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Application of InSAR for monitoring deformations at the Kiirunavaara Mine

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ABSTRACT
An integral part of sublevel cave underground mining is the associated caving of the surrounding host rock. This causes mining-induced ground surface deformations on both the hangingwall and footwall side of the orebody. The municipality of Kiruna, in northern Sweden, is located in close proximity to the LKAB Kiirunavaara mine and is thus unavoidably affected by the mining activities. To be able to plan for an urban transformation, as the effects of mining approach the city infrastructure, it is necessary to monitor the ground deformations on a regular basis. Historically, GPS-monitoring has been used, with an extensive network of measurement hubs in place. New techniques for monitoring ground deformations are, however, constantly evaluated. As part of this process, LKAB has conducted a five-year research and development project on deformation measurements using radar satellites and the InSAR technology. The project has included a monitoring component and a research- and technology transfer component. The overall findings of the monitoring program, and the associated research and development work are presented. Particular emphasis is put on achieved accuracy and the implications for the ability to reliably monitor the progressing deformations toward the municipality and existing infrastructure. Lessons learnt from the conducted work are presented, followed by recommendations on future use of InSAR for this type of application.
KEYWORDS: Sublevel caving; mining-induced deformations; DInSAR; CTM; CR

1. INTRODUCTION

1.1 Background

It is an undisputable fact that sublevel cave mining results in ground deformations, in particular on the hangingwall side of the orebody, but to some extent also on the footwall side. The deformations are categorized into continuous deformations, not causing fracturing and/or damage, and discontinuous deformations, in which fracturing and caving develops (Figure 1). In the long-term perspective, it is not possible to have any residential buildings or infrastructure within the fracture zone and cave zone.

The Kiirunavaara mine, in northern Sweden, is an iron ore mine owned and operated by the Luossavaara-Kiirunavaara Aktiebolag (LKAB) mining company. The mine is currently exclusively mined underground using large-scale sublevel caving. Annual production amounts to 28 million metric tons of crude ore.

The municipality of Kiruna is located in close proximity to the mine and thus subject to a process of "urban transformation", as the effects of mining approach the city infrastructure. Monitoring of ground deformations on a regular basis is necessary to be able to plan for this urban transformation accordingly.

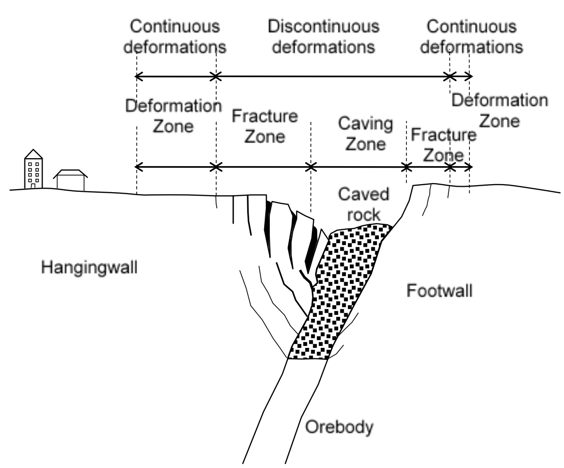

Figure 1: Mine-induced fracturing and deformations on the hangingwall and footwall in sublevel cave mining (schematic, not to scale).

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GPS-monitoring is used in Kiruna for this purpose, with a measurement network presently (fall of 2015) comprising 372 hubs. Readings are taken four times per year. The allowable mining-induced ground deformations in Kiruna are regulated through a ruling in the Environmental Court in Sweden. The "environmental criterion" states that the ground outside the mining industrial area cannot be affected by more 0.3 % strain (horizontally) and 0.2 % tilt (vertically), illustrated schematically in Figure 2.

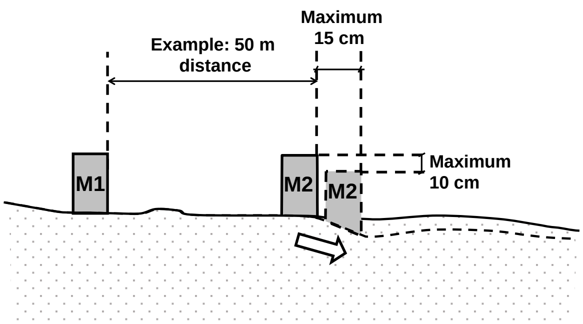

Figure 2: The environmental criterion for allowable mining-induced ground deformations, illustrated for a hub-to-hub distance of 50 m.

Results from the GPS measurements are generally satisfactory and used for establishing the limits of the environmental criterion per the above. However, the work load associated with these measurements is fairly extensive. Moreover, GPS measurements require installations of measurement hubs, with additional hubs required as the area of mining-induced ground deformation increases as a result of mining at larger depths. New and alternative techniques for ground deformation monitoring are thus constantly being evaluated to fulfill the needs of LKAB.

1.2 Work Description

In 2009, LKAB initiated a five-year research and development project on deformation measurements using radar satellite techniques, so-called InSAR technology. The aim of the project was to investigate the application of InSAR for measuring mining-induced ground deformations, to possibly reach the same, or better, measurement precision as in GPS measurements. The project objectives were to:

– Assess the use InSAR technology for LKAB's purposes — as a replacement and/or complement to current GPS measurements.
– Further develop the InSAR technology for winter conditions in high latitudes, aiming at improving precision.
– Conduct a technology transfer to LKAB with the goal of LKAB being able to produce results (deformation maps) in-house from satellite data.

The project was divided into two major components: (i) monitoring, and (ii) research and technology transfer, as shown in Figure 3. The monitoring work was carried out by MDA Geospatial Services, using data from the RADARSAT-2 satellite. MDA also provided technology transfer from MDA to LKAB. The supplementary research work involved Cranfield University and Luleå University of Technology as research partners. The work was conducted in the form of a doctoral thesis project. In addition, supplementary graduate student projects were carried out at both universities.

The overall research objective was to seek to improve the precision in InSAR-measurements for the conditions at the Kiruna site, i.e., at high latitudes and with snow cover during a large portion of the year. The research work was monitored through a reference- and steering group with representatives from both universities and from LKAB.

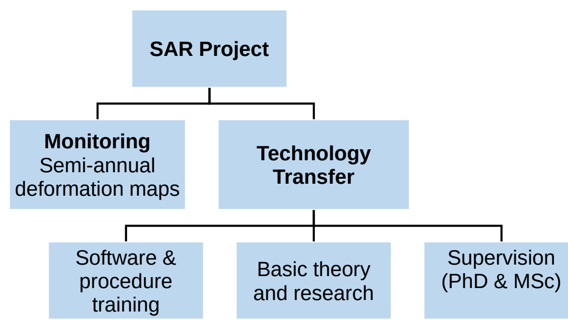

Figure 3: Components of the LKAB InSAR project.

2. MONITORING PROGRAM AND RESEARCH RESULTS

2.1 Historical Analysis

Initially, a historic analysis of InSAR data collected over the time period of 1992 to 2009, was conducted. The data analyzed was from the ERS and ENVISAT satellites, collected from three separate tracks in 74 images. The study was aimed at quantifying the historical ground deformation in the vicinity of the Kiruna mine operations.

A total of 30 deformation maps were created. The recorded deformation pattern was generally as expected, and with the best results obtained for the waste rock dump areas, which provided high coherence between image pairs. The large gaps in the time series of data, and the (relatively) low number of usable image pairs precluded an analysis of so-called "hard targets", or CTM (Coherent Target Monitoring) from these satellites. The work showed, however, that CTM analysis using RADARSAT-2 using a continuous time series during the reminder of the project would likely be successful. The existing infrastructure in the town of Kiruna and the industrial area would provide excellent sources of persistent scatterers year round. Thus, data from 2008 and 2009 from RADARSAT-2 were included in the first deliverable from the monitoring program.

2.2 Monitoring Program

Monitoring of ground deformations was conducted during the period of 2009 to 2014, by MDA Geospatial Services, Inc. Data was obtained from the RADARSAT-2 satellite, with a return period of 24 days. The monitoring program involved using differential InSAR (DInSAR), coherent target monitoring (CTM), persistent InSAR technique (PSInSAR), and supplementary Corner Reflectors (CR) in areas where there were little or no natural or artificial backscatters. A total of 60 corner reflectors (two at each installation point) were initially installed in the Kiruna area, with 6 more reflectors added later, see Figure 4.

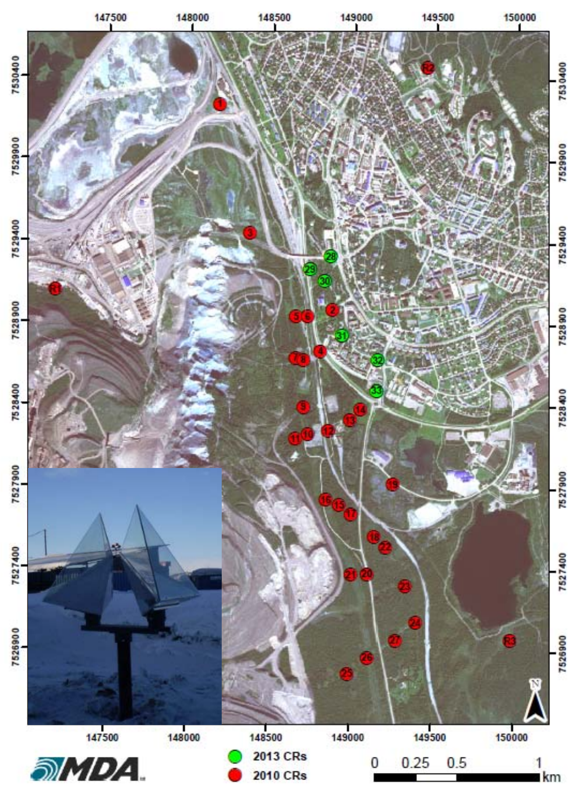

Figure 4: Corner reflectors (CR; see inset) installed in the Kiruna area.

Satellite data is collected for different beam modes, with different incident and aspect angles. Early on, it was found that accuracy in the north-south direction was not satisfactory, primarily due to the polar orbit of (all) satellites (traveling in a nearly north/south orientation). Thus, "line-of-sight", measurements and decompositions into east-west and vertical deformations were more reliable. The final beam combination used for the larger part of the project was U6D, U25A, and U70D.

2.3 Accuracy Assessment

By comparing two independent 3D decompositions, uncertainties in the east/west, vertical, and north/south deformation motion of CRs were found to be 2 mm, 14 mm, and 91 mm, respectively. For the CTM targets, these uncertainties were found to increase slightly to 4 mm, 17 mm, and 113 mm. Uncertainties are minimized for directions with a close to orthogonal basis but the north/south deformation measurement remain poorly constrained.

By considering a 2D decomposition for motion in the east/west (horizontal) and vertical directions, the precision could be further improved, see also Henschel et al. (2015). For a preferred set of 2D decompositions (among a large number tested), the uncertainty in the CR measurements was found to be approximately 2 mm in both the east/west and vertical directions. For the CTM, these uncertainties increase slightly to 4 mm and 3 mm in the east/west and vertical directions respectively.

Thus, by using dual beam coverage, the horizontal east-west and vertical deformation is captured with good precision. The method was applied to all data for the Kiruna site, with previously collected data re-analyzed in the final deliverable.

2.4 Monitoring Data

The data were compiled, analyzed and interpreted, and results then delivered to LKAB every six months, covering the time period from November 2009 to October 2014. The deliverables included: (i) RADARSAT-2 imagery for each beam mode used, (ii) conventional deformation maps, and (iii) time series profiles of individual point targets (including both CR and CTM). Continuous improvements were made for the deliverables during the project.

The CTM results were based on 250,000 points (between the individual beams), and the data was then subsampled to 25 x 25 m cells before the beam combinations were performed. The collocation of available points in each beam resulted in a total of 23,850 points for the motion estimation.

The delivered deformation maps were used to assess overall trends in the data. Moreover, time series plots were created for selected CTM points that were deemed of particular interest for LKAB, and thus subject to more detailed interpretation.

2.5 Comparison with GPS Data

An example of a time series plot for CR targets is shown in Figure 5. Ground deformations from GPS measurements are plotted for comparison, also for the E-W deformation. The GPS data are accumulated deformations from a starting date as close as possible to the start data of the InSAR measurements. The precision in the GPS measurements has been estimated to 7 mm in the horizontal direction (through a repeatability test).

These examples indicate that both the trends and magnitudes of ground deformation are similar for the InSAR and GPS measurements, which lend some reliability to the InSAR data. Additional work should, nevertheless, be undertaken to confirm these findings for other areas and other CRs.

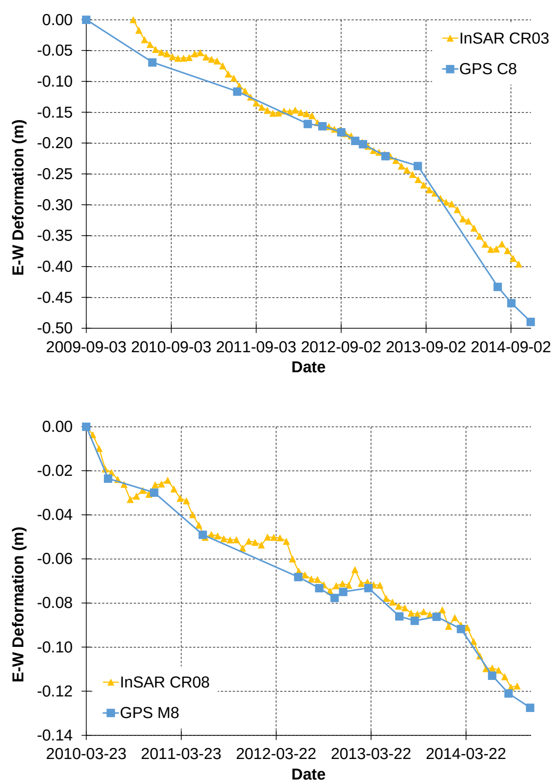

Figure 5: Cumulative deformation measurement for CR03 and CR08, compared with GPS data from nearby points C8 and M8, in the east-west direction.

A different methodology was used by Wickramanayake et al. (2015), in which the GPS-data were first re-calculated to line-of-sight direction to enable more accurate comparison. All calculations were done for the U6D beam model. In addition to using sequential interferograms (interferograms that have the shortest temporal baseline) to extract the CR deformation measurements, the so-called "small baseline subset" (SBS) technique was also used. With this technique, different subsets of interferograms are linked together to extract the complete deformation time series. Two sets of SBS techniques were employed — one in which all interferograms were used, and one in which only interferograms with a high average coherence (threshold set at 0.25) were utilized, essentially meaning that several winter image pairs were discarded.

An example of the results is shown in Figure 6. The difference between GPS and InSAR CR data is large for two of the applied analysis techniques, whereas a relatively good agreement is found when the InSAR data was extracted using only high average coherence interferograms (CR-InSAR-SBAS-COR). The mean error compared to the GPS measurements is 1.1 mm with 10.7 mm standard deviation, and the correlation coefficient is 0.88.

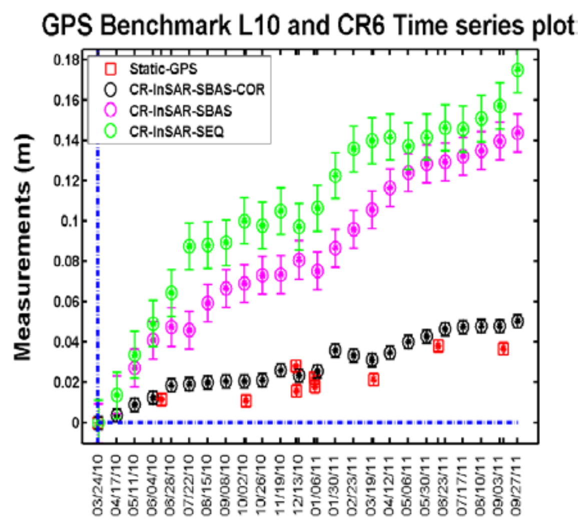

Figure 6: Time series plots of double difference CRInSAR measurements (CR6) and double difference Static-GPS measurements (L10) for different InSAR analysis techniques.

The large difference between the CR-InSAR-SBAS-COR and CR-InSAR-SBAS in Figure 6 may be because the InSAR winter measurements (due to snow) appear to have larger phase errors than the summer measurements. This additional phase can be reduced by using only those interferograms with higher average spatial coherence values and the SBAS techniques, as described above. There is, however, the risk of losing entire sets of interferograms related to a particular (winter) image when interferograms with low coherence are removed. It should also be pointed out that errors resulting from the ground snow layer and from the snow layer on top of the corner reflector shield have not been separated. The next step would be to quantify the error contribution from each component.

2.6 Strain Calculations

An important potential application of the InSAR measurements is the ability to assess the location of where the environmental criterion (cf. Section 1.1) is satisfied. The same methodology as used for GPS measurements was applied to the InSAR data, using CR measurements. An example of the calculated strains is shown in Figure 7, together with the corresponding location of the strain limit calculated from GPS measurements.

The agreement between InSAR-derived strains and GPS-derived strains is reasonably good, with the InSAR data generally slightly larger strains. It appears likely that InSAR data can be used for assessing the "environmental criterion". However, more work is required to come up with a robust method for strain calculation, possibly also requiring additional CRs and/or including CTM targets to increase coverage.

2.7 Seasonal Coherence Variation

In the work by Wickramanayake et al. (2016), the degree of spatial coherence was studied to identify the seasonal variation in interferograms. A total of 561 differential interferograms were used, and arranged in three different ways for the analysis, with the first including common master interferograms (with the summer master image), the second including the sequential interferograms that have the shortest temporal baseline, and the third accounting for all possible combinations of the interferograms (full network of interferograms).

As expected, seasonal variation in spatial coherence due to the ground snow layer in winter was found. Only less than 50% of the available RADARSAT-2 images were suitable for DInSAR deformation measurements. However, there was significant summer-to-summer coherence for some regions even over the course of a few years. The master image should thus be a summer image to achieve high coherence. Even with a longer temporal baseline, the summer-to-summer interferograms for the barren and flat waste rock areas provide almost the same coherence. Forest areas, on the other hand, lose coherence with an increase in the temporal baseline and do not regain it seasonally. A next step would be to study the seasonal variation in coherence in natural or man-made targets/persistent scatterers.

2.8 Technology Transfer

The purpose of the technology transfer was to build up knowledge and know-how within LKAB regarding InSAR-technology. MDA provided LKAB with high-level training for a larger group and more targeted training to a smaller group, including software and hardware tools to be able produce deformation maps independently.

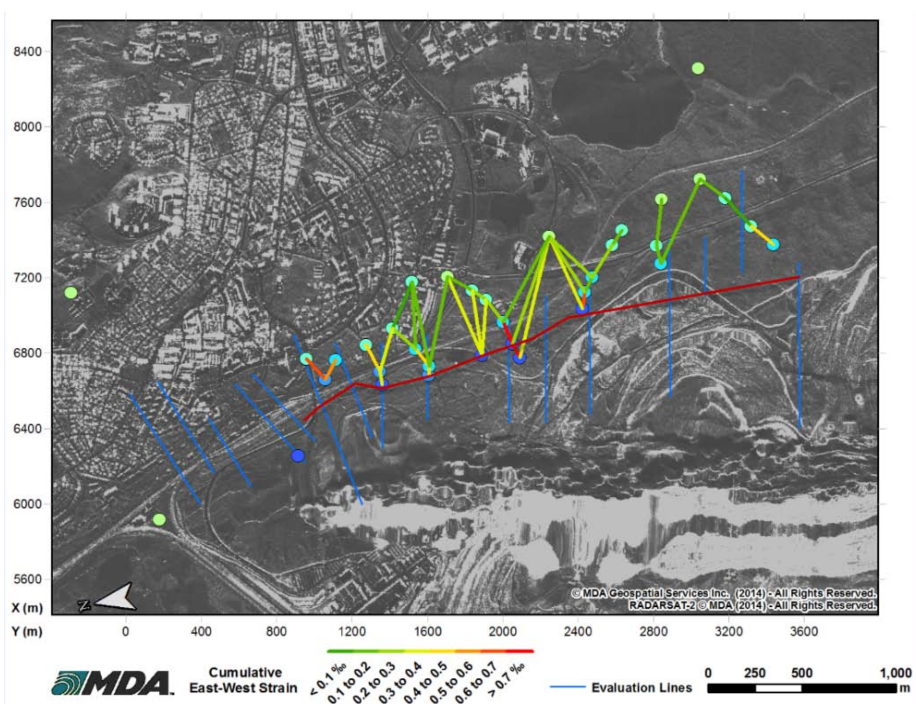

Figure 7: Spatial distribution of CR strain measurements in the east-west direction for the period of March 2010 to April 2014, with green representing low strain and red representing high strain. The environmental criterion limit determined from GPS measurements, corresponding to 0.3 % strain, is shown with a red line.

An "in-house" technology transfer was also accomplished, through regular meetings and training sessions on InSAR processing with LKAB staff. During the course of the project, it became clear that the goal of producing deformation maps independently by LKAB was probably too ambitious. However, the technology transfer ensured that LKAB staff acquired a deeper understanding on InSAR technology, and thus can critically assess results and assumptions made in the analysis.

3. DISCUSSION AND CONCLUSIONS

InSAR-technology allows measurements over large areas, with fewer measurement hubs (CRs) compared to GPS measurements. DInSAR measurements providing deformation maps worked well for identifying trends and patterns in ground deformations. The technique is, however, dependent on achieving high coherence between image pairs, which has proven challenging at the Kiruna site.

Measurements on Corner Reflectors (CR) and "hard targets" (CTM) provided high-precision data for specific points. The CTM measurements are particularly appealing since they do not require installation of reflectors, and were found to work very well in urban environments. A potential problem is the ambiguous phase unwrapping that can arise in cases where deformations between successive satellite passes are large. The project work has shown that by including a large number of measurement points in the analysis, it is possible to reduce the effects of this potential error source, although it cannot be completely eliminated. However, in areas where infrastructure is, or is planned to be removed, due to mining effects, CTM coverage is poor and must likely be supplemented with CR installations.

While the east-west and vertical deformation components can be satisfactorily analyzed, resolving deformations in the north-south direction with an acceptable accuracy was not possible. The improved accuracy obtained through a dual beam acquisition is promising for future work, implying that higher precision can be obtained with fewer beam modes, for east-west and vertical deformations.

Comparison between GPS and InSAR data are important since this provides a tool to "ground truth" the InSAR data at this site. This constitutes an important next stage to further the application of InSAR for the specific tasks of interest for LKAB, particularly for determining the limits to the environmental criterion for allowable deformations.

Coherence effects and whether e.g., certain winter images should be discarded or not from the analysis also warrant further work. A robust methodology must be in place for the data analysis, without risking the loss of important information.

4. RECOMMENDATIONS

The requirements on the possible future use of InSAR in Kiruna should be further defined, including what monitoring and interpretation techniques that are most applicable for these conditions. More work on comparing CR/CTM InSAR data with GPS measurement data should be conducted, to further "ground truth" the InSAR data. The long series of GPS data at Kiruna provide excellent opportunities to "calibrate" InSAR results and minimize e.g., phase and unwrapping errors. This step is also important to determine what methodology should be used for InSAR processing and to what extent images with low coherence can be discarded.

Additional Corner Reflectors should be installed in areas with poor CTM coverage and poor back-scatter. These are relatively inexpensive and would supplement the DInSAR and CTM data. The location of CRs should be based on the results from GPS-measurements, and a geomechanical perspective, to increase understanding of the mining-induced ground deformations. Additional CRs would also help in better delineating the location of the environmental criterion strain limit from InSAR data.

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