Surface Deformation Analysis Over A Hydrocarbon Reservoir Using InSAR with ALOS-PALSAR Data

by

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B.S. Geodesy and Photogrammetry Engineering
Yildiz Technical University, 2008

SUBMITTED TO THE DEPARTMENT OF EARTH ATMOSPHERIC AND PLANETARY SCIENCES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN GEOPHYSICS

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FEBRUARY 2013

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Abstract

InSAR has been developed to estimate the temporal change on the surface of Earth by combining multiple SAR images acquired over the same area at different times. In the last two decades, in addition to conventional InSAR, numerous multiple acquisition InSAR techniques have been introduced, including permanent scatterer (PS) (Ferretti et al., 2001) and small baseline subset (SBAS) (Berardino et al., 2002). Stanford method for persistent scatterers (StaMPS) (Hooper, 2006) is another multiple acquisition method that has been developed for estimating ground deformation and differs from the permanent scatterer technique through the method used for pixel selection.

In this project, we used the SBAS method to detect the surface deformation over a hydrocarbon reservoir in Adiyaman Providence, Turkey. The SBAS technique is performed on combinations of SAR images that are characterized by small orbital distances with large time intervals. By applying singular value decomposition (SVD), the temporal sampling rate is increased and those subsets are connected. We applied the SBAS method to five ALOS-PALSAR fine-beam dual (FBD) mode images, and removed the topographic phase by using a 3 arc-sec SRTM digital elevation model (DEM). The atmospheric artifacts are determined and filtered out based on available spatial and temporal information on processed data.

Our analysis has revealed that due to the effective mitigation measures taken by the oil company, the maximum observed LOS displacement velocity in the oil field is 5 mm/yr with a likely uncertainty of a similar magnitude in the period of 2007-2010. The high uncertainty estimate is due to the other spatially correlated signals of similar and larger magnitude seen in regions outside of the oil field.

Thesis Supervisor: Thomas Herring
Title: Professor of Geophysics
Acknowledgments

This dissertation concludes my master degree at the Massachusetts Institute of Technology. I would like to take this opportunity to express my deepest gratitude to all the people who have helped me reach this point.

First and foremost, I would like to express my sincere thanks to my advisor Professor Thomas Herring, for his invaluable support and advice throughout my years in which I have had the privilege of being his student. I would also like to thank Prof. Brad Hager and Dr. Mike Fehler, for serving on my committee and for their helpful instructions and constructive comments.

I thank to Dr. Robert King for his contributions to the GPS analysis. Special thanks go to Noa Bechor, to whom I gave the most headaches. Her approaches to problems helped shape my own attitudes. I am grateful for her vital lessons. My work would not have been improved without her contributions.

I also thank to my friends and my colleagues, Nasruddin Nazerali for the great discussions we have had and his guidance, Kang Hyeun Ji for always being on call to answer questions, Junlun Li and Abdulaziz Almuhaidib for their good humor, and in particular Martina Coccia, who tirelessly listened to my complaints about life and helped me overcome several difficulties. I owe special thanks to Julia Tierney, for being such a great friend and my ‘personal’ editor.

The Turkish Petroleum Corporation generously supported my work. I would like to thank Mr. Mertkan Akca particularly for his support and for providing the data sets used in this project.

Finally, I am forever indebted to my parents, my sister Berivan Sahin, my uncle Huseyin Beydilli, and my ‘identical twin’ Emre Oguten for their constant support, encouragement and guidance throughout both my academic and personal life.
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<th>Description</th>
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<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>ALOS</td>
<td>Advance Land Observation Satellite</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>CORS</td>
<td>Continuously Operating Reference Station</td>
</tr>
<tr>
<td>CGPS</td>
<td>Continuous Global Positioning System</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DORIS</td>
<td>Delft Object-oriented Radar Interferometric Software</td>
</tr>
<tr>
<td>Envisat</td>
<td>Environmental Satellite</td>
</tr>
<tr>
<td>ERS</td>
<td>European Remote-sensing Satellite</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HP</td>
<td>High Pass</td>
</tr>
<tr>
<td>IGS</td>
<td>International GNSS Service</td>
</tr>
<tr>
<td>InSAR</td>
<td>Interferometric SAR</td>
</tr>
<tr>
<td>JERS</td>
<td>Japanese Earth Resources Satellite</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LS</td>
<td>Least Squares</td>
</tr>
<tr>
<td>LP</td>
<td>Low Pass</td>
</tr>
<tr>
<td>NGS</td>
<td>National Geodetic Survey</td>
</tr>
<tr>
<td>PALSAR</td>
<td>Phased Array type L-band Synthetic Aperture Radar</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PLR</td>
<td>Polarimetric acquisition mode of ALOS PALSAR instrument</td>
</tr>
<tr>
<td>PS</td>
<td>Persistent Scatterer</td>
</tr>
<tr>
<td>PRF</td>
<td>Pulse Repetition Frequency</td>
</tr>
<tr>
<td>RSF</td>
<td>Range Sampling Frequency (Hz)</td>
</tr>
<tr>
<td>RADARSAT</td>
<td>Radar Satellite</td>
</tr>
<tr>
<td>RAR</td>
<td>Real Aperture Radar</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>ROL_PAC</td>
<td>Repeat Orbit Interferometry PACkage</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SBAS</td>
<td>Small Baseline Subset</td>
</tr>
<tr>
<td>SLC</td>
<td>Single-Look Complex</td>
</tr>
<tr>
<td>SNAPHU</td>
<td>Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>STAMPS</td>
<td>Stanford Method for Persistent Scatterer</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$R_r$</td>
<td>Range Resolution</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Pulse Length</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed Of Light</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Lookdown Angle</td>
</tr>
<tr>
<td>$\tau_{eff}$</td>
<td>Effective Pulse Length</td>
</tr>
<tr>
<td>$B_R$</td>
<td>Range Bandwidth</td>
</tr>
<tr>
<td>$R_a$</td>
<td>Azimuth Resolution</td>
</tr>
<tr>
<td>$R$</td>
<td>Slant Range</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$L$</td>
<td>Length Of The Physical Antenna</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Look Angle</td>
</tr>
<tr>
<td>$L_a$</td>
<td>Length Of The Synthetic Antenna</td>
</tr>
<tr>
<td>$V$</td>
<td>Speed Of The Satellite</td>
</tr>
<tr>
<td>$n_a$</td>
<td>The number of times a target is sampled</td>
</tr>
<tr>
<td>$D$</td>
<td>Theoretical Width Of The Synthetic Aperture On The Ground</td>
</tr>
<tr>
<td>$\Delta_a$</td>
<td>The Resolution Of The Synthesized Array</td>
</tr>
<tr>
<td>$\Delta_{focused}$</td>
<td>The Focused Synthetic Array Resolution</td>
</tr>
<tr>
<td>$e$</td>
<td>Exponential</td>
</tr>
<tr>
<td>$i$</td>
<td>$\sqrt{-1}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Phase Of The Interferogram</td>
</tr>
<tr>
<td>$\phi_{scat,1p}$</td>
<td>Scattering Phase Contributions In The First Image</td>
</tr>
<tr>
<td>$\phi_{scat,2p}$</td>
<td>Scattering Phase Contributions In The Second Image</td>
</tr>
<tr>
<td>$B$</td>
<td>Baseline</td>
</tr>
<tr>
<td>$B_\perp$</td>
<td>Perpendicular Baseline</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>Slant Range Difference</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Baseline Orientation Angle</td>
</tr>
<tr>
<td>$H$</td>
<td>Height Of The Sensor</td>
</tr>
<tr>
<td>$\theta_0$</td>
<td>Initial Look Angle</td>
</tr>
<tr>
<td>$\partial \phi$</td>
<td>Interferometric Phase Difference</td>
</tr>
<tr>
<td>$\partial H = -h_p$</td>
<td>Derivative Of The Sensor Height For Pixel $P$</td>
</tr>
<tr>
<td>$\partial \phi_{flat}$</td>
<td>Difference In Phase Due To Different Satellite Positions</td>
</tr>
<tr>
<td>$\partial \phi_{topo}$</td>
<td>The Variation In Phase Due To Topography</td>
</tr>
<tr>
<td>$\partial \phi_{defo}$</td>
<td>The Phase Differentiation Due To Deformation</td>
</tr>
<tr>
<td>$\partial \phi_{atmo}$</td>
<td>The Difference In Phase Due To Atmospheric Delay</td>
</tr>
<tr>
<td>$\partial \phi_n$</td>
<td>The Phase Difference Due To Decorrelation And Noise</td>
</tr>
<tr>
<td>$v_d$</td>
<td>Deformation Velocity</td>
</tr>
</tbody>
</table>
\( T \)  
Temporal Baseline

\( \partial \phi_{\text{nonlinear}} \)  
Nonlinear Component Of The Phase Differentiation Due To Deformation

\( \partial \phi_{\text{dem}} \)  
Artifacts Due To Errors In The Dem

\( \Delta h \)  
Error in the DEM

\( E \)  
Expectation

\( M_i \)  
The Value Of The Pixel In The Master Image

\( S_i^r \)  
The Pixel's Complex Value In The Slave Image

\( \rho \)  
Coherence

\( \rho_{\text{temp}} \)  
Temporal Decorrelation

\( \rho_{\text{spat}} \)  
Spatial Decorrelation

\( \rho_{\text{therm}} \)  
Thermal Decorrelation

\( \rho_{\text{oc}} \)  
Doppler Centroid Decorrelation

\( \rho_{\text{vol}} \)  
Volumetric Decorrelation

\( \rho_{\text{processing}} \)  
Processing Induced Decorrelation

\( N \)  
The Number Of SAR Images

\( M \)  
The Number Of Interferograms

\( a, r \)  
Radar Coordinates: Azimuth And Range

\( t_k \)  
Image Acquisition At Time \( k \)

\( \Delta(t_k, a, r) \)  
Cumulative Ground Deformations At Time \( t_k \)

\( \Delta(t_{k+1}, a, r) \)  
Cumulative Ground Deformations At Time \( t_{k+1} \)

\( t_0 \)  
Initial Acquisition Time

\( \Delta(t_j, a, r) \)  
Deformation Time Series

\( \phi^T \)  
Deformation Array

\( \delta \phi^T \)  
Differential Phase Array

\( P_i \)  
Matrix For Master Images

\( S_i \)  
Matrix For Slave Images

\( A \)  
System Matrix

\( \hat{\phi} \)  
Estimated Deformation Array

\( Z \)  
The Number Of Small Baseline Subsets

\( U \)  
Orthogonal Matrix (Left Singular Vectors Of A)

\( S \)  
Diagonal Matrix

\( V \)  
Orthogonal Matrix (Right Singular Vectors Of A)

\( \nu^T \)  
The Mean Velocity Matrix

\( B \)  
System Matrix

\( W \)  
Model Matrix

\( p \)  
Parameter Vector

\( \nu \)  
Mean Velocity

\( \nu' \)  
Mean Acceleration

\( \Delta \nu' \)  
Variation Of The Mean Acceleration

\( \hat{p} \)  
Least Squares Estimate For Parameter Vector \( p \)
Chapter 1

1 Introduction

Interferometric Synthetic Aperture Radar (InSAR) is a method that combines images acquired over the same area by space or airborne systems at one time or different times in order to produce topography, deformation, and alteration maps of the Earth surface.

Spaceborne repeat-pass radar interferometry, meaning that a radar system acquires an image of an area on the ground at one time, and combines it with images that are acquired at other times, began with topographic mapping applications to generate digital elevation models (DEMs) in the 1980s. Today, elevation models are generated in small and large scales - covering continents, and are used in many fields, e.g. telecommunication, cartography, hydrology mapping, and geophysics.

For the last two decades, the repeat-pass radar interferometry has been applied to many studies for horizontal and vertical deformation detection, and has provided results with mm to cm level accuracy. These deformations on the Earth's surface result from natural and man-made processes. Natural phenomena includes seismic and eruptive events, i.e. due to earthquakes and volcanoes, glacier and ice motions. Anthropogenic phenomena comprise extraction of ground water, oil, and gas, irrigation of farmlands, and underground constructions and explosions. Monitoring long-term surface deformation due to oil production will be discussed in detail in following chapters.

In addition, SAR interferometry is a powerful geodetic instrument to detect the alteration on the surface of the earth. Monitoring forestry operations, soil moisture, vegetation growth, and ice penetration are among InSAR’s thematic mapping applications. Man-made or natural hazards, including floods, landslides, lava streams, and fires and their regional/global effects can also be assessed and quantified through interferometric SAR.

1.1 Deformation Monitoring and Land Subsidence

Interferometric SAR applications on surface deformation extend to many forms and may be organized in numerous groups. One of the most common applications of the repeat-pass interferometry is to measure pre-, co-, and post-seismic deformations, enabling us to examine and better understand the tectonics. Volcanic deformation can also be monitored in pre-, co-, and post- event manner; and by obtaining the long-term records of volcanic activities leads to an improvement in our hazard forecasting capability. Furthermore,
SAR interferometry provides invaluable information on regions where it is very difficult to perform conventional geodetic measurements. In the areas such as Antarctic and Greenland, interferometric observations enable us to track glacier and ice movements. Tracking their rate and direction of motion help us improve our understanding of the forces acting on them. This leads to a development in the determination of the sea-level rise, i.e., at which rate the ice is pouring into the seas, and interpretation of the ice sheet response to global climate change. The applicability of radar interferometry to determine the velocity of the glaciers or ice sheets might be challenging due to the steep topography, melting of snow, and atmospheric changes between two SAR acquisitions. In addition, the time interval over which velocity is determined plays a key role on the applicability of the method. Due to weather-induced changes the temporal decorrelation of the signal occurs, and most temperate glaciers lose coherence after only a few days. This can restrict the use of the method because of the orbital cycle of the satellites, e.g., depending on the operation mode, 1, 3, and 35 days for the European Remote Sensing Satellite (ERS).

Land subsidence, or uplift, due to extraction of ground water or natural resources, or due to underground construction, forms another main group of surface deformation that can be detected by interferometry. However, InSAR might not always be feasible to detect these deformations. The rate of the ground movement combined with the decorrelation due to change in the characteristics of the scatterers and of the atmospheric effects is the determinant factor in the applicability of interferometric measurements in surface displacement. The phase is wrapped in the radar imagery, and the coherence is completely lost in an interferogram if the maximum deformation gradient exceeds a cycle per pixel (Massonnet and Fiegl, 1998). In other words, InSAR measures surface deformation by counting the interferometric phase cycles from steady part to most distorted part of the imaged area. When a large deformation occurs in an area it produces high deformation gradient, and hence the cycles in that part will be so dense that it becomes impossible to count them, e.g., decorrelation due to high displacement gradient near the center of a mine panel. The maximum value to detect displacement gradient is the ratio of the half of the radar wavelength to pixel size, e.g., $1.4 \times 10^3$ (28 mm divided by 20 m) for Envirosat when the pixel size is 20 m x 20 m. If deformation produces strains larger than the maximum value within a time interval shorter than the satellite repeat cycle, it will not be observed. The temporal decorrelation is one of the major limitations in continuous deformation monitoring. However, it has been observed that man-made structures or some natural features remain coherent for long time periods. The latest developments of exploiting stacks of SAR images have shown that many coherent objects can be identified in urban, rural or desert regions (Ferretti et al., 2001; Hooper, 2006). These coherent or persistent scatterers enable us to tackle the temporal decorrelation problem, especially in arid terrains, and hence allow us to monitor long-term surface deformation.
1.2 Displacement On Surface Due To Oil Production

Ground deformation induced by oil production is one of the leading factors of land subsidence all over the world that has been broadly investigated through several methods. Even though GPS, precise leveling, and tiltmeter techniques can be used to perform subsidence monitoring, their lack of area coverage makes it difficult to determine the spatial pattern and extent of deformation. While the spacing of adjacent data points for all other methods is in the order of hundreds to thousands of meters, the areal data spacing over the area of study for InSAR is about 3-20 meters, depending on the radar signal frequency. Therefore, InSAR has become a common analysis tool through which the relationship between oil extraction and subsidence can be identified and quantified at a high spatial resolution. Some oil and gas field examples where surface deformation has been monitored by SAR interferometry are the Belridge and Lost Hills fields in California (Patzek and Silin, 2000; Patzek et al., 2001; van der Kooij and Mayer, 2002), the cyclic steam injection trial in Peace River Pad 40 (Maron et al., 2008), and the CO₂ sequestration trial in Salah, Algeria (Raikes et al., 2008; Vasco et al., 2008).

In this project, spaceborne SAR interferometry is applied to identify the surface deformation in Adiyaman Oil Field, Adiyaman Province, Turkey. The line of sight (LOS) displacements due to oil production will be calculated using ALOS PALSAR images extending from 2007 to 2010. A GPS network, designed by the oil company, analysis to acquire the vertical and horizontal measurement of the deformation will be compared that of the InSAR approach.
Chapter 2

2 Radar

In this chapter, we introduce the principles of radar. After outlining the fundamentals, we will explain the resolution concept in radar imaging and the difference between real and synthetic aperture radar. Detailed information about real aperture radar can be found in Hovanessian (1980), and Sabins (1987).

2.1 Introduction

RADio Detection And Ranging (RADAR) functions by transmitting microwaves with wavelengths ranging from millimeters to meters and measures the travel time and energy of the reflected signals. The travel time yields information about the distance between the radar platform and target, i.e. range, whereas the energy provides information about the target’s shape and physical properties. Table 2.1 presents the commonly used radar microwave bands in spaceborne remote sensing with their corresponding wavelengths and frequencies. In this project, we have used the Advanced Land Observing Satellite - Phased Array L-band Synthetic Aperture Radar (ALOS PALSAR) data with a wavelength of 23.60 cm and frequency of 1.27 GHz, a detailed description of the system will be provided in Chapter 3.

<table>
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<tr>
<th>Radar Band</th>
<th>Wavelength (cm)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>1.1 - 0.75</td>
<td>26.5 - 40</td>
</tr>
<tr>
<td>K</td>
<td>1.7 - 1.1</td>
<td>18.5 - 26.5</td>
</tr>
<tr>
<td>Ku</td>
<td>2.4 - 1.7</td>
<td>12.5 - 18</td>
</tr>
<tr>
<td>X</td>
<td>3.75 - 2.4</td>
<td>8.0 - 12.5</td>
</tr>
<tr>
<td>C</td>
<td>7.5 - 3.75</td>
<td>4.0 - 8.0</td>
</tr>
<tr>
<td>S</td>
<td>15 - 7.5</td>
<td>2.0 - 4.0</td>
</tr>
<tr>
<td>L</td>
<td>30 - 15</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>P</td>
<td>100 - 30</td>
<td>0.3 - 1.0</td>
</tr>
</tbody>
</table>

Table 2.1. Radar Bands and their corresponding wavelengths and frequencies
2.2 Resolution in Radar

2.1.1 Range (Across Track) Resolution

In radar imaging systems, the signal is transmitted perpendicular to the platform's flight direction, known as the slant range direction, and the resolution has two components with respect to the platform's flight track. The resolution in the slant range direction is referred to as the range resolution, $R_r$, and corresponds to the minimum distance between two objects that the return signals can be resolved. This distance is controlled by the transmitted signal's pulse length, $\tau$ (in $\mu$sec). Two targets on the ground can be distinguished as separate objects if the projection of the distance between them onto the slant range direction is more than the half of the distance the signal travels within its pulse length (Figure 2.1)

$$R_r = \frac{\tau \times c}{2}$$

(2.1)

where $c$ is the speed of light (Hovanessian, 1980). For a typical pulse length of 10 $\mu$sec, a 1.5 km range resolution will be obtained.

As can be seen from Equation (2.1), resolution in range direction may be improved by using shorter pulse lengths. However, shortening the signals' pulse length comes at the
cost of reducing the emitted power, thereby reducing signal to noise ratio (SNR). The reflected pulse energy is approximately $10^{-11}$ times smaller than that of the transmitted pulse (Hanssen 2001). The amount of energy that an antenna can transmit in a fixed period is limited. As a consequence, there is also a limit in decreasing the pulse length. In order to overcome this conflict, shorter pulses vs. high-power transmissions, chirp is applied to pulses. A chirp simply is a linear radar signal that is modulated on the radar microwave frequency. Its bandwidth, $B_R$, varies in the range of $(-\tau/2, +\tau/2)$. Applying the chirp compression technique on the returned signal results in a significant reduction in the pulse length. This effective pulse length, $\tau_{eff}$, leads to an increase in the range resolution, referred to as effective range resolution, $\Delta_r$ (Hanssen 2001)

$$\Delta_r = \frac{\tau_{eff} \cdot c}{2} \quad \tau_{eff} = \frac{1}{B_R} \quad (2.3)$$

A bandwidth of 10 MHz would lead an effective pulse length of 100 ns, and hence a range resolution of 15 m, a factor of 300 improvement.

![Figure 2.2. Real aperture radar azimuth resolution](image)
2.1.2 Azimuth (Along Track) Resolution

The second resolution component is called azimuth resolution, i.e. resolution in the radar’s flight direction. This is also the point where real aperture radar (RAR) and synthetic aperture radar (SAR) differ. Objects must be separated by a distance larger than the beam width as measured on the surface in order to be resolved. The beam width is proportional to radar wavelength and inversely proportional to antenna length. Therefore real aperture radar obtains the fine azimuth resolution by using a long physical antenna that will narrow the angular beam (Figure 2.2). The resolution in azimuth direction is defined as

\[ R_a = \frac{\lambda \cdot R}{L} \] (2.4)

where \( R \) is the distance between radar platform and the target, i.e. the slant range, \( \lambda \) is the wavelength of the transmitted signal and \( L \) is the length of the antenna. For a usual X-band system, an antenna with physical size of 10 m, an altitude of 1000km from the object, and a 3 cm signal wavelength will yield an azimuth resolution of 3 km.

Synthetic aperture imaging radar, however, acquires resolution by transmitting relatively broad beam through smaller antennas and applying the Doppler principle, and employing signal processing techniques. We will discuss SAR in detail in Chapter 3.
Chapter 3

3 Synthetic Aperture Radar

In this section, we discuss the basic theory and fundamentals of synthetic aperture radar (SAR). A more comprehensive description of the SAR theory can be found in Massonnet and Feigl (1998), Burgmann (2000), and Hanssen (2001); and detailed information on SAR image formation can be found in Curlander and McDonough (1991) and Cumming and Wong (2005).

3.1 Background

Radar systems were developed in the first half of the 20th century to locate or to track moving vehicles like vessels and airplanes. With the help of the pulse compression signal processing techniques, yielding an improvement in the signal to noise ratio, and the synthetic aperture concept, we are able to acquire spatial resolution on the order of meters with relatively small physical antennas (Soumekh, 1999; Cumming and Wong, 2005). Consequently, SAR has become a widely used excellent geodetic instrument to image the Earth’s surface with high resolution.

The first Earth applications of spaceborne SAR tools date to early 1980s by NASA’s launch of the SEASAT satellite for ocean studies in 1978 (Fu and Holt, 1982). The idea of using spaceborne SARs as interferometers was developed in the 1970s [Richman, 1971; Zisk, 1972] and the first applications of terrestrial interferometric SAR took place in the late 1980s. (e.g., Zebker and Goldstein, 1986; Goldstein and Zebker, 1987).

3.2 Synthetic Aperture Formation and Resolution

As pointed out in Chapter 2, high azimuth resolution in real aperture radar (RAR) systems is achieved by using a large physical antenna, whereas in SAR systems fine azimuth resolution is obtained by transmitting pulses through smaller antennas and applying the Doppler principle and particular signal processing techniques. Two objects, at the same range but slightly different azimuth positions relative to the moving platform have different velocities at any instant with respect to the sensor. Hence, the reflected signals from these two targets in the same beam would have different Doppler shifts. With the flight path information of the imaging radar, we can calculate the precise phase history.
for each point on the ground. Combining information from many reflections enables us to produce a larger aperture synthetically through which different targets can be solved in the same beam. As shown in Chapter 2.1.2, the azimuth resolution for a typical C-band real radar system, 5 cm wavelength with antenna size of 10m, is ~ 5km on the ground. To improve the resolution, let say to 5 m resolution, the image is focused. Focusing enables the entire radar footprint width to be used as the synthetic aperture length. The size of the synthetic aperture $L_a$ varies with respect to the radar footprint in the azimuth direction and is approximately (Curlander and McDonough, 1991)

$$L_a = \frac{R \cdot \lambda}{L}$$

(3.1)

where $R$ is the slant range, $L$ is the physical length of the antenna, and $\lambda$ is the wavelength. The length of the synthetic aperture in terms of the amount of time that a point target on the ground is sampled is given by

$$n_a = \frac{L_a \cdot PRF}{V}$$

(3.2)

where $V$ is the velocity of the satellite, and PRF is the pulse repetition frequency of the signal (Curlander and McDonough, 1991).

<table>
<thead>
<tr>
<th>Platform</th>
<th>$V$ (m/s)</th>
<th>$\lambda$ (m)</th>
<th>PRF (Hz)</th>
<th>$R$ (km)</th>
<th>$L$ (m)</th>
<th>$L_a$ (m)</th>
<th>$n_a$ theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS - 1/2</td>
<td>7125</td>
<td>0.057</td>
<td>1679</td>
<td>~850</td>
<td>10</td>
<td>4845</td>
<td>1143</td>
</tr>
<tr>
<td>Envisat</td>
<td>7125</td>
<td>0.057</td>
<td>2067</td>
<td>~1020</td>
<td>10</td>
<td>5814</td>
<td>1691</td>
</tr>
<tr>
<td>ALOS</td>
<td>7125</td>
<td>0.236</td>
<td>2159</td>
<td>~1020</td>
<td>9</td>
<td>24072</td>
<td>8130</td>
</tr>
</tbody>
</table>

Table 3.1. Length of synthetic aperture for three satellites, from (Curlander and McDonough, 1991).

The length of the synthetic antenna is inversely proportional to the physical size of the antenna, implying that a smaller antenna will lead to a larger synthetic aperture. Reducing the antenna size will increase the antenna footprint width, and subsequently increase the maximum allowed length for the synthesized aperture. This results in collecting more Doppler shifts from the scatterers, and hence better resolution. Using a single antenna for both transmission and reception to sample an array will double the sensitivity of the synthetic array relative to a real array of the same length. The resolution of the synthesized array therefore will be

$$\Delta_a = \frac{R \cdot \lambda}{2D}$$

(3.3)

where $D$ is the theoretical width of the synthetic aperture on the ground, which is less than the size of the real antenna’s footprint, and the focused synthetic array will have a resolution of (Fitch, 1988)
Equation 3.4 remarks that the resolution obtained with a focused synthetic array is independent of range and increases with a decreasing length of a physical antenna. Obtaining high-resolution images with smaller antennas is the fundamental principle behind the SAR system. The smaller the antenna size, the larger the Doppler bandwidth is recorded, which leads to higher resolution. There are several algorithms and implementations (Cumming and Wong, 2005; Maître, 2008) that can be applied to obtain high-resolution images from recorded echoes.

3.3 SAR Fundamentals

3.3.1 Terminology

In synthetic aperture radar (SAR) systems, an aircraft or a spacecraft equipped with a side-looking antenna illuminates a swath or strip on the ground through electromagnetic pulses at a rate of pulse repetition frequency (PRF) in the range of 1-10kHz. As the craft moves along its flight path with a velocity \( V \), at an altitude \( H \), it images an area known as antenna footprint (Figure 3.1). The SAR antenna receives a bulk of signal returns, or echoes, from the scatterers, e.g. rocks, trees, water bodies, or buildings, on the surface and a SAR processor stores them as amplitudes and phases. The energy returned from those scatterers is called the backscatter, and shows variability with respect to the physical properties of the objects.

The swath is scanned with two different characteristics based on the directions. In the azimuth, the swath is swept at the speed of footprint, i.e. at the rate of PRF, whereas in the range, it is imaged at the speed of light and the echo is quantized at a sampling frequency \( f_s \), 16 MHz for ALOS Palsar FBD mode (for detailed discussion see section 3.3.4). We should note that the time scales of these two scanning mechanisms vary by orders of magnitude, and may be considered independently, the so called start-stop approximation assumption (Bamler and Hartl, 1998).

The raw SAR data, and later the focused image, are organized in a two dimensional (2D) array and the coordinates in this matrix are represented by the slant range and azimuth (see section 3.3.2 for a detailed discussion). One physical point in the matrix is called a pixel, and each pixel has a complex value and a size determined by the abovementioned mechanisms, e.g. \( V / PRF \) in azimuth and \( c/2f_s \) in range, where \( V \) is the platform's velocity and \( c \) is the speed of light, respectively. The complete size of the matrix is referred to as the scene size.
Resolution, or the sharpness of the image, in SAR data refers to the minimum distance between two scatterers with the same amplitude at which they can be distinguished as separate echoes. The resolution is determined by the impulse response centered on each pixel and is measured in 2D. The 3dB beam width value, of the impulse response, is generally known as the resolution size, and as stated in previous section smaller beam width values result in higher resolution in the image.

3.3.2 Data Acquisition And Recording

The commonly used imaging geometry in SAR systems is known as Strip-Map mode as depicted in Figure 3.1. The other two mapping approaches, made possible with phased-array antennas, are ScanSAR and Spotlight modes. The azimuth resolution of the image in strip-mode depends on the duration that an object is illuminated, called integration time, and it varies with the length of the antenna. In ScanSAR mode, the azimuth resolution is obtained by periodically transmitting groups of pulses with shorter integration time. The look angle of the beam is changed between the groups to scan a swath parallel to the previously illuminated one. This process continues until the last swath is scanned, then the beam is swept swath by swath, as the SAR antenna returns to its initial look direction. In spotlight mode, the antenna is constantly directed towards a specific patch on the surface to keep that in the view and higher azimuth resolution is achieved by longer integration time at the cost of land coverage. The spotlight mode SAR systems are only capable of scanning selected and isolated patches, whereas Strip-Map mode and ScanSAR systems can image theoretically unlimited length of strips.

As discussed in the previous section, two types of scanning procedures are carried out. The length of the swath is scanned at the speed of the antenna footprint; simultaneously, the swath is swept across at the speed of light. Then the echoes are positioned side-by-
side to generate a raw data matrix that can be considered as a coarse representation of the scatterer on the ground. This suggests that the returns are recorded in the same order as they have been received. The expressions early and late azimuth represent the first and last recorded pulses in the along track direction, whereas near and far range terms correspond to close and far received signals with respect to the path of the platform in the range direction.

The distance between the scatterer and the sensor (range), and the position of the object along the platform’s path on the ground (azimuth) form the coordinates of the 2D raw image. The raw data contain reflected signals from scatterers on the surface of earth. These signals are sampled and separated into two components, together form a complex number that contains information about the amplitude or intensity (brightness) and the phase of the reflected signal, and are stored in different layers. The data layers contain the backscatter information in each of the elements (pixels) and each line comprises sampled reflected signal of one pulse. Hence, an object on the ground appears in many lines (≈1000 for ERS) and the position of it varies in the different lines (different azimuth). The Doppler history is unique for each scatterer and is stored in associated data layers.

### 3.3.3 Data Formats

The data in SAR systems are recorded in so-called raw data format. The initial step in the processing is that the compression, or focusing of these raw data to improve resolution in the range and azimuth direction, sequentially. The focusing is performed by applying match filtering technique, i.e. the convolution of chirp wave in the range and of the Doppler phase shift of a scatterer’s received signals in the azimuth direction (Curlander and McDonough, 1991). This means that many backscatters of a point are combined into one, and the output of the compression is stored in one pixel. If all returned information of a point is used in the compression, then the output data is in single look complex (SLC) format (Figure 3.2). The data are at their highest spatial resolution, which is defined by the radar system characteristics.

![Figure 3.2. Single look complex image of the Adiyaman Region, Turkey.](image-url)
Another alternative data type in SAR systems is the complex multi look data, which is obtained by averaging the neighboring pixels to improve the signal-to-noise ratio. Even though multi looking decreases spatial resolution, it also reduces undesirable effects in an image such as speckle, grainy appearance due to variations in pixel intensities, by averaging.

However, to interpret images visually, the SLC or Multi-look data are converted from complex format to intensity image. In fact, the magnitude of the complex vector provides the intensity of the pixel. The number of looks that have been used in the compression step determines the spatial resolution of the intensity image.

### 3.3.4 SAR Platforms

The history of SAR platforms dates back to late 1970s. SEASAT, deployed by NASA in 1978, was the first earth orbiting synthetic aperture radar satellite developed for remote sensing of oceanographic phenomena. Over the years, several SAR satellites with different scientific purposes have been launched onto the Earth orbit. Table 3.2 shows some of the orbital SAR systems. In this thesis, Advanced Land Observing Satellite (ALOS) data have been used and detailed information of the satellite is given in the following section.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Band &amp; Wavelength (cm)</th>
<th>Max spatial resolution (m)</th>
<th>Polarization</th>
<th>Orbit repeat cycle (Days)</th>
<th>Country &amp; Launch Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>CosmoSkymed</td>
<td>X band – 3</td>
<td>1</td>
<td>HH, VV, HV, VH</td>
<td>16</td>
<td>Italy 2007</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>X band – 3</td>
<td>1</td>
<td>HH, VV, HV, VH</td>
<td>11</td>
<td>Germany 2007</td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>C band – 5.6</td>
<td>3</td>
<td>HH, VV, HV, VH</td>
<td>24</td>
<td>Canada 2007</td>
</tr>
<tr>
<td>ALOS</td>
<td>L-band – 23.5</td>
<td>10</td>
<td>HH, VV, HV, VH</td>
<td>46</td>
<td>Japan 2006</td>
</tr>
<tr>
<td>Envisat</td>
<td>C band – 5.6</td>
<td>23</td>
<td>HH, VV, HV, VH</td>
<td>35</td>
<td>Europe 2002</td>
</tr>
<tr>
<td>Radarsat-1</td>
<td>C band – 5.6</td>
<td>8</td>
<td>HH</td>
<td>24</td>
<td>Canada 1995</td>
</tr>
<tr>
<td>ERS-2</td>
<td>C band – 5.6</td>
<td>23</td>
<td>VV</td>
<td>35</td>
<td>Europe 1995</td>
</tr>
<tr>
<td>ERS-1</td>
<td>C band – 5.6</td>
<td>23</td>
<td>VV</td>
<td>35</td>
<td>Europe 1991</td>
</tr>
</tbody>
</table>

Table 3.2. Several SAR satellites and some of their features

*ALOS*

ALOS is an acronym for Advanced Land Observing Satellite, and is operated by the Japan Aerospace Exploration Agency (JAXA). ALOS carries two optical sensors, including Advanced Visible And Near Infrared Radiometer type-2 (AVNIR-2) and Panchromatic Remote Sensing Instrument For Stereo Mapping (PRISM), and one SAR instrument Phased Array L-band Synthetic Aperture Radar (PALSAR), Figure (3.3).
ALOS performs in a sun-synchronous orbit over a height of 691.56 km and has a repeat cycle of 46 days, (see Table 3.3). Detailed information can be found in Hamazaki (1999), and Osawa (2004).

<table>
<thead>
<tr>
<th>Item</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>Sun synchronous</td>
</tr>
<tr>
<td>Recurrent Period</td>
<td>46 days, sub-cycle: 2 days</td>
</tr>
<tr>
<td>Inclination</td>
<td>98.16 degree</td>
</tr>
<tr>
<td>Generated Power</td>
<td>7 kW (end of life)</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 4000 kg</td>
</tr>
<tr>
<td>Data Recorder</td>
<td>96 Gb, solid-state</td>
</tr>
<tr>
<td>Data link</td>
<td>240 Mbps (via DRTS)</td>
</tr>
<tr>
<td></td>
<td>120 Mbps (direct down link)</td>
</tr>
</tbody>
</table>

Table 3.3. Characteristics of ALOS

**PALSAR**

PALSAR was the only instrument that operates in the L-band in an orbit with different modes until the ALOS completed its operation in May 2011. Operation modes are fine beam single (FBS) polarization (HH or VV), fine beam dual (FBD) polarization (HH+HV or VV+VH), fully Polarimetric (PLR), and ScanSAR. The look angle varies between 7° and 51° corresponding to incidence angle range of 8° - 60°. The ground resolution for FBS and FBD mode is ~10 m and ~20 m, respectively, with a swath width of 70km for both methods. ScanSAR mode has a resolution of 100 m and can sweep a swath up to 350 km width in single polarization (HH or VV). Table (3.4) presents the operating modes and corresponding features of PALSAR.
In addition to offering high resolution in both range and azimuth directions, PALSAR provides a larger critical baseline, i.e. orbital separation that corresponds to a zero coherence value. The high chirp bandwidth $B_R$, also referred to as range bandwidth, together with the long wavelength (L-band: 23.60 cm), results in increase in critical perpendicular baseline length (see Equation 4.4), which can approach 13 km over flat areas for FBS polarization mode (Lu, 2004), thereby decreasing baseline decorrelation. The critical baseline depending on the ground physical properties reduces to 6.5 km and 3.4 km for FBD and PLR modes, respectively. Another advantage of using a longer wavelength is having the capability of penetrating vegetation, leading to better characterization of vegetation structures as well as wetland and ground features. However, due to its longer wavelength PALSAR is subject to more ionospheric delay than other sensors with shorter wavelengths.
4 Interferometric SAR

In this chapter we present the fundamental principles of SAR interferometry and introduce basic InSAR geometry and equations. After introducing the basics, we will discuss the limitations in InSAR, and then remark on the methods to overcome these limitations. Supplementary information on the methodology can be found in Massonnet and Feigl (1998), Burgmann (2000), and Hanssen (2001).

4.1 InSAR Applications on Geophysical Events

InSAR has been applied to numerous geophysics related studies, including ground displacements associated with tectonic strains (Massonnet et al., 1994; Zebker et al., 1994; Simons et al., 2002; Jacobs et al., 2002), and volcanic strains (Massonnet et al., 1995; Rosen, 1996; Avallone et al 1999; Amelung et al., 2000; Pritchard and Simons, 2002; Wicks et al., 2006); crustal deformation and land subsidence associated with geothermal fields (Massonnet et al., 1997), oil and gas fields (Fielding, et al., 1998; van der Kooij and Mayer, 2001; Vasco et al, 2006; Tamburini et al 2010); and aquifer-system compaction (Galloway et al., 1998; Amelung et al., 1999).

4.2 Principles of InSAR

Interferometric Synthetic Aperture Radar, generally referred to as InSAR or IFSAR, is a synthesis of SAR and interferometry. It exploits the phase difference of two (or more) SAR images acquired over the same area of ground either simultaneously with different configurations (e.g. baseline geometry - orbital separation between platforms, or wavelength) or at different times. The different configuration or different acquisition times determine the type of interferometry.

According to the interferometric baseline formed, InSAR can be classified into across-track or along-track interferometry. Across-track interferometry can be achieved either with a one-antenna platform, e.g. ERS, Envisat, and ALOS, or a two-antenna sensor, e.g., SRTM, at which the antenna(s) are directed perpendicular to the flight direction (Figure 3.1). In along-track technique, the interferometry is performed with two antennas and they are directed parallel to the flight direction. InSAR can also be categorized based on
the times of platform passes, e.g. single-pass or repeat-pass interferometry (Gens and Genderen, 1996). Revisit to the same scene is required for a one-antenna SAR system so that the method is called repeat-pass SAR interferometry (Figure 4.2).

Each pixel in a SAR image contains two properties of the radar echo reflected from objects on the ground: the amplitude and phase. Amplitude provides information regarding the physical characteristics of the scatterer like shape, size, orientation, and dielectric constant. Phase, however, is used indirectly due to its strong interaction with the objects in the surrounding area. In fact, we utilize the phase difference of two images acquired from a slightly different position of the sensor after applying the following steps. The second image is first coregistered and resampled to the same geometrical frame of the first image, both of which are in single look complex (SLC) form (Zebker and Goldstein, 1986; Sansosti et al., 2006). After coregistration and resampling of the second image, the two images are “interfered” by multiplying the first image, called master \( I_1 = A_1 e^{i\varphi_1} \), with the complex conjugate of the second image, i.e. the slave image \( I_2 = A_2 e^{i\varphi_2} \). This process results in an image called complex valued ‘interferogram’, Equation (2.1).

\[
I = I_1 \cdot I_2^* = A_1 e^{i\varphi_1} \cdot A_2 e^{-i\varphi_2} = A_1 A_2 e^{i(\varphi_1 - \varphi_2)} = A e^{i\phi} \tag{4.1}
\]

where \(^*\) denotes the complex conjugate. The product of the amplitudes of the two signals \( A = A_1 A_2 \) is the amplitude, and the phase difference between the two images \( \phi = \varphi_1 - \varphi_2 \) is the phase of the interferogram, and wrapped in \((-\pi, +\pi)\), i.e. One color cycle in an interferogram referred as the Envisat and corresponds to a change of \( 2\pi \), or in terms of distance, it represents the half of the wavelength (Figure 4.1). The aim of the unwrapping process, which will be discussed in detail in the next Chapter, is to integrate these \( 2\pi \) phase discontinuities to produce a continuous signal, allowing an easier interpretation of the data, and subsequently yielding displacement information.

### 4.3 Interferometric Phase and Its Components

In this work, we use repeat-pass interferometry as shown in Figure (4.2). The geometric distances from SAR sensors to a scatterer on the ground at an elevation \( h \) are \( R_1 \) and \( R_2 \), respectively. Vector \( \mathbf{B} \) represents the baseline, i.e. separation, between the two platforms that acquire images at two different times.
If we consider that there is no change both in imaging geometry and in the scattering mechanism on the ground, the two signals, apart from the noise, will then be identical, and the interferometric phase would be zero. However, in the real world this phenomenon is never observed. Let us assume that the phase values $\varphi_1$ and $\varphi_2$ in two SAR images for pixel $P$ are (Hanssen 2001)

$$\varphi_1 = -\frac{2\pi * 2R_1}{\lambda} + \varphi_{scat,1p}$$
$$\varphi_2 = -\frac{2\pi * 2R_2}{\lambda} + \varphi_{scat,2p}$$

(4.1)

where $\lambda$ is the wavelength of the transmitting signal, $R_1$ and $R_2$ present the slant ranges at different acquisitions; $\varphi_{scat,1p}$ and $\varphi_{scat,2p}$ are scattering phase contributions in the images. The (-) sign reflects the principle that the decrease in phase corresponds to an increase in range (see Figure 4.2). If the area imaged shows no variation between acquisitions, i.e. has the same scattering characteristics during observations $\varphi_{scat,1p} = \varphi_{scat,2p}$, the interferometric phase can be expressed as

$$\phi = \varphi_1 - \varphi_2 = -\frac{4\pi(R_1 - R_2)}{\lambda} = -\frac{4\pi\Delta R}{\lambda}$$

(4.2)
The difference in path length, ΔR, in Figure (4.2) can be approximated as

$$\Delta R \approx B \sin(\theta - \alpha)$$ \hspace{1cm} (4.3)

by using the parallel ray or far field approximation introduced by Zebker and Goldstein (1986). \( \theta \) represents the satellite look angle relative to nadir, and \( \alpha \) is the orientation angle of the baseline with respect to reference horizontal plane (Rosen et al., 2000).

Due to inaccuracies in the orbit and 2\( \pi \) phase ambiguity, the \( \Delta R \) cannot be determined from the geometry. However, taking the derivative helps us establish the relation between the changes in \( \Delta R \) and \( \theta \),

$$\partial \Delta R = B \cos(\theta_0 - \alpha) \partial \theta = B_\perp \partial \theta$$ \hspace{1cm} (4.4)

where \( \theta_0 \) is the initial value for the reference surface and \( B_\perp \) is the perpendicular baseline. Taking the derivative of equation (4.2) and combining it with equation (4.4) yields the relationship between the variations in look angle and change in the interferometric phase.
\[ \partial \phi = - \frac{4\pi}{\lambda} B \cos(\theta_0 - \alpha) \partial \theta = - \frac{4\pi}{\lambda} B_{1p} \partial \theta \]  

(4.5)

The height of the sensor (see Figure 4.2) from the reference surface is obtained from the ephemerides of the platform, and can be written as

\[ H = R_1 \cos \theta \]  

(4.6)

and its derivative with respect to the look angle for a pixel in the images is

\[ \partial H = -h_p = -R_{1p} \sin \theta_0 \partial \theta_0 \]  

(4.7)

If we define the equation (4.2) with respect to the \( \sin \) function, combine it with (4.3) and (4.5) and expand the expression about \( \theta = \theta_0 \), we will then be able to explain the relationship between the height \( h_p \) and interferometric phase difference \( \partial \phi \) as follows

\[ \phi = - \frac{4\pi}{\lambda} B \sin(\theta - \alpha) \]

\[ h_p = - \frac{\lambda R_{1p} \sin \theta_0}{4\pi B_{1p}^0} \partial \phi_p \]  

(4.8)

where \( B_{1p}^0 = B \cos(\theta_{0p} - \alpha) \). The initial value for \( \theta_{0p} \) is obtained for a random reference body, e.g. sphere or ellipsoid. Introducing reference phase component and combining with Equation 4.8, we obtain

\[ \partial \phi_p = - \frac{4\pi}{\lambda} B \sin(\theta_0 - \alpha) - \frac{4\pi}{\lambda R_{1p} \sin \theta_0} h_p \]  

(4.9)

The first term in equation (4.9) is independent of the height of the reference surface, thus called the reference phase, or \( \text{flat earth} \), component of the interferogram, and the second term is referred as the topographic component due its dependency on the height.

If a surface displacement, \( d_p \), occurs between the two acquisitions, we should consider its contribution on the interferometric phase with respect to the reference body. Combining Equations 4.2, 4.4, and 4.9 yields
The phase in a SAR image is affected largely by range changes, temporal variations of scatterers, and variations in the atmosphere. In general, the variations in an interferometric phase can be written as the sum of the following components,

\[ \partial \phi = \partial \phi_{\text{flat}} + \partial \phi_{\text{topo}} + \partial \phi_{\text{defo}} + \partial \phi_{\text{atm}} + \partial \phi_{\text{n}} \]  

where \( \partial \phi_{\text{flat}} \) is the difference in phase due to the satellite positions corresponding to different acquisition times and can precisely be estimated by combining precise orbit information with a spherical or elliptical earth surface model; \( \partial \phi_{\text{topo}} \) is the phase difference due to topography form slightly different viewing angles; \( \partial \phi_{\text{defo}} \) is the phase differentiation due to deformation on the ground in the line of sight (LOS) direction; \( \partial \phi_{\text{atm}} \) is the difference in phase due to atmospheric delay along the signal track; and \( \partial \phi_{\text{n}} \) is the phase difference due to temporal decorrelation and noise in the SAR system. From equation (4.10) we know that

\[ \partial \phi_{\text{flat}} = - \frac{4\pi}{\lambda} B\sin(\theta_0 - \alpha) \]  

\[ \partial \phi_{\text{topo}} = - \frac{4\pi B_2^0}{\lambda R_1 \sin \theta_0} h \]  

\[ \partial \phi_{\text{defo}} = - \frac{4\pi}{\lambda} d_p \]  

To obtain a ground deformation map between two SAR acquisitions, the flat earth and topographic components must be eliminated. The interferometric phase is given by modulo \( 2\pi \), rather than an absolute phase. Therefore, only relative height between two neighboring points in an interferogram can be calculated. In order to generate a constant interferometric signal map to obtain the relative heights among all points, the phase difference between all adjacent pixels is integrated, even though the solution becomes non-unique because of phase jumps of more than \( \pi \). This process is called “phase unwrapping” and will be reviewed in Chapter 5. The phase can then be transformed to topography by inverting Equation (4.11), after the removal of the flat earth term.
The topography term is removed by using either a digital elevation model (DEM), e.g. from the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) or ASTER, or an additional interferogram (Gabriel et al., 1989). In fact, the last technique necessitates three- or four-platform passes. The difference between the two methods is that one of the images is used to form both the topographic and deformation interferograms in three-pass interferometry. In this study, we used a digital elevation model from SRTM to eliminate the topography component. The DEM is obtained from the US Geological Survey’s website (Figure 4.3).

![Figure 4.3. DEM of Adiyaman Region](image)

After eliminating first two components from Equation (4.11), we obtain the differential interferometric phase

$$
\phi = \phi_{err} + \phi_{defo} + \phi_{atm} + \phi_{n}
$$

(4.15)

where $\phi_{err}^{dem}$ symbolizes artifacts due to errors in the DEM, $\Delta h$, and can be defined as

$$
\phi_{err}^{dem} = -\frac{4\pi B_1^0}{\lambda R_1 \sin \theta_0} \Delta h
$$

(4.16)
4.4 Error Contributions in Interferometric SAR

The main error sources in InSAR measurements are related to surface topography, deformation, atmospheric delay, and refractivity variations in the scatterers. In this section, we will review the most significant artifacts affecting the ground deformation measurements. For detailed discussion see Hanssen (2001).

4.4.1 Phase Noise

The characteristics of the imaged surface determine the quality of the SAR interferometry, as well as the deformation estimates (Zebker and Villasenor, 1992). The quality of the imaging is defined by a coherence, or correlation coefficient, value for each pixel. Coherence, more exactly complex coherence, $\rho$, is defined as

$$\rho_i = \frac{\mathbb{E}(M_i \cdot S_i^*)}{\sqrt{\mathbb{E}(|M_i|^2)\mathbb{E}(|S_i|^2)}} = \frac{\mathbb{E}(M_i \cdot S_i^*)}{\sqrt{\mathbb{E}(M \cdot M^*)\mathbb{E}(S \cdot S^*)}} = |\rho_i| \exp (i\phi_0) \quad (4.16)$$

where $i$ represents the pixel number, $\mathbb{E} \{ \}$ is the expectation, $M_i$ is the value of the pixel in the reference, or master, image and $S_i^*$ is the pixel's complex conjugate value in the second, or slave, image. As can be remembered from Equation 4.1, the product of two images, $A_1A_2e^{i(\varphi_1-\varphi_2)}$, is equal to the expectation of the numerator of the complex coherence. Because the denominator is formed by real values, the phase of the complex correlation is the expected phase of the interferogram, $\phi_0$. (Hanssen, 2001). The magnitude $|\rho_i|$, ranging from 0 to 1 – no correlation to full correlation, is a measure of the phase noise.

The correlation in an interferogram, i.e. coherence, is computed by averaging of neighboring pixels. The main problem in coherence estimation originates from the trade off between dimension of the window and estimated accuracy. The Equation (4.17) yields the relationship between the coherence and signal-to-noise ratio (SNR) (Hanssen, 2001)

$$\rho = \frac{SNR}{SNR + 1} \quad (4.17)$$
4.4.2 Decorrelation

Decorrelation is the chief source of degradation in the accuracy of the phase in an interferogram. The main decorrelation factors can be expressed as (Zebker and Villasenor, 1992)

\[ \rho = \rho_{\text{temp}} \cdot \rho_{\text{spat}} \cdot \rho_{\text{therm}} \]  

(4.18)

where \( \rho_{\text{temp}} \) represents the \textit{temporal decorrelation}, \( \rho_{\text{spat}} \) is the \textit{spatial decorrelation}, and \( \rho_{\text{therm}} \) corresponds to \textit{thermal decorrelation}. It is possible to increase the number of components by introducing the terms \( \rho_{\text{DC}}, \rho_{\text{vol}}, \text{ and } \rho_{\text{processing}} \); Doppler centroid decorrelation, volumetric decorrelation, and processing induced decorrelation, respectively. Doppler centroid decorrelation originates from the variation in Doppler centroids for the two observations; the volumetric decorrelation results from the penetration of the radar signal in the scattering ambiance, which alters with the signal wavelength and/or dielectric properties of the medium. The processing induced decorrelation is caused by the chosen algorithms, e.g. for coregistration and interpolation (Hanssen, 2001).

If the area of interest shows seasonal variation, i.e. due to vegetation, precipitation or volcanic activities, the reflectivity on the surface changes. Thus, the scattering properties vary with time, resulting in loss of coherence in an interferogram, a situation referred to as temporal decorrelation. As a result, InSAR studies have focused mainly on dry and sparsely vegetated areas like the southwest of the U.S., the Northern Africa, the Middle East and the Arabian Peninsula, and the Tibetan plateau.

Imaging geometry may also cause decorrelation or reduction in the quality of an interferogram. The coherent total of the backscatters from small elements in a pixel changes due to the variation in incidence angles. This results from non-zero perpendicular baseline (see Figure 4.2), which causes a difference in repetition of the observation. This phenomenon is known as spatial decorrelation (Zebker and Villasenor, 1992) and increases with increasing perpendicular baselines.

Rotation of the object on the ground with respect to the antenna look direction is another geometrical effect that results in decorrelation. This occurs when the illuminating patches are not entirely parallel at the two times of acquisitions, so called “rotational decorrelation”.

A similar geometrical effect is also observed because of variations in squint angle, the angle through which the space vehicle points forward or backward. A differentiation in squint angle changes the Doppler frequency range in SAR system leading to decorrelation.
Thermal decorrelation arises from the system noise in SAR systems, and can contribute to signal-to-noise ratio (SNR) reduction (Zebker and Villasenor, 1992).

Even though most of these decorrelation effects can be decreased by filtering, there are limits on the baseline and squint angle variation beyond which there is no interferogram coherence (Zebker and Villasenor, 1992). In brief, albeit SAR data sets are obtained in a regular fashion, temporal and geometric decorrelation effects limit the InSAR pairs that can be used to generate interferograms, and hence the temporal resolution.

### 4.4.3 Orbit Errors

Orbit positions of the SAR platforms during the acquisitions significantly affect the accuracy of the interferogram. Artifacts in the calculation of the interferometric baseline, resulting from the errors in the orbital vectors (Figure 4.4), yield inaccurate scaling of the topography phase, and hence imprecise elimination of the flat earth component from the interferometric phase.

![Figure 4.4. Three-dimensional representation of an orbital state vector and velocity vector with error bars included, (Hanssen, 2001).](image)

The errors in the orbital state vectors can be decomposed into three components: the along track, the across track and the radial errors as depicted in Figure (4.4). The along track errors are often corrected in the coregistration step of the interferometry processing. The across track and radial errors will propagate as systematic phase errors in the interferogram, the three-dimensional problem thus transforms to a two-dimensional problem. This allows us to consider the effects in the range and azimuth directions. The orbital errors can be separated in an almost instant component in the range direction, and slow time-dependent component in azimuth direction. Furthermore, because interferometry is performed on the relative basis, the errors required to propagate to the
baseline vector, rather than studied separately. Using precise orbital information, we can obtain rms errors on the order of 5 cm and 8 cm, for radial and across track vectors, respectively (Hanssen, 2001).

4.4.4 DEM Errors

Errors in the digital elevation model (DEM) will result in a direct translation of error in the deformation analysis. The topographic term in Equation (4.9) yields the relationship between changes in surface height $h$ and the corresponding phase change $\delta \phi$. Using image pairs providing a small perpendicular baseline may reduce the effects of DEM artifacts.

For interferograms having larger baselines, it should be noted that difference in the measured scattering center compared to the reported topography height might introduce substantial errors. The elevation provided in the DEM is the regional geoid height, which varies depending on the ellipsoid type used, and the height of the imaged surface may differ on the order of several meters from this elevation. This can cause significant problems, based on the radar wavelength, in urban areas or in vegetated areas where backscatters from tall buildings or high trees interfere with the echoes from other surrounding objects (Askne et al., 1997), resulting in phase error in the interferogram.

4.4.5 Atmospheric Errors

After decorrelation, atmospheric effects are considered as the second major limitation in conventional SAR interferometry. As electromagnetic signals travel through the atmosphere there is a time and space dependent delay due to atmospheric refraction. Studies have shown that the atmospheric delay effect can induce considerable errors in InSAR measurements (Massonet et al., 1994), especially to the repeat pass interferometry.

The effect of the atmosphere in the interferometric phase, $\partial \phi_{atm}$, differs over the image (Hanssen, 2001), and most of the difference in this term results from the variation in the distribution of water vapor in the media. The atmospheric phase is often correlated with the local topography (Onn and Zebker, 2006). For example, areas with significant topography indicate additional variation that associates with the surface elevation. In general, time scale of correlated $\partial \phi_{atm}$ ranges from hours to days. As the time between two SAR data acquisitions is separated by more than a month, 35 days for Envisat and 46 days for ALOS Palsar, atmospheric phase is essentially decorrelated in time.

There are two methods to mitigate the effects of the atmospheric error on SAR interferograms: stacking (statistical) (Zebker et al., 1997; Emardson et al., 2003), and calibration (Delacourt et al 1998; Williams et al., 1998, Wadge et al., 2002). In the
statistical method, the atmospheric delay is considered as white noise, and several independent interferograms of the area of interest on the ground are stacked, i.e. they are averaged, to mitigate the noise. There are two drawbacks associated with the method. First, many high-correlated interferogram pairs are needed in order to obtain a more precise average value. Second, any spatial or temporal variation in the nature of deformation over the period of the stack is lost.

In the calibration method, independent sources of atmospheric delay parameters like zenith delay (ZD) estimates from continuous GPS (CGPS) networks and meteorological data are used to reduce the noise. The only drawback of the method is the sparse geometry of the external data. Yet, it is important to note that GPS sites should be close enough to take microclimates into account when atmospheric effects are investigated in regions where drastic weather change can occur, e.g. volcanic areas. We address the atmospheric phase errors by applying a temporal and spatial filtering technique discussed in Chapter 5.3.5.

4.5 Multiple Acquisition Methods

Multiple acquisition methods are extensions to the above-described conventional InSAR intended to mitigate the effects of decorrelation and atmospheric delay. The multiple acquisition InSAR methods can be categorized into two main groups, each of which is designed based on a particular scattering scheme: persistent scatterer InSAR (PSInSAR) introduced by Ferretti et al. (2001), and small baseline SAR interferometry (SBAS) developed by Berardino et al (2002). Both techniques simultaneously process multiple SAR data sets over the same area to correct the uncorrelated phase noise, yielding reduced errors and hence better deformation estimates.

Figure 4.5. Scattering simulations for a) a distributed scatterer pixel and b) a persistent scatterer pixel. The distributed scatterer pixel has a larger phase variation pattern than the persistent scatter pixel.
The decorrelation amount within a pixel varies with respect to the distribution and the reflectivity of the scattering centers on the ground. In an image, returned signal from each scatterer is the coherent sum of the individual wavelets scattered by several discrete scattering centers (Figure 4.5a). Due to both viewing angle and movement of the scatterers with respect to the platform, some of these wavelets contribute to a trend in which phase and amplitude in the pixel exhibit large variations in the interval \((-\pi, \pi)\) (see the plot below the Figure 4.5a drawing). This results from the random movement of the individual scatterers in a pixel. If one of the wavelets dominates in the pixel’s phase (Figure 4.5b) due to larger amplitude of the scatterer, there will then be little contribution to the phase from the other scatterers. The returned signal for this pixel shows little differentiation with time as the other scatterers randomly move (see the plot below the Figure 4.5b drawing), and any movement of the scatterer can be measured by the phase of the radar echo.

If only one point scatterer had formed the phase of the resolution element, there would be no decorrelation and all images would be used to generate interferograms. All of these interferograms can then be used to estimate deformation. Even though such point scatterers hardly exist in nature, there are pixels in which one scatterer has larger contribution to the phase and thus can be thought as point scatterer, yielding a significant decrease in decorrelation. Examples for such scatterers might be a large rock or a bush in an arid area or at the edge of a waterfall, or a corner of a roof of a building. This is the model for the Persistent Scatterer InSAR (PSInSAR) pixel. PS methods determine the pixels with a single governing point scatterer by applying statistical techniques to all image pairs that are at the maximum possible resolution. After identifying the pixels with single dominant scatterers, the methods use the associated interferometric phase to estimate and remove the atmospheric effect and hence generate a deformation time series.

As mentioned above, if there is no dominant single point scatterer in the pixel, then the interferometric phase varies in the \(\pm \pi\) radians range in a random fashion. In this case, the signal-to-noise ratio can be improved by taking the average of the interferometric phase of the neighboring pixels. This yields a phase due to the average movement of the averaged pixels, which neutralizes the effect of the random phase contributions due to the motion of scatterers. The core of the Small Baseline SAR interferometry (SBAS) methods is formed by this methodology. Stacking numerous interferograms (Sandwell and Price, 1998) with short baselines enable atmospheric effects to be mitigated. Furthermore, using singular value decomposition (SVD) and temporal models, nonlinear deformation can also be estimated from stacked interferograms. In this work, we have used the SBAS method to obtain the LOS displacement on the surface of the Adiyaman oil field with ascending track images acquired over the region, in the southeast of Turkey.
Chapter 5

5 Small BAaseline Subset Method (SBAS)

5.1 Introduction

As mentioned in the previous chapter, differential InSAR has been widely used for monitoring deformations due to seismic (Massonet et al., 1993; Zebker et al., 1994) or volcanic (Massonet et al., 1995; Rosen, 1996) phenomena, all of which necessitate short temporal baselines between two observations to reduce decorrelation. Due to the nature of our application, however, we are interested in low velocity deformation, a condition that forces us to have long intervals between acquisitions. Accordingly, decorrelation dominates phases over large areas, and degrades the use of interferometric phase. In addition to the gap between observations, atmospheric errors cause an extra constraint for all interferograms. As discussed in Chapter 4 to overcome the aforementioned limitations, numerous methods have been examined by Ferretti et al. (2001), Hanssen (2001), Berardino et al. (2002), Usai (2003), and Hooper (2007). In this chapter, we will discuss in detail the technique called small baseline subset (SBAS), which is developed by Berardino et al. (2002).

The use of interferograms with small baselines forms the basis of the method, which leads to a decrease in decorrelation caused by temporal baseline and inaccuracies in digital elevation model (DEM). However, this may result in different subsets of interferograms with no image in common for a given set of data. Lundgren et al. (2001) showed one deformation time series per subset. The method later advanced by using singular value decomposition (SVD) technique to link all subsets (Berardino et al., 2002).

The small baseline subset (SBAS) method is based on the combination of interferograms generated by two SAR images that are characterized by a short orbital separation, i.e. geometric baseline, in order to reduce the spatial decorrelation. The advantage of the system is that the temporal sampling rate can be increased by using SVD method on images that are separated with long time intervals. Instead of removing the error contribution of topographic phase component, the SBAS method employs an estimate of topography error in order to increase the accuracy. Furthermore, errors in the atmospheric phase component are eliminated by a filtering process that is applied on the lines of the resolution element, a technique developed for the permanent scatterer (Ferretti et al., 2001) method, taking the advantage of the high spatial density of the imaged pixel.
5.2 SBAS Methodology

We assume that there are $N + 1$ numbers of SAR images that have been acquired over the same area at chronologically ordered times $t_0, ..., t_N$. Moreover, we assume that each data set can interfere with another more than once to generate interferograms, suggesting that each subset consists of at least two images. In the light of these assumptions, we can now define the expression for a number of potential interferograms, $M$, as (Berardino et al., 2002)

$$\left\lfloor \frac{N + 1}{2} \right\rfloor \leq M \leq N \left( \frac{N + 1}{2} \right)$$ (5.1)

If we remove the topographic phase component and assume that there are no artifacts in phase due to differences in refractivity in the atmosphere between observations and/or due to erroneous removal of the topographic phase element, the decorrelation becomes negligible. The interferogram $\text{int}$ can then be expressed with respect to its azimuth and range coordinates $(a, r)$ in the pixel, following the SAR image acquisitions at times $t_k$ and $t_{k+1}$ as

$$\Delta \phi_{\text{int}}(a, r) = \phi(t_{k+1}, a, r) - \phi(t_k, a, r) \approx \frac{4\pi}{\lambda} [\Delta(t_{k+1}, a, r) - \Delta(t_k, a, r)]$$ (5.2)

where $\lambda$ is the wavelength of the radar signal, $\Delta(t_{k+1}, a, r)$ and $\Delta(t_k, a, r)$ are the line of sight (LOS) cumulative ground deformations at times $t_k$ and $t_{k+1}$ regarding the initial acquisition time $t_0$, assuming that there is no deformation at $t_0$, $\Delta(t_0, a, r) = 0$. Hence, we can characterize the deformation time series as $\Delta(t_j, a, r)$ with $j = 1, ..., N$; and the corresponding phase component as $\phi(t_j, a, r) \approx 4\pi \Delta(t_j, a, r)/\lambda$.

As pointed out in Chapter 4, the interferometric phase is measured by the interval of $[-\pi, \pi]$, the so-called wrapped phase, and therefore a recovery process, called phase unwrapping, is needed to relate the measured data to physical phenomenon. We assume that Equation (5.2) has been obtained after unwrapping and SBAS benefits from the mentioned characteristics of pixels and carries out a pixel-by-pixel analysis. Consequently, the dependency on coordinates can be removed from equation (5.2), and the unknown phases, associated with the deformation of the considered pixel, are arranged in an $N$-component array form as follows

$$\phi^T = [\phi(t_1), ..., \phi(t_N)]$$ (5.3)
To represent the problem in the matrix form, the calculated, i.e. known, differential phases are organized in an M-element array

\[ \delta \Phi^T = [\delta \Phi_1, ..., \delta \Phi_M] \]  

where \( \delta \Phi_k \) \((k = 1, ..., M)\) is the differential interferometric signal with respect to a single pixel. We create two index matrices that correspond to image pairs used to form an interferogram: matrices for the principal - master image (PI) and secondary - slave image (SI)

\[
\begin{align*}
\text{PI} &= [P_{11}, ..., P_{IM}] \\
\text{SI} &= [S_{11}, ..., S_{IM}]
\end{align*}
\]  

Equation (5.6) identifies a system of \( N \) unknowns and \( M \) equations that can be arranged in the following matrix form:

\[ A\Phi = \delta \Phi \]  

where \( A \) is the \( M \times N \) system matrix, \( \forall i = 1, ..., M, A(i, S_i) = -1 \) if \( S_i \neq 0 \), \( A(i, P_i) = +1 \), and zero otherwise. For instance, if \( \delta \Phi_1 = \phi_3 - \phi_2 \) and \( \delta \Phi_2 = \phi_4 - \phi_0 \), then \( A \) would be as follows

\[ A = \begin{bmatrix}
0 & -1 & +1 & 0 & \ldots \\
0 & 0 & 0 & +1 & \ldots \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \vdots & \vdots & \ddots 
\end{bmatrix} \]  

Equation (5.8) that matrix \( A \) depends on the available set of interferograms similar to an incidence-matrix. If a single small baseline subset contains all the acquisitions, then \( A \) would have a rank of \( N \), \((M \geq N)\). This would lead to a system that
is either well- \((M = N)\) or over-determined \((M > N)\). Subsequently, such system can be solved in the least squares (LS) sense as

\[
\hat{\phi} = A^* \delta \phi \quad A^* = (A^T A)^{-1} A^T
\]  

However, a single small baseline subset rarely contains an entire data. Hence, we should consider that the data belong to different subsets and if we use numerous interferograms to increase the temporal sampling, we will encounter with rank deficiency. The rank of \(A\) would decrease with respect to the number of likely subsets in the data, yielding singularity in \(A^T A\). For example, if we acquire \(Z\) different small baseline subsets, the rank of \(A\) will be \(N - Z + 1\), and the system (5.7) will have infinitely many solutions (Berardino et al., 2002).

The system (5.7) can be solved, or be inverted, by simply using singular value decomposition (SVD) method (Strang, 1988). The technique is basically applied to non-square arrays, and consists of multiplication of orthogonal and diagonal arrays. SVD is a vital tool for solving linear inverse problems, and is generally used when other algorithms cannot provide an answer. When we apply SVD on matrix \(A\), we obtain

\[
A = USV^T
\]  

where \(U\) is an \(M \times M\) orthogonal matrix, and its first \(N\) columns, also known as the left-singular vectors of \(A\), are the eigenvectors of \(AA^T\). \(S\) is a \(M \times M\) diagonal matrix and its entries (the singular values \(e_k\)) are the square root of the corresponding eigenvalues of matrix \(A^T A\). In general \((M > N)\), there are \(M - N\) number of zero eigenvalues and \(Z - 1\) additional null eigenvalues due to the singular characteristics of the matrix \(A\). \(S = diag (e_1, e_2, ..., e_{N-L+1}, 0, ..., 0)\). \(V\) is an \(N \times M\) orthogonal matrix and its columns, called the right-singular vectors of \(A\), are the eigenvectors of \(A^T A\).

After decomposing matrix \(A\), the estimate in (5.9) with minimum norm least squares solution for unknown phases takes the form of

\[
\hat{\phi} = A^# \delta \phi \quad A^# = VS^# U^T
\]  

\[
S^# = \begin{bmatrix} S^{-1} & 0 \\ 0 & 0 \end{bmatrix}
\]  

where \(S^{-1} = diag (1/e_1, ..., 1/e_{N-L+1}, 0, ..., 0)\).
This solution is identified by a minimum norm constraint on the phase values, and therefore on deformation (see Equation 5.2). As a result, the method compels the solution to be as close to zero as possible. However, this phenomenon may lead to large discontinuities in the cumulative deformations obtained, and accordingly yield meaningless physical results (Berardino, et. al, 2002).

![Comparison between the minimum-norm phase (dashed line) and the minimum-norm phase velocity (solid line) deformations. Dots and crosses represent the two SB subsets (Berardino, 2002).](image)

Figure 5.1. Comparison between the minimum-norm phase (dashed line) and the minimum-norm phase velocity (solid line) deformations. Dots and crosses represent the two SB subsets (Berardino, 2002).

To acquire physically sound solutions, the system (5.8) is modified such that the unknowns, i.e. phase values, are replaced with the mean phase velocity values of the two time-adjacent observations. This means that applying the minimum norm solution minimizes the mean velocity. Subsequently, the new unknowns transform to

\[
\nu^T = \begin{bmatrix} \nu_1 = \frac{\phi_1 - \phi_0}{t_1 - t_0}, \ldots, \nu_N = \frac{\phi_N - \phi_{N-1}}{t_N - t_{N-1}} \end{bmatrix}
\] (5.12)

and equation (5.7) replaces with

\[
\sum_{k=S+1}^{P} (t_k - t_{k-1}) \nu_k = \delta \phi_i
\] (5.13)

in matrix notation

\[
B\nu = \delta \phi
\] (5.14)
where $B$ is an $M \times N$ system matrix, which has the entries of $B(i,k) = t_{k-1} - t_k$ for $SI_i + 1 \leq k \leq PI_i$, $\forall i = 1, ..., M$, and $B(i,k) = 0$ elsewhere. The SVD method is applied to the matrix $B$, and the mean velocity vector $\mathbf{v}$ has no large discontinuities, Figure (5.1), and can be estimated. We, however, need an extra integration step to obtain the final phase solution $\phi$ from the estimated mean velocities.

### 5.2.1 Addition of Time Model for Phase Behavior

In the presence of an additional time model for phase behavior, our inverse problem may further simplified. For example, we assume that the velocity vector $\mathbf{v}$ has a linear relationship with the model parameter vector $\mathbf{p}$, i.e.,

$$
\mathbf{v} = \mathbf{Wp} \quad (5.15)
$$

where the columns of matrix $\mathbf{W}$ correspond to the vector components of $\mathbf{v}$. Substituting (5.15) in (5.14) yields

$$
\mathbf{BWp} = \delta \phi \quad (5.16)
$$

To illustrate the concept, let us assume a cubic model for time differentiation of the signal phase, the generic term can be expressed as (Berardino et al., 2002)

$$
\phi(t_i) = \bar{v}(t_i - t_o) + \frac{1}{2} \bar{v}'(t_i - t_o)^2 + \frac{1}{6} \Delta \bar{v}''(t_i - t_o)^3 \quad (5.17)
$$

where $\bar{v}$, $\bar{v}'$ and $\Delta \bar{v}''$ are the unknown components of parameter vector $\mathbf{p}$ corresponding to the mean velocity, the mean acceleration, and the variation of the mean acceleration, respectively. The vector $\mathbf{p}$ and the model matrix $\mathbf{W}$ are

$$
\mathbf{p} = [\bar{v} \quad \bar{v}' \quad \Delta \bar{v}']^T \quad (5.18)
$$
\[
W = \begin{bmatrix}
1 & \frac{t_1 - t_0}{2} & \frac{(t_1 - t_0)^2}{6} \\
1 & \frac{t_2 - t_1 - 2t_0}{2} & \frac{(t_2 - t_0)^3 - (t_1 - t_0)^3}{6(t_2 - t_1)} \\
\vdots & \vdots & \vdots \\
1 & \frac{t_N - t_{N-1} - 2t_0}{2} & \frac{(t_N - t_0)^3 - (t_{N-1} - t_0)^3}{6(t_N - t_{N-1})}
\end{bmatrix}
\] (5.19)

In general, system in (5.16) is non-singular for a smooth temporal model, hence leading to a LS estimate for parameter vector \( \hat{\mathbf{p}} \) through the left pseudoinverse matrix \((\mathbf{BW})^\dagger\).

### 5.2.2 Temporal Low-Pass Phase Estimation

After phase values are unwrapped, an estimate of temporal low-pass component of the deformation signal and possible topography errors can be computed by using the least squares solution similar to that of Section 5.2.1. We may form the following system of equations derived from (5.16)

\[
[\mathbf{BM}, \mathbf{c}] \mathbf{p}_c = \delta \mathbf{\Phi}
\] (5.20)

where \( \mathbf{c}^T = [(4\pi/\lambda)(B_{\perp\perp} / R \sin \theta), ..., (4\pi/\lambda)(B_{\perp M} / R \sin \theta)] \) and corresponds to any DEM errors related to the measured InSAR phase. The vector \( \mathbf{p}_c^T = [\mathbf{p}^T, \Delta z]^T \) consists of unknown lower-pass (LP) components and DEM artifacts of the unwrapped phase, respectively. The estimate of \( \mathbf{p}_c \) in (5.20) can be calculated directly from LS method.

\[
\hat{\mathbf{p}}_c = (\mathbf{BM}, \mathbf{c})^T (\mathbf{BM}, \mathbf{c})^{-1} [\mathbf{BM}, \mathbf{c}]^T \delta \mathbf{\Phi}
\] (5.21)

The absolute LP phase for each image may now be formed by using the estimated mean velocity \( (\hat{\mathbf{v}}) \), mean acceleration \( (\hat{\mathbf{v}}') \), the mean acceleration variation \( (\Delta \mathbf{v'}) \), and the given time via equation (5.17).

The estimated LP phase \( \delta \hat{\mathbf{\Phi}} \) and DEM error \( \partial \Phi_{\text{err}}^{\text{dem}} \) are then subtracted from each interferogram with respect to modulo 2\( \pi \). The phase is unwrapped following the subtraction step. It should also be noted that the phase term becomes the residual after this separation, yielding a simpler process due to reduction of the fringe rate. Subsequently, the phase term now consists of nonlinear deformation, atmospheric errors and other phase noise sources. Furthermore, if we add the subtracted unwrapped LP
phase component back to the calculation, we would obtain a refined unwrapped differential phase signal with topographic errors removed.

5.2.3 Deformation estimate

Differential phase $\delta \phi$ in equation (5.14) becomes the refined differential phase and applying the SVD on matrix $B$ will result in an LS estimate of the mean velocity vector $v$

$$Bv = \delta \phi$$

$$\hat{v} = V \begin{bmatrix} S^{-1} & 0 \\ 0 & 0 \end{bmatrix} U^T \delta \phi$$

(5.22)

If we carry out integration on the above system, we will be able to retrieve the signal phase $\phi$ from the estimated mean velocity vector $\hat{v}$ of deformation. It is important to note that the retrieved phase includes both decorrelation and atmospheric effects. Yet, the decorrelation effects are reduced in the interferogram generation stage by using the complex multi look images and phase stability step through highly-correlated pixels.

5.3 Processing via StaMPS

As pointed out in Chapter 4, interferometric phase has different components (Equation 4.9). If there are many interferograms, the topographic error and deformation signal correlate with each other. However, due to varying characteristics of the atmosphere between acquisitions, its contribution is considered uncorrelated. The following subsections provide information on each processing step performed by Stanford Method for Persistent Scatterer (StaMPS) package (for detailed information see Chapter 7).

5.3.1 Phase Stability And Pixel Selection

In contrast to general procedure in interferometric SAR in which unwrapped phases are described on rectangular grid, the differential interferograms include sparse unconnected coherent local patches due to the decorrelation caused by large temporal baselines. Therefore, phase unwrapping is often performed within each regional patch, yet individual patches may have phase biases of multiples of $2\pi$.

To enable the phase unwrapping, we should only use the “good data” based on a given norm. The StaMPS method utilizes the amplitude dispersion index, i.e. the standard
deviation of a pixel’s amplitude over all interferograms divided by the mean amplitude of the pixel, in order to obtain good data. Ferretti et al. (2001) stated that there is a relationship between amplitude dispersion index and phase stability, which can be used to reduce the amount of data that are being analyzed. The phase stability is studied on an initial subset of all the pixels, called persistent scatterer candidates (PSc), in the SBAS, or single master, interferograms. Setting the amplitude dispersion index high yields a selection of PSc to be real persistent scatterers (PS).

After flattening and subtracting the topographic component, an interferometric phase at pixel \( x \) in interferogram \( i \) can be defined as (Hooper et al., 2007)

\[
\varphi_{x,i} = W(\phi_{\text{defo},x,i} + \Delta \phi_{\theta-DEM,x,i} + \Delta \phi_{\text{orb},x,i} + \phi_{\text{atm},x,i} + \phi_{n,x,i})
\]  

where \( W \) operator indicates that the phase values are wrapped, \( \phi_{\text{defo},x,i} \) is the phase change due to deformation in the satellite line of sight (LOS) direction, \( \Delta \phi_{\theta-DEM,x,i} \) is residual look angle error, i.e. DEM error, \( \Delta \phi_{\text{orb},x,i} \) denotes the residual phase due to orbital artifacts, \( \phi_{\text{atm},x,i} \) is the phase caused by atmospheric delay, and \( \phi_{n,x,i} \) symbolizes the noise terms including errors due to change in scatterer characteristics in the pixel, thermal and coregistration. Persistent scatterer (PS) pixels are defined as the points with low noise so that the signal is not obscured by the noise.

The orbital and atmospheric errors and generally the deformation signal are (Hooper et al., 2007) spatially correlated. The look angle error, on the other hand, is partly correlated. Stamps uses a band-pass filtering technique developed by Goldstein and Werner (1998) to obtain the spatially correlated parts of the Equation 5.23. The resulting filtered interferometric phase, \( \bar{\varphi}_{x,i}^c \), is then subtracted from the original phase, yielding spatially uncorrelated part of the deformation signal \( \Delta \phi_{\text{defo},x,i}^{unc} \), look angle error \( \Delta \phi_{\theta-DEM,x,i}^{unc} \), and noise terms \( \phi_{n,x,i}^{unc} \).

\[
W(\varphi_{x,i} - \bar{\varphi}_{x,i}^c) = W(\Delta \phi_{\text{defo},x,i}^{unc} + \Delta \phi_{\theta-DEM,x,i}^{unc} + \phi_{n,x,i}^{unc})
\]  

The estimate of the spatially uncorrelated part of the look angle error is calculated and removed from the Equation 5.24 as described in Hooper et al. (2007).

\[
W(\varphi_{x,i} - \bar{\varphi}_{x,i}^c - \Delta \phi_{\theta-DEM,x,i}^{unc}) = W(\Delta \phi_{\text{defo},x,i}^{unc} + \phi_{n,x,i}^{unc})
\]  

where \( \Delta \phi_{\theta-DEM,x,i}^{unc} \) represents the estimate of spatially uncorrelated look angle error, and \( \bar{\varphi}_{x,i}^c \) is the residual phase due to remainders for all estimated phase components.
The estimate of $\delta \phi_{x,i}^{unc}$ is expected to be very small, we therefore can neglect those terms. This leads us to phase noise in the right hand of the Equation 5.25. PS points are defined as the points with low phase noise. Therefore estimated phase noise is the quality of a point $x$ in interferogram $i$, and its magnitude can be found as

$$\gamma_x = \frac{1}{N} \left| \sum_{1}^{N} \exp \left\{ i(\phi_{x,i} - \phi_{x,i}^{sc} - \delta \phi_{\theta - DEM,x,i}) \right\} \right|$$

(5.26)

where $N$ is the number of interferograms. The estimation is done iteratively. In each iteration step, the resulting value of $\gamma_x$ is used to weight the contribution of each pixel to the estimation of the spatially correlated phase for next step. We define a threshold value for assessing the convergence of the estimation, and the iterations stop when the difference between two successive $\gamma_x$ estimation is above the set threshold value.

Defining a threshold value also initiates the selection of persistent scatterers (PS). The PS contain both PS and non-PS points. In the first part, the magnitude of $\gamma_x$ was defined as a measure for the probability of a pixel being a PS. In the final part, the PS pixels are selected based on the calculated $\gamma_x$ values. The probability density function (PDF) of the PS as a function of $\gamma_x$, $p(\gamma_x)$, is the weighted sum of the PDF for PS pixels, $p_{ps}(\gamma_x)$, and the PDF of non-PS points, $p_{rand}(\gamma_x)$, and are calculated as described (Hooper et al., 2007).

In addition, the selected PS pixels are put through a weeding step in which only pixels with the highest $\gamma_x$ values are kept. Optionally, the selected PS pixels can be re-estimated at this step along with the phase noise. Taking the difference of phase between adjacent pixels, instead of a band-pass filtering the phase, eliminates the spatially correlated phase parts. Up to this point, all wrapped interferometric phase values were resampled to a grid, which enabled a Fast Fourier Transform to be implemented. Then, the gridded phase values were filtered with an adaptive low pass filter, called Goldstein Filter, as described in Goldstein and Werner (1998). Now, it is time to connect the adjacent pixels, or empty grid cells. This is done by using nearest neighbor interpolation by Delaunay triangulation (Delaunay, 1934). The technique connects all neighboring pixels of unevenly gridded data by forming non-overlapped triangles as shown in Figure (5.2). After the selection of the coherent pixels, phase values in each pixel are unwrapped to obtain true phase values of the backscatters.

5.3.2 Phase Unwrapping and Error Terms

Phase unwrapping is considered one of the most challenging steps in an InSAR application. It is the stage where the exact multiple of $2\pi$ to each point in the interferometric phase image is restored.
Numerous phase unwrapping algorithms have been developed in the last three decades (Goldstein et al., 1988; Ghiglia and Romero, 1996; Flynn, 1997; Zebker and Lu, 1998; Costantini and Rosen, 1999; Chen and Zebker, 2001), and as stated earlier it is still one of the most challenging problems in SAR interferometry.

In this project, we have performed an unwrapping technique called Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (SNAPHU), developed by Chen and Zebker (2001) using the StaMPS computer program. The phase unwrapping problem turns into maximum a posteriori (MAP) probability estimation after using suitable nonlinear cost functions. Given the observable values of SAR signals, including wrapped phase, amplitude of the image, and correlation coefficient of the interferogram, the cost functions are formulated via approximate models for the statistics and the expected properties of interferometric SAR signals.

![Delaunay Triangulation](image)

Figure 5.2. Delaunay Triangulation. Note that the method does not extrapolate.

To obtain deformation estimates, we should first unwrap the selected PS pixels and estimate the nuisance terms. StaMPS enables a 3D unwrapping process, spatial (x,y) and time. However, the unwrapping of the gridded phase values become impossible in time, if the atmospheric nuisance term is larger than $\pi$. The solution is that unwrapping over arcs, i.e. natural neighbor found by Delaunay triangulation. As defined earlier the atmospheric signal is spatially correlated, and taking the difference in phase between adjacent pixels mainly eliminates it. Assuming all phase differences are in the range of $\pm \pi$, we can now unwrap the phase differences in time. To obtain smooth data, the unwrapped phase values are low-pass filtered. The results are then used to obtain a-priori PDFs of unwrapped phase difference between neighboring grid cells. Utilizing those PDFs, we acquire cost functions for spatial unwrapping. Finally, the optimization procedure described in (Chen and Zebker, 2001) first unwraps the phase for each grid, then the phase at each point.
We should keep in mind that the phase unwrapping is only applied to those pixels whose expected coherence value is above the selected threshold. This allows for better results because the procedure automatically excludes the signals severely affected by noise.

Once phase is unwrapped, the next step is to estimate the atmospheric, look angle – DEM, and orbital error terms. By estimating the spatially uncorrelated part, which is linearly related to the perpendicular baseline, the look angle error can be found from unwrapped phase values. Orbital artifacts, which are seen as linear ramps in the interferograms, can be calculated using the linear relation in space. Because the ramps are randomly oriented for most satellites, they will cancel out over time. Hence, neglecting the removal of orbital ramps is also common practice. All these error terms exist in the master image; therefore, they will be present in all interferograms. The contribution of the nuisance terms from the master image is determined by low-pass filtering arcs in time of the master image, and recovering the residual of the arc phases at the master acquisition time when the displacement contribution is zero.

The only remaining terms are the slave image contributions of the atmospheric signal to each interferogram. The atmospheric phase component is highly correlated in space, yet uncorrelated in time (Hanssen, 1998; Hanssen, 2001). These characteristics allow us to estimate the contribution by using its correlation in space and time. A good estimation of the contribution can be determined by filtering first unwrapped phase values in time using a high pass (HP) filter, then the resulting phase values in space with a low pass (LP) filter. In general, the estimate of slave image contribution is skipped, particularly when the displacement is expected to be correlated in time. If this is the case, then the contribution to the atmospheric term from the slave images can be considered as noise in the time series analysis. If not, after estimating the atmospheric error contribution, it is subtracted from the estimated deformation phase. Multiplying the phase by the factor of $\lambda/4\pi$ results in the deformation signal.
Chapter 6

6 Area Of Study And Data Set

The area of study, Adiyaman Oil Field, is located in the Adiyaman Province, in the southeastern Anatolia region of Turkey (Figure 6.1). The oil field is in the north of the city center where there are residential areas with concrete buildings. There are also some agricultural areas in the surrounding fields. In addition, Turkey’s major artificial lake, called the Lake Ataturk Dam, is situated in the south of the city (Figure 6.2).

The elevation in the region exhibits a large variation in the range of 500m (1640.42ft) to 1500m (4921.26ft). The oil field, however, has a height changing from 800m (2624.67ft) to 1000m (3280.84ft). The climate is semi-arid; hence, the temperature rises over 40°C(104°F) for most of the time in the summer, and generally drops down to 1°C (33.8°F) in wintertime.

The Adiyaman region has a petroliferous Cretaceous sequence that has been classified as a continental platform type system with numerous rock forms, including mudstones, shales and carbonates (Demirel et al., 2001) (see Figure 6.3). The oil is produced mainly from the Upper Cretaceous fractured dolomites and secondarily from the fractured limestones at a minimum depth of 1500 m within a field of size of ~15x4 km.

Figure 6.1. The location of Adiyaman Province in Turkey
Figure 6.2. Yellow trapezoid shows the oil field. The Lake Ataturk Dam can easily be seen in the image. The gray frames represent the ALOS-PALSAR images acquired between 2007 and 2010. However, due to geocoding errors the image frames do not show the true coverage area (see Figure 7.1). The red squares hence generated manually and approximately show the correct location of the frames.

DATA SET

For this project, we used 5 FBD mode ALOS PALSAR images, all of which were acquired in the summer season span from June 2007 to June 2010, covering the area of interest (Table 6.1). By using data observed in summer season, we were able to minimize decorrelation due to the characteristic change of the scatterers.

<table>
<thead>
<tr>
<th></th>
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<tr>
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<td>740</td>
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<td>8/09/09</td>
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<tr>
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<td>ALPSRP235690740</td>
<td>FBD</td>
<td>594</td>
<td>740</td>
<td>Ascending</td>
<td>6/27/10</td>
</tr>
</tbody>
</table>

Table 6.1. Properties of the ALOS PALSAR data set
Figure 6.3. (a) the region, (b) geological drawings of the Adiyaman region and adjacent areas (Demirel et al., 2001).
Chapter 7

7 InSAR and GPS Data Analysis

This chapter presents our data processing results for both InSAR and GPS methods. The SAR interferograms and displacement maps are obtained by using Repeat Orbit Interferometry Package (ROI_PAC), The Delft Object-oriented Radar Interferometric Software (DORIS), and Stanford Method of Persistent Scatter (StaMPS) programs, whereas GPS data have been processed by using GAMIT/GLOBK software. All the software is open source and free for non-commercial applications.

ROI_PAC is originally developed at Jet Propulsion Laboratory (Rosen et al., 2004). The software can be used for focusing raw data, forming SLC images, and processing interferometry on those SLC images. DORIS is developed at Delft University of Technology (Kampes et al., 2003). It performs interferometry on SLC images from ERS, Envisat, JERS, RADARSAT and ALOS satellites. StaMPS is developed by Hooper et al. (2007), and through years advanced at the University of Iceland and Delft University of Technology. The software can be used for Persistent Scatter (single master approach), Small Baseline Subsets and a combination of these methods.

GAMIT/GLOBK is a complete Global Positioning System (GPS) analysis package developed by MIT, the Harvard-Smithsonian Center for Astrophysics, and Scripps Institution of Oceanography, with contributions of many scientists and currently maintained by T.A. Herring, R.W King, and Simon McClusky. The program can be used to estimate station coordinates and velocities, stochastic or functional representations of post-seismic deformation, atmospheric delays, satellite orbits, and Earth orientation parameters. Detailed information and manuals can be found at http://www-gpsg.mit.edu/~simon/gtgk/index.htm.

7.1 InSAR Processing And The Results

As mentioned in the previous chapter, we used 5 FBD mode ALOS PALSAR images (see Figure 6.2 and Table 6.1), and the image acquired on June 24, 2009 was chosen as the master image. Selecting middle date data as the master image is a common practice in SAR processing in order to obtain optimum temporal baseline among acquisitions. All images are focused by using ROI_PAC, and after determining the area of interest in the master image, all other images are cropped such that the area is contained in all images and placed in the middle of them (Figure 7.1-2).
Figure 7.1. Focused radar images obtained by using ROI_PAC. All images are in radar coordinates. The image in the red box represents the master image, and the yellow rectangle approximately shows the area of interest.
Next, the interferometric processing initialized by co-registering images via DORIS. Coregistration followed by resampling slave images to the grid of the master image, and subsequently interferometric phase between images computed by using Equation (4.1). Figure 7.2(a-d) shows the interferograms obtained by DORIS software after subtracting the reference surface and topography. The topographic phase is removed by using an SRTM 3-arcsec DEM (see Figure 4.3). All parameters applied during interferogram generation, the errors due to DEM, atmosphere and orbit during image acquisition, as well as the wrapping of the phase values in the range of [0, 2\pi] and [-\pi, \pi] are provided in Appendix A (see Figure A.5). The effect of having different baseline characteristics can obviously be seen in these interferograms.

![Interferograms](image1.png)

Figure 7.2. ALOS – PALSAR ascending track interferograms with respect to image acquisition times and their temporal baselines. Note that the images are flipped and color discontinuities correspond to a LOS change of 11.80 cm.
Even though the temporal baseline is high (>300 days) in the interferograms (a), (b) and (d), they exhibit good correlation. Using the images that are taken at the same time, i.e. summer season, of the year resulted in this high coherence (by avoiding seasonal negative effects on scatterers). Interferogram (c) has significantly small temporal baseline (46 days) and perpendicular baseline (200m) with respect to the others; therefore, it has the strongest signal pattern among all four interferograms.

The SAR image pairs that will be used in SBAS inversion are obtained using StaMPS Small Baseline mode (Figure 7.3b). Table 7.1 presents the dates of the images associated with small baseline interferograms. Having relatively low relief in the area of interest, the baseline combination of 9 image pairs that present a minimum coherence of 0.05 were selected (Figure 7.3b). In order to obtain complete time series the gap between the 2008 and 2010 images is eliminated by forming a baseline with the coherence value of 0.03.

After generating the small baseline subsets, StaMPS employs a persistent scatterer (PS) pixel search to investigate for a dominant scatterer over time in the interferograms. Initial PS candidates are selected based on their amplitude dispersion, which is defined as standard deviation of the amplitude divided by its mean (Ferretti et al., 2001). We used amplitude dispersion value of 0.6. This provided us with a wide range of pixels most of which are not PS. An iterative method introduced by Hooper et al. (2007) is applied to estimate the coherent phase for these PS candidate pixels. We applied a threshold value of 0.05 of convergence rate for the successive iterations and by allowing 20 random phase pixels per km² PS pixels were selected. Next, weeding step took place at which only pixels with high coherent phases were kept and adjacent pixels with low coherent values were removed from the selected coherent PS pixels, reducing the noisy pixels. Figure 7.6 shows wrapped interferograms consisting of 167505 PS pixels.
Figure 7.3. Small baseline subset combinations: (a) represents the subset combinations created by StaMPS algorithm with the values of coherence=0.05, temporal baseline=1500 days, and critical baseline=1070m; (b) shows the small baseline combinations with the coherence value of 0.03, temporal baseline of 1500 days, and critical baseline of 2000m.

<table>
<thead>
<tr>
<th>First Image</th>
<th>Second Image</th>
</tr>
</thead>
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<tr>
<td>June 19, 2007</td>
<td>June 21, 2008</td>
</tr>
<tr>
<td>June 19, 2007</td>
<td>August 9, 2009</td>
</tr>
<tr>
<td>June 19, 2007</td>
<td>June 27, 2010</td>
</tr>
<tr>
<td>June 21, 2008</td>
<td>June 24, 2009</td>
</tr>
<tr>
<td>June 21, 2008</td>
<td>August 9, 2009</td>
</tr>
<tr>
<td>June 21, 2008</td>
<td>June 27, 2010</td>
</tr>
<tr>
<td>June 24, 2009</td>
<td>August 9, 2009</td>
</tr>
<tr>
<td>June 24, 2009</td>
<td>June 27, 2010</td>
</tr>
<tr>
<td>August 9, 2009</td>
<td>June 27, 2010</td>
</tr>
</tbody>
</table>

Table 7.1. Small baseline interferogram combinations
The individual wrapped interferograms yield basic information about the surface deformation in the region (see Figure 7.5a-b). The black box in Figure 7.5a specifies the oil field that is moving farther from the satellite and causing an increase in phase change between scenes. The red and blue lines represent the East-West and North-South cross sections along the azimuth and range axes, respectively, in the oil field. The wrapped phase values for those profile lines have been shown in Figure 7.5b.
Figure 7.5. a) Oil field boundary and wrapped phase values in the region from 19 June 2007 – 21 June 2008 interferogram. The image is in radar coordinates range pixels and azimuth lines (x, y). b) The wrapped phase profiles across the oil field. 1 radian corresponds to ~19 mm.
Figure 7.6 exhibits the geo-referenced, i.e. radar coordinates \((x,y)\) are converted to geographic coordinates (longitude, latitude), wrapped small baseline subset interferograms with phase values in the range of \([-\pi, \pi]\) via StaMPS processing. Atmospheric and orbital errors can be seen in the interferograms generated with the image 06/24/2009 (see Figure A.1). Note that the related image is not the master image in SBAS analysis.

Figure 7.6. Wrapped small baseline subset (SBAS) interferograms
Next, we subtracted the DEM, atmospheric and orbital errors (see Figure 7.7). The difference among the phase values before and after the subtraction of the associated errors can easily be seen when we compare Figure 7.6 and 7.7. The elimination leads to a decrease of $\pi/2$ in the phase values most of the interferograms. However, the errors associated with image 06/24/2009 propagates through the analysis, even though the subtraction of the artifacts took place in all interferograms.

![Figure 7.7. Wrapped small baseline subset interferogram phase values, in the range of $[-\pi, \pi]$, after DEM, atmospheric and orbital errors excluded.](image)
As mentioned in Chapter 5.3.2, in order to obtain LOS displacement the phase values have to be unwrapped. We first implemented phase unwrapping to the single master interferograms obtained via DORIS. Figure 7.8 shows the unwrapped interferograms from single master processing, the phase values are relative to the master image 06/24/2009.

The interferograms have all the error sources, including DEM, atmospheric and orbital artifacts. In the small baseline subset wrapped interferograms, we could see that image the image 06/24/2009 was affected by the atmospheric and orbital errors (see Figure A.1). The effect of these artifacts, especially orbital ramps, can be easily seen in the single master interferograms in Figure 7.8. Figure A.2 shows these orbital ramps in the interferograms relative to master image 06/24/2009. Next, we subtracted above-mentioned errors from the interferograms (Figure 7.9).
Figure 7.9. Unwrapped single master interferograms relative to master image 06/24/2009 interferogram atmospheric, orbital, and DEM errors removed.

As can be seen from the Figure 7.9, the errors are significantly eliminated, reducing the phase range to -1.8 and 1.5 from -7.4 and 5.9. Next, we unwrapped the phase values of small baselines subset interferograms. Figure 7.10 demonstrates the phase values with error sources, including DEM, atmospheric and orbital errors. Figure 7.11 displays the corrected unwrapped phases for those artifacts.
In Figure 7.10, we can observe that the orbital artifacts propagate through SBAS interferograms number 4, i.e. row 2 column 1, number 7 and 8, row 3 column 1 and 2, respectively. Next, we subtract the DEM error, atmospheric and orbital artifacts. Figure 7.11 shows the SBAS interferograms without errors.
Figure 7.11. Unwrapped SBAS interferograms corrected for DEM errors and orbital ramps. The orbital artifacts still exist in the SBAS interferogram 4, 06/21/2008 - 06/24/2009, interferogram 7, 06/24/2009 - 08/09/2009, interferogram 8, 06/24/2009 - 06/27/2010. Among all interferograms, the interferogram 7 is the most effected interferogram from orbital errors.

Due to the existence of the orbital errors in the SBAS interferograms 4, 7, and 8, we excluded them from the satellite line of sight (LOS) displacement velocity estimation. In
order to make a comparison between two processing methods, single master vs. SBAS, we provided velocity estimation from both single master and SBAS interferograms. The estimates from single master interferograms are presented in Figure 7.12, and that of form small baseline interferograms are shown in Figure 7.13. Note that the negative displacement values indicate a movement towards satellite.

Figure 7.12. Line of sight (LOS) displacement velocity estimation using single master interferograms. The Black boundary shows the oil field. Negative velocities are towards the satellite.
Maximum observed LOS displacement rates for single master interferograms are in the range of 22.2 and -24.2 mm/yr (see Figure 7.12); for that of SBAS interferograms are 23.7 and -26.9 mm/yr (see Figure 7.13).

After overlaying the LOS displacement velocity estimation map onto Google Earth, the displacement within and around the oil field has been revealed (see Figure 7.14). The area of subsidence above the oil field seemed to be situated in an agricultural region, and most likely the extraction of groundwater for irrigation is leading to this subsidence in the zone. The uplift in the northeast of the image coincides with rugged topographic zone in the region. This might be due to the digital elevation model error that could not have been corrected for that specific part of the interferogram.
Figure 7.14. Overlay velocity map onto Google Earth
Figure 7.15. Overlay image of the oil field onto the Google Earth. a) The wells in the field. b) The GPS campaign sites in the field.
The time series of the surface deformation in the oilfield, relative to the master image of June 24, 2009, is shown in Figure 7.15. In the graph, the LOS deformation of the wells 13, 14 and 18, as well as the GPS campaign sites, including AD06, AD07, AD08, AD14, AD26, AD38, AD51 were plotted. We have removed the results from image acquired in August 08 2009 in order to obtain 1 year spacing between images. The overall displacements of four years for associated points are provided in Table 7.2.

Figure 7.16. Time series analysis

<table>
<thead>
<tr>
<th>Point</th>
<th>LOS Displacement Velocity (mm/year)</th>
<th>Standard Deviation (mm/yr)</th>
</tr>
</thead>
<tbody>
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<td>AD26</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>AD06</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>AD07</td>
<td>4.7</td>
<td>0.8</td>
</tr>
<tr>
<td>AD14</td>
<td>3.1</td>
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<td>0.8</td>
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</tr>
<tr>
<td>AD38</td>
<td>3.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Well-13</td>
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<td>Well-14</td>
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<tr>
<td>Well-18</td>
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</tr>
</tbody>
</table>

Table 7.2. LOS Displacement Velocities. The results were obtained by using linear regression analysis, standard deviations are computed assuming uncorrelated noise estimates based on the root mean square (RMS) scatter of the LOS displacement about the linear trend. These are lower bounds on the uncertainties.
7.2 GPS Data Analysis

To provide a comparison with the InSAR results, we utilize data from GPS measurements of 12 campaign sites, acquired by Turkish Petroleum Corporation, together with data from 10 continuous International – Global Navigation Satellite System (GNSS) - Service (IGS) stations. These data were collected over a 2-day period in August 2011 and July 2012. The analysis of the data aimed at determining the positions of the GPS sites in each campaign used the GAMIT/GLOBK software (http://www-gpsg.mit.edu/~simon/gtkk/index.htm). The data were collected with an average of 7 hours static-observation sessions in both years. Among campaign sites, the AD01 and AD09 were excluded from the processing due to the loss of data during observation, caused by a defect in the receiver. Moreover, all velocity estimates seen in the figures are determined within 95% confidence interval. Figure 7.17 shows all GPS measurement points used in this project along with their velocity estimates. While Figure 7.18a illustrates the distribution of the campaign sites, Figure 7.18b demonstrates their velocity estimates.

The Appendix B shows the time series of the campaign sites that have been measured in the 2-day period in both years. The plots are for sites AD38 from 2011 epoch, and the sites AD08, and AD14 from 2012 epoch. The TPAO control site has been measured in the 2-day observation period in both epochs. In the time series for year 2011, both sites, AD38 and TPAO, have small residuals and uncertainties in the horizontal estimates for
both days, and relatively bigger standard deviations for the vertical estimates. In 2012 time series, we see that all available campaign sites have good estimates both horizontally and vertically.

Figure 7.18. GPS measurement locations in the oil field a) Google Earth view b) GAMIT/GLOBK Velocity Estimates relative to AD26, which is shown with a dot. 95% confidence ellipses are shown.

The GAMIT/GLOBK solution of the GPS campaign data processing has been summarized in Table 7.3. The displacements are given in the local topocentric coordinate
system: east (E), north (N), and height (H), which then can be converted to a geocentric coordinate system with the Earth Centered and Earth Fixed (ECEF) frame (Hoffmann-Wellenhof et al. 2001). As can be seen from the table, the horizontal displacement for most of the sites is centimeter and sub-centimeter level. All of the GPS observations were acquired on dormant wells during the 2011 GPS measurement epoch. However, some of the wells were reactivated during 2012 observation. We therefore obtained an excessive horizontal and vertical movement values, which were out of the range of the computation parameters, in site AD06 due to change in measurement point location. The oilfield has also undergone a construction process in between the two epochs. The TPAO site was re-located due to construction between the two surveys and so we are unable to find a reliable velocity estimate for this site as well. Therefore, the solution for this site should be ignored due to large offset caused by the replacement and the site should be named differently in the 2012 and prospect analyses.

Due to abovementioned factors as well as antenna-induced artifacts, we are unable to reach any conclusions concerning the vertical motions of the sites. We have obtained high vertical deformation values, around 30 cm/yr, for several of the sites, which are not considered to robust estimates.

<table>
<thead>
<tr>
<th>Site</th>
<th>Longitude (deg)</th>
<th>Latitude (deg)</th>
<th>E Vel. (mm/yr)</th>
<th>N Vel. (mm/yr)</th>
<th>E+ (mm/yr)</th>
<th>N+ (mm/yr)</th>
<th>H Vel. (mm/yr)</th>
<th>H+ (mm/yr)</th>
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<td>-</td>
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<td>7.44</td>
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Table 7.3. GPS campaign data processing results relative to ITRF08

In order to evaluate the quality of the processing, we have provided the results from the continuous GPS stations (see Table 7.2). Both the horizontal and vertical displacements are in mm level as expected. Figure 7.19 demonstrates the comparison of our velocity solutions (black arrows) with respect to the velocity estimates from International Terrestial Reference Frame 2008 –ITRF08 (red arrows) solutions. Among the stations, ISER and ISSD have been deployed in 2011 by National Geodetic Survey (NGS) as part
of Continuously Operating Reference Stations (CORS) network. These stations therefore have no velocity record in ITRF08 to compare with.

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<tr>
<th>Station</th>
<th>Longitude (deg)</th>
<th>Latitude (deg)</th>
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<th>N Vel. (mm/yr)</th>
<th>E + (mm/yr)</th>
<th>N + (mm/yr)</th>
<th>H Vel. (mm/yr)</th>
<th>H + (mm/yr)</th>
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Table 7.4. Results for continuous GPS stations

![Comparison between velocity estimates](image)
Chapter 8

8 Conclusion and Recommendation

In this study, we performed the Small Baseline Subset InSAR (SBAS-InSAR) method to quantify deformation in the Adiyaman oil field, Turkey, because the capability of this method to reduce decorrelation originating from large temporal baselines.

ALOS PALSAR FBD mode images were acquired in the same season of the year. Choosing images from the same time of the year has both advantages and disadvantages. It yields similar decorrelation due to seasonal effects on scatterers; however, due to lack of images from different time of the year, we are unable to comprehend the magnitude of these effects. Our preliminary results show that the maximum observed LOS displacement velocity in the oil field is 5 mm/yr. with a similar uncertainty of the same magnitude. The results are obtained through software that has been designed to analyze many interferograms. In this project, the separation of the signals, i.e. displacement, topography, and atmosphere, were performed by using only 5 images. Therefore, the outcomes would likely be less unique than if more interferograms were available. In addition, we should mark that the observed displacements are in the radar’s LOS from only ascending track. This means that the main factor, i.e. east-west or vertical movement, of the displacement in the region will be obtained after analyzing the descending track images of the area.

Continued oil production in the region along with the mitigation measures taken, e.g. reinjection of water, should fill in pores between the grains of layers of the carbonate. This helps increase the pressure within the layers and results in reduction in subsidence or occasional uplift. We thus conclude that re-injecting water to keep subsurface pressure in equilibrium is limiting the amount of subsidence in the oil field. In addition, because subsidence has also been observed outside the area of study, irrigation might also contribute to the deformation in the region.

This project is a pilot study in the area, and therefore further analysis using additional images with less temporal and orbital baselines will contribute to the obtained accuracy. Furthermore, as more data both from ascending and descending orbits become available long-term deformation on the surface of the oil field, East-West and vertical components, will be better understood.

Recommendation

The observed LOS deformation rates can be improved in several ways. Even though, the interferograms showed good coherence in general, it would be interesting to analyze the
displacement with shorter baselines. The time interval between the images is one year except for the ones acquired in 2009. Thus, it would be advantageous to study the deformation in the region using a smaller temporal separation.

The time series analysis of the displacement can be constrained better when the number of images, subsequently the interferogram quantity, is increased. By applying both the PS and SBAS methods with the increased number of images, the velocity estimates can be compared with our initial results.

Use of a different DEM, e.g. ASTER GDEM, might be employed to examine its effects on the analysis. In addition, processing images from descending orbits would be another interesting test to see whether the same phenomena could be observed.

A dense network of continuous GPS stations would provide more reliable results in terms of horizontal and vertical deformation, and hence would enable us to validate our analysis. Furthermore, ionospheric and orbital errors would be better studied, and can be corrected in the InSAR data.
Appendix A

InSAR Data Parameters: Interferogram Generation

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<th>Comment</th>
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Table A.1. Master (06/24/2009) – slave image coregistration parameters
Figure A.1. Atmospheric and orbital errors due to image 06/24/2009

Figure A.2. Orbital ramps in single master images relative to master image 06/24/2009
Figure A. 3. Atmospheric and orbital errors due to slave images

Figure A. 4. DEM error calculated from SBAS interferograms
Figure A. 5. The wrapping of the phase values in the range of \([0, 2\pi]\) and \([-\pi, +\pi]\). The graph under the plots belong the azimuth line 640 in the images. Red lines indicate the phase values wrapped around \(0\) \(2\pi\) range, and blue lines show the phase values spanning from \(-\pi\) to \(+\pi\).
Appendix B

GPS Time Series Analysis

Plots show the residuals from the weighted mean, i.e. long term repeatability or rate, values of the topocentric coordinates (North, East, and Up) of some of the campaign sites in each epoch. The normalized root mean square (NRMS) is the square root of chi-squared per degree of freedom and should be near unity. Weighted root mean square (WRMS) is the square root of the mean of residuals squared weighted by the estimated variance of the residuals.

Site: AD38, August 2011 (day of year: 228, 229)
Site: TPAO, August 2011 (day of year: 228, 229)
Site: AD08, July 2012 (day of year: 189, 190)
AD14 North Offset 4206969.411 m
wmean(mm) = 9404.44 ± 2.48 nrms = 2.70 wrms = 9.5 mm # 2

AD14 East Offset 3362439.842 m
wmean(mm) = 9841.58 ± 2.12 nrms = 0.14 wrms = 0.4 mm # 2

AD14 Up Offset 888.625 m
wmean(mm) = 8627.48 ± 9.42 nrms = 0.27 wrms = 3.6 mm # 2

Site: AD14, July 2012 (day of year: 189, 190)
TPAO North Offset 4204539.504 m
\[ \text{wmean}(\text{mm}) = 9503.36 \pm 2.62 \quad \text{nrms} = 0.06 \quad \text{wrms} = 0.2 \text{ mm} \# 2 \]

TPAO East Offset 3363314.204 m
\[ \text{wmean}(\text{mm}) = 4203.61 \pm 2.27 \quad \text{nrms} = 0.26 \quad \text{wrms} = 0.8 \text{ mm} \# 2 \]

TPAO Up Offset 753.655 m
\[ \text{wmean}(\text{mm}) = 3659.86 \pm 9.84 \quad \text{nrms} = 0.50 \quad \text{wrms} = 7.0 \text{ mm} \# 2 \]

Site: TPAO, July 2012 (day of year: 189, 190)
Bibliography


Vasco, D. W., Ferretti, A., and Novali, F. Reservoir monitoring and characterization using satellite geodetic data: Interferometric Synthetic Aperture Radar observations from the Krechba field, Algeria, Geophysics, 73, WA113-WA122, 2008.


