Evaluation of InSAR Technology for Monitoring Ground Movement in New Mexico
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1 INTRODUCTION

An evaluation of various InSAR techniques was conducted to determine the suitability of this space-based technology for monitoring ground movement related to oil and gas activity in North Western New Mexico. The focus of the study was directed at identifying and subsidence or uplift due to oil and gas extraction. This evaluation investigated different InSAR techniques, assessing the advantages and limitations of each. Recommendations regarding the establishment of an operational InSAR monitoring program are also included in this document.

Section 7 includes a brief background to InSAR and the techniques that were employed in this study.

2 SCOPE OF WORK

Objectives of the New Mexico site evaluation were:

1) Evaluate the suitability of RADARSAT repeat pass interferometry for detecting, mapping and measuring geotechnical surface motion.

2) Prepare and deliver RADARSAT interferometric data and products for use in the evaluation of the site suitability.
3) Prepare a report summarizing the results of the analysis and providing recommendations for the application of RADARSAT InSAR for operational geo-hazard monitoring.

3 DATA

4 RADARSAT archive images were processed for this evaluation and were acquired between January 2004 and October 2006:

January 22, 2004
August 15, 2006
October 2, 2006
October 26, 2006

All imagery used for the evaluation were RADARSAT Fine 1 Near Beam mode, acquired in an ascending satellite orbit. RADARSAT Fine beam imagery has a spatial resolution of approximately 8m. The Fine 1 Near Beam mode has a steep incidence angle making it suitable for monitoring the vertical displacement that was expected in the study area.

Shuttle RADAR Topographic Mission (SRTM) Digital Elevation Model (DEM) data was downloaded from the USGS web site (http://seamless.usgs.gov/) and used as a coarse elevation input. This DEM has postings of 30x30m.

4 METHODOLOGY

All images were processed with the MDA InSAR Toolbox software to generate the products listed in this report. High-level processing steps included:
1) **Image Co-registration** - Fine registration process results in image matching of ~1/16\(^{th}\) of a pixel

2) **Baseline Optimization** – Generates accurate estimation of the locations of the satellite’s position during image acquisition. This is required for accurate InSAR processing.

3) **Subtraction of Topography** – Phase associated with topography is eliminated to isolate possible motion within the interferogram

4) **Coherence Image** – Index of areas of noise vs areas suitable for InSAR processing

5) **Line-Of-Sight Conversion** – LOS measurements converted to vertical displacement (assumed displacement motion).

6) **Point Target Candidate Identification** – Selection of possible point targets within the study area.
5 RESULTS

Figure 5-1 Amplitude Image of study area in New Mexico
5.1 Average Amplitude Image

Figure 5-1 demonstrates an average amplitude image that is a composite of all 4 RADARSAT images that were acquired for this study. RADARSAT-1 is a Synthetic Aperture Radar (SAR) sensor which means it is an active sensor that emits and receives a signal. The strength of the received signal is referred to as amplitude. Within Figure 5-1 dark areas such as water or asphalt reflect very little energy back to the satellite and appear dark whereas urban areas or artificial surfaces with right angles reflect strong energy back to the satellite and appear bright. As each RADARSAT image is collected they are co-registered to ~1/16th of a pixel and are combined to generate this “average” image. Averaging the image removes some of the noise or speckle that is inherent to SAR sensors.

Average Amplitude Images are bi-products of the InSAR process and can be used for ground feature identification and as a reference with other InSAR products and imaging sources. During the evaluation process these images are also used to identify areas that cannot be imaged due to the sensor geometry (shadow or layover) and to select the optimum configuration.

5.2 Coherence Images

Differential InSAR (DInSAR) is the process of comparing the phase from two separate image acquisitions to detect ground movement. The level of coherence of an area will determine the success of DInSAR. Coherence is an indicator of changes that are occurring on the ground. High coherence indicates little to no change and low coherence indicates that changes have occurred between image acquisitions. Areas with vegetation will normally have very low coherence and arid and urban areas will have high coherence. Without sufficient coherence, point targets are required to measure ground movement with InSAR.
The coherence image displayed in Figure 5-2 shows areas of high coherence in white and areas of low coherence in white, black or grey. The dry climate with minimal vegetation in the region
provide ideal conditions for InSAR monitoring during the spring, summer and fall. The images used for this coherence image were August 15 and October 2. 48-days passed between image acquisitions meaning that there were two RADARSAT orbits (RADARSAT orbits are 24-days) between images. Despite the 48 day delay, the coherence is strong in the area allowing for measurements to be made.

Figure 5-3 Coherence between images acquired on August 15 and October 26, 2006.
Figure 5-3 displays the coherence between August 15 and October 26, 2006. An additional 24 days transpired between image acquisitions and the coherence has degraded compared with the image in Figure 5-2 however measurements are still possible.

Figure 5-4 Coherence between images acquired on January 22, 2004 and August 15, 2006
One long-term interferogram was generated between images acquired on January 22, 2004 and August 15, 2006. The resulting coherence image is displayed in Figure 5-4. Very little coherence is present within the image making differential InSAR results very difficult. The long temporal baseline (> 2 years) and the seasonal changes (winter/summer) are the likely reasons for the poor coherence. Point target interferometry and shorter temporal baselines can overcome these limitations.

5.3 Point Targets

Typical point targets are buildings, urban infrastructure, exposed rocks and other ground features that return a strong, consistent signal to the satellite. The presence of suitable point targets will permit InSAR monitoring in areas that otherwise lack sufficient coherence. Movement or stability at each point target can be measured to sub cm accuracy. In areas lacking both coherence and existing point targets, artificial point targets (corner reflectors) can be installed in order to increase the monitoring area.
Figure 5-5 shows the study area with potential point targets indicated in red. These targets were identified in all 4 image acquisitions and provided a strong, relatively stable signal. These candidate targets can be used to measure movement if Point Scatterer InSAR (See section 7.2.2) techniques are employed for monitoring movement. This technique can be implemented so that
it is not subject to the same interference caused by vegetation, atmosphere and snow that is present in DInSAR applications. For monitoring the study area throughout the winter months PS-InSAR techniques can be implemented in order to receive timely and reliable measurements. Many PS-InSAR techniques require large image “stacks” consisting of 20-30 images acquired from similar orbits. In the case of monitoring ground movement at the study area, if non-moving stable reference points were identified and confirmed a PS-InSAR monitoring program could be initiated within a few months.

In areas where no targets exist and there is poor coherence, artificial targets (corner reflectors) can be installed in order to increase the spatial extent of the monitoring.

5.4 Ground Movement

Because of the poor coherence of the images between 2004 and 2006 no interferometric measurements could be made. This section will focus on the results from the images acquired in the summer and fall of 2006.

Interferometric measurements originally show movement that has taken place between two images in the Line-Of-Sight (LOS) of the spacecraft. Ground movements (landslides, subsidence etc) are measured only as differences between distances of the sensor and the moving feature. Ground movements contain movement components in both the vertical and the horizontal planes and InSAR will not necessarily capture the full measurement depending on the orientation of the movement versus the orientation of the image acquisition. All measurements displayed in this report assume vertical displacement and the LOS measurements have been converted accordingly. An InSAR measurement can be calibrated to identify the full motion by integration with ground data such as a DEM, GPS, inclinometer or other field data. Minimal filtering and interpolation have been used in order to demonstrate both the benefits and limitations of InSAR.
Figure 5-6 Displacement Map 1 generated from images acquired on August 15 and October 2, 2006.
Displacement Map 1: August 15 – October 2 - Although there were 48 days in between image acquisitions, environmental and ground cover conditions were ideal for generating movement measurements. Despite the ideal conditions, minimal movement was observed. Figure 5-6 displays the movement measured for the study area. Movement is indicated by 2cm colour cycles: each full color cycle (ex: purple – purple) is 2cm of movement. Areas that appear black or speckled have poor coherence (likely due to active mining or extremely rapid ground movement) and no measurements are available for these areas.

The colour differences in Figure 5-6 are likely attributed to atmospheric effects and illustrate the fact that very little movement occurred between the acquisition dates. Atmospheric effects can introduce and error of ~1cm.
Displacement Map 2: August 15 and October 26, 2006 – Despite the 72 day temporal baseline conditions were still strong for InSAR measurements. Once again, minimal
movement was detected in the study area. Figure 5-7 demonstrates that little movement is detected during the time of acquisitions. Changes can be detected in colours throughout the image however these changes can be attributed to atmospheric differences. Changes due to movement would show sharp differences over short distances.

Large Area Displacement Map – This study was focused on obtaining measurements primarily from the area of interest but analysis of displacement on a larger scale was also investigated. Figure 5-8 shows a displacement map generated of the entire imaged area. Very little movement is detected throughout the region although further in-depth analysis may identify areas of movement associated with oil and gas extraction. One mine site in the Western portion of the image did display movement.
Figure 5-8 Large Area Displacement Map. Large scale atmospheric effects can be seen in the image.
RECOMMENDATIONS / CONCLUSIONS

InSAR techniques were successfully applied in North Western New Mexico for monitoring ground movement. The environmental conditions of the area of interest and surrounding region provided ideal conditions (minimal vegetation and dry climate) for the application of InSAR techniques. This project demonstrated the advantages of InSAR technology:

- High accuracy movement measurements – sub cm
- High spatial resolution – 8m resolution
- Ability to identify previously unknown ground movement
- Large area coverage
- Flexible monitoring frequency – Monthly to weekly coverage is possible
- Complementary technology to existing tools (prisms, GPS, inclinometers etc)

Despite the success of the project, limitations of the technology were also identified. These limitations are listed with potential solutions:

**Limitation:** Variable ground cover (Snow, etc). During the winter months the snow cover on the ground interferes with the ability of InSAR to reliably measure ground movement.  
**Solution:** Using small temporal baselines of 24 – 48 days will lessen the effects of seasonal changes. Implementing PS-InSAR techniques to collect movement information from exiting point targets. If coverage of existing targets is insufficient, cost-effective artificial corner reflectors can be installed where required. PS-InSAR techniques will permit for accurate, reliable motion monitoring year round in varying conditions.

**Limitation:** Limited knowledge of the geo-technical activity by MDA staff. Simple assumptions were made regarding the nature of the ground movement. The conversion of LOS measurements to real ground movement will be more accurate with a better geo-technical understanding.  
**Solution:** Increased integration with ground based measurements and cooperation with geo-technical engineers. Using accurate point information generated from prisms, inclinometers and GPS can better calibrate LOS measurements with accurate movement vectors. Geo-technical
experts with site specific experience will also provide vital information for improving the accuracy of the measurements.

InSAR will be a valuable tool for monitoring ground movement associated with oil and gas extraction. Conditions in the area are ideal to take advantage of the accuracy and spatial coverage of InSAR. A customized program can be implemented in coordination with known periods of activity. For example acquisitions can take place throughout the year and products generated according to periods of steam or water injection for a cost-effective monitoring solution.
7 INTERFEROMETRY BACKGROUND

7.1 What is InSAR?

Synthetic aperture radar interferometry (InSAR) is a technique that uses the differences in phase between successive SAR images, acquired by aircraft or satellite, to infer very subtle changes on or of the Earth’s surface. SAR sensors send out signals of microwave energy at a specific wavelength. Some of this energy is absorbed, but most bounces off the surface of the earth and is reflected back to the sensor, which records it as data. This data, which includes phase information, is later downloaded and analyzed. When phase information is compared between subsequent image acquisitions, it can be used to detect very small (cm to mm) movements on the Earth’s surface. InSAR is used for monitoring seismic activity, landslides, subsidence from oil or water extraction, mines, pipelines, and dam integrity.

The preliminary InSAR output product—the interferogram—is an image that visually shows the differences in phase between successive images. These phase differences include changes in elevation or motion at the Earth’s surface, baseline effects (differences in the positions of the satellite at the time of image acquisition), and atmospheric noise components. Digital elevation models (DEMs) and mathematical processes are used to remove the topography and baseline components from the preliminary interferogram, thereby isolating the motion and noise components.
7.2 InSAR approaches

There are two approaches to InSAR analysis, each with specific advantages and disadvantages: differential InSAR (DInSAR) and permanent scatterer InSAR (PS-InSAR).

7.2.1 Differential InSAR

DInSAR infers a measurement of surface motion, such as ground subsidence, by accurately measuring the phase differences for each data pixel in two successive images. This approach can be used to produce a high-resolution motion field. DInSAR requires high coherence between image acquisitions, making it well-suited to areas with a stable surface environment, having little vegetation or minimal seasonal changes. Arid regions are ideal for DInSAR applications. DInSAR requires as few as two images, and can be accurate to the centimetre.

DInSAR requires an accurate DEM to remove the topographic phase component, and is subject to layover and shadow. These factors can limit the utility of DInSAR over steep terrain. It also cannot be used to remove the atmospheric noise component. Its effectiveness is limited over areas of poor coherence, i.e., constantly changing surfaces such as those with vegetation or snow.
DInSAR offers the advantages of high spatial resolution, centimeter scale accuracy, and wide area monitoring coverage. Its limitations are that it is not suitable for vegetated areas, and is subject to atmospheric noise.

7.2.2 PS-InSAR

PS-InSAR provides a measurement of phase differences of permanent scatterers that produce a stable SAR signal return over time. PS-InSAR is ideal for areas that have a high density of permanent scatterers, typically man-made structures such as buildings, dams, and towers. Certain natural features, such as exposed rock, may also be used. PS-InSAR is effective in areas with poor coherence where DInSAR may not be suitable. PS-InSAR can provide accuracy to the millimetre, in relative measurement. In critical motion areas, corner reflectors can be installed to provide additional information and increased monitoring coverage.

To eliminate atmospheric noise and improve accuracy, PS-InSAR requires more images than DInSAR—usually a "stack" of about 15—or the use of known stable reference points. Stable local reference points can be used to eliminate local atmospheric noise and achieve millimetre accuracy with as few as 5 images.

PS-InSAR offers the advantages of millimetre accuracy, suitability for nearly all land-cover types, wide area coverage, and flexible monitoring made possible with corner reflectors. Limitations of PS-InSAR are that it requires points that change very little over time.

PS-InSAR measures phase differences of corresponding point targets in a "stack" of several images acquired over time.