Measuring deformation from space

by Davide Colombo, Tele-Rilevamento Europa TRE

InSAR (Interferometric Synthetic Aperture Radar) uses satellite radar imagery to precisely measure ground deformation. TRE developed advanced techniques, PSInSAR and subsequently SqueeSAR, as 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 millimetre level displacements over long periods and large areas, SqueeSAR analysis can be considered complementary to conventional geological and geomorphological studies in landslide detection and monitoring, supporting also the effectiveness of landslide inventories at regional scale.

SqueeSAR interferometry, the latest evolution of PSInSAR technology, is an advanced technology for ground deformation analysis and monitoring. It exploits long temporal series of satellite radar data, acquired over the same area of interest at different times, to identify “natural radar targets” (Measurement Points or MP), that return stable radar reflections over time back to the satellite, where very precise displacement information can be retrieved [1, 2 and 3].

Thanks to its capability of detecting millimetre level displacements over long periods and large areas, SqueeSAR analysis can be considered complementary to conventional geological and geomorphological studies in slope instability detection and monitoring.

The availability of surface displacement time series for all the radar targets identified also makes it possible to change the scale of analysis from regional to local, allowing indepth studies into the evolution of single instability phenomena, supporting the design of traditional monitoring networks and even verifying the efficiency of remedial works.

After a brief excursus on the basics of the technique, examples of the use of SqueeSAR data in various applications are provided. In fact, surface deformation has been used to identify and monitor landslides, and is also exploited as a precious source of information by the oil and gas industry in order to improve the knowledge of the subsurface. Examples on the profitability of such data in mining application are also provided.

Technology overview

Interferometric synthetic aperture radar (InSAR), also referred to as SAR Interferometry, is the measurement of signal phase change, or interference, over time. When a point on the ground moves, the distance between the sensor and the point changes and so the phase value recorded by a SAR flying along a fixed orbit will be affected, too. As a consequence, any displacement of a radar target along the satellite line of sight, creates a phase shift in the radar signal that can be detected by comparing the phase values of two SAR images acquired at different times. Fig. 1 shows the relationship between ground movement and the corresponding shift in signal phase between two SAR signals acquired over the same area. Fig. 1 also shows that InSAR measurements obtained from a single orbit can only measure the projection of the surface displacement along the line-of-sight (LOS) from the satellite to a reflection point on the ground.

Although the basic idea is quite easy to grasp, the development of reliable InSAR algorithms was a time-consuming process due to the difficulties related to atmospheric phase delay and decorrelation phenomena due to reflectivity changes with time. After the seminal work of Gabriel et al [4], it took almost ten years, for the InSAR community, to design a reliable approach that could increase accuracy and reliability of InSAR measurements. In 1999, the first results of the so-called Permanent Scatterer technique (PSInSAR) was presented by the SAR group of Politecnico di Milano.
Immediately after, many other teams started working on similar algorithms based on the detection of coherent (i.e. “good”) rather targets (the Permanent Scatters – PS) available over the area of interest, where atmospheric effects could be estimated and removed via the exploitation of a long temporal series of SAR acquisitions (rather than just two scenes, as in conventional interferometry) and proper filtering algorithms. In a nutshell, PSInSAR was a way to pass from qualitative to quantitative information, providing also error-bars to displacement rate values inferred from SAR data. Limitations still remained in areas where just a few PS were available. This is why research activities at POLIMI and TRE (a spin-off company founded in 2000 to promote the application of this technology) focused primarily on the optimisation of the PS density in non-urban areas. In 2010, about ten years after the first PSInSAR results, it was possible to start the operational use of this new InSAR approach, called SqueeSAR [5].

This “second-generation PS analysis” allows the identification of a much higher spatial density of measurement points in remote areas and a more effective filtering of the atmospheric disturbances affecting InSAR data. It should be noted that even the latest InSAR algorithms do not allow the identification of measurement points in heavily vegetated areas or where snow and ice change the radar reflectivity of the area of interest for most of the year.

Common to GPS, PS and SqueeSAR data are differential measurements, with respect to the first acquisition over the area of interest and relative to a reference radar target supposed motionless, or where prior information is available, typically from permanent GPS stations. What is actually measured is the possible variation of the projection of the 3D displacement vector affecting a certain point along the satellite line of sight: InSAR data are inherently 1D displacement data. However, by properly combining observations from different orbits it is possible to infer the vertical and the east-west components of the displacement field. An example is shown in Fig. 2. Because of the almost polar orbit of the satellite, the north-south component cannot be measured, since it does not create any significant range variation.

**A nation in motion, the Italian case**

As interferometry has become a standard monitoring technology in Italy, the Ministry of Environment funded a global project to investigate geohazards throughout the country. As an outcome, more than 14-million targets have been identified, carrying information about the displacement occurred across the country from 1992 to 2010.

The Italian geologic community uses this data to map and classify landslides and also to study volcanic activity related to nearby seismic faults. Moreover, through the analysis of subsidence bowls, it is possible to correlate ground instability to subsurface activity (water, oil or gas extraction), allowing geomechanics experts to improve the knowledge of the subsurface in terms of porosity and structural characteristics.

**Structure monitoring**

During the construction of tunnels for underground infrastructures, satellite remote sensing data can help to evaluate the works-induced ground movements in the surrounding area. In urban environments, these movements can affect existing surface and structures, and satellite remote sensing is particularly suitable for monitoring building responses to excavation. Satellite monitoring data can be combined with traditional data, allowing not only local damage phenomena to be detected, but even large scale surveying, taking into account wide area displacement. The integrated application of traditional and satellite techniques can provide a complete monitoring system.

In the framework of the high-speed Milan to Naples railway construction, a tunneling work under the city of Bologna (Italy) has been recently completed. It is...
a double-track tunnel with an excavation area of approximately 130 m², crossing urban surroundings at shallow depths (approximately 10 m) with a high density of commercial activities and residential housing (Fig. 3).

In order to highlight the displacements induced by tunneling activities alone, it was considered appropriate to select a reference point in such a way to minimise the displacement gradients due to generalised subsidence and to detect the sole displacements induced by the excavation works.

Fig. 4 shows an example of an historical displacement time series of a measurement point located near the tunnel centre line. After the first section of the time series (2003 – 2007), which exhibits a general stability, the image shows an increase in the displacement values during 2007 and 2009 – 2010, both followed by stable periods. This behaviour is in perfect agreement with the site work activities: the first increase in displacement values is related to the construction of ten micro-tunnels between March and October 2007; the second is related to the tunnel advance in the first months of 2010. In the subsequent period the excavation front was far from the considered point (MP), and displacement stopped, confirming the final stable section of the displacement time series.
Surface effect of the London Jubilee line construction

The SqueeSAR algorithm has been used with data acquired from all over the world. Another notable example of InSAR derived measurement applicability is the potential to detect and characterise underground facilities, such as tunnels and excavations. In fact, underground tunnels create voids in the surrounding rock and soil, which often cause the overlying surface to subside. This subsidence is indeed extremely small (millimetres to centimetres); although craters and collapses may be detectable using other techniques, these broader, subtle subsidence are easily detected using such methods.

As a matter of fact when analysing data acquired during the 90s over the London city area, a clear subsidence track (almost 2 cm displacement) was detected. The London Jubilee line was excavated during this period and joined the existing line in 1999 (see Fig. 5).

SqueeSAR applications in oil and gas

Oil field subsidence monitoring

In this study, SqueeSAR analysis has been carried out over a productive oil field, where enhanced oil recovery operations are carried out in order to aid the production. Results, thanks to millimetric accuracy, allow the detection of immediate compartmentalisation of the reservoir; in this particular case, inversion was carried out with an analytical geomechanical model and compared with the distribution of the known faults at reservoir level.

A comparison with the pressure change maps from the reservoir simulation over the time in question shows a good areal agreement between the predicted and estimated pressure changes (see Fig. 6).

Underground gas storage

Another successful application for SqueeSAR is the surface monitoring of gas storage areas. Surface deformation related to underground gas storage depends on a number of factors, including the reservoir depth and geometry, the geomechanical properties of the injected rock and the overburden and the pore pressure changes induced by gas injection and/or extraction.

Applications for the mining sector

Underground mining operation – Metropolitan colliery, Australia

The Metropolitan Colliery is one of the oldest continually operating coal mining operations in Australia (over
120 years. Ground movement has been observed over this area, and the surface above underground operations has been monitored in recent years (survey campaigns beginning in 2003). There is interest in obtaining a complete overview of historic displacement occurring over this site, including both vertical and horizontal components of movement.

Therefore, the objective of this study was to identify vertical and horizontal movement occurring over the Metropolitan mine and examine the suitability of this environment for InSAR. Results provided a detailed overview of historic LOS movement, as well as vertical and east-west horizontal ground movement over most of the area (see Figs. 7 and 8).

Underground mining operation – Silesian coal basin, Poland

The Upper Silesian coal basin (USCB) is located in south-western Poland and in the north-eastern Czech Republic. The USCB basin forms the western part of the Silesia-Cracow Upland and peripheral part of the Silesian Beskids.

Coal mining activity in the USCB has been conducted since seventeenth century. In 2012 in the Upper Silesian coal basin about 79,2-million tons of hard coal was mined. At present in this region are 30 active coal mines. Average depth of coal extraction is about 700 m below surface and the longwall mining method with caving or hydraulic stowage are used. In the USCB, hazardous ground deformations are caused primarily by mining workings and operations. The subsidence in this region reaches velocities of a few centimetres per month but in some cases can reach even 5 mm per day (see Fig. 9).

Open pit mine – Chile

The SqueeSAR approach was tested over an heavy mined area in Chile, both on the pit itself and on the surrounding area. We have been able to detect consistent displacement, in the pit and in the nearby facilities; in fact, subtle millimetric subsidence is affecting some waste piles, while the tailing dams suffer from significant displacement rates (see Figs. 10, 11 and 12).

Conclusion

Unlike traditional surveying techniques (optical levelling, GPS, tiltmeters, etc.) SqueeSAR provides a high spatial density of displacement measurements with high precision and low costs over long periods. For this reason satellite data represents an important tool for the analysis of surface deformation, and can be complementary to conventional approaches (geological, geophysical, geochemical investigations, core and log analysis, well testing, etc.).

It is important to underline how advances in processing algorithms have significantly increased measurement point density in non-urban areas. Furthermore, X-band satellites with faster repeat times and higher ground resolution have also improved both temporal and spatial resolution of results. The results obtained demonstrate the usefulness of these set of measurements for heavy industries involved in the oil and gas, and mining sectors. Studying the correlation between human activity and surface deformation helps to improve the knowledge of characteristics of the productive field, thereby increasing both safety and profitability of these areas.

Acknowledgement

This paper was presented at SASGI 2013 and is republished here with permission.

References


Contact Davide Colombo, TRE, davide.colombo@treuropa.com and Ian du Toit, Optron, Tel 021 421-0555, idutoit@optron.com