MINING SUBSIDENCE MONITORING USING THE COMBINED INSAR AND GPS APPROACH

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Abstract

Compared to opencut mining, underground coal mining is more common in Australia due to its lesser impact on the environment. Although there are several underground mining methods, such as the longwall, pillar, bord, and miniwall, longwall mining is the most commonly used method due to its high efficiency. However, longwall mining does lead to significant ground subsidence. Mining subsidence is so common that in order to ensure the safety of surface transportation and local residents, current monitoring programs in many mines have included GPS surveys, conventional precise levelling and theodolite surveys, EDM surveys, and remote electronic monitoring (Hebblewhite et al, 2000). These techniques are costly and inefficient compared with remote sensing techniques such as that afforded by Synthetic Aperture Radar Interferometry (InSAR). However, InSAR results may not be accurate enough for this application due to the uncertainties in the SAR satellite orbit and the signal disturbances due to the atmosphere. GPS surveys can be used to account for these biases.

The Satellite Navigation And Positioning (SNAP) group at The University of New South Wales, with its strength in GPS deformation monitoring, and the Radar Interferometry Group at Stanford University, with its strength in InSAR data processing, have developed a joint project to monitor ground subsidence due to underground mining, by combining the techniques of InSAR and GPS. In order to test the combined technique, both radar corner reflectors and GPS receivers are collocated in the mining region whenever the SAR satellite (ERS-2) passes over. The reflectors can be seen as bright spots on the SAR image to facilitate precise image co-registration during InSAR data processing, while the GPS measurements are used as ground control points to mitigate errors in the InSAR results. Technical details on how to collocate the radar reflectors and GPS receivers are discussed. Two components of the project, the 'soft' and 'hard' densification schemes, are described.

1. Introduction

The maintenance of accuracy and integrity in carrying out mine surveying and monitoring, and in the preparation, maintenance and checking of plans is of paramount importance in relation to the safety and efficiency of operations. This is particularly the case for underground mines, but is also of importance in surface mines, in open pitwall stability monitoring, in open pits intersecting old underground workings, and surface control over existing underground workings. The need to ensure accurate survey control for mapping of operations, and as the basis for monitoring programs, are some of the reasons that mine surveying remains a registered occupation (requiring statutory appointment) in Australia, for example, under the Mines Safety and Inspection Act 1994.

The history of mining disasters includes cases of subsidence and collapse into workings, and also a number of inrushes into underground mines, where deficiencies in surveying and monitoring, or in the maintenance and interpretation of plans, were prime causes. Failures and oversights can have, and have had, catastrophic consequences. The most recent such event in Australia was at Gretley Colliery in the state of New South Wales (NSW) in 1996. In this accident four men were drowned by inrushing water from the long abandoned old workings of the Young Wallsend Colliery, because the mine was working to a plan showing the Young Wallsend Colliery more than 100m away from the point of holing-in, while it was actually only 7 or 8 metres away (NSW Department of Mineral Resources, 1998). The accident did show that controls and checks on standards of practice and verification of precision and integrity are lacking in some cases, and the process needs to be better managed, with adequate monitoring and mentoring by professionals with in-depth experience, with the support of integrated geodetic techniques.

In the established mine fields of eastern Australia it is becoming increasingly difficult to select underground minesites which avoid major engineering structures, both on the surface and underground (highways, bridges, buildings, abandoned workings of old underground mines, and so on). The Tower Colliery, an underground longwall mine southwest of Sydney, is a representative example, with the surface topography overlying the mine consists of several steep-sided river gorges. The surface is traversed by a freeway that crosses one of the gorges on twin, six-span, box-girder bridges. Consequently, a major surface subsidence monitoring program has been in place for several years, including intensive conventional, GPS and EDM surveying, plus real-time monitoring of critical components of the bridge structure (Hebblewhite et al, 2000).

However, current subsidence monitoring techniques are both time-consuming and costly. Hence, the monitoring is usually constrained to very localised area, and there is no way to monitor any regional deformation induced by underground mining. In addition, even in the localised area, the monitoring points are not usually dense enough to assist in understanding the mechanisms involved in ground subsidence. Therefore this colliery site has been selected for the test described in this paper, with the objective of monitoring the surface deformation through an integration of several geodetic techniques.

In this paper, the integration of the two geodetic techniques of the Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) is proposed to address applications such as ground subsidence monitoring.

2. Mining subsidence monitoring using the combined InSAR and GPS approach

During the last decade of the 20th century, GPS has increasingly become an indispensable tool for high precision positioning. Current GPS capabilities permit the determination of inter-receiver distances at the sub-cm accuracy level, for receiver separations of tens to hundreds of kilometres, from which can be inferred the rate-of-change of distance between precisely monumented groundmarks. This is the basic geodetic measure from which can be inferred the ground deformation. The pattern of ground subsidence due to mining, determined from the analysis of such measures across a GPS network, is an important input to models that seek to explain the mechanisms for such deformation, and hopefully to mitigate the damage to society caused by such (slow or fast) ground movements. However, continuous GPS monitoring has generally been considered relatively expensive for many localised ground subsidence monitoring applications.

InSAR is a technique first suggested in 1974 and, after more than two decades of development, is now well developed with many applications in mapping topography, and topographic change determination following earthquakes (Massonnet et al, 1993). Although InSAR for ground subsidence monitoring has been a research topic in recent years, it has not become an operational technique because of the presence of biases that seriously degrade the accuracy of InSAR-only results (Goldstein, 1995; Zebker et al, 1997).

Continuously-operated GPS (CGPS) receiver networks have been established in many parts of the world to address a variety of geodetic and survey applications, on a range of spatial scales. These include measuring ground subsidence over small areal extents (due to underground mining, extraction of fluids, etc.), tracking surface crustal deformation on local and regional scales associated with active seismic faults and volcanoes, and local monitoring of slope stability (caused by open pit mining operations, unstable natural features, etc.). Among them, the GEONET (GPS Earth Observation Network) operated by the Geographical Survey Institute (GSI) of Japan, has evolved into the world's densest GPS network, with almost one thousand GPS receivers established with an average spatial resolution of 25km, and a temporal resolution of 30 seconds (this is the receiver data sampling rate).

Although high temporal resolution is a significant advantage of CGPS, the spatial resolution (defined by the inter-receiver distances) is not usually adequate for characterising or monitoring ground subsidence due to localised effects such as underground mining. For such applications sub-km level spatial resolution is required. InSAR, on the other hand, exhibits around 25m spatial resolution. Without the need for any ground-based receiver or cooperative target, InSAR can, in principle, monitor every corner of the Earth. However, InSAR is very sensitive to biases due to atmospheric propagation effects (tropospheric delay, ionospheric delay, etc.), satellite orbit error, condition of the ground surface and temporal decorrelation. When present in the InSAR image, these errors can be very misleading and lead to misinterpretation. Furthermore, the repeat cycle of 24 (RADARSAT), 35 (ERS-1&2) to 44 (JERS-1) days of SAR satellites may not provide sufficient temporal resolution for monitoring ground subsidence.

Data from GPS networks can be used to map tropospheric water vapour and ionospheric disturbances, and hence these results can be used to calibrate the atmospheric effects in InSAR. GPS coordinates can be considered as being 'absolute' in the sense that they are tied to a well-defined terrestrial reference system. On the other hand, InSAR results are 'relative' measurements. In addition, InSAR results, with their high spatial resolution, can be used to densify GPS results in a spatial sense. Therefore it is obvious that the two techniques are complementary. However, there are several densification strategies that can optimise the integration of GPS and InSAR for ground subsidence monitoring. Among them, the following two are discussed in this paper:

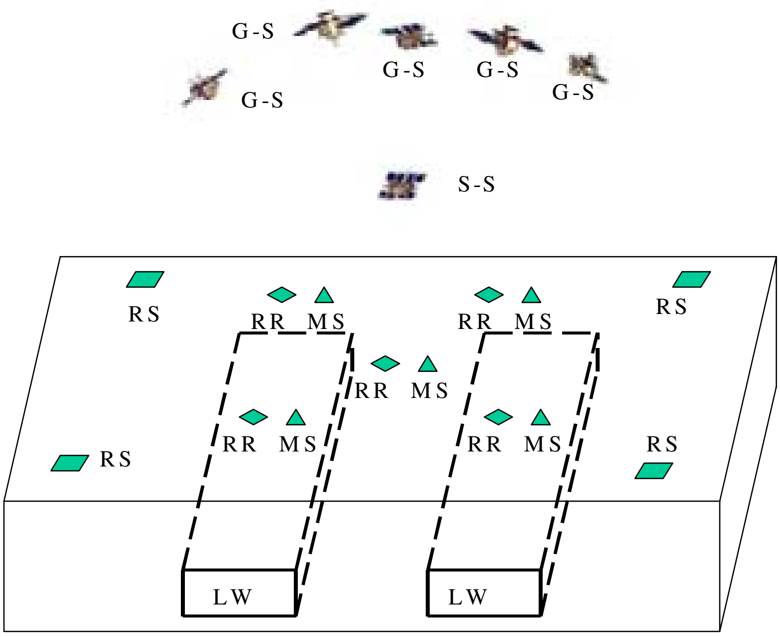
- the integration of GPS and InSAR - the so-called "soft spatial densification" scheme, and
- the integration of dual- and single-frequency GPS receiver instrumentation - the so-called "hard spatial densification" option.

As illustrated in Figure 1, in the proposed integrated monitoring technique, both GPS (G-S) and SAR (S-S) satellites can be used. On the ground, three or four permanent dual-frequency GPS receivers, located on geologically stable marks, are used as reference stations (RSs). RSs can be up to 100km away from the area of interest. Several single-frequency GPS receivers, installed directly above the mine site, are used as monitoring stations (MSs) to in-fill the RS network. Meanwhile, several radar reflectors (RRs) are co-located with the MSs for the purpose of calibrating InSAR results.

3. Collocation of GPS receivers and radar reflectors

3.1 The radar reflectors

Figure 2 shows an assembled radar reflector used for the project. In the figure, Item 7 is one of the three panels. The other two are omitted for clarity. The left, right, and upper beams (Items 1, 2, and 3 respectively) are designed to support the panels, while three long (Item 4) and three short (Item 5) braces are used to strengthen the structure. The reflector is fixed on the ground using three pipes (Item 9). For the reflector material, solid, perforated, or mesh panels may be used. Although the lightest, use of mesh panels is not the best choice because the mesh grating gives a lower radar cross section compared to solid or perforated panels. Moreover, the mesh is much harder to assemble due to sharp edges that are created in the cutting process. Although solid panels would give the maximum radar cross section, use of perforated panels is considered the optimum design because they provide drainage in wet weather, and work well in windy conditions.



G-S: GPS satellite	S-S: SAR satellite	LW: underground mining longwall
RR: radar reflector	RS: GPS reference station	MS: GPS monitoring station

Figure 1. Integrated space geodetic techniques for ground subsidence monitoring (not to scale).

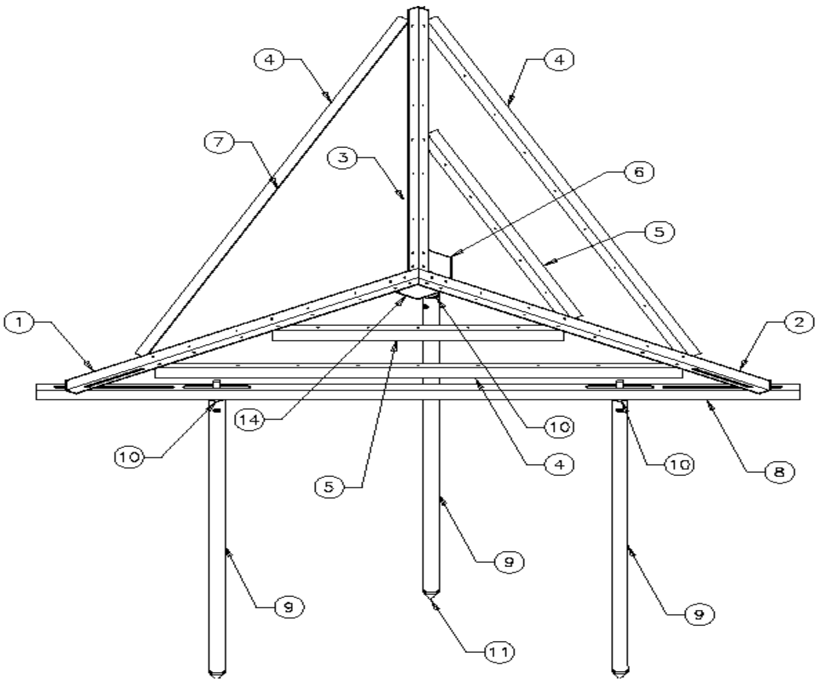


Figure 2. The assembled radar reflector.

In terms of the material for the panel, no significant difference would be noticed between, for example, aluminum and galvanised iron, as long as the panels are solid. However, it is suggested that sheet metal thickness of the order of 0.060" should be used, otherwise the sheet metal will not be uniformly flat. The key is making a perfect corner with no imperfections or undulations in the panels. Aluminum sheet metal is light and cheap compared to, for example, galvanised iron sheet metal, hence this material has been chosen for the reflectors used in this project.

3.2 Deployment of the radar reflectors

The reflectors described in section 3.1 are primarily designed to be used with RADARSAT. In order to use them with ERS-2, it is crucial to align them in the direction to the satellite so that the response of the radar reflector is significant compared with the background clutter. Figure 3 is a sketch of a radar reflector.

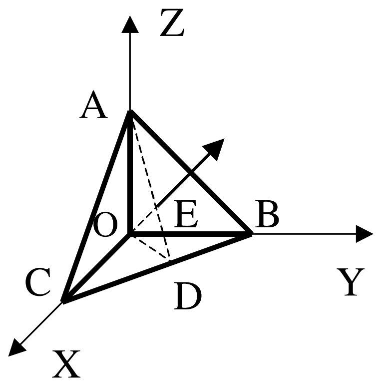


Figure 3. Geometry of the radar reflector.

Assume that OA, OB and OC are all unit length, i.e.

OA = OB = OC = 1

Then AB = BC = CA = 1.414

OD = OBsin(∠OBD) = 0.707
∠OAD = $\tan^{-1}$(OD/OA) = 35.3^0

Suppose that OE is normal to the plane ABC and plane OBC is horizontal. The zenith angle of OE would be:

∠AOE = 90^0 - ∠OAD = 54.7^0

Let θ be the look angle of the radar satellite. In order that OE points to the satellite, side BC would have to be raised by:

DD' = OD sin(∠AOE - θ)

Where D' is the projection of D on the horizontal plane. Here DD' is in fact a scale factor. As shown in Figure 4, θ is 23^0 for ERS-2. If OA of the reflector is 1.00m, for the ERS-2 satellite DD' will be 0.37m. Table 1 has listed DD' for some radar satellites.

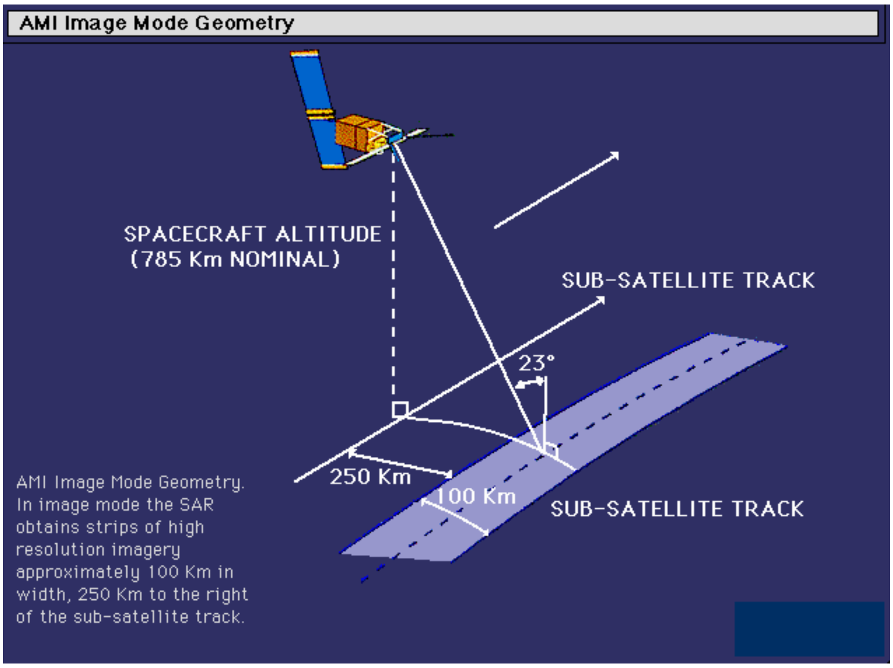


Figure 4. Imaging geometry of ERS satellites (after ESA, 2000).

Table 1. Scale factor DD' for some radar satellites.

Satellite	ERS-1&2	RADARSAT	JERS-1
Orbit inclination	98.5°	98.6°	98°
Look angle	23^0	$10^0 \sim 59^0$	35^0
DD'	0.37	0.50 ~ - 0.05	0.24

Therefore, to collocate the reflectors and the GPS receivers in the field, the procedure would be:

- Link reflector site O to the collocated GPS site by GPS survey.
- Rest plane OBC on the ground (assumed to be horizontal).
- Determine whether plane ABC should face east or west by checking whether the pass is a descending or ascending one (for ERS-2, face east for descending pass and west for ascending pass, see Figure 5), and point BC to north.
- Rotate the reflector around OA axis clockwise (descending) or anti-clockwise (ascending) for an angle of (i - 90°) (i is the inclination of the satellite orbit, Figure 5).
- Raise side BC by DD'.

Although corner radar reflectors are in the trihedral design to ensure that radar waves can be reflected back to the satellite, the alignment of the effective reflecting surface to the satellite can make a big difference as evident in Figure 6. In Figure 6a, the effective reflecting area is at a maximum while in Figure 6b it is at a minimum.

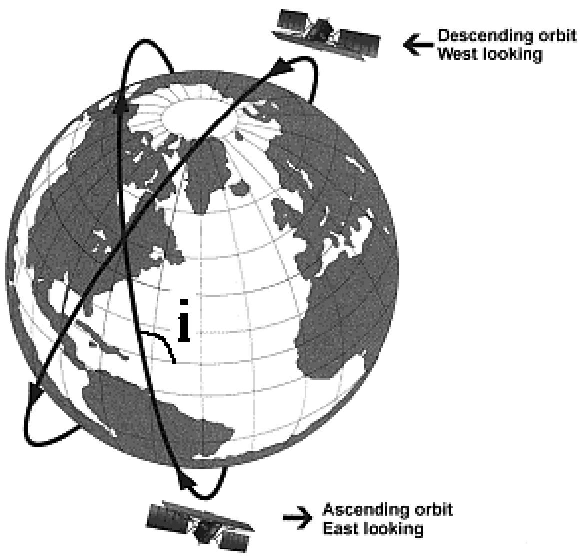


Figure 5. ERS ascending and descending orbits.

(b)

(a)

Figure 6. The maximum (a) and minimum (b) effective reflecting area of a reflector.

The deployment of the reflectors is further complicated by the fact that for the radar missions the satellite must be programmed to acquire data. As there is a constraint on acquisition time due to the available electric power, only a certain number of scenes per orbit can be acquired. It is possible to acquire a scene only if the satellite is in view of a ground station, in order to transmit the data through high rate links, but this may give rise to conflicts during local daytime with the optical missions. As shown in Table 2, for example, Track 173 has been unable to be programmed due to conflict at the ground station with data reception from optical sensors.

After its commissioning, ERS-2 was immediately placed in an orbit giving a 35-day Multidiscipline cycle, and is expected to be operated on this cycle for the rest of its working life. This provides total SAR coverage within the reception zones of the ERS ground stations. However, coverage in the Multidiscipline phase is, in reality, provided at a greater frequency than 35 days due to the swath overlap and the use of both ascending (ID No 1 and 3) and descending (ID No 2 and 4) orbits, as shown in Figure 7. For example, in Table 2, coverage of the Tower Colliery area is provided as follows: if the first pass takes place on day 1 (16 January 2001 13:04UTC), there are two further passes on days 5 (20 January 2001) and 21 (5 February 2001) before the cycle restarts 35 days later on day 36 (20 February 2001). From Figure 8, it can be seen that the region around the Tower Colliery is a good test site for this project because there are no other features with strong reflection.

Table 2. ERS-2 satellite image acquisition programming.

				UTC			EST (UTC+11)	
Orbit	Track	Frame	Delta	Date	Time	Status	**Date**	**Time**
30023	109	6489	0	20010116	13:04	V Tower	**20010117**	**0:04**
30087	173	4293	0	20010120	23:52	V Tower	**20010121**	**10:52**
30252	338	6507	0	20010201	13:02	V UNSW	**20010202**	**0:02**
30316	402	4293	0	20010205	23:49	Tower &UNSW	**20010206**	**10:49**
30524	109	6489	0	20010220	13:04	V Tower	**20010221**	**0:04**
30588	173	4293	0	20010224	23:52	V Tower	**20010225**	**10:52**
30753	338	6507	0	20010308	13:02	V UNSW	**20010309**	**0:02**
30817	402	4293	0	20010312	23:49	Tower &UNSW	**20010313**	**10:49**
31025	109	6489	0	20010327	13:04	V Tower	**20010328**	**0:04**
31089	173	4293	0	20010331	23:52	V Tower	**20010401**	**10:52**
31254	338	6507	0	20010412	13:02	V UNSW	**20010413**	**0:02**
31318	402	4293	0	20010416	23:49	Tower &UNSW	**20010417**	**10:49**
31526	109	6489	0	20010501	13:04	V Tower	**20010502**	**0:04**
31590	173	4293	0	20010505	23:52	V Tower	**20010506**	**10:52**
31755	338	6507	0	20010517	13:02	V UNSW	**20010518**	**0:02**
31819	402	4293	0	20010521	23:49	Tower &UNSW	**20010522**	**10:49**

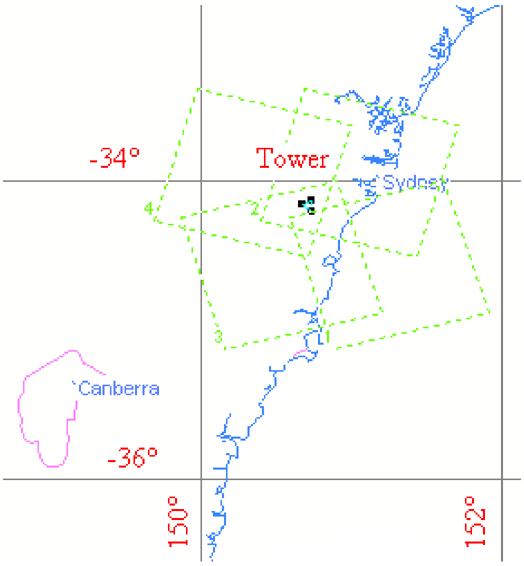


Figure 7. Plot of ERS-2 SAR planning for subsidence monitoring at the Tower Colliery.

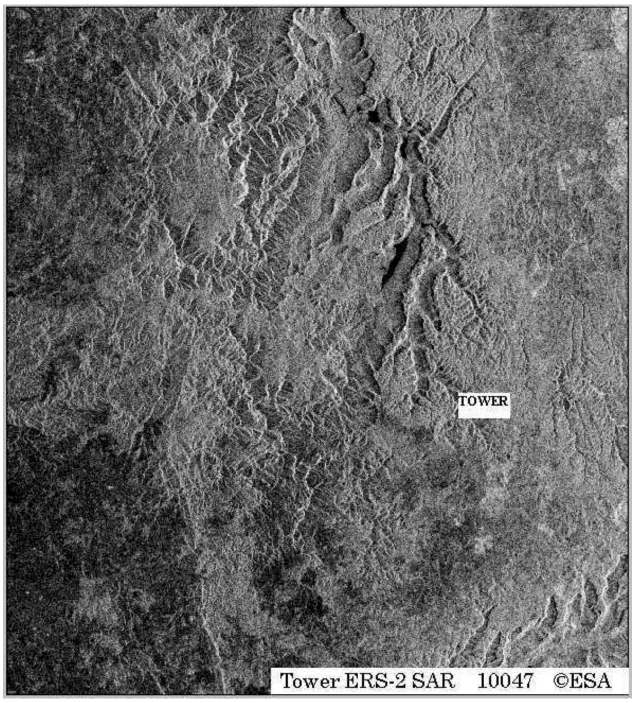


Figure 8. ERS-2 SAR amplitude image of the Tower Colliery area, Track 173, acquired on 22 March 1997.

4. Soft spatial densification

Soft spatial densification is achieved by the integration of GPS with techniques such as differential Synthetic Aperture Radar Interferometry (InSAR) (referred to as 'soft densification' as no additional GPS hardware is needed, see Ge et al, 2000a). In contrast to the GPS technique, InSAR is capable of very high spatial resolution (of the order of 25m), but with a relatively low temporal resolution (35 days for the ERS-2 mission). However, InSAR requires some ground GPS receivers to aid in the mitigation of measurement biases that degrade the accuracy of the InSAR-only results. The integrated InSAR-GPS technique has the potential to measure deformations at sub-centimetre levels of accuracy with unprecedented spatial coverage (Bock & Williams, 1997).

The proposed GPS-InSAR integration technique is referred to as "double interpolation and double prediction" (DIDP). In the DIDP approach the first step is to derive atmospheric corrections to InSAR from GPS analyses. Analysis of the GPS data can give estimates of precipitable water vapour (in a technique referred to these days as "GPS meteorology"), as well as the ionospheric delay (possible because of the available dual-frequency GPS observations). The second step is to remove or mitigate the SAR satellite orbit errors by using GPS results as constraints. In a third step the GPS observations, separated by one or several InSAR repeat cycles within the SAR image, are 'densified' onto a grid. This is done by interpolation in the spatial domain using as a basis a distribution model derived from the GPS-corrected InSAR results. The densified gridded values are then interpolated in the time domain using as a basis a dynamic model derived from the daily, hourly, or even 30 second sampling rate of the GPS data series, incorporating known geophysical information such as the locations and geometries of active faults (Ge et al., 2000b). The adaptive filter can be used in this step. In a fourth step, based on the double interpolation result, forward filtering (e.g. Kalman filtering) can be used to predict the deformation at all points on the grid - in effect a double prediction in both the temporal and spatial domains.

5. Hard spatial densification

Hard spatial densification is effected by the use of low-cost receivers (e.g. single-frequency receivers) to densify a sparse dual-frequency continuous GPS (CGPS) network. The high cost of dual-frequency GPS receivers (typically of the order of US$10,000-20,000 each, excluding monument and infrastructure construction costs) has resulted in the CGPS inter-station distance being of the order of a few tens of kilometres in the case of the best instrumented networks, such as in Japan, and many times that in the case of typical CGPS networks in other countries. This is far too sparse for ground subsidence monitoring. The proposed 'hard densification' design is based on an integrated, dual-mode network consisting of low-cost GPS receivers installed at monitoring stations across the area of interest, surrounded by a sparser CGPS network of dual-frequency receivers installed at reference stations. Through enhanced data processing algorithms such a dual-mode CGPS network is able to deliver better than centimetre level accuracy (Rizos et al, 2000). This scheme can be used to complement and verify the soft densification technique referred to in section 4.

6. Concluding remarks

A joint project between the University of New South Wales and the Stanford University to monitor ground subsidence due to underground mining, by combining the techniques of InSAR and GPS, has begun. Technical details on how to collocate the radar reflectors and GPS receivers are discussed. Two components of the project, the ‘soft’ and ‘hard’ densifications, have been presented. First results of InSAR are expected in early 2001.

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