Application of Satellite Remote Sensing on Mountain Glacier and Coastal Zone Classification And Monitoring in South Asia

DISSEETATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By
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The Ohio State University
2015

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Abstract

Observations from Earth’s remote sensing satellites have been a promising tool for studies on land cover and its changes, and related environmental phenomena. In this study, we demonstrate two environmental related land cover classification applications using integrated methods that involve multiple passive and active remote sensing sensors onboard different satellites, including Landsat Thematic Mapper (TM) and other optical/infrared imageries, synthetic aperture radar (SAR) system such as the Phased Array type L-band Synthetic Aperture Radar (PALSAR) onboard of the Advanced Land Observing Satellite (ALOS), and radar altimeters such as the Environmental Satellite (ENVISAT), etc.

Firstly, we did a case study in Geladandong glacier of classifying and obtaining the rock/glacier boundary using Landsat data as well as integrated SAR methods, including polarimetric SAR classification and repeat pass SAR correlation coefficients technique. Over 40 years, the shrinkage of the glacier was observed from the results of analyzing and classifying Landsat series data. The estimated retreating rates are 0.148 km²/year and 0.134 km²/year in region B and C of Geladandong glacier during 1973~2014. The Randolph Glacier Inventory (RGI) 4.0 does not provide this dynamic changing of the glacier extent. Moreover, considerable biases have also been observed in several regions. To further strengthen the finding, we employed SAR and polarimetric SAR data by applying correlation coefficient calculation and polarimetric SAR decomposition and
segmentation. The results were consistent with those from Landsat classification in every particular small glacier region.

Secondly, data from multiple satellite sensors, including Landsat series, ALOS-1 PALSAR Synthetic Aperture Radar and ENVISAT altimeter are employed for the purpose of analyzing the water extent in polder regions and its changing trend in last 40 years and of surveying the impact on polder embankments caused by erosion and sedimentation. In Polder 14, the surface elevation was approximately 30 centimeters higher in May than in August, given by ENVISAT surface elevation data. River channel boundary change in Arpangasia is also investigated. The river channel shape has been changed with approximately 1.4km² on both sides of the river segment in the past 40 years. In the estuary region Polder 50~57, delta displacement in delta boundaries is observed in the water/land classification results based on Landsat data from 1972 and 2011. Moreover, the results from applying H/A/Alpha Wishart classification algorithm with full polarization SAR data provided more detailed surface types that can help monitoring and estimate the potential flooding risk of the region.
Dedication

This document is dedicated to my family.
Acknowledgments

Over the past six years I have received support and encouragement from a great number of individuals. I’m heartily thankful to my advisor Dr. C.K. Shum, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. Dr. Shum has been a mentor, colleague, and friend. His guidance has made this a thoughtful and rewarding journey. I’m sincerely grateful for the support and guidance he showed me throughout my dissertation writing.

I would like to extend my sincere appreciation to my dissertation committee members, Professors. Alan Saalfeld and Michael Durand for their invaluable advice and comments during the reviews of this manuscript.

In particular, I am grateful to Dr. Junyi Guo for his advice and help in keeping my research on schedule. Dr. Guo spent countless hours proofreading and listening to me talk about my research and provided needed encouragement and insights. I have learned much though our conversations. I would also like to thank my colleagues. Thanks to Jin Woo Kim for his encouragement and detailed guidance in SAR data processing. I would like to thank Yuanyuan Jia, Qi Guo and Xiaoli Su for generously sharing their ideas and spending time for discussion. Thanks to Arie H. Tan for his several proof reading of this dissertation. I owe particular thank to Hok Sum Fok and Steven Tseng for sharing their experience and encouraging me during the hard time. Thanks to Dr. Xiaochun Wang for giving me a chance to get started when I sank under trouble in my research.
I owe particular thank to Peter Luk for his kind help and care in the past several years. I would also like to thank Brent Curtiss and Daniel Dunlap who helped me fix computer issues and set up videoconference for my oral defense. Thanks to Ms. Angeletha Rogers, our graduate specialist, who always shows her friendliness and answers questions patiently.

Lastly, I would like to thank my parents for their unconditional love and support during the course of dissertation. Finally, I am immensely grateful for the love and support of my fiancée, for sparking my interest in life, she made all of the difference. No written words can adequately express our deep love. To her and lil QQ, I am eternally grateful.
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Publications


Fields of Study

Major Field: Geodetic Science
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CHAPTER 1: Introduction

1.1 Background

The 2013 Intergovernmental Panel for Climate Change (IPCC) Fifth Assessment Report (AR5) estimated that for the period 2003–2009, the contribution of all glaciers globally to sea level rise, including those glaciers surrounding the periphery of the two ice sheets, is 0.71 [0.64 to 0.79] mm yr$^{-1}$ sea level equivalent (SLE) [IPCC, 2013]. This large glacier contribution to sea-level rise, at 29–70% of the observed rate (~2 mm/yr), does not leave much room for other contributors, including ice-sheets, oceanic thermal expansion, hydrological imbalance, and thus remains controversial. The Asian High Mountain (AHM) glaciers, consisting of 8 glacier systems and encompassing a total glacierized area of 79,299 km$^2$, represent significant water resources to 3 billion people in the region, or 43% of world’s population. The Asian High Mountain glaciers are perhaps the least observed glacier system and have the largest uncertainty in their mass balance estimates. There are very few in situ observations: data from only 15 glaciers among the 15,000 Himalayan glaciers were used to estimate the current mass balance. Glacier boundaries determination is a vital reference data for estimating the mass balance.

Bangladesh is one of the few countries to go through potentially disastrous consequences of climatic change. A 1.5 m sea level rise eventually affects 22,000 km$^2$ of land and threaten 15% of the population i.e. 17 million people. Bangladesh is already
severely affected by tropical cyclones and storm surges. Tragic cases in the past have caused damage up to 100 km inland. Therefore, it remains important that the people of Bangladesh take more consideration of sea level rise as well as other climate change influences in reforming their policies and coastal management plans. At the present, the net impact of sea level rise in Bangladesh remains a controversial topic.

Ultimately, the significant outcome of sea level rise, tropical cyclones, storms or tsunami is the permanent inundation of Bangladesh coastal areas, which can have serious impacts upon the natural environment and socio-economic conditions in the coastal zone. The floods can also aggravate coastal erosion by transporting submerged sediments. However, a bunch of bewildering factors that needs to be taken into account before stating that a country like Bangladesh is and actually will loose ground as a result of forecast climatic change and associated rise in sea level. Finally, many estimates of the land area that would be lost due to sea level rise are misleading since they do not factor in the embankments that protect much of the coast.

Satellite remote sensing has been considered a useful technology for terrestrial and marine monitoring due to its ability to provide synoptic, repetitive and consistent information of the Earth’s surface. Therefore, we propose to monitor glacier boundary and coastal regions land cover patterns changes by applying multiple classification methods with difference remote sensing data sources.

1.2 Science Objective

The science objective of this research includes:
1. We aim to do case studies of classifying and obtaining the rock/glacier boundaries in some specific glacier regions on Asian High Mountain using Landsat data as well as integrated SAR methods, including polarimetric SAR classification and repeat pass SAR correlation coefficients classification. Based on the resulting boundaries, retreat or advance of glaciers are estimated and analyzed. By comparing to the existing glacier boundary libraries (RGI), advantages or corrections are expected.

2. In Bangladesh coastal regions, with the aid of our integrated classification methods, we also propose to do case studies to (1) monitor coastal polder boundaries as well as water extent distribution and (2) analyze the effect of erosion and sedimentation in certain river channel segments.

1.3 Dissertation Outline

In Chapter 2, the principles of satellite radar remote sensing are presented.

In Chapter 3, the specific study of glacier boundary determination on Asian High Mountain is presented.

In Chapter 4, the study of coastal region monitoring using combined methods in Bangladesh is presented.

The conclusions and future study is shown in Chapter 5.
CHAPTER 2: Principles of Satellite Remote Sensing

2.1 An Overview of Remote Sensing

Remote sensing is the acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to in situ observation. The broad definition of remote sensing includes vision, astronomy, space probes, most of medical imaging, nondestructive testing, sonar, observing the Earth from distance, as well as many other areas [Scott, 2007]. Remote sensing makes it possible to collect data on dangerous or inaccessible areas. Particularly, orbital platforms collect and transmit data from different parts of the electromagnetic spectrum providing researchers with ample information to monitor trends such as El Niño, MJO and other natural long and short term phenomena.

For the purpose of our subject, it is generally restricted to earth observation from airborne or spaceborne sensors. Remote sensing is split into passive remote sensing and active remote sensing.

Passive remote sensing

The Sun is a major source of energy or radiation for our globe providing a convenient source of energy for remote sensing. This energy is either reflected (visible wavelengths) or absorbed and then re-emitted (thermal infrared wavelengths). Remote sensing systems, which measure the energy that is naturally available, are called passive sensors. Passive
remote sensing can only be used to detect energy when the naturally occurring energy is available. It can only take place during the time when the sun is illuminating the Earth. There’s no reflected energy available from the sun at night. Energy that is naturally emitted, such as thermal infrared, can be detected day or night as long as the energy is strong enough to be detectable.

**Active remote sensing**

In contrast to passive remote sensing, active sensors emit energy to scan objects or areas and then detect and measure the radiation that is reflected from the target. The microwave sensors of Synthetic Aperture Radar (SAR) are hardly affected by light and weather condition. By applying different microwave bandwidths of X-, C-, L-, P- and Ku-bands, SAR data can be used to image land surface, canopies, glaciers or vegetation with different levels of penetration. The imaging products can be further used for surface type classification.

**2.2 Optical Remote Sensing**

**2.2.1. Introduction**

Optical remote sensing employs sensors detecting visible, near infrared and short-wave infrared spectra to form images of the earth's surface by detecting solar radiation reflected from targets on the ground. Different materials reflect and absorb the solar radiation differently at different wavelengths. Hence, the targets can be differentiated by their
spectral reflectance. Optical remote sensing systems include the following different types based on the number of spectral bands used in the imaging process:

2.2.1.1 Multispectral Imaging System

The sensor of a multispectral imaging system gives a few spectral bands. Each channel is sensitive to radiation within a narrow wavelength range. Examples of multispectral systems are Landsat series, SPOT HRV-XS and IKONO MS, etc.

2.2.1.2 Superspectral Imaging Systems

A superspectral imaging sensor provides more spectral channels than a multispectral sensor. The bands have narrower bandwidths that render more accurate spectral characterization of the observing targets. Typical examples of superspectral imaging systems are MODIS and MERIS.

2.2.1.3 Hyperspectral Imaging Systems

Hyperspectral imaging system acquires images in a hundred or more intensive spectral bands. The precise spectral information contained in a hyperspectral image gives even better characterization of targets. The example of a hyperspectral system is Hyperion on EO1 Satellite.

2.2.2 Landsat Program Overview

The Landsat series are multispectral imaging satellite programs for Earth surface observing. Landsat program started to bring data in remote area since 1972 (Landsat 1, Multispectral Scanner) and it is the longest running program for acquiring satellite imagery of Earth.
The description of the Landsat instruments that provide data in our study is listed in Table 2.1.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Picture</th>
<th>Launch</th>
<th>Duration</th>
<th>Bands/ resolution</th>
</tr>
</thead>
</table>
| Landsat 1   | ![Landsat 1 Image](image1) | Jul 23, 1972 | 3 years  | MSS – 79 m  
Band 4 - Visible green (0.5 to 0.6 µm)  
Band 5 - Visible red (0.6 to 0.7 µm)  
Band 6 - Near-Infrared (0.7 to 0.8 µm)  
Band 7 - Near-Infrared (0.8 to 1.1 µm) |
| Landsat 2   | ![Landsat 2 Image](image2) | Jan 22, 1975 | 3 years  | MSS – 79 m  
Band 4 - Visible green (0.5 to 0.6 µm)  
Band 5 - Visible red (0.6 to 0.7 µm)  
Band 6 - Near-Infrared (0.7 to 0.8 µm)  
Band 7 - Near-Infrared (0.8 to 1.1 µm) |
| Landsat 5   | ![Landsat 5 Image](image3) | Mar 1, 1984  | Still Active | Thermal Mapper  
Band 1 - Visible (0.45 - 0.52 µm) 30 m  
Band 2 - Visible (0.52 - 0.60 µm) 30 m  
Band 3 - Visible (0.63 - 0.69 µm) 30 m  
Band 4 - Near-Infrared (0.76 - 0.90 µm) 30 m  
Band 5 - Near-Infrared (1.55 - 1.75 µm) 30 m  
Band 6 - Thermal (10.40 - 12.50 µm) 120 m  
Band 7 - Mid-Infrared (2.08 - 2.35 µm) 30 m |
| Landsat 7   | ![Landsat 7 Image](image4) | April 15, 1999 | Still Active | Enhanced Thermal Mapper Plus  
Band 1 - Visible (0.45 - 0.52 µm) 30 m  
Band 2 - Visible (0.52 - 0.60 µm) 30 m  
Band 3 - Visible (0.63 - 0.69 µm) 30 m  
Band 4 - Near-Infrared (0.77 - 0.90 µm) 30 m  
Band 5 - Near-Infrared (1.55 - 1.75 µm) 30 m  
Band 6 - Thermal (10.40 - 12.50 µm) 60 m  
Band 7 - Mid-Infrared (2.08 - 2.35 µm) 30 m  
Band 8 - Panchromatic (0.52 - 0.90 µm) 15 m |

Table 2.1. Description of the Landsat program instruments used in our study. [USGS, 2014]
2.3 Synthetic Aperture Radar (SAR)

2.3.1 Development Of Imaging Radar

Imaging RADAR has been considered as a capable Earth remote sensing tool since 1978 as the SEASAT satellite equipped with Synthetic Aperture Radar (SAR) was successfully launched. Despite its short lifetime of 105 days, SEASAT-SAR [Jordan et. al., 1980] was the pioneering mission, which has leaded the SAR technology to the present and future state-of-the-art status [Evans et. al. 2005].

The potential applications of SAR is realized in a variety of geoscience and engineering fields after the SEASAT. The second spaceborne SAR was ERS-1 SAR in 1991 [Attema, 1991]. During the time between these two spaceborne SAR projects, effort was made to develop and experiment new techniques mainly with airborne SARs and Shuttle Imaging Radar (SIR) series. The SIR-A mission was in 1981 with a L-band HH-polarization SAR on board similar to SEASAT-SAR. The SIR-B mission [Cimino et. al., 1986] was in 1984 operating at the same frequency and polarization as those of SIR-A, but varying incidence angles by a mechanically steered antenna [Granger, 1983]. The SIR-C/X-SAR was carried into orbit in 1994, which operated at multi-frequency X-, C- and L-bands with a full polarimetric mode [Jordan et. al., 1991; Evans, 2006]. The Shuttle Radar Topography Mission (SRTM) carried a modified radar system, which was based on SIR-C/X-SAR, and flew on board the Space Shuttle Endeavour during a 11-day mission in February 2002 [Farr et. al., 2000; Werner et. al. 2001; Rabus et. al., 2003.]. A second outboard antenna separated by a 60 m long mast was applied, which allowed single-pass interferometry to generate a digital elevation model (DEM) of approximately 80% of
<table>
<thead>
<tr>
<th>Satellite/Platform</th>
<th>Agency/Country</th>
<th>Year Launched</th>
<th>Band</th>
<th>Resolution</th>
<th>Polarization</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEASAT-SAR</td>
<td>NASA/USA</td>
<td>1978</td>
<td>L</td>
<td>6, 25</td>
<td>HH</td>
<td>2,290</td>
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<tr>
<td>SIR-A</td>
<td>NASA/USA</td>
<td>1981</td>
<td>L</td>
<td>7, 25</td>
<td>HH</td>
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<td>1984</td>
<td>L</td>
<td>6, 13</td>
<td>HH</td>
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<td>1991</td>
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<td>JERS-1 SAR</td>
<td>NASDA/Japan</td>
<td>1992</td>
<td>L</td>
<td>6, 18</td>
<td>HH</td>
<td>1,400</td>
</tr>
<tr>
<td></td>
<td>NASA/USA</td>
<td></td>
<td>C/L</td>
<td>77.5, 13</td>
<td>quad</td>
<td>11,000</td>
</tr>
<tr>
<td>SIR-C/X-SAR</td>
<td>DLR/Germany</td>
<td>1994</td>
<td>X</td>
<td>6, 10</td>
<td>VV</td>
<td>(approx.)</td>
</tr>
<tr>
<td></td>
<td>ASI/Italy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RADARSAT-1</td>
<td>CSA/Canada</td>
<td>1995</td>
<td>C</td>
<td>8, 8</td>
<td>HH</td>
<td>3,000</td>
</tr>
<tr>
<td>SRTM</td>
<td>NASA/USA</td>
<td>2000</td>
<td>C</td>
<td>15, 8</td>
<td>dual</td>
<td>13,600</td>
</tr>
<tr>
<td></td>
<td>DLR/Germany</td>
<td></td>
<td>X</td>
<td>8, 19</td>
<td>VV</td>
<td>(payload)</td>
</tr>
<tr>
<td>ENVISAT-ASAR</td>
<td>ESA</td>
<td>2002</td>
<td>C</td>
<td>10, 30</td>
<td>dual</td>
<td>8,211</td>
</tr>
<tr>
<td>ALOS-PALSAR</td>
<td>JAXA/Japan</td>
<td>2006</td>
<td>L</td>
<td>5, 10</td>
<td>quad</td>
<td>3,850</td>
</tr>
<tr>
<td>SAR-Lupe</td>
<td>Germany</td>
<td>2006-2008</td>
<td>X</td>
<td>0.5, 0.5</td>
<td>quad</td>
<td>770</td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>CSA/Canada</td>
<td>2007</td>
<td>C</td>
<td>3, 3</td>
<td>quad</td>
<td>2,200</td>
</tr>
<tr>
<td>Cosmo-SkyMed</td>
<td>ASI/Italy</td>
<td>2007-2010</td>
<td>X</td>
<td>1, 1</td>
<td>quad</td>
<td>1,700</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>DLR/Germany</td>
<td>2007</td>
<td>X</td>
<td>1, 1</td>
<td>quad</td>
<td>1,230</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>DLR/Germany</td>
<td>2009</td>
<td>X</td>
<td>1, 1</td>
<td>quad</td>
<td>1,230</td>
</tr>
<tr>
<td>RISAT-1</td>
<td>ISRO/India</td>
<td>2012</td>
<td>C</td>
<td>3, 3</td>
<td>dual</td>
<td>1,858</td>
</tr>
<tr>
<td>HJ-1-C</td>
<td>China</td>
<td>2012</td>
<td>S</td>
<td>5, 20</td>
<td>VV</td>
<td>N/A</td>
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<tr>
<td>KOMPSAT-5</td>
<td>Korea</td>
<td>2013</td>
<td>X</td>
<td>1</td>
<td>quad</td>
<td>1,400</td>
</tr>
<tr>
<td>Sentinel-1</td>
<td>ESA</td>
<td>2014</td>
<td>L</td>
<td>1, 3</td>
<td>quad</td>
<td>2,120</td>
</tr>
<tr>
<td>ALOS-2/PALSAR-2</td>
<td>JAXA/Japan</td>
<td>2014</td>
<td>L</td>
<td>1, 3</td>
<td>quad</td>
<td>2,120</td>
</tr>
</tbody>
</table>

**Table 2.2.** Space-borne and Shuttle-borne SAR satellites and platforms modified and updated from [Ouchi, 2013].
2.3.2 SAR Basics

2.3.2.1 Introduction

Synthetic Aperture Radar (SAR) is a well developed microwave remote sensing technique for producing high-resolution radar images of Earth’s surface from airborne and spaceborne platforms. The SAR sensor operates in a side-looking geometry with an illumination perpendicular or with a squint angle to the flight line direction. The imaging system emits microwave pulses toward the Earth’s surface and receives the electromagnetic signal backscattered. A 2-D high spatial resolution image of the Earth’s surface is then generated by applying signal processing algorithms.

Since SAR is an active sensor and uses the microwave band in the broad radio spectrum as in Figure 2.1, it has a day-and-night imaging capability with the ability of penetrating cloud, fog, smoke, and rain to some extent.

![Figure 2.1. Band designation of microwave spectrum used for SAR. [Lee & Pottier, 2009]](image)
2.3.2.2 SAR Geometry

A simple monostatic SAR system consists of a transmitter, an antenna for both transmission and reception, and a receiver unit. The system is mounted on a moving platform, e.g. a satellite, operating in a side-looking geometry as shown in Figure 2.2. The SAR platform operates at a height $H$ with a velocity $V_{\text{SAR}}$. The flight direction is referred to as azimuth direction ($y$). The antenna beam directs slant-wise toward the ground with an angle of incidence $\theta_0$. The radial is referred to as slant-range ($r$). The coverage area in plane defined by ground range ($x$) direction and azimuth ($y$) directions is the antenna footprint. As the platform flying along the azimuth direction, the area scanned by the antenna beam is the radar swath.
Figure 2.2. The geometry of a SAR system in strip-map mode. [Lee & Pottier, 2009]

Given the antenna’s physical dimensions $L_x, L_y$, as well as the wavelength of the carrier frequency of the transmitted signal, the antenna apertures $(\theta_x, \theta_y)$ can be represented as [Lee & Pottier, 2009]

$$\theta_x \approx \frac{\lambda}{L_x} \quad \text{and} \quad \theta_y \approx \frac{\lambda}{L_y} \quad (2.1)$$

The range swath $\Delta X$ and azimuth swath $\Delta Y$, which are depicted in Figure 2.3, can also be represented as [Lee & Pottier, 2009]

$$\Delta X \approx \frac{R_0 \theta_x}{\cos \theta_0} \quad \text{and} \quad \Delta Y \approx R_0 \theta_y \quad (2.2)$$
where $R_0$ is the distance between the radar and the antenna footprint center.

**Figure 2.3.** SAR geometry in (a) ground-range domain; (b) azimuth domain. [Lee & Pottier, 2009]

### 2.3.2.3 Spatial Resolution

Spatial resolution describes the ability to separate two closely spaced scatterers. In order to achieve high resolution and also a sufficient signal-to-noise ratio (SNR) in range, pulses with short durations and high energy are necessary, which however is difficult to be achieved with practical transmitters. As a result, a longer “chirp” pulse is applied to generate high energy. Pulse compression technique [Skolnik, 1981] is used, which consists of emitting pulses (chirp) that are linearly modulated in frequency domain for duration of time $T_p$. The frequency of the signal sweeps a band $B$ centered on a carrier at frequency $f_0$. The received signal is then processed with a matched filter that compresses the long pulse to an effective duration that equals to $1/B$ [Carlson, 1986; Turin, 1976]. Given the incidence angle, the slant ground resolution is then shown as
In the along-track direction, two targets in the azimuth or along-track direction can be separated only if the distance between them is larger than the radar beamwidth. The azimuth resolution with real aperture for a range $R_0$ is

$$\delta y_{\text{real}} = \Delta Y = R_0 \theta_Y = \frac{R_0 \lambda}{L_Y}$$

(2.4)

The solution to achieve high resolution without the use of a large antenna is given by the concept of synthetic aperture. The basic idea of synthetic aperture is to build a longer antenna based on the movement of the real sensor along the azimuth direction. The length for the synthetic aperture equals to the size of the antenna footprint on the ground in azimuth direction $\Delta Y$. [Lee & Pottier, 2009] Hence, the azimuth resolution is

$$\delta y_{\text{syn}} = \frac{L_Y}{2}$$

(2.5)

Interestingly, the azimuth resolution is only determined by physical size of the real antenna and independent of range $R_0$ or wavelength $\lambda$.

2.4 Polarimetric SAR

2.4.1 Development of Polarimetric SAR

Polarimetric radar imaging research began in 1940s. Scientists used polarized radar echoes to characterize aircraft targets. Afterward, the value of polarimetry was found in
geophysical parameter estimation and research such as ocean wave and current remote sensing.

In the 1980s and 1990s, Jet Propulsion Laboratory (JPL) played an important role in developing polarimetric SAR remote sensing application and analysis. In 1985, the first fully polarimetric AIRSAR at L-band was successfully built by JPL. As part of NASA’s Earth Science Enterprise, the AIRSAR platform first flew in 1988, with the capability to operate at three different frequencies (P-, L- and C-band). The AIRSAR platform flew its last mission until 2004. During the operating period, AIRSAR was the main polarimetric imaging contributor. The polarimetric SAR data from AIRSAR and later on from the space-borne SIR-C/X-SAR during April and October 1994 aroused the research in polarimetric SAR imaging as well as polarimetric data analysis approaches. J.J. van Zyl introduced a polarization signature plots to represent the scattering mechanisms. He also developed a polarimetric scattering decomposition method based on eigenvector decomposition of the polarimetric covariance matrix [van Zyl et. al., 1987]. Freeman and Durden then developed a model-based polarimetric scattering decomposition [Freeman & Durden, 1998].

European Space Agency (ESA) continued in polarimetric SAR research after AIRSAR stopped its operation. E-SAR (Experimental SAR) is built and flew by the Microwaves and Radar Institute of the German Aerospace Research Centre (DLR). E-SAR operated with full-polarization at L-band and later expanded to P-band. E-SAR presented better spatial resolution than AIRSAR with better calibration. Then, the development of polarimetric SAR interferometry (Pol-InSAR) techniques gave researchers the
opportunity to establish a new application in forest height estimation [Papathanassiou & Cloude, 2001]. Another airborne polarimetric SAR system, EMISAR, was built by the Electro-Magnetics Institute (EMI), the Technical University of Denmark (TUD) and the Danish Center for Remote Sensing (DCRS). It operated at either C- or L-band with full-polarization. It provided an ever better 3-meter resolution. Krogager developed the Sphere/Deplane/Helix target decomposition method and verified it with EMISAR data [Krogager & Czyz, 1995]. Other polarimetric systems include: the RAMSES from France with multiband (Ka-, X-, C-, S-, L-, P-bands); the CONVAIR 580 SAR from the Canadian Centre for Remote Sensing (CCRS) with X-, C-, P-band experimental SAR systems; the PI-SAR from Japan Aerospace Exploration Agency.

The space-borne Polarimetric SAR application initiated when the SIR-C/X-SAR was successfully launched onboard the Space Shuttles Endeavour in 1994. The platform flew for two short ten-day missions. The SIR-C, which operated at C-band and L-band, collected SAR data with full-polarization mode. In the 2000s, the Japanese Advanced Land Observing Satellite (ALOS), which carried full-polarized SAR sensor Phased Array type L-band Synthetic Aperture Radar (PALSAR), was launched by JAXA in January 2006. TerraSAR-X, launched by DLR in Jun 2007, operated in full-polarization SAR mode at X-band. Canadian SAR sensor RADARSAT-2 operates in full-polarization mode at C-band. These three satellites are considered as a major data resource for the related remote sensing research.
<table>
<thead>
<tr>
<th>Name</th>
<th>Agency/country</th>
<th>Year</th>
<th>Band</th>
<th>Polarization mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRSAR</td>
<td>NASA/JPL(US)</td>
<td>1987~</td>
<td>P/L/C</td>
<td>full</td>
</tr>
<tr>
<td>CONVAIR-580/X_SAR</td>
<td>CCRC(Canada)</td>
<td>1974~</td>
<td>C/X</td>
<td>dual/full</td>
</tr>
<tr>
<td>EMISAR</td>
<td>TUD/EMI(Denmark)</td>
<td>1989~</td>
<td>C</td>
<td>full</td>
</tr>
<tr>
<td>E-SAR</td>
<td>DLR(Germany)</td>
<td>1988~</td>
<td>X/C/L/P</td>
<td>full</td>
</tr>
<tr>
<td>PI-SAR</td>
<td>JAXA-NICT(Japan)</td>
<td>1996~</td>
<td>L/X</td>
<td>full</td>
</tr>
<tr>
<td>RAMSES</td>
<td>ONERA-DEM(R(France)</td>
<td>2002~</td>
<td>P/L/S/C/X/Ku/Ka/W</td>
<td>full</td>
</tr>
<tr>
<td>SETHI</td>
<td>ONERA-DEM(R(France)</td>
<td>2007</td>
<td>VHF/P/L/X</td>
<td>full</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Agency/country</th>
<th>Year</th>
<th>Band</th>
<th>Polarization mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIR-C/X-SAR</td>
<td>NASA/DARA/ASI</td>
<td>1994</td>
<td>L/C</td>
<td>full</td>
</tr>
<tr>
<td>ENVISAT/ASAR</td>
<td>ESA</td>
<td>2002</td>
<td>C</td>
<td>dual</td>
</tr>
<tr>
<td>ALOS/PALSAR</td>
<td>JAXA/JAROS</td>
<td>2006</td>
<td>L</td>
<td>full</td>
</tr>
<tr>
<td>TerraSAR-X</td>
<td>DLR/BMBF/Astrium</td>
<td>2007</td>
<td>X</td>
<td>full</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>DLR</td>
<td>2010</td>
<td>X</td>
<td>full</td>
</tr>
<tr>
<td>RADARSAT-2</td>
<td>CSA/MDA</td>
<td>2007</td>
<td>C</td>
<td>full</td>
</tr>
<tr>
<td>ALOS-2/PALSAR-2</td>
<td>JAXA</td>
<td>2014</td>
<td>L</td>
<td>full</td>
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Table 2.3. Airborne and space-borne polarimetric SAR sensors.
<table>
<thead>
<tr>
<th>(a) AIRSAR (NASA/JPL)</th>
<th>(b) Convair-580C/X-SAR (CCRS/EC)</th>
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<tr>
<td>(c) EMISAR (DCRS)</td>
<td>(d) E-SAR (DLR)</td>
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<tr>
<td>(e) PI-SAR (JAXA-NICT)</td>
<td>(f) RAMSES (ONERA-DEMR)</td>
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**Figure 2.4.** Aireborne polarimetric SAR sensors. [Courtesy of ESA, NASA-JPL, CCRS, DCRS, DLR & JAXA]
<table>
<thead>
<tr>
<th>(a) SIR-C/X-SAR (NASA)</th>
<th>(b) ENVISAT/ASAR (ESA)</th>
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<tbody>
<tr>
<td>(c) ALOS-PALSAR (JAXA)</td>
<td>(d) TerraSAR-X TanDEM-X (DLR)</td>
</tr>
<tr>
<td>(e) RADARSAT-2 (CSA)</td>
<td>(f) ALOS-2 (JAXA)</td>
</tr>
</tbody>
</table>

**Figure 2.5.** Spaceborne polarimetric SAR sensors. [Courtesy of ESA, NASA, JAXA, DLR & CSA]
### 2.4.2 Polarimetric SAR Basics

#### 2.4.2.1 Polarimetric Scattering Vector

The physical nature of polarization can be understood through a classical $2 \times 2$ Sinclair matrix, which is also referred to as scattering matrix. This matrix contains four complex elements that characterize the transformation of the polarization of an incident wave upon a reflective medium to the polarization of the backscattered one. It is represented as follows [Lee & Pottier, 2009]

$$
S = \begin{bmatrix}
S_{xx} & S_{xy} \\
S_{yx} & S_{yy}
\end{bmatrix}
$$

(2.6)

where $S_{ij}$ is the complex scattering amplitude. The diagonal elements $S_{xx}$ and $S_{yy}$ are co-polarized elements, while the off-diagonal elements $S_{xy}$ and $S_{yx}$ are cross-polarized elements.

The scattering mechanism of polarization can also be described in the following vector form [Lee & Pottier, 2009]

$$
\tilde{k} = \frac{1}{2} Tr(S\Psi)
$$

(2.7)

where $\Psi$ is a complete set of $2 \times 2$ complex basis matrices which are constructed as an orthogonal set under the Hermitian inner product.
For a reciprocal target, in the monostatic backscattering case, the reciprocity hold the Sinclair scattering matrix to be symmetrical, which means $S_{xy} = S_{yx}$. Thus, the four-element polarimetric target vectors reduce to three-element polarimetric target vectors.

There are two bases widely used for the vectorial presentation: Lexicographical basis and Pauli basis. [Lee & Pottier, 2009]

The lexicographical basis contains the following basis matrices:

$$\{\Psi_L\} = \left\{ \begin{bmatrix} 2 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, 2\sqrt{2} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, 2\sqrt{2} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \right\}$$

(2.8)

The corresponding scattering vector with **Lexicographic** basis is

$$\bar{k}_L = \begin{bmatrix} S_{xx} & \sqrt{2}S_{xy} & S_{yy} \end{bmatrix}^T$$

(2.9)

The Pauli based expression:

$$\{\Psi_P\} = \left\{ \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \sqrt{2} \begin{bmatrix} 0 & 1 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \sqrt{2} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \right\}$$

(2.10)

And the corresponding scattering vector with **Pauli** basis is

$$\bar{k}_L = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{xx} + S_{yy} & S_{xx} - S_{yy} & 2S_{xy} \end{bmatrix}^T$$

(2.11)

### 2.4.2.2 Polarimetric Coherency $T$ and Covariance Matrices $C$

Since most radar targets are in a changing environment and subject to spatial and temporal variation but not stationary or fixed, a concept of “distributed target” is introduced to characterize the scattering property of this kind of radar target. The concept
of space and time varying stochastic processes can be introduced and the properties of the scattering can be extracted from polarimetric coherency or covariance matrices.

The $4 \times 4$ polarimetric Pauli coherency $T_4$ matrix and the Lexicographic covariance $C_4$ matrix are generated from the outer product of the associated target vector with its conjugate transpose [Lee & Pottier, 2009]

$$T_4 = \langle \bar{k}_p \cdot \bar{k}_p^* \rangle$$
$$C_4 = \langle \bar{k}_l \cdot \bar{k}_l^* \rangle$$

(2.12)

where $\langle \ldots \rangle$ means temporal or spatial ensemble averaging.

For a reciprocal target matrix in the monostatic backscattering case, the Sinclair scattering matrix is restricted to be symmetrical, which means, $S_{xy} = S_{yx}$, the $4 \times 4$ coherency $T_4$ and covariance $C_4$ matrices reduce to $T_3$ and $C_3$ [Lee & Pottier, 2009]

$$T_3 = \langle \bar{k}_l \cdot \bar{k}_l^* \rangle = \left[ \begin{array}{ccc} |k_1|^2 & k_1k_2^* & k_1k_3^* \\
 k_2k_1^* & |k_2|^2 & k_2k_3^* \\
 k_3k_1^* & k_3k_2^* & |k_3|^2 \end{array} \right]$$

(2.13)

$$= \frac{1}{2} \begin{bmatrix}
\langle S_{xx} + S_{yy} \rangle & \langle (S_{xx} + S_{yy})(S_{xx} - S_{yy})^* \rangle & 2\langle (S_{xx} + S_{yy})S_{xy}^* \rangle \\
\langle (S_{xx} - S_{yy})(S_{xx} + S_{yy})^* \rangle & \langle S_{xx} - S_{yy} \rangle^2 & 2\langle (S_{xx} - S_{yy})S_{xy}^* \rangle \\
2\langle S_{xy}(S_{xx} + S_{yy})^* \rangle & 2\langle S_{xy}(S_{xx} - S_{yy})^* \rangle & 4\langle |S_{xy}|^2 \rangle
\end{bmatrix}$$
2.4.2.3 Polarimetric Scattering Mechanisms

A real radar target usually produces a complex scattering response as a consequence of its complex geometrical structure and its reflectivity properties. Backscattering recorded on the image is considered as a function of the surface roughness. Within the radar remote sensing wavelengths’ scale, vegetation is treated as a rough surface, which appears gray or bright grey in the radar images. Urban areas are always characterized by its double bounce property due to the streets and the cubical buildings. Water areas always render dark pixels in radar image because of the “mirror reflection” of the incident waves. There are four types of scattering mechanisms presented and explained blow:

**Surface Scattering**

Radar signals that incident on a smooth surface (i.e. a peaceful water surface) are reflected in the forward direction away from the emitter. Very little energy of the incident signal is reflected to the radar-receiving antenna. As a result, smooth surface appears
extreme dark in SAR image. Smooth rocks, still water and bare soil show the property of smooth surface scattering.

**Rough Surface Scattering**

If the incident radar signals are scattered in all directions, the property of the ground is labeled as rough surface. Part of the incident energy is reflected back to the receiving antenna. The rougher the surfaces are, the higher the backscattered energy is. Wavy water surface and bumpy soil surface are good examples of rough surface.

**Volume Scattering**

Volume scattering is defined as the scattering occurring in a medium the radar signal transmits from one medium to another medium. There are two examples of the model of volume scattering: one is scattering by widely distributed particles like rain drops, the other one is scattering in uneven media with different permittivity. Scattering by trees or branches, subsurface or soil layers, snow layers are examples of volume scattering.

**2.4.2.4 Polarimetric Decomposition and Classification**

The distinguishing property of SAR polarimetry is that it can discriminate different types of scattering. Compared to single channel SAR, the polarization can improve the performance of classification significantly. Some direct physical properties of the scattering process can be interpreted by some particular models [Cloude & Pottier, 1996]. Furthermore, some ground parameters such as soil moisture and surface roughness can also be estimated with unsupervised classification methods [Cloude et. al., 1999].
objective of target decomposition theory is to express the average scattering mechanism as the sum of independent elements to associate a physical mechanism with each component [Touzi et. al., 2004]. Thus, the polarimetric decomposition breaks the original signal into several different components with orthogonal polarimetric signatures [Cloude & Pottier, 1996]. Target decomposition methods can be divided into coherent and incoherent categories.

Coherent target decomposition refers to the case when the scattered waves are completely polarized. Well-known coherent decomposition methods include: Pauli decomposition [Cloude & Pottier, 1996]; the Sphere/Deplane/Helix decomposition [Krogager & Czyz, 1995]; the Cameron decomposition [Cameron et. al., 1996].

Incoherent target decomposition refers to the case that the scattered waves are partially polarized. Canonical incoherent target decomposition approaches include: Cloude-Pottier [Cloude & Potter, 1997]; the Freeman-Durden [Freeman & Durden, 1998]; the Moriyama decomposition [Moriyama et. al., 2005].

Below, the decomposition methods applied in this research are discussed.

**Pauli Decomposition**

The objective of the coherent decompositions is to express the measured scattering $S$ matrix as a combination of basis matrices corresponding to classical scattering mechanisms. [Cloude & Pottier, 1996]

$$S = \sum_{k=1}^{N} \alpha_k S_k$$  \hspace{1cm} (2.15)
The Pauli decomposition is one of the basic polarimetric SAR data analysis techniques. It is a coherent decomposition approach in which the target scattering matrix is expressed in terms of the Pauli matrices [Cloude & Pottier, 1996]. The decomposition expresses the scattering $S$ matrix as the complex sum of the Pauli matrices, which represent different scattering mechanisms: the surface, double bounce and 45 degree tilted double bounce.

$$S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = \frac{a}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + \frac{b}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} + \frac{c}{\sqrt{2}} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} + \frac{d}{\sqrt{2}} \begin{bmatrix} 0 & -j \\ j & 0 \end{bmatrix}$$

(2.16)

where $a$, $b$, $c$ and $d$ are all complex and are given as

$$a = \frac{S_{HH} + S_{VV}}{\sqrt{2}} \quad b = \frac{S_{HH} - S_{VV}}{\sqrt{2}} \quad c = \frac{S_{HV} + S_{VH}}{\sqrt{2}} \quad d = j \frac{S_{HV} - S_{VH}}{\sqrt{2}}$$

(2.17)

In the monostatic case, where $S_{HV} = S_{VH}$, the Pauli matrix basis can be reduced to the first three matrices and $d = 0$. It also follows the span value principle:

$$\text{Span} = |S_{HH}|^2 + 2|S_{HV}|^2 + |S_{VV}|^2 = |a|^2 + |b|^2 + |c|^2$$

(2.18)
Pauli matrix | Scattering mechanism | Interpretation
--- | --- | ---
\[
\begin{bmatrix}
1 & 0 \\
0 & 1 \\
\end{bmatrix}
\] | Plane surface, single or odd-bounce scattering | Surface, sphere, trihedral
\[
\begin{bmatrix}
1 & 0 \\
0 & -1 \\
\end{bmatrix}
\] | Double bounce, even-bounce scattering | Dihedral
\[
\begin{bmatrix}
0 & 1 \\
1 & 0 \\
\end{bmatrix}
\] | 45° tilted double bounce, even-bounce scattering | 45° tilted dihedral

Table 2.4. Interpretation of different mechanisms based on Pauli decomposition. [Lee & Pottier, 2009]

**H / A / \bar{\alpha} Polarimetric Target Decomposition**

Cloude and Pottier [Cloude & Pottier, 1997] proposed an incoherent decomposition method on eigenvector/eigenvalue analysis for extracting parameters from polarimetric SAR data using a smoothing algorithm based on second-order statistics. Based on the eigenvalue analysis of the coherency $T_3$ matrix, the method applies a three-level Bernoulli statistical model to generate estimates of the average target scattering matrix parameters.

Since the coherency matrix $T_3$ is Hermitian positive semi definite matrix, it can be calculated to generate a diagonal form of the coherency matrix, which can be physically, interpreted as statistical independence between a set of target vectors. The coherency matrix can be given as
where $\Lambda$ is the diagonal eigenvalue matrix of $T_3$, $\lambda_1 > \lambda_2 > \lambda_3 \geq 0$ are the eigenvalues and $U_3$ is a unitary matrix whose columns correspond to the orthogonal eigenvectors of $T_3$.

\[
T_3 = U_3 \Lambda U_3^{-1} = U_3 \Lambda U_3^{-1} U_3^{-1}
\]

where $\beta$ and $\alpha$ represents the orientation of the radar target about the radar line of sight and the $\alpha$ angle, respectively.

A statistical model of the scatterers is considered as three-symbol Bernoulli process, where the target is modeled as the sum of three $S$ matrices, represented by the columns of the $U_3$ matrix, occurring with pseudo-probabilities $P_i$, shown as below

\[
P_i = \frac{\lambda_i}{\sum_{k=1}^{3} \lambda_k} \quad \text{where } \sum_{k=1}^{3} P_k = 1
\]

Thus, the mean parameters of the dominant scattering mechanism are extracted from the coherency matrix as a mean unit target vector $u_0$, given as

\[
\bar{u}_0 = e^{i\phi} \begin{bmatrix}
\cos \alpha \\
\sin \alpha \cos \beta e^{i\delta}
\end{bmatrix}
\]
where \( \phi \) is physically equivalent to an absolute target phase and where the parameters \( \alpha \), \( \beta \), \( \delta \) and \( \gamma \) are defined as

\[
\bar{\alpha} = \sum_{k=1}^{3} P_k \alpha_k, \quad \bar{\beta} = \sum_{k=1}^{3} P_k \beta_k, \quad \bar{\delta} = \sum_{k=1}^{3} P_k \delta_k, \quad \bar{\gamma} = \sum_{k=1}^{3} P_k \gamma_k
\] (2.23)

The mean target vector \( \bar{k}_0 \) is defined as

\[
\bar{k}_0 = \sqrt{\bar{\lambda}} \bar{u}_0 = \sqrt{\bar{\lambda}} e^{j\phi} \begin{bmatrix} \cos \bar{\alpha} \\ \sin \bar{\alpha} \cos \bar{\beta} e^{j\bar{\delta}} \\ \sin \bar{\alpha} \sin \bar{\beta} e^{j\bar{\gamma}} \end{bmatrix}
\] (2.24)

Where the parameter \( \bar{\lambda} \) refers to the mean target power (SPAN) and is given by

\[
\bar{\lambda} = \sum_{k=1}^{3} P_k \lambda_k
\] (2.25)

Important parameters can be derived based on the \( H / A / \alpha \) decomposition.

**Entropy**

In order to define the degree of statistical disorder of each distinct scatter type with the ensemble, the polarimetric entropy \( H \) is considered as an efficient basis-invariant parameter and defined as

\[
H = -\sum_{k=1}^{N} P_k \log_N (P_k)
\] (2.26)

This parameter is an indicator of the randomness of the given scattering process. When \( H = 0 \), it refers to deterministic scattering, while when \( H = 1 \), it belongs to total random scattering.
Anisotropy

Another eigenvalue parameter is introduced as polarimetric anisotropy $A$, which is given by

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3}$$

(2.27)

The anisotropy $A$ is considered as a complementary parameter to entropy. The anisotropy measures the relative importance of the second and third eigenvalues of the decomposition. From a practical point of view, the anisotropy can be considered as a key for discrimination when $H > 0.7$. In a word, the anisotropy $A$ plays a key role and becomes a very useful parameter to improve the capability to discriminate different types of scattering process when the polarimetric entropy $H$ reaches a high value.

Alpha Angle $\bar{\alpha}$

The alpha angle $\bar{\alpha}$ represents the type of the scattering mechanism and ranges from 0 and 90°. It is given as

$$\bar{\alpha} = P_1\alpha_1 + P_2\alpha_2 + P_3\alpha_3$$

(2.28)

When $\alpha = 0$, it indicates surface scattering. When $\alpha = 45^\circ$, it represents a dipole scattering. As $\alpha$ reaches $90^\circ$, the scattering process is characterized by double bounce.

$H / A / \bar{\alpha}$ decomposition is widely used in unsupervised segmentation of polarimetric SAR data [Hellmann, 1999; Cloude & Pottier, 1997; Dabboor & Karathanassi, 2005; Park & Moon, 2007; Lee et al., 1999; Cao et. al., 2007].

The entropy $H$ and $\alpha$ can be combined together in a two-dimensional space. This space is called $H / \bar{\alpha}$ plane and can be divided into eight different zones.
Figure 2.7. The $H/\alpha$ plane and interpretation [Lee & Pottier, 2009].

The zones can be used as a reference for unsupervised classification of the polarimetric SAR data. The eight zones can be improved into sixteen by involving the anisotropy parameter and producing a three-dimensional space of the entropy, alpha angle and anisotropy [Pottier & LEE, 1999]. The resulting segmentation is usually used as initial segmentation in other different polarimetric SAR segmentation algorithms [Lee et. al., 1999; Park & Moon, 2007; Cao et. al., 2007].
2.4.2.5 Complex Wishart Classifier For Multilook Polarimetric SAR Data

The covariance matrix has the distinct advantage in that it has a multivariate complex Wishart distribution, which is suited for classification. [Lee et al., 1999] The multilook polarimetric SAR processing requires averaging several independent single-look covariance matrices,

\[ Z = \frac{1}{n} \sum_{k=1}^{n} \bar{u}(k)\bar{u}(k)^T \]  \hspace{1cm} (2.29)

where \( n \) is the number of looks; the vector \( \bar{u}(k) \) is the \( k \)th single-look sample.

Let

\[ A = nZ \sum_{k=1}^{n} \bar{u}(k)\bar{u}(k)^T \]  \hspace{1cm} (2.30)

Thus, the matrix \( A \) has a complex Wishart distribution. The complex Wishart probability density function is

\[ P_A(A) = \frac{|A|^{q-q} \exp[-Tr(C^{-1}A)]}{K(n,q)|C|^n} \]  \hspace{1cm} (2.31)

The parameter \( q \) is the dimension of vector \( \bar{u} \). For monostatic polarimetric SAR in a reciprocal medium, \( q = 3 \). \( Z \) is the maximum likelihood estimator for the expected covariance \( C \). The Bayes maximum likelihood classifier was developed with the same procedure as that for single-look polarimetric SAR data. A distance measure is derived by maximizing \( P(A|\omega_m)P(\omega_m) \):

\[ d(A,\omega_m) = n \ln|C_m| + Tr(C_m^{-1}A) - \ln[P(\omega_m)] - (n-q)\ln|A| + \ln[K(n,q)] \] \hspace{1cm} (2.32)

Since the last two terms are not a function of \( \omega_m \), they can be ignored here. Thus, the distance measure for classification becomes
\[ d_2 (A, \omega_m) = n \ln |C_m| + Tr(C_m^{-1}A) - \ln[P(\omega_m)] \]  
(2.33)

The multilook distance measure is the same as the single-look distance measure when \( n = 1 \). For polarimetric SAR data with unknown priori probabilities of each class, \( P(\omega_m) \) can be assumed to be as equal, which is independent of \( n \). As a result, the distance measure for classification can be further reduced to

\[ d_3 (A, \omega_m) = n \ln |C_m| + Tr(C_m^{-1}A) \]  
(2.34)

Here we call \( d_3 (A, \omega_m) \) the Wishart distance measure. For supervised classification, the class center covariance \( C_m \) is estimated using pixels within a chosen training area. For each pixel to be classified, \( d_3 (A, \omega_m) \) is calculated and the class associated with the minimum distance is assigned to the pixel. This distance measure classification method can be applied for any dimension of coherent SAR data. The different \( q \) values refer to different data types, which is shown in the following table.

<table>
<thead>
<tr>
<th>( q ) value</th>
<th>Data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single polarization intensity data</td>
</tr>
<tr>
<td>2</td>
<td>Coherent dual-polarization data</td>
</tr>
<tr>
<td>3</td>
<td>Monostatic polarimetric SAR data</td>
</tr>
<tr>
<td>4</td>
<td>Bistatic polarimetric SAR data</td>
</tr>
<tr>
<td>6</td>
<td>Single-baseline polarimetric InSAR data</td>
</tr>
<tr>
<td>9</td>
<td>Dual-baseline polarimetric InSAR data</td>
</tr>
</tbody>
</table>

Table 2.5. The different \( q \) values with different data types, for Wishart distance measure classification application. [Lee et al., 1999]
CHAPTER 3: Mountain Glacier Classification And Extent Change Monitoring Using Polarimetric SAR Data And Long-term Landsat Imageries: Case Study for the Geladandong Glacier, Tibetan Plateau

3.1 Introduction

The state of the mountain glaciers on the Qinghai-Tibetan Plateau in the Asian High Mountain (AHM) is sensitive to global climate change, and plays an important role in providing water resources to over 1 billion people downstream in Asia. The knowledge of whether the mountain glaciers in the region are retreating or advancing, and the associated mass balance estimates would advance our understanding of the impacts of the climate change process in the region, and provide insights on practical water resources management. *In situ* mountain glacier measurements are sparse especially over the Asian High Mountain region. The Asian High Mountain glacier mass balance estimates are controversial and with wide ranges [Yao et al., 2007; Duan, 2013; Shum et al., 2015]. Fig. 3.1 shows mass trend estimates by satellite gravimetry data, GRACE, over the Asian High Mountain region, including glacier mass balance [Duan, 2013; Shum et al., 2015]. However, GRACE estimates have coarse resolutions and it has been argued that the
Figure 3.1. GRACE estimated mass variation trend in terms of equivalent water height over Asian High Mountain, including glacier mass balance estimates [Duan, 2013; Shum et al., 2015]. White areas are glacier mask using the RGI [Arendt et al., 2012].

Extra References:

limitation in the GRACE data is its resolution at 300 km or longer, which cannot adequately estimate accurate mass balance. The glaciated area or extent and its changes of the world’s ice-covered region are not well known. Specifically, the total volumes and their areas of global glaciers, including the Asian High Mountain, are highly uncertain [Radić & Hock, 2010]. The estimates of the Himalayan glacier volume vary over an order of magnitude and the 12,000 km³ estimate [Cruz et al., 2007] seem high. Based on statistical methods, the current Asian HM glacier volume estimate is 12,483±462 km³ (area is 114,330±729 km²) [Radić & Hock, 2010], which is ~15% higher than WGI_XF [Cogley, 2009], corresponding to a would-be change of sea-level at 31 mm differences. Himalayan glaciers are rock or debris glaciers, making glacier classification difficult. The most recent glacier mask data product, the Randolph Glacier Inventory (RGI), V4.0 [Arendt et al., 2012], has apparent problems providing an accurate classification of the AHM glaciated surfaces. Here we will demonstrate the use of polarimetric SAR to classify mountain glaciers, including the Geladandong glacier in the Tibetan Plateau. Satellite remote sensing, both passive and active, provides important data sources for the glacier classification and also mass balance research.
Landsat data has long been used for studying and monitoring glacier variation [Williams & Hall, 1993]. The long time-range data accessibility of Landsat series data provides an efficient way to analyze the changes in glaciers. There are some inherent deficiencies to use optical/infrared remote sensing data to measure changes in glaciated regions. First, the performance of thermal mapping is strongly affected by clouds. In regions where clouds are quite common, accessing cloud-free data would be a major problem. Second, snow and ice have similar thermal properties in the glacial and snowpack regions. As mentioned in Chapter 2, Synthetic Aperture Radar (SAR) sensors are neither affected by lack of daylight nor adverse weather conditions. By applying different microwave bandwidths, SAR data can be used to image glacier regions with a certain level of penetration. Dry snow does not change the backscattering from ground significantly in comparison to bare ground, but wet snow can be monitored well with SAR data due to the reduction in backscattering [Baghadi et. al., 1997; Koskinen et. al., 1997; Nagler & Rott, 2000].

Repeat pass SAR coherence was also considered as a tool to determine the snow/glacier boundaries [Shi et. al, 1997]. In this chapter, L-band SAR coherence results are also included as an aid to the glacier boundary determination.

Moreover, it is difficult to discriminate glacial ice from the surrounding land using mono-channel SAR data due to the fact that they have similar characteristics [Konig et. al., 2001]. Polarimetric SAR can highly improve the performance of the data analysis in glacier regions. Airborne experiments also prove that polarimetric SAR is a better tool for glacier monitoring than mono-channel SAR [Konig et. al., 2009b]. In this research, target
decomposition is used as a major method to get features for classification. The results are also compared with those from optical remote sensing classification.

The specific work in this study is to classify and map the rock/glacier extents for estimating the retreat or advance of glaciers over the specific region of Asian High Mountain, Geladandong glaciers, using Landsat time-series, polarimetric Synthetic Aperture Radar as well as repeat-pass SAR correlation coefficients classification techniques. Then we make comparisons between our results with existing glacier mask inventory, the Randolph Glacier Inventory (RGI).

3.2 Description of the study region and data

3.2.1 State of the Asian High Mountain Glaciers

The Asian High Mountain area contains the largest number of glaciers outside the Polar Regions. Such glaciers are the main water source of many prominent Asian rivers and are largely experiencing shrinkage [Yao et. al., 2007].

3.2.2 Specific Study Regions

The Geladandong Glaciers

The Geladandong Mountain, containing the highest peak in the Tanggula Mountains with an average elevation of 6,621 m, is located in central Tibetan Plateau, the southwest of Qinghai Province of China (91°E, 33.5°N). It contains 50 glaciers that are distributed in a 50 km by 30 km mountainous region. The Tanggula Mountains serve as a geographical
boundary between the continental climate and the summer Indian monsoon over the Tibetan Plateau [Zheng & Zhu, 2003]. The north part is subject to continental air masses, while the south is affected by the air masses from the summer Indian monsoon. The two air masses meet right around 33°N, which is the location of Geladandong mountain. The Geladandong mountain glacier region is the origin of Yangtze River in China.

**Bering Glacier - Region for Testing Polarimetric SAR Classification Method**

Due to the relative scarcity of the ALOS-PALSAR polarimetric SAR data in Asian High Mountain area at the beginning of our study, a test region was firstly chosen around the terminus of the Bering glacier in south Alaska. The reason why Bering glacier area is chosen as a test area is (1) the accessibility of ALOS-PALSAR full-polarized SAR data and (2) the similarity between Bering glaciers and Asian High Mountain area glaciers. Runoff from the mountains and large glaciers on the rim of the Gulf of Alaska is a critical driver for ocean circulation in the gulf and a major contributor to global sea level rise. Bering Glacier is the foremost glacier of this system, with one of the largest proglacial lake-river systems in the world [Josberger, 2009].

The Bering glacier terminates in Vitus Lake, which is 9.98 km from the Gulf of Alaska. Warmer temperatures and changes in precipitation over the past century have thinned the Bering Glacier by several hundred meters. Since 1900 the terminus has retreated as much as 12 km (7.5 mi).
3.3 Methodology

In our study, multiple methods and techniques with different types of data are implemented in order to give convincing results and a cogent conclusion.

3.3.1. Optical Classification Methods

Landsat is an excellent data source for monitoring remote glaciers by virtue of its spatial and temporal coverage range. With the Landsat multi-band data, accurate glacier boundary map can be obtained by segmentation of a ratio image from Thematic Mapper channel 4 and 5 [Bayr et. al., 1994; Jacobs et. al., 1997; Paul, 2002]. ISODATA unsupervised algorithm is then applied to get better classification results. The full name of the technique is “Iterative Self-Organizing Data Analysis Technique yAy”. It was developed by Geoffrey H. Ball and David J. Hall [Ball & Hall, 1965]. This is an unsupervised classification method using an iterative approach to recalculate means and reclassify pixels with respect to the new means until the percentage of pixels that change classes during an iteration is less than the specified change threshold or maximum number of iterations is reached.

3.3.2. Repeat-Pass SAR Correlation Coefficient Classification Method

Repeat-pass SAR correlation coefficient can be used as an efficient tool to determine the boundary of glacier area by differentiating wet/water surface from plain rock with its low correlation characteristic. A particular calculation method based on multiple bands is implemented in order for differentiating ice from rock.
3.3.3 Polarimetric SAR Classification Methods

In this study, polarimetric SAR data is also considered as a source to support our classification results. Unsupervised classification algorithm is preferred due to the lack of \textit{in situ} data in remote regions, such as the Tibetan Plateau. Unsupervised classification algorithms can be divided into three categories [Lee & Pottier, 2009]

1. Algorithms that are developed based on the inherent statistical characteristics of class. A number of clustering methods are applied in order to render classification results;

2. Algorithms that are based on physical scattering characteristics of polarimetric SAR data. It classified the ground as odd bounce, even bounce or volume scattering.

3. Algorithms based on target decomposition theory. The scattering mechanisms are characterized by entropy, anisotropy and alpha angle. $H/\alpha$ was divided into eight zones, which represent different ground type with different scattering characteristics.

$H/A/\alpha$ decomposition as well as classification technique is applied in this study. The polarimetric entropy $H$ is an indicator of the randomness of the given scattering process. When $H = 0$, it refers to deterministic scattering, while when $H = 1$, it belongs to total random scattering.

Anisotropy $A$ measures the relative importance of the second and third eigenvalues of the decomposition.
The alpha angle $\alpha$ represents the type of the scattering mechanism and ranges from 0 and 90°. When $\alpha = 0^\circ$, it indicates surface scattering. When $\alpha = 45^\circ$, it represents a dipole scattering. As $\alpha$ reaches $90^\circ$, the scattering process is characterized by double bounce.

3.4 Results and Discussion

3.4.1 Test Area – Bering Glacier

Since polarimetric SAR data is not widely used for classifying glacier boundary, we need to firstly study the feasibility of this method. Meanwhile, due to the relative scarcity of the ALOS-PALSAR full-polarized SAR data in Asian High Mountain area at the beginning of our study, a test region was firstly chosen around the terminus of the Bering glacier in south Alaska. Moreover, in this case study, the advantage of using polarimetric SAR data over using Landsat data for classifying glaciers is also presented.

The data used in this experiment is the ALOS PALSAR Level 1.1 full-polarimetric (HH, VH, HV, VV) SAR data set on Apr. 1st, 2007. The original scene size is 18432 by 1248 pixels (azimuth by range), with pixel spacing of 3.57 meters in azimuth and 9.37 meters in slant range.
Figure 3.2. Test area showing terminus of Bering Glacier, Alaska (60.34°N, 143.35°W).

We applied $H/A/\alpha$ decomposition and classification with the test full-polarized SAR data. The decomposition results are shown in the following figures:
The data occurrence in the $H/\alpha$ plane as well as the classification results are shown in Figure 3.4.

Firstly, water area, including lakes and river, are clearly identified as surface reflection (SR) with extremely low randomness. Secondly, ice area is differentiated as SR with moderate randomness. Finally, all other areas are classified as bare rock characterized by volume diffusion (VD) with higher entropy. Double bounce (DB) is scarce because of no buildings in this region.
Figure 3.4. (a). Polarimetric data occurrence in the $H/\alpha$ plane; (b). & (c). Unsupervised $H/A/\alpha$ classification mechanism and result.

The result is geocoded and refined with a better palette. RGI data of the region is plotted as an overlay for making comparison Landsat image at the same time.

The result fits RGI well, especially at the glacier terminus near lake (D). While RGI include some of the bare mountain (A) and river (C). It is possibly because L-band SAR ignores thin ice or snow layers due to the penetration property. Evidence can be found by
comparing with Landsat image, in which all-mountainous areas (A), lakes (B, D) and rivers(C) are all in white and cannot be distinguished.

Figure 3.5. (left) Landsat image (left); (right) geocoded classification result (white - glacier, blue - water, green – rock) and RGI glacier mask (pink).

3.4.2 Geladandong Glacier

As our major region of interest, Geladandong Mountain, the highest peak in the Tanggula Mountains, is located in the central Tibetan Plateau at 33.5°N, 91.1°E. The Tanggula Mountain is considered as an orographic boundary between the continental air masses to the north and the summer Indian monsoon to the south of the Tibetan Plateau [Zheng & Zhu, 2003]. The two air masses meet between 32°N and 34°N. Geladandong Mountain is
the headwaters of the Yangtze River, which serves as a major water source of China. There is a need for a basic understanding of the sensitivity of these glaciers to long-term change.

In the classification application, we further included classification results from thematic mapper data as comparison. With the TM4/TM5 ratio image method, all debris-free glacier ice, as well as snow, is classified as glacier. The most important task for glacier studies with Landsat TM is to find a cloud-free and snow-free scene of the glaciers. These requirements are highly affected by local temperature and precipitation.
In Geladandong glacier region, the temperature and precipitation characteristics are affected by both sides of the mountains: Accumulation on the glaciers on the south side of the Tanggula mountains depends mainly on water vapor transported from the south and southeast. The moisture source for the glaciers on the north side is from the east [Ding et al., 1992]. The temperature and precipitation statistics are shown in the following table and figure.

<table>
<thead>
<tr>
<th>Position</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geladandong</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean TAG</td>
<td>-18.5</td>
<td>-17.0</td>
<td>-13.1</td>
<td>-7.7</td>
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<td>-15.3</td>
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<td>Mean ELA</td>
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<td>-10.0</td>
<td>-6.7</td>
<td>-2.0</td>
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<td>0.0</td>
<td>-2.7</td>
<td>-10.2</td>
<td>-16.5</td>
<td>-18.7</td>
</tr>
</tbody>
</table>

Table 3.1. Mean monthly air temperature in °C, at mean equilibrium line altitude (ELA) and mean terminal altitude glacier (TAG) (1960~1980) [Ding et al., 1992].
According to the temperature and precipitation distribution in the area, a cloud free Landsat TM scene is selected for the processing. The data information of the selected data is recorded in Table 3.1. Both Thermal Mapping data and SAR data sources are included.
3.4.2.1 Classification Using Landsat Data

By applying the TM4/TM5 ratio method, the resulting black and white glacier map is shown in Figure 3.8 (right). Landsat-5 TM in RGB mode with RGI boundaries in red color is show on the left as reference.

Figure 3.8. (Left) Landsat-5 TM in RGB mode with RGI glacier mask overlaid (red boundaries); (Right) Landsat-7 TM4/TM5 ratio result, white and black areas represent glacier and non-glacier regions, respectively.
In order to determine and clarify the boundaries of the glaciers, further processing is implemented on the TM4/TM5 ratio result. ISODATA technique is applied in order to cluster pixels. In our case, we define the number of classes to be five with maximum iterations of ten and changing threshold percent as 2%. The classification result is shown in Figure 3.9.
Figure 3.9. Advanced classification result from Landsat TM4/TM5 ratio overlaid with RGI 4.0 glacier masks.

From the result, we find that the classification result generally agrees with the glacier masks from RGI 4.0 (December 1st, 2014 version). In RGI, large parts of Central Asia are
covered by the GLIMS database, where the data in China were from the first Chinese Glacier Inventory [Shi et. al., 2009], and are of heterogeneous and generally slightly lower quality than the other glacier data used in the inventory. In version 4.0, the CGI glaciers were recovered from the May 24, 2011 version of GLIMS.

However, there are some significant discrepancies between the classification result based on Landsat data and RGI database. Four major ambiguous regions are marked as “A”, “B”, “C”, “D” and “E” in Figure 3.9. We could find a convergent characteristic in the four areas that the RGI glacier range is much larger than our result from Landsat. Thus, we proposed two procedures to assess the validity of the glacier boundary estimation:

1. A series of Landsat data in chronological order between 1973 and 2014 is collected and classified with the same routine. We took data by the same standard that the data should be cloud-free and collected in snow-free time-period in a year.

The information of the data that we collected and applied in the classification procedure is shown is the table below.
<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Sensor/Mode</th>
<th>SCENE_ID</th>
</tr>
</thead>
<tbody>
<tr>
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<td>06/10</td>
<td>Landsat_1 / MSS</td>
<td>LM11490371973161AAA04</td>
</tr>
<tr>
<td>1976</td>
<td>10/25</td>
<td>Landsat_2 / MSS</td>
<td>LM21490371976299XXX01</td>
</tr>
<tr>
<td>1977</td>
<td>08/27</td>
<td>Landsat_2 / MSS</td>
<td>LM214903719777239AAA03</td>
</tr>
<tr>
<td>1986</td>
<td>07/30</td>
<td>Landsat_5 / TM</td>
<td>LT51380371986211BJC00</td>
</tr>
<tr>
<td>1991</td>
<td>08/29</td>
<td>Landsat_5 / TM</td>
<td>LT51380371991241BJC00</td>
</tr>
<tr>
<td>1992</td>
<td>08/15</td>
<td>Landsat_5 / TM</td>
<td>LT51380371992228BJC00</td>
</tr>
<tr>
<td>1999</td>
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</tr>
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<td>LANDSAT_7 / ETM</td>
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<tr>
<td>2003</td>
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<tr>
<td>2005</td>
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<td>2006</td>
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<td>2007</td>
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<td>08/12</td>
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<td>LE71380372011224PFS00</td>
</tr>
<tr>
<td>2012</td>
<td>10/01</td>
<td>LANDSAT_7 / ETM</td>
<td>LE71380372012275PFS00</td>
</tr>
<tr>
<td>2013</td>
<td>08/01</td>
<td>LANDSAT_7 / ETM</td>
<td>LE71380372013213PFS00</td>
</tr>
<tr>
<td>2014</td>
<td>07/03</td>
<td>LANDSAT_7 / ETM</td>
<td>LE71380372014184PFS00</td>
</tr>
</tbody>
</table>

**Table 3.2.** Landsat scenes, 1973–2014, used in the analysis of glacier area/extent changes of the Geladandong glacier, Tibetan Plateau.
The selected classification results between 1973 and 2014 with Landsat TM/ETM data is shown in Figure 3.10. It should be noted that the striping on some of the ETM Landsat-7 data is caused by the failure of the scan line corrector (SLC) in 2003. As full view of the Geladandong glacier, we can easily find constant differences and deviations between our classification results and RGI boundaries in several particular areas. Specific investigation and analysis is implemented in region A, B, C, D and E respectively.
Figure 3.10. Geladandong glacier classification results between 1973 and 2014 using Landsat TM/ETM data.
Region A

We find the classification results through forty years generally agree with the RGI database in region A (Figure 3.11). There’s no major deviation between our results and the red polygon in the glaciers at the 6 o’clock direction. However, there is a large discrepancy in the red polygon at the 12 o’clock direction. By using Landsat data, we find no sign of glacier existence in the region with 40 years’ classification results as evidence.

Figure 3.11. Selected frames in region A (1973–2014).
Region B

In region B of Geladandong glacier (Figure 3.12), we find the inadequacy of RGI in monitoring glaciers. Here we focus on the glacier at center of the scene. In 1973 and 1986, we speculate that the RGI database generally depicts the boundary of the glacier during that period. However, when we consider all the results between 1973 and 2014 as a time series, it is clearly shown that the glacier is retreating constantly. Approximately, the glacier has retreated a total amount of 3000 meters during the period 1986-2014. The RGI doesn’t provide any clue of this retreating process.

Figure 3.12. Selected frames in region B (1973~2014).
Region C

The scenario in region C (Figure 3.13) further confirms our speculation. The two pieces of glaciers at 5 and 6 o’clock direction give additional evidence to demonstrate the glacier retreating progress that RGI does not show. In the glacier at the 5 o’clock direction, an area loss of approximately 5.5 km$^2$ with retreating rate of 0.134 km$^2$/year is estimated during the period 1973-2014.

Besides, from the comparison in the glacier at 10 o’clock direction, we can find the glacier didn’t change much in shape. However, there’s an apparent deviation between our result and the reference. Therefore, registration problem is speculated as another issue with RGI database. Further evidence and discussion will be presented for region E.

Figure 3.13. Selected frames in region C (1973–2014).
Region D

From the results in region D, we can find that some of the glaciers like the one at the center of the scene don’t change too much in shape during decades. However, there is a constant deviation between RGI boundaries and our classification results. In order to judge which is correct, we need to implement additional methods based on completely different data source, for which polarimetric SAR data are used. Further results and discussions are given in the following section.

Figure 3.14. Selected frames in region D (1973–2014).
Region E

It is interesting to find that the RGI database in this region generally agrees with the shape of our classification result. However, an apparent deviation can be found in the comparison during the 40 years period between 1973 and 2014. A further verification of this bias is also shown in the next section with polarimetric SAR data.

Figure 3.15. Selected frames in region E (1973–2014).
3.4.2.2 Classification based on Repeat Pass SAR Correlation Coefficients

There are two techniques that can be applied as a classifier for glaciers based on SAR data. The first one uses interferometric correlation results from processing repeat pass SAR data pair as a reference for classification. The low coherence over wet snow region is basically caused by the rapid change in scattering properties and geometry as a result of wet snow metamorphism due to the water movement as well as ice grow and loss. The high coherence is regularly observed over snow-free areas, like bare ground.

The repeat pass SAR pair information is listed in the following table:

<table>
<thead>
<tr>
<th></th>
<th>SAR scene #1</th>
<th>SAR scene #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scene ID</td>
<td>ALPSRP03889660</td>
<td>ALPSRP4560660</td>
</tr>
<tr>
<td>Date</td>
<td>Oct-17-2006</td>
<td>Dec-02-2006</td>
</tr>
<tr>
<td>Sensor Mode</td>
<td>PLR</td>
<td>PLR</td>
</tr>
<tr>
<td>Polarization Channel</td>
<td>HH</td>
<td>HH</td>
</tr>
<tr>
<td>Data Level</td>
<td>L1.0</td>
<td>L1.0</td>
</tr>
</tbody>
</table>

*Table 3.3. Repeat pass SAR data information.*

The correlation result in Geladandong region is shown in Figure 3.16. The left part of the figure is the single look complex intensity image of the scene. We can find singularities (bright spots as mountain ridges) that are caused by the steepness of the mountains. Those singularities not only affect the quality of the image but also compromise the condition for the geocoding process. Therefore, we can find that the final correlation
result is not with high quality or accuracy. However, the results in specific regions can reinforce our previous inferences based on Landsat data.

Figure 3.16. (left) PALSAR-HH SLC data; (right) repeat pass coherency result.

Figure 3.17 and Figure 3.18 show the comparisons between correlation coefficient and the classification results based on Landsat data in region A, B, C, D and E respectively. Particularly, we find that in region B and C the absence of glacier shown in Landsat
classification results highly agree with the characteristics presented in correlation coefficients. This is strong evidence supporting the conclusion that the RGI database is inaccurate in Geladandong glacier region.

Figure 3.17. Comparison between correlation coefficient and the classification results based on Landsat data. (Region A, B and C)
3.4.2.3 Classification with Polarimetric SAR data

For single polarization SAR image, as mentioned previously, the glacier (ice) is hard to be distinguished from bare ground. Hence, full-polarized data is obtained and implemented to do the job. In this section, several methods are implemented to render glacier classification results. Both unsupervised and supervised approaches are included. The polarimetric SAR scene is processed in the following procedure: First, an original scene with 1 looks in the azimuth direction and 1 look in the range direction is prepared.
for further processing. Second, Lee Sigma filter is implemented to cut off the noise of the speckle noise [Lee et al., 2009]. Third, target decomposition is applied. Finally, multiple classifiers are used for image classification. After the procedure, the results are geocoded with the aid of DEM information.

<table>
<thead>
<tr>
<th>Scene ID</th>
<th>ALPSRP03889660</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Oct-17-2006</td>
</tr>
<tr>
<td>Sensor Mode</td>
<td>PLR</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH/HV/VH/VV</td>
</tr>
<tr>
<td>Data Level</td>
<td>L1.0</td>
</tr>
<tr>
<td>Pass Direction</td>
<td>Ascending</td>
</tr>
<tr>
<td>Incident Angle</td>
<td>21.5°</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>14.990 m</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>4.425 m</td>
</tr>
</tbody>
</table>

**Table 3.4.** SAR data used in polarimetric classification.

The H/A/Alpha decomposition is shown in Figure 3.19. We can find a high average value of entropy in the whole region, which indicates a relative high randomness of scattering mechanism. According to the scattering mechanism, the entropy in wet snow or ice region should be higher than that in land region; from the entropy result, we can find qualitative prove of it. Moreover, $\alpha$ is another good indicator to help classify glaciers. Surface scattering is usually the dominant component over the land, while it is not the significant scattering mechanism on ice. Based on the principle, $\alpha$ can also be included
as an important parameter to determine the glacier boundaries. The parameter $\bar{\lambda}$ refers to the mean target power ($SPAN$). From $\bar{\lambda}$ distribution, we can find the regions that are affected by foreshortening and shadow effects, since the area is mountainous and therefore uneven. Based on the geometry of the SAR platform, we can find the extremely bright area indicates the “sunny slope” facing the SAR sensor directly, or in other words, perpendicular to the direction of the incident radar beam. The dark area right next to the bright spots reveals the shady side of the mountains. As a result, quality of the rendered SAR scene and even classification results are compromised to some extent.
Figure 3.19. H/A/Alpha decomposition results in Geladandong (H, A, Alpha and Lambda, respectively)
The H/alpha segmentation result in Geladandong region is shown in Figure 3.20. The two plots on the right are H/alpha distribution plane and classification plane, respectively. As shown in plot, the so called $H/\alpha$ plane can be divided into eight zones. The zones can be used as a tool for unsupervised classification of the polarimetric SAR data. In the classification plane, the blue/dark blue area refers to surface scatter while the red/dark red area refers to double bounce scattering mechanism. The green/dark green area represents volumes scattering. According to the analysis and conclusion with both SAR data and in-situ observation in mountainous glacier regions [Huang, 2011]: (1) the entropy in glacier area is higher than that in soil land; (2) the surface scattering is the dominant component on the soil, but its contribution is lower on the ice.
Figure 3.20. H/Alpha Classification results for the Geladandong glacier, Tibetan Plateau.
We can further analyze the specific regions mentioned before: zoom-in versions of the classification results are given in region B (Figure 3.21) and region C (Figure 3.22). In region B, although the polarimetric SAR result is affected by the mountainous condition, we can still clearly find the big absence of glacier in contrast to RGI presentation. The shape and size of the “blank” region as shown in the polarimetric SAR classification result highly agrees with the result based on optical data, which is shown in the Figure 3.21 (right). Similar scenario happens in region C too. The difference between RGI and our previous classification result is further supported by polarimetric SAR classification.
3.5 Conclusions

Glaciers have long been recognized as sensitive indicators of climate change. The mass balance at the surface of a glacier is determined by the climate changes. The Asian High Mountain area contains the largest number of glaciers outside the Polar Regions. Such glaciers are the main water source of many prominent Asian rivers and are largely experiencing shrinkage. Geladandong glacier is chosen as a typical glacier area in our study. Over 40 years, the shrinkage of the glacier is observed from the results of analyzing and classifying Landsat series data. It is evident that there is a large difference between our classification result and RGI data. On the one hand, the RGI is not able to provide a time series of the change of the glacier extent. On the other hand, we speculate that the RGI has considerable bias in several specific regions that adversely impairs its reliability. In order to further strengthen our conclusion, SAR and polarimetric SAR data
are introduced. The results from both SAR correlation coefficient and polarimetric SAR decomposition and segmentation are consistent with that from Landsat classification results in every particular study region. In summary, these findings strongly supported the conclusion that Geladandong glacier is shrinking over the past four decades with estimated rates of 0.148 km$^2$/year and 0.134 km$^2$/year in region B and C.
CHAPTER 4: Coastal Embankment and Riverbank Erosion Monitoring Using Landsat Optical and SAR/PolSAR data In Coastal Bangladesh

4.1 Introduction

It is broadly recognized that Bangladesh suffers from the most severe impacts from climate change because of its meteorological, hydrologic and geographical characteristics, coupled with its high population density and poor infrastructure. The most crucial effects will be on agriculture and water security, adversely affecting human health in a number of ways [IPCC, 2007]. The warming trend over recent decades has already contributed to increased morbidity and mortality in many regions of Bangladesh and climate-health relationships pose increasing health risks under future projections of climate change [Patz, et. al., 2005].

High vulnerability to the impacts of climate change makes the people of Bangladesh particularly susceptible to adverse health risks [Khan, 2011]. Therefore, it is considered critical to monitor the Bangladesh coastal region changes, including the long-term embankment (polders) subsidence and riverbank erosions, to mitigate or to adapt to coastal vulnerability due to present and future sea-level rise and seasonal monsoonal flooding hazards.
Due to the difficulty in accessing part of the coastal region, field surveys for mapping land cover changes and polder or embankment subsidence in coastal Bangladesh are very difficult to undertake. Remote sensing techniques based on multiple data sources offer promising solutions to this problem.

### 4.1.1 Coastal Bangladesh

Bangladesh is a country located at the Bay of Bengal in South Asia. It is one of the most densely populated countries with over 160 million people living in the delta regions.

![Figure 4.1: An Overview of Bangladesh – Political Map (left) and Satellite Imagery (right).](image)

The physical geography of Bangladesh includes three regions. Most of the country in the south is dominated by the arable Gauges-Brahmaputra delta with a 720-kilometer coastline that meets the encroaching Bay of Bengal in the south [Hossain, 2010]. The
Ganges delta, or the Bangladesh delta is at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers and their tributaries.

**Figure 4.2.** Map of Bangladesh showing the large delta at the confluence of three large rivers: the Ganges, Brahmaputra and Meghna [Halliday & Davey, 2007].

### 4.1.2 Relative Sea-Level Rise Hazard in Coastal Bangladesh

#### 4.1.2.1 Sea-Level Rise Scenarios

In Bangladesh, large areas of coastal settlements are situated just above sea-level. As a result, one-third of the country is vulnerable to flooding [Myaux, et. al., 1997; Paul, 1997]. Between 1954 and 1996, Bangladesh experienced 28 major floods, of which 11 were classified as “devastating” and five as “most devastating”. Global sea-level rose at
an average rate of 1.8 (1.3 to 2.3) millimeters per year between 1961 and 2003, according to IPCC estimates. The rate accelerated to about 3.1 (2.4 to 3.8) millimeters per year between 1993 and 2003 [IPCC, 2007], but the estimated acceleration could or is likely affected by interannual or longer variations and due to the short data span used. The IPCC 2013, Assessment Report Five (AR5) provided a similar estimate. However, none of the sea-level rise estimates and projections accounted for land subsidence in the IPCC studies, nor the estimated or projected sea-level rise is at the regional scale, allowing one to realistically assess the sea-level rise hazards in coastal Bangladesh.

<table>
<thead>
<tr>
<th>Climate Change Scenarios Given by the IPCC (AR4, 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 (low), Year 2080 (sea-level rise 15 centimeters)</td>
</tr>
<tr>
<td>A2 (high), Year 2050 (sea-level rise 27 centimeters)</td>
</tr>
<tr>
<td>A2 (high), Year 2080 (sea-level rise 62 centimeters)</td>
</tr>
<tr>
<td>A2 (high), Year 2080 (sea-level rise 62 centimeters + 10 percent rainfall)</td>
</tr>
</tbody>
</table>

Table 4.1. Climate Change Scenarios, Given by the AR4 [Source: Institute of Water Modeling and Center for Environmental & Geographic Information Service, Bangladesh]

According to the analyses of the impact of inundation depth in Bangladesh by the year of 2080, there would be 13 percent more inundation area in the monsoon season as a result of a 62-centimeter sea-level rise based on the scenarios proposed by IPCC (Table 4.1) [Khan, 2010]. Based on the conditions of 2005 (Table 4.2), if the sea level rise is accompanied by a 10 percent increase in rainfall, the anticipated inundated area would
further increase to around 16 percent. Under the scenario of 1-meter sea level rise, about 13 polders along the coastal region could be overwhelmed with water. 17.5 million people (15 percent of the total population) will be affected. While under the worst-case scenario (for high greenhouse gas emission at 62 cm sea-level rise), 51 percent of total population is expected to expose to high inundation (>50 cm) risk. Furthermore, an additional 5.5 million people will be exposed to inundation of 50 to 100 centimeters within the next 40 years due to cyclone-induced storm surges, under the high emission scenario and a sea-level rise of 27 centimeters [UK Dept. for Environment, 2007]. However, this study does not consider the land subsidence nor it has an appropriate spatial scale to allow the coastal vulnerability study of coastal Bangladesh.
### Table 4.2. Area (ha) Inundated due to Sea-Level Rise, During Monsoon and Dry Season in Bangladesh [Source: Institute of Water Modeling and Center for Environmental & Geographic Information Services. Bangladesh.]

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Monsoon Season</th>
<th>Dry Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inundated area (hectares)</td>
<td>Additional inundation (hectares)</td>
</tr>
<tr>
<td>Base condition, Year 2005</td>
<td>1,720,200 (50 percent)</td>
<td>-</td>
</tr>
<tr>
<td>B1 (low), Year 2080</td>
<td>1,863,600 (54 percent)</td>
<td>143,500 (4 percent)</td>
</tr>
<tr>
<td>(sea-level rise 15 centimeters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2 (high), Year 2050</td>
<td>1,972,200 (57 percent)</td>
<td>252,000 (7 percent)</td>
</tr>
<tr>
<td>(sea-level rise 27 centimeters)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2 (high), Year 2080</td>
<td>2,271,700 (66 percent)</td>
<td>551,500 (17 percent)</td>
</tr>
<tr>
<td>(sea-level rise 62 centimeters + 10 percent rainfall)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.2.2 Flooding History in Bangladesh

**Bangladesh Floods in 1998**

The 1998 flood of Bangladesh leads to severe damage to the country. The floods covered over two-thirds of Bangladesh in water for 50 days. The capital Dhaka was submerged under two-meter of water. Thousands people were dead and 30 million people were homeless. It is estimated that the flood caused a total of $1 billion of damages [Del Ninno & Lundberg, 2005].
Figure 4.3. Cyclone Sidr, 2007 (left) and Cyclone Aila, 2009 (right) in the Bay of Bengal near peak intensity [Image courtesy, MODIS Rapid Response Project at NASA/GSFC].

Cyclone Sidr (2007)

In November of 2007, the tropical cyclone “Sidr” resulted in one of the worst natural disasters in the history of Bangladesh. It made landfall on Bangladesh, November 15, 2007 in the southern coast, killed 3,447 people, destroyed 500,000 homes and affected 845,000 households. [BBC, 2007]. The estimated damage is at $1.7 billion (2007 USD). [Reuters, 2008].

Cyclone Aila (2009)

As of 27 May 2009, the landfall of Cyclone Aila resulted in 330 people dead, and at least 8,208 people missing. Throughout the country, Aila left an estimated 500,000 people homeless.[Telegraph, 2009] The landfall of Cyclone Aila resulted in 33 injured by the storm and 3.3 million were affected. [United Press International, 2009]
Damages to water embankments throughout the country was estimated at Tk. 1 billion (US$14.4 million). [The New Nation, 2009]

4.2 Characteristics of the Study Regions

Seasonal monsoonal flooding causes riverbank erosion, and coastal embankment (polders) degradation, sediment-induced land subsidence caused severe relative sea-level rise, coupled with episodic devastating cyclones events, there is a need of an efficient monitoring of river channel changes, river erosion and land cover change in coastal Bangladesh. In this research, we focused primarily on the monitoring of coastal embankment or polders in coastal Bangladesh.

The coastal polders of Bangladesh are characterized by extremes in terms of both challenges and opportunities. The polders are home to about 8 million people, where 85% of rural householders live under the national poverty line. The polders are subjected to flooding during the rainy season; drought and salinity intrusion during the dry season, and episodic cyclones [UK Dept. for Environment, 2007].

4.2.1 Bangladesh Polders Overview

A polder is a tract of lowland reclaimed from a body of water, often the sea, by the construction of dikes roughly parallel to the shoreline, followed by drainage of the area between the dikes and the natural coastline. [Encyclopedia Britannica Online, 2015]

In 1961, the Bangladesh Government attached the Coastal Embankment Project. With the help of donors, 139 large-scale polders were constructed in the 1960’s and 1970’s. The
polder zone occupies an area of about 1.2 million hectares. [Nair, 2014] The distribution of polders in Bangladesh is shown in Figure 4.4.

![Figure 4.4. Polder System in Bangladesh [Source: Center of Environmental and Geographic Information Service, Bangladesh].](image)

The polders had an immediate positive effect on agricultural production, which increased tremendously during the following decades. People in the polders experienced a boost in income and standard of living. However, over a period of time sedimentation and erosion begin to affect the polders.
4.2.2 Hazards and Damages to Polders by Cyclones

Together with the river inflow, the rainfall contributes to the annual inundation of large areas of the country during the seasonal monsoonal floods. In the active flood plains the main rivers are constantly changing course, leading to both riverbank erosion and accretion of new land. It has been estimated that 1 million people each year are affected by riverbank erosion, primarily through loss of land [Elahi et. al., 1991]. Moreover, there are increasing cyclonic activities in the last 20 years. Although cyclones may cause damage when passing over land, the most excessive damage is caused by accompanying surges and high tides. In such instances, surges of 5–6 m high swept across the low-lying areas, killing thousands of people and causing extensive damage to houses and infrastructures [Lein, 2000]. The coastal polders of Bangladesh are densely populated, home to about 8 million people. Most polders are critically affected by the
cyclones in 2007 and 2009. The polders are unable to provide protection against storm surge. As a consequence, the living condition in the affected regions is severely degraded, which lead massive migration.

4.2.3 Specific Study Region

Our specific objectives in this study are (1) using combined methods with Landsat and SAR /PolSAR data to monitor Bangladesh polder boundary and water extent dynamic changes, and (2) analyzing the effects of erosion and sedimentation in river channel segments.

As examples, the specific study regions are in (1) Polder 14 and (2) Polder 50–57. Polder 14 is encompassed by a significant number of river channels. Multiple data sources are available in the region such as Dual polarization SAR data for classification, Landsat optical/infrared data for long-term land cover change, ENVISAT altimetry and backscatter, and other data sources. Based on the multiple data sources, we would be able to better monitor the river channel boundary changes and water cover area over a long time period, i.e., using Landsat data.

As for the case in polder 50–57, the study region is chosen for monitoring erosion and sedimentation in an estuary delta scenario. It is speculated that the erosion and sedimentation have changed the shapes of both the river channels during the past 40 decades. Moreover, there are full-polarized SAR data available over a limited time period in the region. A comparison between full-polarized and semi-polarized SAR classification could shed light on the performance of the semi-polarized SAR
classification, as the full-polarized SAR data are much less readily available. The study regions are shown in Figure 4.6.

**Figure 4.6.** The study regions shown in Google earth. The rectangle in blue refers to polder 14, while the rectangle in red refers to polder 50–57.

### 4.3 Data Description

#### 4.3.1 Landsat Data

Landsat provided the world's longest continuously acquired collection, barring data outages because of cloud covers, of space-based moderate-resolution land remote sensing
data. Four decades of imagery constitutes a unique resource for land cover monitoring. The Landsat data used in our study range from 1972 to 2014, including different instruments: Landsat-1 (MSS), Landsat-5 (TM), Landsat 7 (ETM+) and Landsat-8 (OLI).

**Landsat-1 / Landsat Multispectral Scanner (MSS)**

Landsat-1 images consist of four spectral bands with 60-meter spatial resolution. Approximate scene size is 170 km north-south by 185 km east-west.

<table>
<thead>
<tr>
<th>Multispectral Scanner (MSS)</th>
<th>Landsat 1-3</th>
<th>Wavelength (µm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 4</td>
<td>0.5-0.6</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Band 5</td>
<td>0.6-0.7</td>
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<td></td>
</tr>
<tr>
<td>Band 6</td>
<td>0.7-0.8</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Band 7</td>
<td>0.8-1.1</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.3. Specific frequency band designations of Landsat-1 MSS [USGS, 2014].*

**Landsat-5 / Landsat Thematic Mapper (TM)**

Landsat-5 TM images consist of seven spectral bands with a spatial resolution of 30 meters for Bands 1 to 5 and 7. Spatial resolution for Band 6 (thermal infrared) is 120 meters, but is resampled to 30-meter pixels. The scene size is approximately 170 km north-south by 183 km east-west.
<table>
<thead>
<tr>
<th>Thematic Mapper (TM)</th>
<th>Landsat 4-5</th>
<th>Wavelength (μm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>0.45-0.52</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 2</td>
<td>0.52-0.60</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 3</td>
<td>0.63-0.69</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 4</td>
<td>0.76-0.90</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 5</td>
<td>1.55-1.75</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 6</td>
<td>10.40-12.50</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Band 7</td>
<td>2.08-2.35</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.4.** Specific frequency band designations of Landsat-5 TM [USGS, 2014].

**Landsat-7 / Landsat Enhanced Thematic Mapper Plus (ETM+)**

Landsat-7 images consist of eight spectral bands with a spatial resolution of 30 meters for Bands 1 to 7. The resolution for Band 8 (panchromatic) is 15 meters. The scene size is about 170 km north-south by 183 km east-west.
<table>
<thead>
<tr>
<th>Enhanced Thematic Mapper Plus (ETM+)</th>
<th>Bands</th>
<th>Wavelength (micrometers)</th>
<th>Resolution (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>0.45-0.52</td>
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<td></td>
</tr>
<tr>
<td>Band 2</td>
<td>0.52-0.60</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 3</td>
<td>0.63-0.69</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 4</td>
<td>0.77-0.90</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 5</td>
<td>1.55-1.75</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 6</td>
<td>10.40-12.50</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Band 7</td>
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</tr>
<tr>
<td>Band 8</td>
<td>.52-.90</td>
<td>15</td>
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</tbody>
</table>

Table 4.5. Specific band designations of Landsat-7 ETM+. [USGS, 2014]

**Landsat-8 /Operational Land Imager (OLI)**

Landsat-8 images consist of nine spectral bands with a spatial resolution of 30 meters for Bands 1 to 7 and 9. New band 1 (ultra-blue) is useful for coastal and aerosol studies. New band 9 is useful for cloud detection. The resolution for Band 8 (panchromatic) is 15 meters. The scene size is approximately 170 km north-south by 183 km east-west.
<table>
<thead>
<tr>
<th>Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) Launched February 11, 2013</th>
<th>Bands</th>
<th>Wavelength (µm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 - Coastal aerosol</td>
<td>0.43 - 0.45</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 2 - Blue</td>
<td>0.45 - 0.51</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 3 - Green</td>
<td>0.53 - 0.59</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 4 - Red</td>
<td>0.64 - 0.67</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 5 - NIR</td>
<td>0.85 - 0.88</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 6 - SWIR 1</td>
<td>1.57 - 1.65</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 7 - SWIR 2</td>
<td>2.11 - 2.29</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Band 8 – Panchromatic</td>
<td>0.50 - 0.68</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Band 9 - Cirrus</td>
<td>1.36 - 1.38</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.6.** Specific band designations of Landsat-8 OLI [USGS, 2014].

### 4.3.2 Synthetic Aperture Radar Data

In this study, JAXA’s ALOS-1 PALSAR data are our major synthetic aperture radar data source. The Phased Array type L-band Synthetic Aperture Radar (PALSAR) acquisition strategy features routine observations at different sensor modes (Table 4.7).
In this study, two major types of PALSAR data are used. For polarimetric SAR classification, Fine Beam Double (FBD) and Polarimetry (PLR) mode data are processed separately. The data level for this processing is Level 1.1.
<table>
<thead>
<tr>
<th>Sensor Mode</th>
<th>Polarization</th>
<th>Off-nadir angle</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Beam</td>
<td>HH</td>
<td>34.3°</td>
<td>Global</td>
</tr>
<tr>
<td>Single pol.(FBS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine Beam</td>
<td>HH+HV</td>
<td>34.3°</td>
<td>Global</td>
</tr>
<tr>
<td>Dual pol. (FBD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine Beam</td>
<td>HH+HV+VH+VV</td>
<td>21.5°</td>
<td>Regional</td>
</tr>
<tr>
<td>Polarimetric (PLR)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>FBS</th>
<th>FBD</th>
<th>PLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Frequency</td>
<td>1270 MHz</td>
<td>1270 MHz</td>
<td>1270 MHz</td>
</tr>
<tr>
<td>PRF</td>
<td>1500 - 2500 Hz (discrete stepping)</td>
<td>1500 - 2500 Hz (discrete stepping)</td>
<td>2 x FBS PRF</td>
</tr>
<tr>
<td>Range Sampling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>32 MHz</td>
<td>16 MHz</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Chirp bandwidth</td>
<td>28 MHz</td>
<td>14 MHz</td>
<td>14 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>HH or VV</td>
<td>HH/HV or VV/VH</td>
<td>HH/HV + VV/VH</td>
</tr>
<tr>
<td>Incidence angle [deg]</td>
<td>7.9-60.0</td>
<td>7.9-60.0</td>
<td>8-30</td>
</tr>
<tr>
<td>Swath Width [Km]</td>
<td>40-70</td>
<td>40-70</td>
<td>20-65</td>
</tr>
<tr>
<td>Bit quantization [bits]</td>
<td>5</td>
<td>5</td>
<td>3 or 5</td>
</tr>
<tr>
<td>Data rate [Mbps]</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 4.7. PALSAR different working modes and specific parameters. [Courtesy: JAXA ALOS, 2006]
4.3.3 ENVISAT Altimeter Data

ENVISAT (ENVIronmental SATellite) was launched on February 2002 by ESA (European Space Agency). It carries 10 scientific instruments including the RA-2 altimeter (Advanced Radar Altimeter) [Wehr et. al., 2001], which is a dual-frequency radar altimeter measuring the round-trip time of the radar pulse to infer the distance between satellite and the nadir earth surface. It should be noted that the S-band altimeter system has problems, and it was not used as designed to remove first order ionosphere delays from the altimeter range measurements. The backscatter coefficient is computed from the returned power of radar signal. In this study, we use Ice-1 retracker [Wingham et al., 1986] computed data from the ENVISAT GDR.

<table>
<thead>
<tr>
<th>Repeat cycle</th>
<th>35 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>782.4-799.8 km</td>
</tr>
<tr>
<td>Frequencies</td>
<td>Ku-Band: 13.575GHz; S-Band: 3.2GHz</td>
</tr>
<tr>
<td>Footprint diameter</td>
<td>Ku-Band: 3.4 km; S-Band: 4.8 km</td>
</tr>
</tbody>
</table>

Table 4.8. ENVISAT major parameters description [ESA, 2002].
4.4 Methodology and Processing

4.4.1 Landsat Data Processing Methods

4.4.1.1 Bands Composition

Landsat series satellite sensors record measurements in multiple bands. By means of the basic color rendering mechanism Red Green Blue (RGB), it is possible to construct several band combinations. There are a number of band combination strategies. In our research, combination methods that enhance the difference between water and land is chosen. For Landsat-1 MSS data, the combination is chosen as 6, 7, 5; for Landsat-5 and Landsat-7, the combination is chosen as 4, 5, 3; for Landsat-8, the combination is chosen as 5, 6, 4. [USGS, 2013]

4.4.1.3 Landsat Classification

For further classification of Landsat data, both unsupervised and supervised classification methods are applied in some part of the study. A commonly used unsupervised method, ISODATA, which was introduced in Chapter 2, is implemented as an effective tool for the aims in the work.

4.4.2 Polarimetric SAR data processing

4.4.2.1 Unsupervised Classification Based On Scattering Mechanisms

\[ H / A / \bar{\alpha} \] Polarimetric Target Decomposition

Our main tool for polarimetric SAR classification in the study is \[ H / A / \bar{\alpha} \] target decomposition and derived segmentation methods. It is an incoherent decomposition
method on eigenvector/eigenvalue analysis for extracting parameters from polarimetric SAR data using a smoothing algorithm based on second-order statistics proposed by Cloude and Pottier [1997].

The unsupervised classification processing procedures are listed in Figure 4.7.

![Figure 4.7. Unsupervised Classification procedures applied in this study.](image)

4.4.2.2 H/A/α - Wishart Classifier

The classification result from target decomposition method is not good enough since not all the information from the coherency matrix is used. Also, clusters may not be well located in the $H / \alpha$ plane. Therefore, a combination of unsupervised target decomposition classifier and the supervised Wishart classifier is then applied. The algorithm, proposed by [Lee et. al., 1999] applied the unsupervised target decomposition
classifier and the supervised Wishart classifier. The algorithm applies unsupervised target
decomposition classification first, and uses the results as training sets to the Wishart
classifier. From the initial classification map, the cluster center of coherency matrices
computed for pixels in each zone:

\[ V_i = \frac{1}{n} \sum_{j=1}^{n} T_{ij} \text{ for all pixels in class } \omega_i \]  

(4.1)

Then, each pixel is classified with Wishart distance measure again

\[ d(T, V_m) = \ln |V_m| + Tr \left(V_m^{-1}T\right) \]  

(4.2)

The new results show improvement in details. Further improvement is possible by
iteration. The classified image is used to update the coherency matrices again and again
until the number of pixels switching class becomes smaller than a predetermined number.

4.5 Result and discussion

4.5.1 Polder 14

The latitude and longitude ranges that we applied for studying polder 14 is
“22.2°N~22.5°N, 89.2°E~89.45°E”. The profile of Polder 14 is shown in Figure 4.8 with
a true color composition of Landsat8 OLI data in 2014. The polygon in orange depicts the
boundaries of Polder 14 and adjacent polders. We can see that Polder 14 is surrounded by
a number of river channels. The area that charted out in viridian is Sundarban, the natural
region in Bangladesh that provides the world’s largest single block of tidal halophytic
mangrove forest.
Figure 4.8. True Color Overview of Polder 14 Region in 2014 (Landsat 8 OLI RGB composition result).
Water Level And Coverage Change:

<table>
<thead>
<tr>
<th>1972 Day 346</th>
<th>2014 Day 336</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="1972 Image" /></td>
<td><img src="image2.png" alt="2014 Image" /></td>
</tr>
</tbody>
</table>

**Figure 4.9.** Landsat Composite Images. (left) Polder 13/14 in 1972 (Landsat 1 MSS); (right) Polder 13/14 in 2014 (Landsat 8 OLI).

Figure 4.9 shows a general contrast between the Landsat composite results in 1972 and 2014 respectively. For the 1972 case, Landsat-1 Multispectral Scanner data is used. Band 5 (0.6µm–0.7µm), band 6 (0.7µm–0.8µm) and band 4 (0.5µm–0.6µm) are chosen to generate the RGB composite. For 2014 case, Landsat 8 Operational Land Imager data is used. The RGB composite mode is chosen as: band 5 – (NIR) 0.85µm–0.88µm, band 6 (SWIR 1) 1.57µm–1.65µm, band 4 (Red) 0.64µm–0.67µm. The principle for the composite strategy is based on the idea of differentiating the land and the water to the
maximum level. In both composition methods, the land/water boundary can be very clear
and vegetation types can be more clearly defined. It demonstrated that not only the shape
of the river channels in the region has substantially changed over 40 years, but also that
the water extents inside the polders have seasonal or longer changes.

In order for studying the water extent changing patterns, we compared the use of the
SRTM 1-Arcsec DEM and ASTER-GDEM models as reference DEMs over polder 14,
and found that they have substantial differences (Figure 4.10).

The SAR systems used during the SRTM mission were actually developed and flown on
two Endeavour missions in 1994. SRTM 1 Arc-Second Global elevation data offer
worldwide coverage of void filled data at a resolution of 1 arc-second (30 meters) and
provide open distribution of this high-resolution global data set. The SRTM 1 Arc-
Second Global (30 meters) data was released in September 2014 [USGS, 2015].

The ASTER-GDEM, i.e., the Advanced Spaceborne Thermal Emission and Reflection
Radiometer (ASTER) Global Digital Elevation Model (GDEM), was developed jointly
by the NASA and Japan’s Ministry of Economy, Trade, and Industry (METI). ASTER is
capable of collecting in-track stereo using nadir- and aft-looking near infrared
cameras. Since 2001, these stereo pairs have been used to produce single-scene (60x60
km) DEM having vertical (root-mean-squared-error) accuracies generally between 10
and 25 m [JPL, 2004]. The data are posted on a 1 arc-second (approximately 30 m at the
equator) grid and referenced to the 1984 World Geodetic System (WGS84)/1996 Earth
Gravitational Model (EGM96) geoid [JPL, 2004].
By comparing SRTM (1994) and ASTER-GDEM (2001), the topography shown in the two data sets differs considerably. It is speculated that the reason of the difference is from instrumental bias and error due to different data acquisition/processing methods.

![Figure 4.10. DEM data in Polder 13/14 Region: SRTM 1-Arcsec (30m); ASTER-GDEM (30m).](image)

We can find differences between the elevations to the east in the results from two DEM models. It is due to the instrument bias caused by the C-Band SAR interferometry for SRTM. The limitation of the SAR interferometry also caused the void data points in river channels. However, we still can find several substantial similar features. The elevation in Polder 14 is much lower than that in Sundarban mangrove regions. Particularly in
ASTER-GDEM, we discover that the average elevation in polder regions is lower than the river channels, which is another reason that Polder 14 faces additional risk of flooding. We then lay emphasis on polarimetric SAR classification results in the region in order to detect the water extent change patterns. Two ALOS-1 PALSAR FBD (Fine Beam Double Polarization) scenes are processed and compared. The data is in level 1.1 (Single Look Complex mode). The acquisition date and the scene ID number of the two scenes are [May 11, 2008, ALPSRP122330430] and [August 14, 2009, ALPSRP189430430]. By the use of decomposition and segmentation, the comparison diagrams are shown in Figure 4.11.
Figure 4.11. H/A/Alpha Decomposition entropy results and H/Alpha Wishart Classification results are compared. Two ALOS-1 FBD data scenes that acquired in May, 2008 and Aug. 2009 are used, respectively.
The polarimetric entropy shows the degree of statistical disorder of each distinct scatter. When the entropy is low (H<0.3), the scattering object may be regarded as weakly depolarizing and the dominant scattering mechanism in terms of a specifically identifiable equivalent point scatterer may be recovered. Therefore, low entropy occurs over the river as well as water area. High entropy occurs over dry land areas and forest areas (volumes scattering).

In H/Alpha Wishart classification, 4 specific classes are defined and depicted: water, dry land and trees are depicted in blue, yellow and orange/red respectively, and the forest (orange) in Sundarban as well as in several regions in the polders are distinctively shown. There is a notable difference of water (blue) coverage range between May and August. In May, half of the polder area is water, while the rest part remains dry (yellow). In August, however, almost all the polder area is covered by water (blue). The seasonal change is likely to be caused by: (1) local farming traditionally is to begin the irrigation in Jun until October; and/or (2) as the polder embankments are damaged, part of the polder area susceptible to have water draining into the polder during the rainy season.

To validate the SAR classification results, ENVISAT GDR altimeter retrieved height data in this area are used. We gathered all the ENVISAT data between 2002 and 2011 at a single point located in polder 14 regions and plotted the elevation change versus time. It is evident that the ENVISAT altimetry water level fits a seasonal pattern, which is dropping to the lowest point in the dry season (January ~ March) and raising to higher level in the rainy season (August ~ October) (Figure 4.12). The date that the polarimetric
SAR (FBD) data scenes obtained is marked with colored circles. It is clearly revealed that the point in May is in the bottom phase of the changing cycle, while the point in August is in the peak phase of the changing cycle. In August, the surface level is approximately 30 centimeters higher than that in May, which can only be interpreted as the rise of water level in the polders. Here, ENVISAT altimetry data in part validated the SAR classification results, which depicts high-resolution water extent changing patterns. The polder regions are confronted with higher risk of flooding during the rainy season or due to episodic cyclone-induced landfall flooding. It is not only due to the precipitation and occasional cyclone storm surge, but also because of sediment compaction induced polder or coastal embankment subsidence. Here we illustrated the usefulness of high spatial resolution full-polarimetric SAR all-weather classification results of water extent changes within the polder (polder 14).
Figure 4.12. ENVI SAT GDR Altimeter Data Surface Height in Polder 14. Red and green rings are elevation points correspond to the SAR (FBD) acquisition data in the previous section. [Courtesy: Qi Guo]

In Figure 4.13, the Landsat composition results in polder 14 regions through 1972 ~ 2014 are given as time series. From 1972 to 1980, the data source is Landsat-1 or Landsat-2 and the band composition strategy is 5,6,4. While from 1980 to 2014, the data source is Landsat-5, Landsat-7 or Landsat-8. For Landsat-5 and Landsat-7, the band combination is 4, 5, 3, while for Landsat-8 the band combination is 5, 6, 4.

The evolution of the river channels caused by erosion and sedimentation can be clearly observed in several specific scenes. Beyond what has been stated, we find that the water extent in this polder has been expanded gradually during the past four decades.
Figure 4.13. The Landsat composition results in polder 14 region through 1972 ~ 2014 (selected imageries are shown here). The changing process of the river channels that caused by erosion and sedimentation can be observed apparently. Moreover, the water extent in the polder has been expanding during the last 4 decades.
**Monitoring of River Channel Change**

As mentioned in the results in Figure 4.13, the river channel boundary change is a significant issue for evaluating the vulnerability and flooding risk in the polder regions. Hence, we deliberately introduce edge detection tools for extracting the river channel boundaries. By implementing Canny Edge Detector [Canny, 1986], the changes in river channels are clearly detectable from either polarimetric SAR decomposition results or Landsat composite result. A demonstration result is given in Figure 4.14.

For the polarimetric SAR data processing, the software PolSAR pro 5.0 [ESA, 2015] is used as the major tool to do the classification job when using ALOS-PALSAR Level 1.1 data.
The particular small frame as depicted in Figure 4.15 of the Polder 14 has been chosen for a focused study. The river segment in this frame is round 400 meters wide. We discovered that the polder boundaries are originally connected to the snaked river channel in 1972, especially in the second curve on the right hand side. During the last forty years, the sedimentation accumulated and expanded gradually. Based on our calculation the area expanded approximately 0.80 km$^2$. Meanwhile, the land on the opposite side at the same spot has been eroding significantly during the past 40 years. The eroded area is estimated as 0.61 km$^2$. Thereby, the river channel in this specific region has narrowed and its shape altered under the gradual impact of both sedimentation and erosion. By applying edge
detection tool, the river channel shape changing process is illustrated in Figure 4.15(e).

The river channel boundaries in the four different years are stacked together as layers in order for quantifying the changing pattern.
River channel boundary change. Detected by edge detector (image processing toolbox) based on Landsat composition results in (a) ~ (d).

**Figure 4.15.** River channel boundary change caused by erosion and sedimentation between 1972 and 2011.
4.5.2 *Polder 50~57*

Comparing with Polder 14, Polder 50~57 region is in the estuary area. This region with polder boundary polygons is depicted in Figure 4.16 (left). The images (Fig. 4.16, right) show the landscape and topographic characteristics of the study region, including both the mangrove and farming land.

![Image of Polder 50~57](image)

**Figure 4.16.** (left) An overview of Polder 50~57, Landsat true color composition, 2011; (right). Photo of local land cover characteristics [Basakpalash, 2008].
With similar methods and procedure, a time series of the Landsat composite results from 1972 to 2011 is shown in Figure 4.17. In the whole 40-year time period, we find that the areas of small islands have been gradually increasing on the ocean-side by sedimentation, while losing land on the opposite side by erosion. The process over decades has made several islands “downward” and “larger”. As a result, the polders always have to be modified, or maintained in order to accommodate the sediment-induced changes. Long-term Landsat time series and the high-resolution all-weather SAR classifications provide a means to offer information for decision makers for Bangladesh polder reconstruction and maintenance.
Figure 4.17. Polder 50~57 region erosion and sedimentation changes during 1973~2011 (selected imageries are shown here). The area in purple-blue depicts the water and ocean, the area in orange represents forest or mangrove and the rest part are mostly farm land.

In order to better differentiate water and other surface classifications in the region, land classification based on full polarization SAR data is used here. We used the ALOS-1
PLR mode level 1.1 data for high-resolution all-weather land cover classifications. The data was collected on March 14, 2007.

Figure 4.18. Example unsupervised classification results based on fully polarimetric ALOS-1 data (PLR) in Polder (embankment) 50~57 region, Bangladesh, to classify embankment condition (land cover, water intrusion, and erosion). The data was collected on March 14, 2007.

Figure 4.18 (left) is the result from the H/Alpha Wishart classifier using 8 original classes. We not only clearly differentiate water and land, but also are able to accurately identify different land types such as mangroves and normal farming vegetation. The farming fields are further classified into two slightly different classes: land in orange denotes irrigated field, while land in dark blue represents dry field. Besides, a special class that is considered as potential sedimentation area is shown in gold. This class is not
land but shallow water that has a high possibility to become land by the process of sedimentation. To enhance the classification performance, we then apply H/A/Alpha Wishart classification algorithm to process the same scene. The classes are correspondent to those by using H/A method. An additional land type is generated as drier land or residential building area.

4.6 Conclusions

Two-thirds of Bangladesh total population is confronting with and have been adversely affected by climate change and sea-level rise at present and in the near future. It is of importance to develop a means to efficiently monitor and estimate the possible risk of flooding and conditions of coastal embankment or polders. In this study, multiple satellite data sources, including Landsat series, ALOS-1 PALSAR polarimetric Synthetic Aperture Radar, and ENVISAT altimeter data, have been used for the purpose of (1) quantifying the changes of the water extent within the polders during last 40 years, and (2) of monitoring coastal embankment or polder changes caused by erosion and sedimentation.

In Polder 14, there is a notable difference of water extent in the polders between May and August. Moreover, the surface level is approximately 30 cm higher in May than in August, as validated by ENVISAT altimetry water level data. Specific river channel boundary change is also investigated. The river channel shape has been changed with an approximately 1.4 km$^2$ area change on both sides of the river during the past 40 years. In the estuary region of Polder 50~57, delta boundary displacement is also studied based on
the Landsat data from 1972 and 2011. The shape of the polder has changed during the last 4 decades. A more convincing high-resolution classification result based on all-weather, full polarization SAR data validated the Landsat results, and provides evidence of usefulness of SAR classifications for more detailed information of local agricultural and aquacultural farming distribution.
CHAPTER 5: Conclusions and Future Study

Observation from multiple satellite sensors is providing ample knowledge about land cover characteristic temporally and spatially on a large scale. The applications in this study not only show integrated classification methods with different techniques based on diverse satellite imaging data sources, but also exemplify the broadening field of works that is feasible under the progress of improving satellite technologies.

The improvement contributed in this study, in terms of glacier extent change, is presented in a case study of Asian High Mountain region. Over the past 40 years, the shrinkage of the Geladandong glacier is observed from the results of analyzing and classifying Landsat series data and reinforced by polarimetric SAR and SAR correlation coefficient classification results. The time series give a better understanding of the rate and amount of glacier shrinkage than the Randolph Glacier Inventory. Moreover, it is speculated that the RGI has considerable bias in several specific regions that adversely impairs its reliability.

The second contribution is in the case study in Bangladesh costal region. The country is confronting adversely affected by climate change and sea-level rise in the near future. In polders, seasonal change of water level in polders is detected based on Landsat classification results as well as ENVISAT surface elevation data. Moreover, the studied river channel shape has been changed with an approximately 1.4 km² displacement for both sides of the river fragment in the past 40 years based on the results from Landsat. In
the real estuary region, delta boundary displacement is also studied based on the data from 1972 and 2011. The boundary change of the polders indicates more risk of flooding in the area. Classification results based on full polarization SAR data provided detailed information of local agricultural and aquacultural farming distribution, which may produce better estimation of flooding risk in the region.

In future studies, we will make further comparison between normal SAR and polarimetric SAR classification results and analyze the difference. Additional data sources will be integrated into our classification and analysis. In the Asian High Mountain case, we will further add GRACE gravity data to our results in order to estimate the amount of glacier mass change in the region. In Bangladesh case, a quantitative estimation of potential sedimentation area will be done.
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