Study of Low Cost InSAR for SAGD Steam Chamber Monitoring

LOOKNorth Report
R-15-033-6055

Prepared for:
PTAC PETROLEUM TECHNOLOGY ALLIANCE CANADA

Revision 2.1
2015-07-07

Captain Robert A. Bartlett Building
Morrissey Road
St. John's, NL
Canada A1B 3X5

T: (709) 864-8354
F: (709) 864-4706

Info@looknorth.org
www.looknorth.org

Registered to ISO 9001:2008

This page is intentionally left blank

Study of Low Cost InSAR for SAGD Steam Chamber Monitoring

Prepared for:

PTAC PETROLEUM TECHNOLOGY ALLIANCE CANADA

Prepared by:

LOOKNorth

Report Number:

R-15-033-6055
Revision 2.1
2015-07-07

LOOKNorth
Centre of Excellence for Commercialization and Research

Captain Robert A. Bartlett Building
Morrissey Road
St. John's, NL
Canada A1B 3X5

T: (709) 864-8354
F: (709) 864-4706

Info@looknorth.org
www.looknorth.org

Registered to ISO 9001:2008

The correct citation for this report is:
LOOKNorth. Study of Low Cost InSAR for SAGD Steam Chamber Monitoring, LOOKNorth Report R-15-033-6055 v1, January 2006.

Project Team

Mark Kapfer (Project Manager)
Pierre-Jean Alasset

DISTRIBUTION LIST

COMPANY	NAME	NUMBER OF COPIES
PTAC PETROLEUM TECHNOLOGY ALLIANCE CANADA	Soheil Asgarpour	1 electronic copy
Potfire Associates Inc	Marc Godin	1 electronic copy

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

LOOKNorth has been contracted by the Petroleum Technology Alliance of Canada (PTAC) under contract R-15-033-6055 to report on low cost Interferometric Synthetic Aperture Radar (InSAR) monitoring solutions for Steam Assisted Gravity Drainage (SAGD) Steam Chamber Monitoring. This report lays out the various options, techniques, and expected results of using InSAR as the basis for a monitoring program during SAGD operations.

The first section of this report presents a general overview of radar theory as well as an introduction to InSAR processing techniques. These well established techniques used in combination with polar orbit spaceborne SAR systems can provide highly accurate deformation information in both vertical and East-West directions depending on the acquisition configuration. This section will also explain the basic concepts and configuration requirements of the two specific techniques that are relevant to SAGD operations monitoring.

The second section provides a detailed description of data costs and ordering specifications from the most current commercial satellite providers. In this section, factors such as cost, data spatial resolution, spatial coverage and repeat cycle are explained.

The third section presents the most common SAR processing techniques and points out both natural and spacecraft phenomena that tend to affect the accuracy and sometimes feasibility of InSAR monitoring.

Finally, the last section discusses the reporting schedule and how derived InSAR results can potentially be integrated into geotechnical and geomechanical modeling.

2 UNDERSTANDING SAR TECHNOLOGY

Interferometry is a family of techniques in which waves, usually electromagnetic, are superimposed in order to extract information about the waves. Interferometry is an important investigative technique and is quite relevant to identifying surface deformation. Interferometry makes use of the principle of superposition to combine waves in a way that will cause the result of their combination to have some meaningful property that is diagnostic of the original state of the waves. This works because when two waves with the same frequency combine, the resulting pattern is determined by the phase difference between the two waves—waves that are in phase will undergo constructive interference while waves that are out of phase will undergo destructive interference and be captured through coherence, or lack thereof.

A SAR-based satellite carries a radar antenna pointed to the Earth's surface in a plane perpendicular to the orbit. The radiation transmitted from the radar has to reach the scatterers on the ground and then reflect back to the radar in order to form the SAR image (two-way travel). The microwave energy is backscattered by features on the earth's surface (i.e. rocks, vegetation, buildings etc.) and the phase and amplitude of the return signal are measured at the radar platform which carries amplitude and phase information and is represented as a number for a pixel in an image.

SAR systems provide unique images that contain information based on the dielectric constant of backscatterers as well as on the geometric configuration of the SAR platform and earth surface, in nearly all weather conditions. Since they provide their own illumination, SARs can image in daylight or at night. If two or more SAR images from different times of acquisition are compared (InSAR pair), their phase difference (interferometric fringes) can be usefully exploited to generate ground deformation maps once topographic corrections (from very high resolution DTM) are made. This radar InSAR technique uses several radar images spaced in time over a defined area of interest and measures the ground deformation over well correlated backscatters.

Any very high resolution (3m or better) radar image footprint can cover as much as a 1,500 km^2 area and high resolution (5-8m) can image a surface larger than 4,000km^2. Due to the size of SAGD region in the Canadian oils sands, the technique becomes interesting when large scale monitoring is required, as is the case for steam chamber monitoring.

SAR satellites are positioned in a polar orbit, and the data is acquired in the direction perpendicular of its flight path. In descending mode (SAR satellite travelling to the South), the satellite views the earth at an approximate 278° direction (0° is the geographic North), whereas in an ascending mode (SAR satellite travelling to the North), the satellite images in an 82° direction. The inclination of the antenna with respect to the nadir (direction pointing directly below) is usually between 15 to 50 degrees. Vertical and East-West movement are the most

SAR-sensitive directions whereas a North-South movement of an infrastructure will be significantly less detectable.

Several satellites from different international data providers are accessible at various costs. The resolution, the revisit time, the annual number of scenes acquired over the site, the promptness to deliver the data and other data parameters will have an impact on the overall project cost. It will also help make the decision on what InSAR technique is best suited to be used for a specific application.

For each candidate site and application, a 3-step analysis is recommended to adequately select the optimal InSAR monitoring technique. The first phase typically consists of a feasibility study to determine optimal geometric configuration to minimize some of the technique limitations (see section 4.1). The Differential SAR InSAR technique (D-InSAR, described in section 4.3) is used and a small number of data is required for a feasibility study. For steam chamber activity, surface heave is the key indicator, which typically leads to acquisitions near nadir to maximize sensitivity in the vertical direction. The second stage will be to determine actual and potential deformation from archived and new datasets, thus a data stack will be acquired or retrieved for archive over the shortest amount of time. Finally, an on-going monitoring phase with a cost-effective monitoring plan (section 4.4) should be in place with an annual risk revision (satellite failure, changes in SAGD operations etc).

Radar interferometry techniques include two main and different techniques: a short-term differential method based on the difference of two radar scenes called D-InSAR (one image annually and determine the total displacement for the year, section 4.3); or a long term stacking technique (PSI – Persistent Scatterer Interferometry, section 4.4) that sums 20 or more images to provide an enhanced monitoring with less residual noise and better precision. This technique is more expensive, provides higher accuracy and offers seasonal variation monitoring. Depending on the natural scattering of the area of interest, this PSI technique could be performed on natural and building backscatters only, and/or on artificial tri-hedral reflectors called corner reflectors.

3 DATA COLLECTION OVERVIEW

Several satellite SAR data suppliers are available around the world. Each system has its own characteristics, but can be differentiated based on the number of satellites and age of the systems (Table 1).

The Canadian C-Band satellite Radarsat-2 was launched in 2007. The system is in its last year of the design lifespan, however, the Radarsat-2 predecessor, Radarsat-1, extended its life from 5 to 11 years. MacDonald Dettwiler and Associates (MDA), the Radarsat-2 prime contractor, expects to extend the Radarsat-2 life similarly. Unfortunately, the future Radarsat satellites, Radarsat Constellation Mission (RCM, not before 2018-2020), will not be compatible with Radarsat-2 data.

X-Band constellation European satellites from Germany (TerraSAR-X) and Italy (COSMO-SkyMed). Both constellations began being launched in 2007 and have 2 and 4 satellites available respectively as of November 1st, 2014. Even if both systems have already passed their original lifetime specifications, they are still operationally effective. Moreover new compatible satellites are either ready to be launched or will be in the next few years to extend the overall data coverage. That should also extend data availability beyond the 2018-2020 timeframe.

The new European Space Agency Sentinel-1 data offers a free data policy. This new satellite has been in operation since October 2014, with a second one expected to form a constellation within the next two years.

Table 1. List of SAR satellites commercially available as of Nov 1st, 2014.

Satellite Name	Number of actual Satellite(s)	Number of future Satellite(s)	Available Since	Original Lifetime
Radarsat-2	1	0	2008	2015
TerraSAR-X	2	1	2008	2013*
COSMO-SkyMed	4	2	2008	2013*
Sentinel-1	1	1	2014	2021

*The date indicates the end of life of the first satellite from the constellation.

The number of data required to perform cost-effective monitoring, the existence of archive imagery and the duration of the satellite monitoring project will help guide the decision as to what system to use.

3.1 DATA COST

Commercial rates from the four satellite data providers listed in Table 1 are presented in this section. The rates are for a new, single acquisition and are valid as of November 1st, 2014. Intensive SAR monitoring, with a minimum bulk of 10 to 15 images per year depending on satellite provider, will offer a 50-60% discount on imagery cost. Moreover, archive imagery (i.e. 30 to 90 days old) is usually 50% discounted. For SAGD operations, high to very high resolution (1 to 10m spatial resolution) are also considered in this report.

3.1.1 *Radarsat-2.*

This satellite offers the largest beam and mode selection among all the available SAR satellites. This is a 1 satellite system with an interferometry revisit of 24 days (~16 images per year). A significant archive database is available since 2008. As previously stated, the original lifetime is 7 years. Table 2 presents the commercial cost of a new single image with various spatial resolution and scene size.

Table 2. Radarsat-2 Commercial Product Rates in $CAD as of Nov 1st, 2014.

Mode Group	Spatial Resolution	Scene Size (Range x Azimuth in kilometers)	Price Range
Spotlight	1m	18 x 8	$8,400
Ultra-Fine	3m	20 x 20 to 50 x 50	$5,400 - $7,800
Extra-Fine	5m	125 x 125	$7,500
Fine	8m	50 x 50 to 150 x 150	$3,600 - $7,500

Range refers to the across-track dimension perpendicular to the satellite direction, while azimuth refers to the along-track dimension parallel to the satellite direction. SAR satellites have a polar-orbit where range corresponds roughly to East-West direction (width of the image) whereas azimuth is along North-South direction (length of the image).

3.1.2 *TerraSAR-X.*

This German satellite flies in tandem with a 2010 twin satellite and will be joined by a third Spanish satellite next year (PAZ satellite). The actual interferometric revisit is 11 days (~34 images per year). Once PAZ becomes fully operational, the constellation will provide a 4/7 days revisit for interferometric applications. The original lifetime is 5 years, but the German Space Agency (satellite owner) has extended that for another 5 years. Table 3 presents the commercial cost of a new single image with various spatial resolution and scene size.

Table 3. TerraSAR-X Commercial Product Rates in $CAD as of Nov 1st, 2014.

Mode Group	Spatial Resolution	Scene Size (Range x Azimuth in kilometers)	Original Price (Euro)	Price in $CAD*
Spotlight	1m	10 x 5	€ 5,950	$8,627
Stripmap	3m	30 x 50	€ 2,950	$4,277

* Cost has been converted in $CAD from Euro using 1.45CAD = 1 Euro rate.

3.1.3 *COSMO-SkyMed.*

This is a 4 satellite constellation with satellite launch dates ranging from 2007 to 2010. Each satellite has an interferometric revisit time of 16 days and within the 16-day cycle there are 4 interferometric acquisitions. Therefore a total of 90 images per year are available with this system. The system operational lifetime is 15 years, with individual satellite lifetimes of 5 years

(Battagliere et al., 2011). A second generation of two satellites is currently under construction with main goals of assuring performance improvement and operational continuity. The first of the new satellites is scheduled to be operational in the first half of 2017. Table 4 presents the commercial cost of a new single image with various spatial resolution and scene size.

Table 4. COSMO-SkyMed Commercial Product Rates in $CAD as of Nov 1st, 2014.

Mode Group	Spatial Resolution	Scene Size (Range x Azimuth in kilometers)	Original Price (Euro)	Price in $CAD
Spotlight	1m	7 x 7	€ 6,150	$8,917
Stripmap	3m	40 x 40	€ 3,600	$5,220

3.1.4 Sentinel-1

Sentinel-1 is a space mission from the European Space Agency and comprises a constellation of 2 satellites (one in operation since October 2014 with the second being launched in 2016). The operational lifespan for each satellite is 7 years (with consumables for 12). Sentinel-1 works in a pre-programmed operational mode (cannot order data) to avoid conflicts and to produce a consistent long-term data archive built for applications based on long time series. Therefore, data products are made available systematically and free of charge to all data users including the general public, scientific and commercial users.

Table 5. Sentinel-1 Commercial Product Rates in $CAD as of Nov 1st, 2014.

Mode Group	Spatial Resolution	Scene Size (Range x Azimuth in kilometers)	Original Price (Euro)	Price in $CAD
StripMap	5	80 x N.A.	0	$0
Interferometric Wide Swath (IWS)	5 (Rg) x 20 (Az) m	250 x N.A.	0	$0

The StripMap mode will be used in exceptional cases only, to support emergency management actions, the IWS mode will be the most common product.

3.2 DATA PRIORITY AND DELIVERY

In a high demand area, conflicts between different acquisitions are probable. To avoid these, it is possible to request that the satellite provider guarantee the acquisition with a priority fee (CAD$100 - $1,000+ per image). This conflict problem primarily exists with a single satellite system. With the new generation of constellations, there is a larger selection of candidate acquisitions that reduce the risk of conflicts.

Data can be processed quickly by the satellite provider and rush-delivered, but precision of exact position of the satellite is not refined. This inevitably will have a time impact during the

InSAR processing. Fortunately in most cases specific to InSAR monitoring for the purposes of annual reporting, there is no need to rush the delivery and pay a premium to guarantee data acquisition. The sections below present the cost for each provider.

3.2.1 Radarsat-2

To guarantee the acquisition and avoid conflicts, a programming fee is charged as described in Table 6.

Table 6. Radarsat-2 Priority Services Rates in $CAD as of Nov 1st, 2014.

Programming Group	Minimum time before acquisition	Priority Level	Cost
Non Time Critical	72hours (3 days)	Low	$0
Time Critical	72hours (3 days)	Medium	$600
Guaranteed Time Critical	72hours (3 days)	High	$1,800

The Table 7 shows the different delivery options.

Table 7. Radarsat-2 Processing Services Rates in $CAD as of Nov 1st, 2014.

Processing Group	Maximum delivery time (less than)	Cost
Regular	5 days	$0
Rush	1 day	$600
Near Real-Time	4 hours	$1,200

3.2.2 TerraSAR-X

High priority services can be offered but this has to be negotiated, a standard priority is complimentary (Table 8).

Table 8. TerraSAR-X Priority Services Rates in $CAD as of Nov 1st, 2014.

Programming Group	Minimum time before acquisition	Priority Level	Cost
Non Time Critical / Standard	72hours (3 days)	Medium	$0

Data is usually delivered within 5 business days for free but a rush product is available with a fee (Table 9).

Table 9. TerraSAR-X Processing Services Rates in $CAD as of Nov 1st, 2014.

Processing Group	Maximum delivery time (less than)	Original Price (Euro)	Cost in $CAD*
Regular	7 days	0	$0
Near Real-Time	7 hours	700	$1,015

* Cost has been converted in $CAD from Euro using 1.45CAD = 1 Euro rate.

The Spanish PAZ satellite (owner and operator: Hisdesat) will be launched in 2015 into the same orbit as TerraSAR-X and TanDEM-X. The three satellites will operate within a constellation with similar cost.

3.2.3 COSMO-SkyMed

Priority services can be offered but this has to be negotiated. There is no fixed price (Table 10).

Table 10. COSMO-SkyMed Priority Services Rates in $CAD as of Nov 1st, 2014.

Programming Group	Minimum time before acquisition	Priority Level	Cost
Non Time Critical	48hours (2 days)	Medium	$0

Data is usually delivered within 3 business days for free but different time critical products are available with a fee (Table 10).

Table 11. COSMO-SkyMed Processing Services Rates in $CAD as of Nov 1st, 2014.

Processing Group	Maximum delivery time (less than)	Original Price (Euro)	Cost in $CAD*
Regular/Standard	3 days	0	$0
Rush/Fast	1 day	200	$290
Near Real-Time	8 hours	800	$1,160

3.2.4 Sentinel-1

Sentinel-1 is the European Radar Observatory, representing the first new space component of the GMES (Global Monitoring for Environment and Security) satellite family. It has a data free policy where raw data could be accessed from the ESA website using Sentinel-1 Toolbox (open source software).

Table 12. Sentinel-1 Priority Services Rates in $CAD as of Nov 1st, 2014.

Programming Group	Minimum time before acquisition	Priority Level	Cost
Conflict free	72hours (3 days)	Low	$0

Table 13. Sentinel-1 Processing Services Rates in $CAD as of Nov 1st, 2014.

Programming Group	Maximum time to deliver data (less than)	Cost
Near Real-Time	24 hours	$0

4 INSAR DATA POST-PROCESSING OVERVIEW

The data processing methods can be varied according to the identified needs. Independent from the selected processing methodology, the following are either satellite instrument or weather factors that have to be considered to ensure the maximum results precision: temporal, baseline and atmosphere decorrelation. The following section will explain each of these factors in more detail. Following the overview of these factors, the two most frequently used InSAR methodologies (D-InSAR and Persistent Scatterer InSAR) will be explained.

4.1 FACTORS AFFECTING INSAR RESULTS

Because InSAR measures relative changes in phase, the measurement accuracy can be on the order of a fraction of the radar wavelength, which are from 2-5 cms depending the selected satellite. Correctly measuring ground movement using InSAR techniques requires some estimate of change in the radar phase over the monitoring interval due to factors other than the change on the ground. Some phenomena that can cause phase changes are changes in the reflectivity (and the relative location) of the ground (temporal decorrelation), by changes in the viewing perspective (baseline decorrelation), and by changes in the atmosphere. In the worst cases, these factors will prevent the determination of ground movement by causing consecutive data acquisitions to become decorrelated.

4.1.1 Temporal Decorrelation

Probably the most important limiting factor in the application of InSAR is temporal decorrelation of the ground between the data acquisitions, and hence a loss of meaningful phase relation between corresponding pixels in an image pair. Temporal decorrelation usually results from changes in the complex reflection coefficient of the imaged surface (Zebker & Villasenor, 1992). Changes in the reflection coefficient are generally due to variation in the moisture content or the vegetation. Thus, decorrelation times can be as long as months to years for arid terrain and as short as several hours to several days for rainy and/or forested areas. Sparsely vegetated terrain can have decorrelation times between several days to several months. Snow covered and frozen terrains are generally coherent over short-terms, but are sensitive to melting and snowfall. Since each pixel in a SAR image is formed by the coherent sum of the backscatter from thousands of cells on the scale of the radar wavelength, temporal decorrelation can also result from the relative movement of the scattering cells within the SAR resolution. This is particularly relevant to slope movement, since in some instances relative motion of the ground on a scale smaller than the SAR resolution may occur.

The extent to which temporal decorrelation occurs is also dependent on the radar frequency. L-Band and P-Band SARs have fewer problems with temporal decorrelation than C or X-Band, particularly with vegetation. L and P band wavelengths generally interact with trunks and stems while C and X-band interact more with leaves and needles in vegetated region. Since the latter tends to change significantly between passes, C/X-band InSAR is generally not applied to forests and regions with heavy, fast growing vegetation.

Temporal decorrelation due to changes in the complex reflectivity of the ground or the vegetation can be mitigated through the use of phase-stable targets, such as buildings, other anthropogenic infrastructure, rock or gravel outcroppings, or radar reflectors — as shown in Figure 1— that are installed specifically for this purpose. In these cases, however, with reflectors, the ground movement can only be measured at isolated points.

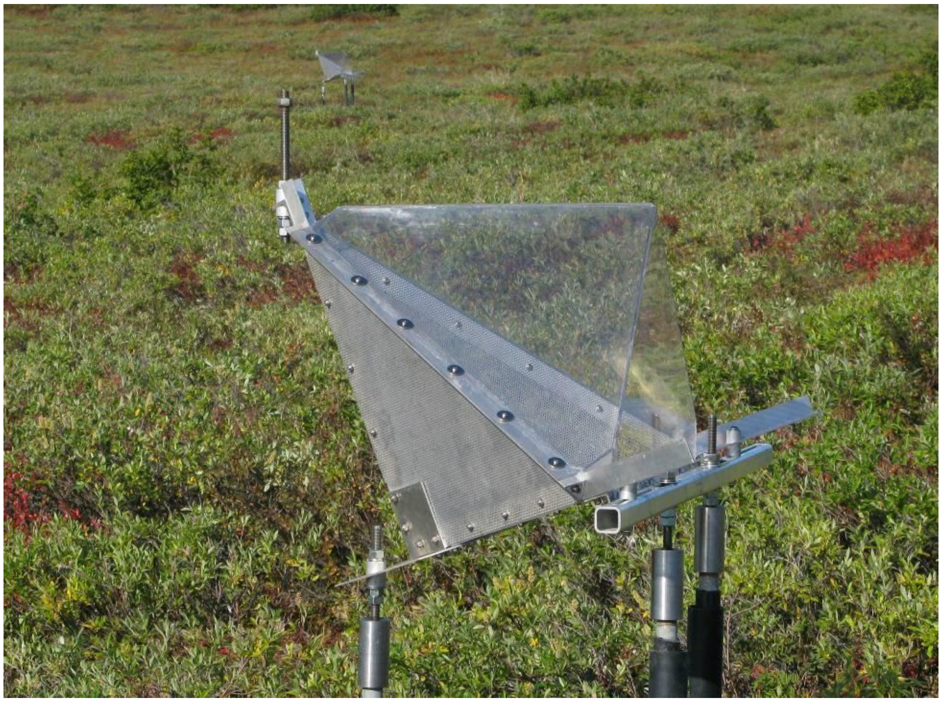

Figure 1. 60cm corner reflectors with snow cover and GPS mount can be used to mitigate the problem of temporal decorrelation (C-CORE, 2009).

To ensure reliable, year round InSAR analysis, radar reflectors can be mounted with a plexi-glass cover to prevent snow accumulation in the reflector. An added benefit of reflectors are that they can be designed to allow for GPS antenna mounting and serve as a ground truth monument point. Spatial resolution and satellite frequency will command different sizes as seen in Table 14.

Table 14. Corner Reflectors size versus spatial resolution from satellite images.

Spatial Resolution of Image for C- and X- Band satellite	Minimum Corner Reflector Size
1m	30cm
3-5m	60cm
8m	1m

4.1.2 Baseline Decorrelation

Variation in the phase occurs with different viewing geometries, since the relative locations of the scattering cells depend on the viewing position (Zebker & Goldstein, 1986). The different viewing geometries are denoted by the satellite baseline, or the difference in orbit position from one satellite pass to the next. Satellite baseline position (both parallel and perpendicular) is illustrated in Figure 2. As a general rule of thumb, a 1000m baseline for C-band and a bit less for X-band are the critical limits before denoting significant coherence loss due to baseline decorrelation. Further, the coherence of an interferometric pair depends on the spectral correlation between the two observations at different viewing geometries (Gatelli et al., 1994).

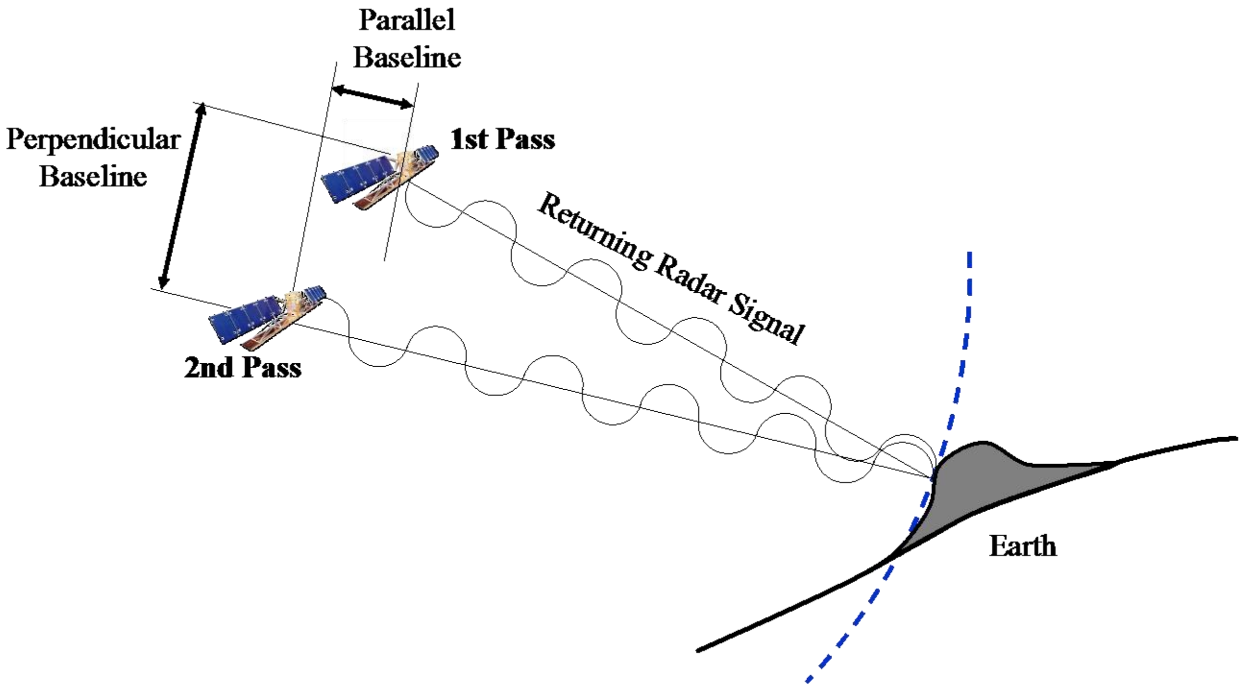

Figure 2. Orbit baseline changes can produce varying phase shifts

One should note that the current satellites providers acquire interferometric data within the critical baseline window.

4.1.3 Atmospheric Decorrelation

There are numerous studies on the influence of atmospheric effects on radar signals. These effects range from homogeneous effects to heterogeneities in both the troposphere and the ionosphere (Tarayre & Massonnet, 1996). Phase shifts due to homogeneous atmospheres produce additional interferometric fringes and can be accounted for by adjusting the satellite baseline. Given sufficient coherence, heterogeneities can often be recognized on the interferogram. Alternatively, the variation due to atmospheric effects can be isolated from multiple interferograms (Fruneau & Sarti, 2000). This is also the approach in using interferometric stacks and in permanent scatterers analysis. In particular, for large numbers of interferograms, the atmospheric effects can be identified as a random process over time and thereby separated from other contributions to the interferometric phase.

4.2 DIGITAL TERRAIN MODEL - DTM

One of the main pre-processing tasks for any interferometric technique is to convert a Digital Terrain Model - DTM into a simulated radar image in radar geometry to remove topographic information.

If no topographic information is available, the clients might incur extra expense to obtain a high resolution DTM from third-party. Generally a LiDAR (Light Detection and Ranging with metric precision) or any equivalent product is preferred. If this type of DTM cannot be used, other avenues are possible with lower resolution and accuracy. Geobase database from Open Government of Alberta Licence data sets and Natural Resources Canada website have both 10 to 25 metres resolution DTM available at no cost.

Another DTM source can be obtained from a high resolution Optical Photogrammetric technique. Data will have to be ordered and processed during non foliage coverage. For example, DigitalGlobe is one of the largest data providers with his Worldview satellite constellation. The approximate cost is $60 per square kilometre, with accuracy from 30 to 50 cms and more if steep slopes are present. It will take from 6 to 8 weeks to get a DTM completed (acquisition and processing) before delivery.

4.3 DIFFERENTIAL INTERFEROMETRY TECHNIQUE – D-INSAR

InSAR is based on the combination of two complex (magnitude and phase) and co registered (aligned) radar images (two or more) of the same area from an almost identical perspective. The phase difference for each pixel in the resulting interferogram is a measure of the relative change in distance between the scatterer (the ground) and the SAR antenna (Figure 3). In particular, Figure 3 is a simplified illustration of the variation in phase due to ground movement. The change in the distance (*d*) between the satellite and any point on the ground (change along the line-of-sight of the SAR) is simply the fraction, as determined from the interferogram phase ($\phi_2 - \phi_1$) for the two images, of half the radar wavelength (λ).

Most of the time, the observation points for the two images composing the interferogram are slightly different (the baseline), then topographic and deformation information is combined. To derive deformation a terrain model is required to simulate the topographic phase contribution in the interferogram. This technique is generally referred to as differential InSAR (D-InSAR) and allows the generation of very high accuracy (sub-centimetre or millimetre level) deformation maps.

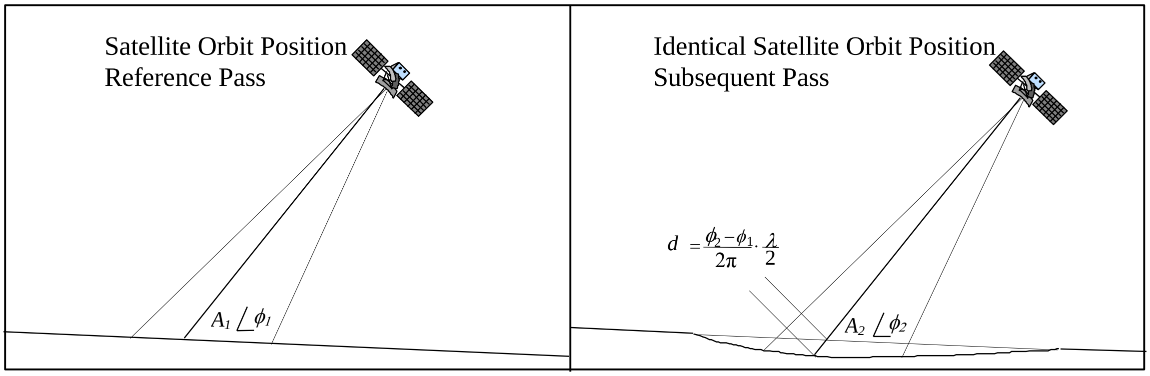

Figure 3. InSAR Measurement of Ground Movement

The time separation between satellite observations can be a fraction of a second to years. The multiple images can be thought of as "time-lapse" imagery. A target movement will be detected by comparing the images. Distance variations can be determined by computing on a pixel by pixel basis the phase difference (interferometric phase) between two (or more) SAR images. This technique measures the phase differences of the pixels in each pair of the multiple SAR images.

The conversion from measured change along the look direction to the actual ground movement relies on an understanding of the ground dynamics in order to interpret the direction, and hence magnitude, of movement from the change measured in the satellite look direction. When possible, measurements from another look direction may also be used to help decipher the actual ground movement.

For this particular technique, the time lapse between the two acquisitions could be affected by temporal decorrelation. Understandably, InSAR results can be derived only at locations within the image where the coherence is relatively high. Coherence defines the degree of similarity between two radar images and can be affected by vegetation change, snowfall or melt, or ground freeze or thaw.

This technique requires minimum processing due to a limited number of data and processing steps (co registration, topographic phase modeling from external Digital Surface Model, interferogram generation, unwrapping of the interferometric phase and finally conversion into the vertical direction for SAGD operation).

A typical output with a subsidence example is presented in Figure 4. In this figure subsidence movement is noticed in the central Pecuario Well in the Toluca Valley (Mexico) due to excessive groundwater pumping from compressible aquifers (Calderhead et al., 2010).

The location shows noticeable subsidence affecting structures over a period of 175 days. Calderhead et al., 2010 estimated that most of the compaction due to pumping occurs in the upper 100 m of the groundwater flow system, where the pores lose saturation, compressible materials are newer, and clay content is high.

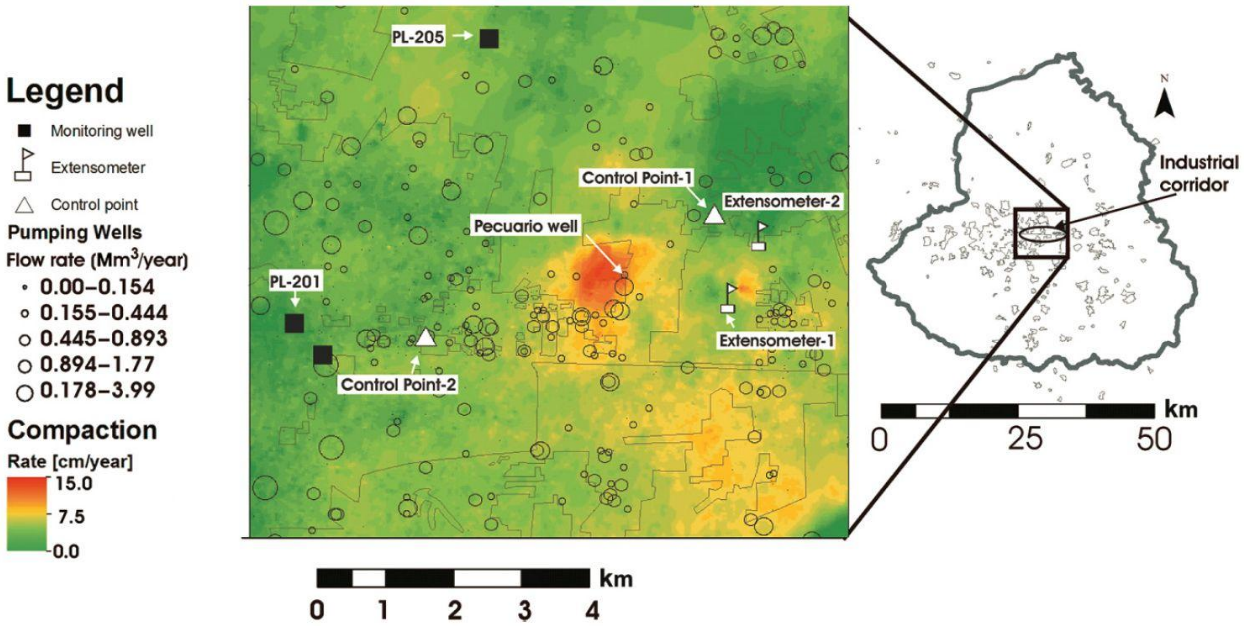

Figure 4. InSAR-measured subsidence rate map of the Toluca Valley basin obtained from ENVISAT ASAR InSAR pair (5 December 2007 and 28 May 2008) with location of extensometers, control points, monitoring wells, and pumping wells with rates (from Calderhead et al., 2010).

For SAGD operations, a two or three image dataset are required if the sole objective is to estimate a general heave trend with sub centimetre precision.

4.4 PS INTERFEROMETRY

The Persistent Scatterer Interferometry technique (PSI) is based on identifying point targets that are coherent over an extended timeframe and therefore act as stable reference points. Unlike the D-InSAR technique that uses two SAR images, the PSI technique requires 20 or more images (Ferretti et al. 2000, 2001 and Werner et al. 2003). The goal is to exploit temporal and spatial characteristics of InSAR signatures collected from point targets to map deformation histories, heights, and to correct for relative atmospheric path delays. Typical persistent scatterers are subpixel scale objects, mostly part of man-made metal or masonry structures (building, well, drill rig) and to a lesser degree natural rocks (Ferretti et al., 2005). In recent years, interest has been increasing in the use of persistent scatterers for SAR interferometry, which is normally referred to as PSI (Ferretti, Prati & Rocca, 2000; Ferretti, Prati & Rocca, 2001; Werner, C. et al., 2003). It is based on identifying point targets that are coherent over an extended timeframe. By measuring the interferometric phase at such points over multiple timeframes, the topographic, atmospheric, and decorrelation noise contributions can be isolated, thereby permitting an accurate assessment of the differential phase due to ground movement. Specifically, the technique relies on using the characteristic temporal and spatial scales of these contributions to aid in their identification. Accuracies approaching a millimeter have been obtained based on interferogram stacks of 40 to 60 ERS-1/2 scenes. Permanent scatterer InSAR is known to improve at higher resolutions due to the increased number of permanent scatterers that exist at the higher resolutions (Infoterra, 2008).

Any of the three methods PS, MBAM and DS can be used for these backscatters. The latter will significantly increase the cost of data processing.

Different heavy computational methods of processing can be used on natural backscatters and corner reflectors. A single reference image can be used for a large dataset for persistent scatterer (PS) whereas a multi baseline method (MBAM) can be used for a smaller and short time dataset. The first increases the quality of the InSAR absolute phase image by utilizing several single-look complex images whereas the other decreases the errors of the deformation estimation through iteration. More recently a more intensive processing methodology is applied to increase potential spatial coverage by exploiting spatially distributed scatterers (DS). PS usually corresponds to man-made objects, these distributed scatterers are typically identified as homogeneous ground, scattered outcrops, debris flows, non-cultivated lands and desert areas. This new approach provides additional data in low-reflectivity homogeneous areas (i.e. not heavy vegetated areas). Essentially, well distributed corner reflectors act as ideal scatterers.

5 THIRD STEP: REPORTING AND DATA INTEGRATION INTO MODELING

The frequency of reporting should be dictated by the client's need.

Discussion on desirable frequency of various reporting is the topic of this section. Any new project should separate the potential project into 3 steps:

- Step 1: Feasibility study
- Step 2: Intensive Measure monitoring to determine preliminary movement
- Step 3: On-going Updates

These steps will allow the client to have a quick check for optimal acquisition conditions, establish the baseline surface behavior, then focus the on-going monitoring on the SAGD field priorities and needs with the different reports.

5.1 STEP 1: FEASIBILITY STUDY

Before starting any long term monitoring, the client should evaluate the optimal geometry for potential vertical movement over the SAGD area or any mining facility and time lapse between acquisitions. The basic steps consist of ordering two interferometric pairs in both ascending (satellite travelling the North and looking to the East) and descending (satellite travelling to the South and looking to the West) geometries. Since vertical movements are expected, a near nadir view should be requested from any satellite provider.

The selection of the satellite provider depends of the type of monitoring required by the client (15 to 90 scenes per year can be ordered).

The results derived from the two interferometric pairs using the differential interferometry technique D-InSAR as presented in section 4.3 will be presented in a report. This first step is quick and consists of a few days worth of processing and reporting. The recommendations will be issued at the end of the study with a report.

5.2 STEP 2: INTENSIVE MEASURE MONITORING TO DETERMINE PRELIMINARY MOVEMENT

From the feasibility study results, the optimal geometry would have been selected. Shortly after, a certain number of data will be collected with a main objective to set a baseline at the end of the first year. If surface heave with sub centimetre precision is the objective, only a few images will be processed using the D-InSAR technique.

5.3 STEP 3: ON-GOING UPDATES

If more intensive monitoring is desired to fulfill not only the mandate of the regulator but also to determine more precisely surface heave with millimetre order and/or steam chamber activity a Persistent Scatterer Interferometry (PSI) technique as described in section 4.4 should be implemented. Within the first year, using any satellite constellation a 15+ large dataset can be collected and processed.

In both cases, at the end of the first year a report with preliminary movement analysis will be obtained. From these results an on-going monitoring plan should be drawn with a number of options available to continue monitoring the area for the duration and maybe post exploitation. The chosen approach will be largely dependent on the types of movements expected and also what the previous monitoring results have indicated.

5.4 MORE CONSIDERATIONS ON REPORTING

The new SAR satellite constellations offer tremendous flexibility in that new acquisitions can be planned on average every 4 to 6 days. However the all inclusive approach will undoubtedly not be necessary on any long term plan and an approach consisting of regular (bi-weekly, monthly or quarterly basis?) acquisitions with more focussed acquisitions based on expected events (seasonal variations, abnormal activity) would be sufficient to characterize the deformation in the area of interest.

Note that the time to derive deformation by comparing a single image to an existing set of data is not significantly less than deriving the information on multiple images, thus to save costs, processing can be done on sets of images.

A yearly final report should be enough to fulfill most of the SAGD operations. A six month period intermediate report can be included if enough images (4+) have been acquired to update the PSI processing and ultimately, the deformation map.

All the derived products should be in GIS (Geographic Information System) format in order to integrate, analyze and display geographic information with client database. GIS applications are tools that allow users to create interactive queries (user-created searches), analyze spatial information, edit data in maps, and present the results of all these operations.

Since every pixel contains its geographic information and deformation values, that can be used as an input for geomechanical and geotechnical numerical modeling.

Ultimately, each client has differing requirements that they need to meet. Some are regulatory while others are based on company need. Conducting a feasibility study of those requirements either internally or externally will help determine the proper reporting schedule and also lead to selecting the proper techniques, imagery vendor, reflector options etc summarized in Table 15.

Table 15. Estimated InSAR standard time for different monitoring scenario per report cycle.

	Step 1	**Step 2**	**Step 3**		
Objective	**Feasibility Study**	**Intensive Measure monitoring**	**Fulfill the mandate of the regulator**	**Fulfill the mandate of the regulator and characterize precisely surface heave**	
Year #	Year 1	Year 1 Preliminary Analysis	Year 2+	Year 2+	Year 2+
Technique	D-InSAR	PSI with natural backscatters	D-InSAR	PSI with natural backscatters	PSI with Corner Reflectors (CR)
Data number per year	2-3	15+	2-4	4-10	4-10
Additional Cost	-	-	-	-	Build and Install CRs
Ordering & Processing Time (hours)	40-50	100-150	30-60	50-70	50-70
Report & Meeting Time (hours)	25-35	35-50	20-30	20-30	20-30

A last cost not included in this table is the duplication of the spaceborne radar monitoring with two different datasets when transitioning from an old system to a newer system.

6 FINAL STEP: CONSIDERATIONS

Table 16. List of items to considered for InSAR monitoring program

Item	Options	Cost	Impact on Accuracy
Data Sources	Current Missions (cf Table 1): • Radarsat-2 • TerrasSAR-X • COSMO-SkyMed • Sentinel-1 • RISAT-1 • ALOS-2 Future Missions: • Radarsat Constellation Mission (RCM,2018).	Single image cost (Price listed in Table 2 to Table 5): • Radarsat-2 from $3,600 to $8,400 • TerrasSar-X from $4,200 to $8,600 • COSMO-SkyMed from $5,200 to $8,900 • Sentinel-1 $0 • RISAT-1 is an Indian C-band satellite that is not yet ready for InSAR application. • ALOS-2 data is free but can be used for research only. • RCM cost model is to be determined. Most missions would provide up to a 60% discount on large orders. Archive image (30-90 days old) are usually 50% discounted.	Differential InSAR analysis requires a minimum of 2 images. Few more images can be ordered for seasonal changes with no impact of accuracy (~1cm). Adding more data improves accuracy of measurements by making Persistent Scatter Interferometry techniques feasible, reducing noise and by reducing area lost to non-coherence. It is expected an accuracy improvement to 3-5 mm with a stack of 20 images using natural backscatterers. Adding Corner Reflectors will improve the precision to 1-3mm. It comes with an extra cost for manufacturing and installing the CRs.
Spatial Resolution & Accuracy (Price listed in Table 2 to Table 5)	3 general image modes are available: • Spotlight mode (1m) • Highest Strip Map (~3 m) • Medium Strip Map (5-10 m)	Single image cost for Radarsat-2, TerraSAR-X and COSMO-SkyMed: • Spotlight mode starts at $8,000 • Highest Stripmap from $4,200 to $7,500 • Medium Stripmap from $3,600 to $7,500 Most missions would provide up to a 60% discount on large orders.	Increasing the spatial resolution and accuracy would have minimal effect on the measured vertical displacement of a distributed target. Increased spatial resolution would provide better depiction of the shape of a deformed area; this may be important if the intent is to link deformation to a particular target or structure. For distributed targets (ground surface) spotlight mode is not required; Best strip map (~3) or even medium strip map (5-10 m) is likely sufficient. Balancing spatial resolution and coverage is key.

Item	Options	Cost	Impact on Accuracy
Scene extent / Coverage	3 general image modes are available: • Spotlight mode scene size is 10km x 10km or less • Highest Strip Map: 20km x 20km to 50km x 50km • Medium Strip Map: 40km x 40km to 150km x 150km	Single image cost is similar to Spatial Resolution & Accuracy tab. Data is sold on a per scene basis: larger cover size lowers cost per ground area. Therefore there is a cost savings per ground area covered by choosing a data source with larger coverage. This is valid only if the additional area is useful information or data can be shared with another O&G adjacent site.	A larger coverage area does not improve measurement accuracy unless it gives access to more needed ground control points. Usually C-band satellites tend to offer a slightly larger coverage than X-band.
Wavelength	3 frequency modes are available: • C-Band (Radarsat-2, Sentinel-1, RISAT-1, RCM) • X Band (COSMO-SkyMed, TerraSar-X,) • L Band (ALOS-2)	Any cost changes are related to mission selection.	In the case of a major movement (cm+ movement), the wavelength could limit the movement detect-ability. The longer the wavelength the larger the displacement can be measured between consecutive passes. Half of the wavelength sets the limit of detect-ability. This varies from 1.5cm to 2.8cm and finally 11.5cm for X-, C- and L-band respectively. C-band is less sensitive to atmospheric moisture; phase measurements may be slightly more reliable, hence more usable data. X-Band is more sensitive to fine scale surface roughness; ground surface detail may be slightly improved at X-band but this does not affect subsidence measurement. X-band may be slightly more difficult to unwrap.

Item	Options	Cost	Impact on Accuracy
Data Priority (cf. Table 6, 8, 10 and 12)	Usually 3 groups: • Non Time Critical (NTC) • Time Critical (TC) • Guaranteed Time Critical (GTC)	The cost per scene is mission dependent: • NTC: By default it is $0 for all missions. • TC: $600 or negotiable with data provider. • GTC: $1,800 or negotiable with data provider. Sentinel has a data free policy but there is no guarantee to obtain the image.	In the case where acquisitions must occur on specific days, users can pay a fee to guarantee that the acquisition is not bumped (e.g. Radarsat-2). This may be necessary for one satellite mission (i.e. Radarsat-2) because a missed acquisition results in a 24 day gap in coverage. It would not be necessary with a current and future constellation such as COSMO-SkyMed because an alternate satellite would be available within a few days as an alternative.
Data Processing / Delivery fees (cf. Table 7, 9 11 and 13)	Usually 3 groups: • Regular/Standard • Rush/Fast • Near Real Time (NRT)	The cost per scene is mission dependent: • Standard: Few days it is $0 for all missions. • Rush: 1 day varies from $290 to $600. • NRT: Few hours from $1,000 to $1,200. Sentinel has a data free policy but there is no guarantee to obtain the image.	For regulatory compliance, there is no need for NRT processing. For exceptional operational support and emergency NRT processing may be necessary but it will also imply a NRT InSAR processing.
Data ordering but not processed	Acquisition only for archive, as a background mission.	The client can negotiate directly with data providers to task a satellite to acquire image over area of interest without processing the images. Sentinel has a data free policy.	Some vendors allow users to program and acquire data and hold it in reserve as a precaution in the event it is needed. A programming fee is charged but no processing and data are not actually delivered. Other missions (Sentinel 1) acquire set coverage with no fees. This allows users to have data available if and when it is needed at a significantly reduced cost. This tool can be considered when transitioning to one dataset to another one.

Item	Options	Cost	Impact on Accuracy
Sensitivity & Radiometric Resolution (NESZ)		Any cost changes are related to mission selection	Lower NESZ might improve coherence over some distributed target scenes without natural corner reflectors; effect likely minimal.
Reliability of Acquisition	Usually not specified by vendor	No price associated; not all vendors provide accurate statistics	Acquisition reliability may be a critical factor affecting InSAR monitoring. A program relying on relatively infrequent passes (e.g. the repeat cycles of Radarsat-2) has little tolerance for missed acquisitions (i.e. the gap in coverage is too large to accurately depict movement events or may cause loss of coherence). A constellation of satellites, where InSAR measurements can be made between data from different satellites in the constellation means that more passes could be missed without seriously affecting a monitoring program (see Data priority)
Ground control	Installing several corner reflectors along key operational areas.	Manufacturing a 2 or 3 feet large corner reflector with a snow cover to provide measurement even during winter time can require several weeks. Manufacturing and shipping may cost from $4k to $7k per unit. Installation is a separate expense. Once installed the corner reflectors are maintenance free.	Adding corner reflector will bring the accuracy to its highest level.

Table 17. Technical Risk Assessment

Risk	**Mitigation**	**Retirement Criteria**	**Probability**	**Impact**
Sites have low coherence and not suitable for InSAR analysis	O&G SAGD area should provide enough echoes back to satellite. For certain low coherence area corner reflectors can be installed to mitigate that concerns.	Coherence estimates confirmed via InSAR analysis.	Low	Medium
Data lost due to conflicts with other clients or for technical failure	Work with satellite agency order desk to free orbits for the project.	All data acquired	Low to medium depending on the number of satellite available.	Medium to high. A one satellite mission (e.g. Radarsat-2) will have a big impact force to wait a new orbit cycle (24 days) to get new acquisition.
Satellite failure – loss of satellite during project execution	If one satellite mission, need to revert to other suitable platforms including German provider and its TerraSAR-X. For constellation missions there is at least another satellite to use.	Data acquisitions complete	Low with new satellites but medium with aging satellites	Medium to high. A one satellite mission (e.g. Radarsat-2) will disrupt the monitoring and create a gap in the monitoring program to comply with AER regulations.

In summary, the recommended approach to conducting InSAR surveillance of SAGD operations depends on the desired accuracy and detail of the coverage. From consultation with Oil Sands operators, it appears there are 2 potential applications for detailed surface deformation mapping: regulatory compliance imposed by the Alberta Energy Regulator (AER) and operational support. From this, two scenarios for each application are presented below (scenarios #1 and 2 for AER role whereas scenarios #3 and 4 for SAGD operational support).

Please note that when starting a new project one time extra expenses should be considered for example collecting a Digital Terrain Model (DTM), converting the DTM into radar geometry and preparing any other GIS derived products.

Data cost is derived from the Tables in the report (word document). Processing cost is based on industry hourly rate standards.

For regulatory compliance, the required specifications are vague. No accuracy (vertical or horizontal) is specified and other than an annual requirement to submit, there is no time period over which the deformation measurement must be made. Deformation mapping for operational support is also not well specified as the extent to which InSAR measurements are used to support operations vary from company to company. LOOKNorth believes that there are 2 main accuracy levels that can be achieved that relate to the use of the data. The first level would accurately measure approximately a centimetre of relative vertical deformation or more and would be adequate for regulatory compliance. The second level would achieve few millimetres of relative or absolute vertical position and would likely be desired for providing operational support. The following table presents two scenarios for each solution respectively.

With centimetre accuracy, Differential Interferometry (D-InSAR Technique, section 4.3 of report) would be the appropriate technique. Scenario 1 is the most basic one with 3 to 4 images acquired over one year. In case of noise on one image, there are still at least 2 images that can be used. The differential interferometric processing outputs consists in generating displacement maps in line-of-sight and vertical directions. Scenario 2 presents the largest effort to comply with AER monitoring using D-InSAR technique.

Beyond 6-8 images, it is most cost effective to start a more intensive data acquisition with one yearly report using the Persistent Scatterer Interferometry technique (PSI, presented in section 4.4 of the report) as described in scenario 3. This is still a relative measurement but improving significantly the precision of the movement (from cm to mm level).

Finally, in case of low coherence, or to enhance absolute accuracy, corner reflectors can be considered. Scenario 4 shows the cost for a 15 images plan with a yearly report for both natural and corner reflectors. Each technique requires its own processing chain, and corner reflectors need to be manufactured and shipped on site. Installation is an extra because it is site dependent (type of footings, depth of footings, safety training/orientations required, personnel from InSAR service company, etc).

7 SELECTING A MONITORING SCENARIO

Table 18. InSAR Monitoring Scenarios

Scenario #	Monitoring Objective	Technique Description	Data Cost	Ordering, Processing (Pre-, Post) and Reporting cost	Other cost (corner Reflector ...)	Estimated Total
1	AER compliance ground movement monitoring	D InSAR for small displacement rate <2-3cm/year. Based on a distributed acquisition plan over time to avoid displacement underestimation	2-4images per year: $10k to $20k for 3m to 5m resolution	1 report/yr: $15k-25k	None	$25k to $45k
2	AER compliance ground movement monitoring	Differential InSAR for movement <6-10cm/yr. Based on more frequent distributed acquisition over time.	6-8 images per year: $20k to $40k for 3m to 5m resolution	1 report/yr: $35k-55k	None	$55k to $95k
3	AER compliance ground movement monitoring SAGD operations with seasonal and long term analysis	PSI analysis on natural backscatters only	15 images per year: - $25k to $30k for 3m to 5m resolution and coverage less than 2,000km^2 - $45k+ for 3m to 5m resolution and coverage greater than 2,500km^2	1 report/yr: $30 to $50k depending the size of the area	None	Depending onthe size of image: - $55k to $80k or - $75k to $95k
4	AER compliance ground movement monitoring SAGD operations with seasonal and long term analysis with absolute precision	PSI analysis on natural backscatters and on installed Corner Reflectors	15 images per year: - $25k to $30k for 3m to 5m resolution and coverage less than 2,000km^2 - $45k+ for 3m to 5m resolution and coverage greater than 2,500km^2	1 report/yr with dual analysis: $55k to $100k depending the size of the area.	Depending on the size the unit cost ranges from $4k to $7k. For 10 units, without installation cost should be $40k to $70k.	Depending on the size of image: - $120k to $200k or - $140k to $215k

Note: Sentinel-1 was not included in the above scenarios due to uncertainty in data quality, cost, reliability etc.

8 REFERENCES

Battagliere, M. L., Covello, F., Coletta, A. (2011). Cosmo-SkyMed constellation fully deployed: overview and exploitation, *Proceedings of IAC 2011 (62nd International Astronautical Congress)*, Cape Town, South Africa, Oct. 3-7, 2011, paper: IAC-11-B1.5.2

Calderhead, A., Martel, R., Alasset, P.-J., Rivera, A., Garfias, J. (2010). Land subsidence induced by groundwater pumping, monitored by D-InSAR and field data in the Toluca Valley, Mexico, *Canadian Journal of Remote Sensing,* vol. 36, no. 1, pp. 9-23, Sept. 2010.

C-CORE. (2009). Coastal Environment Monitoring with Advanced InSAR Techniques - Corner Reflectors' Installation Report, C-CORE Report R-09-044-649 v1.0, November 2009.

C-CORE. (2011). Critical Infrastructure Monitoring for the Energy Sector Final Report, Volume II: Technical Report, C-CORE Report R-10-099-648 v1, April 2011.

Ferretti, A., Prati, C. and Rocca, F. (2000). Nonlinear Subsidence Rate Estimation using Permanent Scatters in Differential SAR Interferometry. *IEEE Transactions on Geoscience and Remote Sensing,* vol. 38, no. 5, pp. 2202-2212, Sept. 2000.

Ferretti, A., Prati, C., and Rocca, F., (2001). "Permanent scatterers in SAR interferometry", *IEEE Transactions on Geoscience and Remote Sensing*., vol. 39, no. 1, pp. 8-20, Jan. 2001.

Ferretti, A., Prati, C., and Rocca, F., Casagli, N., Farina, P., and Young B (2005). Permanent Scatterers Technology: a powerful state of the art tool for historic and future monitoring of landslides and other terrain instability phenomena. *Proc. International Landslide Symposium - ISL2005* Vancouver – Canada

Gamma RS. (2010). GAMMA *Interferometric Point Target Analysis Software (IPTA): Users Guide*, December 2010.

Golder Associates. (2004a). Report on Geotechnical Considerations - East Urban Community, Ottawa Ontario. A report (No. 03-1120-245) submitted to Stantec Consulting Ltd.

Golder Associates. (2004b). Supplementary Report on Geotechnical Considerations - East Urban Community, Ottawa Ontario 03-1120-245. A report (No. 04-1120-039) submitted to Stantec Consulting Ltd.

Rosen, P.A., Hensley, S., Joughin, I.R., Li F.K., Madsen, S.N., Rodriguez, E., Goldstein. R.M. (2000). Synthetic aperture radar interferometry. In *Proc. of the I.E.E.E.* 88, pp. 333-382.

Wegmüller, U., IEEE, Walter, D., Spreckels, V., and Werner, C. (2010). Nonuniform Ground Motion Monitoring With TerraSAR-X Persistent Scatterer Interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 4, pp. 895 904, Feb. 2010

Werner, C., Wegmuller, U, Strozzi, T. and Wiesmann, A. (2003). Interferometric Point Target Analysis for Deformation Mapping. *IGARSS*, Toulouse, France 21-25 July 2003.

LAST PAGE OF DOCUMENT