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13. ABSTRACT (*Maximum 200 words*)

The primary application and technology presented herein is subsidence monitoring using repeat pass Differential Interferometric Synthetic Aperture Radar (DInSAR). The use of satellite-based DInSAR provides the possibility of continuous spatial coverage over an extended area of, for example, 50 km by 50 km using RADARSAT-1 Fine Mode. Furthermore, the accuracy possible for displacement measurements using DInSAR is approximately 5 mm (0.2 in), which is about an order of magnitude better than simple GPS surveys.

Ground subsidence due to resource extraction at the Belridge oil fields in the San Joaquin Valley of California is well known. The ground movement there is currently being monitored by global positioning system (GPS) surveys of 65 monuments. The ground subsidence due to oil extraction at the Belridge oil fields was derived from RADARSAT-1 SAR images acquired over the period from February to September 2001. The average rate of movement derived from the DInSAR analysis agrees well with that determined through GPS surveys made throughout 2000 and 2001. In areas where there is little vegetation change over the time frame of the orbit repeat cycle, satellite-based SAR thus provides the possibility of measuring ground movement with an accuracy on the order of millimeters. In areas where vegetation change is significant, then reliable ground movement estimates can only be obtained at phase-stable targets.

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RESEARCH SUMMARY

Title: Differential InSAR Measurement of Ground Movement along Pipeline Right-of-Ways, North Belridge, California (2001)

Contractor C-CORE

GRI Contract Number 7092

Principal Investigators Desmond Power, James Youden, Charles Randell

Report Type Final Report
Report Period September 2001-March 2002

Objectives

The objective of this study was to evaluate the application of repeat pass Differential Interferometric Synthetic Aperture Radar (DInSAR) for subsidence monitoring along pipeline right-of-ways. DInSAR has demonstrated the capability of measuring ground movements on the order of centimeters, and therefore it may be suitable for measuring small incremental movements whose cumulative effects on pipeline integrity are felt over a span of years.

Technical Perspective

Traditional monitoring techniques typically require regular costly site visits with the total operational expenses increasing significantly if numerous geographically dispersed sites need monitoring. The distributed nature of most pipeline systems gives rise to the potential of wide area remote sensing technologies for operational monitoring. The anticipated benefits include both reduction of some of the costs of operation and maintenance activities, and possibly the demonstration of due diligence by improved practices beyond current standards. Ground movement delineation and measurement is one potential remote sensing technology application that may serve the industry well. The demonstrated strength of satellite remote sensing is the ability to cover large areas of a system at relatively low cost to, at a minimum, detect where ground movement may be acting on buried pipelines through to providing a measurement of such movements.

Technical Approach

Ground subsidence due to resource extraction at the Belridge oil fields in the San Joaquin Valley of California is well known. Of interest to Southern California Gas Company (SoCalGas) is the rate of subsidence along their gas pipeline route (Line 1203) that runs through the North Belridge fields. The ground movement there is currently being monitored by global positioning system (GPS) surveys of 65 monuments. The use of satellite-based DInSAR provides the possibility of continuous spatial coverage over an extended area of, for example, 50 km by 50 km using RADARSAT-1 Fine Mode. Furthermore, the accuracy possible for displacement measurements using DInSAR is approximately 5 mm (0.2 in), which is about an order of magnitude better than simple GPS surveys.

Results

The ground subsidence due to oil extraction at the Belridge oil fields was derived from RADARSAT-1 SAR images acquired over the period from February to September 2001. The maximum movement measured during the monitoring intervals of 24 days was between 30 mm and 60 mm (1.2 in and 2.4 in). The average rate of movement derived from the DInSAR analysis agrees well with that determined through GPS surveys made throughout 2000 and 2001. In areas where there is little vegetation change over the time frame of the orbit repeat cycle, satellite-based SAR thus provides the possibility of measuring ground movement with an accuracy on the order of millimeters. In areas where vegetation change is significant, then reliable ground movement estimates can only be obtained at phase-stable targets.

For regions experiencing significant lateral movement, three directions of movement can be extracted by using a data fusion technique with satellite data from different look directions. The ground movement at Belridge is known to be both vertical and lateral, thus the combination of available GPS survey data and satellite images from 2000-2001 afforded the opportunity of validating this technique. The resulting analysis showed that the DInSAR data correlated well with the GPS data to within the expected 5 mm (0.2 in) error for all three movement directions (vertical, East-West, North-South). It was shown that the vertical and East-West movement measurements are better than those in the North-South direction; however, meaningful measurements were obtained in all three directions. The analysis of vertical and lateral movement was performed by a graduate student of Memorial University of Newfoundland (Canada), with in-kind funding by C-CORE.

The correct citation for this report is:

C-CORE (2002) Differential InSAR Measurement of Ground Movement along Pipeline Right-of-Ways, North Belridge, California (2001): Final Report, C-CORE Report R-01-39-552 for Gas Research Institute.

EXECUTIVE SUMMARY

The primary application and technology presented herein is subsidence monitoring using repeat pass Differential Interferometric Synthetic Aperture Radar (DInSAR). The technology's development to its current operational state was initiated through collaborative technology development projects under the auspices of the PRCI and subsequently through application on the facilities of Southern California Gas Company (SoCalGas).

Ground subsidence due to resource extraction at the Belridge oil fields in the San Joaquin Valley of California is well known. Of interest to Southern California Gas Company (SoCalGas) is the rate of subsidence along their gas pipeline route (Line 1203) that runs through the North Belridge fields. The ground movement there is currently being monitored by global positioning system (GPS) surveys of 65 monuments. The use of satellite-based DInSAR provides the possibility of continuous spatial coverage over an extended area of, for example, 50 km by 50 km using RADARSAT-1 Fine Mode. Furthermore, the accuracy possible for displacement measurements using DInSAR is approximately 5 mm (0.2 in), which is about an order of magnitude better than simple GPS surveys.

The ground subsidence due to oil extraction at the Belridge oil fields was derived from RADARSAT-1 SAR images acquired over the period from February to September 2001. The maximum movement measured during the monitoring intervals of 24 days was between 30 mm and 60 mm (1.2 in and 2.4 in). The average rate of movement derived from the DInSAR analysis agrees well with that determined through GPS surveys made throughout 2000 and 2001. In areas where there is little vegetation change over the time frame of the orbit repeat cycle, satellite-based SAR thus provides the possibility of measuring ground movement with an accuracy on the order of millimeters. In areas where vegetation change is significant, then reliable ground movement estimates can only be obtained at phase-stable targets.

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ACKNOWLEDGEMENT

C-CORE would like to thank GTI and the PRCI for their financial support of this project. Thanks is also made to Mr. Rick Gailing of Southern California Gas Company (SoCalGas), who facilitated this project and provided the location for this study. SoCalGas also provided financial support for the radar archive work (Chapter 4) and gave permission to include the results in this report. C-CORE gratefully acknowledges the support of Mr. Greg Irwin, of SoCalGas, who provided all GPS surveys that were conducted for this project.

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1 INTRODUCTION

Ground movements impact various infrastructure as either massive instantaneous movements leading to catastrophic failures or as small incremental movements whose cumulative effects on pipeline integrity are felt over a span of years. The latter incremental movements, which may be on the order of centimeters per year, are more common. Monitoring the spectrum of ground motion and assessing its impact are presently done using techniques such as periodic surveys of installed monuments, slope inclinometers, accelerometers, strain gauges and thermisters to gather inputs to pipeline/soil interaction and stress analyses which are performed on a site-by-site basis. These techniques typically require regular costly site visits with the total operational expenses increasing significantly if numerous geographically dispersed sites need monitoring.

The distributed nature of most pipeline systems gives rise to the potential of wide area remote sensing technologies for operational monitoring. The anticipated benefits include both reduction of some of the costs of operation and maintenance activities, and possibly the demonstration of due diligence by improved practices beyond current standards. Ground movement delineation and measurement is one potential remote sensing technology application that may serve the industry well. The demonstrated strength of satellite remote sensing is the ability to cover large areas of a system at relatively low cost to, at a minimum, detect where ground movement may be acting on buried pipelines through to providing a measurement of such movements.

The primary application and technology presented herein is subsidence monitoring using repeat pass DInSAR (Differential Interferometric Synthetic Aperture Radar). The technology's development to its current operational state was initiated through collaborative technology development projects under the auspices of the PRCI and subsequently through application on the facilities of Southern California Gas Company (SoCalGas).

Ground subsidence due to resource extraction at the Belridge oil fields in the San Joaquin Valley of California is well known. Of interest to SoCalGas is the rate of subsidence along their gas pipeline route (Line 1203) that runs through the North Belridge fields. The ground movement there is currently being monitored by global positioning system (GPS) surveys of 65 monuments throughout this area of $\sim 10\ \mathrm{km}^2$. The use of satellite-based differential interferometric synthetic aperture radar (DInSAR) provides the possibility of continuous spatial coverage over an extended area of, for example, 50 km by 50 km using RADARSAT-1 Fine Mode. Furthermore, the accuracy possible for displacement measurements using DInSAR is approximately 5 mm (0.2 in), which is about an order of magnitude better than simple GPS surveys.

The current report includes an overview of DInSAR for the measurement of ground motion, as well as the details relevant to the measurements at Belridge oil fields. The results from the DInSAR analysis, including the associated errors, are compared to the estimates of ground movement obtained through GPS surveys. Included is an indication of the costs of the operational application of DInSAR to ground motion monitoring.

2 Site Preparation and Data Collection

2.1 Monitored Area

SoCalGas operates a vast pipeline network in the San Joaquin Valley that serves a variety of commercial and industrial customers as well as receives and transports interstate and local producer gas supplies south to the Los Angeles basin. Local gas supplies come from many of the large oil fields throughout the San Joaquin Valley, some of which are still very active in producing large volumes of oil annually.

The Belridge oil fields have maintained high-volume production rates for many years. Historic oil production and the relatively recent production increase of the field have led to widespread ground subsidence. In 1999, it was reported that in certain areas of the field the ground had subsided approximately 1.5 metres (4.9 feet) in the previous 10 years, a rate of around 150 millimetres (0.5 feet) per year. More recent surveys conducted by SoCalGas along and adjacent to its Line 1203 pipeline right-of-way have shown that the ground surface was subsiding at a rate of 450 millimetres (1.5 feet) or more per year. The survey also revealed that the ground surface was moving in various lateral directions, which explains the damages incurred to buried pipelines and other buried and aboveground facilities in the area over the past decade, including Line 1203.

As illustrated in Figure 1, Line 1203 traverses through the North Belridge oil fields. Survey monuments along the pipeline route, as well as elsewhere both within and outside of the field are being monitored via GPS surveys. This region, as well as the South Belridge and Lost Hills oil fields, was included within the SAR image acquisitions.

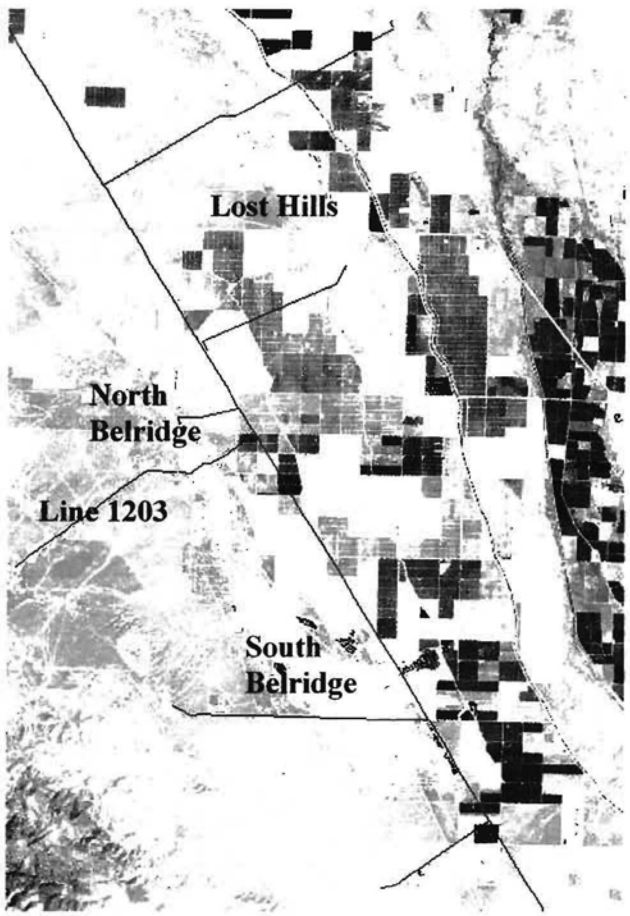

Figure 1. San Joaquin Valley showing the SoCalGas pipelines (blue lines) in the vicinity of the Belridge oil fields.

2.2 Radar Reflector Instrumentation

The major limitation of height change determination through DInSAR is temporal decorrelation of the scatterers in the pair of SAR acquisitions. Temporal decorrelation arises when the electromagnetic scattering properties of the ground changes significantly from one acquisition to the next, usually due to changes in vegetation or soil moisture, but which may also arise due to changes associated with industrial activity. For the San Joaquin Valley site, the moisture and vegetation changes are insignificant throughout much of the year. However, in the area of maximum subsidence within the Belridge oil fields, there is extensive industrial activity, which includes movement of equipment and machinery, and even digging and grading of the ground. To ensure adequate temporal coherence at least at isolated monitoring points, seven radar reflectors were installed in the region of interest (Figure 2 and Figure 3; see also Figure 7). Four of these were within the area of highest subsidence, two were on the outskirts of the subsidence area, and one was outside of the known subsidence and was therefore used as a reference. A list of the reflector locations is given in Table 1.

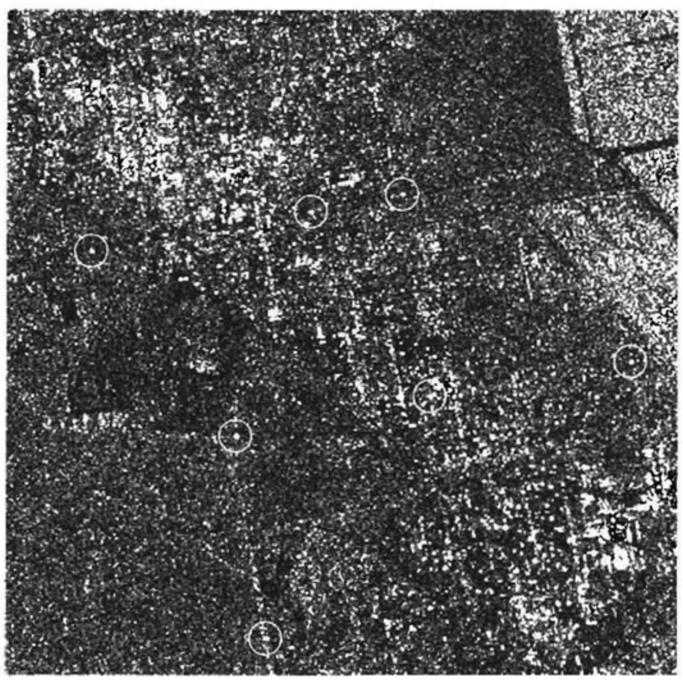

Figure 2. The RADARSAT-1 SAR image from February 25, 2001 showing the locations of the radar reflectors in the North Belridge oil fields.

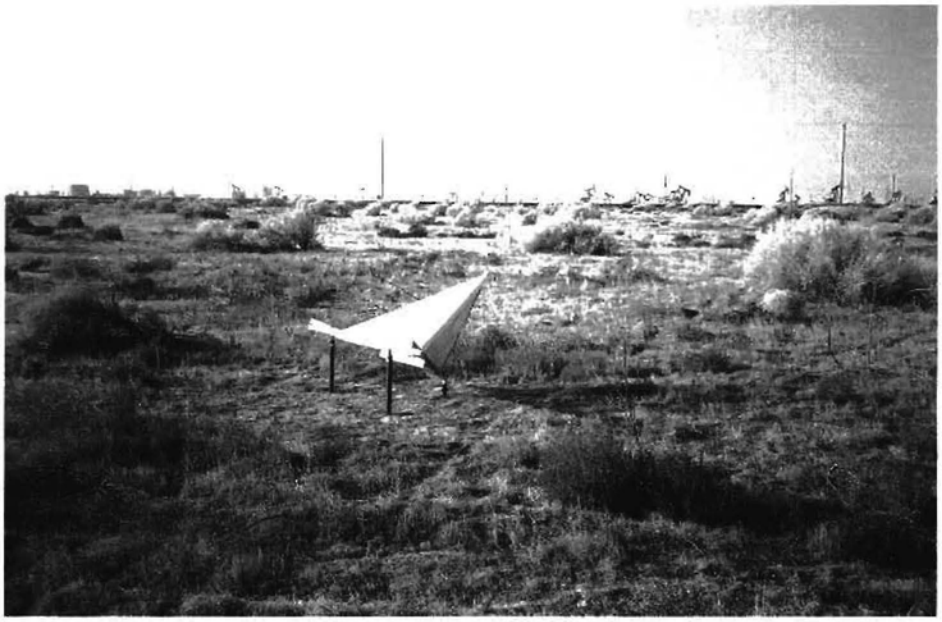

Figure 3. Example radar reflector installed in Belridge.

The design for the radar reflectors used in the present project has evolved through several years of verification and demonstrations of the application of DInSAR techniques to monitoring ground motion in areas with generally poor temporal coherence. The most recent design incorporates features to ensure minimum influence from adverse weather, along with easy and efficient transportation to and assembly at remote sites.

Table 1: Summary of installed radar reflectors.

Reflector Number	Location	
	Easting (m)	Northing (m)
R1	247995	3933560
R2	248045	3934347
R3	248834	3934325
R4	249623	3934303
R5	247659	3935135
R6	248475	3935112
R7	248928	3935099

2.3 Image Acquisitions

The area of interest, approximately 10 km^2 within the North Belridge oil fields, as well as neighboring resource areas, most notably the South Belridge and the Lost Hills oil fields, were easily covered by a RADARSAT-1 Fine Mode (~8 m resolution) scene of 50 km by 50 km. The first SAR data were acquired on February 25, 2001, with the nine subsequent SAR scenes acquired at every repeat cycle of 24 days, up to September 29, 2001 (Table 2). Each consecutive pair was used to derive the ground movement over the 24-day cycles. In general, the orbit was maintained within ±1 km, which was especially suited for DInSAR analysis.

The Digital Elevation Model (DEM), which is required to remove the variation in the radar phase due to the topography, was derived from tandem mode data of the European ERS-1 and ERS-2 satellites. Since the time interval between the acquisition of the ERS-1 and ERS-2 SAR images of the same area is only one day, decorrelation in the phase due to changes in the scattering properties of the ground, or indeed due to ground movement, is minimized. The specific acquisitions that were used were chosen based on the baseline separation between the two satellite passes, as well as the weather during the 24-hour interval between the ERS-1 and ERS-2 acquisitions.

3 DInSAR Analysis

3.1 DInSAR Derived Measurements

Synthetic aperture radar (SAR) is an active, coherent radar system that uses the motion of the sensor platform to obtain a relatively high resolution in the along track direction, and pulse compression techniques to increase the resolution in the across track direction. The phase of the backscattered radiation is a function of the electromagnetic properties of the ground as well as the distance between the sensor and the ground. If viewed from two slightly different perspectives, the topography may be derived from phase differences between two SAR images. This may be achieved either by two radar antennas mounted at different locations on the same platform, or by using one antenna and making a repeat pass of the same area. In the latter case, it should be noted that the scattering characteristics of the ground should not change between the two passes, since otherwise the measured phase differences will not depend solely on the change in viewing distances, as desired. Furthermore, for repeat passes along similar flight or orbit paths, the SAR phase differences are sensitive to any ground movement, and any variation in the phase due to topography can be easily removed using a digital elevation model (DEM). Thus, as long as the scattering characteristics of the ground remain consistent, one can derive ground movement over the time frame between two SAR acquisitions to an accuracy on the order of millimeters.

To derive the DInSAR estimates of ground movement, the differential phase is converted to movement in the look direction of the SAR, and then assuming a specific direction of ground movement, for example, vertical subsidence, the measured component can be used as a basis to estimate the actual movement. Any residual trends in the data can be eliminated by identifying stable areas, and then ensuring that such areas show no change in the SAR derived estimates.

Table 2: Dates of the RADARSAT-1 F1 Ascending acquisitions.

Acquisition Date*	Perpendicular Baseline (m)
February 25	Reference
March 21	-382
April 14	53
May 8	-677
June 1	305
June 25	787
July 19	-1156
August 12	-583
September 5	1507
September 29	321

*Interval is one orbit cycle, or 24 days.

The DInSAR estimates of the subsidence at North Belridge oil fields, over the duration of the monitoring period from February 25 to September 29, 2001, are shown in the 3.5 km by 4.1 km subarea of Figure 4. Within this area, the maximum subsidence over the 216-day period was 443 mm (17.5 in). The subsidence for the nine 24-day intervals at the positions of the survey monuments is shown in Figure 5. The maximum subsidence over the 24-day intervals varied from around 30 mm up to 60 mm (1.2 in up to 2.4 in). The greatest movement occurred for the monitoring intervals of June 25 to July 19, and August 12 to September 5. Relatively large subsidence also occurred during the interval of September 5 to September 29, and April 14 to May 8. The movements for the remaining 5 monitoring intervals were of similar magnitude, being within the range of 30 mm to 40 mm (1.2 in to 1.6 in) over the 24-day cycles.

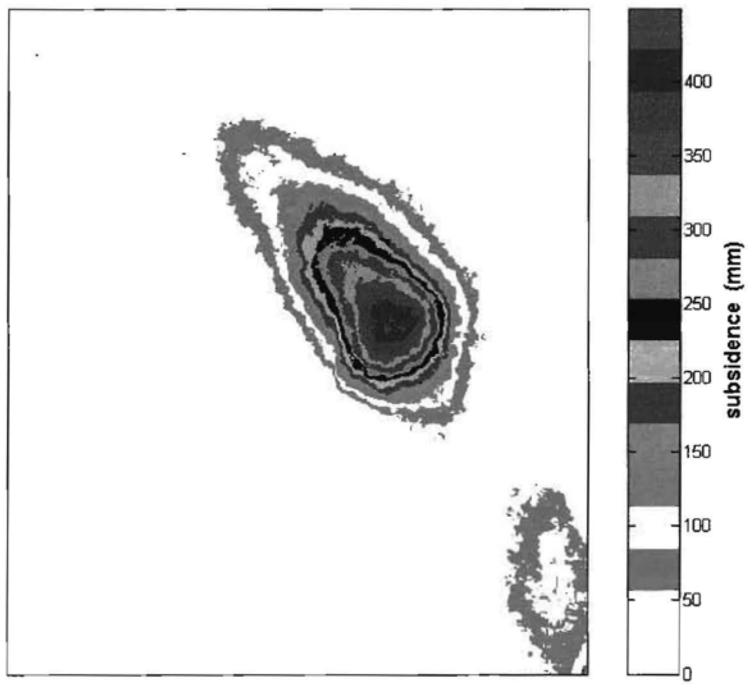

Figure 4. The DInSAR derived estimates of the ground subsidence at the North Belridge oil fields, over the 216 days from February 25 to September 29, 2001. The subarea displayed is 3.5 km by 4.1 km.

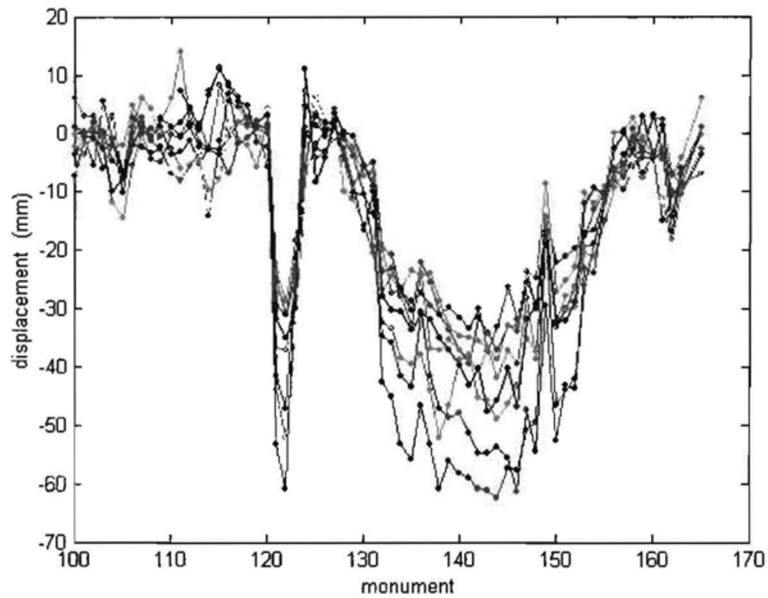

Figure 5. The DInSAR derived estimates of the ground subsidence at the locations of the survey monuments for the North Belridge oil fields, over the 24-day SAR monitoring intervals.

Within the area covered by the 50 km by 50 km RADARSAT-1 scenes, other notable areas of subsidence were the South Belridge oil fields and the Lost Hills oil fields to the northeast. These regions are shown in the overview subsidence map of Figure 6, from which it is evident that all three fields exhibit significant subsidence on the order of tens of millimeters over the 24-day monitoring intervals. Also evident in Figure 6 are the agricultural areas along the eastern half of the image. The prevalence of the rectangular fields in the image, which exhibit phase changes over the duration between SAR acquisitions, is due to significant vegetation and/or moisture changes. Such areas can be easily identified in the SAR analysis and segmented from legitimate movement.

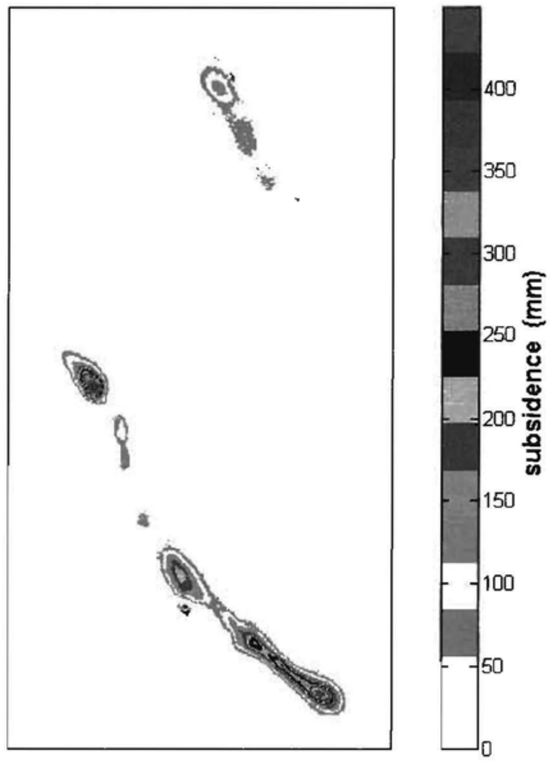

Figure 6. The DInSAR derived estimates of the ground subsidence at the Belridge and Lost Hills oil fields, over the 216 days from February 25 to September 29, 2001.

DInSAR analysis is known to yield accuracies on the order of millimeters in areas that maintain good temporal coherence, that is, areas that do not experience significant vegetation or moisture changes. Otherwise, as in the agricultural areas to the east of the Belridge region (Figure 6), the SAR phase is dominated by changes arising from variation in the electromagnetic scattering properties. In such areas, however, valid differential measurements can still be obtained at isolated points by identifying phase-stable scatterers. These may be areas of rock or gravel outcroppings, buildings, or radar reflectors or transponders that are purposely installed to ensure phase stability at a limited number of points. In the North Belridge area, seven radar reflectors were installed near survey monuments, both in the highest subsidence region as well as in areas that were known to be stable and therefore used for reference. In the former case, the reflectors were used to ensure that measurements could be obtained despite the high level of activity that was present around the oil wells. The subsidence that was derived from the radar reflectors was consistent with that derived through the complete DInSAR analysis, as well as through the

GPS surveys. Additional operational demonstration projects are taking place along pipeline right-of-ways in northwestern Alberta, in areas that rely on artificial phase-stable targets for analysis due to the extensive vegetation cover, the variation in the vegetation with the seasons, and the wet climate.

3.2 GPS Survey Measurements

GPS surveys were made of 65 monument positions during 2000 and 2001. Six surveys were made throughout 2000 and 4 were made in 2001, up to September 28, that is, up to the end of the DInSAR monitoring period. Although the movement was monitored via DInSAR only for the time frame from February 25 to September 29, 2001, all the GPS measurements for 2000 and 2001 were used to estimate the average movement, in order to reduce the variation in the GPS measurements. Assuming Gaussian statistics, the fluctuations in the combined GPS results are thus reduced to less than 1/3 of the individual measurement variation.

The locations of the monuments are displayed in Figure 7. Most are along the gas pipeline route of interest, especially in the area of highest subsidence. The others are scattered throughout the oil field area, as well as outside where there is expected to be little or no ground movement. The Easting, Northing, and vertical components of the ground movement at the monument locations, as determined from the 10 GPS surveys, are shown in Figures 8 to 10. While the major component of the ground movement is obviously subsidence, there are also lateral components, especially in the east and west directions.

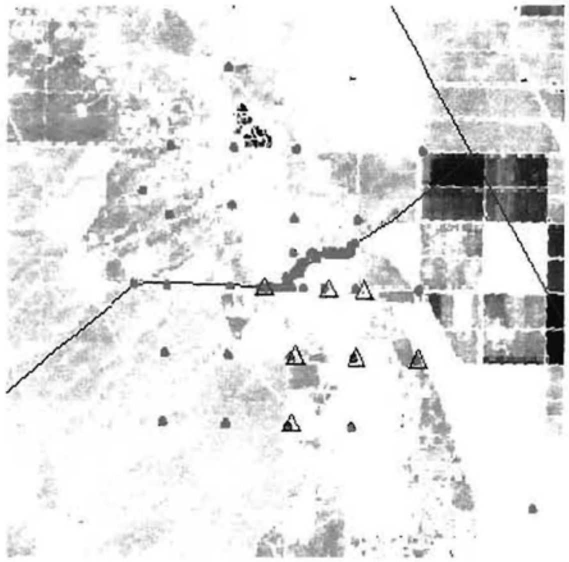

Figure 7. The locations of the GPS survey monuments (red points) in the North Belridge oil fields. Also shown are the locations of the radar reflectors (open blue triangles) and the SoCalGas pipelines (blue lines).

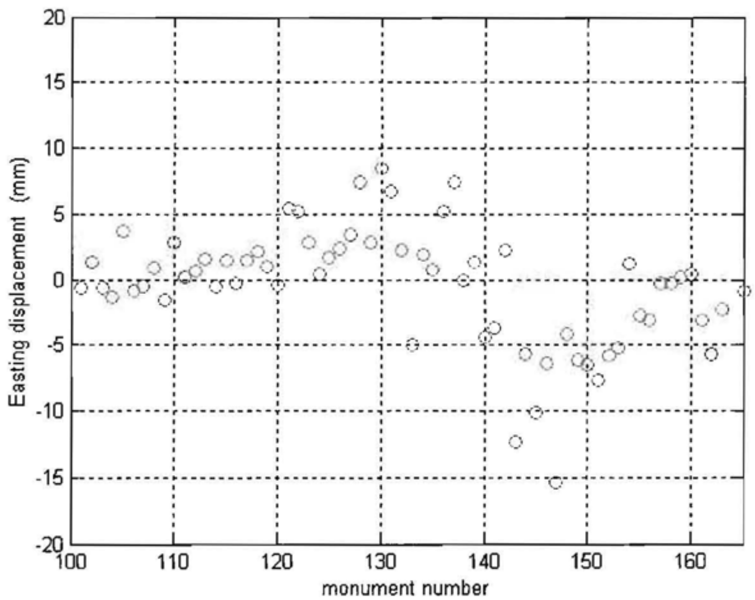

Figure 8. GPS measured Easting displacement of survey monuments at the North Belridge oil fields.

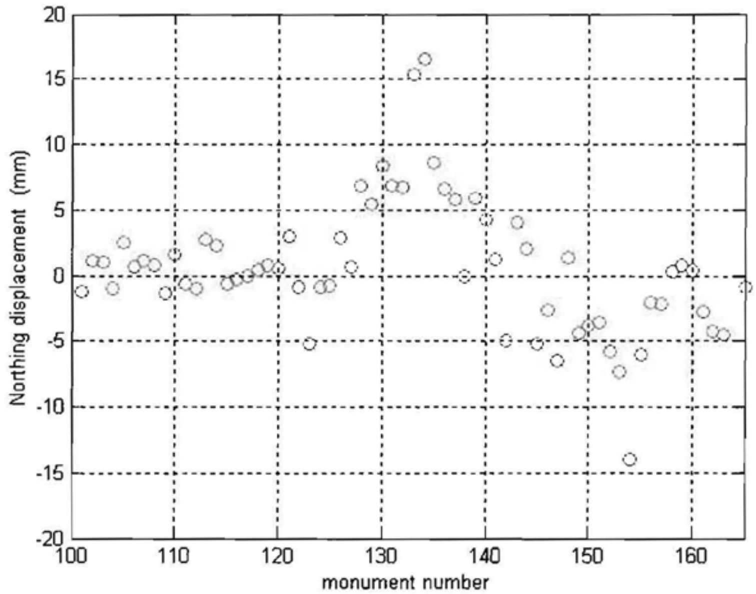

Figure 9. GPS measured Northing displacement of survey monuments at the North Belridge oil fields.

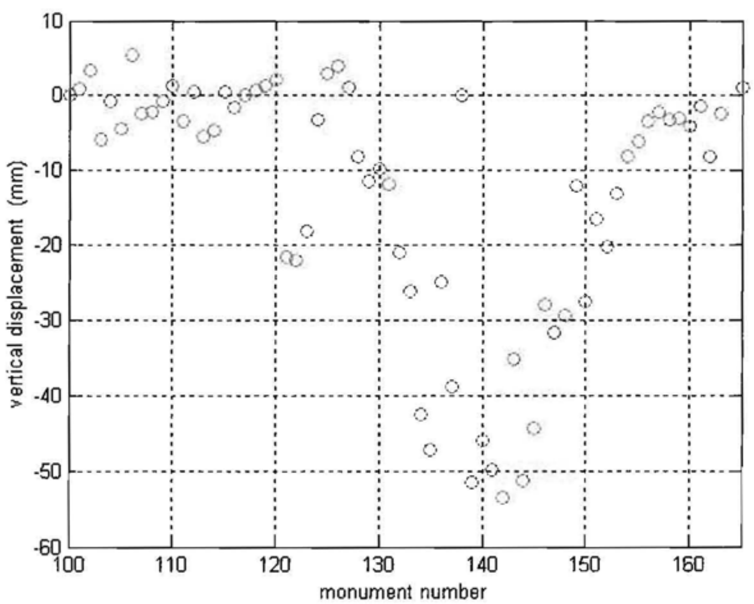

Figure 10. GPS measured vertical displacement of survey monuments at the North Belridge oil fields

3.3 DInSAR and GPS Comparison

Since DInSAR measures the component of the ground movement along the SAR look direction, the comparison between the DInSAR and GPS results is based on this component of movement only. Specifically, the resultant ground movement at each monument, determined through GPS, was projected along the SAR look direction to yield the desired component. This could then be compared directly with the displacement associated with the measured change in SAR phase at the specified monument locations. The average displacements measured via DInSAR and via GPS are shown in Figure 11, from which it is evident that both techniques yield similar results. A direct comparison between the two techniques is shown in Figure 12. The scatter in the correlation between DInSAR and GPS measurements is due mainly to the uncertainty in the GPS measurements, as well as phase noise in the SAR measurements. Phase variation due to scatterer change may be especially significant in the area of highest subsidence, since this is also the area of high industrial activity. From the accompanying figures it is evident that for the areas of little or no subsidence there appears to be discrepancies between the two techniques of around ±5 mm (±0.2 in) or less, while for the area of large subsidence, there is a systematic variation of about ±5 mm (±0.2 in).

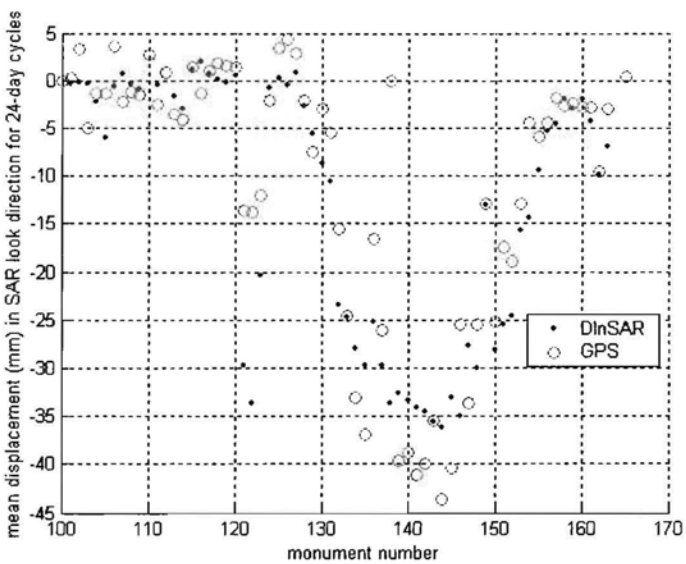

Figure 11. A comparison between the DInSAR and the GPS derived subsidence at the survey monuments within North Belridge oil fields.

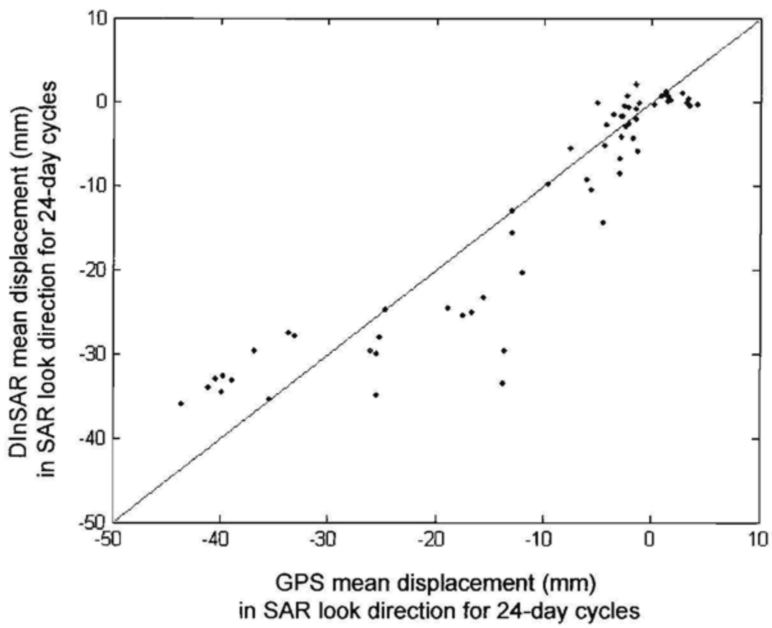

Figure 12. A comparison between the DInSAR and the GPS derived subsidence at survey monuments within the North Belridge oil fields. The solid line represents the ideal 1:1 correlation.

As noted in the GPS measurements, there are significant lateral components to the ground movement at North Belridge. The interpretation of the SAR data here is based on image acquisitions from one look direction only, namely from the descending RADARSAT-1 pass so that the look direction is roughly in a westerly direction. Since only one component of the ground motion was measured, the DInSAR estimate thus has to rely on a priori geotechnical knowledge. Alternatively, additional SAR acquisitions from other look directions could be used to measure a different component of the ground movement. This is the topic of additional research by C-CORE, and is discussed in more detail in Chapter 5.

4 Radar Archive Subsidence Measurements

To better estimate the amount of ground subsidence that has taken place over the lifetime of the pipeline, archived SAR data acquired by the European ERS-1 and ERS-2 satellites were used to derive estimates for 1992 to 2000. Specifically, the subsidence was derived for 8 DInSAR pairs within the 8-year period, where the time interval for each pair varied from a minimum of 70 days (2 orbit cycles) to a maximum of 245 days (7 cycles), with the majority of the intervals being 105 or 140 days (3 or 4 cycles). The estimate for the total subsidence over the 8-year time frame is shown in Figure 13. The North Belridge oil fields are located just left of center, while the South Belridge Fields extends down to the lower right. The Lost Hills area is in the upper right. The rectangular areas along the right half of the image are agricultural areas, which exhibit phase changes over the duration between SAR acquisitions due to significant vegetation and moisture changes. Such areas can be easily identified in the SAR analysis and segmented from legitimate movement. These areas have been identified and masked out as illustrated in Figure 14. Over the 8-year time frame, the maximum movement at the North Belridge area was 1,850 mm (72.8 in), or an average of 15 mm (0.6 in) over a 24-day period. This is only one quarter to one half of that measured in 2001, which varied from 30 mm to 60 mm (1.2 in to 2.4 in). This indicates that oil production from Belridge had increased significantly in 2001 over the previous 8 years.

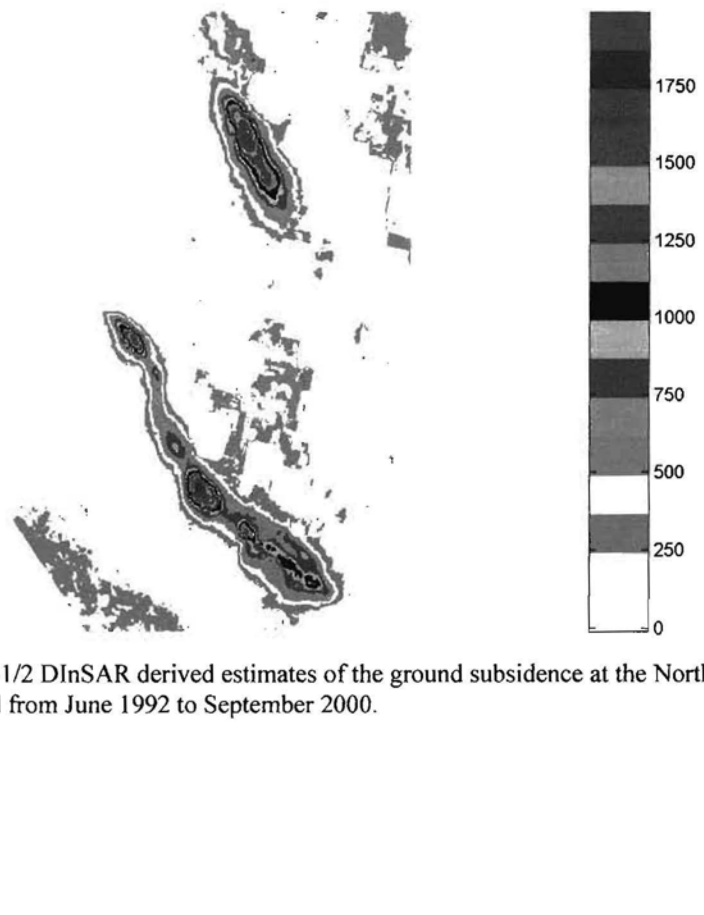

Figure 13. The ERS-1/2 DInSAR derived estimates of the ground subsidence at the North Belridge oil fields, over the 8-year period from June 1992 to September 2000.

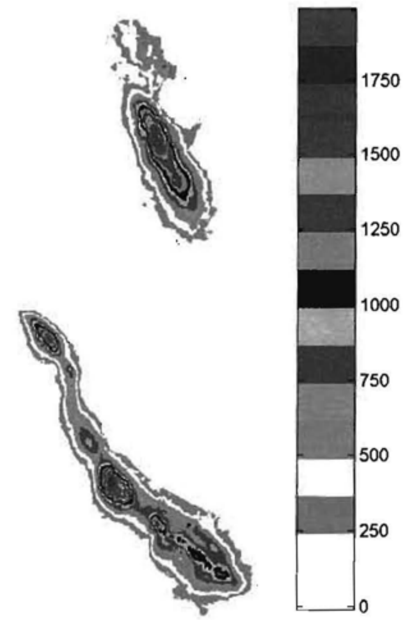

Figure 14. Subsidence measurements from Figure 12 with agricultural regions masked.

5 Lateral Movement Measurement via DInSAR

The previous chapters have described the measurement of subsidence movement via DInSAR. In this case, the series of satellite images that were used to derive subsidence were from a single look direction. Strictly speaking though, if one look direction is used to obtain ground movement estimates, then only one dimension of movement can be derived. Other directions of movement must then be assumed from the topography. For example, slopes are generally assumed to be moving along the slope direction. This would be a poor assumption if there are known "slumps" along the slope. Also, regions that are generally flat are assumed to have no lateral movement component such that the only movement is vertical (heave or subsidence).

The general assumption of zero lateral movement can produce significant subsidence measurement errors. This is true especially in the case of localized movement, whereby the sides of the moving region "cave in" towards a central maximum as shown in Figure 15. This is exactly the case for the San Joaquin Valley, Belridge region, whereby oil production is causing significant localized deformation, as evidenced by the 2001 DInSAR subsidence measurements presented in chapter 3. The errors that can occur in the derivation of subsidence with a zero lateral movement assumption are also evidenced in Figure 12. Specifically, the monuments with mean 24-day GPS measurement of between 10 and 30 mm (~0.4 and 1.2 in) have a much higher deviation off the trend line, indicating the possibility that these points have significant lateral movement which biases the subsidence estimates. This is confirmed by observing Figures 8 and 9, which show the highest lateral movement in monuments ranged from 128 to 137 and from 143 to 156.

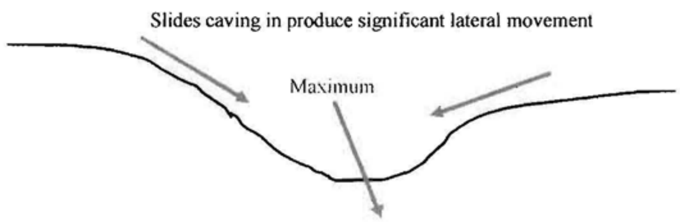

Figure 15. Sliding from both sides to produce lateral movement.

In the case of satellite SAR, there is generally two look directions from which to choose, including the ascending (South to North) and descending (North to South) orbit paths of the satellite. If both of these look directions are used to derive movements, then in theory, two components of movement can be derived. With some knowledge of type of movement being experienced in a region, which for example could be derived from a single look DInSAR derived subsidence map, methods can be used to fuse the data from these two look directions to derive all three dimensions of movement. This was the topic of a Master of Engineering thesis, sponsored by C-CORE (Sircar, 2003). While the complete details of the technique are not provided here, a summary of the results and conclusions are discussed below.

5.1 Data Fusion Geometry

As mentioned previously, space borne SAR allows imaging of two look directions from ascending and descending passes. Figure 16 provides an illustration of the orbital path of a typical polar orbiting satellite that allows two different look directions from these two passes.

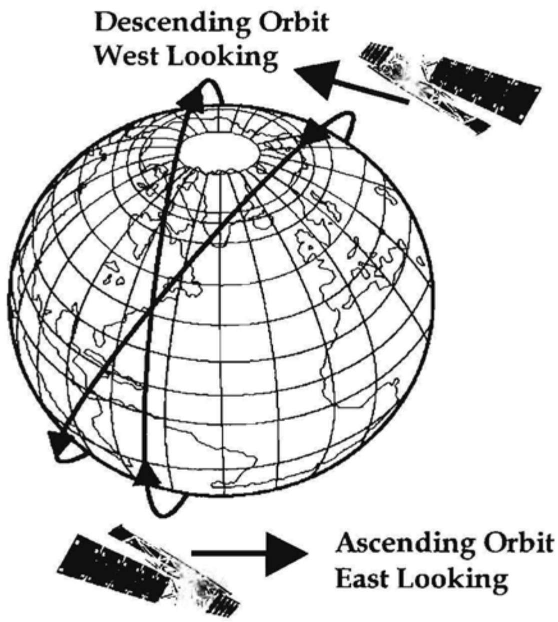

Figure 16. Descending and ascending orbits. (RADARSAT International, 1995)

Most polar orbiting satellites look in a single direction either to the left or the right of their orbital path. For example, RADARSAT-1 and ERS are right looking satellites, such that their look direction is to the East on the ascending pass, and to the West on the descending pass. As Figure 16 illustrates, the orbital path is tilted slightly off the poles; for RADARSAT-1 and ERS this tilt is roughly 8 degrees from true North at the equator. Given the general East to West look directions of the satellite, the sensitivity of lateral movement measurement is much higher in the East-West direction compared with the North-South direction. This does not imply that North-South movement cannot be measured; rather the minimum measurable movement is much higher in the North-South direction than the East-West direction. For Fine mode RADARSAT-1 data, the satellite look direction is inclined at 32-48 degrees from normal incidence at the earth's surface, thus the sensitivity to movement measurement is roughly the same for vertical and East-West movement.

5.2 Additional Imagery

To validate the performance of fusion algorithms described by Sircar (2003), an additional five descending orbit RADARSAT-1 images were capture over Belridge and processed to extract movement data. These five descending orbit images were combined with five ascending images, for a total of eight DInSAR pairs (Table 3).

Table 3: RADARSAT-1 Ascending and Descending pairs used for 3D Fusion.

Orbit Type	DInSAR Pairing	
Ascending	February 21	April 10
Ascending	April 10	June 21
Ascending	June 21	September 1
Ascending	September 1	September 25
Descending	February 25	April 14
Descending	April 14	June 25
Descending	June 25	September 5
Descending	September 5	September 29

The data from these pairs were fused to produce three dimensions of movement, and then averaged and normalized over a 24-day cycle for comparison with the GPS data. Movements extracted from each of the 65 monument positions are plotted in Figures 17 through 19 below. The following observations can be made from these plots.

- All three movement directions show a good correlation between DInSAR and GPS, and the scatter about the trend line is within expected error of ±5mm (±0.2 in).
- The fusion of two look directions has improved the error for the vertical (subsidence) measurements such that the bias has been removed for monuments with 10-30 mm (0.4-1.2 in) of movement.
- The vertical movement has the best correlation, while the North South movement has the worst correlation. However, meaningful movement data has been produced for all three directions.
- A better North-South correlation could be anticipated in regions experiencing higher levels of lateral movement. In this example, the largest North-South movement was only on the order of a centimeter over 24 days.

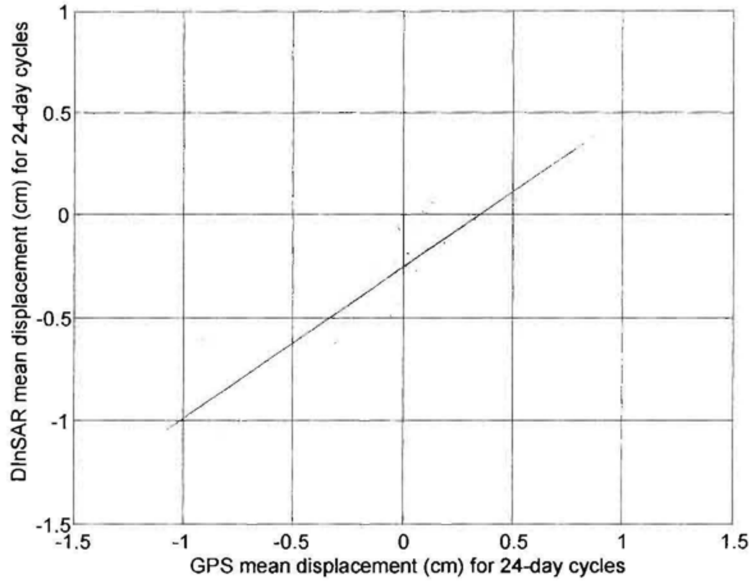

Figure 17. Lateral Movement comparison of GPS and DInSAR for the East-West direction.

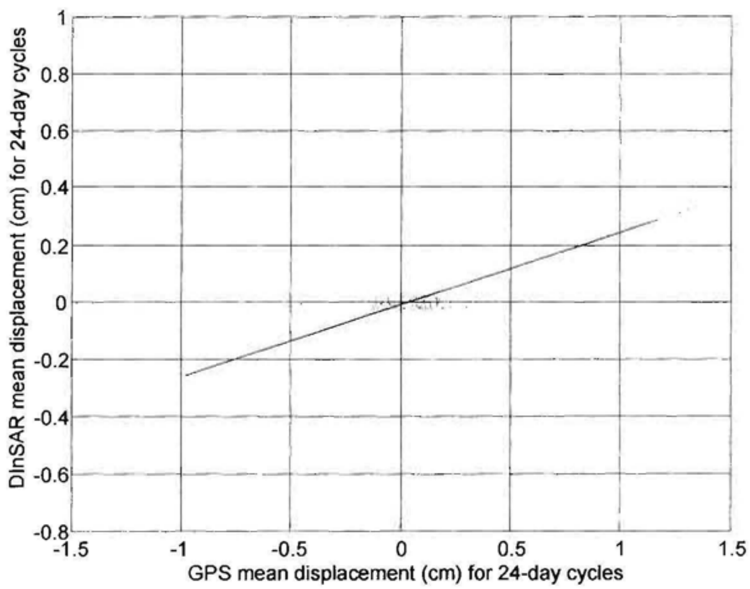

Figure 18. Lateral Movement comparison of GPS and DInSAR for the North-South direction.

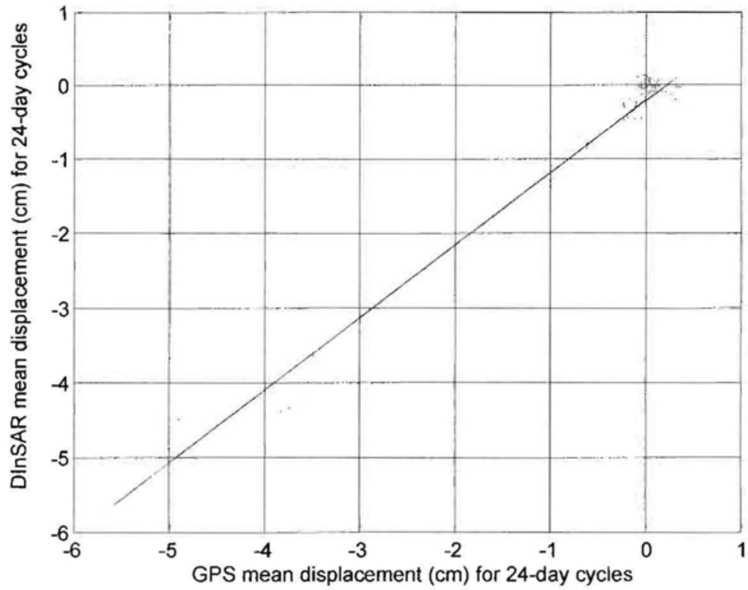

Figure 19. Vertical movement (subsidence) comparison of GPS and DInSAR.

6 Operational Costs

Operational costs of performing ground movement analysis using DInSAR may be subdivided into three different areas:

1. Generation of Digital Elevation Model (DEM);
2. Generation of ground movement measurements from SAR data; and
3. Installation of radar reflectors (if required).

The cost of generating a DEM is composed of the cost of the SAR image pairs (usually an ERS Tandem mode pair), and the cost of the labour to perform the processing, generally about 3-4 person days. Additional labour may be necessary if a high positional accuracy on the resulting derived ground movement is required. This may mean that additional ground control points may be required to geocode the DEM. Alternately, a suitable DEM may already be available, which would eliminate this cost. A suitable DEM will be gridded elevation data, spaced uniformly at a spacing of 25 metres (~80 feet) or better. These data may be available within company archives or obtained at local state or provincial mapping departments.

The cost of generating a ground movement pair is composed of the cost of the SAR image pair and the cost of the labour to perform the processing. The amount of labour required to perform processing is generally dictated by the size of the area being considered for ground movement. Small regions (about 1-2 square miles) may be processed in 1-2 days, while larger areas (10 square miles) may require 5 or more days to process. Once the first image pair has been processed, provided the duration for the next movement measurement is within a few months, it may be assumed that only one additional SAR image be required to perform the second and subsequent measurements.

If the region to be monitored is highly vegetated, or the region is prone to significant precipitation, then radar reflectors may be required. For this project, a field assembled radar reflector was designed that can be fabricated at most machine shops for about $500-$600 per unit. If the monitoring region is accessible by a pickup truck, then the cost of installation of the reflectors is generally the cost of the vehicle and labour expenses. For a two-person installation, it takes about 1 day to mobilize to the site and about 1 day to install 4-5 reflectors. If the monitoring region is remote and accessible only by helicopter, then the cost of helicopter time should also be considered, along with additional time to mobilize equipment to the sites. However, it is worthy to note that once the installation is completed, the site need not be visited on a regular basis, and consequently, the reflector installations are an upfront cost only.

Based on the above analysis, a table of costs has been derived to provide a guide to determining the actual costs. Several assumptions have been made to devise this table including the following:

- Labour cost: $500/day
- Living Expenses (for reflector installation, does not include hotels): $100/day
- Reflectors: $600 each in small quantities
- SAR Data Costs
    1. ERS/ENVISAT: $1,000 per image (60 x 60 miles)
    2. RADARSAT-1: $2,500 per image (30 x 30 miles)

It should be noted that the cost of SAR data given above is given for the extreme high case. Substantial discounts ranging to as high as 50% can be realized on data purchase in quantity. For example, 50 % discount is applied to the purchase of additional ERS scenes of the same region after the first scene is purchased, and 50% discounts may be realized on RADARSAT-1 data if the quantity of the purchase exceeds 25 images.

The quoted labour rates are also a variable. For example, the installation of reflectors may be accomplished using internal company labour. Ordering and processing of the data is usually accomplished via an external contractor. The rates quoted here are provided conservatively high; it is known that a complete DInSAR monitoring service may be provided at more competitive rates than those quoted in Table 4.

Table 4: Costs of InSAR Monitoring.

Item	Cost Item Amount	Total Cost
Up Front Costs		
DEM Generation		
SAR imagery (ERS tandem mode data)	2 x $1,000	$2,000
DEM generation	4 person-days	$2,000
Radar reflector installation (if required):		
Radar reflectors (Slope Stability, 5 reflectors per site)	5 x $600	$3,000
Field installation Labour	3 days	$1,500
Field installation Expenses	3 days	$300
Mobilization Expenses (vehicle rental, helicopter, etc.)	Variable	
Ongoing Costs		
Ground movement (RADARSAT per monitoring interval):		
SAR imagery (RADARSAT-1 Fine Mode)	2 x $2,500	$5,000
DInSAR analysis	2-6 person-days	$1,000 to $3,000
Ground movement (ERS/ENVISAT per monitoring interval):		
SAR imagery (RADARSAT-1 Fine Mode)	2 x $1,000	$2,000
DInSAR analysis	2-6 person-days	$1,000 to $3,000

The information provided in Table 4 can be clarified by providing example scenarios based on various situations. Two examples are provided here, one that requires the use of radar reflectors and one that does not. The first example is for a slope along a narrow vegetated right-of-way requiring the use of a helicopter to drop radar reflectors and personnel on site. RADARSAT-1 is used in this example due to the availability of their Fine resolution mode (8-9 metre or 26-29 foot resolution) that is more suitable for narrow pipeline corridors. The second example is for a two square-mile region (such as North Belridge in the San Joaquin Valley) in which the terrain is suitable to provide good coherence without radar reflectors. ENVISAT data is used for this second example. Both these examples do not include the cost of more comprehensive engineering analyses and detailed paper reports, as is sometimes required by various pipeline companies. As the table suggests, the highest cost is for the initial setup (with the DEM and reflector installation). This setup cost could be reduced if a DEM was already available for the region of interest. Ongoing costs are quite reasonable, and in many cases much lower than that of a traditional survey. Several scenarios of operational monitoring programs have been provided in Table 5 below.

Table 5: Example Monitoring Program.

Item	**Cost**
Example Scenario 1: Narrow Vegetated Pipeline Slope	
Setup Costs: DEM	$4,000
Setup Costs: Reflector Installation $3,000 for reflectors $3,000 helicopter time $1,000 miscellaneous vehicle and travel expenses Labour 6 person days (2 people): $3,000	$10,000
Data processing and imagery (4 person days, $5,000 for 2 images)	$7,000
Total: First Movement (includes setup)	*$21,000*
Ongoing Measurements (3 person days, $2,500 for 1 image)	*$4,000*
Example Scenario 2: Ongoing Monitoring of two square mile region	
Setup Costs: DEM (data and labour)	$4,000
First Movement Measurement (4 person days, $2,000 for 2 images)	$4,000
Total: First Movement (includes setup)	*$8,000*
Ongoing Measurements (3 person days, $1,000 for 1 image)	*$2,500*

Based on the scenarios provided above in Table 5, several conclusions may be reached:

- For large area surveys, where radar reflectors are not required and a large quantity of monuments must be surveyed using conventional means (transit or theodolite), DInSAR analysis is very cost competitive. The quality of the data is also higher, in that ground movement data may be derived with DInSAR over a wide grid instead of on individual monuments.
- For small surveys involving a small quantity of monuments using GPS type systems, the DInSAR analysis may not be competitive if the survey region is close to local company infrastructure. This is due to the fact that GPS surveys may be performed very quickly, especially if the survey location is not remote, thereby reducing the transportation time to the site. However, as has been demonstrated here, the quality of the data derived from GPS surveys is not as good as DInSAR analysis, especially if the survey is done rather quickly.
- For surveys involving the use of radar reflectors, the competitiveness of DInSAR analysis is mainly dictated by the reduction in costs associated with not having to repetitively send personnel to the field to perform traditional surveys. For remote regions where personnel transportation costs are high, ongoing monitoring of regions

with DInSAR is very competitive. The up front costs of installing radar reflectors is high, but the real cost gains may be accomplished through ongoing monitoring without the need of sending company personnel back into the field.

7 SUMMARY AND RECOMMENDATIONS

The ground subsidence due to oil extraction at the Belridge oil fields was derived from RADARSAT-1 SAR images acquired over the period from February to September 2001. The maximum movement measured during the monitoring intervals of 24 days was between 30 mm and 60 mm (1.2 in to 2.4 in). The average rate of movement derived from the DInSAR analysis agrees well with that determined through GPS surveys made throughout 2000 and 2001. In areas where there is little vegetation change over the time frame of the orbit repeat cycle, satellite-based SAR thus provides the possibility of measuring ground movement with an accuracy on the order of millimeters. In areas where vegetation change is significant, then reliable ground movement estimates can only be obtained at phase-stable targets.

For regions experiencing significant lateral movement, three directions of movement can be extracted by capturing data from different satellite look directions. In this case, the vertical and East-West movement measurements are better than those in the North-South direction; however, meaningful measurements can be obtained in all three directions. The anticipated accuracy of the movement measurements are on the order of millimeters.

DInSAR thus provides a cost-effective and operator resource-efficient method in detecting and then systematically monitoring large areas. Furthermore, such a monitoring program's ground movement measurement outputs are suited to serve as input in pipeline/soil interaction modeling and structural analysis to assess/forecast accumulated/projected strains. Comparison of the structural modeling outputs to limiting strain criteria (based on pipeline material and weld properties as well as the particular line's construction and operating history) provides an operator with an indication of the need for intervention to ensure the pipeline's ongoing operating integrity.

For the terrain conditions of the study area(s), the technology has been demonstrated to be applicable for both hindsight and forensic analysis and for ongoing proactive ground movement management. It can also be extended (albeit possibly needing phase-stable targets such as reflectors or transponders) to managing other subsidence and heave hazards such as pipeline right-of-ways above underground mining and for pipelines traversing permafrost terrain, respectively. In most situations, ongoing monitoring using DInSAR is very competitive compared to traditional analysis, especially if the monitoring region is very large or remote. DInSAR analysis may not be cost-competitive when the number of survey monuments are small, when the region of interest is conveniently reached by company personnel (e.g., nearby a compressor station) or when quick GPS surveys are adequate.

REFERENCES

Sircar, S. (2003), "Measuring Lateral Movement with Synthetic Aperture Radar Differential Interferometry: Technique and Validation," Master of Engineering Dissertation, Faculty of Engineering and Applied Science, Memorial University of Newfoundland.

RADARSAT International (1995). "RADARSAT Illuminated, Your Guide to Products and Services" RADARSAT International Client Services, Richmond, BC, Canada.