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Ground Deformation Monitoring by Radar Interferometry and Subsurface Modeling of Oil Sands

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Ground Deformation Monitoring by Radar Interferometry and Subsurface Modeling of Oil Sands

by

Jin Baek

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOMATICS ENGINEERING
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Abstract

The monitoring of surface displacements at Canadian oil sands sites, where carbon dioxide enhanced oil recovery (CO₂-EOR) and cyclic steam stimulation (CSS) methods have been utilized, is conducted by applying radar interferometry. It is determined from differential interferometric synthetic aperture radar (DInSAR) results that surface elevation at the CO₂-EOR site remains unchanged from January 2002 to September 2004, whereas noticeable surface deformation occurs between July 2007 and March 2011 at the CSS site. Additional investigation into surface displacements at the CSS site using the small baseline subset (SBAS) algorithm is performed to retrieve time-series maps of the cumulative surface deformation, which accounts for temporal evolutions of the changes in surface elevation. The temporal analysis confirms that the ground surface at the CSS site experiences non-linear time-varying deformations that either return to its initial level or stay unrecovered. The surface subsidence and heave during 3.7 years, reaching up to -33 cm and +72 cm, are observed from the SBAS-derived cumulative surface deformation maps. Subsurface modeling using cumulative surface displacements is performed to infer fractional volumetric changes at the reservoir level for the CSS site. By applying the geomechanical inversion with the Tikhonov regularization technique using reservoir-related parameters and InSAR-derived surface displacements, the fractional volumetric changes in the subsurface are estimated over time. The fractional volumetric changes at the reservoir level range from -1.8 % to +3.9 % for the 3.7 year period. InSAR-driven surface displacements are interpreted with information on CSS operations. The surface deformations coincide with the steam injection and show a time lag of 0 to 6 months.
between the peak steaming rate and maximum surface heave. The linear regression result indicates that the linear relationship between the fluid volume changes, which are caused by the steam injection and bitumen/water production, and the surface/subsurface deformations is positive with the square of correlation coefficients ($R^2$) greater than 0.5 for all cases. Overall, it is concluded from this study that the surface deformation monitored by radar interferometry conforms well to oil recovery activities at the CSS site.
Acknowledgements

Above all, I would sincerely like to express my deepest appreciation and thank to my supervisor, Dr. Jeong Woo Kim, who has provided me the possibility to accomplish this thesis throughout the memorable journey of my graduate studies. I would never have been able to finish my doctoral thesis without his continuous assistance and guidance.

I owe special thanks to Dr. Sang-Wan Kim at Sejong University for his invaluable advice and knowledge needed whenever I encountered discouraging problems in the field of radar interferometry. I also wish to acknowledge all the committee members, Dr. Michael J. Collins, Dr. Quazi K. Hassan, Dr. Seonghwan Kim and Dr. Wooil M. Moon who have taken their valuable time for reviewing and giving great suggestions for this thesis.

I am ever grateful to my dear colleagues and friends in the gravity and Earth observation groups for sharing joyful moments as well as unforgettable friendship. Among my fellow graduate students, the most acknowledges are given to Hojjat Kabirzadeh who often had a boring discussion on solving research problems with me, and Tasnuva Hayden for having cheerful conversations particularly on Halloween night with the best samosa I ever tried. Thanks also to my closest Korean friends, Eunju Kwak and Jiyoung Ahn, who have been encouraging and supportive of me all the time.

Last but not least, I am deeply indebted to my lovely parents and husband for their unconditional love and endless sacrifice throughout the years. Thanks to God for always blessing me and my family.
To beloved parents, Kwang Hyun Baek and Kyung Soon Go

To wonderful husband, Woonki Yeo
Table of Contents

Abstract.......................................................................................................................... ii
Acknowledgements......................................................................................................... iv
Dedication ............................................................................................................................ v
Table of Contents............................................................................................................. vi
List of Tables .................................................................................................................... vii
List of Figures ................................................................................................................... viii
List of Acronyms ............................................................................................................... ix
List of Symbols ................................................................................................................. xii

CHAPTER I. INTRODUCTION ......................................................................................... 1
  1.1 Research Background .............................................................................................. 1
  1.2 Research Objectives ................................................................................................ 7
  1.3 Thesis Outline .......................................................................................................... 11

CHAPTER II. LITERATURE REVIEW ........................................................................... 15
  2.1 Ground Surface Monitoring Techniques ................................................................. 15
  2.2 Ground Surface Monitoring using Radar Interferometry ......................................... 16
  2.3 Subsurface Volumetric Change Modeling ................................................................. 22

CHAPTER III. DESCRIPTION OF STUDY AREA AND DATA ........................................ 27
  3.1 Study Area ............................................................................................................... 28
    3.1.1 Carbon Dioxide Enhanced Oil Recovery (CO$_2$-EOR) Site ............................... 29
    3.1.2 Cyclic Steam Stimulation (CSS) Site .................................................................. 32
  3.2 Datasets and Software ............................................................................................. 37
    3.2.1 Radar Satellite Data .......................................................................................... 37
    3.2.2 Digital Elevation Model (DEM) ......................................................................... 40
    3.2.3 Optical Satellite Data ....................................................................................... 41
    3.2.4 Software ........................................................................................................... 43

CHAPTER IV. METHODOLOGY .................................................................................... 44
  4.1 Radar Interferometry ............................................................................................... 44
    4.1.1 Interferometric Synthetic Aperture Radar (InSAR) ............................................ 45
    4.1.2 Differential Interferometric Synthetic Aperture Radar (DInSAR) ..................... 49
  4.2 Time-series Analysis ............................................................................................... 55
  4.3 Subsurface Volumetric Change Modeling ............................................................... 65
    4.3.1 Deformation in a Poroelastic Half-space ......................................................... 65
    4.3.2 Modeling Subsurface Deformations .................................................................. 68
    4.3.3 Geomechanical Inversion ............................................................................... 71

CHAPTER V. RESULTS .................................................................................................. 78
  5.1 Radar Interferometry .............................................................................................. 78
5.1.1 Carbon Dioxide Enhanced Oil Recovery (CO₂-EOR) Site ........................................78
  5.1.1.1 Interferometric Pair Selection .........................................................78
  5.1.1.2 Radar Interferograms .................................................................79
5.1.2 Cyclic Steam Stimulation (CSS) Site ..................................................95
  5.1.2.1 Interferometric Pair Selection .......................................................95
  5.1.2.2 Radar Interferograms .................................................................98
5.2 Time-series Analysis of Surface Deformation .............................................102
5.3 Modeling Volumetric Changes in Subsurface ...........................................125
5.4 Interpretation .............................................................................................131
  5.4.1 Surface Displacements for 2007 – 2008 ..............................................137
  5.4.2 Surface Displacements for 2009 – 2010 ..............................................143
  5.4.3 Surface Displacements for 2010 – 2011 ..............................................149
  5.4.4 Deformation Analysis with CSS Operation Data ..................................153

CHAPTER VI. CONCLUSIONS AND DISCUSSION .............................................162
  6.1 Conclusions .............................................................................................162
  6.2 Discussion .................................................................................................168
  6.3 Future Works .........................................................................................169

REFERENCES .................................................................................................171
List of Tables

Table 1. Summary of available SAR data................................................................. 37
Table 2. Frequency bands of commonly used SAR systems...................................... 38
Table 3. Specifications of ERS-2 and ALOS-1 SAR systems...................................... 39
Table 4. ERS-2 SAR data for the CO2-EOR site....................................................... 80
Table 5. Selected interferometric pairs for the CO2-EOR site...................................... 81
Table 6. ALOS-1 PALSAR data for the CSS site .................................................... 96
Table 7. Selected interferometric pairs for the CSS site............................................. 97
Table 8. Mean RMSE of interferometric pairs for the CSS site................................. 124
Table 9. Physical properties of hypothetical reservoir used for subsurface modeling ... 126
Table 10. The maximum volumetric increase and decrease in the subsurface with LSQR residuals ................................................................. 129
Table 11. Phase numbers in each deformed zone..................................................... 136
Table 12. Steam injection schedule in 2008 at zone #3........................................... 143
List of Figures

Figure 1. Oil reserves in the world................................................................. 2
Figure 2. Locations of Canadian oil sands deposits........................................ 2
Figure 3. Flow diagram of overall data processing steps carried out in this thesis .... 14
Figure 4. Illustrations of (A) CO₂-EOR and (B) CSS oil recovery methods .......... 29
Figure 5. (A) Average pore pressure and (B) CO₂/water injection rates with
microseismicity events at the CO₂-EOR site................................................... 31
Figure 6. Regional stratigraphy of the Clearwater Formation at CNRL’s oil sands
project areas....................................................................................................... 34
Figure 7. The location of CSS site selected for this study .................................. 34
Figure 8. Pictorial presentations of (A) steaming strategy for CSS and (B) side view
along section A.................................................................................................... 36
Figure 9. SAR intensity images of (A) ERS-2 and (B) ALOS-1 enlarged into the CO₂-
EOR and CSS sites selected for this study ....................................................... 39
Figure 10. ASTER GDEMs for (A) CO₂-EOR and (B) CSS sites ....................... 41
Figure 11. Landsat-5 TM imagery for the CSS site............................................ 42
Figure 12. Illustration of InSAR geometry .......................................................... 46
Figure 13. Schematics of flat Earth correction ..................................................... 51
Figure 14. Block diagram of SBAS implementation ............................................ 64
Figure 15. Vertical deformation at a surface observation point estimated by summing
contributions from all source points ................................................................ 69
Figure 16. Inversion solution under- and over-smoothed by regularization parameters .. 75
Figure 17. The general form of L-curve indicating proper selection of a regularization
parameter at the corner ...................................................................................... 77
Figure 18. Flow diagram for the estimation of subsurface volumetric changes using
InSAR-derived surface displacements ............................................................ 77
Figure 38. Residuals of interferometric phase simulated by forward modeling 122
Figure 39. L-curves and regularization parameters selected at the Tikhonov corner 128
Figure 40. Subsurface volumetric changes overlaid on Landsat-5 TM imagery 130
Figure 41. Distribution of CNRL’s Primrose project regions 132
Figure 42. Phase reference map of CNRL’s Primrose project as of 2008 134
Figure 43. Three deformed zones superimposed on Landsat-5 TM imagery 136
Figure 44. Cumulative surface deformation between August 2007 and October 2008 137
Figure 45. Steam injection rate at phases in zone #1 between 2007 and 2008 139
Figure 46. Steam injection rate at phases in zone #2 between 2006 and 2008 142
Figure 47. Cumulative surface deformation between August 2009 and June 2010 143
Figure 48. Steam injection rate at phases in zone #1 between 2009 and 2010 144
Figure 49. Steam injection rate at phases in zone #2 between 2009 and 2010 147
Figure 50. Steam injection rate at phases in zone #3 between 2009 and 2010 148
Figure 51. Updated phase reference map of CNRL’s Primrose project as of 2010 150
Figure 52. Cumulative surface deformation between October 2010 and March 2011 151
Figure 53. Steam injection rate at phases in zone #2 between 2010 and 2011 152
Figure 54. Phase locations in zone #1 superimposed on Landsat-5 TM imagery (middle) with surface displacement map of March 2011 (left) and enlarged phase reference map (right) 154
Figure 55. Steam injection rate, accumulated steam volume and surface deformation at phases 51 to 55 in zone #1 for the CSS site 156
Figure 56. Linear relationship between InSAR-derived surface deformation and fluid volume change in the reservoir 160
Figure 57. Linear relationship between fractional volumetric change and fluid volume change in the reservoir 161
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>ALOS-1</td>
<td>First Advanced Land Observation Satellite</td>
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# List of Symbols

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<td>Complex SAR signals</td>
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Chapter I. INTRODUCTION

1.1 Research Background

Canada is endowed with a considerable amount of crude oil resources, in the order of two trillion barrels of oil in place, which are the world’s third largest oil reserves after those of Saudi Arabia and Venezuela (Government of Alberta, 2012, 2013a) as shown in Figure 1 (Government of Alberta, 2013b). Among the Canadian provinces, massive deposits of heavy oil are present in Alberta and Saskatchewan. These oil deposits are known to be capable of supplying the entire needs of North America (i.e., Canada and United States) for about 100 years at current consumption levels, with the assumption that only 30% of them have been produced to date (Dusseault, 2002). A number of oil sands projects have been in operation using various recovery technologies in Alberta and Saskatchewan.

In particular, Alberta has huge deposits of oil sands that underlie more than 140,200 km² and can be separated into three major oil deposits: Peace River, Athabasca and Cold Lake, as shown in Figure 2 (CAPP, 2013). The largest one is the Athabasca deposit, which is located in the Regional Municipality of Wood Buffalo in the province’s northeast, and the second-largest oil sands deposit is referred to as the Cold Lake deposit, which is south of the Athabasca deposit. The Peace River deposit, which is located in northwest-central Alberta, is the smallest of major oil sands deposits in Canada (Government of Alberta, 2013a).
Figure 1. Oil reserves in the world (Government of Alberta, 2013b)

Figure 2. Locations of Canadian oil sands deposits (CAPP, 2013)
By definition, oil sands are a mixture of sand, water, clay and heavy oil, which is known as bitumen. The bitumen from oil sands is too thick to flow or to be pumped without being diluted or heated. The oil sands are in general recovered through one of two primary production methods: 1) surface mining and 2) in-situ methods by drilling wells and injecting steam to heat up the bitumen. Alberta’s oil sands located close enough to the surface (within 75 m) are being recovered by open-pit mining, using trucks and shovels.

For oil sands too deep to support economic surface mining operations, both non-thermal and thermal in-situ methods have been used for oil sands production. Non-thermal in-situ technology includes primary and enhanced oil recovery (EOR) techniques, which basically utilize either energy already in the oil reservoir or miscible gas injection at high pressure. On the other hand, thermal in-situ recovery methods, such as steam assisted gravity drainage (SAGD) or cyclic steam stimulation (CSS), involve the injection of steam at high temperatures and pressures through vertical or horizontal wells, in order to heat the bitumen and allow it to flow to the well bore (Government of Alberta, 2013a). Of the Albertan reserves that remain unrecovered, about 82% is considered recoverable by in-situ methods; and, the rest is producible by surface mining methods (Government of Alberta, 2007; Percy, 2012).

The elevated pressures and temperatures due to steam injection into oil-bearing formation can alter rock stresses sufficiently to cause shear failure within and beyond the growing steam chamber (Collins, 2007). The shearing and dilation of the oil sands consequently result in volumetric increase within the reservoir, which can lead to surface
displacements and rotations. Reservoir dilation and shear induced by subsurface steam injection propagate to the surrounding soil formations and extend to the ground surface, resulting in surface heaves (Collins, 2007; Nanayakkara and Wong, 2009). Moreover, pore pressure decreases and changes in petro-physical properties due to the withdrawal of fluids from reservoirs can cause reservoir compaction and the corresponding surface subsidence (Finol and Farouq Ali, 1975; de Waal and Smits, 1988; Bruno, 1998; Muntendam-Bos and Fokker, 2009).

The invaluable information on subsurface volumetric changes, as well as oil production progress can be obtained by monitoring surface displacements (Dusseault and Rothenburg, 2002). A variety of geodetic and seismic techniques for measuring surface deformation has been used by the petroleum industry; and, the most commonly used technologies include, for example, seismic reflection surveying, microseismic monitoring, land surveying, global navigation satellite system (GNSS), tiltmeter and interferometric synthetic aperture radar (InSAR) (Monfared, 2009; Verdon et al., 2013). Although the accuracy of land surveying is at the millimetre level, it is accompanied by the typical limitation that periodical field work necessary for mapping elevation changes becomes more labour intensive. GNSS also provides the accuracy in the order of millimetres to centimetres, but is not preferable when monitoring a large area over a long time span, as GNSS requires many stations along the surveyed base line (Stancliffe and van der Kooij, 2001).

Among the existing monitoring techniques, space-borne InSAR monitoring has been widely used to observe the Earth’s surface by taking advantage of its high vertical
resolution, which in ideal conditions is in the order of millimetres (Stancliffe and van der Kooij, 2001). Furthermore, recent advances in radar interferometric techniques that, for instance, aim to reduce inherent phase noise and digital elevation model (DEM) errors and to increase temporal/spatial resolutions have contributed to the improved quality of InSAR-derived surface deformation measurements. Therefore, the use of such innovative InSAR techniques enables the periodical provision of accurate surface deformation measurements over wide areas without labour- and time-consuming fieldwork.

Monitoring of the ground surface has played a key role in providing reservoir engineers with indirect information about shear displacements, casing failure locations, geological fractures, reservoir volume changes and steam migration at the subsurface level. Therefore, surface displacements in petroleum fields are often inverted to estimate production-related responses of the reservoir at depth, such as aerial distribution of volumetric changes, changes in reservoir properties or hydraulic fracturing (Du and Wong, 2005; Vasco and Ferretti, 2005; de Peter et al., 2008; Du et al., 2008; Muntendam-Bos et al., 2008; Maxwell et al., 2009; Khakim et al., 2012). Measurements with an accuracy of ±1 cm are typically sufficient for reasonably accurate inversion, given the massive deformations involved (Dusseault and Rothenburg, 2002).

The recent research works present that the geomechanical inversion of InSAR-derived surface deformation estimates offers a possibility for monitoring physical processes in the steam chamber of oil sands being developed using steam injection at high temperatures and pressures (Vasco et al., 2008; Ferretti et al., 2010; Vasco et al., 2010; Khakim et al., 2012). Apart from benefits for the oil industry, a better
understanding of the environmental impacts due to oil recovery can also be achieved by periodical monitoring of the ground surface using radar interferometric methods. Therefore, the detection and quantification of surface deformations that have taken place in oil sands areas are essential, in terms of not only helping oil developers evaluate oil recovery progress, but also providing information on our surrounding environment influenced by inevitable human activities, such as producing underground resources.

In this study, radar interferometric methods are applied using SAR datasets acquired from the second European Remote-Sensing Satellite (ERS-2) (ESA, 2013) and the first Advanced Land Observation Satellite (ALOS-1) (JAXA, 2007) over two Canadian oil sands areas where either carbon dioxide (CO$_2$) EOR method or CSS method has been in operation. The surface displacements occurred during periods of 2002 – 2004 for the CO$_2$-EOR site and 2007 – 2011 for the CSS site are first examined using a differential InSAR (DInSAR) application.

The differential interferometric phases from DInSAR results are exploited, in order to analyze the temporal evolution of the detected surface deformation using the concept of a small baseline subset (SBAS) algorithm. The implementation of the SBAS algorithm using radar interferometric results provides information on the temporal trends of vertical surface deformations, which are further utilized in order to estimate subsurface volumetric changes at the CSS site over time. The cumulative surface displacement maps resulting from the SBAS algorithm are subsequently interpreted with historical information on the steaming operations, in order to examine whether or not the observed surface displacements coincide with oil recovery activities.
The potential application of InSAR-driven surface deformation measurements for the inference of fractional volumetric changes in the subsurface that are possibly induced by oil productions as time elapsed is also examined in this study. By combining a time-series analysis based on radar interferometric techniques (i.e., DInSAR and SBAS algorithm) and the geomechanical inversion of surface deformation measurement, the time-varying displacements at both the surface and subsurface levels over a long time span of 3.7 years for the CSS site are investigated.

The observed variations in surface elevation and subsurface volume are interpreted with the fluid volume changes at the reservoir level that are caused by the steam injection and bitumen/water production at the CSS site. The linear regression method is utilized to analyze the relationship between the surface/subsurface deformations and fluid volume changes at depth.

The proposed study is expected to be beneficial in terms of monitoring temporal variations in surface elevation associated with volumetric changes at the reservoir depth using very limited information on physical parameters describing the subsurface system without time- and labour-intensive fieldwork for direct surface deformation measurements.

1.2 Research Objectives

The ground surface can be displaced by numerous causes, such as natural geological processes (e.g., earthquake, volcanic eruption) or human activities (e.g.,
construction, reclamation, and natural resource exploration). Efforts have been made to detect such disturbances that are indicated by either horizontal and/or vertical changes in surface elevation. Currently available monitoring technologies have their own advantages and limitations, in terms of total cost, labour, temporal/spatial resolution and achievable accuracy. Accordingly, it is important to choose the most appropriate technique for the efficient monitoring of various types of surface displacements.

Of the present monitoring techniques, radar interferometry, including InSAR, DInSAR, Permanent Scatterer InSAR (PSInSAR) and SBAS algorithm, has been one of the most precise monitoring methods with the advantages of imaging surface deformation over a large area in all weather conditions with high accuracy, theoretically in the order of millimetres. The application of such radar interferometric techniques for surface monitoring is beneficial, particularly when detailed information on an inaccessible area with a wide spatial coverage is not obtainable. Radar interferometry results (i.e., interferograms or differential interferograms) contain useful information on surface displacements that can be presented as a series of countable fringes. Details on surface displacements, such as spatial extent, direction (e.g., upward or downward) and the amount of surface elevation changes, can be obtained by further analyzing resultant interferograms.

Since in-situ oil recovery methods, such as CO$_2$-EOR, CSS and SAGD, cause reservoir dilation and compaction depending on recovery cycles, outward displacements at the ground surface level are an undoubtable response to the subsurface behaviour at Canadian oil sands areas. It is reported that the maximum surface heave due to the SAGD
process is generally 2% of the total thickness of reservoir, from which the oil can be produced at profitable rate (i.e., reservoir’s net pay thickness), and can gradually taper off up to 10% at a distance of twice the reservoir depth (Collins, 2007). The ground surface responses to volumetric changes of poroelastic reservoirs have been well-established with the point source response function given by Green’s function that explains the interrelationship between the surface and subsurface deformations caused by oil production (Vasco et al., 1998). The volumetric changes at the subsurface level retrieved by the geomechanical inversion of available surface deformation measurements can be thoroughly examined to monitor production progress and undesirable environmental changes for both industry and public perspectives.

Previous research works on the inversion of surface deformation measurements for the estimation of volumetric changes in the subsurface have proposed the use of surface displacement measurements from conventional monitoring methods (e.g., land surveying, tiltmeter) or radar interferometric techniques (e.g., DInSAR, PSInSAR). The direct surface deformation measurements obtainable from conventional monitoring methods are, however, not fully publicly available in most cases, and require labour- and time-consuming fieldwork. Furthermore, the spatially dense surface deformation measurements cannot be obtained, because conventional monitoring methods are limited to specific locations, either survey stations or an array of tiltmeters.

InSAR-derived surface deformation measurements that have been used for other research studies include the linear velocity of vertical surface deformation or the extent of surface displacements that take place during specific periods between SAR data
acquisition dates of each interferometric pair. These InSAR-derived surface deformation measurements are not suitable for the analysis of the non-linear surface displacement that occurs with time-varying surface deformation rates and consequently fluctuates over time.

The temporal evolution of surface displacements should, therefore, be analyzed by means of advanced radar interferometric techniques (e.g., PSInSAR, SBAS algorithm), which enable the time-series analysis of surface displacements. However, the quality of PSInSAR-derived surface deformation measurements can be degraded when the spatial density of permanent scatterers (PSs) is low, due to either a long distance between radar satellite’s positions (i.e., long baseline) or the lack of the sufficient number of such PSs distributed in the imaged area. Therefore, DInSAR and SBAS algorithm are used for the monitoring of surface displacements that take place with time-varying surface deformation rates in the heavily vegetated areas.

Many of the oil sands projects distributed across Alberta and Saskatchewan have used various in-situ methods for bitumen extraction. However, none of the studies about the geomechanical inversion of InSAR-driven surface deformation measurements for the estimation of subsurface volumetric changes in Canadian oil sands has yet been published. Thus, DInSAR is applied in this study to monitor the ground surface at two Canadian oil sands areas located in Alberta and Saskatchewan where field measurements are not obtainable. The SBAS algorithm is implemented for the time-series analysis of surface deformation at the CSS site where the spatial density of PSs is low.

The geomechanical inversion in analytical way with a regularization technique using radar interferometric results is applied for the modeling of volumetric changes at
the reservoir level over time. The observed changes in surface elevation are further interpreted with minimal information on oil production provided by the oil developers. The comprehensive results achieved in this study will contribute toward better understanding of the temporal responses of the surface and subsurface to oil sands recovery using remotely sensed radar satellite data and limited information on the reservoir and oil production.

1.3 Thesis Outline

The conventional and advanced radar interferometric techniques, including InSAR, DInSAR and SBAS algorithm, are exploited in order to detect vertical displacements of the ground surface at oil sands using available radar satellite data. For the investigation of different surface responses to various oil recovery activities, CO₂-EOR and CSS project sites located in Saskatchewan and Alberta, respectively, are selected for case studies. The most suitable images for the InSAR application in this study are found to be ERS-2 SAR data taken over the CO₂-EOR site and ALOS-1 phased array type L-band SAR (PALSAR) data for the CSS site.

Surface deformation monitoring is carried out using a conventional radar interferometric technique (i.e., InSAR, DInSAR). The radar interferometry results in general indicate whether the targeted area remains stable or experienced significant changes in surface elevation, possibly due to oil recovery activities. It is confirmed by InSAR-derived surface deformation measurements that the ground surface at the CO₂-
EOR site is not considerably influenced by oil production; however, noticeable surface deformations are detected in both the upward and downward directions over the CSS site. Thus, the CSS site, where huge differences in radar interferometric phases are consistently present over time, becomes the focus of this study. 

Temporal monitoring of surface displacements that occur along with repetitive CSS cycles for a long period is rather challenging, as it is typically expected that ground surface heaves and subsides simultaneously at the CSS sites. The temporal analysis of detected surface displacements is, therefore, necessarily used, enabling the examination of detailed trends of fluctuating surface elevation induced by repetitive steaming and production operations at the CSS site. Using the surface deformation derived by DInSAR, the temporal evolution of detected surface displacements for more than 3 years is further analyzed by means of the SBAS algorithm. The temporal analysis of ground surface deformations monitored at the CSS site is presented in this study.

For potential application of the time-series analysis results, the cumulative surface deformation maps resulting from the temporal analysis are inverted to infer fractional volumetric changes in the subsurface for the monitoring of the subsurface behaviour that can possibly be attributed to the CSS operations. The temporal responses of subsurface to CSS operations for each acquisition date of ALOS-1 PALSAR data are examined using the geomechanical inversion with a regularization technique. Consequently, the subsurface movements at six different dates of SAR data acquisitions with approximately half-year intervals for 3.7 years are identified in this study, showing the quantitative fractional volumetric changes of the reservoir associated with the successive CSS
operations. The variations in surface elevation and subsurface volume at the CSS site are further interpreted by referring to physical information of oil recovery activities. The relationship between surface/subsurface deformations and CSS operations are examined by means of the linear regression method.

In summary, this study presents: 1) application of radar interferometric techniques, including DInSAR and SBAS algorithm, for monitoring the temporal surface displacements at specific Canadian oil fields; 2) geomechanical inversion of InSAR-derived surface deformation measurements for the estimation of fractional volumetric changes in the subsurface over time; and, 3) interpretation of surface/subsurface deformation measurements using physical information on the CSS operations and the linear regression method. The overall data processing carried out in this thesis follows the illustrative flow diagram shown in Figure 3.

This thesis consists of six chapters. Chapter 2 provides a literature review of ground surface monitoring methods, radar interferometric techniques and their applications, especially for monitoring natural geological processes and natural resource explorations cases, subsurface volumetric change monitoring from surface deformation measurements, and the use of radar interferometry results for subsurface modeling. Chapter 3 describes the details of the selected study areas in Canada (i.e., CO2-EOR and CSS sites), as well as all types of datasets and software used in this study. Chapter 4 summarizes the principle theories of the methodologies used (i.e., radar interferometry, time-series analysis and geomechanical inversion). Chapter 5 presents the results, including radar interferograms, surface deformation maps, profile analysis, maps of
subsurface volumetric changes and interpretation of surface/subsurface deformations using information on the CSS operations. Chapter 6 includes the conclusions and discussion of the presented study with limitations and recommendations for future work.

Figure 3. Flow diagram of overall data processing steps carried out in this thesis
Chapter II. LITERATURE REVIEW

2.1 Ground Surface Monitoring Techniques

Surface deformation measurements are used not only to infer reservoir volumetric changes, but also to understand fluid flow and the heterogeneity of flow properties within the reservoir in petroleum fields (Vasco, 2005; Vasco, 2008). The most common techniques for monitoring the ground surface include land surveying, GNSS, tiltmeter and radar interferometry.

Land surveying is one of the oldest monitoring methods and requires a station network established over the area of interest. The surface movement in a network of stations can be individually observed with the accuracy at the millimetre level. This method is, however, usually time-consuming and costly; and, its application may be limited to offshore fields (Nagel, 2001). Furthermore, the area of interest should be periodically resurveyed to obtain the maps of surface elevation changes (Stancliffe and van der Kooij, 2001). The surface deformation measurement can also be collected on a regular basis using the GNSS method. The vertical and horizontal movements of GNSS receivers are determined with the accuracy at the centimetre level. However, many monitoring stations along the surveyed base line and receiver systems are necessary for GNSS monitoring (Stancliffe and van der Kooij, 2001; Monfared, 2009).

The observation of ground surface deformations can be achieved by tiltmeter, which measures displacement gradients (i.e., tilts) in the order of $10^{-9}$ radians in tilt
change. Its capability of continuous data collection enables the real-time monitoring of the ground surface (Monfared, 2009). The tilt measurements are, however, limited to certain locations; and, a large number of observations are needed to map the surface deformations (Xu, 2002). In addition, the problem due to accumulated zero-base drift can cause a systematic error and swamp the long-term signals (Dusseault and Rothenburg, 2002).

Radar interferometric techniques, such as InSAR, DInSAR, PSInSAR and SBAS algorithm, are more recently developed methods for monitoring the ground surface. The changes in surface elevation can be measured using radar interferometric phases of SAR data pairs at the millimetre level. The radar interferometric techniques have more desirable advantages in terms of high spatial resolution and periodical data collection at low cost, compared to other ground monitoring methods (e.g., land surveying, GNSS, tiltmeter). However, the applicability of radar interferometric techniques is occasionally limited, due to the errors caused by atmospheric inhomogeneity and temporal/spatial decorrelation problems (Stancliffe and van der Kooij, 2001; Xu, 2002).

2.2 Ground Surface Monitoring using Radar Interferometry

The initial concept of SAR was introduced by Carl Wiley at Goodyear Aircraft Corporation in 1951, and the first successful experiment was implemented by a research team at the University of Illinois in 1953 (Sherwin et al., 1962). The practical application of SAR for the retrieval of topographic information was conducted in 1974 (Graham,
Research into space-borne SAR satellite started in 1978 with the launch of SEASAT, which was the first satellite that orbited the Earth for the remote sensing of the Earth’s oceans with an L-band SAR system onboard. SEASAT was capable of retrieving topographic and geologic information, and topography (i.e., terrain elevation) was successfully recovered using SEASAT SAR data acquired over Cottonball Basin of Death Valley in the United States (Goldstein et al., 1988).

After the application of the DInSAR for measuring changes in terrain height in the direction between the SAR antenna and the point on the ground surface (i.e., satellite’s line-of-sight (LOS)) was presented in 1989 (Gabriel et al., 1989), the mapping of the displacement field induced by natural geological processes was demonstrated in early 1990s. The ground surface displacements caused by an 1992 earthquake at Landers, California were mapped by constructing a interferogram with SAR data from ERS-1 in 1994 (Massonnet et al., 1993; Zebker et al., 1994). The observed surface deformation agreed well with displacements measured by surveying in the field. Long-term monitoring of Mount Etna in Sicily, Italy, was achieved using DInSAR in 1995 (Massonnet et al., 1995). They successfully observed the deflation as a result of volcano eruption and quantified it using a simple model based on pressure changes. DInSAR has since been widely used, not only for the observation of surface displacements, but also for the monitoring of surface anomalies and natural geological processes.

Apart from DInSAR application to earthquake and volcano monitoring, DInSAR has been applied in many other geophysical fields. Goldstein et al. (1993) mapped a grounding line of Rutford Ice Steam, Antarctica using satellite radar interferometric
method. The ice flow velocity was also retrieved through their study, which agreed well with previous ground-based data. Ice motion in the source areas of four West Antarctic ice streams was mapped using Canada’s RADAR SAT-1 datasets in 1999 (Joughin et al., 1999). This study determined a thickening rate of 0.49 m/year on average, which was found to be the largest rate ever reported in Antarctica.

The capabilities of SAR interferometry for detecting landslide-induced deformation were investigated in 2005 (Strozzi et al., 2005). It was verified that the use of L-band SAR data from the first Japanese Earth Resources Satellite (JERS-1) (JAXA, 2002) performs better than the C-band ERS-1/2 SAR data for monitoring landslides that occurred in vegetated areas because L-band radar signals penetrate the vegetation canopy, and, therefore, highly coherent interferograms over vegetated areas can be achieved. The post-slide motion at the Frank Slide in the Canadian Rockies was monitored using RADARSAT-1 SAR data over the period from 2000 to 2004 (Singhroy et al., 2005). The slide deformation was found to be localized and related to seasonal and local weather conditions. Monitoring deformation caused by the Vallcebre landslide in the eastern Pyrenees in Spain was performed with DInSAR (Crosetto et al., 2013). The interferograms generated using 4 ENVISAT SAR data showed several patterns of surface displacements that had occurred at corner reflector locations since December 2006. In addition, the technical aspects of using artificial corner reflectors, such as installation, type selection and network design of corner reflectors, were stated in their study.

Ground surface deformations induced by the exploitation of natural resources, such as coal, gas or water, have been successfully detected by radar interferometric
techniques. The modeling of surface subsidence at a coal mining area in the United Kingdom was studied in 1997 (Wright and Stow, 1997). The mining subsidence model was further improved by feeding precise information on elevation changes derived via radar interferometry using ERS SAR data. Repeat-pass DInSAR using ERS SAR data was also applied for monitoring a coal pit at Silesia, Poland (Perski and Jura, 2003). This study demonstrated that interferograms could provide quantitative information regarding the subsidence rate, as well as qualitative information concerning the shape and extent of the subsiding area over one of the largest coal mining fields in Europe.

The advanced PSInSAR technique was developed in early 2000 with the purpose of minimizing decorrelation problems by considering time-coherent pixels of SAR data (Ferretti et al., 2000, 2001). The applications of PSInSAR in surface deformation monitoring were extensively carried out soon after the PSInSAR was proposed. For example, the crustal deformations due to tectonic activity at Ranafjord in northern Norway were measured by means of conventional DInSAR and PSInSAR using ERS SAR data covering the time span of 1992 to 2000 (Dehls et al., 2002). The drawbacks of conventional DInSAR application that are typically attributed to extremely slow deformation rate (a few mm/year) and resultant phase incoherence over a long time span were overcome by applying PSInSAR in this study. Moreover, the progressive time-uniform and seasonal deformations for the southern part of the Hayward Fault and San Jose at the northwestern end of the Santa Clara Valley in the United States, respectively, were measured with high accuracy using PSInSAR (Colesanti et al., 2003).
Kim et al. (2007) tested PSInSAR for monitoring surface subsidence in the urban areas of Incheon and Busan, Korea, using JERS-1 SAR datasets. It was found that the subsidence over a reclaimed area occurred at an approximate rate of 3 cm/year in Incheon, while subway construction resulted in considerable subsidence at 20 – 30 cm/year in Busan. They also examined land subsidence associated with soil consolidation at a reclaimed area in Mokpo, Korea, by means of PSInSAR using JERS-1 SAR data acquired between 1992 and 1998, and further analyzed subsidence field maps with linear and hyperbolic models (Kim et al., 2008, 2010). The hyperbolic model, which consists of linear and time-varying components of surface deformation, was exploited to predict future subsidence more precisely. It was concluded from the validation of the surface subsidence prediction with ENVISAT SAR data for 2004 – 2005 that the prediction accuracy was significantly improved using the hyperbolic model.

Various radar interferometric techniques, including DInSAR and PSInSAR, have been utilized for monitoring oil fields worldwide. Stancliffe and van der Kooij (2001) presented the applicability of repeat-pass DInSAR using JERS-1 SAR data for the land subsidence at the Cold Lake oil field in Canada, with a resolution in the order of a centimetre. They concluded that the observed elevation gain was mainly due to steam injection into the reservoir in the Cold Lake oil sands area, while surface subsidence indicated that the steaming operations were completed and production started. PSInSAR and tiltmeter measurements were also used to quantify the surface deformation at an Athabasca oil field in Canada (Dubucq et al., 2008). The surface deformation measured
for six months using the two different monitoring methods (i.e., PSInSAR, tiltmeter) showed deformation of no more than 2 cm, which agreed with geomechanical modeling.

The application of radar interferometry for the oil and gas industries has been comprehensively presented with a number of examples on surface displacement observations (Ferretti et al., 2010). This study confirmed that the use of InSAR techniques was advantageous in terms of high accuracy, fast data processing, regular updates and cost efficiency. Moreover, PSInSAR was successfully applied for monitoring EOR and carbon capture and sequestration (CCS) sites in the Middle East and Algeria (Tamburini et al., 2010). The vertical and horizontal surface deformations and the gradient fields of the maximum vertical surface displacements at the millimetre level were obtained by processing RADARSAT and ENVISAT SAR datasets for both sites. It was found that the spatial distributions and gradient fields of vertical surface displacements showed good correlation with major fault distributions.

The SBAS algorithm was established to overcome the limitations of standard DInSAR and PSInSAR, such as baseline decorrelation problem or low spatial density of time-coherent pixels. The SBAS algorithm was introduced and validated using ERS-1/2 SAR datasets taken over active caldera of Campi Flegrei and the city of Naples in Italy (Berardino et al., 2002). Further improvement was made in order to analyze local deformations by investigating full spatial resolution (i.e., single-look data) of differential interferograms (Lanari et al., 2004). The capability of the SBAS algorithm in monitoring surface subsidence in an urban area at Nordic latitudes was demonstrated (Lauknes et al., 2005). The subtle rate of land subsidence (5 mm/year) in Oslo, Norway was detected
using ERS-1/2 SAR data. SBAS results were compared with the average relative velocity of surface displacement estimated by PSInSAR, and it was concluded that the patterns of surface subsidence were nearly identical for both cases.

An innovative algorithm that combines the PSInSAR and SBAS approaches was presented by Hooper in 2008. The proposed algorithm maximized the spatial sampling of useable SAR signals by incorporating both PSInSAR and SBAS algorithm and enabled the extraction of the surface deformation signals at more points. They stated that the improvements in spatial sampling were essential for not only increasing the resolution of deformation signals, but also allowing reliable phase unwrapping.

The extended SBAS (E-SBAS) algorithm was proposed in order to analyze surface deformation that takes place over much larger areas than SAR-derived deformation maps typically cover (Casu, 2009). The E-SBAS algorithm was performed using 264 descending ERS SAR datasets taken over central Nevada in the United States, extending up to a spatial coverage of about 600 km × 100 km.

2.3 Subsurface Volumetric Change Modeling

There have been many reported applications for relating surface deformation measurement and subsurface sources causing ground surface deformation (Dusseault et al., 1993; Bruno and Bliak, 1994; Bruno, 1998). An analytical linear forward model using the nucleus of strain concept was first introduced in 1973 (Geertsma, 1973). The nucleus of strain approach describes the elastic deformation at a source point in the reservoir that
is assumed to be uniform, homogeneous, isotropic and poroelastic in a half-space. By integrating the contribution of all points over the reservoir, the resulting surface displacements can be calculated. The forward and inverse models have been widely used on the basis of the nucleus of strain method for the inference of volumetric changes in the subsurface (Vasco et al., 1988; Dusseault et al., 1993; Marchina, 1996; Dusseault and Rothenburg, 2002).

Numerical and analytical methods, especially for the estimation of reservoir dilation using surface deformation measurements, have been described in many studies (Fokker, 2002; Muntendam-Bos and Fokker, 2009; Nanayakkara and Wong, 2010). A new model for subsidence prediction by combining analytical and numerical approaches was presented, and regularization for the inversion problem with a multi-layer linear elastic model was used to determine reservoir behaviour (Fokker, 2002). Since the numerical method is accompanied by the solution of an inversion problem, which is inherently ill-posed in geophysical fields, the use of Tikhonov regularization was suggested for parametric studies (Nanayakkara and Wong, 2010).

The use of a tiltmeter for monitoring steam chamber associated with fluid injection and withdrawal has been demonstrated in many studies (Vasco et al., 1998; Wright et al., 1998; de Peter et al., 2008; Du et al., 2008; Dubucq et al., 2008; Maxwell et al., 2009). The concept of mapping fractures at depth by tiltmeter was introduced in 1998 (Wright et al., 1998). Vasco et al. (1998) presented a method to infer shallow subsurface fluid movement and consolidation using tiltmeter measurements. The appropriateness of
using highly accurate tiltmeter measurements in estimating volumetric changes at depth due to fluid injection or withdrawal was highlighted in the study.

The volumetric changes of a reservoir were characterized by the inversion of tiltmeter-based surface deformation data in another study (Du et al., 2008). Tiltmeter-based reservoir monitoring was applied to two CSS projects in Shell’s Peace River area and showed areal coverage of non-uniform volumetric changes at the reservoir level. Maxwell et al. (2009) proposed the integration of microseismic events, which were associated with deformation due to thermal expansion of the wellbore and induced fracturing in the reservoir, with volumetric strain that was inverted from the surface deformation measured by tiltmeters. The geomechanical response of the reservoir to the initial steam injection was interpreted by comparing microseismic deformation with the ground surface uplift.

In addition to tiltmeter measurements, InSAR-driven surface deformations have also been used for subsurface modeling using similar inversion processes. The lateral variations in volume strain at a geothermal field were successfully resolved using range changes by means of radar interferometry (Vasco et al., 2002). It was found that predominant volume changes at depth could be attributed to the faults that are oriented along the north/south direction.

The applicability of PSInSAR-driven ground surface displacements for understanding fluid flow in the subsurface was demonstrated by Vasco and Ferretti (2005). The variations of reservoir permeability and fractional volumetric variations at Wilmington oil field in California were inferred through their study. It was concluded
that the PSInSAR observation was indeed compatible with the measured reservoir volume fluxes, because the observed surface deformation was a weighted spatial average of the reservoir volume change.

The advantage of using remotely sensed radar satellite data for the geomechanical inversion was further verified with an application to a case of CO₂ injection at Krechba field in Algeria (Vasco et al., 2008). In their study, the consistent land uplift at the CO₂ injection area was identified using the PSInSAR technique. The annual rate of surface heave on average was subsequently inverted to determine the geomechanical responses of reservoir, such as changes in reservoir pressure and permeability. The distribution of reservoir displacements was accurately estimated using surface heave information obtained through the application of DInSAR (Khakim et al., 2012). A two-step inversion method was tested in their study for the accurate estimation of depth, volumetric changes and deformation distribution of a reservoir, confirming that InSAR-derived ground surface deformation worked well using their proposed inversion technique.

The surface displacements measured by tiltmeter, DInSAR and PSInSAR have been used for modeling the volumetric variations in the subsurface as presented in aforementioned researches. All of these researches, however, considered surface deformations measured at specific locations where an array of tiltmeters was deployed or the time-coherent ground targets were present in SAR datasets. Furthermore, only the mean velocity of surface displacements or vertical surface deformation occurred during a short period between SAR acquisition dates of each interferometric pair has been utilized for the geomechanical inversion to date. Therefore, previous research lacks a method for
inferring the temporal evolution of reservoir volumetric changes using spatially dense surface deformation measurements when non-linear surface deformation with time-varying rate is involved.
Chapter III. DESCRIPTION OF STUDY AREA AND DATA

Among the oil sands projects in Canada, two specific oil sands sites that are operated with different recovery methods are studied. The chosen areas are sufficiently far apart that independent research investigations can be performed, without interference from each other. The selected sites can be individually characterized by particular properties, such as geological settings, geographical locations, oil recovery activities and geomechanical factors related to subsurface structure. Therefore, the ground surface responses associated with oil sands production are expected to differ at each site.

The collection of datasets containing crucial information on ground surface displacements is a key to the success of this study. The most fundamental dataset to be utilized for the application of radar interferometric techniques in this study is a series of SAR data taken from radar satellites of ERS-2 and ALOS-1. Optical satellite imagery is required in order to provide geographical information in spectral band of visible wavelengths. The terrain height information from external DEMs is necessary for the estimation of surface displacements using DInSAR. In addition, several parameters describing subsurface systems, including overburden and oil-bearing formation, are imperative for the estimation of subsurface behaviour that could have accompanied successive oil recovery activities. The reservoir-related parameters used in this study include reservoir depth and thickness, Poisson’s ratio, Skempton’s pore pressure coefficient and fluid density.
Lastly, software for the implementation of radar interferometric techniques and geomechanical inversion is required to create meaningful results out of the collected datasets. The following sections briefly describe the two study areas, datasets and software used in this study.

### 3.1 Study Area

According to previous studies, including those introduced in Chapter 2, either subsurface injection or withdrawal of fluids generally induces ground surface deformations (i.e., land settlement and/or uplift). Surface deformation due to the unique processes of various oil recovery technologies may, therefore, depend on relevant factors, such as the amount of fluid injected or extracted, geomechanical characteristics of the reservoir and overburden, and geological properties of targeted formation (Teatini et al., 2011; Khakim et al., 2012).

In this study, two Canadian oil sands sites, where CO₂-EOR and CSS methods have been used in oil production, are chosen for the monitoring of ground surface displacements that may have been caused by different types of oil production activities. In Figure 4, the concepts of CO₂-EOR and CSS operations are illustrated (Shah et al., 2010). Both sites are mainly covered by heavy vegetation and/or under cultivation, which possibly cause the changes in scatterer position, with randomly distributed water bodies. Only a few man-made structures, including access roads, oil facilities or well pads, which encompass vertical or horizontal wells for the injection and production of fluids, are
sparsely located over the entire study areas. For a better understanding of the possible geomechanical responses, the details on the study areas, including general descriptions of oil recovery methods used at each site are concisely explained in following subsections.

![Illustrations of (A) CO₂-EOR and (B) CSS oil recovery methods (Shah et al., 2010)](image)

**Figure 4. Illustrations of (A) CO₂-EOR and (B) CSS oil recovery methods (Shah et al., 2010)**

### 3.1.1 Carbon Dioxide Enhanced Oil Recovery (CO₂-EOR) Site

EOR methods can be divided into three major categories: 1) miscible flooding, 2) chemical flooding, and 3) thermal recovery. CO₂-EOR is a type of miscible flooding method, which utilizes CO₂ gas to reduce the viscosity of bitumen (Schumacher, 1980; Shah et al., 2010). CO₂ injected into the oil-bearing layer eventually mixes with oil under high pressure, producing additional oil in the final phase in most recovery cases, as shown in Figure 4(A) (Shah et al., 2010). Furthermore, through the use of CO₂ as a miscible flooding agent for EOR operation, CO₂-EOR supports CCS projects that are aimed at reducing CO₂ emissions to atmosphere for a sustainable atmospheric concentration (Metz et al., 2005). In CCS-involved CO₂-EOR operations, a considerable
annual CO₂ injection rate, even at deeper depth, is likely to cause reservoir-level strain that can possibly be transferred to the Earth’s surface (Sweatman and McColpin, 2009).

The CO₂-EOR site selected for this study is developed using CO₂ injected into the reservoir in order to improve the oil recovery from the Midale Beds in Saskatchewan. It is reported that approximately 3 billion standard cubic metre of CO₂ has been injected with the injection rate of 5,000 ton/day since production commenced (Cantucci et al., 2009). It is also reported that the pore pressure has increased since 2000 when CO₂ injection at this mature oil field is initiated, and varied across the field (Verdon et al., 2013). A model of the average pore pressures across the region, where microseismic monitoring is conducted, is matched with oil production histories, as shown in Figure 5(A) (Verdon et al., 2013). The pore pressure drops to 6 – 7 MPa from the initial hydrostatic condition of 15 MPa, due to unsupported production. Water injection from 1965 brings the pore pressure back to the initial condition and it remains stable; and, CO₂ injection increases the pore pressures to 20 MPa.

The monitoring of geomechanical deformation of the reservoir at this oil field is performed using a microseismic array of eight geophones installed in 2003. In general, the microseismic events that are triggered during reservoir deformation are detected using geophones installed in boreholes around the reservoir, representing a tangible manifestation of geomechanical deformation at the reservoir level. The resulting microseismicity rates are compared with the rates of water and CO₂ injection through the vertical well and displayed in Figure 5(B) (Verdon et al., 2013). Note that the shaded areas represent the periods when the monitoring arrays are not operative. The higher
microseismicity event rates are detected when the injection rate increases in June 2004; however, low microseismicity event rates are observed from 2006 to 2010. It can be concluded that the low rate of microseismicity events indicates that there is either little geomechanical deformation or deformation occurred without generating microseismic events (Verdon et al., 2011).

Figure 5. (A) Average pore pressure and (B) CO$_2$/water injection rates with microseismicity events at the CO$_2$-EOR site (Verdon et al., 2013)
The seismic findings are, however, insufficient to monitor the reservoir deformation and corresponding surface displacements at the CO₂-EOR site, because the geomechanical response at the CO₂-EOR site seems to be complicated since injection and production occur simultaneously, and the characteristics of reservoir and overburden generally vary site by site. Therefore, additional monitoring methods need to be considered in order to investigate the subsurface volumetric changes and resulting surface displacements at the specific CO₂-EOR site selected in this study, unless direct field measurements or previous research data are available.

3.1.2 Cyclic Steam Stimulation (CSS) Site

Thermal EOR methods typically involve producing bitumen from oil sands by applying heat energy, which serves to decrease oil viscosity and vaporize lighter components. Heavy oil consequently becomes more mobile as thermal EOR processes, such as steam flooding, CSS and SAGD, advance over time (Shah et al., 2010).

In the CSS site, the high pressure steam that is the source of the heat energy is injected into a single well for a period of months and remains for many weeks during its soak stage. The injected steam distributed throughout the reservoir heats the oil up to a temperature of 300 °C, at which the oil viscosity drops so low that it flows. The injection wells are then put back into production, in order to pump the heated oil out of the well for another period of months, as demonstrated in Figure 4(B) (Shah et al., 2010). This cycle
is repeated until the oil production is no longer economic (Dusseault, 2002; Shah et al., 2010).

Canadian Natural Resources Limited’s (CNRL) Primrose CSS project area in Alberta is selected in this study to examine the capability of the surface monitoring and subsurface modeling techniques. Oil production at this CSS site is presently in progress, with a maximum steam injection rate of 2,100 to 2,500 m$^3$/day. The Primrose area belongs to Cold Lake oil sands deposit, where various geological formations are found. Of all the geological formations, the Clearwater Formation is known to contain bitumen; and, CNRL has developed oil sands from this formation with CSS operations since the project is activated.

Figure 6 (Canadian Natural, 2008) presents the regional stratigraphy that explains the cross-section of valley systems along CNRL’s oil sands projects (i.e., Wolf Lake, Primrose, and Primrose East), which are distributed from southwest to northeast. These valley systems, in which estuarine deposits vary from valley to valley in the Clearwater Formation, are distributed over the Cold Lake oil sands area with distinct boundaries. According to CNRL’s annual presentation (Canadian Natural, 2008), the Primrose projects target the reservoirs in Orange, Blue and Yellow valley sands, which are situated approximately at a depth of 460 m, as shown in Figure 6. The spatial extent of the CSS site is delineated by the red box on the map of valley system distributions in Figure 7. The CSS site chosen for this study appears to be located right above Blue valley sands, as illustrated in Figure 7 (Canadian Natural, 2008).
Figure 6. Regional stratigraphy of the Clearwater Formation at CNRL’s oil sands project areas (Canadian Natural, 2008)

Figure 7. The location of CSS site selected for this study (Color indicates geological structure explained in Figure 6) (Canadian Natural, 2008)
It has been reported in previous research that both the CSS and SAGD production methods can result in seismic and surface deformations (Chopra, 2010). In particular, more surface deformations are likely to occur with CSS, because this method typically involves the use of higher injection rates and pressures than the SAGD method (Chopra, 2010). The steam injection for CSS is usually scheduled on many pads, which eventually come on line together and create a steaming zone. The steaming zone typically migrates across the oil fields, as shown in Figure 8 (modified from Stancliffe and van der Kooij, 2001).

In general, a newer pad develops more surface heave during the steaming stage and more subsidence afterwards than an older pad, which can be interpreted as an artifact of steam and rock interaction (Stancliffe and van der Kooij, 2001). Therefore, surface elevation gain can be observed when steam is being injected into the reservoir. The surface sinks a little as the steamed reservoir subsequently enters a soaking cycle. The steamed pads are switched to the production cycle after the soaking cycle, and the surface returns to its initial elevation. Given the repetitive CSS cycles, changes in the ground surface elevation at the Cold Lake site are expected.
Figure 8. Pictorial presentations of (A) steaming strategy for CSS and (B) side view along section A (modified from Stancliffe and van der Kooij, 2001)
3.2 Datasets and Software

3.2.1 Radar Satellite Data

The main dataset for radar interferometry is a series of SAR data that cover the selected study areas. SAR data are obtainable from various radar satellites that are either currently in operation or already retired, such as ALOS-1/2 PALSAR, ENVISAT, ERS-1/2, RADARSAT-1/2, and TerraSAR-X. The details of the available SAR data are summarized in Table 1.

Table 1. Summary of available SAR data

<table>
<thead>
<tr>
<th>Mission</th>
<th>Start Date</th>
<th>End Date</th>
<th>Band</th>
<th>Repeat Cycle (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOS-1</td>
<td>2006/01/24</td>
<td>2011/04/21</td>
<td>L-Band</td>
<td>46</td>
</tr>
<tr>
<td>ALOS-2</td>
<td>2014/05/24</td>
<td>-</td>
<td>L-Band</td>
<td>14</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>2002/03/01</td>
<td>2012/04/08</td>
<td>C-Band</td>
<td>35</td>
</tr>
<tr>
<td>ERS-1</td>
<td>1991/07/17</td>
<td>2000/03/10</td>
<td>C-Band</td>
<td>35</td>
</tr>
<tr>
<td>ERS-2</td>
<td>1995/04/21</td>
<td>2011/09/05</td>
<td>C-Band</td>
<td>35</td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>1995/11/04</td>
<td>2013/03/29</td>
<td>C-Band</td>
<td>24</td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>2007/12/14</td>
<td>-</td>
<td>C-Band</td>
<td>24</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>2007/06/15</td>
<td>-</td>
<td>X-Band</td>
<td>11</td>
</tr>
</tbody>
</table>

Imaging radar has a unique characteristic of operating at a particular microwave wavelength or frequency, a so-called band (Henderson and Lewis, 1998). In principle, the longer wavelength radar signal is more capable of penetrating deep into the vegetation canopy, while shorter wavelength radar signal is more likely to interact with top layer of the canopy. In other words, the ground surface where transmitted radar signal arrives is regarded as smooth when the surface roughness is less than a microwave wavelength.
The intermediate microwave wavelengths are the most commonly used bands, and their sensitivity to the surface roughness are concisely presented in Table 2 (Sahu, 2008). Thus, it is obvious that SAR data with longer wavelength are preferable for this study, as both selected oil sands sites are covered predominantly with heavy vegetation.

Table 2. Frequency bands of commonly used SAR systems

<table>
<thead>
<tr>
<th>Band</th>
<th>X-Band</th>
<th>C-Band</th>
<th>L-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave Wavelength</td>
<td>2.4 to 3.8 cm</td>
<td>3.75 to 7.5 cm</td>
<td>15 to 30 cm</td>
</tr>
<tr>
<td>Sensitivity to Surface Roughness</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Considering land cover types, geographical coverage and period of interest for both selected sites, all available SAR data listed in Table 1 are carefully examined and the most suitable SAR datasets are chosen from ERS-2 for the CO₂-EOR site and ALOS-1 PALSAR for the CSS sites in this study. The European Space Agency (ESA) offers a free multi-platform interactive tool, through which users can access and search for its Earth observation data products, such as ENVISAT and ERS-1/2 SAR data (ESA, 2013). ALOS-1 PALSAR data can also be searched and ordered from the Japan Aerospace Exploration Agency (JAXA) using the Globe-Portal or CROSS-EX systems. The raw data products of ERS-2 (level 0) with VV (i.e., vertically transmitted and vertically received) polarization and ALOS-1 PALSAR (level 1.0) with HH (i.e., horizontally transmitted and horizontally received) polarization are successfully acquired for this study. The previews of SAR intensity images acquired from the ERS-2 and ALOS-1 satellites for the CO₂-EOR and CSS sites are presented in Figure 9. The sensor specifications of the ERS-2 and ALOS-1 satellites are also listed in Table 3.
Figure 9. SAR intensity images of (A) ERS-2 and (B) ALOS-1 enlarged into the CO₂-EOR and CSS sites selected for this study

<table>
<thead>
<tr>
<th></th>
<th>ERS-2</th>
<th>ALOS-1 PALSAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging Mode</td>
<td>SAR Image Mode</td>
<td>Imaging Mode</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.3 GHz</td>
<td>Frequency</td>
</tr>
<tr>
<td>SAR Antenna</td>
<td>10 × 1 m</td>
<td>SAR Antenna</td>
</tr>
<tr>
<td>Incidence Angle</td>
<td>20 – 26 degrees</td>
<td>Incidence Angle</td>
</tr>
<tr>
<td>Swath Width</td>
<td>100 km</td>
<td>Swath Width</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>25 m</td>
<td>Spatial Resolution</td>
</tr>
<tr>
<td>Orbital Altitude</td>
<td>785 km</td>
<td>Orbital Altitude</td>
</tr>
<tr>
<td>Orbit Type</td>
<td>Sun-synchronous</td>
<td>Orbit Type</td>
</tr>
</tbody>
</table>
3.2.2 Digital Elevation Model (DEM)

The external DEMs encompassing the same spatial coverage with collected SAR datasets are acquired for both CO$_2$-EOR and CSS sites. There are topographic data available from two DEMs: 1) SRTM (Shuttle Radar Topography Mission) DEM (USGS, 2009) and, 2) ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global DEM) (METI et al., 2009).

The SRTM DEM generated in 2000 has a resolution of 3 arc-seconds ($\approx$ 90 m at the equator), except for the United States regions that are available at an 1 arc-second resolution (approximately 30 m). Since 2009, the ASTER GDEM has been released by United States Geological Survey (USGS) with a resolution of 1 arc-second. The SRTM DEM has better vertical accuracy than the ASTER GDEM, while the ASTER GDEM contains more topographic information, due to its finer spatial resolution (Wang et al., 2011). The estimated accuracies for ASTER DEM have been determined to be 20 m at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data (METI et al., 2009).

In this study, the ASTER GDEM is selected for its benefit of matching spatial resolution of SAR datasets as close as possible. The ASTER GDEMs downloaded for the two study areas are displayed in Figure 10. The terrain height ranges from approximately 533 m to 614 m for the CO$_2$-EOR site, while a slightly higher elevation range from 615 m to 779 m is observed at the CSS site.
3.2.3 Optical Satellite Data

In addition to the SAR and DEM data for InSAR-related processes, optical satellite imagery is collected for this study. Optical satellite imagery is commonly used for its capability of providing multi-spectral information on the Earth’s surface. Of currently available optical satellite data, Landsat-5 thematic mapper (TM) (USGS, 2012) imagery is chosen for the CSS site. The acquired Landsat-5 TM imagery is utilized to investigate the land cover and to obtain information regarding the spatial distribution of oil recovery facilities at the CSS site.
The visible bands (i.e., red, green and blue (RGB)) of the Landsat-5 TM imagery acquired on September 13, 2011 with cloud coverage less than 10 % are combined to yield a natural look image to be used as a background when displaying a series of radar interferometric results, such as differential interferograms or surface deformation maps, and contours that indicate fractional volumetric changes in the subsurface. The Landsat-5 TM imagery enlarged into the CSS site is visualized in Figure 11, which exhibits a sequence of well pads and access roads shown in white. Most of the areas, excluding those developed for oil recovery, are covered by dense vegetation and forest.

Figure 11. Landsat-5 TM imagery for the CSS site
3.2.4 Software

GAMMA radar remote sensing software, developed by GAMMA Remote Sensing Research and Consulting AG in Switzerland, is mainly used for the application of the radar interferometric techniques (i.e., InSAR and DInSAR). GAMMA is a command-based software that is specifically designed to apply a variety of radar interferometric methods, ranging from raw SAR data processing to point target monitoring (GAMMA Remote Sensing, 2012). The six different modular packages available from GAMMA are: 1) Modular SAR Processor (MSP) for raw SAR data processing, 2) InSAR Processor (ISP), 3) DInSAR (DIFF), 4) Geocoding (GEO), 5) Land Application Tools (LAT), and 6) Interferometric point target analysis (IPTA). The modules of MSP, ISP, DIFF and GEO are utilized for creating differential interferograms for both selected sites in this study.

Other ancillary software includes ERDAS ER-Mapper v.7.2 and MATLAB®. ERDAS ER-Mapper (ERDAS, 2008), which is a commercial remote sensing tool, is used for post-processing the radar interferometric results as well as data visualization. The mathematical operations, SBAS algorithm application and geomechanical inversion are performed using MATLAB®.
Chapter IV. METHODOLOGY

The three main methodologies adopted for this study are: 1) radar interferometry, 2) time-series analysis, and 3) modeling subsurface volumetric change. The fundamental theory about radar interferometry applications for surface deformation monitoring is stated in Section 4.1. The advanced radar interferometry algorithm for deriving the time-series maps of accumulated surface deformation and the geomechanical inversion process for the modeling of subsurface volumetric changes estimated from InSAR-derived surface deformation measurements are summarized in Sections 4.2 and 4.3, respectively.

4.1 Radar Interferometry

The phase information contained in SAR measurements enables the detection of relative distances between the onboard SAR sensor and the targeted point on the ground surface as a fraction of the radar wavelength (Hanssen, 2001). The space-borne InSAR algorithm is developed based on the use of two time-separated SAR data taken on the same satellite orbit with different incidence angles. The phase shifts recorded in two SAR data are used to generate an interferogram. DInSAR is developed to measure the phase shift differences attributed to the changes in surface elevation by removing the topographic effect from an interferogram, consequently yielding a differential interferogram. The differential interferogram ideally represents the changes in distance
from the SAR sensor to the ground point during a specific period determined by the acquisition dates of the SAR data.

The geodetic applications of the resulting interferograms and differential interferograms include topographic mapping with an accuracy of 10 to 50 m, deformation monitoring at millimetric to centimetric accuracies, thematic mapping and atmospheric delay mapping with millimetric to centimetric accuracies in terms of the excess path length (Madsen et al., 1993; Massomet and Feigl, 1998; Hanssen, 2001).

Two conventional radar interferometric techniques (i.e., InSAR, DInSAR) are first implemented to determine whether the ground surface elevation at both CO₂-EOR and CSS sites remains unchanged or are affected by vertical surface deformations in this study. The fundamentals of these radar interferometric techniques are stated in the following subsections.

### 4.1.1 Interferometric Synthetic Aperture Radar (InSAR)

The backscattered radar signals measured from SAR antenna positions, \( P_1 \) and \( P_2 \), are related to the topography, Earth’s curvature, atmospheric effect, phase noise, which is possibly due to temporal change of the scatterers and/or different incidence angles, and ground surface displacements in the LOS direction of the radar beam if the surface displacement occurs. The interferometric phase can be expressed by:

\[
\phi = \phi_{\text{top}} + \phi_{\text{flat}} + \phi_{\text{def}} + \phi_{\text{atm}} + \phi_{\text{noise}}
\]  

(1)
where $\phi$ is radar interferometric phase retrieved by InSAR, $\phi_{\text{topo}}$ is the topographic phase, $\phi_{\text{flat}}$ is the so-called flat Earth phase caused by the Earth’s curvature, $\phi_{\text{def}}$ is the surface deformation phase, $\phi_{\text{atm}}$ is the atmospheric phase, and $\phi_{\text{noise}}$ is the residual noise phase (Hanssen, 2001). The geometry of InSAR is illustrated in Figure 12 (Baek et al., 2008) with descriptions of each parameter.

\[ B \quad \text{Baseline} \quad B_{\perp} \quad \text{Perpendicular baseline} \]
\[ B_{\parallel} \quad \text{Parallel baseline} \quad B_{H} \quad \text{Horizontal baseline} \]
\[ B_{V} \quad \text{Vertical baseline} \quad \theta \quad \text{Incidence angle} \]
\[ \alpha \quad \text{Baseline direction} \quad \rho \quad \text{Slant range} \]
\[ H \quad \text{Satellite altitude} \quad z \quad \text{Topographic height} \]
\[ P_{1} \quad \text{Reference antenna} \quad P_{2} \quad \text{Repeat antenna} \]
\[ r_{n} \quad \text{Earth radius at nadir} \quad r_{t} \quad \text{Earth radius at target} \]

**Figure 12. Illustration of InSAR geometry (Baek et al., 2008)**

Two SAR data taken on the same orbit over the same area are necessary for radar interferometry. After the co-registration of the second SAR data (i.e., slave image) to corresponding locations of first SAR data (i.e., master image), an interferogram can be mathematically expressed by the pixel-wise conjugate multiplication of complex radar
signals \((y_1, y_2)\) contained in two time-separated SAR data (Hanssen, 2001). Accordingly, a complex interferogram \((v)\) can be generated as follows:

\[
v = y_1^* y_2 = \| y_1 \| y_2 \exp(j(\psi_1 - \psi_2))
\]

where \(^*\) stands for the complex conjugate, and \(\psi_1\) and \(\psi_2\) are the phase components of the two SAR data.

The observed phase values \((\psi_{1R}, \psi_{2R})\) in the two SAR data for a resolution cell of \(R\) are:

\[
\psi_{1R} = -\frac{2\pi2\rho_1}{\lambda} \quad \psi_{2R} = -\frac{2\pi2\rho_2}{\lambda}
\]

where \(\rho_1, \rho_2\) are the geometric distances, and \(\lambda\) is wavelength of the radar signal. Therefore, the interferometric phase for a resolution cell of \(R\) can be represented as:

\[
\phi_R = \psi_{1R} - \psi_{2R} = -\frac{4\pi(\rho_1 - \rho_2)}{\lambda} = -\frac{4\pi\delta\rho}{\lambda}
\]

Consequently, Eq. (4) is simply the subtraction of the phase contained in the slave images from master image. According to Eq. (4), it is obvious that the interferometric phase \((\phi_R)\) is a function of the radar signal wavelength and the path length difference (i.e., slant range difference denoted as \(\delta\rho\) in Eq. (4)). The slant range containing slight changes in the path length measured at the second SAR data acquisition time can be geometrically expressed by (Henderson and Lewis, 1998):

\[
(\rho + \delta\rho)^2 = \rho^2 + B^2 - 2\rho B \sin(\theta - \alpha)
\]
where $B$ stands for the baseline, $\theta$ is the incidence angle and $\alpha$ indicates the baseline orientation. If $\delta \rho$ term is relatively small enough to satisfy $\delta \rho \ll \rho$, Eq. (5) becomes:

$$\delta \rho \approx \frac{B^2}{2\rho} - B \sin(\theta - \alpha) \quad (6)$$

By simplifying Eq. (6) with the assumption that the condition of $B \ll \rho$ can be met in most cases, the interferometric phase can be subsequently reformulated by considering Eqs. (4) and (6) as follows:

$$\phi = -\frac{4\pi}{\lambda} B \sin(\theta - \alpha) \quad (7)$$

The derivative of Eq. (7) with respect to incidence angle is:

$$\delta \phi = -\frac{4\pi}{\lambda} B \cos(\theta - \alpha) \delta \theta \quad (8)$$

Eq. (8) represents the relationship between the interferometric phase change and variation in the incidence angle.

The resulting phase ($\phi$) calculated from Eq. (7) indicates the interferometric phase, due to slant range variations. The spatial baseline ($B$) can be split into two components – parallel baseline ($B_\parallel$) and perpendicular baseline ($B_\perp$) – as illustrated in Figure 12. These two baseline components are functions of the incidence angle and baseline direction, and can be represented by:

$$B_\parallel = B \sin(\theta - \alpha) \quad (9)$$
\[ B_\perp = B \cos(\theta - \alpha) \]

By comparing Eqs. (7) to (9), it can be found that the interferometric phase in Eq. (7) is proportional to the parallel baseline, while the derivative of interferometric phase in Eq. (8) is proportional to the perpendicular baseline.

### 4.1.2 Differential Interferometric Synthetic Aperture Radar (DInSAR)

The fundamental goal of DInSAR application is the extraction of the phase component due to ground surface deformation from interferograms. As presented in Eq. (1), the interferometric phase is composed of not only the radar signal related to surface deformation, but also other undesired phase components contributed by the terrain height, Earth’s curvature, atmospheric inhomogeneity and signal noise. It is, therefore, essential to subtract the topographic and other effects from the radar interferometric phase, in order to retrieve only the surface deformation contribution.

The phase components associated with the topographic effect and the Earth’s curvature can be eliminated from the resulting interferograms by DInSAR. The topographic phase can be estimated using an external DEM that is co-registered with the generated interferograms; and, the phase due to the Earth’s curvature can be mathematically computed using orbital information of the SAR platform. The differential interferometric phase contributed by vertical surface deformation that takes place between the acquisition dates of two SAR data, can be retrieved with accuracy levels of centimetres to millimetres through DInSAR application.
The $k^{th}$ differential interferogram contains the differential interferometric phase composed with following components (Hanssen, 2001; Kampes, 2006):

$$\phi_{\text{diff}}^k = \phi_{\text{DEM error}}^k + \phi_{\text{def}}^k + \phi_{\text{atm}}^k + \phi_{\text{noise}}^k$$  (10)

where $\phi_{\text{diff}}^k$ is the total phase of the $k^{th}$ differential interferogram, and $\phi_{\text{DEM error}}^k$ is the phase caused by an error in the external DEM.

The phase components to be eliminated for surface deformation retrieval (i.e., topographic and Earth’s curvature phases) can be mathematically formulated by InSAR geometric parameters. The detailed description of DInSAR procedures with mathematical formulation of three differential interferometric phase terms (phase noise effect excluded) shown in Eq. (10) is outlined in following subsections.

- **Flat Earth Correction**

  The additional phase associated with the ellipsoidal shape of the Earth is always included in an interferogram. This phase term can be estimated using precise orbital information, and simply removed from an interferogram by a well-established mathematical model. The removal of the phase due to the Earth’s curvature is called the flat Earth correction or phase flattening (Cracknell and Rowan, 1989). From Figure 13, (Baek, 2006), the incidence angle ($\theta$) can be expressed with distance ($b$) between the satellite position and the centre of the Earth, Earth’s radius at the location of local ground target ($r$), and the slant range ($\rho$) as follows:
Figure 13. Schematics of flat Earth correction (Baek, 2006)

\[
\eta = \cos(\theta) = \frac{(b^2 + \rho^2 - r_n^2)}{2\rho b}
\]  

(11)

\(H\) and \(r_n\) in Figure 13 stand for the radar satellite altitude and Earth’s radius at nadir, respectively.

Eq. (11) is subsequently differentiated with respect to slant range and can be expressed by:

\[
\frac{\delta \theta}{\delta \rho} = \frac{1}{\sin(\theta)} \left( \cos(\theta) - \frac{\rho}{b} \right)
\]  

(12)
By substituting Eq. (12) into Eq. (8), Eq. (8) finally becomes:

$$\frac{\delta \phi}{\delta \rho} = -\frac{4\pi B \cos(\theta - \alpha)}{\sin(\theta)} \left( \cos(\theta) - \frac{\rho}{b} \right)$$

(13)

Using Eqs. (7) and (13), the approximate flat Earth correction can be expressed by:

$$\phi = -\frac{4\pi B}{\lambda} \left( 1 - \eta^2 \right)^{1/2} \cos(\alpha - \eta \sin(\alpha))$$

(14)

where $\eta$ is given in Eq. (11).

- **Topographic Effect Removal**

As long as the topographic effect still remains in radar interferometric phase, it is definitely impossible to solely interpret ground surface deformations. Since the slant range varies along with the local terrain height, the interferometric phase is significantly influenced by topography. The derivative of the interferometric phase in Eq. (7) with respect to terrain elevation becomes:

$$\frac{\delta \phi}{\delta z} = \frac{4\pi}{\lambda} B \cos(\theta - \alpha) \frac{\delta \theta}{\delta z}$$

(15)

The altitude of the satellite above the reference Earth ($H_{sat}$) is represented as follows (Hanssen, 2001):

$$H_{sat} = \rho \cos(\theta)$$

(16)
The derivative of Eq. (16) with respect to incidence angle represents the change rate in incidence angle \( \delta \theta \) with respect to altitude difference \( \delta H_{sat} \):

\[
\delta H_{sat} = -\rho \sin(\theta) \delta \theta
\]  

(17)

Using Eqs. (7), (8) and (17), the relationship between the satellite height above the reference body and the interferometric phase can be found as:

\[
H = -\frac{\lambda \rho \sin(\theta)}{4\pi B_\perp} \delta \phi
\]  

(18)

By replacing \( \delta \phi \) with \( 2\pi \), which is one complete cycle of radar interferometric phase, the equation for the altitude of ambiguity \( H_a \) is derived as follows:

\[
H_a = \frac{\lambda \rho \sin(\theta)}{2B_\perp}
\]  

(19)

The resulting term \( H_a \), often called the altitude of ambiguity, presents the height variation corresponding to \( 2\pi \) phase shift. Therefore, altitude of ambiguity indicates the sensitivity of the interferometric phase to the changes in surface elevation. The topography-related phase can be easily calculated by inverting Eq. (18).

- **Surface Deformation Retrieval**

After successful elimination of phase components contributed by the topographic effect and Earth’s curvature from an interferogram, the remaining phase in an ideal case
(i.e., no atmospheric effect and phase noise) should solely indicate surface deformations measured along the LOS direction that take place during the period between two SAR data acquisition dates. The differential interferometric phase due to surface deformation can be readily formulated as:

$$\phi_{\text{def}} = -\frac{4\pi}{\lambda} \delta \rho$$

(20)

From Eq. (20), it can be inferred that the ground surface deformation causing a phase change of $2\pi$ (i.e., 1 fringe) in a differential interferogram corresponds to $\lambda/2$, which translates to 2.3 cm for C-band (e.g., ERS-2) and 11.75 cm for L-band (e.g., ALOS-1) in radar interferometry.

However, the isolated phase component contributed by surface deformations that occur between two SAR data acquisition dates is ambiguous, because the differential interferometric phase is inherently wrapped modulo $2\pi$. The physical measurement of surface deformation requires the additional process for unwrapping the differential interferometric phase, so-called phase unwrapping. The phase unwrapping should be applied to the resultant differential interferograms before retrieving the surface deformation. Since the unwrapped differential interferograms are still relative to each other, differential interferometric phases should be scaled with respect to a reference point located in the non-deformed stable area with a high coherence that is continuously preserved over time. The unwrapped and scaled differential interferograms provide physically meaningful information on vertical surface deformations measured along the
LOS direction. The successfully unwrapped and scaled differential interferograms can be converted to surface displacements in the LOS direction by multiplying a factor of \( -\frac{\lambda}{4\pi} \).

After unwrapping the differential interferograms, the surface displacements in the LOS direction can be converted into vertical surface deformation \( \Delta S \) under the assumption of negligible horizontal surface deformation by (Camec and Massonnet, 1996):

\[
\Delta S = \frac{\delta \rho}{\cos(\theta)}
\]

Therefore, the vertical displacements at the ground surface level can be measured by DInSAR implementation as explained in this section.

4.2 Time-series Analysis

In principle, only the surface deformation that occurs during the periods between two SAR data acquisition dates can be observed using conventional DInSAR. Moreover, the errors involved in traditional radar interferometric techniques, such as temporal and geometrical decorrelations, and atmospheric inhomogeneity, often limit their feasibility (Zebker and Villasenor, 1992; Kampes, 2006; Kim et al., 2007).

Of the numerous algorithms developed to overcome typical decorrelation problems of conventional radar interferometric methods, the recently developed PSInSAR and SBAS algorithm have been widely used for more precise detection of
surface deformation. Both methods address the limitations of standard InSAR techniques (e.g., temporal/spatial decorrelation problems, atmospheric effects, DEM errors) through the use of multi-temporal SAR datasets. Using a stack of multi-temporal SAR data enables not only the resolution of typical InSAR problems, but also the retrieval of the temporal trend of observed surface deformation at a point of interest (Lauknes et al., 2008).

The PSInSAR begins with the generation of differential interferograms with respect to a common master image using all available SAR data regardless of baseline. The PSs that remain coherent over a long time span need to be identified, in order to solve temporal decorrelation problem and to maximize the number of SAR data to be utilized for the radar interferometry (Ferretti et al., 2001). A sufficient spatial density of PSs (approximately 5 – 10 PS/km²) and at least 25 SAR data are generally required for the proper estimation of atmospheric artifacts and reliable analysis (Colesanti et al., 2003). However, the spatial density of PSs may become low with either a long spatial baseline or the lack of the number of such PSs distributed in the imaged area. The PSInSAR-derived surface deformation measurements typically get noisier when the density of PSs is low (Ferretti et al., 2011).

The SBAS algorithm, on the other hand, suggests the use of multiple subsets of the differential interferograms with a small baseline (SB) to surpass the inherent limitation of PSInSAR. The use of SB subsets, which are defined as groups of SAR data pairs characterized by a small spatial separation between orbits (i.e., short spatial baseline), mitigates the spatial decorrelation effects that are possibly caused by a long
spatial baseline of interferometric pairs. Furthermore, the number of SAR data used for interferogram formation can be increased through the combination of SB subsets using singular value decomposition (SVD) (Berardino et al., 2002; Lanari et al., 2004). The application of the SBAS algorithm to a stack of differential interferograms also allows for the temporal analysis of surface displacements at each SAR data acquisition date (Berardino et al., 2002).

Since the obtained SAR datasets over the CSS site contain fewer than 25 data and the selected site exhibits only a few potential PSs (e.g., roads, buildings, man-made facilities.) as shown in Landsat-5 TM imagery (Figure 11), the PSInSAR application unfortunately turns out to be inappropriate for this study. Hence, the SBAS algorithm is applied for post-processing the differential interferograms, taking advantage of increased temporal resolution and spatial density of surface deformation maps. The application of the SBAS algorithm is, therefore, expected to benefit this study, in terms of achieving a better quality of results, especially for the areas predominantly covered by dense vegetation with a fewer number of SAR datasets.

In principle, the SBAS algorithm consists of two main steps: 1) evaluation of the low-pass (LP) phase component, including linear surface deformation at large spatial scale, topographic error of the external DEM and atmospheric phase artifacts, and 2) determination of the high pass (HP) components decoupled into residual surface deformation and topographic phase signal (Lanari et al., 2004). With \( N + 1 \) SAR data ordered in the ascending time of \( t_0, \ldots, t_N \), the number of possible interferometric pairs \( (M) \) for differential interferogram generation falls within a range of:
when assuming $N$ is odd number. The input differential interferograms should contain phase values that are already unwrapped and scaled with respect to a reference point.

If the vector of $N$ unknown surface deformation phases at the acquisition dates of each SAR data and $M$ known differential interferometric phases exist, these phases can be arranged as:

$$
\phi^* = [\phi(t_1), \ldots, \phi(t_N)], \quad \delta\phi^* = [\delta\phi_1, \ldots, \delta\phi_M]
$$

(23)

where $*$ stands for the transpose of the matrix. A stack of $M$ differential interferograms can be reconstructed with following two index matrices as follows:

$$
IS = [IS_1, \ldots, IS_M], \quad IE = [IE_1, \ldots, IE_M]
$$

(24)

where $IS$ and $IE$ indicate acquisition time indices of the slave and master SAR images sorted in chronological order.

The unwrapped phase of the $m^{\text{th}}$ differential interferogram can then be expressed by:

$$
\delta\phi_m(x,r) = \phi(t_{IE_m}, x,r) - \phi(t_{IS_m}, x,r)
$$

(25)

where $x$ and $r$ are the azimuth and range pixel coordinates, respectively; and, $\phi(t_{IE_m}, x,r)$ and $\phi(t_{IS_m}, x,r)$ denote the phase components of master and slave SAR images, respectively, with $\forall m = 1, \ldots, M$ (Berardino et al., 2002; Lanari et al., 2004).
Eq. (25) can, therefore, be defined as a linear system of $M$ known and $N$ unknown components; and, this linear relationship can be simply represented by:

$$K \phi = \delta \phi$$  \hspace{1cm} (26)$$

where $K$ is an $M \times N$ matrix defining the combination of SAR data used to create each radar interferometric pair. The elements of $K$ for the $m^{th}$ differential interferogram are defined as $K(m, IS_m) = -1$ when $IS_m \neq 0$ and $K(m, IE_m) = +1$, and zero otherwise. If the 1\textsuperscript{st} differential interferogram is created using the combination of $IE_4$ and $IS_2$ fulfilling $\delta \phi_1 = \phi_4 - \phi_2$, for example, the component of $K$ corresponding to the 1\textsuperscript{st} differential interferogram is constructed as follows:

$$K = \begin{bmatrix} 0 & -1 & 0 & +1 & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \end{bmatrix}$$

The solution may introduce large discontinuities in cumulative surface displacements when more than two SB subsets are involved and $K$ in Eq. (26) exhibits a rank deficiency. Substitution of the phase term ($\phi$) in Eq. (26) with the surface deformation phase velocity ($v$) between acquisition dates of two time-adjacent SAR data is, therefore, considered for more feasible solutions (Berardino et al., 2002). In this case, the mean phase velocity measured between the time-adjacent SAR data acquisitions dates is considered to be an unknown parameter. Accordingly, the linear system represented in Eq. (26) can be reorganized, leading the following expression of:
where $v$ is the mean phase velocity, and $C$ is a system matrix composed with time-
adjacent SAR data acquisition dates. $C$ is a $M \times N$ matrix with the generic element
being $C(m,k) = t_{k+1} - t_k$ for $IS_{k+1} \leq k \leq IE_k$; and, $C(m,k)$ becomes zero elsewhee.

The new unknown ($v$) can be defined as:

$$v^* = \begin{bmatrix} v_1 = \frac{\phi_1}{t_1-t_0}, \ldots, v_N = \frac{\phi_N - \phi_{N-1}}{t_N - t_{N-1}} \end{bmatrix}$$

(28)

By considering Eq. (28), Eq. (23) becomes:

$$\sum_{k=IS_m+1}^{IE_m} (t_k - t_{k-1}) v_k = \delta \phi_m$$

(29)

where $\forall m = 1, \ldots, M$.

If time-model information of surface deformation such as the mean phase velocity
($\bar{v}$), mean phase acceleration ($\bar{a}$) and mean phase acceleration variation ($\bar{\Delta a}$), is
available, it can be additionally incorporated into Eq. (27). The deformation-related phase
velocity vector ($v$) is related to model parameter vector $p$ as follows:

$$v = Tp$$

(30)

where matrix $T$ indicates vector components.
For example, if a cubic model is assumed for the phase due to surface
displacements, $p$ can be defined as $p^* = [\bar{v}, \bar{a}, \Delta \bar{a}]$ and $T$ becomes:

$$
T = \begin{bmatrix}
1 & \frac{t_1 - t_0}{2} & \frac{(t_1 - t_0)^2}{6} \\
1 & \frac{t_2 - t_1 - 2t_0}{2} & \frac{(t_2 - t_0)^3 - (t_1 - t_0)^3}{6(t_2 - t_0)} \\
\vdots & \vdots & \vdots \\
1 & \frac{t_N + t_{N-1} - 2t_0}{2} & \frac{(t_N - t_0)^3 - (t_{N-1} - t_0)^3}{6(t_N - t_{N-1})}
\end{bmatrix}
$$

Accordingly, Eq. (27) can be reformatted by replacing $v$ in Eq. (30) and expressed as:

$$
CTp = \delta \phi
$$

(31)

The LP component of the $m^{th}$ differential interferogram at $(x, r)$ position with its
perpendicular baseline ($B_\perp$) can be formulated as (Berardino et al., 2002; Lanari et al.,
2004):

$$
\delta \phi_m^{LP}(x, r) \approx \frac{4\pi}{\lambda} \left[ d^{LP}(t_{IEm}, x, r) - d^{LP}(t_{ISm}, x, r) \right]
+ \frac{4\pi}{\lambda} \frac{B_\perp \Delta z^{LP}(x, r)}{r \sin(\theta)}
+ \left[ \phi_{am}(t_{IEm}, x, r) - \phi_{am}(t_{ISm}, x, r) \right] + \Delta n_m^{LP}(x, r)
$$

(32)

where $d^{LP}$ and $\Delta z^{LP}$ are the LP components associated with the surface deformation and
topographic errors of DEM, respectively; $\phi_{am}(t_{IEm}, x, r)$ and $\phi_{am}(t_{ISm}, x, r)$ represent the
phases due to atmospheric inhomogeneity when master and slave SAR images are
acquired, respectively; and $\Delta n_m^{LP}$ accounts for phase noise contributions. The temporal
LP component of possible topographic artifacts due to DEM error \((\Delta z^{LP})\) can be estimated from the system of equations derived from Eq. (31) as follows:

\[
[CT, c]p_c = \delta \phi
\]

(33)

where \(c^* = \begin{bmatrix} \frac{4\pi B_{\perp 1}}{\lambda \rho \sin(\theta)} & \cdots \frac{4\pi B_{\perp M}}{\lambda \rho \sin(\theta)} \end{bmatrix} \), which can be derived from Eq. (18); and, \(p_c^* = [p^*, \Delta z^{LP}] \).

Taking the unwrapped differential interferograms as the input of Eq. (27), (31) or (33), the phase velocity term \((v)\) or model parameters \((\bar{v}, \bar{a}, \bar{\Delta a})\) due to surface displacements can be estimated by inversion methods. If all of the differential interferograms are grouped in a single SB subset, the number of possibly generated differential interferograms is always larger than the total number of SAR data \((M \geq N)\). This fact leads the whole system to be either well-determined \((M = N)\) or over-determined \((M > N)\). Therefore, \(C\) becomes the \(N\) rank matrix, and the system solution of Eq. (27) can be obtained with a traditional method, such as the least squares method (Twomey, 2002), as follows:

\[
\bar{v} = (C^* C)^{-1} C^* \delta \phi
\]

(34)

When multiple SB subsets are considered, however, the system occasionally encounters a rank deficiency problem with the rank of \(N - L + 1\), where \(L\) is the number of subsets. Accordingly, the least squares solution is not unique, but rather the system has infinite solutions. This problem can be resolved by using SVD method that estimates one
solution with a minimum norm among all of the least squares solutions (Strang, 1988). The pseudo-inverse matrix of $C$ that gives the minimum norm least squares solution can be obtained by the SVD method as follows (Lauknes et al., 2005):

$$\tilde{v} = V \begin{bmatrix} \Sigma^{-1} & 0 \\ 0 & 0 \end{bmatrix} U^* \delta \phi$$

(35)

where $V$ is an orthogonal $M \times M$ matrix, the first $N$ columns of which have eigenvectors of $C^*C$; $U$ is an orthogonal $N \times M$ matrix, the first columns of which are the eigenvectors of $CC^*$; and, $\Sigma = \text{diag}(\sigma_1^{-1}, ..., \sigma_{N-L+1}^{-1})$ where $\sigma$ is the square root of an eigenvalue of $CC^*$.

Once the LP component in Eq. (33) is estimated, the residual phase, which is related to the HP contributions, can be obtained by subtracting the LP components from each differential interferogram. This operation typically reduces the high fringe rate that is possibly caused by rapid surface deformations, yielding more reliable unwrapped residual phases. Consequently, the refined unwrapped differential interferometric phase can be retrieved by adding back the subtracted LP phase component to the unwrapped residual phase. The mean velocity of vertical surface deformation between acquisition dates of two time-adjacent SAR data can be estimated from differential interferograms by applying an SVD-based inversion, and the surface displacements measured at each SAR data acquisition date becomes available through integration step (Berardino et al., 2002).

If significant atmospheric artifacts are involved, a filtering operation can be applied to the SVD-derived results in order to mitigate remaining atmospheric effects.
The concept of filtering, which is originally introduced in PSInSAR, is based on the fact that atmospheric phenomena are highly correlated in the spatial domain, but exhibit low temporal correlation (Ferretti et al., 2000, 2001). After filtering out the atmospheric effects, the final results can be converted to a surface deformation signal by multiplying a factor of \( -\frac{\lambda}{4\pi} \). The overall implementation of the SBAS algorithm is presented as the block diagram in Figure 14 (Berardino et al., 2002).

Figure 14. Block diagram of SBAS implementation (Berardino et al., 2002)
4.3 Subsurface Volumetric Change Modeling

4.3.1 Deformation in a Poroelastic Half-space

InSAR-derived surface deformation provides valuable information on volumetric changes, mechanical properties and fluid flow in a reservoir (Vasco and Ferretti, 2005; Vasco et al., 2008). The inversion of surface deformation measurements using point source response function allows for the estimation of the reservoir volumetric changes either numerically or analytically. In this study, analytical inversion is applied to the time-series maps of surface deformation to estimate the subsurface volumetric changes that possibly result from the fluid injection into or extraction from the subsurface for oil recovery.

A reservoir can be regarded as a source of subsurface volume change that is transferrable to the ground surface, causing surface deformation if the overburden is considered to be poroelastic (i.e., porous and elastic) (Vasco et al., 1998; Vasco et al., 2000; Muntendam-Bos et al., 2008). The poroelastic case can be considered when the fluid flow is confined to the reservoir, the volume of which is regarded to be embedded in a poroelastic medium (Vasco et al., 2000). The assumption of the overburden behaving elastically is valid in most cases and can be relaxed if specific information on shear banks or a plastic volumetric deformation region in overburden is available (Dusseault and Rothenburg, 2002). Therefore, the relationship between the overburden behaviour and the reservoir volumetric change that results from the variations in reservoir fluid pressure can be expressed as a linear system of equations with the assumption of a poroelastic medium (Vasco et al., 2008).
Assuming a uniform, isotropic, homogeneous, fluid-infiltrated poroelastic half-space structure of the subsurface matrix for simplicity, the volumetric strain ($\varepsilon_{kk}$) in the solid matrix that is related to the mean stress ($\sigma_{kk}$), and the total changes in pore fluid content ($\Delta v$) can be expressed by (Segall, 1985; Vasco et al., 1998):

$$\varepsilon_{kk} = \frac{\sigma_{kk}}{3K_u} + \frac{B_0\Delta v}{\rho_0}$$  \hspace{1cm} (36)

where $K_u$ stands for the undrained bulk modulus, $B_0$ is Skempton’s pore pressure coefficient ranging from 0 to 1, and $\rho_0$ is the density of the fluid in the reference state. The stress term in Eq. (36) can be eliminated in order to consider only the strain term (e.g., displacement) in a displacement-displacement (D-D) problem (Palmer, 1972). From Eq. (36), the stress-free transformational strain ($\varepsilon_{kk}^T$) caused by the fluid content variation simply follows:

$$\varepsilon_{kk}^T = \frac{B_0\Delta v}{\rho_0}$$  \hspace{1cm} (37)

The surface displacement at an observation point ($x$) at the surface level ($u_m(x)$) is proportional to the elastic response of a half-space acting on a source point ($s$) in the subsurface as defined by:

$$u_m(x) = DG_m(x, s)$$  \hspace{1cm} (38)
where \( D \) describes a constant of proportionality given by \( D = \frac{B_0 \Delta v(s)}{\rho_0} \) \( dV_r \), \( m \) stands for the direction of surface displacements, and \( G_m(x, s) \) is the Green’s function relating the subsurface volumetric change to the surface displacement component.

The integration of all elemental volume changes represented in Eq. (38) over the entire source volume (i.e., whole reservoir volume, \( V_r \)) defines the total amount of vertical surface deformation induced by subsurface volume changes as follows:

\[
u_m(x) = \frac{B_0}{\rho_0} \iiint_{V_r} \Delta v(s)G_m(x, s) dV_r
\]

(39)

where \( \Delta v(s) \) represents the fractional volumetric change of subsurface, which is defined by \( \Delta V_r / V_{r0} \), and \( V_{r0} \) indicates initial reservoir volume. For 2D problem, \( G_m(x, s) \) for an anomalous body that is assumed to be infinitely long in one direction is given by (Vasco and Johnson, 1985):

\[
G_m(x, s) = \frac{2}{3\pi} (\nu + 1) \frac{s_3}{S^2}
\]

(40)

where \( \nu \) is Poisson’s ratio for a half-space, \( s_3 \) indicates the vertical coordinate of the point source, and \( S \) is the distance from the surface observation point, \( x = (x_1, 0, 0) \) to the source point, \( s = (s_1, 0, s_3) \), as formulated by:

\[
S = |x - s| = \sqrt{(x_1 - s_1)^2 + s_3^2}
\]

(41)
In the case of the fully 3D system concerned, $G_m(x, s)$ becomes (Vasco and Johnson, 1985; Vasco et al., 1998):

$$G_m(x, s) = \frac{1}{3\pi} (\nu + 1) \frac{s_3}{S^3}$$  \hspace{1cm} (42)

and $S$ is given by:

$$S = |x - s| = \sqrt{(x_1 - s_1)^2 + (x_2 - s_2)^2 + s_3^2}$$ \hspace{1cm} (43)

where the surface observation point and source point are $x = (x_1, x_2, 0)$ and $s = (s_1, s_2, s_3)$.

Accordingly, the Green’s function for a particular point at the ground surface can be constructed as a function of the distance between the surface and subsurface points, as well as Poisson’s ratio.

### 4.3.2 Modeling Subsurface Deformations

The inference of $\Delta v(s)$ in Eq. (39) from the surface deformation measurements ($u_m(x)$) requires geomechanical inversion. The inverse formulation starts with the division of the whole subsurface where the volumetric change occurs in non-overlapping rectangular blocks; and, the total amount of vertical surface displacements can be obtained by summing the contributions from each point source defined as rectangular blocks at the reservoir level, introducing the concept of nucleus of strain (Figure 15) (modified from Nanayakkara and Wong, 2010). This process assumes that a point centre
of dilation, referred as a point source in the subsurface, undergoes a uniform volumetric change (Nanayakkara and Wong, 2010). The discretized reservoir blocks should be sufficiently large even when utilizing high resolution datasets (e.g., InSAR-driven surface deformation measurements), because too many small blocks can not only be resolved mathematically, but can also lead to undetermined inversion problems (Dusseault and Rothenburg, 2002). A single layer of grid blocks for a simple subsurface system is often used to make the inversion problem to be well-determined (Vasco et al., 2008).

After defining the gridded subsurface system, the fractional volumetric change of the \( j^{\text{th}} \) block \( (\Delta v_j) \) can be inversely obtained from the surface deformation measurement at a point \( x \ (x_1, x_2, x_3 = 0) \), with the assumption of constant volumetric changes within

![Figure 15. Vertical deformation at a surface observation point estimated by summing contributions from all source points (modified from Nanayakkara and Wong, 2010)]
each reservoir block. The integration of the Green’s function over the total volume of \( j \)th reservoir block \((V_j)\) multiplied by \( \Delta v_j \) represents vertical surface deformation \((u^j_m(x))\) that is contributed by \( \Delta v_j \). Therefore, the relationship between surface displacements and fractional volumetric changes, which are attributed to the \( j \)th block in the subsurface, can be defined by:

\[
u^j_m(x) = \frac{B_0}{\rho_0} \Delta v_j \iiint_{V_j} G_m(x, s) dV_r
\]  

(44)

The total amount of vertical surface displacement at an observation point \((x)\) can be represented by the summation of all \(u^j_m(x)\) over entire reservoir volume \((V)\), which are subdivided into \(N\) blocks, as follows:

\[
u_m(x) = \frac{B_0}{\rho_0} \sum_{j=1}^{N} u^j_m(x) = \frac{B_0}{\rho_0} \sum_{j=1}^{N} \Delta v_j \iiint_{V_j} G_m(x, s) dV_r = \frac{B_0}{\rho_0} \sum_{j=1}^{N} \Delta v_j \Gamma_j (x)
\]  

(45)

where \( \Gamma_j (x) = \iiint_{V_j} G_m(x, s) dV_r \).

With the surface deformation measurements at \(M\) observation points, Eq. (38) can be simply reconstructed through a linear system as:

\[
d = G \Delta v
\]  

(46)

where \(d\) is a set of \(M\) ground surface deformation observations, \(G\) indicates an \(M \times N\) coefficient matrix containing the Green’s function elements given in Eqs. (40) to (43), and \(\Delta v\) represents \(N\) unknown fractional volumetric changes in the subsurface. In
some cases, the coefficient matrix should have the larger number of surface deformation measurement \( M \) than the number of discretized reservoir blocks \( N \). In other words, \( G \) becomes over-determined, i.e., satisfying \( M > N \) (Dusseault and Rothenburg, 2002).

By inverting the linear system in Eq. (46), fractional volumetric changes in the reservoir can be subsequently estimated from the surface displacement measurements. Various inversion algorithms can be considered depending on the system properties. Since the system of linear equations above is nearly singular in many cases, inversion solutions become susceptible to numerical noise and errors in the input data and modeling process. Therefore, direct inversion using a common approach for minimizing the sum of squared residuals, can lead to numerically unstable solutions (Vasco et al., 1998; Vasco and Ferretti, 2005). In order to stabilize the inversion solutions, a more robust approach to find fractional volumetric changes at the reservoir level is required.

### 4.3.3 Geomechanical Inversion

The characteristics of a linear system determine the approach to the inversion problem. The system can be characterized by considering the following aspects (Nanayakkara and Wong, 2010):

- Degree of ill-conditioning of the coefficient matrix \( G \)
- Rank of the coefficient matrix \( G \)
- Degree of perturbations in the measurements \( d \)
In the field of numerical analysis, the degree of ill-conditioning and rank of the coefficient matrix can be assessed by calculating the condition number and the number of linearly independent rows or columns in the matrix. The degree of perturbations typically results from contaminations or errors in the surface deformation measurements.

When difficulties in solving the linear system, such as numerical noise, modeling error and noise in observations, are involved, direct inversion by means of standard inversion techniques is not feasible (Vasco et al., 2000, 2008; Nanayakkara and Wong, 2010). In these cases, the acceptable solution of a given system should be stabilized using regularization techniques. The linear combination of least squares and a penalty function can be minimized by finding a regularized solution vector (Lawson and Hanson, 1987; Parker, 1994). Tikhonov regularization (Tikhonov, 1977) is one of the well-established regularization techniques and is adapted in this study to approximate stable solutions. The expansion of Tikhonov regularization for subsurface inversion modeling mainly follows that of Nanayakkara and Wong (2010).

Taking the linear system in Eq. (46) with $M$ measurements and $N$ unknowns, the Tikhonov regularized solution vector $\{\Delta v^{reg}\}$ can be provided as follows:

$$\{\Delta v^{reg}\} = \arg \min_{\Delta v} \left\{ \| [G]_{M \times N} \{\Delta v\}_{N \times 1} - \{d\}_{M \times 1} \|_2^2 + \mu^2 \| [L] \{\Delta v\}_{N \times 1} \|_2^2 \right\}$$  \hspace{1cm} (47)

where $\mu$ denotes the regularization parameter; and, $L$ is either the identity matrix ($I$) for Tikhonov regularization of order zero, the surface gradient operator for Tikhonov regularization of order one or the Laplacian operator for Tikhonov regularization of order two. The regularized solution defined in Eq. (47) is given by a least squares objective
function and a penalty function that are defined by the square of the residual norm \[ \left\| \begin{bmatrix} G \end{bmatrix}_{M \times N} \{\Delta v\}^{N_{\perp} 1} - \{d\}^{M_{\perp} 1} \right\|_2^2 \] and the square of the discrete smoothing norm, \[ \left\| \begin{bmatrix} L \end{bmatrix}_{N \times 1} \{\Delta v\}^{N_{\perp} 1} \right\|_2^2 \], respectively. Regularization with the identity matrix dampens the components that have the large magnitude of unwanted oscillations; whereas a higher order of regularizations (i.e., stronger regularizations using orders greater than one) reduce undesirable components that are in moderate amplitudes. Tikhonov regularization of order zero is used in this study.

If a priori model for desired solution \((\Delta v_0)\) is available, it can be included in the discrete smoothing norm as expressed by:

\[
\{\Delta v^{\text{reg}}\} = \arg \min_{\Delta v} \left\{ \left\| \begin{bmatrix} G \end{bmatrix}_{M \times N} \{\Delta v\}^{N_{\perp} 1} - \{d\}^{M_{\perp} 1} \right\|_2^2 + \mu^2 \left\| \begin{bmatrix} L \end{bmatrix}_{N \times 1} \{\Delta v - \Delta v_0\}^{N_{\perp} 1} \right\|_2^2 \right\} 
\]

(48)

If the identity matrix is considered for \(L\) (i.e., Tikhonov regularization with order zero), Eq. (48) can be rewritten as:

\[
\{\Delta v^{\text{reg}}\} = \arg \min_{\Delta v} \left\{ \left\| \begin{bmatrix} G \end{bmatrix}_{M \times N} \{\Delta v\}^{N_{\perp} 1} - \left\{ \begin{bmatrix} d \end{bmatrix}^{M_{\perp} 1} \right\} \right\|_2^2 \right\} 
\]

(49)

The SVD of the coefficient matrix \((G)\) with \(M \geq N\) is theoretically given by:

\[
G = [A]_{M \times N}[\Sigma]_{N \times N}[F]^{\dagger}_{N \times N} \quad \text{(50)}
\]
where \([F]\) is an orthogonal matrix with right singular vectors of \(\{f_1, f_2, \ldots, f_N\}\), \([\Sigma]\) is a diagonal matrix composed with singular values of \(\{\xi_1, \xi_2, \ldots, \xi_N\}\), and \([A]\) is an orthogonal matrix with left singular vectors of \(\{a_1, a_2, \ldots, a_N\}\).

Considering the Moore-Penrose pseudo-inverse technique (Hansen, 1998), Eq. (49) can be reformatted into:

\[
\{\Delta v^{\text{reg}}\} = \sum_{i=1}^{N} \frac{\xi_i}{\xi_i^2 + \mu^2} \{d\} f_i + \sum_{i=1}^{N} \frac{\mu^2}{\xi_i^2 + \mu^2} \{\Delta v_0\}
\]  

(51)

The filter factor (\(\beta\)) defined as \(\beta_i = \frac{\xi^2}{\xi_i^2 + \mu^2}\) can be incorporated in Eq. (51) yielding:

\[
\{\Delta v^{\text{reg}}\} = \sum_{i=1}^{N} \beta_i \frac{\xi_i}{\xi_i^2} \{d\} f_i + \sum_{i=1}^{N} (1 - \beta_i) \{\Delta v_0\}
\]  

(52)

Therefore, Eq. (52) can be reduced when \textit{a priori} model is zero \((\Delta v_0 = 0)\) as follows:

\[
\{\Delta v^{\text{reg}}\} = \sum_{i=1}^{N} \beta_i \frac{\xi_i}{\xi_i^2} \{d\} f_i
\]  

(53)

The filtering term \(\frac{\xi}{\xi_i^2 + \mu^2}\) in Eq. (51) serves to filter out the unstable solution components that are contributed by small singular values. The impact of small singular values can be reduced by setting a proper regularization parameter \((\mu)\). In other words, \(\mu\) has very little effect on the solution component that is associated with large singular values of \(G\), since filtering term becomes \(\frac{\xi_i}{\xi_i^2 + \mu^2} \approx \frac{1}{\xi_i}\) for \(\mu \ll \xi_i\). On the other hand,
the filtering term becomes \( \frac{\zeta_i}{\zeta_i^2 + \mu^2} \approx \frac{1}{\mu^2} \) when the singular value is much smaller than \( \mu \). That is, the regularization parameter plays a role in controlling the degree of filtering solution components. Therefore, an over-smoothed solution is given when \( \mu \) is too large, resulting in the small smoothing norm at the expense of a large residual norm. On the other hand, the value of \( \mu \) that is too small gives excessive high frequency variations in the solution; therefore, the smoothing norm becomes large with the residual norm being small as represented in Figure 16 (modified from Dusseault and Rothenburg, 2002).

![Inversion solution under- and over-smoothed by regularization parameters](image)

**Figure 16. Inversion solution under- and over-smoothed by regularization parameters**  
(modified from Dusseault and Rothenburg, 2002)

In the oil and gas fields, the proper regularization parameter can be found using a trade-off curve, as introduced in other publications (Dusseault and Rothenburg, 2002; Du et al., 2008; Nanayakkara and Wong, 2010). The trade-off curve shows the errors of
fitting the surface deformation measurements (e.g., InSAR observations, tiltmeter records) versus the roughness of the volumetric strains at the reservoir level for various regularization parameters. The best regularization parameter can be selected at the corner of trade-off curve; and, the most reasonable solution with small residual and smoothing norms can be found by setting a proper regularization parameter (Du et al., 2008).

The L-curve (i.e., trade-off curve) is a plot of the smoothing norm and the corresponding residual norm for all regularization parameters considered. A corner of the L-curve typically corresponds to the optimal regularization parameter, which balances the minimization of the two aforementioned norms. The vertical part of the L-curve indicates the solutions dominated by noise oscillation in the high frequency domain; whereas the horizontal wing corresponds to a small smooth norm at the cost of a large residual norm (i.e., over-smoothed solution) (Hansen, 1994; Nanayakkara and Wong, 2010). The general form of the L-curve is shown in Figure 17, (modified from Hansen, 1994) which concisely represents typical characteristics and shape of an L-curve.

In this study, the fractional volumetric changes in the subsurface denoted by $v$ in Eq. (46) are estimated by inverting InSAR-driven surface deformation measurements using the Tikhonov regularization technique with an order of zero. An appropriate regularization parameter is also found by examining the L-curves, in order to obtain stable inversion solutions based on a coefficient matrix generated for this study. The geomechanical inversion of InSAR-derived surface displacements for the inference of subsurface volumetric changes using the Tikhonov regularization technique is illustrated as a flow diagram in Figure 18.
Figure 17. The general form of L-curve indicating proper selection of a regularization parameter at the corner (modified from Hansen, 1994)

Figure 18. Flow diagram for the estimation of subsurface volumetric changes using InSAR-derived surface displacements
Chapter V. RESULTS

5.1 Radar Interferometry

5.1.1 Carbon Dioxide Enhanced Oil Recovery (CO₂-EOR) Site

5.1.1.1 Interferometric Pair Selection

InSAR is implemented using ERS-2 SAR single look complex (SLC) data with VV polarization, generating a number of interferograms. Each interferometric SAR pair is selected by considering the spatial baseline, SAR data acquisition date, variation in antenna pointing (e.g., Doppler frequency centroid), orbital pass and coherence. A shorter spatial baseline and time interval between SAR data acquisition dates, smaller variation in Doppler frequency centroid and higher coherence are preferred for reliable phase measurements. The appropriate pairing of SAR data is essential for the minimization of temporal and spatial decorrelation problems.

The maximum allowable spatial baseline, often referred to as the critical baseline, is approximately 1,050 m when using ERS-2 SAR datasets (Balmer, 1997). In general, a higher coherence of interferograms can be obtained when using SAR data acquired in the same season with shorter temporal separation and spatial baseline. The specific criteria for searching suitable SAR interferometric pairs of ERS-2 SAR are defined as: 1) temporal separation: 0 to 700 days, 2) spatial separation (i.e., spatial baseline): 0 to 800 m, and 3) Doppler frequency centroid separation: 0 to 1000 Hz. A total of 33 ERS-2 SAR data are collected and 39 interferometric SAR pairs are determined using the
aforementioned criteria. Note that combinations of different orbit passes are not considered in this study, due to processing complexity. The detailed descriptions of ERS-2 SAR data and radar interferometric pairs are listed in Tables 4 and 5.

5.1.1.2 Radar Interferograms

The differential interferograms are generated by subtracting the Earth’s curvature effect and by applying the flat Earth correction using GAMMA and visually examined to determine which interferograms preserve good radar interferometric coherence. For a preview of several interferograms, 24 interferograms are selected and are displayed in Figure 19, with an intensity SAR image in black and white for background. The interferograms shown in Figure 19 are flipped vertically or horizontally, depending on the orbit passes (i.e., ascending, descending).

Some interferograms contain phase signals with high coherence but others display interferometric phases, which are totally corrupted by temporal or spatial decorrelations, exhibiting low coherence. For example, the first interferogram in Figure 19, which is generated using SAR data taken on January in 2002 and 2003, shows only a background image in black and white with interferometric phases completely corrupted by decorrelations, possibly resulting from heavy snow in winter or other undesired factors. The coherent interferometric phases are, however, observable over an entire interferogram created using SAR data that are acquired in June and July in 2002, respectively.
Table 4. ERS-2 SAR data for the CO₂-EOR site

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*Pass - A: Ascending / D: Descending*
Table 5. Selected interferometric pairs for the CO$_2$-EOR site

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<th>Doppler Centroid (Hz)</th>
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<td>18</td>
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For a more detailed investigation, incoherent and coherent interferograms that are enlarged into the CO$_2$-EOR site represented as the red box in Figure 19 are displayed in Figure 20. An interferogram generated using ERS-2 SAR data collected on March and July in 2010 shows significantly corrupted interferometric phases (Figure 20(A)). Good interferometric coherency is found only around a certain area near the river running from the left-bottom corner of the imaged area. The temporal, spatial and Doppler centroid frequency separations of this pair are 105 days, 147 m and 278 Hz, respectively. The corruption of interferometric phases is most likely due to the different seasons when acquiring SAR data, causing temporal decorrelation.

Figure 19. Preview of selected interferograms covering the CO$_2$-EOR site
Figure 19. Continued. Preview of selected interferograms covering the CO₂-EOR site
Figure 20. Examples of (A) incoherent and (B) coherent interferograms enlarged into the CO₂-EOR site indicated by the red box in Figure 19.

On the other hand, an interferogram formed with ERS-2 SAR data taken on August and October in 2010 shows fairly good quality of phase signals (Figure 20(B)). The temporal, spatial and Doppler centroid frequency separations are 70 days, 437 m and 116 Hz. Although the baseline (437 m) is larger than that of the incoherent pair (147 m) in Figure 20(A), the interferometric phase seems to be more reliable, as represented in continuous phase changes over entire area. The well-preserved coherence of this pair may be attributed to similar land cover during the relatively shorter period between two SAR data acquisition dates and shorter Doppler centroid frequency separation.

Prior to retrieving surface displacements from differential interferograms, the SNAPHU (Statistical-Network-Flow Algorithm for Phase Unwrapping) method, which is developed by Stanford University (Chen and Zebker, 2001) and written in C, is used for phase unwrapping in this study. Since the quality of phase unwrapping can be significantly degraded by incoherent pixels, masking these pixels should be conducted by
utilizing coherence maps with a certain threshold. The coherence maps are generated by computing the cross-correlation of the co-registered SAR data pair over a small window. The coherence ranges from 0 (total decorrelation and no phase information available) to 1 (perfect correlation and no phase noise). The pixels that exhibit coherence below the user-defined threshold of 0.3 in this study are not to be considered, but are replaced with a null value while performing the phase unwrapping process. Therefore, incoherent regions appear to be coloured black or transparent when displayed in a 2D image format.

The differential interferograms are created by DInSAR that allows for the elimination of unwanted phase mainly due to the terrain height using an external DEM. The phase contributed by the surface deformation, which causes the changes of slant range in the LOS direction of two SAR data, can be retrieved from differential interferograms. The differential interferograms that preserve high coherence are zoomed into the red box in Figure 19 and shown in Figure 21. Since the temporal coverage of interferograms ranges from January 17, 2002 to September 23, 2004, the surface monitoring for the CO₂-EOR site is limited to the period between these dates.

The successfully unwrapped differential interferograms still exhibit a wide range of phase values from -10 to +30 radians. This phenomenon is attributed to the relative nature of the unwrapped phase and can be corrected by scaling phase values. A common area, which is non-deformed and consistently coherent in all interferograms, is defined by examining coherence maps that are enlarged into the red box in Figure 21. The selected coherent area is delineated by the black polygon and labeled as ‘High_cc’ on the coherence maps in Figure 22.
Figure 21. Unwrapped differential interferograms in radians at the CO$_2$-EOR site.
Figure 22. Coherence maps zoomed into the red box in Figure 21 and the highly coherent region labeled as ‘High_CC’
The unwrapped interferometric phase needs to be scaled with respect to a coherent region labeled as ‘High_CC’ in Figure 22 where the phase signals are regarded as remaining reliable throughout all interferograms over time. The mean phase values computed using pixels only within a coherent region serve as reference phases for each differential interferogram. The mean phase values are simply subtracted from individual unwrapped differential interferograms at all pixel positions, resulting in unwrapped phase values falling within similar phase intervals. It is assumed that the reference phase is not affected by surface deformation, unexpected factors and considerable phase noise.

For a more detailed examination, the unwrapped and scaled differential interferograms are enlarged into the red box in Figure 19, where CO₂-EOR is in operation during the period considered in this study and displayed in Figure 23. The differential interferograms in Figure 23 show smoothly varying phase values with the nearly same phase ranges, although the phase corruption that is locally displayed as transparent is still observed for some regions.

The differential interferometric phases shown in Figure 23 are converted to vertical surface displacements in centimetres as presented in Figure 24. The mapped area has oil production operations using the CO₂-EOR method during the whole time span that the surface deformation maps cover (i.e., 2002/01/17 – 2004/09/23). The overall surface deformation appears to be around zero, as indicated by greenish colour in surface deformation maps (Figure 24), although some regions locally present abrupt phase variations, possibly due to various error sources, such as phase unwrapping error or undesired phase contributions (e.g., atmospheric effects).
Figure 23. Unwrapped and scaled differential interferograms superimposed on ERS-2 SAR intensity image for the CO₂-EOR site
Figure 24. Vertical surface deformation maps superimposed on ERS-2 SAR intensity image for the CO$_2$-EOR site.
The abrupt changes in interferometric phase and surface elevation observed in Figures 23 and 24 are mostly found where the majority of pixels are previously masked out prior to phase unwrapping implementation, due to their extremely low coherence. According to the visual presentation of surface deformations in Figure 24, the radar interferometric decorrelation becomes greater for longer temporal separations or different seasons of the SAR acquisition dates. The phase signals at crop fields or vegetated areas are also corrupted, because the relatively shorter wavelength of the C-band SAR signals is more sensitive to canopy disturbances and scatterer changes, possibly resulting from cultivation, seasonal growth or decrease of certain vegetation types in study area, than the L-band SAR signals (Henderson and Lewis, 1998; Strozzi et al., 2005; Sahu, 2008). The phase unwrapping error occasionally occurs when the connections of neighbouring pixels are not properly established, due to null values assigned on masked pixel positions.

Another source of unexpected phase variations could be atmospheric inhomogeneity. The 2003/08/02 – 2003/09/06 pair in Figure 23, for example, exhibits gradual phase variations represented as a yellowish colour along the river that potentially influences atmospheric conditions at the time of SAR data acquisition. The constant phase variation along the river is, however, not observed in other differential interferograms with overlapped temporal coverage (e.g., 2002/11/30 – 2003/10/11 or 2003/07/31 – 2004/09/23 pairs). A similar phase variation randomly appears in several surface deformation maps over a comparably large area, but seems to not have been temporally correlated, leading to the conclusion that the observed phase variation could be contributed by atmospheric condition that randomly changes at each SAR data
acquisition date. Excluding those affected areas, the overall phase rarely changes throughout all of the surface deformation maps without showing clear evidence of vertical surface displacements that are typically represented by a sequence of fringes in radar interferometry.

InSAR-driven surface displacements, the variations of which fall within a 95 % confidence interval, are taken based on the 3-sigma rule in order to remove outliers. The SAR data acquisition date and the duration that each interferometric pair covers are presented with the mean and standard deviation (STD) of the surface deformation measurements within a 95 % confidence interval in Figure 25. For further investigation into the surface deformation measurements that are pruned out for outlier removal, a profile line passing through the CO₂-EOR site with a length of 12 km is defined and shown as the red line on the ERS-2 SAR intensity image in Figure 26. The surface displacements that preserve high coherence and fall within two standard deviations from the mean are taken along a profile line and plotted in Figure 27. The longest and shortest durations that the surface deformation maps cover, are 429 days and 35 days.

The overall trend of surface deformations shown in Figure 27 tends to stay around the zero deformation level with a standard deviation of far less than ±0.1 cm in all cases, as presented in Figure 25. DInSAR results show that the surface elevation at the CO₂-EOR site appears not to be significantly affected by vertical surface deformation from 2002 to 2004; therefore, no further processes for more detailed surface deformation analysis or phase noise minimization are considered in this study. It is concluded that no significant surface displacements take place between January 2002 and September 2004.
Figure 25. Duration with the mean and standard deviation of surface displacements within a 95% confidence interval.

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<td>35 days</td>
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<td>0.005 cm</td>
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Figure 26. Horizontal profile line on ERS-2 SAR intensity image.
Figure 27. Vertical surface displacements along the profile line in Figure 26
5.1.2 Cyclic Steam Stimulation (CSS) Site

5.1.2.1 Interferometric Pair Selection

A total of 14 ALOS-1 PALSAR data in SLC format with HH polarization are used for the radar interferometric analysis for the CSS site. The SAR data acquisition dates and polarization information of the acquired ALOS-1 PALSAR data over the CSS site are summarized in Table 6. The signal frequency of ALOS-1 PALSAR is L-band with the radar wavelength of 23.5 cm, which is much longer signal than the ERS-2 SAR signal (C-band with the radar wavelength of 5.6 cm). Hence, the coherence of ALOS-1 PALSAR signal is typically less sensitive to scatterers on the ground, as the L-band signals penetrate the top layer of vegetation canopies. The use of ALOS-1 PALSAR data for InSAR application is, therefore, expected to yield more coherent interferograms, especially for the CSS site, where dense vegetation and forest are predominant over the entire area.

Due to the small stack of ALOS-1 SAR data acquired over the CSS site, every possible radar interferometric pair is considered, and all physically interpretable differential interferograms are selected by a later coherence investigation. The details of 30 interferometric pairs exhibiting relatively high interferometric coherence are summarized in Table 7, with the acquisition time interval, baseline and Doppler centroid separations for each pair. The SAR acquisition time interval ranges from 42 days to 1,242 days, which approximately corresponds to 3.4 years; and, the perpendicular baseline ranges from -3,755.8 m to 3,035.4 m as shown in Table 7.
**Table 6. ALOS-1 PALSAR data for the CSS site**

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5.1.2.2 Radar Interferograms

All 30 differential interferograms are formed by eliminating the topographic phase from the interferograms. The phase unwrapping and geocoding are then applied, resulting in unwrapped differential interferograms that are overlaid on ALOS-1 PALSAR intensity image and displayed in Figure 28. Only the pixels that occur in high coherence are included in the phase unwrapping process, in order to exclude noise affected pixels that hypothetically have a negative impact on phase unwrapping performance. These differential interferograms are not yet phase adjusted, as the phase correction is performed as a step in the time-series analysis presented in following Section 5.2.

Although the differential interferometric phases shown in Figure 28 are still relative to each other, showing individual phase ranges, noticeable phase variations constantly appear over the entire imaged area. The changes in the differential interferometric phases are mostly observed around either the northern or southern parts of the imaged area. Since these distinct phase changes at the same locations are detected in all of the consecutive differential interferograms, this phenomenon can be regarded as resulting not from other phase error sources, but from surface deformations.

The deformed region situated in the northern central area with approximate dimensions of 14 km × 23 km is specifically chosen for more precise investigations, including the analysis for the temporal evolution of detected surface displacements. The selected site bounded by the red box in Figure 28 appears not to be significantly influenced by undesirable phase errors due to, for example, phase unwrapping error, decorrelations or local atmospheric effects.
Figure 28. Unwrapped differential interferograms for the CSS site
Figure 28. Continued. Unwrapped differential interferograms for the CSS site
The spatial boundary of the SAR data used in this study encompasses the Cold Lake oil sands area, in which several oil production projects have been ongoing using various types of oil recovery methods. The physical locations of Cold Lake oil sands operations as of 2006 (modified from Cizek, 2008) are displayed with a differential interferogram covering the period between 2007/07/09 and 2007/08/24 superimposed on the ALOS-1 PALSAR intensity image in Figure 29. The red box in Figure 29 indicates the approximate location of the CSS site chosen in this study. The comparison with a differential interferogram with the Cold Lake oil sands operation map supports that the selected region belongs to CNRL’s Primrose CSS project area. The detailed analyses for monitoring the surface displacements at CNRL’s Primrose CSS project area are described in Section 5.2.

Figure 29. Differential interferogram overlaid on ALOS-1 PALSAR intensity image (left) and Cold Lake oil sands operation map (right) (modified from Cizek, 2008)
5.2 Time-series Analysis of Surface Deformation

The temporal evolution of surface deformation can be examined by applying PSInSAR or SBAS algorithm. PSInSAR requires the generation of interferograms with respect to common SAR data (i.e., master image). This often leads to spatial decorrelation caused by a long baseline of interferometric pairs. Furthermore, the number of targets with high coherence at a long baseline becomes fewer in non-urban areas (Berardino et al., 2002). It is recommended that spatially dense PSs and more than 25 SAR data should be used for a reliable PS analysis (Colesanti et al., 2003). Unfortunately, our study areas are mostly covered by heavy vegetation without noticeably large urban areas; and, the total number of SAR datasets acquired over the CSS site is far fewer than 25. Therefore, the SBAS algorithm is implemented using differential interferograms that are cropped onto the CSS site for the temporal analysis of surface displacements. Two important improvements, in terms of increasing the temporal sampling rate by using all SAR data and providing spatially dense deformation maps, are achieved by the SBAS.

In order to define SB subsets, the temporal separation and mutual perpendicular baseline of each interferometric combination listed in Table 7 are graphically plotted and presented in Figure 30. Since only highly coherent interferograms are selected among all possible interferometric pairs by analyzing the coherence and visual interpretability, the maximum perpendicular baseline and temporal separation including all selected interferometric pairs are considered with the assumption that spatial and temporal decorrelations are rarely involved in these pairs. It is shown that all of the interferometric pairs fall along a single SB subset as depicted with dashed lines in Figure 30.
Since the unwrapped differential interferometric phases are relative to an arbitrary reference pixel, all point-wise phase values should be scaled with respect to a common area assumed to be non-deformed and coherent over time. The commonly appearing coherent area is determined by examining coherence maps that are enlarged into the area indicated by the red box in Figures 28 and 29 and displayed in Figure 31. The detailed procedure for scaling relative interferometric phases is already explained in subsection 5.1.1.1. A non-deformed and coherent area appearing in all differential interferograms is defined, and the mean phase within a coherent area is subtracted from phase values. Consequently, unwrapped and phase scaled differential interferograms, which are zoomed into CNRL’s Primrose area indicated by the red box in Figures 28 and 29 and displayed in Figure 32, are used for the SBAS algorithm and subsurface modeling.

Figure 30. Temporal separation and mutual perpendicular baseline of interferometric pairs for the CSS site
Figure 31. The coherence maps enlarged into the CSS site
Figure 31. Continued. The coherence maps enlarged into the CSS site
The SBAS algorithm supports the determination of the linear phase component, which needs to be removed from input datasets, resulting in the phase reduction of the original differential interferograms. However, the observed phase variations over CNRL’s Primrose area in Figure 32 present non-linear surface deformation with the time-varying deformation rates in both increasing and decreasing LOS directions, without showing commonly appearing linear deformation trends. The elimination of linear deformation phase estimated by the conventional SBAS algorithm from differential interferograms in this study instead yields additional phase errors that are mostly
attributed to subtracting the linear approximation of surface deformation trend from the non-linearly deformed points. Therefore, the application of linear phase model subtraction seems to be unworkable for the LP components of the atmospheric effect and topographic error in this case.

However, the amount of unwanted phases contributed by atmospheric effect and phase noise can be presumed to be significantly less than those of the surface deformation phases, since the most coherent differential interferograms without severe phase corruptions caused by phase contributions other than surface deformations are being used for all processing steps. Furthermore, the relatively even topography at the CSS site is supposed not to have caused considerable atmospheric artifacts, which are locally rendered along with topographic aspects in most cases.

As stated in many published works regarding radar interferometry applications (Casu, 2009; Forster, 2012; Wang et al., 2014), pixels exhibiting coherence above a certain threshold – 0.85 in this study – are first chosen for temporal analysis. The time-series analysis part of the SBAS algorithm is directly applied to infer the temporal evolution of the detected surface deformations. Given the single SB subset used for this study, the estimation of surface deformation at each SAR data acquisition date from the input differential interferograms does not involve the rank deficiency problem in the linear inversion process. The surface deformation rates (cm/day) at points preserving sufficiently high coherence above 0.85 are estimated by the implementation of the SBAS algorithm. The pixels with low coherence are filtered out and simply filled by an interpolation to obtain 2D surface deformation measurements.
Figure 32. Unwrapped and scaled differential interferograms for the CSS site
Figure 32. Continued. Unwrapped and scaled differential interferograms for the CSS site
SBAS-derived surface deformation rates are spatially LP filtered by the built-in function of MATLAB® using 2D digital filtering windows as large as or slightly bigger than 1 km × 1 km, based on the fact that atmospheric perturbations are regarded as low-frequency signals, due to the spatial correlation distance of 1 km (Hanssen, 1998). The spatially LP filtered maps of surface deformation rate presented in Figure 33 indicate the daily deformation velocities between the acquisition dates of two time-adjacent SAR data. It is observed that the CSS site experiences vertical surface deformation rates that locally vary in upward and downward directions. The maximum heave and subsidence rates are approximately +0.8 cm/day and -0.3 cm/day with a standard deviation of 0.01 cm/day. The spatial patterns of surface deformation rate appear to be inconsistent, and considerably change over time. An interesting observation from two last maps in Figure 33 is that the direction of surface displacements is completely altered in just 3 months.

In addition, daily rates of vertical surface deformation are processed to obtain the amount of surface displacements accumulated since the first SAR data acquisition date (i.e., July 09, 2009). The surface deformation velocities are multiplied by the number of days counted from the first SAR data acquisition date; and, the resulting surface deformation maps, which are arranged in ascending time order in Figure 34, enables the examination of the extent and location of the cumulative surface displacements monitored at each SAR data acquisition date. The entire time span (i.e., 2007/07/09 – 2011/03/04) covers roughly 3.7 years from the very first SAR data acquisition date. The rounded maximum surface heave and subsidence during the period of 3.7 years are +72 cm and -33 cm, respectively, with an approximate standard deviation of 1 cm.
Figure 33. Surface deformation rate between the acquisition dates of two time-adjacent SAR data
Figure 34. Cumulative surface deformation maps at each SAR data acquisition date
As the surface deformation rates change at the individually deformed areas over time, the accumulated amount of surface deformations demonstrates locally varying patterns of either land settlement or heave. It can be seen from Figure 34 that the northwest part of the CSS site consistently experiences surface heave since August 2007; and, the southwest region also develops surface heave since August 2009, consistently showing a similar shape of spatial coverage. After mid-2010, the ground surface at the slightly east of the central CSS site moves along the upward direction. In particular, the surface heave observed at the bottom of the CSS site from February and October in 2008 shows an interesting spatial pattern of surface displacements horizontally elongated over distance of 8 km and then gradually fades away afterwards.

Surface subsidence is also obvious on the east and west of the central CSS site. Two subsiding zones are presented in a deep blue colour on the cumulative deformation maps from August 2007 to June 2010. However, the surface subsidence at the west central area is interrupted by newly evolving land uplift since August 2009; and, the overall surface deformation at this location begins to be mixed up with presence of two different types of surface displacements. Another subsidence in the east central area is also disturbed by a surface heave phenomenon appearing since 2010, resulting in the land settlement disappearing. The active progress of the rising surface elevation, which becomes the area with the most heave, is continuous till the last date of entire time span (i.e., March 4, 2011).

It is evident from the visual interpretation of the cumulative surface deformation maps that the surface displacements at the CSS occur with non-linearly changing surface
deformation rates over time. This finding supports that the application of the SBAS algorithm is not fully viable, as the removal of the linear phase terms becomes difficult, due to the non-linearity of surface displacement rates in this case.

For better visual interpretation, six InSAR-derived surface deformation maps that are 6 – 8 months apart from each other since August 2007 are displayed in the 3D domain by superimposition on Landsat-5 TM satellite imagery taken on September 13, 2011, as shown in Figure 35. It can be seen from Landsat-5 TM imagery that the CSS site encompasses access roads and well pads, which include horizontal wells for the injection and production of fluids. Note that the surface deformation values in Figure 35 are exaggerated, because the ranges of surface displacements are relatively too small to be efficiently expressed. The comparison of the locations affected by surface deformation with well pad deployments confirms that the observed surface displacements are most likely correlated with human activities at the CSS site.

An interesting finding is that oil production at CNRL’s Primrose project area does not cause the significant changes in surface elevation around the south central and southwest regions, where the oil facilities are narrowly distributed, but causes more surface displacements in the central areas that encompass sparsely distributed facilities and in the southeastern area mainly covered by vegetation. More detailed information on the oil recovery at CNRL’s Primrose CSS project area can contribute to understanding the actual mechanisms of the measured surface deformations and subsurface behaviours at the reservoir level.
Figure 35. 3D presentation of accumulated surface deformations at the CSS site
Figure 35. Continued. 3D presentation of accumulated surface deformations at the CSS site.
The surface displacements at specific geographical points are plotted for the time-series analyses. Temporal evolution of the surface deformations at selected pixels is presented in Figure 36. The locations of these pixels are displayed on a cumulative surface deformation map of March 2011, which is overlaid on Landsat-5 TM imagery, with the geographical coordinates of all selected points in Figure 37. The time-series analysis at these pixels determines that the ground surface elevation locally changes with the non-linear surface deformation rates that significantly vary over time.

Some areas are affected by surface displacements that finish around a zero deformation level as shown, for example, in the graphs of P4, P7, P8, P11, P13 and P16 in Figure 36. Other regions remain less deformed (e.g., P2) or experience unrecovered surface displacements (e.g., P1, P3, P5, P6, P9, P10, P12 and P14 – P16) for 3.7 years. The surface deformation that occurs after 2010 at P3 and P5 reaches the total amount of +70 cm only for about a year. It is determined from time-series analyses that the surface deformation rates at the CSS site tend to vary with specific time and location.

It can, therefore, be concluded that both land uplift and settlement occur simultaneously, even in the same regions; and, these events correspondingly induce considerable surface elevation changes at CNRL’s Primrose project area for approximately 3.7 years. It may be possible to relate oil recovery activities, such as steam injection, fluid extraction or groundwater withdrawal, with the temporal and spatial patterns of ground surface deformation that is remotely measured by radar interferometric techniques in this study. Thus, further information on oil recovery operations during the same period is expected to contribute to the determination of geomechanical relationships.
Figure 36. Time-series analyses of surface deformation at selected points
Figure 36. Continued. Time-series analyses of surface deformation at selected points
The unwrapped differential interferograms are simulated by means of forward modeling to analyze the residuals between the SBAS- and DInSAR-based differential interferometric phases. The estimated residuals indicate errors that are associated with the inversion process in the SBAS algorithm (e.g., SVD-based inversion). All 14 maps of SBAS-based cumulative surface deformations at each SAR data acquisition date are first converted back to phase values in radians. The unwrapped differential interferograms are then simulated using phases converted from the cumulative surface deformation maps by referring to the date combinations of the individual interferometric pairs. The simulated differential interferograms are compared with original ones that are derived by means of conventional DInSAR.
The residual phases can be readily computed by subtracting the original differential interferometric phases from the simulated ones pixel by pixel. For the quantification of the error related to the inversion process of the SBAS algorithm, the traditional root mean square error (RMSE) is calculated using (Khakim et al., 2012):

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2}
\]  

(54)

where \( P_i \) is the modeled value (i.e., forward modeled interferometric phases by the SBAS algorithm), and \( O_i \) is the observed value (i.e., original interferometric phases by DInSAR). The residual phases in radians for all interferometric pairs are represented in Figure 38. The RMSE at individual pixel positions is averaged to compute the mean RMSE of each interferometric pair and the mean RMSE is listed in Table 8.

The relatively higher residuals are consistently found at several locations in Figure 38. The high residuals can be interpreted as the SBAS-derived phase that is contaminated, possibly due to either the quality of original differential interferograms or the LP filtered surface deformation rates. The residual phases of the remaining interferometric pairs, however, appear to remain around zero radians, as presented in greenish colour in Figure 38. It is concluded from the residual phases shown in Figure 38 and the mean RMSE in Table 8 that the inversion process in the SBAS algorithm yields non-significant errors in surface deformation phases in this study.
Figure 38. Residuals of interferometric phase simulated by forward modeling
Figure 3.8. Continued. Residuals of interferometric phase simulated by forward modeling.
Table 8. Mean RMSE of interferometric pairs for the CSS site

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<td>2010/06/01</td>
</tr>
<tr>
<td>2007/08/24</td>
<td>2010/07/17</td>
<td>0.0098</td>
<td>2010/07/17</td>
</tr>
<tr>
<td>2007/08/24</td>
<td>2010/09/01</td>
<td>0.0181</td>
<td>2010/07/17</td>
</tr>
<tr>
<td>2007/08/24</td>
<td>2010/10/17</td>
<td>0.0236</td>
<td>2010/07/17</td>
</tr>
<tr>
<td>2008/02/24</td>
<td>2011/01/17</td>
<td>0.0220</td>
<td>2010/09/01</td>
</tr>
<tr>
<td>2008/10/11</td>
<td>2009/08/29</td>
<td>0.0063</td>
<td>2010/09/01</td>
</tr>
<tr>
<td>2009/08/29</td>
<td>2010/06/01</td>
<td>0.0029</td>
<td>2010/10/17</td>
</tr>
<tr>
<td>2009/08/29</td>
<td>2010/07/17</td>
<td>0.0077</td>
<td>2010/12/02</td>
</tr>
<tr>
<td>2009/08/29</td>
<td>2010/09/01</td>
<td>0.0024</td>
<td>2011/01/17</td>
</tr>
</tbody>
</table>
5.3 Modeling Volumetric Changes in Subsurface

InSAR-derived surface deformation is inverted for the modeling of subsurface volumetric changes as introduced in Section 4.3. Prior to applying the geomechanical inversion, the overburden at the CSS site is assumed to be isotropic and homogeneous in a half-space and to behave poroelastically over the period of interest. The relationship between the subsurface and surface deformations is, therefore, considered a linear system as formulated in Eq. (46).

In general, detailed production- and reservoir-related parameters are rarely available to the public, and information on specific oil fields is very limited. However, the inversion of the surface deformation measurements has been an appropriate method for analyzing underground processes when accurate parameters, such as compressibility of reservoir rock or well data are not obtainable (Marchina, 1996).

Six maps of cumulative surface deformation that are approximately 6 – 8 months apart from each other since August 2007 are selected. For computational efficiency, the six surface deformation maps are further averaged by moving a window, yielding a reduction in the total number of pixels. The whole volume of the reservoir is then subdivided into a finite number of non-overlapping reservoir blocks in a single layer with a reservoir thickness of 50 m. Each reservoir block covers approximately 500 m × 400 m. The size and number of grid blocks, as well as the shape of the block-containing subsurface layer at depth, are determined by considering the aforementioned principles and computational efficiency.
The calculation of subsurface volumetric changes is performed using Eq. (45), which requires the use of InSAR-derived surface deformation measurements and basic reservoir parameters such as Poisson’s ratio, Skempton’s pore pressure coefficient and fluid density. The necessary parameters for defining an oil reservoir system at the CSS site are collected from available publications (Macrides and Kanasewish, 1987; Canadian Natural, 2008; Wong and Lau, 2008; Nanayakkara and Wong, 2009).

The reservoir depth and thickness are necessary for subsurface system generation and data kernel integration. The depth of the oil sands reservoir, which belongs to the Clearwater Formation, is approximately 450 m deep; and, the reservoir thickness in the Primrose CSS project area is about 50 m (Canadian Natural, 2008; Teatini et al., 2011). The physical properties of hypothetical reservoir used for subsurface modeling are summarized in Table 9.

Table 9. Physical properties of hypothetical reservoir used for subsurface modeling

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir depth</td>
<td>450 m</td>
</tr>
<tr>
<td>Reservoir thickness</td>
<td>50 m</td>
</tr>
<tr>
<td>Skempton’s pore pressure coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Fluid density</td>
<td>1,040 kg/m³</td>
</tr>
</tbody>
</table>

The inversion process begins with building the coefficient matrix (i.e., data kernel) given by Green’s function for an elastic half-space, often called a point source response function (Vasco et al., 1998). A simple isotropic, homogenous and poroelastic reservoir in a half-space is considered in this study, since theoretical models on the basis
of these assumptions have been verified to be good approximations of real cases (Okada, 1985). The coefficient matrix relates the surface deformation observed by the SBAS algorithm to the volumetric change in the reservoir located at 450 m deep at the CCS site. Data kernels should be generated for all of surface deformation measurement points by considering the location of a specific surface observation point and the entire subsurface blocks at the reservoir level. As explained in Chapter 4, the integration of each point source response function for discretized reservoir blocks over the entire reservoir volume is, in principle, required to estimate the total volumetric changes in the subsurface.

After constructing a coefficient matrix for the surface points, the inversion using the Tikhonov regularization technique, and sparse linear equations and least squares (LSQR) built in MATLAB® is applied to InSAR-derived surface deformation measurements, in order to estimate the fractional volumetric changes in the subsurface for each SAR data acquisition date. For an appropriate selection of regularization parameters, the L-curve, which is a trade-off curve of the smoothing and residual norms presented in a log-log scale, is generated using the coefficient matrix (Figure 39).

The regularization parameters for all six cases are chosen by taking the distinct Tikhonov corner of the L-curves, as shown in Figure 39. The regularization parameter is used to construct the filtering term explained in subsection 4.3.3. The filtering term is applied to find more optimized inversion solutions. The regularized solution of the reservoir volumetric changes is approximated from InSAR-derived surface deformation measurements using the geomechanical inversion with the Tikhonov regularization and LSQR methods.
Figure 39. L-curves and regularization parameters selected at the Tikhonov corner
The fractional volumetric changes in the subsurface that are estimated using the regularization parameters chosen from the L-curves are further scaled into percentages for better interpretation. The maximum increase and decrease of subsurface volume with respect to its initial state at six different dates are determined, as listed in Table 10, with the relative residuals at the LSQR convergence for each inversion case. It is found from Table 10 that the fractional volumetric changes in the subsurface tend to be gradually amplified for 3.7 years.

The fractional volumetric changes in the subsurface at the CSS site are displayed in Figure 40 with contour lines superimposed on Landsat-5 TM imagery. It can be seen from Figure 40 that the fractional volumetric changes in the subsurface in both the upward and downward directions occur simultaneously, particularly around the well pads in white, as expected from the cumulative surface displacements derived by the SBAS algorithm. Since the imaginary subsurface is presumed to have the same spatial coverage with the surface deformation map, the location of subsurface movements agrees with it of surface displacements.

Table 10. The maximum volumetric increase and decrease in the subsurface with LSQR residuals

<table>
<thead>
<tr>
<th>Date</th>
<th>Volumetric Increase (%)</th>
<th>Volumetric Decrease (%)</th>
<th>LSQR Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007/08/24</td>
<td>+1.174</td>
<td>-0.768</td>
<td>0.0140</td>
</tr>
<tr>
<td>2008/02/24</td>
<td>+1.835</td>
<td>-1.707</td>
<td>0.0150</td>
</tr>
<tr>
<td>2009/08/29</td>
<td>+1.706</td>
<td>-1.565</td>
<td>0.0082</td>
</tr>
<tr>
<td>2010/03/01</td>
<td>+2.425</td>
<td>-1.629</td>
<td>0.0054</td>
</tr>
<tr>
<td>2010/09/01</td>
<td>+2.478</td>
<td>-1.750</td>
<td>0.0050</td>
</tr>
<tr>
<td>2011/03/04</td>
<td>+3.900</td>
<td>-1.836</td>
<td>0.0140</td>
</tr>
</tbody>
</table>
Figure 40. Subsurface volumetric changes overlaid on Landsat-5 TM imagery
The extent of the fractional volumetric changes at the reservoir level ranges from -1.836 % to +3.900 %, and the maximum changes are observed on the most recent SAR data acquisition date (e.g., March 4, 2011). The rate of fractional volumetric variations in the subsurface appears to be temporally inconsistent, but rather changes randomly over time. The local changes in the subsurface volume may be associated with individual CSS operations, such as the steam injection, soaking and production stages for each CSS cycle. The derived subsurface volumetric changes and corresponding surface displacements need to be further investigated with production-related information in order to find the geomechanical relationship among them.

5.4 Interpretation

The fractional volumetric changes of the oil sands reservoir and corresponding variations in surface elevation are detected through the application of well-established radar interferometric techniques (i.e., DInSAR and SBAS algorithm) and subsurface modeling by geomechanical inversion, as previously described. The study results provide information on the temporal variations in the surface elevation and subsurface volume during the period between July 2007 and March 2011; therefore, an analysis of geomechanical responses to the CSS operations at the surface and reservoir levels becomes possible. The detailed interpretation of the obtained results with information on the CSS operations is provided in this section by referring to CNRL’s annual presentations (Canadian Natural, 2008, 2009, 2011, 2012), which are currently available
to the public and also downloadable from the Alberta Energy Regulator (AER) website (www.aer.ca).

Prior to the interpretations of the study results, general information on CNRL’s Primrose CSS project should be reviewed for a better understanding of overall oil recovery activities. CNRL’s oil sands projects in the Cold Lake area have been operated in three major regions: Primrose North, Primrose South and Primrose East. The CSS site selected in this study is located in the Primrose North and covers a small part of the Primrose South region. The spatial distribution of CNRL’s oil sands project regions in the Cold Lake oil sands is displayed with the average steaming rate (barrel/day) and the steaming initiation dates for each project in Figure 41 (modified from Jocksch, 2012). The dashed red line indicates the approximate boundary of the selected CSS site. Note that Figure 41 covers only the southern part of the CSS site chosen in this study.

![Figure 41. Distribution of CNRL’s Primrose project region (modified from Jocksch, 2012)](image-url)
CNRL reports that the Primrose North project started in November 2005 and that the project region is subdivided into several areas that include different phase groups. The phase group reference map of Primrose North is provided by CNRL and displayed in Figure 42 (Canadian Natural, 2008). The phase group reference map shows the locations of individual phases (PH 1 to PH 55) and phase groups (AREA 1 to AREA 7) with the horizontal wells that are used for fluid injection/production and represented by thin black lines in Figure 42. Since 2010, Area 8 has been further developed, as discussed in Section 5.4.3 and is shown in Figure 51.

The steam injection at high pressure during CSS operations induces fracturing of the reservoir at Primrose project area, indicated by subsurface pressure changes. CNRL’s annual presentations also state that the extensive areal and vertical dilations at depth are confirmed by extensometer readings (Canadian Natural, 2008). The overall CSS operations at Primrose project area can be categorized into three stages: 1) steaming, 2) flow back, and 3) pumping, according to CNRL’s annual presentations. Therefore, vertical displacements of the ground surface could be expected to differ with each CSS operation stage, due to the corresponding pressure changes in the subsurface.

Since production-related information is available yearly from CNRL’s annual presentations, comparisons and analyses of the retrieved study results with the physical facts about oil recovery activities taken from CNRL’s presentations are carried out for each year from 2007 to 2011. The average steam injection rates (m$^3$/day) at each phase location are available from the well pad plots provided by CNRL, which represent the production and injection rates of fluid as well as the steam-to-oil ratio (SOR).
Figure 42. Phase reference map of CNRL’s Primrose project as of 2008 (Canadian Natural, 2008)
Since the steam injection rates, which are obtained from the well pad plots in appendix section of CNRL’s annual presentations, are not available in numerical format, but in pictorial plots, graphs of average steam injection rates at each phase location are reproduced by referring to CNRL’s annual presentations. These graphs of steam injection rates provide approximate trends of streaming operations at the phase locations on a monthly basis.

The CSS site is split into three deformed zones according to the spatial pattern of surface displacements that are detected from SBAS algorithm for more convenient interpretation. The three surface deformation zones are marked with the red boxes on the Landsat-5 TM imagery as shown in Figure 43. The phase numbers that geographically belong to each deformed zone that is predefined in this study are taken from the phase group reference map displayed in Figure 42. The corresponding phase numbers are listed in Table 11, in order to match the area, in which the ground surface is displaced during the period between 2007 and 2011, with the well pad distributions at CNRL’s Primrose North project area.
Figure 43. Three deformed zones superimposed on Landsat-5 TM imagery

<table>
<thead>
<tr>
<th>Zone No.</th>
<th>Phase No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone #1</td>
<td>12, 13, 14, 51, 52, 53, 54, 55</td>
</tr>
<tr>
<td>Zone #2</td>
<td>29, 30, 31 (28, 59, 62 and 66 are added in 2010)</td>
</tr>
<tr>
<td>Zone #3</td>
<td>1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 21, 27, 28</td>
</tr>
</tbody>
</table>
5.4.1 Surface Displacements for 2007 – 2008

All three maps of the accumulated surface deformation for the period between August 2007 and October 2008 are presented in Figure 44, with the approximate locations of the three deformed zones indicated by the red boxes. These three maps are approximately 6 – 8 months apart from each other. Interestingly, the surface deformation seems to occur in all of three deformed zones. It can be seen from Figure 44 that land settlement and uplift simultaneously take place in all deformed zones during the given period.

The unique patterns of surface response to steam injection operations at the CSS site are interpreted by matching the steam injection history between 2007 and 2008, as shown in Figures 45 and 46. The interrelationship between vertical surface deformations observed by InSAR techniques and steaming operations at the CSS site are explained for each zone in following subsections.

![Figure 44. Cumulative surface deformation between August 2007 and October 2008](image)
• Zone #1

The observed surface heave tends to grow further north, while the amount of subsidence becomes larger in the southern part of zone #1. For a more detailed analysis of the interrelationship between steam injection and the resulting surface displacements, the average rate of monthly steam injection for zone #1, which includes phases 51 to 55, from January 2007 to December 2008 is considered and shown in Figure 45.

The steaming operations for phase 51 in zone #1 are temporarily terminated in May 2007, for phase 52 in August 2007, for phase 53 in October 2007, for phase 54 in November 2007 and for phase 55 in April 2008, as shown in Figure 45. The steam injection does not occur again for phases 51 and 52 until the end of 2008; however, next steaming operations for phases 53 to 55 commence in February, May and September 2008, respectively.

It is evident that the steam injection migrates from the south (phase 51) to the north (phase 54) in 2007 as represented in Figure 45; and, this observation agrees with the typical steaming strategy for the Cold Lake oil sands areas. The southern part of zone #1 surrounding phases 51 and 52, where steam injection is no longer active since May and August 2007, respectively, enters the production stage, causing surface subsidence (blue coloured at zone #1 in Figure 44) as expected. In contrast, the phase 53 and 54 locations, which keep undergoing active steam injection until late 2008, still develop reservoir dilation, inducing the ground surface moving upward in 2007 and 2008, as seen in Figure 44.
Figure 45. Steam injection rate at phases in zone #1 between 2007 and 2008
Moreover, the ground surface heaving at the far north of zone #1 may be related to steam injection activities at phase 55 in 2007 and 2008. It can be noticed from the last graph in Figure 45 that steam injection for phase 55 is active during the periods of September 2007 to April 2008 and August 2008 through the end of 2008. The distinctive steam injection causes the development of land uplift at the phase 55 location, as shown in surface deformation maps of 2008/02/24 and 2008/10/11 (Figure 44).

Overall, the repetitive steam injection process coincides with the spatial pattern of observed surface deformations that occur in the period between 2007 and 2008, confirming that steaming and production operations in zone #1 proceed along a line of well pads expanding toward north.

- Zone #2

Surface subsidence is mainly observed in zone #2 during the same period. Steaming is active in all three phases of zone #2 (i.e., phases 29 to 31) until July 2007; and, another injection begins in December 2008 at only the phase 30 location (Figure 46).
As the amount of injected steam in zone #2 declines and finally becomes zero before the date for which the first surface deformation is mapped (i.e., 2007/08/24), ground surface subsidence may be a result of all phases being in the production stage in zone #2.

- Zone #3

The observed surface heave in zone #3 is interpreted with CNRL’s steam injection schedules stated in their annual presentation of 2008 (Table 12). Zone #3 includes phases 5 to 7, 18 to 20, 27 and 28, which are undergoing steam injection activities in 2008 according to Table 12. These targeted phases are located west to east of the southern part of Primrose project area, as seen in Figures 42.

The steam injection into the wells deployed in these phases likely causes the horizontally elongated shape of surface heave, once the steaming starts. Therefore, the corresponding upward displacements at the surface level are related to the steam injection activity that newly commences in 2008, as is visible in the south of the surface deformation maps of 2008/02/4 and 2008/10/11. The surface heave and subsidence observed in the east of zone #3 appear first, as phase 28 is already in the first cycle of steam injection in 2007, according to CNRL’s annual presentation for 2007. The ground surface at phase 28 location is more heaved, since another steaming operation begins in February 2008.

New steaming operations that start in January 2008 over phases 5, 18 and 27 develop horizontally distributed surface displacements along these phase locations. The steam injection at phases 6, 7, 19 and 20 in May and October 2008 amplifies surface
heave that already occurs in the west to east of zone #3. Therefore, the land uplift starts from phase 28 and continues to expand west across the horizontally distributed phases, because the steaming is performed in the locations of phases 5 to 7, 18 to 20, and 27, as scheduled in 2008.

Figure 46. Steam injection rate at phases in zone #2 between 2006 and 2008
Table 12. Steam injection schedule in 2008 at zone #3

<table>
<thead>
<tr>
<th>Scheduled Date</th>
<th>Phase No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>January, 2008</td>
<td>5, 18, 27</td>
</tr>
<tr>
<td>February, 2008</td>
<td>28</td>
</tr>
<tr>
<td>May, 2008</td>
<td>6, 19</td>
</tr>
<tr>
<td>October, 2008</td>
<td>7, 20</td>
</tr>
</tbody>
</table>

5.4.2 Surface Displacements for 2009 – 2010

Three maps of the accumulated surface deformation between 2009 and 2010 are chosen for comparison and are displayed in Figure 47, with the approximate locations of the three deformed zones indicated by the red boxes. The steam injection graphs for each zone are created and shown in Figures 48 to 50. The entire period of steaming history spans from January 2009 to September 2010, which includes the dates of selected surface deformation maps (i.e., August 2009 to June 2010).

Figure 47. Cumulative surface deformation between August 2009 and June 2010
• Zone #1

The ground surface moves in both vertical directions between 2009 and 2010 in zone #1. The steaming operations at the phase 51 location initially start in February 2009 and are terminated 6 months later, and no more steaming operations begin until September 2010, as presented in Figure 48. The surface heave, which is caused by continuous steam injection until August 2009 at the phase 51 location, can be clearly seen from the surface deformation map in Figure 47.

However, the lack of steam injection after August 2009 is reflected in the surface subsidence in 2010, possibly indicating that phase 51 is brought into the production cycle. This phenomenon is previously observed at phase 51 location between 2007 and 2008 for the same reason. The steaming process for the rest of the phases (52 to 55) continues from May 2009 to September 2010; and, as already observed between 2007 and 2008, the steam injection pattern migrates north. The continuous steam supply into the reservoir is accordingly followed by the surface heave between 2009 and 2010 in zone #1.

Figure 48. Steam injection rate at phases in zone #1 between 2009 and 2010
Figure 48. Continued. Steam injection rate at phases in zone #1 between 2009 and 2010
• Zone #2

The surface subsidence is dominant between August 2009 and the beginning of 2010 in zone #2, as previously observed. The subsidence remains almost constant since August 2007 – approximately 2 years. However, surface displacements in the opposite direction at the north of the main subsidence area observed in March 2010 appear to be mixed with surface subsidence. The surface heave in this location can be related to new steam injection stage that begins in August 2009 at phase 29 (Figure 49). The steam injection at phases 30 and 31, which is active between November 2009 and September 2010, may explain the newly appearing land uplift above the main subsidence area shown in deep blue colour in Figure 47. The ground surface heave, therefore, shifts from the phase 29 location northward over time, as the steaming activities move from the phase 29 (i.e., south) to phase 31 (i.e., north) locations. Given the different steam injection processes at each phase location, the surface reaction to steaming reservoir is mixed, with both the upward and downward displacements as of June 2010.

• Zone #3

Several phases are included in zone #3, and the available steaming information at each phase is plotted in Figure 50. The well pads are densely distributed throughout zone #3, as seen in Figures 42. Only phases 7, 8, 20 and 27 undergo steam injection during the period between early 2009 and September 2009. This unique CSS operation is revealed as a rising surface elevation in zone #3.
The surface heave detected on the east side of zone #3 may be due to steam injection at phase 27 between March and August in 2009. This location experiences the same routine of surface heave and subsidence as monitored in many other phase locations. It is possible to infer that the heaved area around phase 27 location may also be influenced by steam injection at phase 29 in zone #2 later, showing steam injection migration northward. Moreover, the vague surface heave that appears in the middle of
zone #3 can be interpreted as the effect from steam injection at phases 17 and 20, and the remaining trace of steaming operations performed in the previous period of 2007 to 2008. The overall amount of surface heave tends to decrease and more surface subsidence is observed, as no steam injection is performed at all phase locations in zone #3 since August 2009.

**Figure 50. Steam injection rate at phases in zone #3 between 2009 and 2010**
The interpretation of cumulative surface displacements is only possible until the last date of SAR data acquisition (i.e., March 4, 2011 in this study). It should be noted that CNRL develops a new production area further east of Area 6 in 2010, labelled as Area 8; and, several phases (58, 59, 62 and 66) are additionally assigned in Area 8. The updated reference phase map shown in Figure 51 (Canadian Natural, 2011) indicates where these phases are newly added in Area 8.

Three maps of cumulative surface deformation for the period between 2010 and 2011 are selected and presented in Figure 52, with the approximate locations of the three
deformed zones indicated by the red boxes. Since the similar patterns of surface
displacements are consistently detected throughout zones #1 and #3, only observations at
zone #2 are discussed. The steam injection at the phases in Areas 4 and 8 (i.e., phases 29,
30, 58, 62 and 66) are presented in Figure 53.

Figure 51. Updated phase reference map of CNRL’s Primrose project as of 2010
(Canadian Natural, 2011)
The impressive finding from the surface deformation map of October 2010 is that the significant land settlement in zone #2 almost disappears, due to successive expansions of surface heave over time. In addition, the ground surface seems to heave up to its maximum of +72 cm until March 2011. While no steam injection is performed at phases 29 to 31 in Area 4, steam injection is active in additional phases 58, 62 and 66 in newly developed Area 8. The steaming operations at these phases are ongoing, except for a three-month break between June 2010 and August 2010.

Interestingly, the trends of steam injection rate at phases in Area 8 are similar to each other, so that ground surface reactions to the steam injection may be amplified, as represented by a considerable amount of surface heave. This observation supports that more surface displacements are expected for the newer well pads at the CSS site (Stancliffe and van der Kooij, 2001). Therefore, it is possible to predict that the dominant increase in the ground surface elevation in zone #2 may result from the comparably large amount of steam injected into the reservoir in newly developed phases located in Area 8.
Figure 53. Steam injection rate at phases in zone #2 between 2010 and 2011
From the interpretation of InSAR-derived surface deformations with the history of steaming operations, it is evident that non-linear time-varying surface displacements are dependent on the physical operation of steam injection at the Primrose project area. The direction of the vertical surface deformation conforms to different CSS stages, which are generally accompanied by changes in the subsurface volume. Thus, it can be concluded that the surface and subsurface behaviours observed between 2007 and 2011 are mostly associated with the CSS operations, given the good agreement between them.

5.4.4 Deformation Analysis with CSS Operation Data

The temporal relationship between InSAR-driven surface deformation and the volume of steam injection into the reservoir are examined in this section. The linear relationship between surface/subsurface deformations and fluid volume changes in the reservoir is also investigated by means of the linear regression method. Zone #1 is experimentally selected and divided into five phases (i.e., phases 51 to 55) according to
the phase reference map as shown in Figure 42 (Canadian Natural 2008). Figure 54 indicates the approximate locations of zone #1 (red box) and phases 51 to 55 (yellow boxes) superimposed on Landsat-5 TM imagery of the CSS site chosen for this study.

![Figure 54](image)

**Figure 54.** Phase locations in zone #1 superimposed on Landsat-5 TM imagery (middle) with surface displacement map of March 2011 (left) and enlarged phase reference map (right) (modified from Canadian Natural, 2008)

InSAR-derived surface deformation measurements at the selected phase locations are extracted and simply spatial averaged to obtain the mean values of the vertical surface deformations at each phase. The average rate of the steam injection (m$^3$/day) at the selected phase locations for each month during the period between July 2007 and March 2011, which is equivalent to the range of SAR data acquisition dates, is obtained from CNRL’s annual presentations. The total amount of injected steam that is accumulated for the period between July 2007 and March 2011 is calculated using the average steam injection rates, in order to examine the approximate volume of steam injected into the reservoir for 3.7 years. Unknown factors affecting the changes in the injected steam
volume at the reservoir level, such as steam condensation or leakage, are not considered in this case.

These variables (i.e., mean surface displacements, average steam injection rate and total amount of accumulated steam in the reservoir) are plotted in the same graphs using dual y-axis and displayed in Figure 55. Despite the lack of surface deformation measurements with high temporal resolution, Figure 55 shows that the surface displacements follows the general pattern of steam injection during the period of 2007/07 – 2011/03. It is, therefore, found in most cases that the steaming operation causes the changes in surface elevation that take place with a certain time lag.

The time lag between the dates of the peak of steaming rate and the surface deformation at maximum is approximately 0 – 6 months in zone #1. However, it becomes more difficult to estimate the surface deformation trend and the corresponding time lag when the complicated geomechanical responses are involved, due to either steam being injected more than twice during the given period or other factors that are not considered in this study (e.g., geological aspects or casing failure).

At phase 51, for example, ground surface subsidence is observed from the first SAR data acquisition date (i.e., July 2007), because progressive steam injection is already terminated as of April 2007. Steaming operation again commences at the beginning of 2009 and continues for about 6 months with the steam injection rate reaching up to approximately 19,500 m$^3$/day. The steaming operations consequently cause surface uplift and return surface elevation to the zero deformation level, with the amount of 6 cm that occurs about 4 months after the peak of steaming rate is observed on April 2009.
Figure 55. Steam injection rate, accumulated steam volume and surface deformation at phases 51 to 55 in zone #1 for the CSS site
The surface deformation at the phase 52 location follows a pattern similar to that of phase 51. The ground surface subsides until the end of 2008, due to previous oil recovery activities. Steam injection, however, begins in June 2009 and continues for 4 months, with a maximum steam injection rate of 23,000 m$^3$/day in August 2009. The steaming operation that recurs in 2009 consequently causes the ground surface heave; and,
surface elevation tends to return to its initial level (i.e., zero deformation with respect to July 2007).

From the last three graphs for phases 53 to 55 in Figure 5, there are distinctive peaks of the accumulated amount and the average rate of steam injection. The temporal trends of surface displacements also exhibit several peaks, corresponding to individual steaming activities that are completed in 2010. The total amount of surface uplift at phases 53 to 55 is larger than the extent of surface heave at phases 51 and 52. It could be explained by the CSS operations with more amount of steam injection at phases 53 to 55 during the given period. The surface elevation tends to move toward the zero deformation level after the third steaming operation is terminated in 2010.

Interestingly, the maximum surface heave is around 15 cm for both phases 53 and 55, regardless of the different volume of accumulated steam. On the other hand, the amount of surface displacements is more amplified for phase 54 than phases 53 and 55. Two peaks of surface heave are observed on September 2008 and August 2010, and these are observed approximately 1 – 3 months after second and third daily steaming rates become the maximum in 2008 and 2010 at the phase 54 location. The surface elevation rapidly drops after the second steaming operation is temporarily terminated as of the end of 2008, but again increases when the third steaming operation commences in November 2009. Given the huge surface heaves that already occur during first and second steam injection cycles, the surface deformation becomes more unrecoverable, leaving the ground surface lifted about 12 cm above the zero deformation level.
The linear relationship between CSS operations and the corresponding responses in the surface and subsurface is examined by the linear regression method. The linear trendlines of a best-fit line for the observed surface/subsurface deformations and the fluid volume changes that are computed by subtracting the total volume of the produced bitumen and water from the steam injection volume are displayed with a linear equation and square of correlation coefficient (R²) in Figures 56 and 57. The total volume of bitumen and water produced from phases 51 to 55 between July 2007 and March 2011 is estimated based on CNRL’s annual presentations (Canadian Natural, 2008, 2009, 2011, 2012). Note that the fluid volume changes before July 2007 and after March 2011 are not considered and that possible leakage or complicated geomechanical behaviour of injected/produced fluids is ignored in this study.

Despite the outliers far away from the regression lines, the linear relationship between the fluid volume changes and corresponding surface displacements is found to be positive with R² ranging from 0.5813 to 0.7447. A positive linear relationship between fluid volume changes and subsurface volumetric changes is also found with R² ranging from 0.5154 and 0.9921. Hence, it can be concluded from linear regression analysis of surface displacements and subsurface volumetric changes with information on the CSS operations that the variations in the ground surface elevation and subsurface volume mainly result from fluid injection and production at each phase. In order to relate the geomechanical responses of the surface and subsurface to physical oil recovery activities at the CSS site in greater detail, information regarding other factors, such as geological settings, reservoir characteristics, CSS operations or casing failure, is required.
Figure 56. Linear relationship between InSAR-derived surface deformation and fluid volume change in the reservoir
Figure 57. Linear relationship between fractional volumetric change and fluid volume change in the reservoir
6.1 Conclusions

The monitoring of ground surface deformation at two Canadian oil sands sites – the carbon dioxide enhanced oil recovery (CO₂-EOR) and cyclic steam stimulation (CSS) sites – is performed with space-borne SAR interferometric techniques in this study. The two sites are selected in order to investigate the changes in surface elevation that may have been influenced by oil recovery activities with the CO₂-EOR and CSS technologies. The synthetic aperture radar (SAR) datasets for both sites are acquired from radar satellites of the second European Remote-Sensing Satellite (ERS-2) and the first Advanced Land Observation Satellite (ALOS-1) phase array type-L SAR (PALSAR) for the radar interferometry application.

The differential interferograms generated by implementing differential interferometric SAR (DInSAR) using all 33 SAR datasets from ERS-2 for the CO₂-EOR site exhibit no significant phase variations over the entire time span from January 2002 to September 2004. Although abrupt phase variations locally appear on several interferograms, observed phase variations are more likely associated with possible phase contributions, such as phase unwrapping error or atmospheric artifacts, because these are not temporally and spatially consistent throughout all differential interferograms. However, the consistent phase variations due to the changes in surface elevation that are generally represented as a sequence of fringes in the successive differential
interferograms are not detected during a period considered in this study (i.e., January 2002 to September 2004).

The surface displacements, the variation of which falls within a 95 % confidence interval, are obtained using the 3-sigma rule in order to remove outliers. For further investigation into the surface deformation measurements that are pruned out for outlier removal, a profile line passing through the CO$_2$-EOR site is defined. InSAR-driven surface displacements that preserve high coherence and fall within two standard deviations from the mean are taken along the profile line and plotted in a graph format for visual interpretation. The profile analysis for each interferometric pair shows that there are no significant surface displacements caused by the CO$_2$-EOR oil recovery and that the ground surface elevation remains unchanged during the given period at the CO$_2$-EOR site.

Both the surface deformation maps and profile analysis confirm that the ground surface experiences nearly zero deformation with respect to the initial surface elevation at the very first date of SAR data acquisition (i.e., January 2002) with minimal values of the mean phase variations, which are far less than ±1 cm. Therefore, further analysis of InSAR-based surface deformations at the selected CO$_2$-EOR site for more detailed investigation or noise minimization is not considered in this study.

In contrast, noticeable phase variations are clearly detected throughout all of the differential interferograms created using ALOS-1 PALSAR datasets covering the CSS site. The phase changes that are displayed as fringes in the consecutive differential interferograms are first unwrapped and converted to metric units (cm), producing the maps of vertical surface deformation for the CSS site.
For the temporal analysis of vertical surface deformation monitored by radar interferometry, the small baseline subset (SBAS) algorithm is subsequently applied to InSAR-derived surface deformation maps. As a result of the SBAS implementation, the maps of the cumulative surface deformation are successfully retrieved, and the temporal changes in surface elevation at specific surface points are analyzed. The time-series analysis on the surface displacements at the CSS site confirms that vertical surface deformation rates are non-linear and time-varying along both the upward and downward directions. The temporal trends of vertical surface deformation observed at specific points indicate that the ground surface elevation either remains unchanged or experiences vertical surface displacements for the 3.7 year time period starting in July 2007.

The maximum amounts of surface subsidence and heave observed during the given period at the CSS site are determined to be -33 cm and +72 cm, respectively. The accumulated surface deformation maps resulting from the application of the SBAS algorithm is further examined by means of calculating the root mean square error (RMSE), which shows insignificant error ranges involved in the inversion process of the SBAS algorithm.

As found from many previous research works, measurable surface deformation at oil sands production sites can be induced by oil recovery activities, causing reservoir compaction or dilation that is associated with the considerable changes of reservoir pressure. Subsurface modeling based on the surface deformation measurements derived by radar interferometric techniques is carried out in this study. By applying the concept of nucleus of strain and a well-established geomechanical inversion algorithm with a
regularization technique, the fractional volumetric changes at the reservoir level are estimated with the available reservoir parameters (i.e., reservoir depth and thickness, Poisson’s ratio, Skempton’s pore pressure coefficient, fluid density) and simple assumptions of a hypothetical reservoir (i.e., isotropic, homogeneous and poroelastic in a half-space with a single layer) for the CSS site. The fractional volumetric change of the subsurface for the measured 3.7 years ranges from -1.836 % to +3.900 % and coincides well with the pattern of surface deformations estimated by the SBAS algorithm.

The resulting surface deformation measurements are interpreted with historical records of steam injection, which are available from annual presentations of Canadian Natural Resources Limited (CNRL). The location and spatial pattern of the detected surface deformations conform to CNRL’s steaming operation during different CSS cycles at the Primrose North project area. An interesting finding from the study results is that the more active steam injection with larger amounts of steam at the newer well pads since 2010 results in rapid growth of the surface heave, reaching its maximum extent of +72 cm. Moreover, it is determined that the particular routine of surface heave and subsidence follows the typical stages of CSS operations (i.e., steaming, soaking and producing cycles) in most cases. A detailed investigation into the relationship between the steaming operations and InSAR-derived vertical surface deformation is further conducted by plotting the steam injection rate, accumulated steam volume and surface elevation change. The graphs show that surface deformation trends follow the overall patterns of the steaming operation at phases 51 to 55 located in predefined zone #1 at the CSS site.
In addition to the spatial similarity of steam injection and corresponding vertical surface deformation, a time lag between the peak steaming rate and the maximum surface heave is also found in most cases. The time lag is approximately 0 to 6 months, perhaps depending on the steaming strategy and other complicated factors. Hence, examining patterns of surface displacements provides not only an amount of physical changes in the ground surface elevation, but also indirect information on the progress of the oil sands production at the CSS site even in case of ancillary information unobtainable.

The relationship between the detected surface/subsurface deformations and the fluid volume changes that are computed by subtracting the total volume of the produced bitumen and water from the steam injection volume are examined through linear regression analysis. The positive linear relationships are found with the square of correlation coefficient ($R^2$) greater than 0.5 in all cases. The linear regression results support that the CSS operations accompanied by both injection and production of fluids cause the corresponding deformations at surface and subsurface levels.

The innovative contributions of this study can be summarized as the temporal analysis of the surface and subsurface behaviours in response to the CSS operations at a Canadian oil sands site by the means of both the radar interferometric methods, including DInSAR and SBAS algorithm, and the geomechanical inversion with the Tikhonov regularization technique. The geomechanical inversion of InSAR-driven surface deformation measurements with the Tikhonov regularization technique enables the simple inference of subsurface behaviours over time under the assumption that the surface displacements are mainly caused by oil recovery activities.
It is possible in this study to estimate temporal variations of fractional volumetric changes at the reservoir level by the inversion of InSAR-derived surface displacements without the detailed parameters related to the oil reservoir and direct field investigations. Therefore, this study reveals the possibility of combining time-series analysis based on radar interferometric techniques and subsurface modeling by the geomechanical inversion of radar interferometric results for the CSS site, where the ground surface elevation is expected to significantly change in both the upward and downward directions with repetitive CSS cycles. Therefore, the outcomes of this study are expected to provide new insight into the assessment of the environmental impacts of human-related activities and the evaluation of the overall progress of bitumen recovery processes at oil sands.

This study can be finally summarized as:

- The ground surface at two Canadian oil sands sites (i.e., CO₂-EOR and CSS sites) is monitored using DInSAR with remotely sensed radar satellite data.
- Temporal evolution of the vertical surface deformation at the CSS site is analyzed by means of the SBAS algorithm.
- Subsurface modeling is conducted through the geomechanical inversion of InSAR-derived surface deformation measurements with the Tikhonov regularization technique using limited information on the subsurface system.
- Surface displacements are interpreted with information on the steaming operations, leading to the conclusion that the surface deformation coincides well with steam injection.
• Linear relationship between surface/subsurface deformations and fluid volume changes in the reservoir is found by the linear regression method.

6.2 Discussion

Only the ERS-2 SAR datasets are available for the CO₂-EOR site, where dense vegetation and cultivation are dominant during the period between 2002 and 2004. Therefore, the temporal decorrelation problem cannot be solved by utilizing longer wavelength SAR data. The temporal decorrelation may degrade the overall quality of interferograms for the CO₂-EOR site, due to the use of short wavelength radar signals.

For the CSS site, the mitigation of unwanted phase terms contributed by the digital elevation model (DEM) error in differential interferograms is not conducted during the application of the SBAS algorithm, since the phase contributed by the surface deformations at the CSS site are rather non-linear and significantly fluctuate over time, as anticipated given the repetitive CSS operations. Although the most coherent interferograms are chosen and the spatial low-pass (LP) filtering is applied in order to reduce possible phase noise and the undesired effect from atmospheric inhomogeneity during the implementation of the SBAS algorithm, inherent errors in the global DEM (GDEM) and residual atmospheric effect may still remain.

The validation of surface displacement measurements obtained by radar interferometric techniques is unavailable, due to the lack of ground data for both sites. The simple reservoir model, which is assumed to be isotropic, homogeneous and poroelastic in a half-space with a single layer, and very limited reservoir-related
parameters are used during the implementation of geomechanical inversion for the CSS site. The estimation of subsurface volumetric changes conducted in this study is, thus, primitive, due to the lack of reservoir- or geology-related information at the CSS site. Therefore, the complexities of subsurface system and volumetric changes at the reservoir level are not considered.

The comparison of InSAR-derived surface deformation with information regarding steam injection at the Primrose North project area needs more detailed investigations, because not very accurate steam injection data published in CNRL’s annual presentations are utilized.

The relationship between the surface/subsurface deformations and fluid volume changes in the reservoir is examined using a simple linear regression under the assumption that there is no leakage or complicated geomechanical behaviour of fluids in the reservoir. The temporal resolution of InSAR-derived surface deformation measurements and subsurface volumetric changes estimated by geomechanical inversion in this study is perhaps not sufficient to investigate either the time lag between the maximum steam injection rate and surface heave or the linear relationship between the observed surface/subsurface deformations and CSS operations.

**6.3 Future Works**

Further improvements in the monitoring of surface deformation using radar interferometric methods can be made if other surface measurements that are obtained
from, for example, global navigation satellite system (GNSS), leveling or tiltmeter become available for the selected sites. The use of such ground data is anticipated to solve the uncertainties in the study results, increasing the overall accuracy through a detailed validation.

It is recommended to utilize the SAR data acquired from other radar satellites in order to cross-validate InSAR-derived surface displacements and to increase temporal resolution. The SAR datasets that can be acquired from newly launched radar satellites (e.g., ALOS-2) are also expected to enable more extensive investigations with higher temporal and spatial resolutions. The separation of the undesired phase contributions (e.g., atmospheric effects and errors of external DEM) from differential interferograms can be achieved by fully applying permanent scatterer interferometric SAR (PSInSAR) or SBAS algorithm, when a sufficient number of SAR datasets becomes obtainable and the linear component of surface deformation is present.

The collection of detailed physical parameters describing the subsurface system can absolutely enhance the quality of the subsurface modeling result. The additional information on the subsurface complexity (e.g., distribution of Poisson’s ratio, geological characteristics) is required to develop a more realistic reservoir model. The numerical approaches, such as finite-difference and finite-element techniques, may contribute to increasing the overall accuracy of geomechanical inversion results. Better interpretation of surface displacements can be achieved when greater detailed production-related information and temporally dense surface/subsurface deformation measurements become available for the CSS site.
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