hand, surface effects of underground mining - mainly in terms of subsidence - are being measured with millimeter accuracy. Radar imagery can detect ground displacements that could threaten the integrity and safety of road and rail infrastructure (both at grade and elevated). By identifying natural and man-made ground measurement points, and using only remote sensed data, SqueeSAR\textsuperscript{TM} maps millimeter displacements along the entire length of road and rail networks, aiding risk assessments and highlighting areas that may require maintenance.
1 Introduction

In the past, constant monitoring programs have been applied to small areas of current operations 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 site coverage. The increase in modern SAR satellites with better revisit times and ground resolutions has brought this technology to the forefront of monitoring mine site deformation on a constant basis. Advanced algorithms have brought processing times down and provide better precision. This paper addresses these advantages.

Over the last two decades, InSAR techniques progressively evolved from the use of differential interferograms (Massonnet et al., 1998; Carnec et al., 2000) to Persistent Scatterers Interferometry (Ferretti et al. 2001, Berardino et al., 2002; Werner et al. 2003; Costantini et al., 2008, Ferretti et al. 2011). PSI in fact overcomes limitations related to the atmospheric contributions affecting DInSAR standard technique and allows to reach millimetre precision. Compared to conventional surveying methods, PSI provides higher spatial resolution at lower cost, being particularly convenient for wide areas monitoring. This is particularly true in urban and mining areas, where large number of reflecting features leads into a very dense distribution of measurement points (MP) (up to 100,000/km2).

After a brief technology overview, we present a case study over a mining site, where satellite InSAR has been used to detect and measure instabilities in the pit, over the tailings dams and the waste piles. Infrastructure monitoring is another main topic for PSI technique, both in mining areas and where tunnelling occurs; we present two case studies of metro lines tunnelling monitoring with SqueeSAR™, the first of PSI techniques, in different urban context. SqueeSAR™ has been already applied in several projects related to underground tunnelling (mainly TAV railway tunnels) and resulted to be a useful tool in all stages of a tunnelling project, from design to construction and management.

2 Technology overview

InSAR Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that measures surface displacements. Radar sensors, mounted on dedicated SAR satellites, transmit radar signals toward the earth, some of which reflect off objects on the ground, bouncing back to the satellite. These back scattered signals are captured by the satellite’s sensors and are used to compile radar images of the earth’s surface. Both the amplitude and phase of the ‘Back Scattered’ signal are recorded.

The phase information from a pair of images is compared to detect very small changes in the surface profile. These changes relate to displacement that occurred between the acquisition dates of
the pairs of images under analysis (see Figure 1).

Advanced forms of InSAR, such as SqueeSAR™, process a large number of radar images to determine the displacement of radar targets over time. Stable targets can be naturally occurring features such as rock outcrops, or man-made objects such as buildings and artificial reflectors (referred to as Permanent or Persistent Scatterers) that maximize radar return strength and coherence (Ferretti et al., 2001, Ferretti et al., 2007). The processing of a long series of radar images (Figure 1) introduces a time factor that allows the motion history of a radar target to be observed (including non-linear motion), and increases measurement precision to millimetre level accuracy. This precision is achieved by applying advanced statistical algorithms to remove atmospheric ‘noise’ and orbital effects from the data. The SqueeSAR™ algorithm presents the unique feature of processing the weaker signals from spatially distributed targets covering several pixels (referred to as Distributed Scatterers), which significantly increases the density of measurement points in non-urban areas (Ferretti et al., 2010).

Figure 1: Basic concept of interferometric analysis: comparison between successive measurements of sensor-to-target distance, allowing ground displacement to be determined

2.1 Precision of measurements

Error bars of SqueeSAR™ measurement are extremely complex to be estimated theoretically, before actually processing the data available (Colesanti et al. 2003). In fact, the precision of the displacement measurements depends on many different factors, such as: number of images used for analysis; spatial density of the measurement points (lower the density, higher the error bar); quality of the radar targets (signal-to-noise ratio levels); climatic conditions at the time of the acquisitions; distance between the measurement point and the reference PS; repeat cycle of the satellite (the lower, the better). An overall picture of the typical precision obtained by SqueeSAR™ analysis is
provided in Table 1, which shows the values of standard deviation for average annual velocity, single measurement and positioning in terms of geographical coordinates (North, East, Height).

Table 1. Typical values of precision for a point less than 1 km from the reference point for a dataset of at least 30 scenes spanning a 2-year period

<table>
<thead>
<tr>
<th>Precision (1σ)</th>
<th>C band satellite</th>
<th>X band satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positioning (E-W)</td>
<td>7 m</td>
<td>4 m</td>
</tr>
<tr>
<td>Elevation (referred to ellipsoid WGS 84)</td>
<td>1.5 m</td>
<td></td>
</tr>
<tr>
<td>Average annual velocity</td>
<td>&lt;1 mm/year</td>
<td>&lt; 5 mm/year</td>
</tr>
<tr>
<td>Single Measurement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 Mining Deformation Monitoring

Mining open pit operations require a reliable and efficient monitoring programme to assess the inevitable displacement occurring on pit walls and affecting most of the mining assets. Several geodetic tools (from Total Station to Ground based radar) are used to this purpose, and satellite InSAR proved to be a useful complement to usual survey techniques.

As an example of the information provided, a brief extract of a periodic report is shown. In fact, together with industry standard databases, InSAR services rely on robust, custom-designed, reporting programmes; various update frequencies are available, depending on the Client needs, from weekly to semi-annual.

This monitoring example has been carried out over a very large copper (open pit) mine. The mine spreads for nearly 20,000 hectares, and it is well monitored with several in-situ sensors. This monitoring has been carried out during the first semester of 2013.

3.1 Bird’s eye view – Providing information over the whole mining area

Figure 2 shows the displacement occurred over the whole mining area during the accounted period (4 months). The map has been obtained by means of the analysis of satellite images, hence without the use of any in-situ instrumentation: these set of data are then easily digested in modern GIS, allowing a convenient integration with other measurements.

These maps are produced every requested period (monthly to yearly). Among the various uses, they gained a great importance when planning for an instrumental monitoring programme.
3.2 In pit monitoring

Figure 2: Cumulative displacement over the whole mining area.

Figure 3: In pit zoomed view. Displacement unit: millimetre.
A simple zooming over the global map allows one to identify and measure displacement occurring in the pit, assessing portion of the slope affected by not negligible displacement. As these maps are not based on an a-priori network of measurement point, an easy visualization of the displacement is achievable (Figure 3). In order to complement the displacement information, for every measurement point identified, a proper time series of displacement is provided (Figure 4).

**Figure 4: Time series of displacement. Examples in the pit.**

### 3.3 Heap leach compaction

While the pit is usually well monitored, heap leaches and tailings dams are usually more difficult and hazardous to survey manually due to the harsh and dangerous environment. The particular structures in these areas do not fit the usual ground base instrumental monitoring strategy due to access and financial constraints.

Satellite InSAR, exploiting its unique aerial view (the line of sight is close to be vertical), provide and unprecedented tool to monitor such compaction phenomena.

**Figure 5: Compaction over heap leaches**
3.4 Water reclamation facility: cross-section

Following the same approach, a dam that is in a water reclamation facility is an easy target for InSAR monitoring. In this particular case, the analysis of a cross section shows the area of displacement highlighting weak spots affecting the dam structure.

Figure 6: Water reclamation plant. Cross section of displacement over a dam.

3.5 Third party Infrastructure

Mining activity may affect third party infrastructures, like railways or road, even if not directly used in the framework of upstream activity. This is the case of a major highway passing near the border of a pit, or in proximity of an instable waste pile. The first case is shown, where an evident sliding deformation affecting the mine rim triggers a deformation that spreads towards the highway (Figure 7).
4 Applications in sensitive urban areas

The construction of new underground facilities inevitably interferes with existing surface buildings, even though potential ground movements have been greatly reduced thanks to the progress in the ability of tunnelling machines to cope with difficult ground conditions. So, in urban areas, a remote monitoring system that can detect settlements related to excavation activities can greatly assist contractors, designers and owner involved in the project.

In general it is recommended to carry out an historical analysis “ante-operam”, in order to have an overview of the area before the beginning of excavations. This is possible thanks to the availability of satellite data archives covering the last two decades (since 1992). This procedure will allow the planning of a follow-up monitoring phase during the excavation and which should prolonged till the exhaustion of any long-term settlements.

4.1 Milan, Metro line 5

The M5 is a fully automatic light underground line, crossing the city of Milan (Italy) with a total length of 12.6 km. The first stretch Bignami-Zara has been completed and is operating since February 2013. The second stretch San Siro-Garibaldi is under construction and will be operative for the Expo 2015.
In San Siro-Garibaldi stretch, a double track tunnel has been constructed using EPB machines. The tunnelling construction began in 2010 and was completed in 2013. The SqueeSAR™ analysis of 120 high resolution radar images (TerraSAR X data) acquired from June 2008 to December 2012 identifies the TBM progress and its impact on the buildings above (Figure 8). Although the surface settlements are less than 1 cm, the precision of SqueeSAR™ data allows the detection of very small displacements without install any instrumentations on ground. The time series (displacements over time) shown below highlight the effects of TBM progress during construction period (Figure 9).

![Figure 8: Milan: acceleration map [mm/year²] of measurement points identified from satellite.](image)

![Figure 9: Time series (displacement over time) of measured points 1,2,3 respectively](image)

### 4.2 Vancouver, the Canada Line

The Canada Line is a rapid transit line in the Metro Vancouver (Canada), servicing Vancouver, Richmond, and the Vancouver International Airport. The construction began in October 2005 and was completed in August 2009. Geological settings range from glacial till in the downtown area and along much of the line North of the Fraser River, to landfill along False Creek and the silt and clay deposits of the Fraser Delta in Richmond. These different conditions are likely to produce varied responses in the structures built on these terrains. The availability of archives of satellite data provides the deformational behaviour ante operam. Thereafter monitoring can be conducted during
the construction phase and after the completion of the activities (long term monitoring), to follow in time the deformation. The study area was firstly analysed using 58 RADARSAT-1 images collected between 3 March 2001 and 18 June 2008, comprising ante-operam phase (2001-2005) and tunneling activities (2005-2008).

The historical analysis (Figure 10) highlights significant displacement rates in the area between the Sea Island Centre Station and the YVR-Airport Station.

![Figure 10: Canada Line: velocity map [mm/year] of measurement points identified from satellite. Monitoring time 2001-2008](image1)

![Figure 11: Average velocities map before (left) and after (right) the tunnelling activities.](image2)

Nevertheless subsidence was antecedent the tunnelling activities, accelerations of about 1.5 mm/y^2^ have been measured during the construction. Furthermore, SqueeSAR™ data have been further analysed with PSTime, a software that detects the dates of change a deformation trend, partitioning the time series accordingly, before and after the event (in this case tunnelling). The time series analysis highlights acceleration in most of the measurement points along the Canada Line, between Broadway-City Hall and King Edward (Figure 11). Blue and red points represent displacements toward tunnelling alignment. Differences in colour depend on satellite acquisition geometry.

Figure 12 shows that most of the measurement points in this area, reveals an acceleration in 2007, which corresponds to the year of beginning of tunnelling.
Figure 12: Histogram of measurement points between Broadway-City Hall and King Edward recording acceleration.

We observed a stable phase followed by a displacement’s step of 2 cm in 2007, to the left and right side of the Canada Line (Figure 13) coinciding with the construction phase.

Figure 13: Time series of a Measurement Points to the left (a) and right (b) of the Canada Line

Figure 14: Velocities before the tunnelling, during, and 3 years later

Post-construction monitoring continues to verify the stability of long term displacements due to new construction near the transportation corridor. A data stack composed of 34 Radarsat-2 images, acquired from February 2009 and 11 March 2011, was processed with the SqueeSART™ algorithm. Following this approach it was possible to assess the displacement before, during and after the construction works (Figure 14).
5 Conclusion

The technological advances in Satellite data specifications and InSAR processing techniques have brought deformation monitoring from space born platforms to the forefront of mine site and infrastructure applications. All mining assets can be monitored from a single sensor easing data compatibility issues across corporations and allowing a better understanding of the occurring phenomena. Moreover, the use of such measurement guide the deployment of network of sensors, both during the planning phase and the operational phase of underground and surface operations.

6 References