

2013

Application of advanced InSAR techniques for the measurement of vertical and horizontal ground motion in longwall minings

Javier Duro
Altamira-Information

David Albiol

Oscar Mora

Blanca Payàs

Follow this and additional works at: <https://ro.uow.edu.au/coal>

Recommended Citation

Javier Duro, David Albiol, Oscar Mora, and Blanca Payàs, Application of advanced InSAR techniques for the measurement of vertical and horizontal ground motion in longwall minings, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2013 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019
<https://ro.uow.edu.au/coal/442>

APPLICATION OF ADVANCED INSAR TECHNIQUES FOR THE MEASUREMENT OF VERTICAL AND HORIZONTAL GROUND MOTION IN LONGWALL MININGS

Javier Duro, David Albiol, Oscar Mora and Blanca Payàs

ABSTRACT: Synthetic aperture radar interferometry technology detects ground motion with millimetric precision. The measurements are taken remotely from space and represent a very efficient tool for ground motion measurement even in large and remote areas where land-based measurement techniques are inconvenient and costly. Furthermore and due to the availability of archive radar images, InSAR technology is the only technology able to provide measurements of ground deformations that occurred in the past. Past data allow the establishment of early baselines before any coal production starts and before any subsidence induced by previous production activities. This allows the total levels of subsidence to be identified and allows mine decision-makers to determine the vulnerable zones that could be affected by subsidence. Results of a recent ground motion study on a longwall mine in the Southern Coalfields of NSW, Australia are discussed. The results were obtained using an advanced differential interferometric chain, Stable Point Network, (SPN) which is capable of processing radar images at millimetric precision and very high density of measurements. The paper aims to compare the advanced InSAR retrieved motion with surveying data and to show that InSAR can retrieve the vertical and the horizontal motion that can be present in this type of mining.

INTRODUCTION

Radar satellites continuously orbit the earth on a fixed polar orbiting track, taking more or less 100 min to complete one full orbit. Since the earth is rotating below the satellite, its path successively moves around the globe, meaning that over time satellites build up complete images of the whole globe. The satellite can revisit the same location after a few hours to 46 d on a regular basis, depending on the mission. Space borne Synthetic Aperture Radar (SAR) sensors are active systems on board satellites that acquire during day and night and operate in the microwave domain (cm to dm wavelength) providing global acquisitions almost independent from the meteorological conditions. These radar satellites provide high resolution images which have a wide range of applications and are suitable for operational monitoring tasks.

SAR interferometry (InSAR) is one of the main applications of radar imagery because it fully exploits the geometric precision of the SAR systems (in the order of the sensor wavelength, few millimetres). These radar satellite images, unlike optical satellite images, provide an accurate measurement of the distance between the satellite and the ground. The principle of interferometry is based on the superposition of waves from two images in order to detect differences in distance measured in wavelength fractions (Massonnet and Feigl, 1998).

For ground motion monitoring projects several satellite images taken at different times are compared. By means of the analysis of the evolution of the distance between the sensor and the ground of the different acquisitions, information regarding the topographical relief and ground deformation can be extracted, see Figure 1. These two main components are superimposed in the interferometric signal jointly with other unwelcome contributions, the most critical one being the one due to the variations in the state of the atmosphere during the image acquisition. It is important to properly filter these unwanted variations in order to avoid possible errors when interpreting the InSAR data. Altamira Information owns an InSAR processing technique, Stable Point Network (SPN), which estimates and compensates all these undesired phase components, allowing the achievement of millimetric precision in the measurements of ground motions.

SPN offers very high density of measurements (~ 600 point/km²) over wide areas (tens of kilometres), which allows the identification of the perimeter of those areas with motion and the gradients of the ground deformations. For these reasons the application of this technology in longwall mining is very suitable and

it can complement local and *in situ* surveying techniques, particularly over the areas surrounding the longwall panels where smooth gradients of motions can be expected to occur.

SPN TECHNOLOGY

The Stable Point Network (SPN) (Arnaud, *et al.*, 2003) is an advanced differential interferometric software developed by Altamira Information in order to process large stacks of radar images to achieve millimetric ground motion measurements. This technique requires a minimum number of images to identify the points that are electromagnetically stable during the period of study. This selection process is a crucial step as the precise measurements of ground deformations will be primarily achieved in these electromagnetically stable points.

The basis of the SPN technique is the separation of the different components from the interferometric phase (ϕ_{INTERF}): the topographic component (ϕ_{TOPO}), the movement component, (ϕ_{MOV}), the atmospheric contribution (ϕ_{APS}) and the noise component (ϕ_{NOISE}).

$$\phi_{INTERF} = \phi_{TOPO} + \phi_{MOV} + \phi_{APS} + \phi_{NOISE} \quad (1)$$

The topographic component can be mainly compensated from an external Digital Elevation Model (DEM). Consequently, assuming that ϕ_{NOISE} and ϕ_{APS} are known, using equation 1 the phase contribution due to ground deformation ϕ_{MOV} can be obtained.

Several satellite images covering a series of dates are acquired to properly retrieve the phase contribution related to the ground motion. This large stack of data allows the generation of time series which show the space-time evolution of the deformations (see Figure 1 and Duro, *et al.*, 2003).

The application of SPN is very suitable for longwall panel monitoring as it can cover wide areas at a very high resolution and with millimetric precisions allowing to perfectly define the perimeter and the gradients of the ground deformations over the mined panels and the surroundings. The availability of archive SAR data also offers a unique opportunity to look into the past and to perform historical studies and continuing afterwards with ongoing monitoring to quantify deformation at the land surface.

By using a combination of classical interferometry and SPN, millimetric and centimetric movements can be monitored. Results are provided in GIS format and can be received and analysed by the mine managers and by the owners of surface infrastructure remotely without the need for site visits (Espinosa and Mora, 2012).

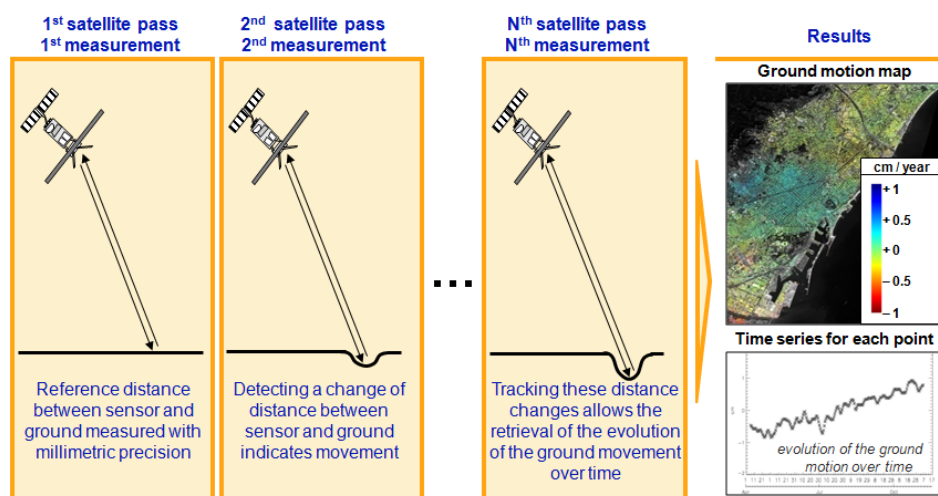


Figure 1 - Performance of InSAR technology to measure the ground deformation from the comparison of the evolution of the distance between the sensor and the ground in repeated satellite passes. On the right side there is an example of the two main outputs: ground deformation maps and vector files with the time series for each measurement point.

INSAR SAMPLING GEOMETRY IN LONGWALL MINING DEFORMATION AREAS

Satellites follow polar orbits (approximately $\pm 14^\circ$ with respect to the North) at a right look direction offering ascending and descending acquisitions from the west and the east side respectively (see Figure 2). Furthermore, space-borne SAR sensors have an oblique geometry of observation, which determines the measurement direction of observation; this is called the Line of Sight (LOS) of the sensor. The LOS of the satellites is rarely direct above, i.e. vertical, and is typically varying from 18° up to 50° with respect to the vertical direction. As shown in Figure 3, depending on the orientation of the true motion vector, the ascending or descending view will measure (sample) different magnitudes of the real motion. In any case, purely vertical or horizontal motions are measured in InSAR LOS with a significant magnitude (left and right case Figure 3). The acquisition geometry of the satellite can be selected in conjunction with the direction of the expected ground motion to get an optimum sampling.



Figure 2 - Illustration example of the two possible acquisition geometries, ascending and descending flights

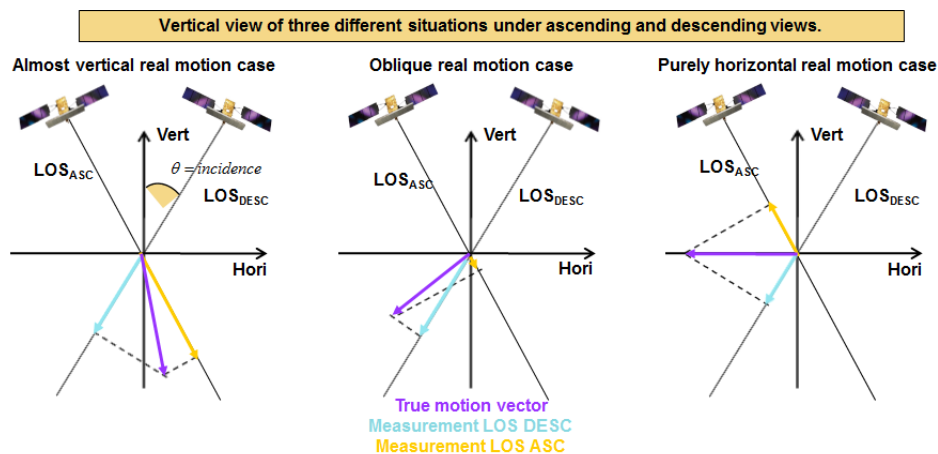


Figure 3 - Illustration example of the detected magnitude in LOS direction in function of different orientations of the true motion vector for ascending and descending views

InSAR techniques measure the ground motions in the LOS of the acquisitions. Consequently, when aiming at decomposing the measured LOS motion into the vertical and horizontal components, i.e. eastings and northings, using InSAR techniques, it will be necessary to combine ascending and descending views of the same motion. However, even if only one acquisition mode is available, it is still possible to obtain the vertical and the horizontal components of the observed movement, but only if external information, such as monitored GPS data, modelling or assumptions about the expected motion is available.

The majority of the sagging subsidence that is seen on the surface occurs over the centre of a mined panel and far less subsidence is seen at and beyond the edges of the panel. Where several panels are mined in a series with chain pillars left between the panels, the observed maximum subsidence, over this series of panels, generally increases after the extraction of each further panel. The horizontal component of mining induced subsidence, in flat terrain and under conventional conditions, increases from zero at the initial pegs that are remote from the edges of the mined panels and to a maximum value near the point of maximum tilt near the edge of the panel.

The magnitude of mining-induced horizontal movements and the directions of these horizontal movements are controlled by a complex interaction of multiple factors, including the magnitude of the vertical subsidence, the presence and proximity of previously extracted panels, the depth of cover, the location of the peg relative to the current and previously extracted voids, the steepness and profiles of the surface topography, the seam dip, the direction of mining in relation to the surface and the seam slope, the geology and thicknesses of the various strata layers, and the magnitude and direction of the *in situ* horizontal compressive stresses.

The acknowledgement of the nature of the observed ground deformations could be used as a priori assumption for the motion decomposition when using one InSAR acquisition mode. As shown in Figure 4, depending on the location of the measurement points with respect to the excavation areas within the active longwalls, the measurement motion can be re-projected to obtain a more accurate interpretation and magnitude. Hence, if the measurement point is close to the centre of an active longwall panel it can be assumed that the main component of the true motion will be in the vertical direction (motion from B to B' in Figure 4). However if the measurement point is in the surroundings it can be assumed that the principal component of the real motion is in the horizontal direction (motion from C to C' in Figure 4). As shown in Figure 4, the resulting re-projected vertical and horizontal vectors (from one mode InSAR LOS measurement) overlay the true motion vector, indicating that the final re-projected magnitude is exactly the same as the original one. Nevertheless in the transition areas (motion from A to A' in Figure 4), where the true motion vector is not purely dominated by the vertical or the horizontal component, the re-projected LOS measurement will present some discrepancies with respect to real magnitude.

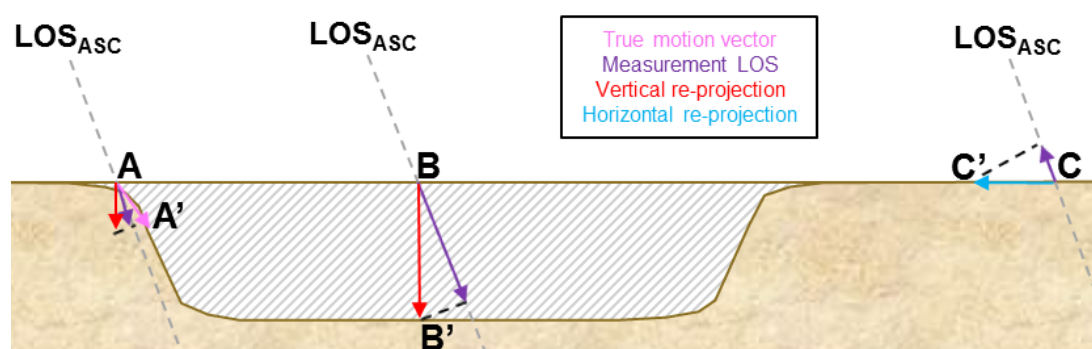


Figure 4 - Illustration of three examples of the detected magnitude in LOS direction and the resulting re-projected vectors in vertical direction (red) and in horizontal direction (blue)

REAL CASE APPLICATION

The case study that is presented in this section was performed using archive past data of the ALOS satellite. This satellite was launched by the Japanese Aerospace Exploration Agency (JAXA) in January 2006 and was operating until 2011. Among other sensors on board, it contains a Phased Array type L-band Synthetic Aperture Radar (PALSAR) which provides resolution images of 4.5 m x 5 m with the fine beam single polarisation mode with a maximum interferometric revisit time of 46 d. A total of 25 ALOS images were acquired between December 2006 and January 2011 over the operating area and its surroundings. The main objectives of this InSAR project were to quantify the subsidence magnitude range and to determine the extent of the subsidence area.

The SPN processing was very successful over this area retrieving a very high measurement point density (800 points/km²) and with precisions of 4 mm. The produced ground deformation map has a uniform distribution of the measurement points through the whole area of interest minimising as much as possible the local areas without measurements. In particular, areas without points are over the rivers (water covered areas), crop fields and over the centre of the active longwall panels.

It is important to bear in mind that the critical factor in determining whether a measurement point can be used is whether the ground surface remains invariant during the period of study. In agricultural and highly vegetated areas, seasonal changes occur which could cause a reduction of the measurement point density over those areas.

As it can be seen in Figure 5, different rates of subsidence at the surroundings of the longwall panels are detected. These rates can be directly linked with the extraction activities taking place in the underground

mine, and thus help to obtain parameters for further planning, helping to anticipate areas that will be vulnerable in the future, or to corroborate and complement the *in situ* measurements and the modelling.

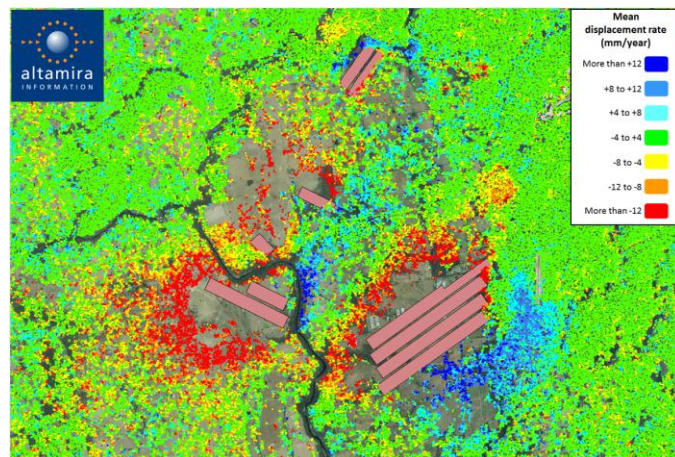


Figure 5 - Mean velocity map in the LOS direction obtained over the area of interest superposed to the longwalls schema

InSAR detected motion compared to ground data

Longwall mining activities present a special behaviour regarding induced ground deformation phenomena. This occurs because the longwall face advances with time generating a strong movement pattern in the area that surrounds the activity. As it can be seen in the spatial profiles in Figure 6 and Figure 7, the centres of the active longwall panels are affected by strong movement (approximately more than 50 cm of accumulated deformation) and cannot therefore be measured by using SPN alone because it exceeds the detection limits (Massonnet and Feigl, 1998). In these cases complementary InSAR techniques (other than SPN) can be applied to measure such abrupt ground motions which occur in the centre of the longwall panels. However, this type of processing is outside the scope of this paper. The comparison between the measured displacements in the LOS direction and ground data shows that movements are underestimated in the areas where there is an important vertical component.

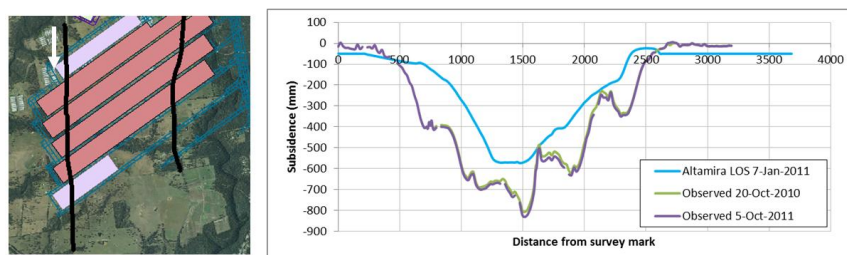


Figure 6- Section views of the ground measured total subsidence compared with satellite subsidence measured in the LOS direction

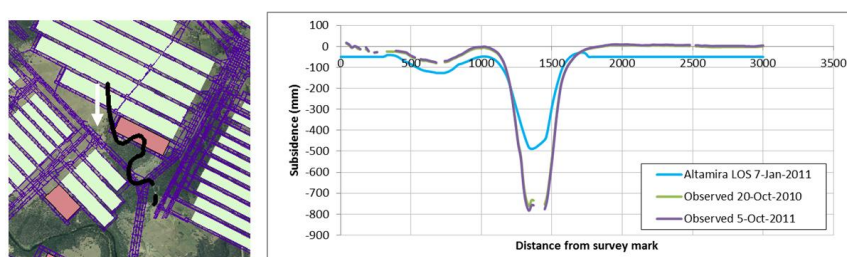


Figure 7 - Section view of the ground measured total subsidence compared with satellite subsidence measured in the LOS direction
InSAR vertically re-projected motion compared to ground data

The LOS measurements have been re-projected into the vertical axis for those areas closer to the centre of the active longwall. This re-projection has been performed taking into consideration that the principal component of the true motion is mainly vertical. As a consequence, the final magnitude is adjusted for each measurement point in accordance with the local angle, which determines the conversion factor (approximately $1/\cos \theta_{incid}$). The direction is set according to the satellite ascending view ground observation geometry given by this archive data.

Figure 8 and Figure 9 show the comparison of ground data with the vertically re-projected InSAR measurements. As can be observed the section profiles of the re-projected InSAR data are similar to the ones obtained by the ground surveys. This comparison confirms the hypothesis of the vertical re-projection over those areas.

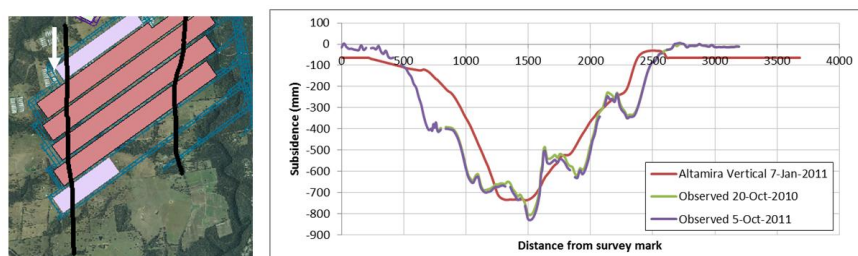


Figure 8 - Section view of the ground measured total subsidence compared with satellite measured motion re-projected to vertical direction

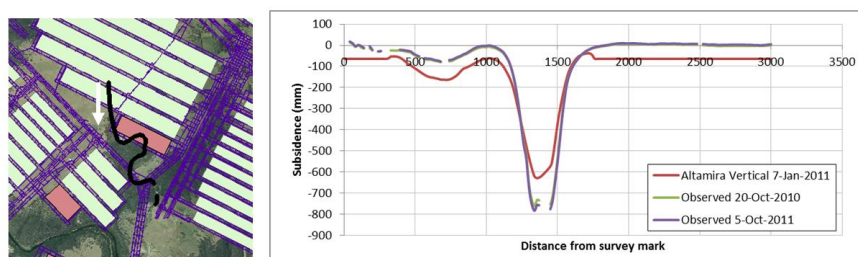


Figure 9 - Section view of the ground measured total subsidence compared with satellite measured motion re-projected to vertical direction

InSAR horizontally re-projected motion

The LOS measurements at the surroundings of the longwall panels are re-projected into the horizontal axis considering the acquisition geometry of the ALOS data. The main assumption made is that the ground motion over these areas has a dominant component which is in the horizontal direction due to mine activities.

As was the case for the vertical re-projection, the final magnitude is adjusted for each measurement point in function of the local angle, which determines the conversion factor (approximately $1/\sin \theta_{incid}$). The direction is set according to the satellite ascending view ground observation geometry given by this archive data.

An example of an area obtained after performing horizontal re-projection is shown in Figure 10. As can be observed, the perimeter of the ground deformation can be precisely defined thanks to the very high density of measurement points. As discussed in the previous section, the re-projection is valid assuming that the true motion vector is predominantly horizontal. In addition, the magnitude and sign of the horizontally projected values are adapted depending on the local acquisition geometry. It is important to remark that this assumption may not be valid for all the areas, like for instance at the boundaries of the creeks where the topography of the river banks can originate changes in the direction of the ground motions.

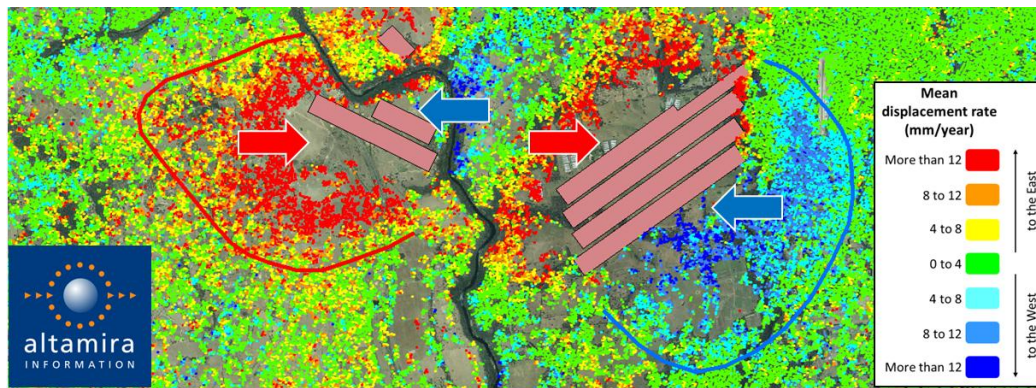


Figure 10 - Horizontal mean deformation rate map over the surroundings of the active longwalls area. The perimeter of ground deformation is marked with the red and blue lines, and the movement direction is indicated with the blue and red arrows

This assumption over the mine far field areas is useful for InSAR motion interpretation. As observed in Figure 10 the areas on the western side of the longwalls move towards the east and the areas on the west side move towards the west at a rate of 10 mm/year. The re-projection also adjusts the magnitude of the measured motion allowing a more accurate analysis of the impact of such deformations. Further studies are ongoing to enhance and validate this approach.

CONCLUSIONS

The application of satellite interferometric techniques is oriented to management measures as these techniques allow identifying and monitoring large areas experiencing different magnitudes and intensities of motion. InSAR measurements provide support in the evaluation of the existing subsidence mechanisms and are effective risk management tools used in mines worldwide to activate mitigation measures when required.

This paper shows an approach to understand and better interpret the measured InSAR motions in longwall mining areas, and in particular how the measurements of vertical and horizontal motions are possible using only one acquisition. This paper also goes a step further proposing the application of different motion direction assumptions based on the location of the measurement points with respect to the active longwalls. In the areas close to the longwall centre improved InSAR measurements are obtained taking into account that the principal component of the ground motion is in the vertical direction. Finally a qualitative comparison of InSAR data with surveying data shows that the correlation between both measurements significantly increases with the re-projection when the assumption is met.

In the same way, the InSAR measurements at the surrounding of the active long wall panels are horizontally re-projected knowing that the ground deformation there has a horizontal dominant component. The results show that the horizontally re-projected InSAR measurements allow defining and mapping the extension of the areas affected by mining-induced horizontal movements and a better definition of the spatial gradients over each single ground structure.

In the presented case study, due to the fact that one satellite mode has been used, external data (modelling, surveying, knowledge of the nature of the ground motion) have been mandatory to identify the areas with predominantly horizontal and vertical motion where the re-projection is properly done. The discussed results demonstrate the suitability and the potentiality of InSAR technology to complement and under certain conditions even supplement other *in situ* surveying techniques for a better characterisation and understanding of the mine induced ground deformations.

The presented case study has been performed using archive data from a low resolution satellite with limited quantity of images and precision, nevertheless the results already show the extreme potential of the technology.

Altamira's InSAR processing techniques adapted for longwall mines demonstrate several distinctive parameters that define this remote sensing methodology as a very promising, effective and cost saving surveying technique, the most important ones being:

- High density of measurements points that allows to precisely set the boundaries of the ground deformation and to map the different shapes and magnitudes affecting each zone (hundreds of points in km² in this case which can be improved to thousands of points in km² when using High Resolution sensors).
- High precision of measurements (4 mm in this case, improved to 2 mm when using High Resolution sensors) that places SPN interferometry as one of the most precise surveying technologies.
- Pixel size (40 m in this case and 3 m in High Resolution sensors) allowing an excellent sampling of the results.

Nowadays, with the current radar satellite constellations it is possible to program an intense data acquisition that, either with one or with two modes, will assure gathering vertical and horizontal motion vectors with maximum precision and accuracy.

ACKNOWLEDGEMENTS

The assistance of Don Kay and Bronwyn Maher of Mine Subsidence Engineering Consultants Pty Ltd (MSEC) who assisted in the preparation of plots in this paper and provided editorial assistance on this paper, particularly in respect of coal mining subsidence issues and their generous assistance is gratefully acknowledged.

REFERENCES

- Massonnet, D and Feigl, K L, 1998. Radar interferometry and its application to changes in the Earth's surface, in *Rev. Geophys.*, 36(4):441-500. doi:10.1029/97RG03139.
- Arnaud, A, Adam, N, Hanssen, R, Inglada, J, Duro, J, Closa, J and Eineder, M, 2003. ASAR ERS interferometric phase continuity, in *Proceedings Geoscience and Remote Sensing Symposium 2003*, IEEE International, 2:1133-1135.
- Duro, J, Adam, N, Arnaud, A, Closa, J and Inglada, J, 2003. High resolution differential interferometry using time series of ERS and ENVISAT SAR data, in *Proceedings FRINGE Symposium*, ESA-ESRIN, p.72.1.
- Espinosa, A and Mora, O, 2012. Tecnologías InSAR en El Teniente Rajo Sur, *Revista Minería Chilena*, Marzo 2012, n 369, p51.