A View From Above: Using InSAR to Eliminate the Uncertainty of Mark Movement

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ABSTRACT

Advancements in measurement technologies and improvements in Australia's national datums have exposed the need to monitor ground surface movements previously thought to be insignificant. Ground surface deformation directly impacts physical survey marks and monuments, in turn causing problems for surveyors trying to determine their position. The uncertainty surrounding mark movement has long plagued the surveying and geospatial industries, with a reliable yet accessible solution being needed. This paper is based on the first author's undergraduate honours research thesis at the University of New South Wales (UNSW), which received the 2023 Excellence in Surveying and Spatial Information (EISSI) University Student of the Year award. It investigates modern measurement techniques and determines their effectiveness and suitability for large-scale ground monitoring across Australia. Specifically, the accuracy and suitability of publicly available Interferometric Synthetic Aperture Radar (InSAR) data is examined by comparing it against trusted ground-based survey methods, i.e. Global Navigation Satellite System (GNSS) positioning and differential levelling. Horizontal and vertical ground velocities determined by InSAR missions in NSW's Southern Coalfield are contrasted against velocities derived using static and Real-Time Kinematic (RTK) GNSS, and differential levelling, to identify the effects of mine subsidence in the region. The results indicate that although the InSAR data could be used to quickly identify areas of concern, the magnitude of the velocity values greatly varies to those derived by ground-based methods. In most instances, InSAR is effective at determining the direction of the ground movement (being either up or down, or east or west). However, the rate of movement not only differs from the ground-based results but also between each individual InSAR mission. Whilst little correlation is evident, the poor spatial resolution of the InSAR data coupled with an assumption of linear velocity rates from the ground-based data are both significant limiting factors of this study. Nevertheless, it is obvious that InSAR has the potential to be an extremely useful tool for surveyors and could finally reduce the uncertainty when establishing reliable survey control following surface deformation.

KEYWORDS: *Deformation, survey mark movement, uncertainty, surveying, InSAR.*

1 INTRODUCTION

Although the need for large-scale deformation monitoring in Australia has long been regarded as unessential, significant advancements in measurement technologies coupled with pronounced improvements in the country's national datums have unearthed the need for a more robust approach to be adopted. With smaller uncertainties in measured values, small changes in the topography of the land can be identified with greater confidence, in turn uncovering their potential impact on the infrastructure upon the land. The impact of this deformation can be directly seen in survey marks and monuments, whose positions are closely monitored and maintained by surveyors across the country.

Presently, a nationwide strategy for managing ground deformation is yet to be established in Australia. A key reason for this is due to the country's vastness and low population density, making it unfeasible and unjustifiable to cover the continent with traditional surveying methods. In addition, the difficulty in reliably determining the true nature and extent of deformation events has led to it being assessed on a case-by-case basis. However, emerging technologies such as Interferometric Synthetic Aperture Radar (InSAR) promise to provide a unique solution to the problem, with many countries around the world already implementing such instruments.

Survey marks and monuments play a vital role in the management of land and infrastructure in Australia. Their primary purpose is to provide a physical reference to an intangible entity, such as the cadastre or an underlying reference frame, i.e. the Geocentric Datum of Australia 2020 (GDA2020). In the case of the cadastre, for most practical applications, property boundaries need to be located on the ground for them to be useful. In the New Zealand Supreme Court case of Equitable Building and Investment Co. Ltd. v. Ross (1886), Judge Richmond states "*Neither the words of a deed, nor the lines and figures of a plan, can absolutely speak for themselves. They must, in some way or other, be applied to the ground.*" In this statement, Richmond implies that for property boundaries to be useful, they must be administered to the physical world. From this vein stems the notion of a 'monumented cadastre', whereby physical features are the sole means of identifying the location of property boundaries.

The benefit of using marks and monuments over measurements and descriptions is that they are far less ambiguous. Whilst a boundary dimension or a coordinate may be stated to an accuracy at the millimetre level, errors in measurement mean there is almost always a degree of uncertainty in the values. This notion is explored by Richmond (1886), when he remarked: "*Land-surveying is a practical art; which is as much to say that it is not capable of the ideal precision of the mathematics*."

However, this presents the controversial predicament where figures on a plan or stated coordinates of marks disagree with what a surveyor may deem to be their real-world position. In such a situation, an investigation may be required in order to answer the following questions:

- Are the stated figures or coordinates correct? Were they incorrectly stated when established?
- Have new errors been introduced into the survey? Are the new measurements correct?
- Have the positions of any of the marks or monuments changed between surveys?

These questions can be very difficult and sometimes impossible to answer. As such, drawing the conclusion that a value *is* incorrect or a monument *has* moved requires a substantial amount of evidence. If not enough proof can be found, the point of truth will often reside with the original features. That said, in the instance where a mark has likely changed position (i.e. there are no errors in the survey work), it is important to determine the true nature of the movement as it is probable that future surveys will also discover the same discrepancies.

This paper investigates modern measurement techniques and determines their effectiveness and practicality for large-scale ground deformation monitoring across Australia. Specifically, the accuracy and suitability of publicly available InSAR data is examined by comparing it against trusted ground-based survey methods, namely Global Navigation Satellite System (GNSS) positioning and differential levelling. Using publicly available data, this paper tests the validity of InSAR data from the point of view of an ordinary cadastral surveyor. In particular, the gap between geodesy and cadastral surveying will be bridged using this public data, providing new strategies that can be applied to modern-day surveying tasks.

2 GROUND DEFORMATION IN AUSTRALIA

From a climate and environmental standpoint, Australia is an extremely diverse country that leads to a landscape with a vast array of characteristics. As a result, the landscape must adapt to suit changing weather patterns and tectonic anomalies. Furthermore, it is also exceptionally rich in natural resources, which form a key part of the nation's economy. Tapping into these resources can put great strain on the landscape and in turn lead to human-induced (anthropogenic) deformation. As such, it is useful to differentiate between the causes of ground deformation based on the level of human influence.

2.1 Natural Deformation

The Australian continent sits entirely within the Indo-Australian tectonic plate, and hence no major fault lines run through or near the landmass. Interactions between plate boundaries are the main cause of large earthquakes around the globe, thus Australia is not subject to such events. However, intraplate earthquakes – earthquakes occurring within the interior of a tectonic plate – have been recorded in the past and some have been known to noticeably shift the Earth's surface. The 1988 Tennant Creek earthquake in the Northern Territory is the largest ever recorded in Australia. The event comprised a series of three earthquakes, with approximate magnitudes of 6.3, 6.4 and 6.7 (Bowman et al., 1990). The authors reported that the quakes caused deformation of 0.5-1.5 m by low-angle thrusts and 1.0-1.5 m by horizontal thrusts. Even in a rural setting, this amount of movement is enough to severely affect survey infrastructure and property boundaries. That said, this event is a significant outlier in the history of earthquakes in Australia, with most events not large enough to cause surface rupture. Nevertheless, earthquake deformation is still very possible across the continent, and so it should be treated as a noteworthy threat to survey infrastructure, albeit infrequent.

Another source of natural ground deformation in Australia is soil type and structure. The two main types in this category are reactive soils and soil creep. Reactive soils are fairly common in Australia and are typically associated with the moisture content of clay-based soil. These soils will swell when large amounts of water are present and alternatively shrink during dry spells. This can lead to a somewhat cyclic motion where the surface level of the area rises and falls. In the NSW Land & Environment Court (NSW LEC) case of Mine Subsidence Board v. Maria Vervoorn (2008) (see section 2.3), reactive soils were examined to determine if they were the cause of structural building damage in the area of Lithgow. Expert witnesses in the case determined that much of the area was undergoing cyclic movements in the range of ±20 mm and attributed this movement to reactive soils.

Soil creep is the gradual movement of volumes of soil due to gravity. Conducting an extensive study in the Northern Territory and NSW, Clarke et al. (1999) found that annual creep rates could be up to almost 8 cm^3/cm. This unit indicates the volume of a column of soil with 1 cm width moving past a given contour. Figure 1 illustrates a method for measuring volumetric creep and highlights the resultant volumetric units. However, Clarke et al. (1999) found that rates were highly unpredictable, and few correlations could be seen between the rates and the characteristics of the landscape. Nonetheless, this evidence proclaims that soil factors may indeed offer sufficient movement to have a detrimental effect on the accuracy of survey marks.

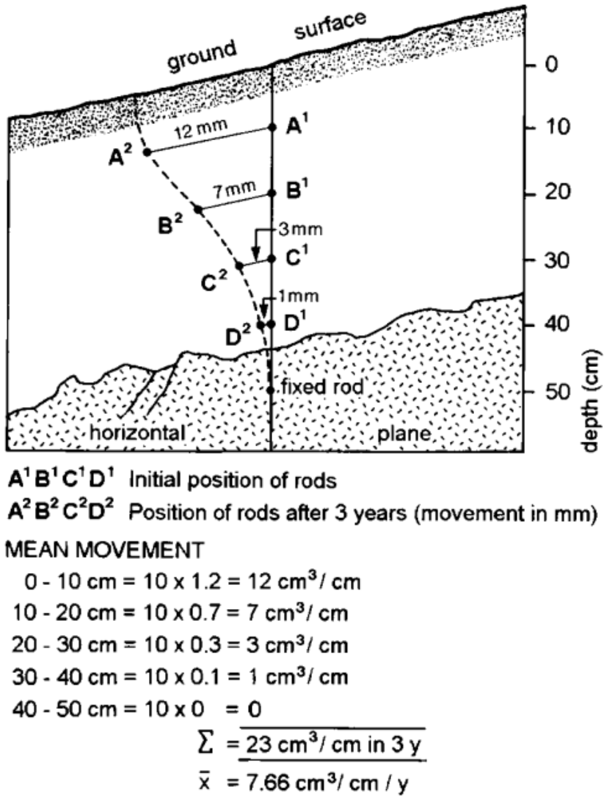

Figure 1: A method for determining volumetric creep (Clarke et al., 1999).

A source of natural deformation closely linked to soil properties are landslides. It is worth noting that landslides are also often the result of human interference through excavation and demolition, but for the purpose of this paper they will be treated as a natural source of deformation. Landslides are typically seen after extreme weather events possessing excess volumes of rain. This aberrant amount of water may weaken the structure of the soil and, if coupled with a significant slope, can cause the land to give way. Depending on the scale of the landslide, many if not all the survey marks and structures in the immediate zone will be disturbed or destroyed. Additionally, marks surrounding the event may be more subtly affected as the land settles and subsides. Although devastating, these incidents are often localised and only affect small areas at a time. As a result, it may be easier to identify which marks may or may not have moved after a landslide than it would for an event of larger scale.

2.2 Anthropogenic Deformation

Australia's abundance of natural resources has led to a prolific mining industry. Many mining operations extract enormous quantities of material from the ground to harvest the precious deposits, leaving behind large voids in or beneath the Earth's surface. Whilst ground deformation can still be seen around open-pit mines, the most significant surface distortions are caused by underground mines. When volumes of earth are mined using techniques such as longwall mining, the surface above the void may tend to subside under its own weight. Mine subsidence is particularly common in the coal-rich regions along the east coast of Australia, particularly in central-eastern NSW. Figure 2 illustrates the locations of recent mining operations in Australia.

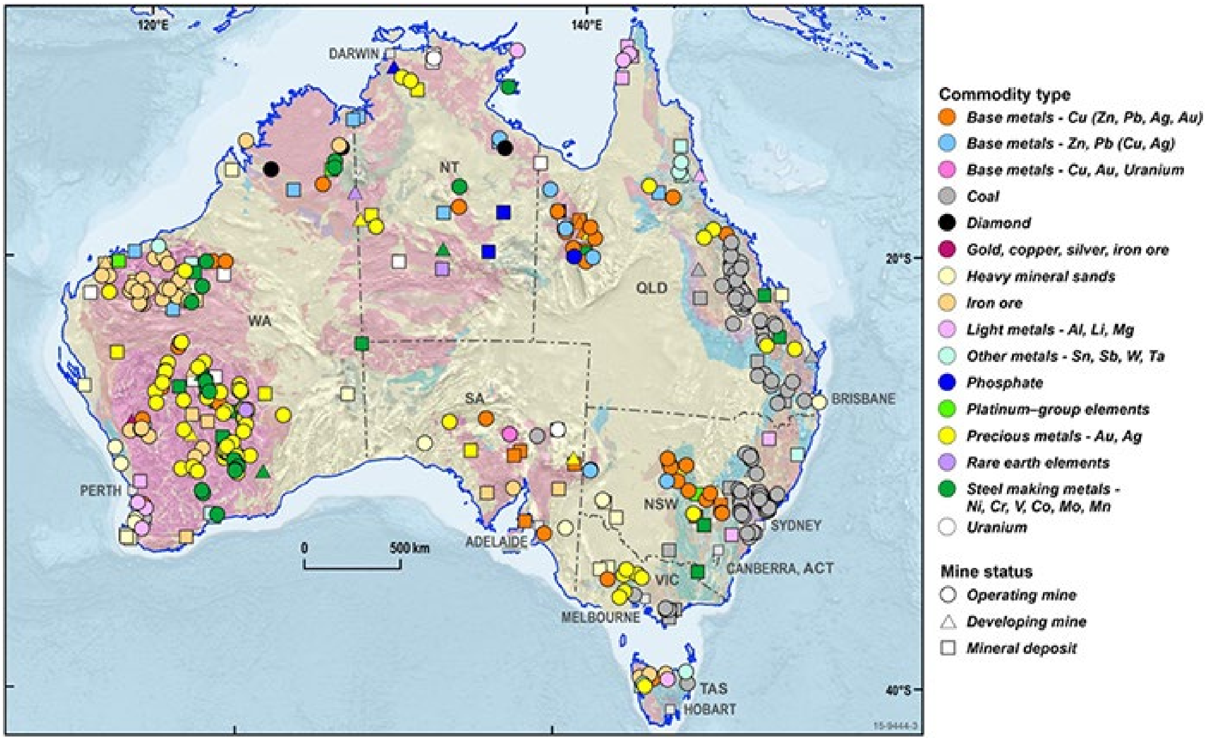

Figure 2: Major mining operations and mineral deposits as of 2016 (GA, 2017).

Other sources of 'man-made' ground deformation are groundwater extraction and poor landfill compaction. In some regions of Australia, groundwater is a primary source of usable drinking water and is extracted from the ground in enormous quantities. When water is extracted from underground aquifers via bores, the ground above the aquifer may sink under its own weight in a similar process to mine subsidence. Conversely, deformation due to poor landfill compaction occurs when voids in the ground are inadequately filled. When large weight forces are exerted on the surface above these voids (due to construction), the ground can compress and cause a sinking effect. This emphasises the fact that ground deformation can occur in both urbanised and regional areas, making it a significant threat to survey infrastructure across the entire country. Fortunately, these specific examples generally affect a concentrated area and can therefore be easily identified in most cases.

2.3 Case Study: Mine Subsidence Board v. Maria Vervoorn

There have been several court disputes involving damage to residencies where surveyors have played a key role in determining the cause and extent of the damage. In the case of Mine Subsidence Board v. Maria Vervoorn (2008), surveyors placed monitoring points to determine the movements of a damaged structure and measured to distant survey marks to act as a point of reference. The permanent survey marks were situated around 400-500 m from the site at locations determined to be unaffected by the proposed subsidence. However, the results confirmed that the survey marks were also moving in a similar fashion to the damaged structure. Experts in the case disagreed on the cause of the movements, and specifically whether the marks and the structure were being moved by the same forces. This highlights the fact that (as with all measurements) establishing a rigid datum is critically important.

According to the court proceedings, the survey marks were originally placed in 1995. Mrs Vervoorn made an initial complaint about cracking in 1991, and then again in 1998. After the latter complaint, the Mine Subsidence Board began monitoring of the structure. It is unclear how many (and at what time) surveys were completed between 1998 and the final survey in 2007. However, the following statement from Prof. Galvin reveals the inconsistencies in the measurements: "*In absolute terms comparing 1998 to March 07 the points are down, they're lower than 1998. In terms of trends the trends are up, down, up, down, and who knows how many more because of the frequency of the surveys*." This assertion highlights the importance of the temporal aspect of monitoring surveys in gaining a true understanding of how a landscape is behaving.

In an ideal world, around-the-clock monitoring of the features in question would provide the most certainty when ascertaining the relative mark movements in this case. This, however, is unfeasible for virtually all traditional surveying methods, as they are far too reliant on human operation. Although proven to be highly accurate, instruments such as GNSS receivers, total stations and automatic or digital levels all require considerable human operation in order to function. This dilemma has unearthed the need for an efficient and cost-effective method to actively monitor large expanses of land, at an accuracy level comparative to that of traditional surveying methods.

3 INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

InSAR presents a modern alternative to geodetic monitoring with capabilities beyond the realm of most traditional methods. Using its own pulses of microwave energy emitted from a sensor onboard a radar satellite, Synthetic Aperture Radar (SAR) is an *active* remote sensing technique that can operate day and night and in all weather conditions. A SAR image is created using the amplitude and phase of the returned signal, which has been 'scattered' off the Earth's surface, providing information about the slope and nature of the terrain.

InSAR uses the SAR images acquired at different epochs to map ground movement and changes in the topography. Specifically referred to as Differential InSAR (DInSAR), where two images have been taken over the same area with the same imaging geometry at different epochs, a phase shift will occur if the ground has undergone deformation (Garthwaite and Fuhrmann, 2020). The authors explain that this technique allows for maps to be produced with metre-level spatial resolution and precision at the centimetre level. Figure 3 illustrates the principles of DInSAR and the resultant phase shift after two passes over the same area.

As previously mentioned, image geometry is an important factor when generating a DInSAR image. It specifically refers to what phase of its orbit a satellite is in when an image is captured. When the satellite is travelling from north to south, it is said to be in a *descending* pass, and contrarily when the satellite is travelling from south to north, it is said to be in an *ascending* pass (Figure 4).

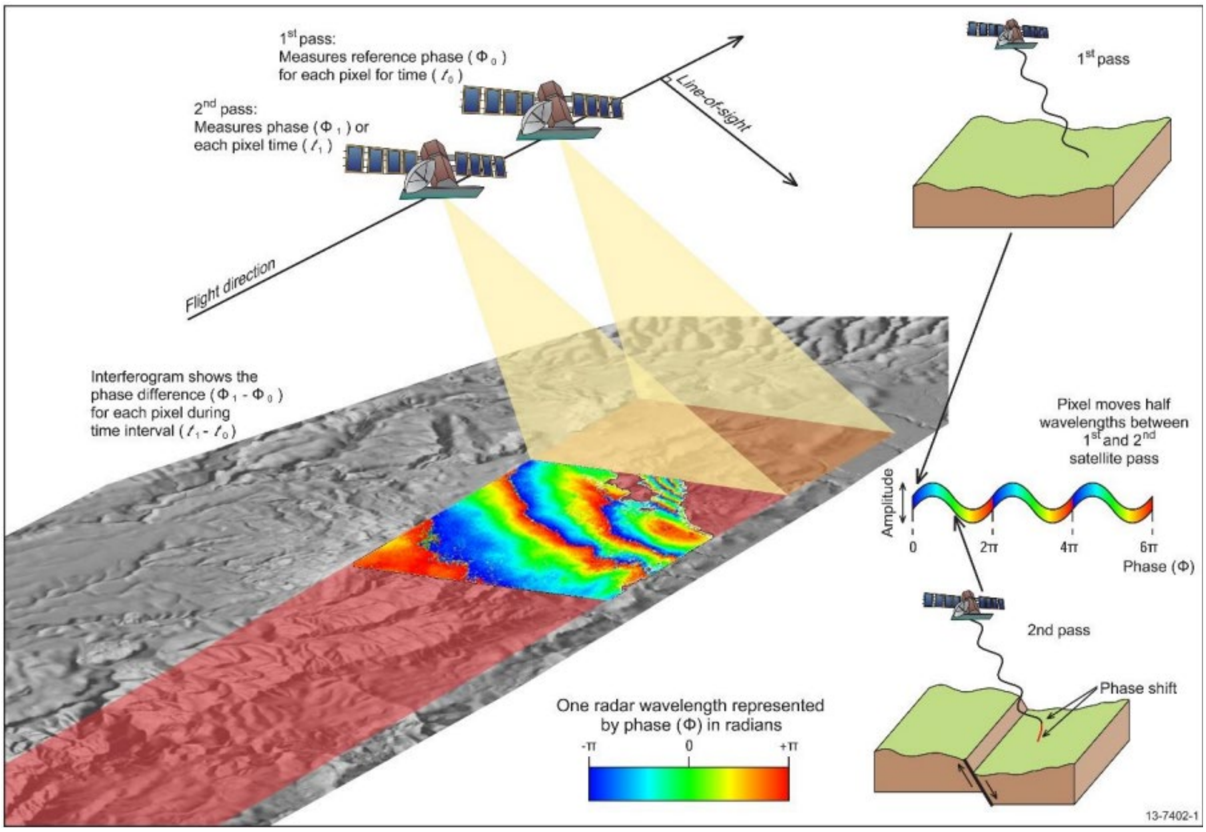

Figure 3: Illustration of the concepts of DInSAR and the principle of a phase shift that has occurred due to ground deformation (Garthwaite and Fuhrmann, 2020).

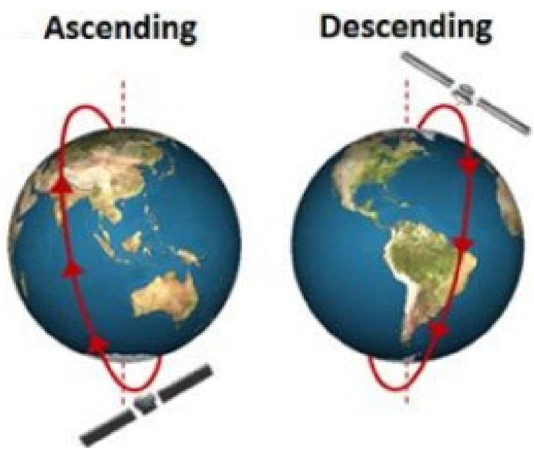

Figure 4: Diagrammatic representation of an ascending and a descending orbital pass (Garthwaite and Fuhrmann, 2020).

This distinction is important because SAR is a side-looking system whereby the sensor is orientated perpendicular to the direction of flight (Macchiarulo et al., 2023). This creates a 'slanted style' image (see Figure 3) that is only representative from this particular viewing angle. In other words, a SAR image captured on an ascending pass can only be used to create a DInSAR image with other ascending images, and vice versa for descending passes. However, if an ascending and descending pass both capture the same area on the ground, the two resultant DInSAR signals can be used to validate and improve the accuracy of the final image as they are both independent representations of the same area. Furthermore, this combination can greatly help to distinguish the true vertical and horizontal ground displacements as the singular 'slanted' images can generate misleading results. The typical 'revisit time' (i.e. the time taken for a satellite to return to the same viewing location) per viewing geometry is around 24 days, meaning that an ascending and descending image is captured around every 12 days.

With the ability to cover widths of several to hundreds of kilometres in a single pass and achieve centimetre-level precision on the ground, it is clear to see how InSAR is an extremely valuable tool in geodetic monitoring. That said, the technique is not without its limitations, which at times, can greatly hinder its performance. The most obvious restriction of many current InSAR techniques is that it is generally noticeably weaker in the horizontal direction than in the vertical. This is primarily due to the viewing geometry of the sensor, and the fact that radar satellites have a typical orbital altitude of around 800 km. This is not to say that the horizontal component of InSAR scans is unusable, but rather that it should simply be treated with a degree of caution.

Another significant limitation of InSAR (and most other space-borne monitoring systems) is due to atmospheric effects. Specifically, the troposphere has the most considerable impact on the SAR signals, with the water vapour in the wet part of the layer causing variability of up to several centimetres (Klees and Massonnet, 1998). The authors also explain that an additional factor affecting the suitability of InSAR is temporal decorrelation, whereby the environment or climate may change but the ground surface does not. This is an issue because the changing environment may indicate a phase shift that is misinterpreted as a shift due to ground deformation. For example, ‘environmentally dynamic’ areas such as forests and vegetated areas suffer from significant decorrelation, whereas arid areas such as deserts are typically unaffected. As a result, InSAR cannot be utilised over the ocean because the decorrelation is too great.

Whilst InSAR has already promised to be an extremely useful tool to identify and measure areas of deformation, there are still doubts over the precision of the technique, and if it could ever be used as the primary method for re-establishing and updating survey infrastructure affected by an event.

4 SUBSIDENCE IN THE NSW SOUTHERN COALFIELD

Making up the southern portion of the Sydney Basin, the Southern Coalfield of NSW produces premium-quality hard coking coals typically used in the production of steel. There are several operating mines within the Southern Coalfield, with one of the largest operations located approximately 80 km south-west of Sydney, near the township of Tahmoor.

The Tahmoor Coking Mine commenced underground mining operations in 1980, by means of bord and pillar extraction. After 1987, longwall mining was implemented, and remains the primary method of coal extraction. The Tahmoor Coking Mine has consent to produce up to 3 million tonnes of coal per annum (SIMEC, 2024). Removing this amount of material from the ground exerts enormous strain on the overlying surface and has inevitably led to significant subsidence in the area. As part of the mine extends under the Tahmoor township, many survey marks have been affected by the subsidence, with a large portion requiring regular checks and upgrading. Private surveyors in the area notified DCS Spatial Services about the potential deformation and requested that an investigation be undertaken to determine its severity and re-establish survey control.

5 GROUND-BASED SURVEY STRATEGY

DCS Spatial Services, a unit of the NSW Department of Customer Service (DCS), conducted thorough ground-based surveys in March and May 2018, throughout the town of Tahmoor and surrounding suburbs. Before the majority of affected marks could be updated, accurate survey control had to be re-established throughout the area to confirm and validate the future results. Specifically, stable marks (i.e. marks unaffected by the subsidence) had to be found and measured using static GNSS in order to add a level of redundancy to the survey. After achieving this, the accurate information of these marks could be used to help update the coordinates and heights of a subset of the affected marks, which also had been measured using static GNSS. Although static GNSS is one of the most accurate variants of the GNSS technique, it is rather time consuming, with each mark possibly needing to be occupied for a minimum of up to 60 minutes per occupation. As a result, static GNSS was in this case only used to re-establish a horizontal and vertical datum throughout the area, so that more time-efficient techniques could be utilised later. The final product of this survey is a dispersion of marks across the affected area with new, accurate coordinates and heights. The location of selected control marks in relation to the approximate area of interest around Tahmoor is shown in Figure 5.

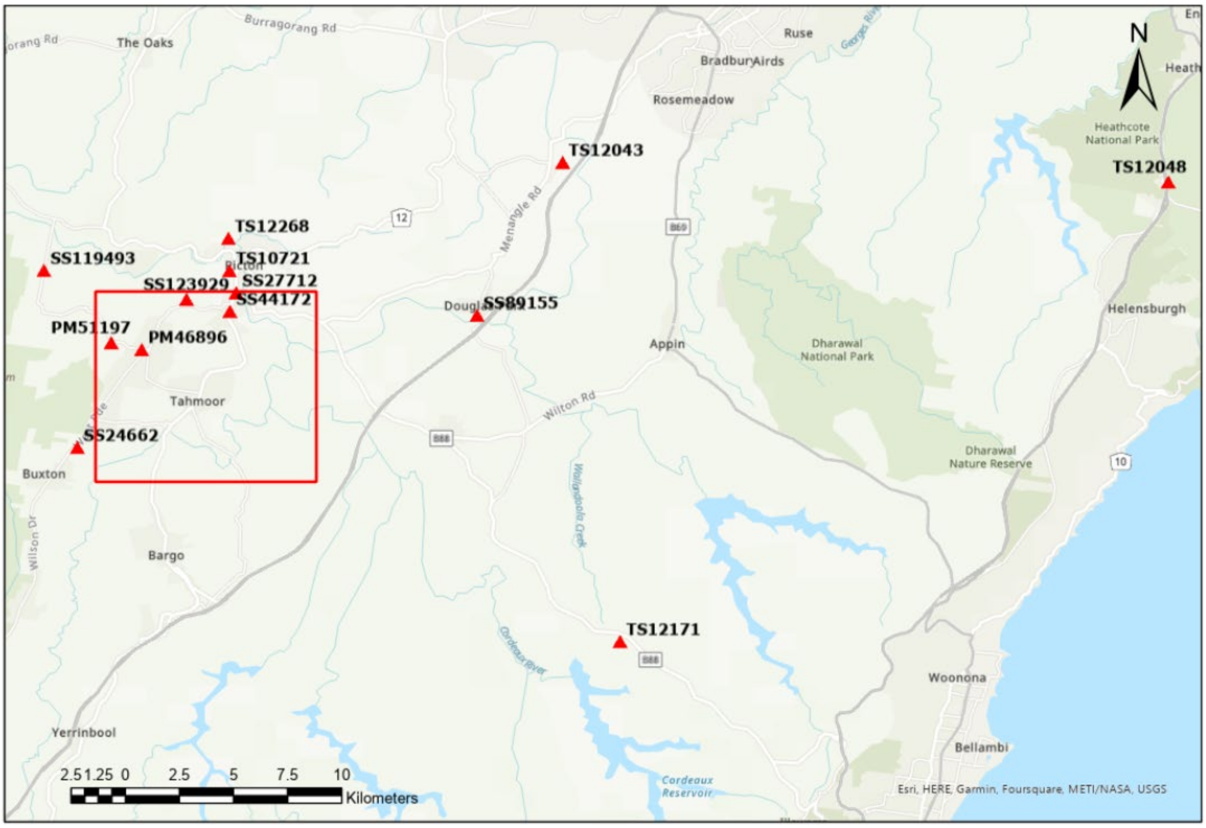

Figure 5: Location of selected control marks in relation to the approximate area of interest.

As expected, Figure 5 shows that many of the chosen control marks reside outside the potential subsidence zone. There is a good coverage of marks encompassing the area of interest, with a denser coverage closer to the suspected area of deformation. It is also evident that the distance between many of the marks is quite large, which greatly inflates the time spent in the field. The three eastern-most marks (TS12043 MENANGLE CORS, TS12048 WATERFALL CORS and TS12171 CORDEAUX CORS) are existing GNSS Continuously Operation Reference Stations (CORS) belonging to CORSnet-NSW (Janssen et al., 2016; DCS Spatial Services, 2024), and were included in the survey to improve the redundancy and geometry, without the need to occupy them. In total, 6 days were spent performing the initial static GNSS control survey, highlighting how time-exhausting the process is to re-establish survey control over a large area.

In total, the information of 36 survey marks was updated as part of this initial control survey, resulting in a localised network of marks with current and high-quality coordinates to be used to help improve surrounding marks in the immediate area. Densification of the improved survey network was conducted using the Real-Time Kinematic (RTK) GNSS technique due to the time-efficiency and economical gains it provides. Whilst it is known that RTK does not have the accuracy capabilities of static GNSS, it can still achieve levels of ±0.025 m (Mekik and Arslanoglu, 2009), which is sufficient for identifying areas of deformation and in some cases can still be used to update survey mark information. As a high-quality local control network had been newly established, it was deemed acceptable to use RTK observations to update the coordinates and heights of many additional survey marks in the area, although any marks updated using this technique would only achieve a maximum Class D. The purpose of this RTK densification survey was not only to increase the number of marks with current, good-quality information, but to also determine the general severity of the ground deformation in the area.

The final step in the overall campaign was to verify and update a series of accurately levelled marks in Tahmoor. In order to best preserve the accuracy of the Class LB marks, 2-way differential levelling was chosen due to its high accuracy, efficiency and the fact that the marks were quite close together.

Adjustment and analysis of these surveys revealed that many marks had moved horizontally, vertically or both. Although the results are reliable, the time and human resources exhausted to achieve these results were very significant. Moreover, as the physical ground deformation cannot be seen with the naked eye, all survey marks in the suspected area of interest need to be individually checked to see if they have been affected. There is also no guarantee that the marks will have finished moving after the surveys have been completed, thus further checking may be required until the movement has ceased.

6 INSAR DATA COMPILATION

InSAR data was used to compare against the ground-based survey methods described above. This data was obtained through Geoscience Australia's NationalMap platform (GA, 2024), a publicly available online tool providing spatial data acquired by Australian government agencies through a map-based platform. The relevant dataset in this case is the Camden Environmental Monitoring Project (CEMP) InSAR, which contains horizontal and vertical ground surface displacements and velocities derived from radar satellites. Together with their respective uncertainties, the values obtained using this method were thoroughly examined to determine the effectiveness of InSAR as a frontline management tool for ground deformation. Detailed information about this campaign can be found in Garthwaite and Fuhrmann (2020).

The CEMP utilised data from three satellite radar missions: ALOS, Envisat and Radarsat-2. Using combined ascending and descending viewing geometries, values have been derived in the vertical (up-down) and horizontal (east-west) directions for each mission. Due to the nature of slanted line-of-sight InSAR, values in the north-south direction cannot be obtained, thus the horizontal values are strictly limited to east-west. Figure 6 provides an example of a product available via NationalMap, displaying up-down velocities derived from ALOS. It is apparent that there are areas that appear sparse, with very little data available. This typically occurs in densely vegetated areas where the radar signals are heavily obstructed. As a result, these areas produce a large amount of signal noise and as such have not been included in the resultant product. In general, ALOS products have a spatial coverage that is denser than Envisat and Radarsat-2, due to ALOS having a longer wavelength (~24 cm as opposed to ~6 cm) which gives it greater penetrability.

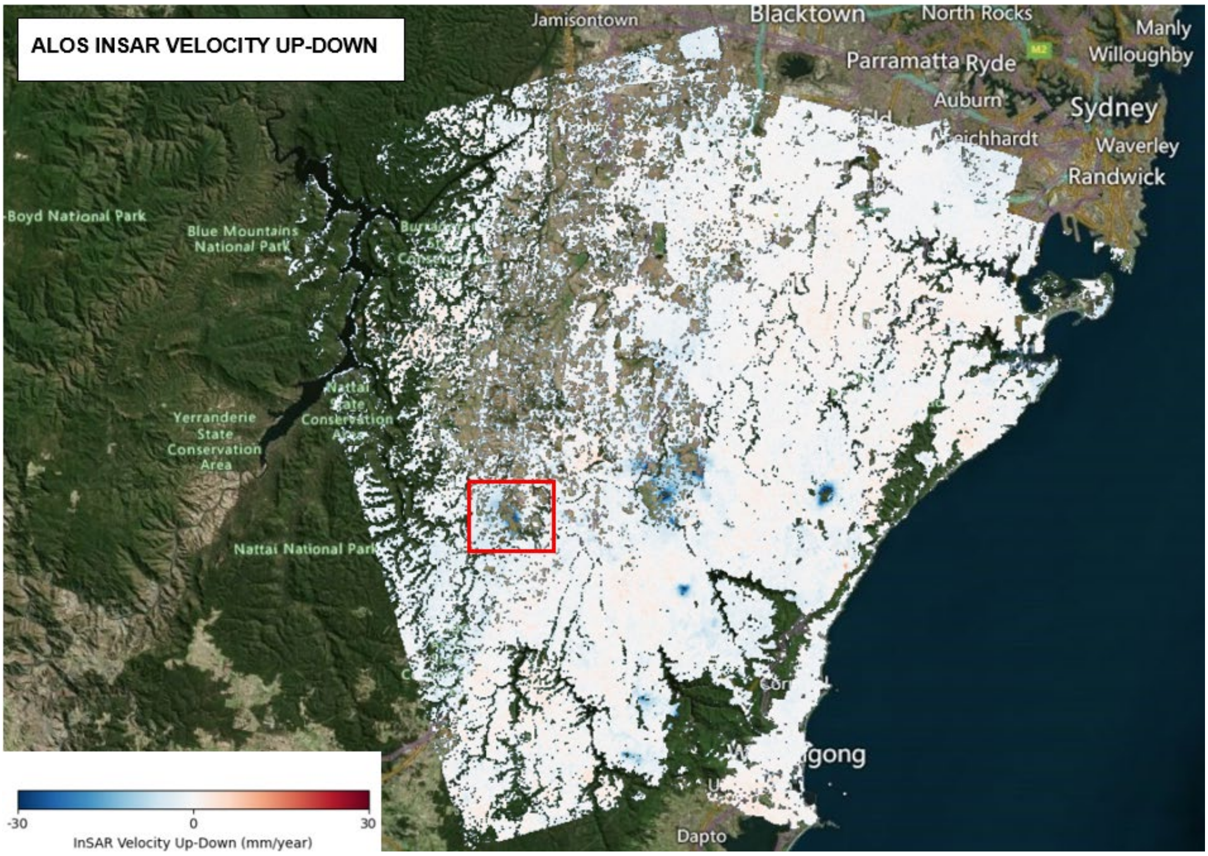

Figure 6: NationalMap product, displaying up-down velocities determined by the ALOS mission, with the addition of the approximate area of interest.

For each mission's final products, the data has been interpolated to 50 m pixel spacing. For an in-depth explanation of the processing techniques and methods employed by Geoscience Australia to produce the final InSAR products, the reader is referred to Garthwaite and Fuhrmann (2020). Both a displacement and a velocity product has been determined for each mission, showing the magnitude (in millimetres) and the linear rate (in millimetres per year) of ground movement, respectively. The time period used to calculate the velocity for each product is approximately 4 years (Table 1). For each interpolated pixel in the displacement and velocity products, an uncertainty has also been calculated for both the up-down and east-west components. Garthwaite and Fuhrmann (2020) explain that these uncertainties arise from error propagation when different viewing geometries are combined during the initial processing phase.

Table 1: Time period used to determine the velocity of each product.

Mission	Start Date	End Date
ALOS	16/05/2006	07/01/2011
Envisat	02/06/2006	25/09/2010
Radarsat-2	15/07/2015	31/05/2019

As the epochs of the InSAR products do not align with the ground-based survey epochs, it was decided to use the average yearly velocity values for a comparison between the techniques, as the displacement values are entirely dependent on the time period at which they were observed. As such, the displacements (mark movement) determined in the ground-based surveys have been converted to velocities (in millimetres per year) to be in keeping with the InSAR values. Although these results may be more generic and approximate, they should be able to adequately identify trends in the ground movement that can be more closely compared to the ground-based survey results. Furthermore, this decision means it is assumed that ground movement occurs linearly, which is certainly not always true.

Figure 7 shows the survey marks selected to act as control for the campaign, overlayed onto the ALOS, Envisat and Radarsat-2 velocity product layers. Although it has already been stated and explained that these marks were selected as control for the survey because they were deemed to be stable and unmoving, the figure provides immediate justification for this selection. It is instantly clear that all control marks are situated in or around yellow-coloured regions of the map, indicating they are in areas of little to no ground movement.

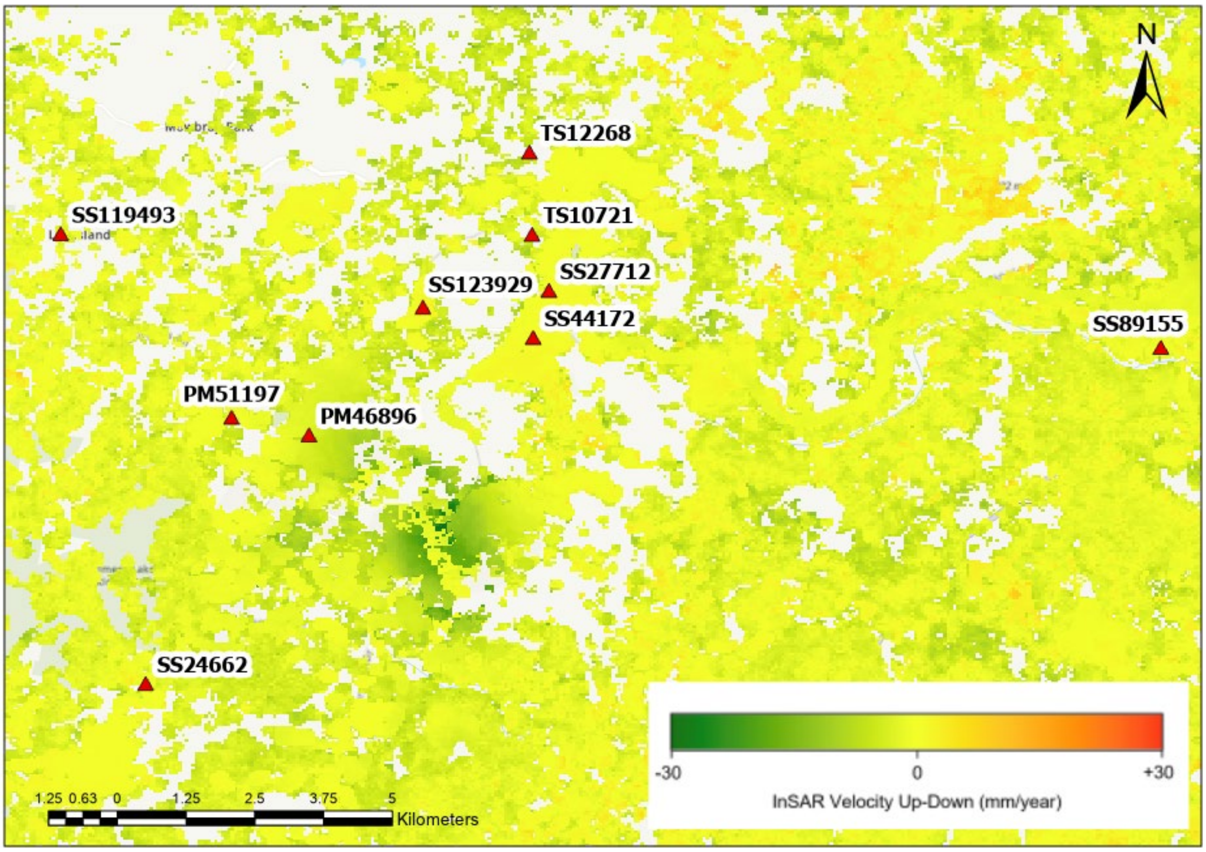

Figure 7: Survey marks selected to act as the initial control of the survey campaign, overlayed onto the ALOS, Envisat and Radarsat-2 velocity products.

Tables 2-5 summarise the values extracted from the NationalMap products for all established survey marks used in the ground-based campaign. To determine these values, the positions of the survey marks were intersected with each InSAR product, and the resultant pixel was adopted to represent the position of a mark. In some instances, no InSAR data was available, due to the issue of sparseness detailed previously. For horizontal (east-west) results, negative velocities indicate westward movement and positive velocities signify eastward movement. Similarly, for vertical (up-down) data, negative velocities indicate downward movement whilst positive velocities suggest upward movement.

Tables 2 & 3 state the velocities and uncertainties (standard deviations) derived by each radar mission for the established survey marks used in the static GNSS control survey. It is immediately evident that there is a large disparity in the velocity values between each mission for the same pixel. Additionally, the standard deviations of the ALOS values are significantly higher than for the other two missions. Specifically, the ALOS standard deviations are around four times larger than Envisat and Radarsat-2, which can be attributed to ALOS having a wavelength that is also approximately four times longer than the other missions. As mentioned previously, the longer wavelength allows ALOS signals to penetrate vegetation more easily, but this comes at the cost of larger uncertainty. Figure 8 illustrates the positions of the established marks in relation to the three InSAR products.

Table 2: Horizontal (east-west) InSAR velocities and standard deviations (mm/yr) for marks used in the static GNSS survey.

Mark	ALOS Vel.	ALOS Std.	Envisat Vel.	Envisat Std.	Radarsat-2 Vel.	Radarsat-2 Std.
PM46911	-	-	18.6	1.4	0.4	1.0
PM82399	-8.1	7.5	-9.3	2.1	0.0	0.8
SS123929	-1.9	19.5	-1.7	1.3	13.6	1.0
PM46896	3.1	3.5	7.6	1.9	3.5	0.7
PM46910	7.8	1.3	-	-	-	-
PM46932	1.4	6.5	1.8	1.3	-	-
PM46899	2.9	3.5	4.3	1.9	6.1	0.7
PM46929	-1.6	1.5	2.4	2.0	-	-
PM46937	11.1	12.3	3.9	0.1	-	-
PM46912	-13.8	21.5	2.3	2.1	-2.0	1.2

Table 3: Vertical (up-down) InSAR velocities and standard deviations (mm/yr) for marks used in the static GNSS survey.

Mark	ALOS Vel.	ALOS Std.	Envisat Vel.	Envisat Std.	Radarsat-2 Vel.	Radarsat-2 Std.
PM46911	-	-	-17.8	0.7	-0.5	0.8
PM82399	-6.1	6.3	-5.1	1.1	-5.4	0.6
PM46910	-6.5	1.0	-	-	-	-
PM46899	-8.6	3.0	-5.4	1.0	1.4	0.5
PM46929	-5.5	0.5	-1.5	0.9	-	-
PM46937	-21.5	10.4	-8.4	0.0	-	-
PM46912	-22.5	21.5	-18.0	1.1	-2.3	0.9

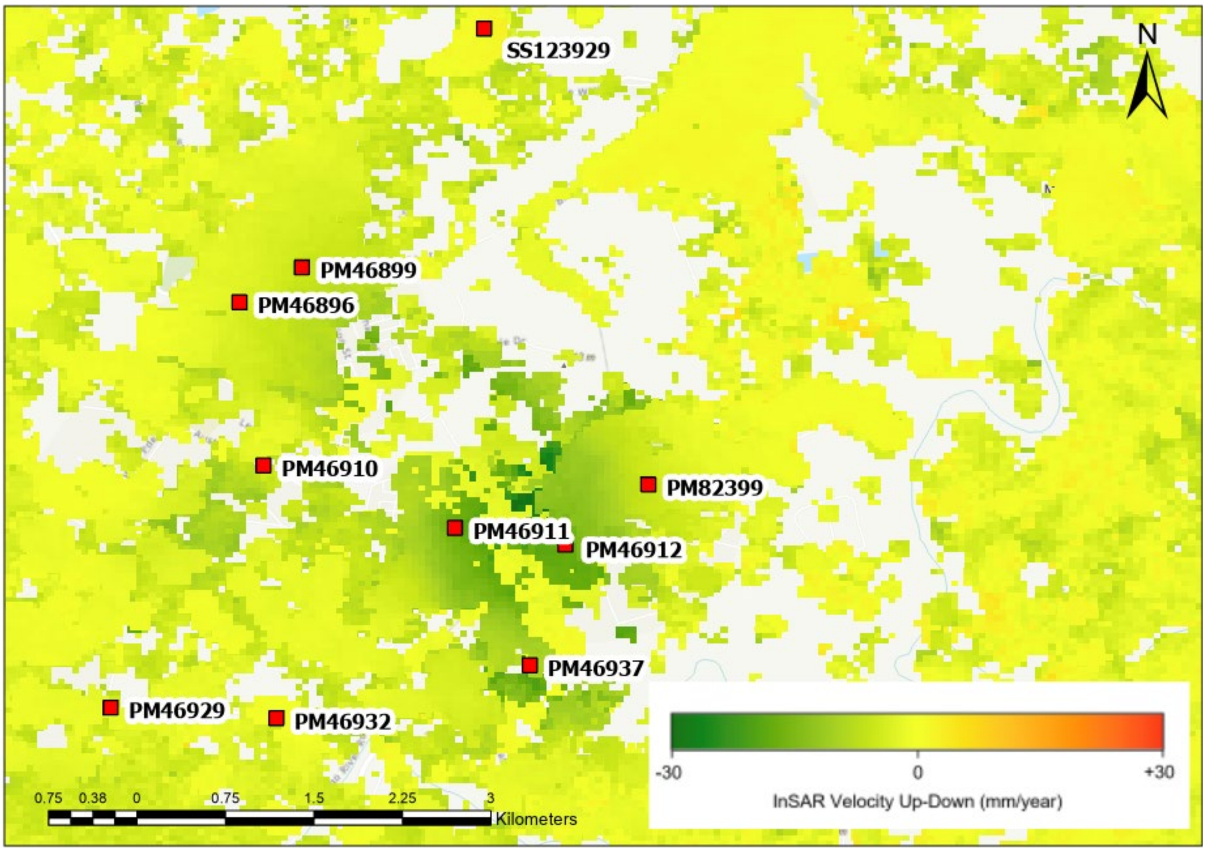

Figure 8: Survey marks measured using static GNSS, overlayed onto the vertical ALOS, Envisat and Radarsat-2 velocity products.

Tables 4 & 5 provide the InSAR values for the established survey marks included in the RTK GNSS and differential levelling surveys. Again, large variation is seen between the InSAR missions for coincident pixels. Unfortunately, this area includes concentrated patches of no available radar data for one or more missions at the locations of some survey marks. Particularly ALOS exhibits very poor spatial coverage over the southern portion of this area, hence no velocities are available for most of the marks in the south-eastern corner of Figure 9.

Table 4: Horizontal (east-west) InSAR velocities and standard deviations (mm/yr) for marks used in the RTK GNSS survey.

Mark	ALOS Vel.	ALOS Std.	Envisat Vel.	Envisat Std.	Radarsat-2 Vel.	Radarsat-2 Std.
PM46936	-	-	7.8	4.3	-0.9	0.9
SS41450	-	-	-	-	-1.6	0.9
PM60507	-	-	-	-	0.2	1.0
PM46900	3.1	10.1	3.2	0.9	8.6	0.7
SS72197	-1.5	11.4	2.1	0.8	7.5	0.6
SS49906	7.7	3.3	10.1	1.9	4.8	0.8
SS72198	-2.1	13.3	2.6	1.3	6.9	0.6
SS91897	10.6	2.0	13.5	4.3	3.5	0.6
SS58699	4.5	3.3	6.9	1.7	-	-
PM66406	2.6	8.4	4.1	4.3	-	-
PM51195	1.4	12.0	-	-	-	-

Table 5: Vertical (up-down) InSAR velocities and standard deviations (mm/yr) for marks used in the RTK GNSS and differential levelling surveys.

Mark	ALOS Vel.	ALOS Std.	Envisat Vel.	Envisat Std.	Radarsat-2 Vel.	Radarsat-2 Std.
PM46900	-4.8	9.1	-3.5	0.5	1.5	0.5
SS41451	-	-	-	-	-0.7	0.8
SS41450	-	-	-	-	-0.5	0.7
SS41447	-	-	-	-	-1.4	0.8
PM60507	-	-	-	-	-2.1	0.8
SS54834	-22.8	21.5	-18.0	1.1	-1.6	0.8
PM46936	-	-	-16.8	2.2	-0.2	0.7
SS54839	-	-	-17.3	1.9	-1.4	0.8

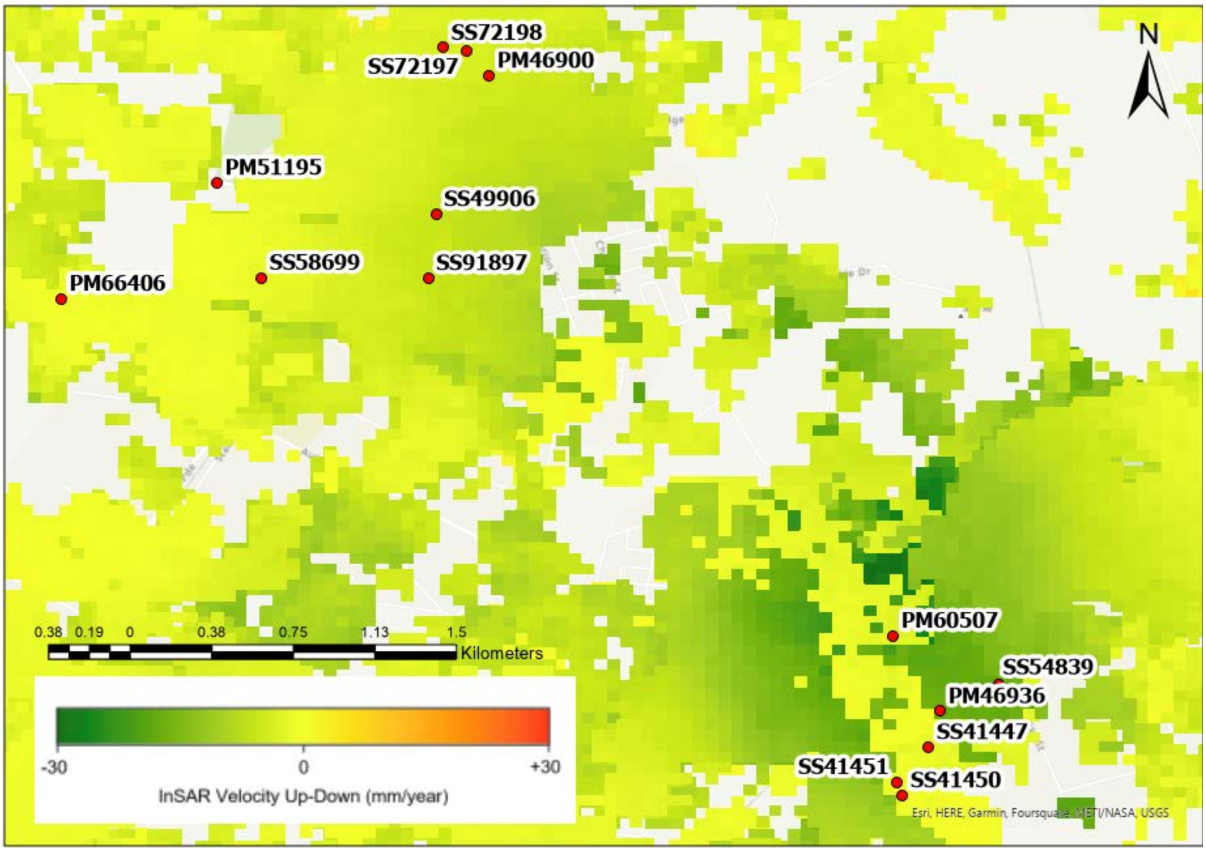

Figure 9: Survey marks measured using RTK GNSS and differential levelling, overlayed onto the vertical ALOS, Envisat and Radarsat-2 velocity products.

After examining the values in the tables above, three factors are apparent. The first is that values for the same pixel between missions are highly inconsistent. Not only do ALOS, Envisat and Radarsat-2 velocities differ in magnitude for the same pixel, but occasionally they also differ in direction. This means that whilst the values from one mission may be indicating downward vertical movement (subsidence), another may be suggesting upward vertical movement (uplift). Without any prior knowledge of the site, these conflicting results make it extremely difficult to decipher how the landscape is actually moving, and in turn how best to deal with the deformation. The second factor is that the standard deviations are typically larger for the horizontal values than for the vertical. This reinforces the fact that InSAR is generally weaker in the horizontal direction as a result of the viewing geometry and orbiting altitude. The third factor is the significant lack of data for many of the marks in the area. For the 25 established marks used from the ground-based survey, there should be 63 horizontal velocities (a value from each mission for 21 horizontally established marks) and 45 vertical velocities (a value from each mission for 15 vertically accurate marks). However, only 48 of the possible 63 horizontal velocities are available, and only 30 of the possible 45 vertical velocities are present. Again, this absence is likely due to overhead obstructions impeding the radar signals, thus creating 'noisy' pixels that have been removed from the NationalMap dataset.

7 COMPARISON OF GROUND-BASED AND INSAR RESULTS

This section details the differences between the deformation results derived via the ground-based survey methods (static GNSS, RTK GNSS and differential levelling) and by InSAR. Before these comparisons can be made, the units of the ground movement need to be made consistent between all techniques. Results determined by ground-based methods are expressed as a total magnitude in metres (difference in coordinates or height), and the InSAR results are represented as velocities in millimetres per year. As previously stated, the starting and ending epochs of the ground-based surveys do not align with those of the InSAR missions, so all results should be expressed as average linear velocities in millimetres per year. Thus, the displacements determined in the ground-based surveys must be converted to velocities using a starting epoch.

To convert the coordinate shifts in the ground-based surveys to velocities, the shift is divided by the number of years between the current survey by DCS Spatial Services and the most recent previous survey. However, if the previous date occurs prior to the commencement of mining activity, the velocities will be skewed as ground movement will only materialise after the underground extraction has begun. As such, the date of each longwall commencement should be found and compared to the date of the initial survey value to determine which should be used as the starting epoch for the velocity calculation. Figure 10 provides an indication of the positions of the underground workings of the Tahmoor mine. Figure 10a was scaled, georeferenced and digitised to create Figure 10b, which shows the approximate locations of the longwalls in relation to the survey marks. Whilst the positions of the longwalls are only roughly known, the accuracy is considered adequate to decipher their probable influence on the ground movement.

To determine the most likely point at which an area of land first began subsiding, the oldest longwall within a mark's vicinity must be identified. Jankowski and Spies (2007) state that other studies in the NSW Southern Coalfield have detected significant subsidence up to 1.5 km from mining panels. With this estimate in mind, a 1.5 km buffer was placed around each survey mark and the oldest longwall it intersected was adopted as the time that ground movement began at that location.

Figure 11 illustrates an example of this process, specifically highlighting the buffer around PM46899. In this case, the oldest intersected longwall is LW21, and so the time at which this longwall commenced is taken as the start of ground movement at the position of that mark. This method is approximate and does not consider the geological nature of the area, but it is the only means available for retrospectively predicting the onset of the ground deformation.

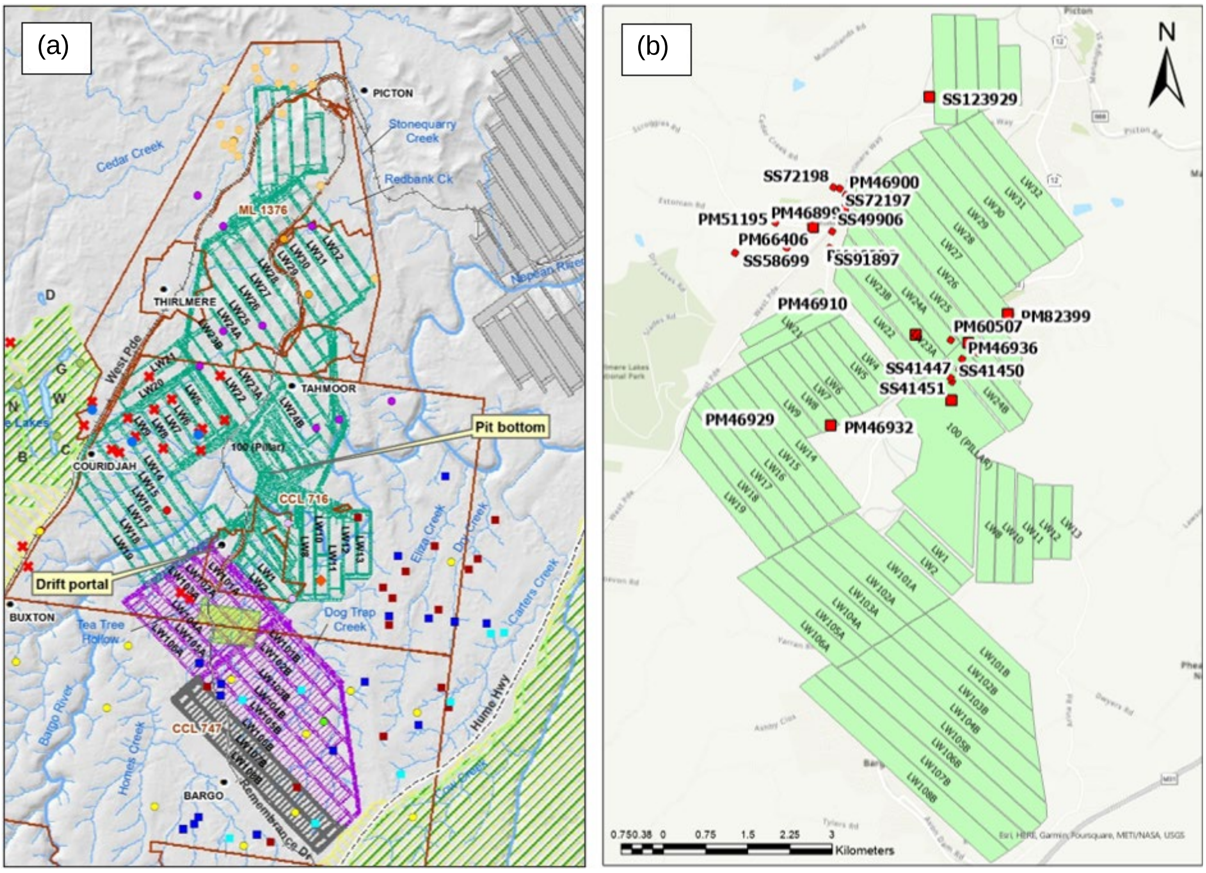

Figure 10: (a) Overlay of the underground workings of Tahmoor mine (SLR Consulting, 2020), and (b) base image after digitisation and georeferencing in relation to the survey marks.

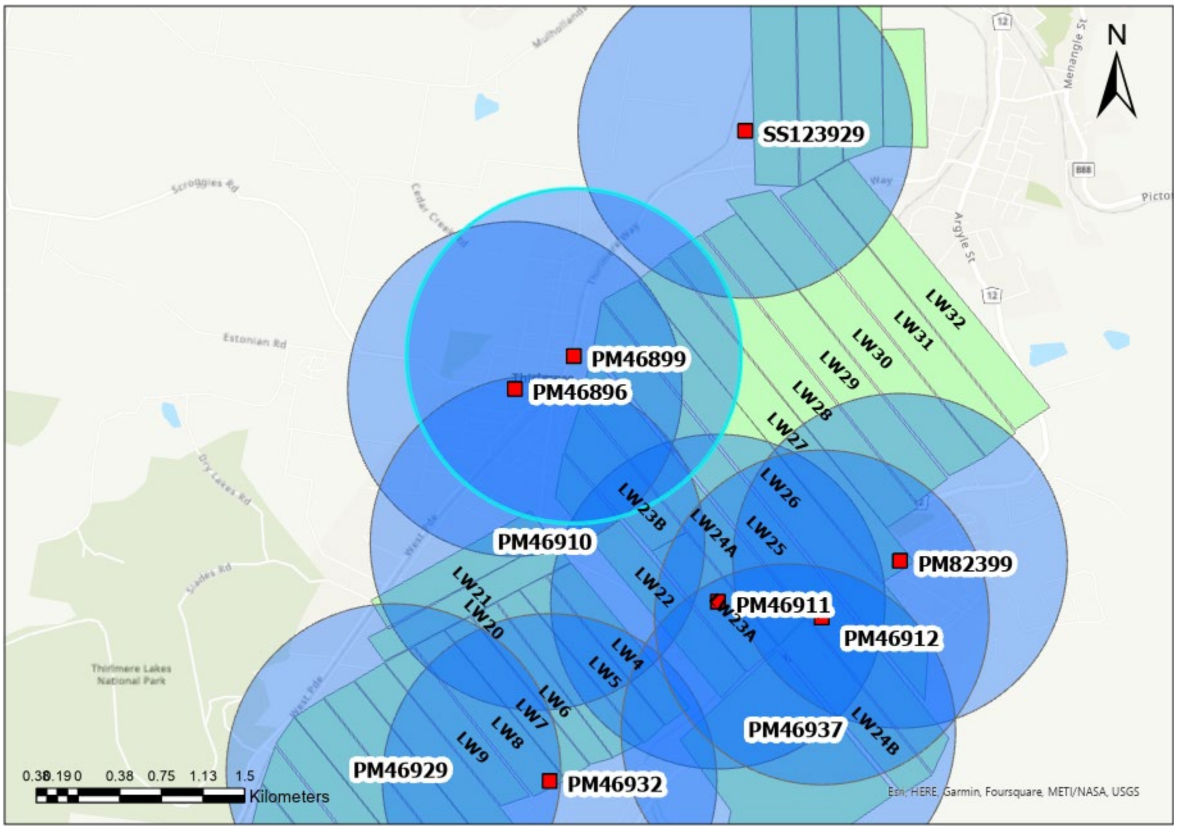

Figure 11: The oldest longwall that a 1.5 km buffer around PM46899 intersects, is LW21.

This process was carried out for all marks, with dates sourced from Ainsworth (2017) and by interpolation. If the date of the longwall succeeds the initial survey date, it is adopted as the initial epoch for the velocity calculation. These velocities can then be directly contrasted against the InSAR values. Figures 12-16 illustrate the differences between the velocities derived by ground-based survey methods and by InSAR for each mark. In these charts, each survey mark has four unique bars (one for the ground-based survey and one for each InSAR mission), indicating the derived direction and magnitude of movement at the site. Ideally, the bars for each mark should be in the same direction and be of a similar length.

Figure 12 highlights the immense disparities between the horizontal velocities obtained by static GNSS and those by each InSAR mission. Only three values appear to closely align, with most disagreeing by more than ±6 mm/yr. For the most part, the derived direction (being either positive or negative) of the ground movement for each mark tends to be consistent between each method with only a few isolated noteworthy variations. One such variation can be seen in the velocities for PM46912, where the ALOS value completely differs in direction to the static GNSS value. The magnitude of horizontal velocities differs considerably for most marks.

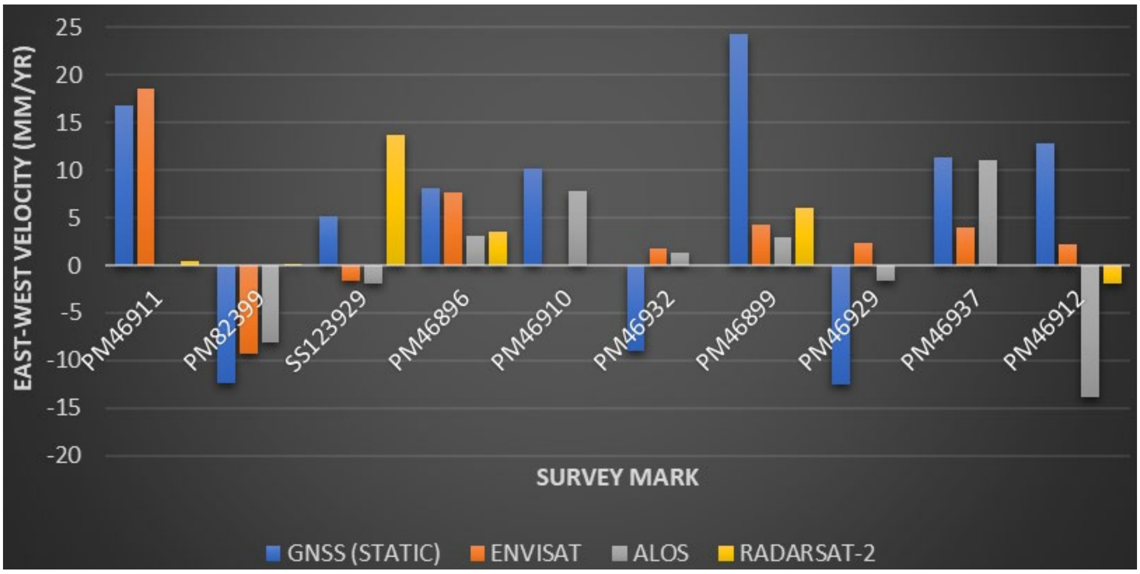

Figure 12: Horizontal (east-west) velocities (mm/yr) determined by static GNSS and each InSAR mission.

The differences between the vertical velocities from static GNSS and the InSAR missions are shown in Figure 13. Again, very little correlation can be seen amongst the ground-based and InSAR results, with several differences exceeding ±20 mm/yr. It is apparent that all but one velocity value has been derived as negative, which supports the already known fact that the area is subsiding. However, as with the horizontal case, the magnitude of the velocities is highly variable between methods with very little correlation seen.

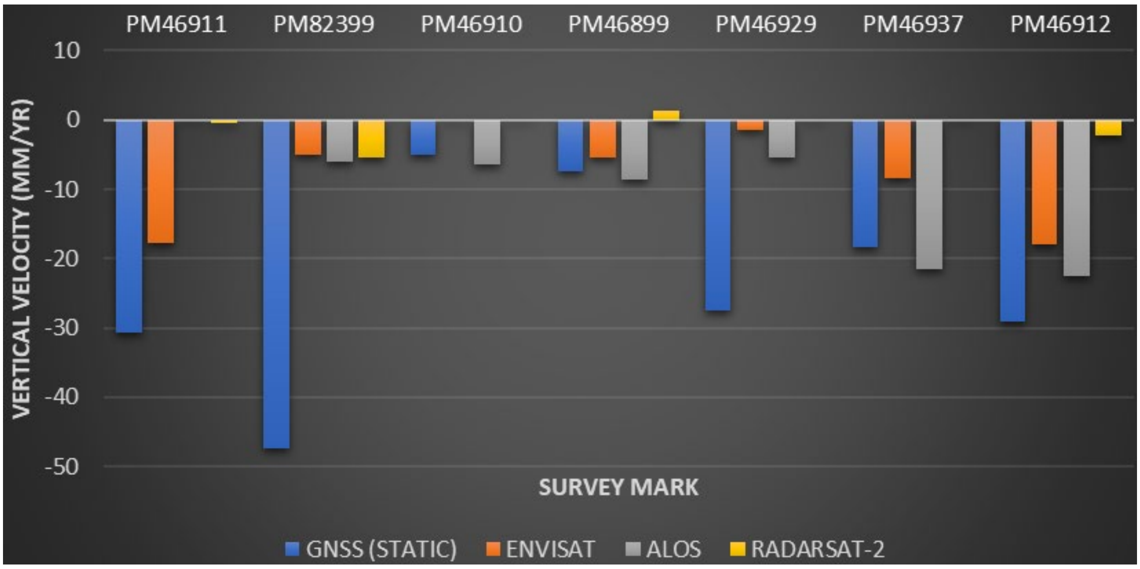

Figure 13: Vertical (up-down) velocities (mm/yr) determined by static GNSS and each InSAR mission.

Figure 14 shows the differences in horizontal velocities derived by RTK GNSS and each InSAR mission. Here, the discrepancies are slightly better than in the static GNSS case, with around an even split between differences above and below ±6 mm/yr. The largest differences are also noticeably less than in the previous case, and overall a closer correlation can be seen. It is once again evident that the derived directions of movement tend to align between methods for most marks in the study, with only five values disagreeing in direction.

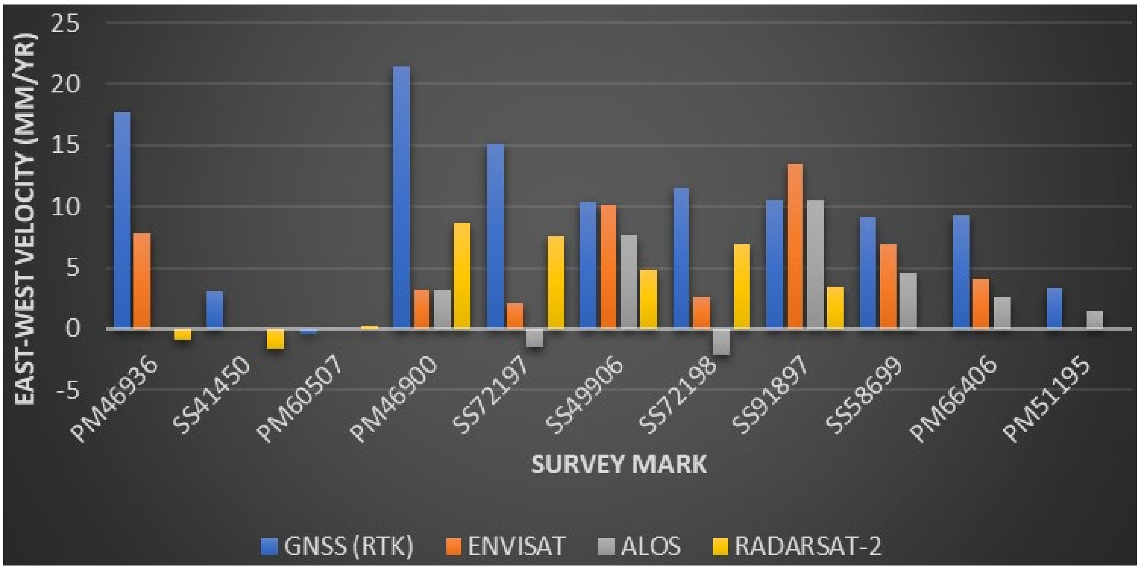

Figure 14: Horizontal (east-west) velocities (mm/yr) determined by RTK GNSS and each InSAR mission.

The differences in vertical velocities between RTK GNSS and each InSAR mission are illustrated in Figure 15. Very little correlation is seen in this dataset, with all but one difference exceeding ±6 mm/yr. Also apparent is a significant lack of data from the ALOS and Envisat missions in this area, which further hinders the analysis. Nevertheless, once more the derived direction of the velocities is mostly consistent between all methods.

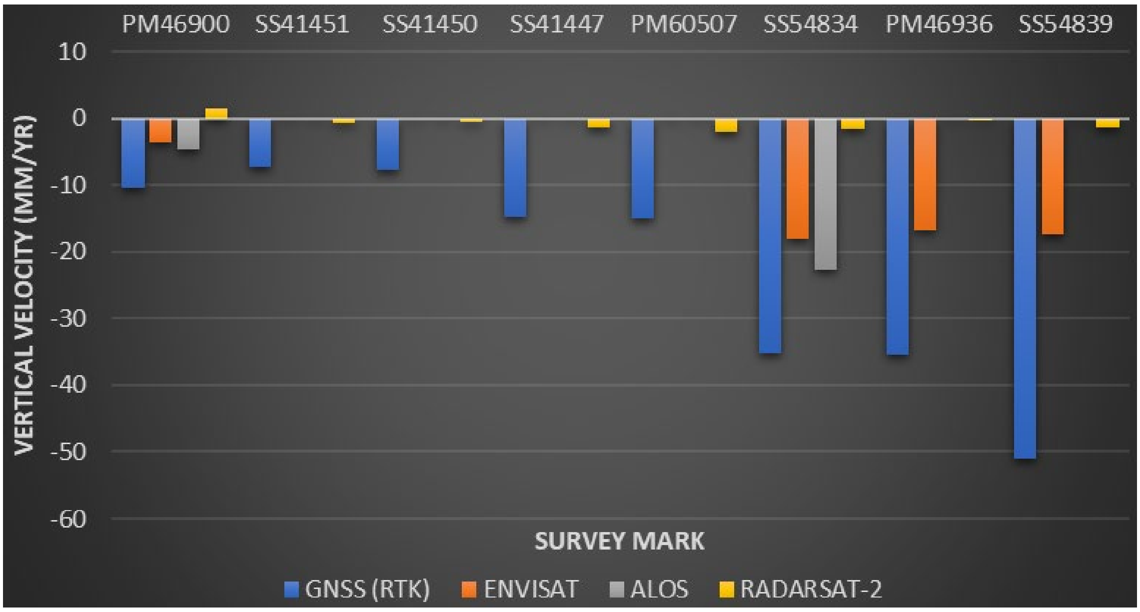

Figure 15: Vertical (up-down) velocities (mm/yr) determined by RTK GNSS and each InSAR mission.

Finally, Figure 16 highlights the differences in vertical velocities determined by differential levelling and each InSAR mission. As with the vertical RTK GNSS results, large variations are evident between each method. Again, there is a lack of data from the ALOS and Envisat missions at the locations of these marks. While the figure highlights the similarities in derived direction between the methods, it is difficult to adequately compare the techniques with almost half of the possible data unavailable.

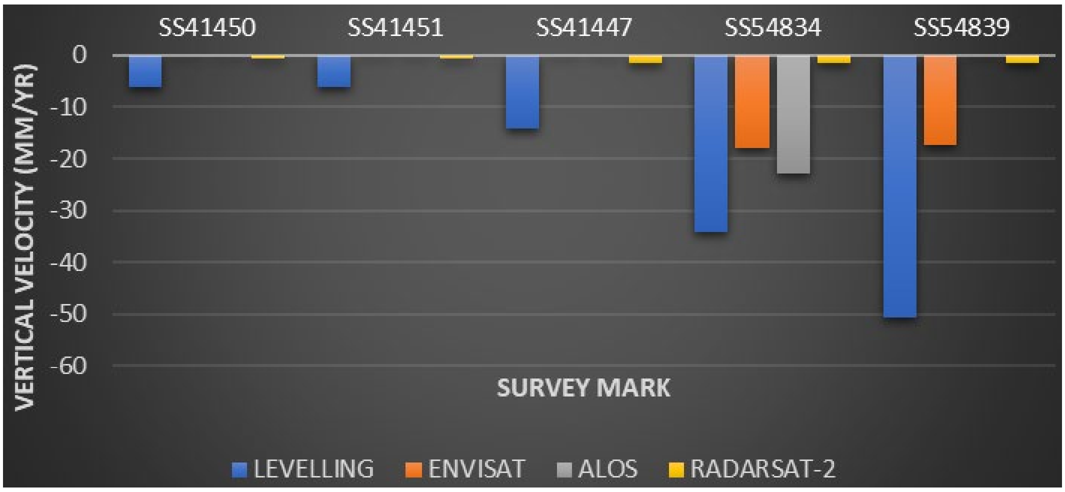

Figure 16: Vertical (up-down) velocities (mm/yr) determined by differential levelling and each InSAR mission.

The results of this study clearly indicate a great dispersion between the InSAR and ground-based velocities, and amongst the InSAR missions themselves. For the most part, the velocity directions derived by all methods tended to agree, but the magnitude of the velocities was highly variable. In other words, all methods were sufficient in determining whether the horizontal movement was either easterly or westerly, and whether the vertical movement was upward or downward, but the amount of movement was highly contentious. Given the standard deviations of the InSAR velocities (see Tables 2-5) were at times as large as the velocity values themselves, it is no surprise that these large discrepancies are present. The ALOS and Envisat values generally showed greater correlation to the ground-based values than Radarsat-2, but they both had large areas of no data. In contrast, Radarsat-2 had the densest covering of data, but the magnitude of the velocities was typically very different from the other two missions. Due to the lack of data, it is difficult to determine with certainty whether InSAR performed better in the vertical or horizontal direction, although the available data suggests that it generally performed equally in both. This is somewhat surprising given that the standard deviations for the horizontal velocities were significantly larger than those for the vertical.

Several factors can be attributed to the variation in results. The first and perhaps most obvious is the large uncertainties derived for the InSAR velocities. Garthwaite and Fuhrmann (2020) explain that areas of large surface displacement (such as above the Tahmoor mine) require a different processing strategy that only uses consecutive interferograms rather than the 'persistent scatter' method, which utilises a selection algorithm to determine pixels with slowly decorrelating phase characteristics. This results in much noisier displacement values, which in turn leads to greater uncertainties being assigned to them. Another limiting factor of the study relates to the interpolation of the InSAR data and the resultant pixel sizes. The 50-metre pixel spacing means that a single displacement and velocity value is assigned to each 50 m by 50 m area. These values have been adopted in this study to represent a singular point (being the location of the survey mark) and compared against ground-based values that have been acquired specifically at that point. It is highly unlikely that the value assigned to a pixel will be truly representative of any singular point within that pixel, and so it is unrealistic to expect that the ground-based and InSAR values will closely align.

Other limiting factors contributing to the discrepancies in velocity values arise from assumptions made in the design of the study. To determine the velocities of the ground-based survey displacements, an assumption was made that ground deformation would most likely begin when mining activity in the immediate vicinity has commenced. This means that if the initial survey date of a mark occurred before mining initiated, the date of mining commencement was adopted to calculate the velocities of the ground-based values. When this occurred, an approximate date of each respective longwall was used for the velocity calculation. Of course, it is impossible to know with certainty whether or not a nearby longwall has had any influence on the timing of localised ground movement. However, no other options were available to adequately perform the calculation. Furthermore, an equally significant assumption made was that ground deformation has occurred linearly between the initial and final epochs. This assumption is not entirely accurate as ground deformation is dependent on a range of factors, and movement may be more or less pronounced from one year to the next. For many of the survey marks in this study, the time range used for the ground-based velocities does not match those of the InSAR missions, and so there is a possibility that the rate of ground movement was different in each period. This means that the discrepancies between methods may be indicating the different rates of ground movement in each respective time period.

These limitations highlight the difficulties associated with retrospectively determining the presence and rate of ground movement. Whilst ground-based methods such as GNSS can provide very accurate positioning results, these results are limited to singular points on the ground. Furthermore, with the exception of CORS, a great deal of time and energy must be spent occupying marks at various epochs in order to determine a representative rate of ground movement because deformation does not always occur linearly. Conversely, while InSAR on its own may not provide positioning information at the level of ground-based methods, it has far superior spatial resolution, with the ability to cover far more land with greater ease. It is evident there is certainly a place for InSAR, allowing for the emergence of several new research areas.

8 NEW NATIONWIDE DATASETS

The InSAR data used in this study was processed and made available by Geoscience Australia specifically for use in the Camden Environmental Management Project. As such, the data is only available over a limited area relevant to the project (see Figure 6). However, nationwide subsidence monitoring is possible, and has already begun, in Australia. Through the Sentinel-1 mission, the entire Australian landmass can be covered at a far greater frequency than previously considered possible. Made available via the Copernicus Australasia Regional Data Hub, data from Sentinel-1 is openly available to the public, albeit in a largely unprocessed state.

The Sentinel-1 mission uses a pair of twin polar orbiting satellites, orbiting at an altitude of around 700 km (ESA, 2024). The platform utilises a range of imaging modes that vary the resolution and swath width of the final images. The modes that enable a full coverage of Australia are the Interferometric Wide (IW) swath mode, and the Extra Wide (EW) swath mode. The IW mode can achieve a swath width of 250 km at a geometric ground resolution of around 5 m x 20 m, whereas the EW mode can achieve a swath width of 400 km but at a lower resolution of around 20 m x 40 m. Both modes use Terrain Observation with Progressive Scans SAR (TOPSAR), which ensures higher quality throughout the image.

Figure 17 shows Sentinel-1's coverage across Australia, while Figure 18 indicates its subsidence management potential, illustrating ground deformation in the NSW Southern Coalfield. In this figure, the Tahmoor coal mine can be seen in the south-western corner of the image. Data from the Sentinel-1 mission therefore has the potential to greatly improve the detection of ground deformation in the study area.

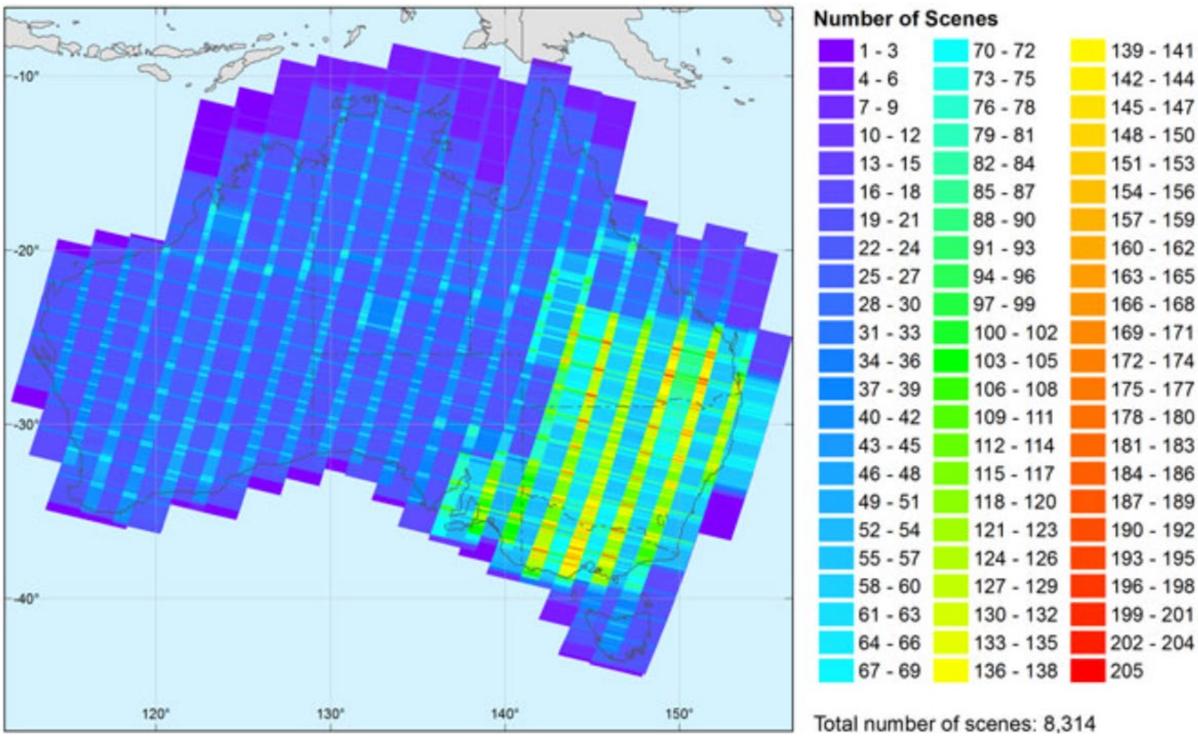

Figure 17: Sentinel-1 data coverage across Australia as of 30 April 2017 (GA, 2017).

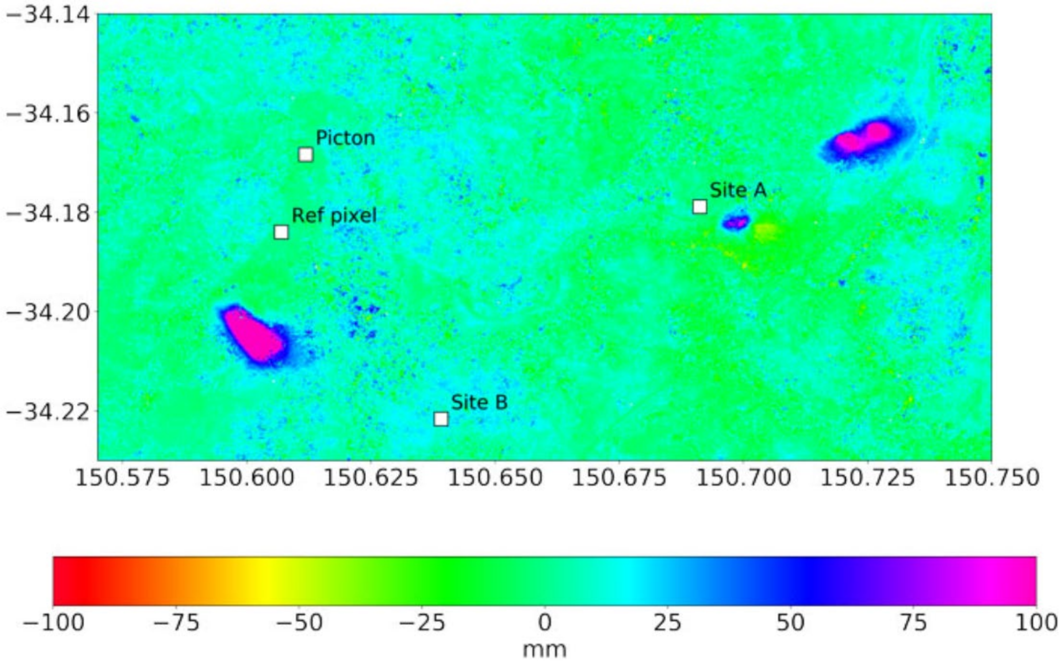

Figure 18: Areas of subsidence in the NSW Southern Coalfield determined using the Sentinel-1 mission. The Tahmoor mine is located in the south-western corner of the image (GA, 2017).

9 CONCLUDING REMARKS

The aim of this study was to compare the accuracy and practicality of modern geodetic measurement technologies for the application of large-scale ground deformation monitoring in Australia. It is desired to find methods that could be implemented to reduce or perhaps eliminate the uncertainty around survey mark movement and ground deformation. Specifically, publicly available InSAR data was examined and contrasted against traditional ground-based survey methods to test the validity of currently accessible techniques that could be utilised by surveyors and geospatial experts.

Following the comparison of ground-based and InSAR velocity results, it was evident that the public InSAR data was highly variable and not capable of providing results accurate enough to be considered as a primary means of re-establishing coordinates of survey marks. That said, the InSAR data used in this study was not designed to be used as a precise positioning tool, which is reflected by the 50-metre pixel spacing of each dataset. In addition, the aim of the study was not to test the most accurate InSAR data available, but instead to use publicly available data that any practising surveyor could access. With this in mind, it is unsurprising and perhaps unrealistic to expect near-perfect results from the public platform. Nevertheless, the InSAR data still proved to be a valuable tool for quickly detecting areas of ground movement and correctly determining its direction. This in itself could greatly benefit surveyors who suspect ground deformation has taken place but are unable to make a decisive judgement. In this case, the public InSAR data would serve as a point of verification to support a surveyor's claim. Furthermore, the use of InSAR would eliminate a lot of the guess work involved with re-establishing survey control after (or during) a deformation event. Using InSAR, areas unaffected by ground movement can be swiftly identified, providing a surveyor with a more certain location to begin their survey.

Although this study was not successful in finding a new frontline solution for managing ground deformation across Australia, it did succeed in uncovering new tools for practising surveyors to utilise. The accuracy and suitability of various geodetic measurement technologies was sufficiently tested in order to make a valid judgement on their practicality. Whilst there were obvious limitations in the design of this study, many of these were unavoidable and the product of compromise. Nonetheless, it proves that InSAR could be used in conjunction with ground-based technologies to monitor the movement of survey monuments and thus work to create greater certainty when determining the extent of ground deformation events. This study has proven to be a stepping-stone in the pursuit of a nationwide strategy to handle ground deformation.

ACKNOWLEDGEMENTS

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