

CRANFIELD UNIVERSITY

ANURA TERANCE WICKRAMANAYAKE

ANDRA BADUGE

**INSAR MEASUREMENTS AT
HIGH LATITUDES**

SCHOOL OF ENGINEERING

PhD

Academic Year: 2014

Supervisor: Stephen Hobbs

October 26, 2014

CRANFIELD UNIVERSITY

SCHOOL OF ENGINEERING

PhD

Academic Year: 2014

ANURA TERANCE WICKRAMANAYAKE

ANDRA BADUGE

**INSAR MEASUREMENTS AT HIGH
LATITUDES**

Supervisor: Stephen Hobbs

October 26, 2014

This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

© Cranfield University, 2014. All rights reserved. No part of this
publication may be reproduced without the written permission of
the copyright owner.

Declaration of Authorship

I, ANURA TERANCE WICKRAMANAYAKE ANDRA BADUGE, declare that this thesis titled, ‘INSAR MEASUREMENTS AT HIGH LATITUDES’ and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

Abstract

This thesis contributes towards understanding of Interferometric Synthetic Aperture Radar (InSAR) measurements at high latitudes. Luossavaara-Kiirunavaara Aktiebolag (LKAB) mining company, the sponsor of this Ph.D. research, intends to use the InSAR techniques for subsidence measurements around the Kiruna underground iron ore mine. The Kiruna underground iron ore mine is located in direct proximity to the city of Kiruna, with the active mining area currently about 1 km west of the city center ($67^{\circ}51'20''$ N, $20^{\circ}13'30''$ E). At present LKAB is exploring the possibility of using InSAR measurements as an operational technique for subsidence measurements. High latitudes InSAR measurements are known to be particularly affected by long periods of ground snow cover that contributes to temporal de-correlation between subsequent radar images.

The objectives of this Ph.D. research are (1) to quantify the seasonal effects in InSAR measurements and (2) to identify techniques to improve the high latitude InSAR measurements.

In this research study, spatial coherence was used to quantify the seasonal effects in the Differential InSAR (DInSAR) measurements for Kiruna region. A comparison between Static Global Positioning System (Static-GPS) and Corner Reflector InSAR (CRInSAR) measurements were carried out to quantify the seasonal effects in CRInSAR measurements. Spatial ground deformation patterns were used to improve the DInSAR measurements. A theoretical analysis for compact active transponders (CAT) was carried out to improve the North-South InSAR measurements. DInSAR, CRInSAR and Coherent Target Monitoring (CTM) techniques were used to evaluate the applicability of InSAR techniques for high latitude mining induce deformation measurements.

The results show seasonal variations in DInSAR, CTM and CRInSAR measurements. Furthermore, DInSAR measurements around the Kiruna iron ore mine can

be improved up to sub-centimeter accuracies by using the spatial ground deformation patterns. Also, the compact active transponders identified as a possible candidate to improve the accuracy of the North-South InSAR measurements.

It is concluded that, all InSAR techniques (DInSAR, CTM and CRInSAR) were affected by the winter snow condition, and only the summer (snow-free) months are suitable for ground deformation measurements. Moreover, the study shows that without the winter images still it is possible to achieve accurate CTM and CRInSAR time series estimations for Kiruna. The East-West vector is the least noisy deformation vector, and both East-West and vertical vectors can be used to determine the LKAB environmental criterion. At present, every year, LKAB is acquiring 45 Radarsat-2 images from three beam modes. However, this study shows that less than 35% of those data are useful for subsidence measurements.

Acknowledgements

Undertaking this Ph.D. research has been a pleasant experience and it would not have been possible to do without the support and guidance that received from many people.

Foremost, I would like to express my sincere gratitude to my supervisor Dr. Stephen Hobbs for his continuous support for my Ph.D. study and research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis and without his guidance and persistent help this dissertation would not have been possible.

Besides my supervisor from Cranfield university, I would like to thank my supervisors from Luleå University of Technology: Dr. Jonas Ekman, Dr. Stefan A. Buehler and my former supervisor Tore Lindgren, for their motivation and support.

Also, I would like to thank my sponsor LKAB mining company for sponsoring my Ph.D. research and providing me with an excellent atmosphere for doing research. I would especially like to thank Britt-Mari Stöckel, Karola Mäkitaavola, Anders Berg, Bo Fjällborg, Eva-Lott Wiklund all at LKAB and Jonny Sjöberg, at Itasca Consultants AB, for their numerous support during my Ph.D. research and Michael Henschel at MDA for providing technical expertise in InSAR processing.

Also, I would especially like to thank Dr. Priya Fernando for introducing me to LKAB and providing me with his valuable advices, motivation and support throughout my study period.

I would also like to thank my parents and my sister. They were always supporting me and encouraging me with their best wishes. Finally, I would like to thank my wife, Tharanganee. She was always there cheering me up and stood by me through the good times and bad.

Contents

Declaration of Authorship	iii
Abstract	v
Acknowledgements	vii
List of Figures	xv
List of Tables	xxi
Abbreviations	xxiii
Physical Constants	xxv
Symbols	xxvii

1 Introduction	1
1.1 The industrial problem	2
1.2 Environmental criterion limit	3
1.3 Kiruna InSAR measurements	4
1.4 The academic goals	4
1.5 Contributions of this dissertation	4
1.6 Outline of this dissertation	5
2 Literature Survey	7
2.1 Introduction to Radar	7
2.1.1 Signal-to-Noise Ratio (SNR)	7
2.1.1.1 SNR for clutter	8
2.1.1.2 SNR for target	8
2.2 Introduction to Synthetic Aperture Radar	8
2.2.1 Backscatter image	9
2.2.2 Multi-looking/Look averaging	10
2.2.3 Stripmap SAR	10
2.3 Interferometric SAR (InSAR)	12
2.3.1 Differential Interferometric Synthetic Aperture Radar	12

2.3.2	2-pass DInSAR processing steps	13
2.3.2.1	Co-registration	14
2.3.2.2	Raw interferogram	16
2.3.2.3	Digital Elevation Model and Topographic phase . .	16
2.3.2.4	Baseline optimization	16
2.3.2.5	Atmospheric Phase Screen (APS)	17
2.3.2.6	Phase unwrapping	18
2.3.2.7	Deformation mapping	18
2.3.3	InSAR time series analysis	18
2.3.3.1	Small Baseline Subset (SBAS) technique	19
2.3.3.2	PSInSAR and similar time series analysis	22
2.3.3.3	Coherent Target Monitoring (CTM) technique . . .	23
2.3.4	Coherence	25
2.4	Ionospheric effect	27
2.5	Atmospheric effect	27
2.6	Corner reflectors	28
2.7	Effects of snow	29
2.8	3D ground movements	31
2.8.1	North-South InSAR accuracy	32
3	Seasonal effects on DInSAR measurements	33
3.1	Introduction	33
3.2	Test site	34
3.3	Methodology	38
3.4	Results	42
3.5	Discussion	47
3.5.1	Seasonal aspects	47
3.5.2	Common master interferograms	49
3.5.3	Sequential interferograms	50
3.5.4	Full network analysis	50
3.6	Conclusion	51
4	Seasonal effects on CRInSAR measurements	53
4.1	Introduction	53
4.2	Available data and measurement techniques	55
4.2.1	Static-GPS measurements	55
4.2.2	CRInSAR measurements	58
4.3	Snow deposition on CRs	61
4.4	Methodology	65
4.4.1	Selection of comparable measurements	65
4.4.2	Converting GPS measurements into radar line-of-sight . . .	65
4.4.3	Double difference calculations, time series plots and scatter plots	66
4.4.4	CRInSAR and GPS velocity plots	67

4.4.5	Uncertainties of GPS and CRInSAR measurements	67
4.4.6	Mean error and Standard deviation of CRInSAR double difference measurements relative to the GPS double difference measurements	69
4.4.7	Mean error and Standard deviation of CRInSAR velocities relative to the GPS velocities	69
4.4.8	Uncertainties of Static-GPS and CRInSAR velocities	70
4.4.9	Student's T test	71
4.5	Results	71
4.6	Discussion	76
4.6.1	Double difference GPS and CRInSAR time series plots	76
4.6.2	Double difference GPS and CRInSAR scatter plots	77
4.6.3	Velocity scatter plots	77
4.6.4	Snow induced phase errors and limitations of CISC technique	78
4.6.5	Assumption	79
4.7	Conclusion	79
5	Improving DInSAR measurements	81
5.1	Introduction	81
5.2	Methodology	82
5.2.1	Ground deformation between two points at the ROI (ground strain)	82
5.2.2	Deformation modeling	84
5.2.3	Using Root Mean Square (RMS) error fitting to find the best-fit parameters	84
5.2.4	Using linear deformation strain rates between two points at the ROI	85
5.2.5	Correlation coefficient between measurement and the model deformation	87
5.3	Simulation	87
5.3.1	Constructing the spatial deformation signals	87
5.3.2	RMS error fitting simulation	90
5.3.3	Correlation coefficient simulation	90
5.4	Validation methodology	90
5.4.1	Selection of the ROI	91
5.4.2	Selection of DInSAR interferogram and CTM targets	91
5.4.3	Selection of points A and B	92
5.4.4	Selection CTM points between A and B	92
5.4.5	Selection of pixels between A and B from the DInSAR interferogram	93
5.4.6	Validation	94
5.5	Results	95
5.5.1	RMS error simulation	95
5.5.2	Correlation coefficient simulation	96
5.5.3	Validation results	98

5.6	Discussion	99
5.7	Conclusion	100
6	Improving North-South InSAR measurements	101
6.1	Introduction	101
6.1.1	Compact Active transponders (CAT)	101
6.2	Proposed method	104
6.2.1	Theory	105
6.2.2	Layover effect	105
6.2.3	CAT response time requirement	106
6.2.3.1	CAT critical response time requirement For Radarsat-2 U6 beam mode images	107
6.2.3.2	CAT typical (recommended) response time requirement for Radarsat-2 U6 beam mode images	109
6.3	Discussion	110
6.3.1	Requirement of Line-of-sight visibility between transponders	110
6.3.2	Layover effect	110
6.3.3	CAT visibility in SAR image	111
6.3.4	Replacing one transponder with a corner reflector	112
6.3.5	3D ground movement measurements by using a single satellite track	112
6.4	Conclusion	112
7	InSAR measurements around Kiruna iron ore mine	115
7.1	Introduction	115
7.2	Region Of Interest (ROI)	116
7.3	Data	117
7.4	Methodology	117
7.4.1	DInSAR interferogram generation	117
7.4.2	DInSAR wide area deformation maps	118
7.4.3	CTM time series maps	119
7.4.4	CRInSAR time series maps	120
7.4.5	Three-dimensional (3D) time series map generation	120
7.4.6	Small Baseline Subset network	121
7.5	Results	122
7.5.1	DInSAR interferograms	123
7.5.2	CTM time series maps	124
7.5.3	CRInSAR time series measurements	125
7.6	Discussion	126
7.6.1	Seasonal effects in CTM measurements	127
7.6.2	DInSAR measurements around Kiruna iron ore mine	127
7.6.3	Kiruna CTM time series measurements	128
7.6.4	Kiruna CRInSAR time series measurements	128
7.7	Conclusion	129

8	Discussion	131
8.1	Limitation of Kiruna InSAR measurements	132
8.2	Improving Kiruna InSAR measurements	132
8.3	InSAR use as an operational technique for Kiruna subsidence measurements	133
8.4	High latitude InSAR processing challenges	134
8.5	Required minimum number of satellite images for Kiruna InSAR measurements	135
8.6	Required minimum number of beam modes for Kiruna InSAR measurements	137
8.7	CTM targets and new Corner reflector installations at Kiruna . . .	137
9	Conclusion	139
9.1	Seasonal effects in DInSAR measurements	139
9.2	Seasonal effects in CRInSAR measurements	140
9.3	Seasonal effects in CTM measurements	140
9.4	Improving DInSAR measurements	141
9.5	Improving North-South InSAR measurements	141
9.6	InSAR measurements around Kiruna iron ore mine	142
9.7	Future work	142
A	Coherence images for Kiruna test site	157
B	Comparison of U6D CRInSAR and Static-GPS measurements	173
C	Simulation plots	187
C.0.1	RMS error plots for simulated signals	187
C.0.2	Correlation coefficient plots for simulated signals	192
D	Image data	197

List of Figures

1.1	Surface deformation zones at mines with sublevel caving mining method [1].	2
1.2	Environmental criterion limit	3
2.1	Radar data acquisition geometry.	9
2.2	Single-look and multi-look radar images for Paris city	10
2.3	SAR modes	11
2.4	2-pass DInSAR processing steps	14
2.5	2-pass DInSAR processing steps	15
2.6	Digital Elevation Model	17
2.7	Coherent targets selection	25
2.8	Coherent targets deformation map.	26
2.9	Corner reflector.	29
3.1	Optical image: Kiruna iron ore mine, Kiruna city and surroundings in the autumn.	35
3.2	Kiruna waste rock area in summer.	36
3.3	Kiruna waste rock area in winter.	36
3.4	Kiruna urban area in summer.	37
3.5	Kiruna urban area in winter.	37
3.6	Kiruna forest area in summer.	37
3.7	Kiruna forest area in winter.	38
3.8	Coherence images for Kiruna test site	43
3.9	Coherence variation in common master interferograms for all test areas.	44
3.10	Coherence variation in sequential interferograms for all test areas.	44
3.11	Coherence variation in all interferograms for forest area.	45
3.12	Coherence variation in all interferograms for urban area.	45
3.13	Coherence variation in all interferograms for waste rock area.	46
3.14	Coherence variation in all interferograms for waste rock area.	46
3.15	An example summer interferogram for the Kiruna area.	47
4.1	GPS and CR network in Kiruna.	56
4.2	GPS measurement points installed prior to 2010.	57
4.3	GPS measurement points installed after 2010.	57
4.4	GPS and CR reference points.	59

4.5	Selected interferograms.	61
4.6	Shielded CR installed in Kiruna without snow.	62
4.7	Shielded CR with a snow layer on top of the shield.	63
4.8	Shielded CR with a ice layer on top of the shield.	63
4.9	CR with inhomogeneous snow cover on top of the shield	64
4.10	Function of the snow shield.	64
4.11	Time series plots for CR-06 and GPS-L10.	72
4.12	Time series plots for CR-10 and GPS-H11.	72
4.13	Time series plots for CR-23 and GPS-T29.	73
4.14	Time series plots for CR-27 and GPS-D57.	73
4.15	Time series plots for CR-06 and GPS-L10.	74
4.16	Time series plots for CR-2 and GPS-M7.	74
4.17	Double difference scatter plot	75
4.18	Velocity scatter plot	75
5.1	Ground deformation between two points at the ROI.	82
5.2	Simulated deformation signal with and without noise. The simulated deformation rate is 3 mm/pixel. SNR is 0.75	88
5.3	Simulated deformation signal with and without noise. The simulated deformation rate is 5 mm/pixel. SNR is 0.5	89
5.4	Simulated deformation signal with and without noise. The simulated deformation rate is 3 mm/pixel. SNR is 0.9	89
5.5	Selected ROI for the validation.	91
5.6	Points <i>A</i> and <i>B</i> : Interferogram is shown in the left, and the backscatter image is shown in the right image.	93
5.7	RMS error between simulated ground deformation and model signal.	95
5.8	RMS error between simulated ground deformation and model signal.	95
5.9	RMS error between simulated ground deformation and model signal.	96
5.10	Correlation coefficient between simulated ground deformation and model signal.	96
5.11	Correlation coefficient between simulated ground deformation and model signal.	97
5.12	Correlation coefficient between simulated ground deformation and model signal.	97
5.13	CTM points between <i>A</i> and <i>B</i>	98
5.14	RMS error between real and model deformation signals.	98
5.15	Deformation from <i>A</i> to <i>B</i> from CTM measurements.	99
6.1	Commercially available CAT device	102
6.2	A CAT device installed at the field	103
6.3	Simple block diagram of a CAT device	103
6.4	Proposed transponder placement in the field.	104
6.5	SAR image acquisition geometry.	107
7.1	Kiruna iron ore mine, Kiruna city and surroundings in summer.	116

7.2	Small baseline subset network for the U6D track.	121
7.3	Small baseline subset network for the U25A track.	122
7.4	Small baseline subset network for the U70D track.	122
7.5	DInSAR summer-to-summer interferogram from U6D beam mode. .	123
7.6	U6D line-of-sight CTM time series deformation measurements. . .	124
7.7	U6D line-of-sight CRInSAR deformation measurements for Kiruna CR network	125
7.8	CRInSAR Time series from U6D, U25A, U70D beam modes and East-West, North-South and Vertical deformation components for CR3.	126
A.1	Coherence images for Kiruna test site.	157
A.2	Coherence images for Kiruna test site	158
A.3	Coherence images for Kiruna test site	159
A.4	Coherence images for Kiruna test site	160
A.5	Coherence images for Kiruna test site	161
A.6	Coherence images for Kiruna test site	162
A.7	Coherence images for Kiruna test site	163
A.8	Coherence images for Kiruna test site	164
A.9	Coherence images for Kiruna test site	165
A.10	Coherence images for Kiruna test site	166
A.11	Coherence images for Kiruna test site	167
A.12	Coherence images for Kiruna test site	168
A.13	Coherence images for Kiruna test site	169
A.14	Coherence images for Kiruna test site	170
A.15	Coherence images for Kiruna test site	171
A.16	Coherence images for Kiruna test site	172
B.1	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	173
B.2	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	174
B.3	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	174
B.4	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	175
B.5	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	175
B.6	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	176
B.7	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	176
B.8	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	177

B.9	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	177
B.10	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	178
B.11	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	178
B.12	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	179
B.13	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	179
B.14	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	180
B.15	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	180
B.16	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	181
B.17	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	181
B.18	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	182
B.19	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	182
B.20	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	183
B.21	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	183
B.22	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	184
B.23	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	184
B.24	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	185
B.25	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	185
B.26	Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements	186
C.1	RMS error between simulated ground deformation and model signal.	187
C.2	RMS error between simulated ground deformation and model signal.	188
C.3	RMS error between simulated ground deformation and model signal.	188
C.4	RMS error between simulated ground deformation and model signal.	189
C.5	RMS error between simulated ground deformation and model signal.	189
C.6	RMS error between simulated ground deformation and model signal.	190
C.7	RMS error between simulated ground deformation and model signal.	190
C.8	RMS error between simulated ground deformation and model signal.	191

C.9	Correlation coefficient between simulated ground deformation and model signal.	192
C.10	Correlation coefficient between simulated ground deformation and model signal.	193
C.11	Correlation coefficient between simulated ground deformation and model signal.	193
C.12	Correlation coefficient between simulated ground deformation and model signal.	194
C.13	Correlation coefficient between simulated ground deformation and model signal.	194
C.14	Correlation coefficient between simulated ground deformation and model signal.	195
D.1	U6D beam heading angle	201
D.2	U6D beam incident angle	201

List of Tables

3.1	Common master interferograms.	40
3.2	Sequential interferograms.	41
4.1	Distance between GPS benchmarks and CRs	58
4.2	Correlation coefficient, Mean error and Standard deviation	71
D.1	Beam characteristics of the selected tracks used for this study. . . .	197
D.2	U6D beam mode images	198
D.3	U25A beam mode images	199
D.4	U70D beam mode images	200

Abbreviations

APS	A tmospheric P hase S creen
CAT	C ompact A ctive T ransponder
CR	C orner R eflector
CRInSAR	C orner R eflector I nterferometric S ynthetic A perture R adar
CTM	C oherent T arget M onitoring
DInSAR	D ifferential I nterferometric S ynthetic A perture R adar
GPS	G lobal P ositioning S ystem
InSAR	I nterferometric S ynthetic A perture R adar
LKAB	L uossavaara K iirunavaara A ktie B olag
MDA	M acDonald, D ettwiler and A ssociates Ltd.
PSInSAR	P ersistent S catter I nterferometric S ynthetic A perture R adar
ROI	R egion O f I nterest
RTK	R eal T ime K inematic
SAR	S ynthetic A perture R adar

Physical Constants

$$\text{Boltzmann constant } K = 1.3806488 \times 10^{-23} \text{ m}^2\text{kg s}^{-2}\text{K}^{-1}$$

$$\text{Speed of Light } c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-1}$$

Symbols

ϕ	interferometric phase	(rad)
P_s	density of snow	(kg m ⁻³)
n_s	Refraction index of snow	

*This dissertation dedicated to my wonderful mother,
Amita Arlin Wickramanayake. Whom watching over me
from heaven...*

Chapter 1

Introduction

Spaceborne interferometric synthetic aperture radar is now a well established technique used for ground subsidence measurements, terrain deformations measurements and landslide measurements with many advantages over the conventional techniques. In late sixties, InSAR was first used for planetary observations [2]. Later, in 1974 Graham [3] and, in 1986 Zebker et al. [4] used InSAR to produce topographic maps. The use of differential Interferometric SAR (DInSAR) for centimeter accuracy surface deformation mapping was first demonstrated by Gabriel et al. in 1989 [5]. Moreover, in 1993, for the first time, Massonnet et al. used InSAR to detect the coseismic displacement field of an Earth earthquake [6]. The InSAR technique measures the ground movement in the line-of-sight direction to the satellite. The Interferometric SAR technique depends on the backscattering signal and thus needs to have strong and stable backscatters to achieve good results. The extreme winter conditions in high latitudes is a major disadvantage for InSAR techniques. Most of the backscatters disappear due to the thick snow cover which in turn leads to high noise disturbance signals in the interferometric measurements. Also, all available SAR satellites are in polar orbits and therefore the line-of-sight measurements are more sensitive to East-West ground movements than the North-South ground movements. In past, InSAR has been used to measure the mine induced subsidence at low latitudes [7–10] but there are no comprehensive investigations carried out for high latitude underground mines. Therefore, it is important to improve our understanding on high latitude InSAR measurements, to identify the InSAR limitations and to investigate the InSAR applicability to this region.

1.1 The industrial problem

Luossavaara Kirunavaara Aktiebolag (LKAB) mining company, the sponsor of this Ph.D. research, runs the world's largest underground iron ore mine. This mine is located in direct proximity to the city of Kiruna, with the active mining area currently about 1 km west of the city center ($67^{\circ}51'20''$ N, $20^{\circ}13'30''$ E). The sublevel caving [11] method is used at the Kiruna mine to extract iron ore. In sublevel caving, the blasted ore is always falling to the lower level. Because of that the overlying host rock fractures, caves and fall into the ore body to fill the void. In a steep ore body the side of the ground rock overlying the orebody is known as the hangingwall. And the side of ground rock underlying the iron orebody, which is called the footwall. During sublevel caving, ground subsidence mainly occurs on the hangingwall side (Figure 1.1).

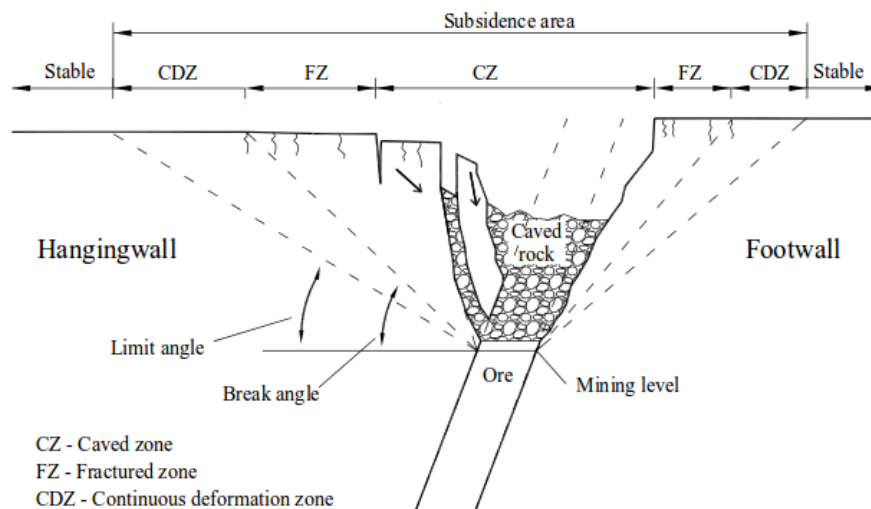


FIGURE 1.1: Surface deformation zones at mines with sublevel caving mining method [1].

Since 2003, LKAB has been using Global Positioning System (GPS) techniques to measure the subsidence at both the hangingwall and footwall sides [12]. The Static-GPS technique (Static-GPS) with one reference station was used between 2003 and 2009. Since then, LKAB has been using the Static-GPS technique with three reference stations. The Static-GPS subsidence measurements have been thoroughly investigated [12] and a well maintained Static-GPS subsidence measurement dataset dating back to 2003 is, therefore, available for the Kiruna region.

Many challenges must be overcome when using the GPS technique. One such challenge consists of the installation of a large number of measurement points to obtain good spatial coverage. This installation also increases the required manpower for surveying. Furthermore, conducting a GPS survey in harsh winter conditions at high latitudes with a thick ground snow covering is difficult.

1.2 Environmental criterion limit

The Environmental criterion limit is used to identify the boundary for the LKAB industrial area. Therefore, the ground deformation outside the LKAB industrial area should be less than Environmental criterion limit. The Environmental criterion limit is defined as maximum allowed strain limit in the horizontal direction as 0.3 % or maximum allowed strain limit in the vertical direction as 0.2 %.

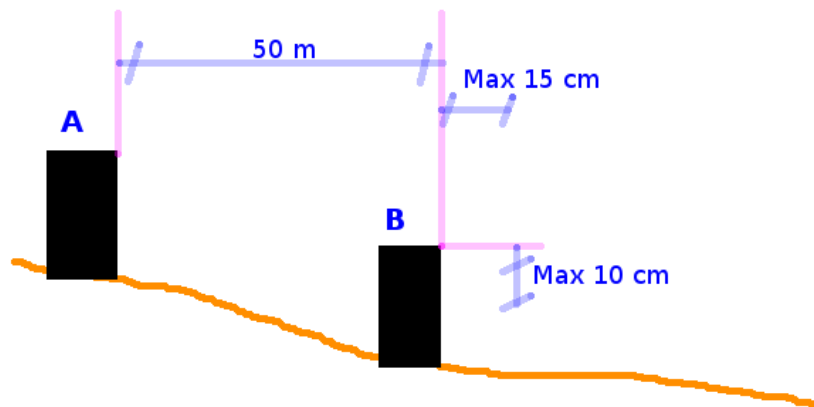


FIGURE 1.2: Environmental criterion limit

For an example if we consider two points on the ground (A and B) and if these points are 50 m apart from each other, then the maximum allowed ground deformation (Environmental criterion limit) should be 15 cm in the horizontal direction or 10 cm in the vertical direction (Figure 1.2).

1.3 Kiruna InSAR measurements

Stable scatterers in the region of interest (ROI) are essential for InSAR monitoring. The Kiruna region features vast areas without stable natural scatterers due to the snow cover in winter and the thick vegetation in the summer.

In 2010, a corner reflector network comprising 60 corner reflectors (CRs) were installed in Kiruna to measure subsidence using InSAR, and in 2013, another 24 CRs were installed to expand the CR network. The corner reflector InSAR measurement (CRInSAR) is a proven technique that uses CRs as highly coherent point targets, especially when stable natural scatterers are unavailable in the ROI. A protective shield was fitted to prevent snow accumulation inside the corner reflectors. However, it is observed that up to 8 cm snow layer can be accumulated on top of these shields during winter. Also, InSAR provides line-of-sight measurements. However, the ground movement around the Kiruna mine is three-dimensional and therefore LKAB is expecting to achieve three-dimensional InSAR measurements. For the period of October 2009 to October 2014, LKAB was acquiring a total of 225 Radarsat-2 images from three beam modes.

1.4 The academic goals

The academic goals of this thesis are,

1. To quantify the seasonal effects in InSAR measurements.
2. To identify techniques to improve the high latitude InSAR measurements.

1.5 Contributions of this dissertation

Some of the novel aspects of this Ph.D. study involve,

1. Quantifying the seasonal effects in the DInSAR measurements for Kiruna region.
2. Quantifying the seasonal effects in CRInSAR measurements.

3. Improving DInSAR measurements using spatial deformation patterns.
4. Introducing compact active transponders to improve the North-South InSAR measurements.

1.6 Outline of this dissertation

The literature survey has been carried out to understand the InSAR techniques, as well as the new developments in this field. Interferograms were analyzed to identify and quantify the phase uncertainty taking place due to seasonal variations, and the results were presented in the Chapter 3. Chapter 4 presents seasonal effects in the corner reflector InSAR measurements. Chapter 5 presents a method to improve the DInSAR measurements by using spatial deformation patterns. Chapter 6 presents a novel technique to improve the North-South InSAR measurements. Chapter 7 presents the InSAR measurements at Kiruna city and around Kiruna underground iron ore mine. Chapter 8 presents the Discussion, and Chapter 9 presents the Conclusion.

Chapter 2

Literature Survey

2.1 Introduction to Radar

Radar is a method of using Electromagnetic waves to detect the existence and position of an object. The word “radar” is derived from the words RAdio Detection And Ranging. The radar equation can be written in few different ways and the general range equation can be written as [13]:

$$P_r = \frac{P_{avg} G \sigma A_e t_{int}}{(4\pi)^2 R^4} \quad (2.1)$$

where, P_r is the received signal energy, P_{avg} is the average transmitted power, G is the antenna gain, A_e is the effective antenna area, σ is the radar cross section of target, t_{int} is the integration time, and R is the range.

2.1.1 Signal-to-Noise Ratio (SNR)

Signal to Noise Ratio (SNR) is a crucial parameter of a radar system which express the desired signal to the level of background noise. The SNR of a SAR signal is often presented as the SNR of the SAR image. SNR of SAR image gives the desired amount of transmitted power to achieve the required level of image quality.

2.1.1.1 SNR for clutter

The distributed features in the SAR image is called as clutter and the SNR for clutter can be calculated as follows [14]:

$$SNR_{clutter} = \frac{P_{ave} G^2 \lambda^3 \sigma^0 c}{256 \pi^3 R^3 K T B_T F_n L_s V \sin \theta_i} \quad (2.2)$$

where, P_{avg} is the average transmitted power, G is the antenna gain, λ is the radar wavelength, σ^0 is the terrain reflectivity (normalized per square meter), c is the speed of light, R is the range to reflector, K is the Boltzmann's constant, T is the temperature of receiver, B_T is the transmitted signal bandwidth, F_n is the receiver noise figure, L_s is the system losses, V is the platform velocity and θ_i is the beam incidence angle.

2.1.1.2 SNR for target

The discrete objects in the dimension of the SAR resolution or finer called as targets, and the SNR for the target calculate as follows [14]:

$$SNR_{target} = \frac{P_T F_a T_a G^2 \lambda^3 \sigma_t c}{256 \pi^3 R^3 K T B_T F_n L_s V \rho_r \rho_a} \quad (2.3)$$

where, ρ_r is the slant range resolution, ρ_a is the azimuth resolution, P_T is the transmitted power, F_a is radar pulse repetition frequency (PRF) and T_a is the duration of the transmitted pulse.

2.2 Introduction to Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is a form of radar, which uses advanced signal processing techniques and movement of a smaller antenna to simulate a larger antenna and this will make a narrow radar beam thus leads to higher resolution [14].

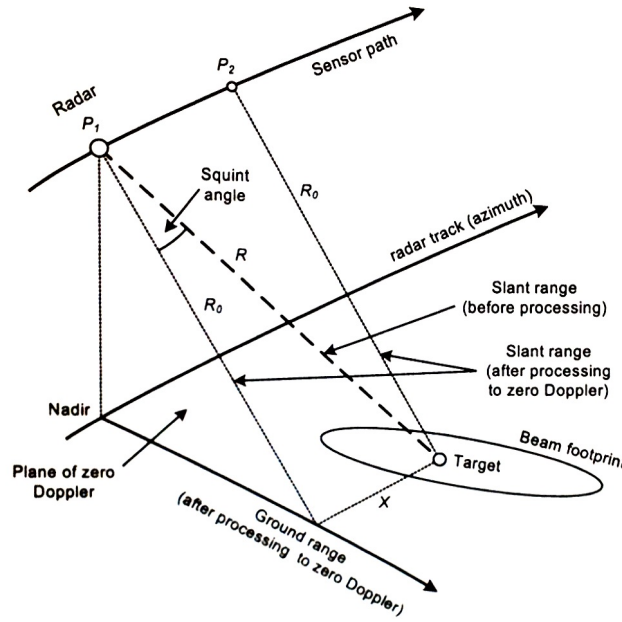


FIGURE 2.1: Radar data acquisition geometry [14].

Figure 2.1 present a typical synthetic aperture radar acquisition geometry. The SAR system produces a two-dimensional image where one dimension in the image is called as range. Range is the “line-of-sight” distance from the radar antenna to the ground (or the target). The range is achieved by the SAR system by measuring the time from transmission of a pulse to receiving the echo from the target. The range resolution depends on the transmitted pulse width. The other dimension is called azimuth is measured along the track direction. The azimuth resolution depends on the size of the aperture of the antenna that needs to focus the transmitted and received energy into a sharp beam. In SAR systems, this large aperture is synthesized by using the spacecraft movement and advanced signal processing techniques [14].

2.2.1 Backscatter image

Backscatter is the portion of the outgoing radar signal that the target redirects directly back towards the radar antenna [15]. The backscatter image can contain both phase and magnitude information or only the magnitude information depending on the sensor configuration. High backscatter targets appear as bright in the backscatter image, and low backscatter targets appear in dark. Figure 2.2 (left) shows a C-band airborne SAR backscatter image of Paris city.

2.2.2 Multi-looking/Look averaging

Radar echoes of the distributed scatter targets will produce the speckle noise in SAR images. The speckle noise will reduce the ability of separating the distributed targets in the image. Multi-looking is combining pixels by averaging. By multi-looking the speckle noise can be reduced from the image. The multi-looking will improve the radiometric resolution of the image but it will reduce the number of pixels in the image and the geometric resolution of the image [16].

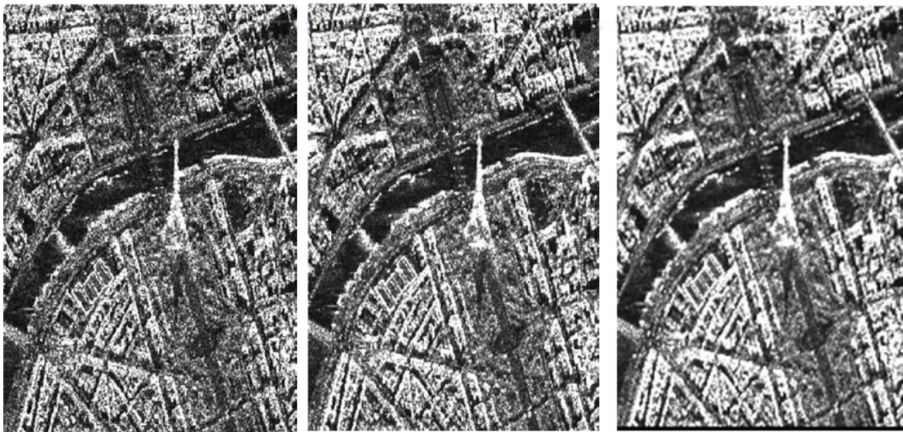


FIGURE 2.2: Multi-looking method applied on an image acquired by the airborne SAR over Paris city [17].

Figure 2.2 (left) shows a single look radar image acquired by the airborne C-band SAR (Sethi) over Paris city. Single look image resolution (range x azimuth) is 3 x 3 m. Figure 2.2 (middle) shows the 2 x 2 multi-look image (2 looks in azimuth, 2 looks in range). The image resolution is 6 x 6 m. Figure 2.2 (right) shows the 3 x 3 multi-look image (3 looks in azimuth, 3 looks in range). The image resolution is 9 x 9 m [17].

2.2.3 Stripmap SAR

In the Stripmap SAR mode, the antenna pointing direction is held unchanged as the radar platform moves. the beam sweeps along the ground at an approximately uniform rate and a contiguous image is formed. A strip of ground is imaged, and the length of the strip is only limited by how far the sensor moves or how long the radar is left on. The azimuth resolution is governed by the antenna length [14].

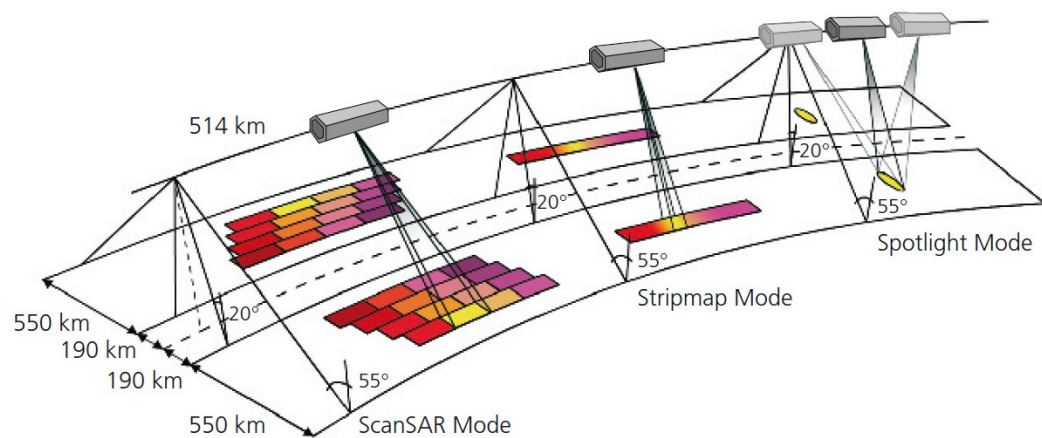


FIGURE 2.3: Radarsat-2 beam modes [18].

Figure 2.3 shows the Stripmap mode [18]. Apart from Stripmap SAR mode, ScanSAR, SpotlightSAR, InverseSAR and BistaticSAR modes are also available.

2.3 Interferometric SAR (InSAR)

Spaceborne InSAR is a well established method of measuring land subsidence/ground deformations. Over the past few years, the InSAR technique has been developed into a fully operational technique that can deliver an accuracy better than 1 cm/year [19, 20]. The InSAR measurement relies on the presence of scatterers that have stable properties over the timescale of interest. There are several InSAR techniques that can be used to measure the ground deformation based on the spatial and temporal availability of these scatterers. The simplest InSAR technique is the DInSAR technique, which can deliver an accuracy of approximately 1 cm/year [19]. This technique works well in barren flat landscapes where a large number of spatially distributed scatterers are available. The DInSAR technique required minimum of two satellite images to produce an interferogram and a digital elevation model (DEM) to remove the topography. Low-pass filtering techniques are used to remove the atmospheric effects from the interferogram. InSAR time series measurement techniques (Persistent Scatterer InSAR (PSInSAR) [21], Coherent Target Monitoring (CTM) [22] etc.) were developed to achieve higher measurement accuracies in areas where natural or man-made individual scatterers are available. These techniques can deliver accuracies better than 5 mm/year. It is also recommended that obtaining more than 15 images is necessary for these techniques [23]. These techniques require visibility of the targets throughout the interferogram stack [23]. When there are no natural or man-made scatterers, artificial radar reflectors (known as corner reflectors) can be used as radar targets, and with the usage of corner reflectors, accuracies better than 3 mm/year can be achieved [24].

2.3.1 Differential Interferometric Synthetic Aperture Radar

DInSAR is a technique that measures surface deformation using complex SAR images. Depending upon the number of SAR images used, the DInSAR technique can be classified into three different categories, which are 2-pass interferometry, 3-pass interferometry and 4-pass interferometry [25]. In 2-pass interferometry, two SAR images are used to generate the interferograms, and an external digital elevation model (DEM) is used to remove the topographic effects. In 3-pass interferometry, three SAR images are used, with two images used to generate the DEM, and the interferogram is generated by combining the unused SAR image with one of the

two other images. In 4-pass interferometry, four SAR images are used, with two images used to generate the interferograms and the remaining two used to generate the DEM. The interferometric phase is related to the imaging path length. The imaging path length depends on several factors, such as atmospheric delay, ground deformation, topography, orbital changes and thermal noise in the sensor as well as, in the arctic, the ground snow cover. The phase components of the interferometric phase can be written as:

$$\Phi = \Phi_{def} + \Phi_{topo} + \Phi_{orb} + \Phi_{atm} + \Phi_{snow} + \Phi_{noise} \quad (2.4)$$

where Φ is the phase difference calculated from the two complex SAR images (from the interferogram), Φ_{def} is the phase difference due to the deformation of the ground, Φ_{topo} is the topographic phase and flat earth phase, Φ_{orb} is the phase due to the incorrect baseline measurements, Φ_{atm} is the phase due to atmospheric water vapour, Φ_{snow} is the phase due to the ground snow layer and Φ_{noise} is the phase due to the thermal noise in the system.

In InSAR deformation measurements, interferometric processing is performed to preserve the interferometric phase related to the ground deformation and to remove any other additional phase components. The accuracy of the deformation measurements will depend on the precision used to remove these additional phase components.

2.3.2 2-pass DInSAR processing steps

Following are the main steps in the two pass differential interferometry processing,

1. Selecting two complex SAR images over an area with nearly identical acquisition geometry.
2. Co-registering the two images and digital elevation model (DEM) with each other.
3. Multi-looking the images to reduce the spatial noise (if necessary).
4. Forming raw (initial) interferogram by multiplying the first image with complex conjugate of the second image.

5. Removing the topographic and flat earth phase from the raw interferograms by using an external DEM and SAR image orbital parameters.
6. Baseline optimization to correct any baseline errors.
7. Atmospheric phase screen generation (APS) for interferograms (optional step).
8. Selecting the region of interest (ROI) and preparing a subset of interferograms (if necessary).
9. Removing atmospheric noise from the interferogram.
10. Filtering, masking (low coherence areas) and unwrapping the interferogram.
11. Calculating the reference phase and subtracting from the interferogram.
12. Creating deformation maps by converting line-of-sight deformation to vertical deformation (by assuming there are no horizontal ground movements).

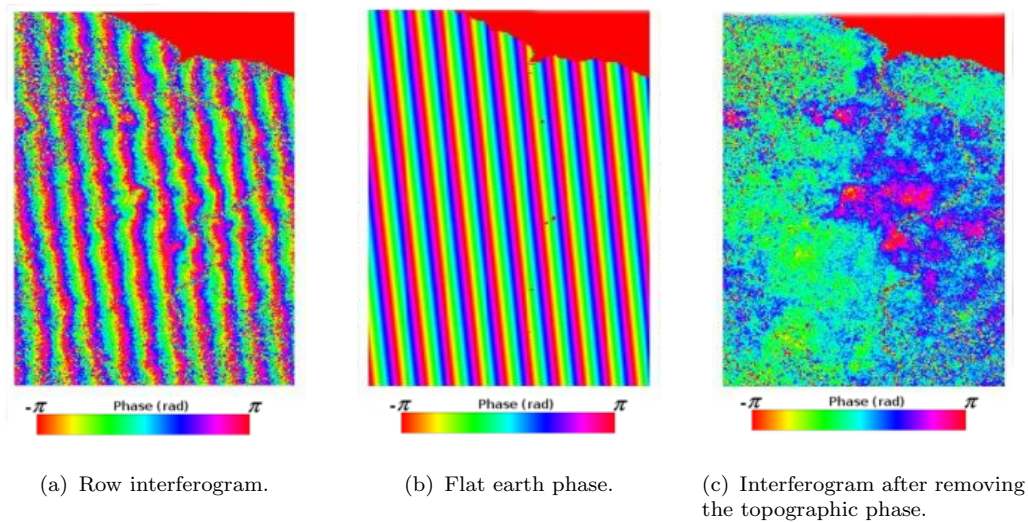


FIGURE 2.4: 2-pass DInSAR processing steps. Topographic phase removal [26].

2.3.2.1 Co-registration

In SAR interferometry, the phase information is extracted by subtracting the first SAR image from the second SAR image and this requires that the pixels in both images should represent the same ground truth. The satellite images for the same acquisition geometry may exhibit pixel shifting, mainly due to the changes

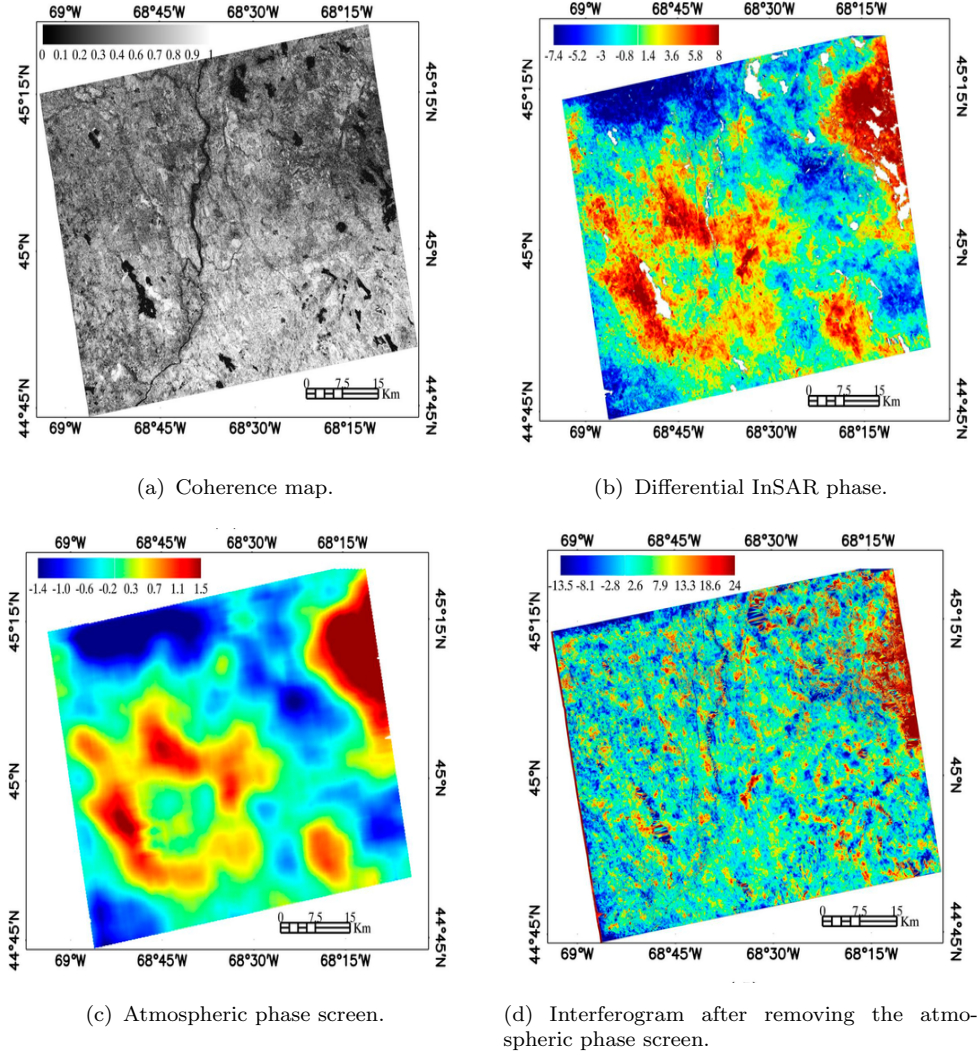


FIGURE 2.5: 2-pass DInSAR processing steps. Atmospheric phase removal [27].

in the baseline. The co-registration process mainly corrects this pixel shifting which ensures that the same pixel in both images represents the same ground truth. Co-registration is a critical step, and poor co-registration could lead to poor coherence. In InSAR processing to achieve high precision co-registration, a subpixel-to-subpixel (fine co-registration) is a must. One of popular techniques to perform co-registration is to compute the complex cross correlation function between images [28]. Also, signal-to-noise ratio (SNR) estimation of the interferogram [29] can be used to perform co-registration. The co-registration parameters can be adjusted using the average fluctuation function of the interferogram [30].

The number of tie points in the image, evenly spatial distribution of the tie points, the size of window uses for tie point matching, the method that uses for the matching, and the used mathematical models for the transformation will determine

the final accuracy of the image co-registration [31]. In high latitude, the winter snow cover will reduce the number of tie points in the image and disrupt the even spatial distribution of the tie points. Therefore, it is important to select the ROI in a way to achieve a sufficient number of tie points. Also, interpolation techniques can be used to achieve evenly distributed tie-point grid. Co-registration accuracy around 1/10 of a pixel is required for reliable interferometric measurements [31].

2.3.2.2 Raw interferogram

Interferograms which contains the deformation phase, topographic phase, flat earth phase and atmospheric phase are called as the raw interferograms. Figure 2.4(a) shows a typical raw interferogram.

2.3.2.3 Digital Elevation Model and Topographic phase

The presence of the perpendicular and parallel baselines will create fringes in the interferogram even without any ground deformation, and the presence of topographical features will enhance these fringes. If there are no any topographical features, no deformation and if the ROI is flat, then the visible fringes are called as the flat earth phase. Figure 2.4(b) show the typical flat earth phase image [26]. The additional phase in the interferogram due to the topography is called as the topographic phase [32]. Digital elevation model contains the elevation information of the terrain. For the 2-pass interferometry, a digital elevation model is used to remove the topographic phase from the raw interferogram. Figure 2.6 shows a typical digital elevation model [33]. Figure 2.4(c) show an interferogram after removing the flat earth and topographic phase.

2.3.2.4 Baseline optimization

Since the perpendicular and parallel baselines will create the flat earth phase, it is important to acquire correct orbital parameters to calculate and remove the flat earth phase. The Baseline optimization step is carried out to optimize the orbital parameters. Baseline optimization is performed by iterating a range of values for the baseline geometry and choosing the optimum value. The definitive orbital parameters are used as the initial orbital parameters for the baseline geometry.

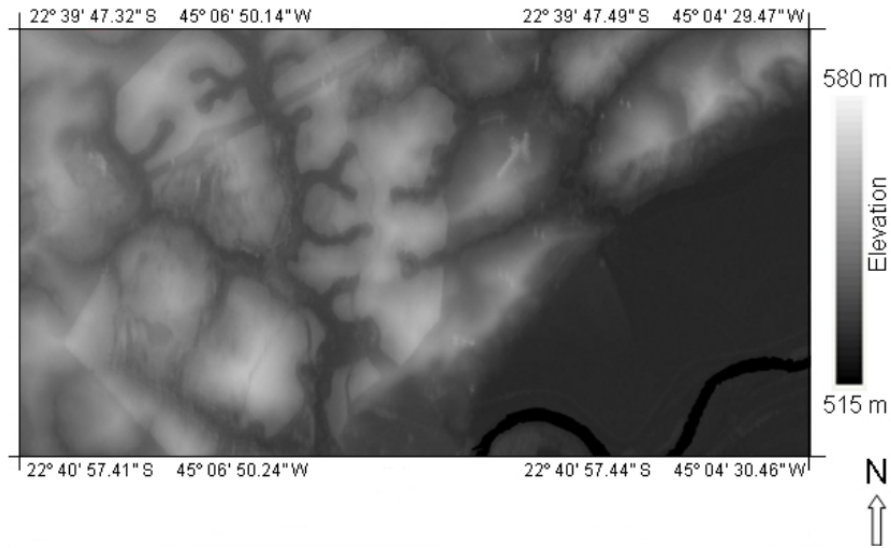


FIGURE 2.6: X-band DEM [33].

The optimum value is the value that gives the highest spatial coherence in the interferogram. Any errors in the baseline estimation could cause the appearance of residual fringes in the interferogram [34].

2.3.2.5 Atmospheric Phase Screen (APS)

The radar waves from the SAR satellite travel through different layers (troposphere, ionosphere, and atmosphere) during their propagation. Each layer has different properties and therefore the speed, and the propagating angle of the radar wave will be affected. The changes in the troposphere, ionosphere, and atmosphere are not spatially or temporally uniform. Therefore, InSAR measurement will contain an additional phase component related to these changes. Atmospheric phase refers to the phase uncertainties occurring in the interferograms due to troposphere, ionosphere, and atmosphere inhomogeneity during InSAR measurements. Figure 2.5(c) show the typical atmospheric phase screen. Figure 2.5(b) shows a interferogram with atmospheric phase screen and Figure 2.5(d) shows a interferogram after removing the atmospheric effects.

2.3.2.6 Phase unwrapping

Each pixel of an InSAR interferogram contains phase information. However, this phase information is restricted to the $-\pi + \pi$ intervals, and this phase is called as the wrapped phase. However, the unwrapped phase is directly related to the ground deformation. The procedure of converting the wrapped phase into an unwrapped phase is known as phase unwrapping in the InSAR processing chain [35].

2.3.2.7 Deformation mapping

In SAR interferometry, it is the slant range (or the line-of-sight) measurements of the ground movements that are obtained. In most cases, the basic assumption made in deformation map making is that the ground has a vertical movement (or horizontal movement). This is followed by taking the vector separation [36]. In the case of 3 D ground movements, this necessitates three slant range measurements from 3 different tracks [37, 38]. Subsequent to the vector separation, geocoding should be carried out to the required map projection.

2.3.3 InSAR time series analysis

The interferometric measurements are affected by the temporal decorrelation, atmospheric noise, perpendicular baseline and ionospheric noise. In time series analysis, time series image stack and different processing techniques are used to minimize the interferometric phase associated with the above noises. Persistent Scatterers InSAR (PSInSAR), Coherent Target Monitoring (CTM) and Small Baseline Subset (SBAS) are commonly used techniques for time series InSAR measurements. The PSInSAR technique uses stable amplitude pixels that have good correlation over the interferogram stack [21, 39]. The CTM technique uses stable phase pixels (targets) in the interferogram stack. Full details of the CTM technique is presented in Section 2.3.3.3. The small baseline subset (SBAS) technique was first introduced by Lundgren et al. [40] and further developed by Berardino et al. [41]. This technique can be used when there are large numbers of unwrapped interferograms with small spatial baselines. Several subsets of small baseline interferograms can exist for a given set of images that give deformation

time series. All the subsets can be linked together, and the complete deformation time series can be extracted [42] by using the commonly used Singular Value Decomposition (SVD) technique. Full details of the SBAS technique is presented in Section 2.3.3.1.

The main difference between PSInSAR and CTM techniques is that, in PSInSAR, pixels (targets) are selected by studying their amplitude stability along the entire set of images. However, in CTM technique, the pixels (targets) are selected by studying their phase stability (spatial coherence) along the entire set of images (Section 2.3.3.2 and 2.3.3.3).

2.3.3.1 Small Baseline Subset (SBAS) technique

Detail description of small baseline subset (SBAS) technique [43] is presented in this section.

An Interferogram phase can be formulated as a linear equation [43]:

$$\Psi_{t_B, t_A} = \varphi_{t_B} - \varphi_{t_A} \quad (2.5)$$

where φ_{t_B} and φ_{t_A} are the phases related to two SAR images taken at time t_B and t_A . Ψ_{t_B, t_A} is the unwrapped interferogram phase.

Let's take that we have a sequential image stack that contain $N+1$ SAR images for a given ROI. After the co-registration of the image stack, we can generate N number of DInSAR interferograms from the image stack. Therefore, this will lead to solving a determined $N \times N$ system of equations (Equation 2.5). However, some interferograms will have higher decorrelation than others due to higher perpendicular baseline, higher temporal baseline and atmospheric effects. By selecting and arranging small baseline interferogram stacks, we can minimize the interferometric phase related to the noise, but it will lead to a rank deficiency in the system.

Let's take a generic pixel of our SAR images which has azimuth coordinate x and range coordinate r . We can write the generic j^{th} (unwrapped) interferogram computed from the SAR acquisitions at times t_B and t_A [43]:

$$\begin{aligned}
\Psi_j(x, r) &= \varphi(t_B, x, r) - \varphi(t_A, x, r) \\
&\approx \frac{4\pi}{\lambda} \{d(t_B, x, r) - d(t_A, x, r)\} + \frac{4\pi}{\lambda} \frac{b_{\perp j} \Delta z}{r \sin \vartheta} + \\
&+ \frac{4\pi}{\lambda} \{d_{atm}(t_B, x, r) - d_{atm}(t_A, x, r)\} + \Delta n_j, \forall j = 1, \dots, M, \quad (2.6)
\end{aligned}$$

where λ , $\varphi(t_B, x, r)$ and $\varphi(t_A, x, r)$ are the extracted phase from two images (used in the interferogram), $d(t_B, x, r)$ and $d(t_A, x, r)$ are the radar line-of-sight projections of the cumulative deformation at t_A and t_B respect to a stable reference point, Δz is the height error in DEM, $b_{\perp j}$ is the perpendicular baseline, r is the distance between sensor to target, ϑ is the look angle, $d_{atm}(t_B, x, r)$ and $d_{atm}(t_A, x, r)$ are the atmospheric phase and, Δn_j is the decorrelation effects.

We can write following two index vectors for the master and slave images of the interferograms. Here we assume that master and slave images are in sequential order [43]:

$$IS = [IS_1, \dots, IS_M], IE = [IE_1, \dots, IE_M] \quad (2.7)$$

where IS is the master image and IE is the slave image.

By using the index vectors (Equation 2.7), left hand side of the Equation 2.6 can be modified as [43]:

$$\Psi_j = \varphi(t_{IE_j}) - \varphi(t_{IS_j}) \quad \forall j = 1, \dots, M, \quad (2.8)$$

Equation 2.8 defines a system of M equations with N unknowns, and we can formulate in matrix form as:

$$A \cdot \Phi = \Psi \quad (2.9)$$

where A is an $M \times N$ matrix, $\forall j = 1, \dots, M$, and, $A(j, IS_j) = -1$ if $IS_j \neq 0$, $A(j, IE_j) = 1$ and 0 otherwise. When $\Psi_1 = \varphi_4 - \varphi_2$ and $\Psi_2 = \varphi_3 - \varphi_0$, A will be [43]:

$$A = \begin{bmatrix} 0 & -1 & 0 & +1 & \dots \\ 0 & 0 & +1 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad (2.10)$$

A is an incidence matrix, which is directly depending on the set of interferograms. If $M = N$ or an over-determined $M > N$ system, then the solution can be obtained using Least Square technique [43]:

$$\Phi = A^+ \cdot \Psi = ((A^T \cdot A)^{-1} \cdot A^T) \cdot \Psi \quad (2.11)$$

where A^+ is the left inverse matrix.

Most of the time SAR acquisitions are, coupled in several different subsets and therefore matrix A exhibits a rank deficiency. Because of that $A^T A$ is singular. Therefore we can use the Singular Value Decomposition (SVD) technique to invert the system.

The SVD of matrix A can be written as [43]:

$$A = U \cdot S \cdot V^T \quad (2.12)$$

where U is an M x M orthogonal matrix. S is an M x M diagonal matrix and V is an N X M orthogonal matrix. Using Equation 2.11 and 2.12, we can write the minimum norm least squares solution for Φ as [43]:

$$\begin{aligned} \Phi &= A^+ \cdot \Psi = \\ &= [V \cdot \text{diag}(1/\sigma_1, 1/\sigma_2, \dots, 1/\sigma_{N-L+1}, 0, \dots, 0) \cdot U^T] \cdot \Psi = \sum_{i=1}^{N-L+1} \frac{\psi^T \cdot u_i}{\sigma_i} v_i \end{aligned} \quad (2.13)$$

where u_i and v_i are the column vectors of U and V and σ_i are the singular values.

To avoid any large discontinuities in the cumulative phase (deformation) measurements, mean phase velocities between time adjacent acquisitions were used in the Equation 2.9. Therefore, new unknowns are [43]:

$$\nu_d^T = \left(\nu_{1d} = \frac{\varphi_1 - \varphi_0}{t_1 - t_0}, \nu_{2d} = \frac{\varphi_2 - \varphi_1}{t_2 - t_1}, \dots, \nu_{Nd} = \frac{\varphi_N - \varphi_{N-1}}{t_N - t_{N-1}} \right) \quad (2.14)$$

And we get a new system of equations [43]:

$$B.v_d = \Psi \quad (2.15)$$

where B is an $M \times N$ matrix, which has following elements [43]:

$$B[j, k] = \begin{cases} t_{k+1} - t_k & IS_j \leq k \leq IE_j, \quad \forall j = 1, \dots, M \\ 0 & \text{elsewhere} \end{cases} \quad (2.16)$$

Using SVD technique now we can estimate the unknown mean velocity vector. Moreover, an additional integration step will be needed to calculate the required deformation phases from the vector v_d [43]:

$$\varphi(t_i) = \sum_{k=1}^i \nu_{kd}(t_k - t_{k-1}) \quad \forall j = 1, \dots, N \quad (2.17)$$

with $\varphi(t_0) = 0$

2.3.3.2 PSInSAR and similar time series analysis

Persistent Scatterer Interferometry PSInSAR techniques use point targets to measure the phase difference. The PSInSAR InSAR technique first proposed by Ferretti et al. in 2001 [21]. There are several similar other algorithms which are currently available to perform persistent scatter processing. Those are Stanford Method (StaMPS) [44], Delft Method (DePSI) [45], Maximum Likelihood method (ML-PS) [44] and SqueeSAR method [46]. The PSInSAR and DePSI are based on the same basic principle. In these methods the amplitude dispersion is used to select the persistent scatter points targets based on the normalized backscattered amplitude in a time series image stack [21, 47]:

$$D_a = \frac{\sigma_a}{\mu_a} \quad (2.18)$$

where D_a is the normalized backscatter amplitude, σ_a dispersion of backscatter amplitude and, μ_a mean of the backscatter amplitude.

The Equation 2.18 shows the calculation of the normalized of the backscatter amplitude of a target in the interferogram. The targets with a low normalized amplitude dispersion have selected as good persistent scatter targets since those targets have low phase dispersion [45, 48]. The technique will identify more targets in the urban areas than the areas where there is diffuse scattering. In the StaMPS method, the amplitude characteristic of a target is used to identify a potential targets but only the targets which have stable phase characteristics are selected as the PS targets [39]. This technique will find more targets in diffuse scattering areas compare to the PSInSAR technique. The ML-PS method uses maximum likelihood test to identify Persistent scatter targets. This technique provides more scatter targets for diffuse scattering areas compare to the StaMPS method [44]. The SqueeSAR method uses point targets and distributed scatterers to identify phase stable targets [46].

2.3.3.3 Coherent Target Monitoring (CTM) technique

The coherent target monitoring technique is first developed Vexcel Canada (formerly Atlantis Scientific), and it is a part of the EV-InSAR software package. Currently, MDA is using modified version of this software for their InSAR processing. The CTM processing steps are different from the PSInSAR processing. The CTM module allows processing of the data with different iteration schemes and different parameter deformation models [49]. In CTM processing first, the Differential interferograms were created from the image stack. The coherent targets were identified by removing the mean coherent phase from a pixel block in the interferogram. Normally a pixel block has a size of 200 m x 200 m ground distance. Each pixel in the interferogram has the following phase contributions [49]:

$$\phi_i = \phi_{def} + \phi_{Hgt} + \phi_{Atm} + \phi_{Noise} \quad (2.19)$$

where ϕ_i is the pixel phase, ϕ_{def} is the deformation phase, ϕ_{Hgt} is the phase error related to the height error of targets, ϕ_{Atm} is the phase error related to the atmospheric delays and, ϕ_{Noise} is the phase error due to the thermal noise.

The coherent mean of a pixel block was calculated by assuming that the atmospheric errors, deformation, and the height errors for that block is constant. Therefore, the mean phase can be written for each block as follows [49]:

$$[\phi^{mean}]_{block} = [\phi_{def}^{mean} + \phi_{Hgt}^{mean} + \phi_{Atm}^{mean}]_{block} \quad (2.20)$$

where ϕ^{mean} is the mean phase of the pixel block, ϕ_{def}^{mean} is the mean deformation phase, ϕ_{Hgt}^{mean} is the mean phase error related to the height error and, ϕ_{Atm}^{mean} is the mean phase error related to the atmospheric delays,

Then the mean phase was subtracted from each pixel [49]:

$$\phi_i = [\phi^{mean}]_{block} + \phi_{\Delta Hgt} + \phi_{Noise} \quad (2.21)$$

where ϕ_i is the corrected phase of the pixel, $[\phi^{mean}]_{block}$ is the mean phase of the pixel block, $\phi_{\Delta Hgt}$ is the height error of the pixel relative to the mean height and, ϕ_{Noise} is the thermal noise.

Then temporal coherence was calculated for the stack at each pixel of the block [49]:

$$\rho_i = \left\| \sum_{p=1}^N \exp[j\phi_{i,p} - [\phi_p^{mean}]_{block}] \right\| \quad (2.22)$$

where ρ_i is the temporal coherence of the pixel, N is the number of pixel in the block and, $[\phi_p^{mean}]_{block}$ is the mean phase of the block.

After selecting the coherent targets, the height of the targets was calculated. Then low pass filtered interferogram was created by using the coherent targets and their height information. As the next step, the low pass filtered interferogram was spatially unwrapped. Then phase of the coherent targets were unwrapped by assuming [49]:

$$|\phi_i - \phi_{mean}| < \pi \quad (2.23)$$

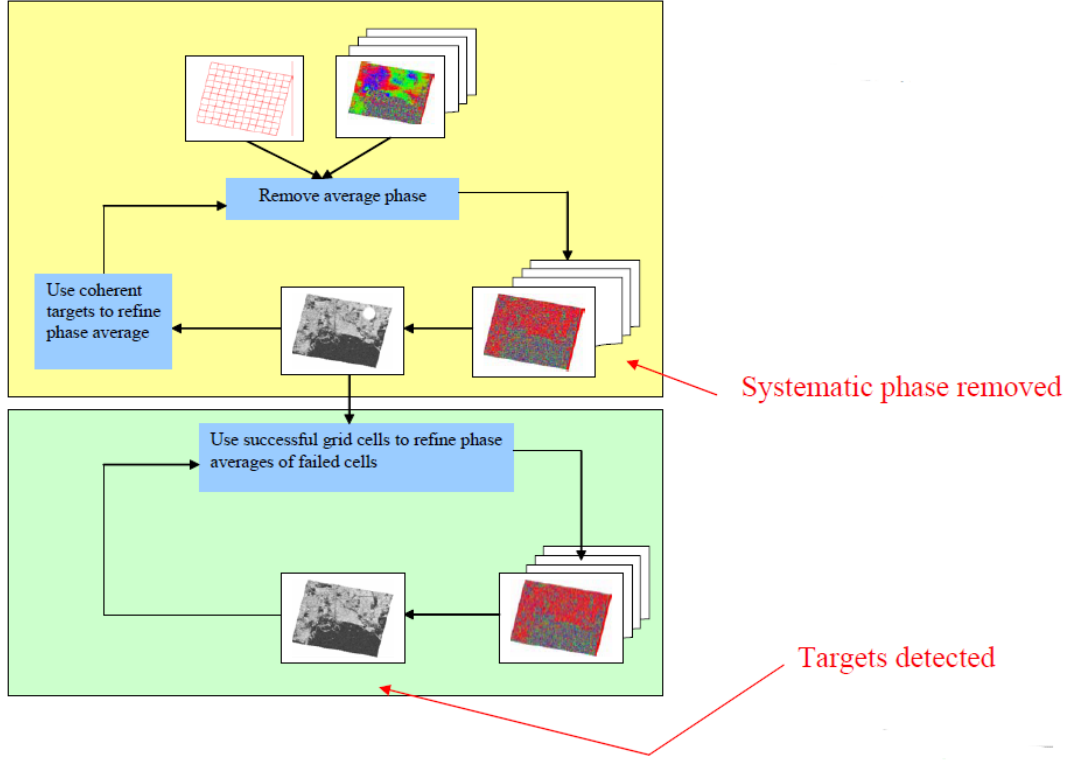


FIGURE 2.7: Coherent targets selection; Here an assumption was made that the phase related to the atmospheric delays, phase errors due to height errors and deformation phase is constant over a Gaussian averaging kernel [49].

where ϕ_i is the unwrapped phase of the coherent target and, ϕ_{mean} is the unwrapped phase of low pass filtered interferogram.

Then the reference phase was calculated from targets that are in the stable area and subtracted it from the target phase. As the next step singular value decomposition (SVD) technique [42] was used to extract the changes in phase over time in the image stack. Finally, deformation maps were created by converting line-of-sight deformation to vertical deformations.

2.3.4 Coherence

When there are two or more complex SAR images (with a temporal baseline), the normalised cross correlation of those images can be calculated to identify the similarity between them. The magnitude of the normalised cross-correlation coefficient is called as the coherence magnitude or the degree of coherence [51]. The coherence magnitude is frequently used as a parameter to measure the phase

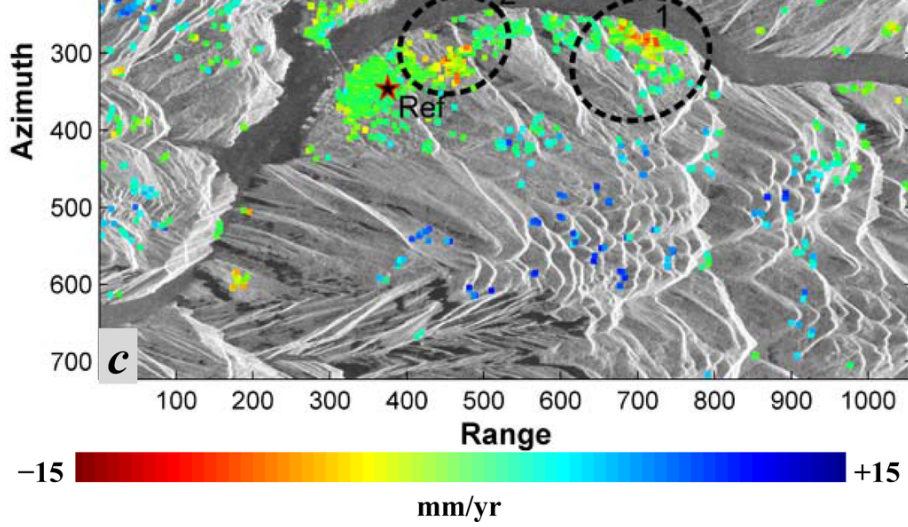


FIGURE 2.8: Typical Coherent targets deformation map. The dots in the map shows the coherent targets. The color bar shows the deformation rate [50].

stability in the interferograms [19]. The normalised coherence of two complex signals can be written as [51, 52]:

$$\gamma = \frac{\langle Z_1 Z_2^* \rangle}{\sqrt{\langle Z_1 Z_1^* \rangle \langle Z_2 Z_2^* \rangle}} \quad (2.24)$$

where γ is the normalised coherence of two complex signals (interferogram), Z_1 and Z_2 are complex values in the master SAR image and the slave SAR image, respectively, and Z_2^* is the complex conjugate of Z_2 . The brackets $\langle \rangle$ indicate a local spatial averaging around an individual pixel. In practice, the magnitude of the normalised complex coherence or degree of coherence ($|\gamma|$) is calculated by coherently averaging the complex values over a finite window [52]. The $|\gamma|$ varies from zero to one. Zero implies the uncorrelation of two signals and one implies the complete correlation of the two signals. Figure 2.5(a) shows a typical coherence image. The $|\gamma|$ can be written as a product of several statistically independent decorrelation factors [53]:

$$|\gamma| = \gamma_{baseline} \gamma_{temporal} \gamma_{thermal} \gamma_{Co-reg} \quad (2.25)$$

where $\gamma_{baseline}$ is the decorrelation due to the perpendicular baseline (across the track distance between two satellite passes). With a baseline optimisation processing step, $\gamma_{baseline}$ can be minimised [54]. $\gamma_{temporal}$ is the temporal decorrelation

of the ground surface and is the main contributor to the $|\gamma|$. γ_{Co-reg} is the decorrelation due to the co-registration errors. $\gamma_{thermal}$ is the decorrelation due to the thermal noise in the SAR sensor, and compared with the temporal decorrelation, this value is very small.

2.4 Ionospheric effect

The presence of the free electrons and ions will be affected to the microwave propagation through the ionosphere. The solar activities will determine the free electron and ion densities. The refractive index for the phase can be written as follows [55]:

$$n \approx 1 - \frac{e^2}{8\pi^2 m_e \varepsilon_0} * \frac{N_e}{f^2} \approx 1 - 40.3 \frac{N_e}{f^2} \quad (2.26)$$

where n is the phase refractive index, e is the charge of the electron, m_e is the mass of the electron, ε_0 is the permittivity of the vacuum, N_e is the electron density and f is the microwave frequency.

The Equation 2.26 shows that the longer wavelength InSAR measurements are more susceptible to ionospheric effects than shorter wavelengths [56].

2.5 Atmospheric effect

Atmospheric effect refers to the phase uncertainties occurring in the interferograms due to atmospheric water vapour. There are two main approaches used to correct the atmospheric effects from the interferograms. The first approach is to use the information available in the interferogram to correct the atmospheric effects. The MDA EVInSAR© (an InSAR processing software developed by MacDonald, Dettwiler and Associates Ltd [MDA], Canada) software uses this approach. The second approach is to use independent measurements or weather models to correct the atmospheric effects. From the weather models, it is possible to calculate the atmospheric parameters (Temperature, pressure, and water vapour) for a given ROI for a given time. In 2001, Shimada et al. reported that accuracy of the deformation estimation for Mt. Fuji, Japan, can be improved from 4 cm to 2 cm with the information from the European centre for medium range weather forecasts (ECMWF) model [57]. Also, in 2000, Shimada et al., in 2006, Foster et

al., in 2007, Puyssgur et al. and in 2008, Pinel et al. reported the usefulness of weather models to improve InSAR measurements [57–60].

The main Disadvantage of the weather model is the limited spatial resolution. These weather models have resolutions in kilometer-scale. However, most of the ROIs for InSAR measurements can be few tens of square kilometers. Also accuracy of the weather models will depend on the physics of the model and the initial parameters [58, 61].

Spatial and temporal inhomogeneity in the troposphere will introduce additional phase to the measurements. In 1997, Zebker et al. argued that the main contributor to the tropospheric delay is the water content in the troposphere [62]. Also, they have pointed out that there can be a phase error due to the pressure and temperature variations, but those are insignificant compared to the error induced by the tropospheric water vapour. Also, the phase errors due to the pressure and temperature can be considered as spatially homogeneous for a small area. Therefore, the topographic error mitigation is mainly focused in removing the phase error induced by the water vapour. Also, they have found that tropospheric water vapour can induce up to 10 cm error to the measurements [62]. In 2001, Hassen et al. reported that thunderstorms during SAR acquisitions can induce phase delays up to 12 cm [63].

2.6 Corner reflectors

Corner reflectors are used to reflect the radar waves back to the satellite. Therefore, the corner reflectors appear as bright targets in the SAR images. Larger the corner reflector, the radar cross section will be large and appear as brighter in the backscatter image. In subsidence measurements corner reflectors are often used as high coherent point targets and CRInSAR measurements have been well-documented for low-latitude regions [48, 64, 65]. The most popular corner reflector design is the triangular trihedral design. Although the large corner reflectors give strong backscattering, manufacturing and deploying is not easy and may lead to errors [24]. In 2001, Donald et. al. has reported that, if the difference of the backscatter power between the corner reflector and the background is larger than 29 dB, then corner reflector can be clearly identified in the Radar image. Moreover, if the above difference falls down below 12 dB, then the corner reflector is difficult

to identify from the background [24]. For this experiment, authors used Radarsat-1 images.

Corner reflector face should be aligned perpendicular to the satellite track. Figure 2.9 shows a typical corner reflector installed in the field.



FIGURE 2.9: A corner reflector installed in the field [66]

2.7 Effects of snow

All InSAR deformation measurement techniques (DInSAR, CTM, PSInSAR, CRInSAR etc.) have been proven for low-latitude areas, but the accuracy of these techniques for high latitude areas needs to be investigated.

The propagation speed and the angle of the radar waves will depend on the refraction index of the snow. In 1986, Sadiku et al. introduced following equations to measure the refraction index of a snow pack [67]. These equations are valid for radar frequencies between 0.8 GHz and 38 GHz.

For $P_s < 0.500 \text{ kgm}^3$

$$n_s = (1 + 1.9 * P_s)^{0.5} \quad (2.27)$$

and For $P_s > 0.500 \text{ kgm}^3$

$$n_s = (0.51 + 2.88P_s)^{0.5} \quad (2.28)$$

where, n_s is the Refraction index of snow, P_s is the density of snow (kg m^{-3}).

In 2004, Yankieluna et al. reported that the refractive index of the snow pack is strongly dependent on wetness of the snow pack [68]. In 1991, Elder et al. has reported that the snow is a layered medium and as same as the whole snow pack each layer differ in thickness and density from site to site. Therefore, the snow density and refractive index vary both horizontally and vertically within the snow pack [69]. Therefore, these density differences will affect to the velocity and the propagation angle of the radar waves when they travel through the snow pack. Ultimately these effects will add additional noise to the deformation measurements.

In high latitudes, during most of the months of the year, the ground is covered with snow. Due to precipitation, wind conditions, and topography, the height and density of the ground snow layer is not spatially or temporally uniform. The ground snow layer will affect the backscatter signal in a few different ways. The first is that, within the snow layer there will be volumetric scattering. This gives rise to differences in the volumetric scatter signal from a pixel to pixel due to the phase changes undergone by the scatter signal. The second is due to the refraction of the radar signal on the snow surface. The signal will illuminate the ground in a different incident angle which leads to a change in phase in adjacent pixels. The third is, the presence of wet snow on the ground will prevent radar waves from reaching the ground [70]. In 2004, Engen et al. reported that (for C-band SAR images with an incidence angle of 23°) a dry snow layer of approximately 16.4 cm (snow density of 200 kg m^{-3}) will introduce a phase difference of 2π to the interferogram [71]. In 2005, Martinez-Vazquez' et al. reported that the coherence in a C-Band radar signal will be lost within a short period due to the changes in snowpack properties. Also, he reported that this coherence loss will be accelerated if there is snow fall taking place [72]. Therefore, even without any surface deformation, snow-covered regions that are only a few meters apart could still show considerable phase differences (unstable phase components) in the interferograms. Hence, identifying and removing these unstable phase components are important to achieve high accuracy measurements. In InSAR deformation measurements, coherence is used to select the stable scatterers to achieve better accuracy [53]. In most cases, the snow covered area will have low coherence and will appear as black color in a coherence image.

In 2010, Jung et al. used coherence as a parameter to study the seasonal water fluctuations in the Amazon flood plain [73]. Few studies have been performed to quantify the seasonal variations in InSAR measurements in high latitudes with regard to deformation measurements. In 1999, Budkewitsch et al. reported that in the Canadian Arctic coherence loss will take place due to compaction or recrystallization of snow packs, accumulation of snow in the drifts and migration of snow drifts [74]. In 2010 Liu et al. used the InSAR technique to detect seasonal and secular surface subsidence over the tundra areas relative to the floodplain areas on the North Slope of Alaska and they have reported seasonal subsidence of 14 cm related to melting of ice in the active layer [75]. In 2001, Weydahl used coherence as a parameter to study the seasonal variations in the ERS Tandem SAR images in glaciers, valleys, and fjord ice in Svalbard [52], and he concluded that the usefulness of the Envisat repeat-pass InSAR measurements in Svalbard is limited due to the temporal decorrelation caused by precipitation and temperature changes.

2.8 3D ground movements

In the past InSAR has been used to monitor volcanic activity [39], mine-induced ground subsidence, earthquakes, and seasonal subsidence [76], among other cases. In these cases, the ground movement is typically studied from a single track of SAR data. That is, a single area is imaged over time from a single imaging geometry. By collecting imagery this way, accurate measurements (typical accuracy of 3 mm) of the line-of-sight change can be collected and understood [48]. In cases where the nature of the ground deformation can be understood from other sources, for instance in an enhanced oil recovery operation, the line-of-sight measurement can be understood to provide the vertical component of ground motion [65]. However, when more complicated motion is known to occur, as is the case with a slope slide, a single line-of-sight measurement may not capture the actual motion. When the motion is both down and along the slope, a single line-of-sight measurement can confuse the ground deformation. In the worst case scenario, if the ground motion is both horizontally toward the radar and down, a single line-of-sight measurement could interpret no motion at all. However, when complementary incident angles are considered, the line-of-sight information can be rotated to provide a horizontal and vertical component of motion. This is accurate when the available incident angles are chosen to be orthogonal and hence form a basis for the two-dimensional

vector space. In the case when three orthogonal beams can be chosen to image a single area, a full description of the vertical, horizontal, and lateral motion can be available [77]. This, however, occurs only in very limited cases with the current set of polar orbiting SAR satellites [77].

2.8.1 North-South InSAR accuracy

Observations of ground movement around mines are very complex. The observed ground deformation may take the form of both subsidence and horizontal or lateral movement. Many attempts have been made to augment standard InSAR measurement techniques to provide a North-South component of motion. The most direct method would be to orthogonally image the same area with three coincident SAR sensors. This technique was applied to ice motion in the Canadian North by Mohr et al. [78]. In his work, he showed that the ice motion may be inferred in very high latitudes. The technique is, however, not applicable to lower latitudes due to the nature of polar orbiting SAR satellites [77, 79]. In the case of RADARSAT-2, the left and right looking characteristics of the satellite might be used to increase the degree of orthogonality of image tracks lower down to say 60° but the operational cost of monitoring with a constant change in look direction is prohibitive. Further attempts in understanding a North-South motion component have come from the look separation technique known as multi-aperture interferometry (MAI). This technique is described by Jung et al. [80] and more recently augmented by Jung et al. [38]. In the case of the MAI, the sensitivity of the measurement has been demonstrated to many centimeters; a measurement thought to be too coarse for creating boundary conditions for geo-mechanical models of rock movement due to underground mining. Other techniques have concentrated on the inclusion of multiple observation points from a combination of InSAR and GNSS systems [81, 82]. These methods have provided wide area surfaces that provide excellent information on the scale of an earthquake.

Chapter 3

Seasonal effects on DInSAR measurements

3.1 Introduction

This chapter presents the results of a study conducted to quantify the seasonal variation of coherence in Synthetic Aperture Radar (SAR) interferograms in Kiruna, Northern Sweden.

The InSAR measurement relies on the presence of scatterers that have stable properties over the timescale of interest. There are several InSAR techniques that can be used to measure the ground deformation based on the spatial and temporal availability of these scatterers. The simplest InSAR technique is the DInSAR technique, which can deliver an accuracy of approximately 1 cm/year [19]. This technique works well in barren flat landscapes where a large number of spatially distributed scatterers are available.

In SAR interferometry (InSAR), coherence is an important concept that provides a good indication of the phase stability of the scatterers [83]. Therefore, in this study, the degree of coherence is used as a parameter to identify the seasonal variation in interferograms.

For this study, 34 Radarsat-2 ultra-fine beam mode (U6D) images of the Kiruna area (67°51'N, 20°14'E) and the improved Digital Elevation Model (DEM) created by merging the Radarsat-2 DEM and ASTER DEM were used to produce 561

differential interferograms. The interferograms were arranged in three different ways for the analysis, with the first including common master interferograms (with the summer master image), the second including the sequential interferograms that have the shortest temporal baseline and the third accounting for all possible combinations of the interferograms (full network of interferograms). Following this step, the variation of coherence for forest areas, urban areas and flat waste rock areas were studied. This study shows that interferograms generated for the Kiruna region exhibit seasonal variations in coherence due to the ground snow layer in winter. Furthermore, when there is water on the ground due to the melting of the snow layer (in the spring) or due to rains in autumn, the coherence is reduced considerably. Another significant feature is that there is a significant change in summer-to-summer coherence for some regions even over the course of a few years. Based on this study, it is clear that the winter Radarsat-2 U6D beam mode images are not suitable for DInSAR deformation measurements in flat waste rock regions in Kiruna. It is expected that even with winter images, PSInSAR or CTM techniques will be able to provide better deformation measurements, but, in this study those techniques were not assessed.

In this work, for the first time, the seasonal variation in repeat-pass, high resolution (2.7 m slant range resolution) Radarsat-2 interferograms for Kiruna, Northern Sweden was quantified. The parameter used to quantify the seasonal variation is the coherence magnitude (degree of coherence) in the interferograms. Furthermore, the annual useful number of Radarsat-2 U6 images that should be used for the Kiruna deformation measurements was quantified.

3.2 Test site

The test site (Figure 3.1) is located in northern Sweden (67°51' N, 20°14' E) around Kiruna city and the Kiruna underground iron ore mine, which is owned by the Luossavaara Kiirunavaara Aktiebolag (LKAB) mining company. The mine is approximately 1 km (to the west side) from Kiruna. Kiruna is a small city with an area of approximately 3 km² consisting of small and medium size buildings, roads, open areas with grass cover, and trees between the buildings (Figure 3.4). Most of the small buildings have slanting roofs, and most of the large buildings have flat roofs. During the winter, most of the rooftops are either fully or partially

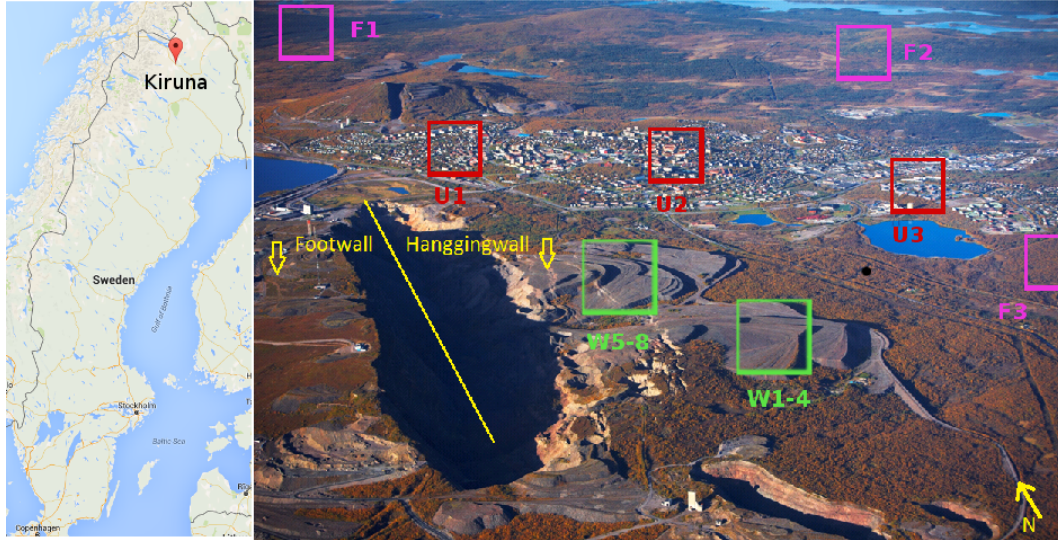


FIGURE 3.1: Left image shows the location of the Kiruna iron ore mine. Right optical image shows the Kiruna iron ore mine, Kiruna city and surroundings in the autumn. Here, selected waste rock areas are marked in green boxes, selected urban areas are marked in red boxes, and selected forest areas are marked in purple boxes (image source: LKAB and Google maps).

covered with snow. The roads and ground in between the buildings are also snow-covered (Figure 3.5). The height and density of the ground snow layer changes spatially and temporally due to the topography, precipitation, wind and human interactions. Kiruna is flanked by forest (such as the F1, F2, F3 areas in Figure 3.1), and forest areas also occur in the regions lying between the mine and the city. The trees grow up to a height of 3 or 4 meters, and the trunks have a diameter ranging from 15–30 cm (Figure 3.6). The leaf growth is very rapid during the spring and summer seasons due to the longer day lengths. Leaf fall occurs during autumn. During the winter, Kiruna experiences heavy snowfalls with the ground snow cover reaching up to 1 m or more in height in the forest areas (Figure 3.7). The height and density of snow in these areas are mostly uneven due to wind and also due to animal and human activities (e.g., ski tracks and road clearing). Barren and flat waste rock areas (such as the W 1–8 areas in Figure 3.1) are common in the hangingwall (the side that the ground rock overlays on the iron ore body) and footwall (the side that the ground rock underlays the iron ore body) sides of the mine. Such areas have been created from the deposition of waste rocks from ore processing (Figure 3.2). The ground snow cover in these areas can be as high as 1 m in winter (Figure 3.3). Here too, the precipitation, topography and wind cause spatial and temporal changes in the height and density of the snow layer. The winter temperatures in Kiruna are not always sub-zero. There are days when

the temperatures are above freezing. These temperatures can initiate the melting of snow and layering in the ground snow cover. For this study, fourteen sample areas were selected in the test site for the analysis, such that three sample areas (F1, F2, and F3 in Figure 3.1) have dominant volumetric scattering (forest area), three (U1, U2, and U3 in Figure 3.1) have dominant dihedral type of scattering (urban areas) and eight (W 1–8 in Figure 3.1) have dominant diffuse scattering (barren waste rock area). The selected forest and urban areas do not exhibit any deformations, but the barren waste rock areas were observed to have surface deformations. Because there were no stable (where there are no deformations) barren and flat areas in the test site, the waste rock areas on the hangingwall side were used. The sample areas W 5–8 were selected to be closer to the mine than the sample areas W 1–4, and therefore the sample areas W 5–8 experience larger surface deformations than the sample areas W 1–4.



FIGURE 3.2: Kiruna waste rock area in summer.



FIGURE 3.3: Kiruna waste rock area in winter.



FIGURE 3.4: Kiruna urban area in summer.



FIGURE 3.5: Kiruna urban area in winter.



FIGURE 3.6: Kiruna forest area in summer.



FIGURE 3.7: Kiruna forest area in winter.

3.3 Methodology

For this study, 34 Radarsat-2 U6D beam mode (from 2008-06-14 to 2010-12-13) images were used. The slant range resolution of the images is 2.7 m. EVInSAR was used for the InSAR processing, and an external DEM was used as an input to the processing chain. MDA provided the DEM. The DEM was created by merging a Radarsat-2 DEM with the ASTER DEM. By merging the Radarsat-2 DEM with the ASTER DEM, the height errors of the DEM were minimized. The first image of the image stack (taken on 2008-06-14) was selected as the master image, and the remaining images and the DEM were co-registered to the master image. A total of 561 raw interferograms (see example in Figure 3.15) were then produced by multiplying one image with the complex conjugate of the other images for all possible image pair combinations. In this interferogram stack, there were 33 common master interferograms (with the 2008-06-14 master image) and 33 sequential interferograms. As the next step, the topographic phase and flat earth phase were removed from the raw interferograms by using the DEM. Based on the technique introduced by Bähr et al. [54], iterations were performed

to minimise the decorrelation effects due to incorrect baseline measurements. The atmospheric phase screens were generated by using the following procedure: First the high-frequency deformation areas in the ROI were masked out. Then a 2D low-pass filter was used to preserve the atmospheric phase and to remove any high-frequency noise from the interferogram. Then the atmospheric phase was interpolated into the masked area. Then the interpolated atmospheric phase was removed from the interferogram.

The next step was to produce the coherence images for the test site. A 5 x 5 pixel moving window (8 m x 14 m) was used for the coherence magnitude (degree of coherence) calculation, which is based on Equation 2.24. As the next step, the coherence images were arranged in 3 different sets (Common master, Sequential and Full network). In the common master coherence images, all the images had the same master image (2008-06-14) and were arranged according to the ascending order of their temporal baseline. Table 3.1 shows the details of the common master coherence image set. In the sequential method, coherence images having a minimum temporal baseline were selected and arranged in ascending order of their master image dates. Table 3.2 shows the selected sequential coherence images. There is a 72-day time break in the image stack and this time break is marked as a black color line in the Figure 3.10. As the next step, the average coherence magnitude was calculated for each test area. Then the average coherence magnitude was plotted against each interferogram. In the full network analysis, the average coherence magnitude was calculated for each test area, and the coherence magnitudes were arranged in an upper triangular matrix. The rows and columns of the upper triangular matrix are the respective master and slave image acquisition dates arranged in ascending order. The coherence magnitude is shown, based on the colour bar.

Int No	Master Image	Slave image	Parallel Baseline (m)	Perpendicular Baseline (m)	Temporal Baseline (days)	Ground condition (Master)	Ground condition (slave)
1	20080614	20080708	-109.38	-102.91	24	Dry	Dry
2	20080614	20080801	-147.54	-49.83	48	Dry	Dry
3	20080614	20080825	-290.87	-295.37	72	Dry	Dry
4	20080614	20080918	-249.33	-245.58	96	Dry	Wet
5	20080614	20081105	-316.87	-231.68	144	Dry	Snow
6	20080614	20081129	-270.09	-65.29	168	Dry	Snow
7	20080614	20081223	-286.21	-113.32	192	Dry	Snow
8	20080614	20090116	-304.24	-179.96	216	Dry	Snow
9	20080614	20090209	-117.36	-65.26	240	Dry	Snow
10	20080614	20090305	-425.07	-488.31	264	Dry	Snow
11	20080614	20090329	-265.44	-244.88	288	Dry	Snow
12	20080614	20090422	-69.83	-41.23	312	Dry	Wet snow
13	20080614	20090703	-31.87	-61.35	384	Dry	Dry
14	20080614	20090820	-78.01	-15.55	432	Dry	Dry
15	20080614	20090913	-319.07	-329.21	456	Dry	Dry
16	20080614	20091007	-233.40	-116.99	480	Dry	Snow or Ice
17	20080614	20091031	-341.43	-247.99	504	Dry	Snow
18	20080614	20091124	-276.17	-139.70	528	Dry	Snow
19	20080614	20091218	-132.28	-89.42	552	Dry	Snow
20	20080614	20100111	-305.91	-207.18	576	Dry	Snow
21	20080614	20100204	-386.73	-331.74	600	Dry	Snow
22	20080614	20100228	-190.88	-48.73	624	Dry	Snow
23	20080614	20100324	-255.85	-231.48	648	Dry	Snow
24	20080614	20100417	-123.77	-66.07	672	Dry	Wet snow
25	20080614	20100511	-62.12	-7.33	696	Dry	Wet snow
26	20080614	20100604	-75.59	-9.45	720	Dry	Dry
27	20080614	20100628	-30.38	-79.03	744	Dry	Dry
28	20080614	20100815	-226.63	-261.04	792	Dry	Dry
29	20080614	20100908	-214.25	-194.91	816	Dry	Dry
30	20080614	20101002	-308.02	-235.16	840	Dry	Wet
31	20080614	20101026	-262.47	-124.14	864	Dry	Snow
32	20080614	20101119	-242.65	-85.22	888	Dry	Snow
33	20080614	20101213	-238.50	-68.44	912	Dry	Snow

TABLE 3.1: Common master interferograms.

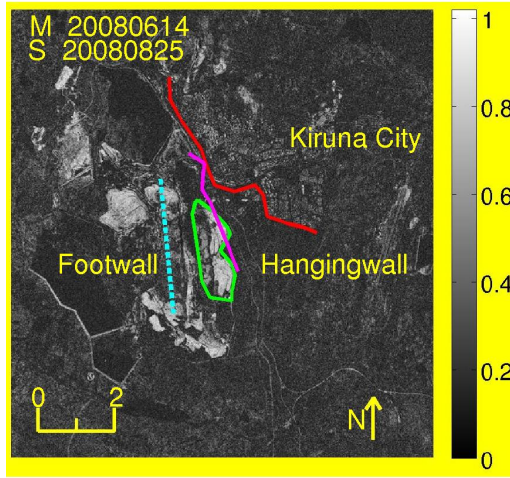
Int No	Master Image	Slave image	Parallel Baseline (m)	Perpendicular Baseline (m)	Temporal Baseline (days)	Ground condition (Master)	Ground condition (slave)
1	20080614	20080708	-109.38	-102.91	24	Dry	Dry
2	20080708	20080801	-38.16	-53.08	24	Dry	Dry
3	20080801	20080825	-143.31	-245.54	24	Dry	Dry
4	20080825	20080918	-41.53	49.80	24	Dry	Dry
5	20080918	20081105	-67.54	-13.88	48	Dry	Snow
6	20081105	20081129	-46.69	166.42	24	Snow	Snow
7	20081129	20081223	-16.09	-48.05	24	Snow	Snow
8	20081223	20090116	-17.98	-66.63	24	Snow	Snow
9	20090116	20090209	-186.75	245.35	24	Snow	Snow
10	20090209	20090305	-307.69	-553.61	24	Snow	Snow
11	20090305	20090329	-159.53	243.49	24	Snow	Snow
12	20090329	20090422	-195.56	286.17	24	Snow	Wet snow
13	20090422	20090703	-37.95	20.09	72	Wet snow	Dry
14	20090703	20090820	-46.12	-76.88	48	Dry	Dry
15	20090820	20090913	-241.03	-313.64	24	Dry	Dry
16	20090913	20091007	-85.54	212.22	24	Dry	Snow or Ice
17	20091007	20091031	-107.89	-130.89	24	Snow or Ice	Snow
18	20091031	20091124	-65.14	108.24	24	Snow	Snow
19	20091124	20091218	-143.76	229.18	24	Snow	Snow
20	20091218	20100111	-173.41	-296.60	24	Snow	Snow
21	20100111	20100204	-80.73	-124.63	24	Snow	Snow
22	20100204	20100228	-195.48	282.98	24	Snow	Snow
23	20100228	20100324	-64.83	-182.73	24	Snow	Snow
24	20100324	20100417	-132.04	165.55	24	Snow	Wet snow
25	20100417	20100511	-61.68	73.50	24	Wet snow	Wet snow
26	20100511	20100604	-13.46	-2.10	24	Wet snow	Dry
27	20100604	20100628	-45.20	69.61	24	Dry	Dry
28	20100628	20100815	-196.20	-340.14	48	Dry	Dry
29	20100815	20100908	-12.34	66.12	24	Dry	Dry
30	20100908	20101002	-93.79	-40.36	24	Dry	Wet
31	20101002	20101026	-45.50	111.11	24	Wet	Snow
32	20101026	20101119	-19.81	38.97	24	Snow	Snow
33	20101119	20101213	-4.10	16.72	24	Snow	Snow

TABLE 3.2: Sequential interferograms.

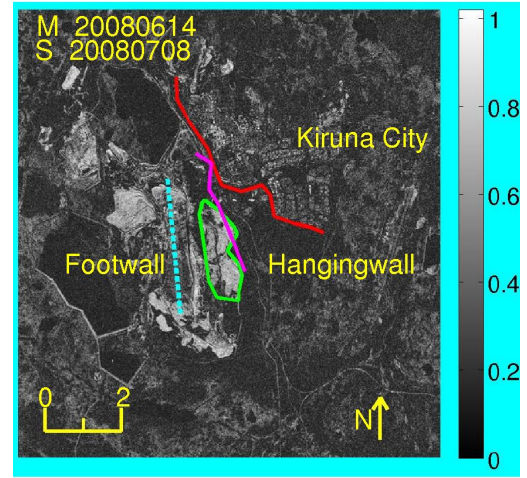
3.4 Results

Figures 3.8(a), 3.8(b), 3.8(b) and 3.8(d) show the variation of the coherence magnitude (degree of coherence) in the test site for the common master (yellow border) and sequential interferograms (cyan border). Based on the common master coherence images, the coherence magnitude is clearly reduced in the winter and regained in the summer. In the sequential coherence images, a high coherence magnitude can be observed in the summer and some winter interferograms. Appendix A presents all coherence images produced for the test site.

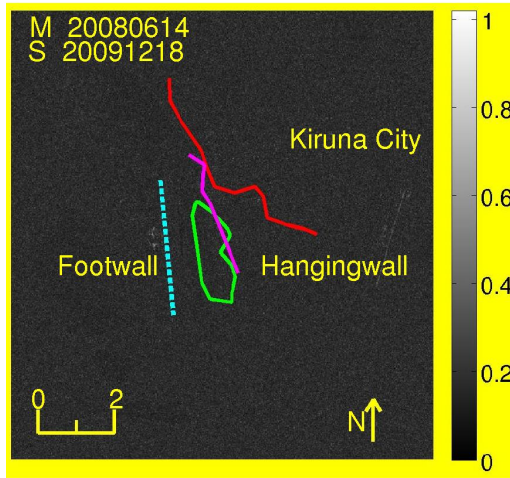
Figure 3.9 shows the average coherence variation for each sample area for the common master interferograms, and Figure 3.10 shows the same for the sequential interferograms. Figure 3.11, 3.12, 3.13 and 3.14 shows the coherence variation in the full network analysis for forest areas (F 1–3), urban areas (U 1–3), waste rock areas (W 1–4) and waste rock areas (W 5–8).



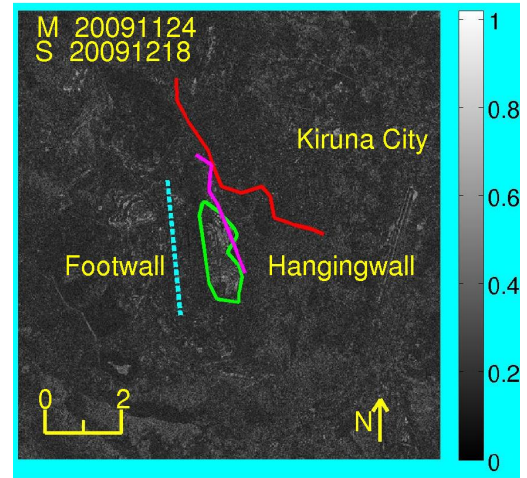
(a) Coherence image from a common master summer interferogram.



(b) Coherence image from a sequential summer interferogram.



(c) Coherence image from a common master winter interferogram.



(d) Coherence image from a sequential winter interferogram.

FIGURE 3.8: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the LKAB industrial area limit. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.

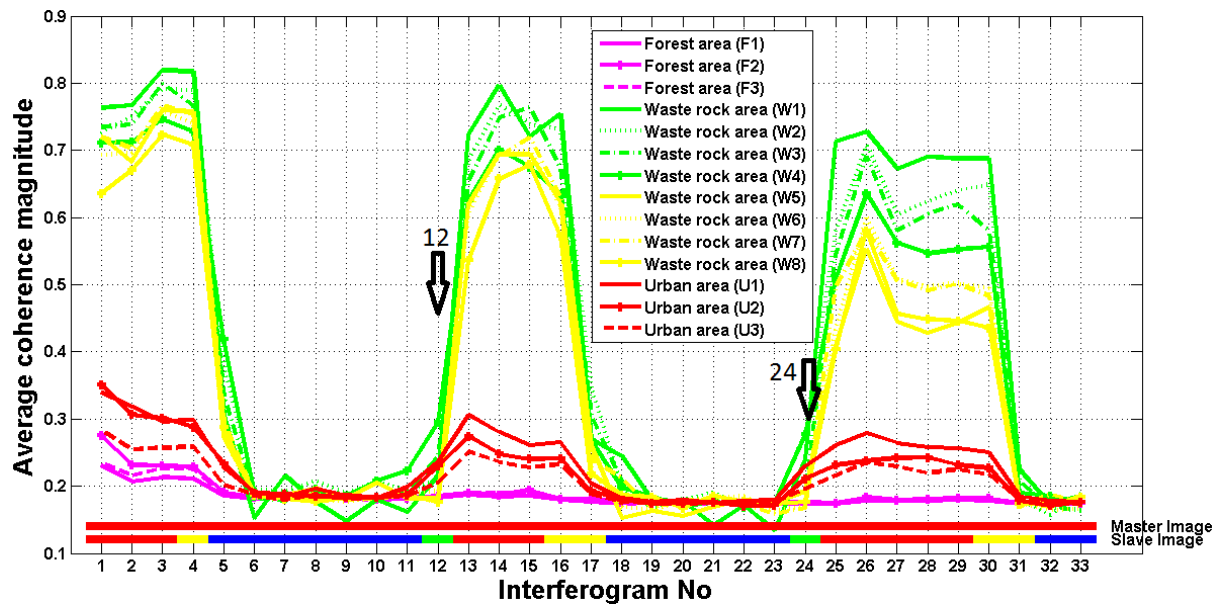


FIGURE 3.9: Coherence variation in common master interferograms for all test areas. In the color bar, red is summer (no snow), blue is winter (with snow), green is spring and yellow is autumn.

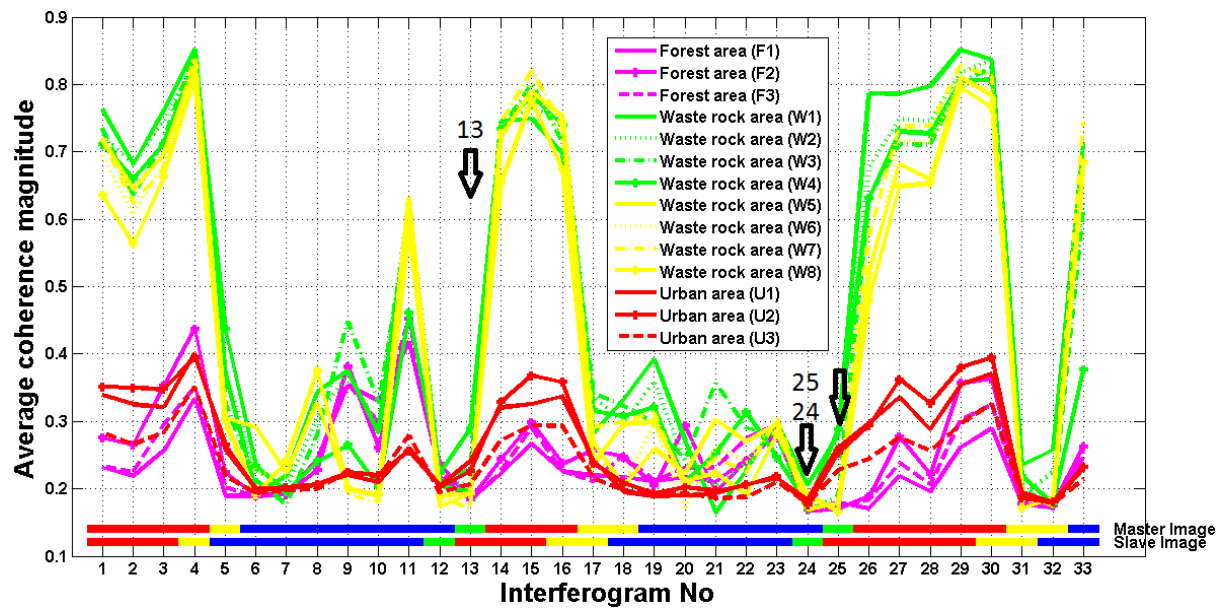


FIGURE 3.10: Coherence Variation in sequential interferograms for all test areas. In the color bar, red is summer (no snow), blue is winter (with snow), green is spring and yellow is autumn.

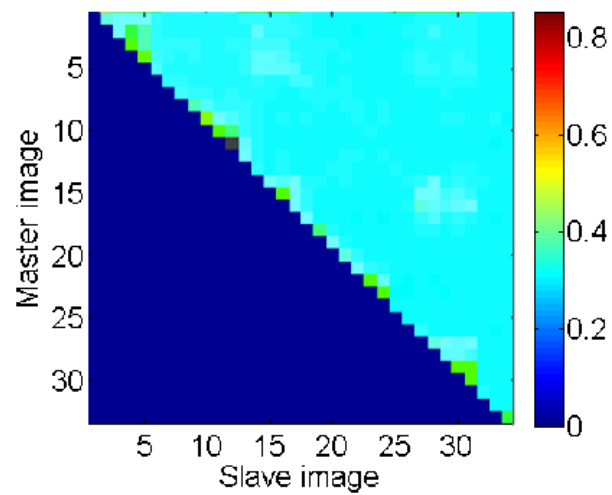


FIGURE 3.11: Coherence variation in all interferograms (full network) for forest area (F 1–3).

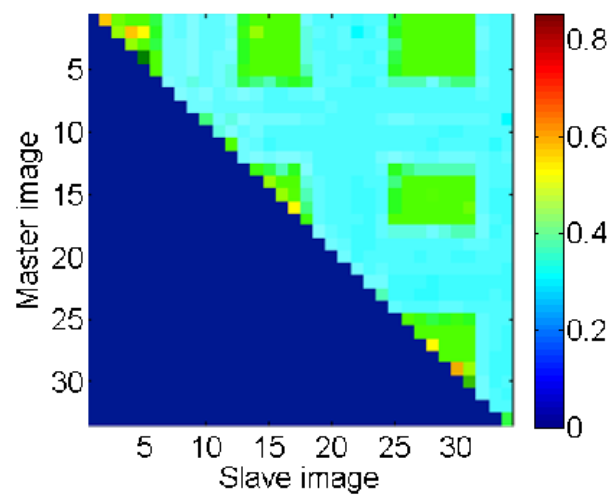


FIGURE 3.12: Coherence variation in all interferograms (full network) for urban area (U 1–3).

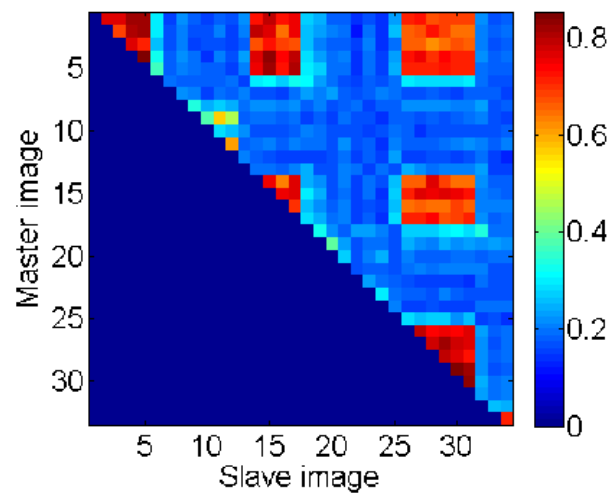


FIGURE 3.13: Coherence variation in all interferograms (full network) for waste rock area (W 1–4).

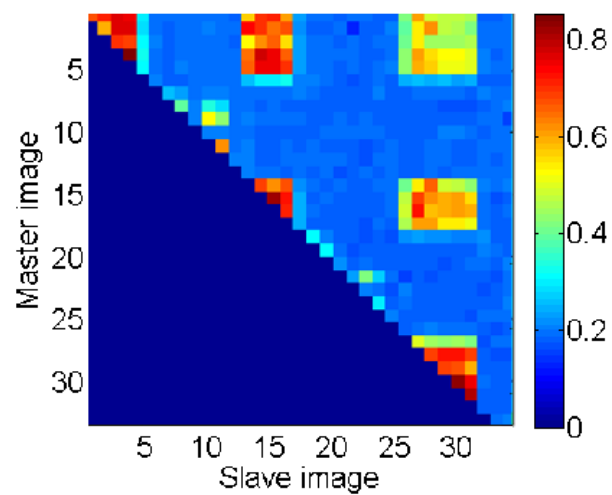


FIGURE 3.14: Coherence variation in all interferograms (full network) for waste rock area (W 5–8).

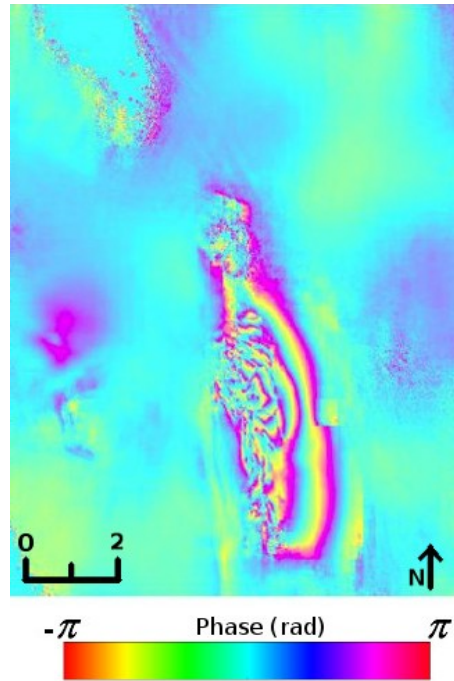


FIGURE 3.15: An example summer interferogram for the Kiruna area (image scale in kilometers).

3.5 Discussion

Seasons will always have an impact on the topographic features, which leads to changes in the coherence.

3.5.1 Seasonal aspects

During the short (2–4 months) summer, the test site experiences almost 24 hours of daylight during some weeks. As a result, the growth rate of vegetation is very high, leading to rapid changes in the forest areas. Therefore, the summer master and summer slave interferograms from images that are only a few months apart show poor coherence. This observation is found to be true for both the common master (coherence magnitude < 0.19) and sequential (coherence magnitude ≈ 0.22 – 0.39) interferograms (Figure 3.9 and 3.10). The barren flat waste rock areas show the highest coherence (coherence magnitude ≈ 0.7 – 0.8) during the summer season as observed in both the common master and sequential interferograms (Figure 3.9 and 3.10). The urban areas show slightly higher coherence (coherence

magnitude ≈ 0.28 in the common master interferograms and ≈ 0.25 – 0.41 in the sequential interferograms) compared with the forest areas and relatively lower coherence compared with the barren and flat waste rock areas (Figure 3.9 and 3.10).

In the spring (April to the beginning of June) and autumn (mid-August to the beginning of October) seasons, it is observed very low coherence (coherence magnitude < 0.2) for all sample areas, even for shorter temporal baselines. This finding is due to the very short duration of spring and autumn in the region, during which rapid changes occur. For example, in Kiruna, the snow begins to melt at the beginning of April and is completely melted by the end of May. During that period, the surface water content is very high in the urban and waste rock areas. However, in the forest areas, the snow melt starts in April and is completed by the end of June. These changes can be observed in Figure 3.10, interferograms 13 and 25 and Figure 3.9, interferograms 12 and 24, respectively. If there is thick snow cover on the ground, the snow melt can take up to 2 months or more. During that period, the achievable coherence is very low, which can be observed in the forest areas (Figure 3.10, interferograms 24 and 25) and the waste rock areas (Figure 3.10, interferograms 24 and 25). This observation cannot be made for the urban areas (Figure 3.10, interferogram 25) because there is no accumulation of snow in the urban areas due to snow ploughing.

In the autumn, it can observe very rapid changes in the landscapes. In the forest and urban areas, the leaves fall from the trees and are deposited on the ground. Kiruna receives rain during autumn, and towards the end of autumn, the first snowfall is expected. The fallen snow melts after a couple of days, creating a wet surface that, for the forest, will lead to elongated wetness due to the leaf litter. All these factors tend to change the ground conditions rapidly, and it is consequently observed very low coherence in the autumn for all the test areas (Figure 3.9, interferograms 17 and 31). In the forest areas, the wind is also acting as a major source of de-correlation. In the summer decorrelation occur due to the shading of the tree leaves and in the winter, decorrelation occur due to the movement of the snow surface. With a repeat cycle of 24 days, Radarsat-2 can take 15 images annually for the ROI, and of those only 7 images can be used for the DInSAR deformation measurements in the flat waste rock areas (high coherence interferograms in Figure 3.9). Figure 3.15 shows a summer high coherence interferogram produced using Radarsat-2 U6D beam mode images. Here, the deformation in the

waste rock area is clearly seen, but the deformation in the Kiruna city area is not clearly visible. The PSInSAR or CTM techniques can provide better deformation measurements especially for the city area, but in this study those techniques were not assessed.

3.5.2 Common master interferograms

In the common master interferograms having a summer master image, there was a high coherence in the summer season but poor coherence during the winter. Waste rock area 1 showed the highest coherence, which is approximately 0.8 and drops to approximately 0.7 after two years. Waste rock area 8 showed a coherence of approximately 0.72 in the first summer, which then dropped to approximately 0.45 after two years. Because waste rock area 8 lies closer to the mine than waste rock area 1, waste rock area 8 experiences larger surface deformation, thereby causing its coherence to drop faster than that of waste rock area 1. Waste rock areas 2–7 also show similar patterns in their coherence changes.

In the common master interferograms, the urban areas lose coherence in the winter, and even with a longer temporal baseline, they will regain a large part of the coherence during the summer (Figure 3.9). However, there was a clear drop in coherence with a longer temporal baseline. When considering the urban areas, it must be remembered that these areas represent a great variety in landscapes, such as open grass-covered areas, grounds between the buildings, roads and trees and that these landscapes are subject to changes over longer temporal baselines. Therefore, these areas exhibit a drop in coherence but no surface deformation over a longer temporal baseline. The different values of coherence for urban areas 1, 2, and 3 can be attributed to the variation of the landscapes in the regions of interest.

In the common master interferograms, the forest areas lost coherence (Figure 3.9) with an increase in the temporal baseline. There was also no regain of the coherence as the temporal baseline increased. Interestingly, even the summer-to-summer common master interferograms showed very low coherence.

3.5.3 Sequential interferograms

In the sequential interferograms, waste rock areas 1–8 (Figure 3.10) showed a seasonal variation in the coherence, but it differed from the common master interferograms. During the summer months, the interferograms had the highest coherence (0.8) with almost the same magnitude. The reason for this observation is that, in the waste rock areas, there are no features that are prone to any type of change during the summer months (although subsidence does occur in the waste rock areas, the rate of the surface deformation is too small to show any changes in the coherence). The winter interferograms showed fluctuations and even high coherence (0.6) values in the winter. The main reason for this observation is the unchanged snow surface between the two radar image acquisitions.

The sequential interferograms for the urban areas (Figure 3.10) showed similar coherence changing patterns as the waste rock areas during the summer, but with lower values (0.3–0.4). The lower values in the summer are due to the variations occurring in the landscape (trees, grass cover and open areas) between the two radar image acquisitions. The winter sequential interferograms showed lower coherence values (< 0.25) in the urban areas compared with the waste rock and forest areas. The reason for this observation is that there are rapid changes occurring in the snow surface due to human activities (e.g., snow ploughing).

The sequential interferograms showed that the forest areas had relatively high (0.5) but fluctuating coherence during the winter season. These relatively higher changes are due to similar snow conditions on the ground between the two acquisitions. Because the coherences had higher fluctuations during the winter, it is possible to eliminate the change in the scattering mechanism (volumetric scattering in the tree leaves or dihedral scattering from the tree trunks) as the main contributor to these changes and instead confirm snow as the main contributor.

3.5.4 Full network analysis

Based on the full network analysis (Figure 3.13), it is clearly visible how the seasonal variation in coherence occurs for all possible combinations of the interferograms, and the common master interferograms with a winter master image clearly have poor coherence (< 0.2) in both the summer and winter. Hence, this

full network analysis showed the importance of the inclusion of a summer master image in the DInSAR interferograms.

3.6 Conclusion

The interferograms developed for Kiruna region with a summer master image shows a clear seasonal variation in coherence. The master image should be a summer image to generate high spatial coherence interferograms. Even with a longer temporal baseline, the summer-to-summer interferograms for the barren and flat waste rock areas provide almost the same coherence. Therefore, the summer-to-summer interferograms are the most suitable for subsidence measurements. Forest areas lose coherence with an increase in the temporal baseline and do not regain it seasonally. Urban areas show similar seasonal variation as that of barren and flat waste rock areas but with a lower magnitude of coherence. If the ground snow layer remains unchanged during two consecutive images, then high coherence can be achieved even with a ground snow layer. In spring, the coherence becomes very poor due to the melting snow and surface water, and in the autumn, the coherence is reduced due to leaf fall, shedding of the tree leaves due to wind, surface water from rain, and due to the first snow fall. Additionally this study showed that the winter Radarsat-2 U6D beam mode images are not suitable for DInSAR deformation measurements in flat waste rock areas in Kiruna.

Chapter 4

Seasonal effects on CRInSAR measurements

4.1 Introduction

Interferometric Synthetic Aperture Radar (InSAR) measurements of ground deformation at high latitudes are known to be particularly affected by long periods of ground snow cover. This ground snow cover contributes to temporal de-correlation between subsequent radar images. Artificially introduced radar targets, such as corner reflectors (CRs), that remain coherent over time are required to be used as stable scatterers in such regions. The Corner Reflector InSAR measurement (CRInSAR) is a proven technique that uses CRs as highly coherent point targets, especially when stable natural scatterers are unavailable in the ROI. CRInSAR measurements have been well-documented for low-latitude regions [48, 64, 65, 84]. In 2010, 60 CRs were installed in Kiruna to measure subsidence using InSAR. Building a protective shield at high latitudes is essential to prevent the accumulation of snow within the reflector. However, it is observed that snow can still accumulate on the CR protective shield during winter. Since 2003, LKAB has been using Global Positioning System (GPS) techniques to measure the subsidence at both the hangingwall and footwall sides [12]. The Static-GPS technique (Static-GPS) with one reference station was used between 2003 and 2009. Since then, LKAB has been using the Static-GPS technique with three reference stations [85]. In this study, deformation measurements by the Static-GPS and Corner Reflector InSAR (CRInSAR) were compared. GPS measurements had been used

in the past along with InSAR measurements to improve the ground deformation monitoring at low latitudes, correct the atmospheric effects in the InSAR measurements etc. [81, 86]. Methods for processing and combining InSAR and GPS data are described in many studies [64, 87–90]. However, there were not many previous studies of high latitude areas that compare Static-GPS measurements with CRInSAR measurements or studies carried out to quantify errors in CRInSAR measurements when snow is on the ground and/or on top of CRs.

The inclination angle of the GPS satellites is 55° . Therefore, no satellites signals are received in the zenith direction north of the corresponding latitudes. If we are making GPS measurements above latitude 55° (Kiruna is at latitude $67^\circ 51' 20''$ N) the elevation angle of the satellites is reduced as the latitude increases. Because of this we get better horizontal satellite geometry, but worse vertical satellite geometry compared to the situation at low latitudes. Therefore, this will decrease the accuracy of the GPS vertical measurements.

This study had two primary objectives. The first was a comparison of Static-GPS and CRInSAR measurements to quantify the measurement bias, identify a suitable CRInSAR processing scheme, and validate the use of CRInSAR for high-latitude regions in a generalised context. The second objective was to investigate and quantify the effect of snow (on the ground and/or on top of CRs) in CRInSAR measurements.

In this study, Static-GPS subsidence measurement data were used as a reference dataset to quantify CRInSAR measurement errors.

The novelty of this study involves comparing, for high latitudes, the measurement of a large and wide area CR network with the measurements of a Static-GPS network, and this comparison was used to determine a suitable CRInSAR processing scheme that can minimise the snow-induced measurement errors.

4.2 Available data and measurement techniques

4.2.1 Static-GPS measurements

Approximately 400 GPS measurement points are currently situated on both the hangingwall and footwall sides of the Kiruna iron mine (Figure 4.1). These measurement points were mostly installed as lines starting from the mine proximity and spreading toward Kiruna city (at the hangingwall side). All GPS measurement points are measured each summer. Additionally, approximately 100 GPS measurement points (in areas of strategic interest) are measured once in every three months. Twenty-six GPS measurement points were selected to be compared with CRInSAR, for which 87 GPS measurements are available from January 2010 to December 2011. Of these measurements, 42 were taken in winter or spring (i.e., periods of snowfall), and the rest were taken in summer or autumn.

A typical GPS measurement point installed before 2010 consists of a concrete cylindrical structure installed deep in the ground. This depth typically reaches the bedrock or 2.5 m (the ground is frozen approximately 2 m deep in winter). Figure 4.2 shows a typical measurement point install before 2010. Since 2010, these concrete structures have been replaced with steel pipes. Figure 4.3 shows a measurement point installed after 2010.

GPS antennae were placed on 10 GPS measurement points clustered together (For measurement points installed before 2010, the GPS antennae were placed on top of tripods and the tripods were carefully aligned with the measurement points; For measurement points installed after 2010, the GPS antennae could be placed directly on the steel pipes). Measurements were taken over 30 minutes, after which 8 out of 10 antennae were moved to new measurement points (as a cluster), and the measurements were continued for another 30 minutes. This procedure was followed until all the GPS measurement points were covered. LKAB uses GPS data from 3 base stations (Figure 4.4) around the Kiruna mine, owned by the Swedish land survey organization to calibrate the equipment. The data downloaded from the GPS instruments and base stations were processed to produce GPS deformation maps of the area. Leica GPS1200+ Surveying Systems instruments were used for the measurements, and the Leica “Geo Office” software package was used to process the GPS data. The measurement accuracies (2σ) for the GPS instrument



FIGURE 4.1: GPS and CR network in Kiruna. The red box in the left image shows the general area where corner reflectors are installed. Right image shows the CR installed area in high resolution. CRs are marked in purple, and GPS measurement points are marked in yellow. Selected areas of the image are masked out to protect LKAB proprietary information (image source: LKAB and Google maps).



FIGURE 4.2: GPS measurement points installed prior to 2010 (source: LKAB).



FIGURE 4.3: GPS measurement points installed after 2010 (source: LKAB).

(static measurements with post processing) is 6 mm+ 0.5 ppm in the verticle direction and 3 mm+ 0.5 ppm in the horizontal direction [91].

4.2.2 CRInSAR measurements

To measure the deformation in the Kiruna region, both the ascending and descending tracks were used. Therefore, the CR structure consists of two trihedral corners placed at the same base (CR pairs) oriented towards both tracks. Figure 4.6 shows such a CR pair. A total of 30 CR pairs were installed in the study area, 3 of which were installed in stable areas where no deformation was expected. MDA installed the corner reflectors at the test site. These 3 CR pairs were used as reference points (Figure 4.4) for the InSAR measurements. The remaining 27 CRs

TABLE 4.1: Distance between GPS benchmarks and CRs

CR Point	GPS Point	E-W distance from CR (m)	N-S distance from CR (m)
CR2	L14	20	2
CR3	C8	16	-1
CR4	M12	29	45
CR5	A8	9	6
CR6	L10	18	-8
CR7	M7	38	4
CR8	M8	31	1
CR9	M11	20	-6
CR10	H11	165	-27
CR11	H13	35	-8
CR12	H16	4	-20
CR13	H18	28	6
CR14	H32	7	6
CR15	S10	17	-2
CR16	S8	36	21
CR17	S11	49	-27
CR18	S13	62	-41
CR19	N51	0	-14
CR20	T25	25	8
CR21	T23	29	7
CR22	S15	58	-30
CR23	T29	29	-8
CR24	D60	25	-7
CR25	D50	19	-3
CR26	D53	26	4
CR27	D57	28	-6

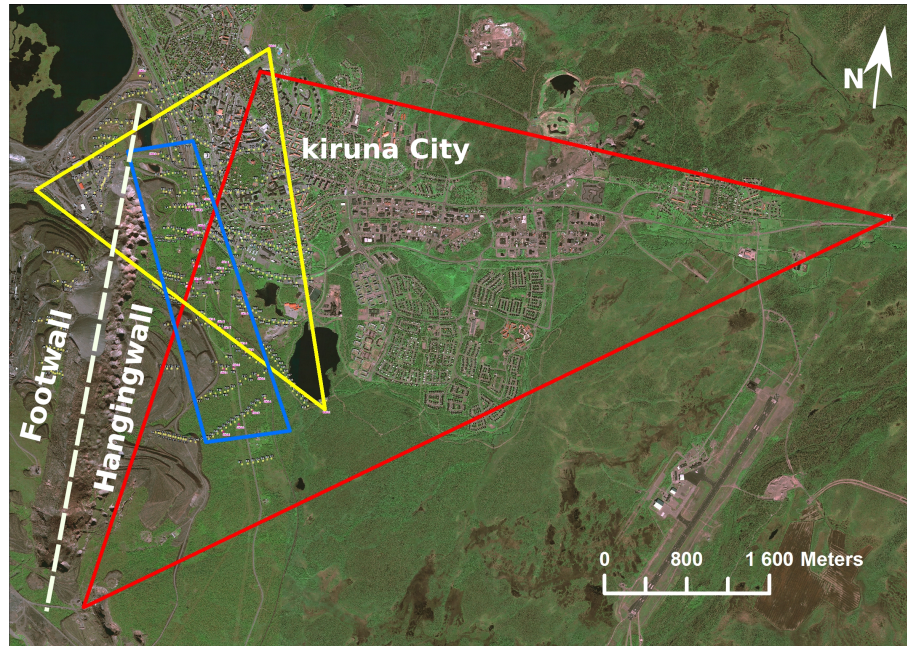


FIGURE 4.4: GPS and CR reference points. Corners of the red triangle are the GPS reference stations, and the corners of the yellow triangle are the reference CRs. The blue rectangle indicate the area where the CRs are installed (image source: LKAB).

were installed at deformation areas without stable natural scatterers. Figure 4.1 shows the distribution of CR and GPS measurement points in the Kiruna area. Twenty-two Radarsat-2 U6D beam mode images (from March 2010 to September 2011) and 26 CRs (one CR from each CR pair) were used for this study. The EVInSAR (an InSAR processing software developed by MacDonald, Dettwiler and Associates Ltd. (MDA), Canada) was used for InSAR processing. An external digital elevation model (DEM) was used as an input to the processing chain. MDA provided the DEM, and it was created by merging a Radarsat-2 DEM with the ASTER DEM.

Overall, 231 interferograms were produced using 22 images as follows:

1. Initially, the 2010-03-24 image was selected as the master image (this was the first image acquired after CR installation).
2. The rest of the images and the DEM were co-registered to the master image.
3. Raw interferograms were then produced for all possible image pair combinations.

4. The topographic and flat earth phases were subsequently removed from the raw interferograms by using an external DEM and Radarsat-2 orbit information.
5. The baseline errors were then optimized and corrected.
6. Atmospheric phase screens (APS) were generated and filtered out from the interferogram stack, and the average coherence for the ROI was then calculated.
7. The phase was unwrapped next.
8. Phase unwrapping errors were corrected by using an adaptive deformation model based on sequential deformation.
9. After the phase unwrapping step, the CR deformation measurements were extracted from 3 different techniques.
 - (a) CRInSAR-SBAS-Corrected (CISC) technique: In this technique, only the interferograms (Figure 4.5 shows the selected interferograms), which have a higher average coherence (a coherence threshold value of 0.25, which is the smallest coherence threshold that precludes any loss of sequential interferograms) was selected. There were 122 such interferograms. Then SBAS technique was used to extract the CR deformation measurements.
 - (b) CRInSAR-SBAS (CIS) technique: In this technique, all (231) the interferograms were selected and the SBAS technique was used to extract the CR deformation measurements.
 - (c) CRInSAR-Sequential (CISQ) technique: In this technique, sequential interferograms (interferograms that have the shortest temporal baseline) were used to extract the CR deformation measurements.

The surface snow density (0-30 cm from the air-snow surface) of the ground snow layer around CRs between 2010-10 and 2011-04 was recorded and the density was found to be between 0.15 g/cm^{-3} and 0.4 g/cm^{-3} . The assumption was made that the density of the snow layer on top of the corner reflectors was the same or less than the ground snow layer.

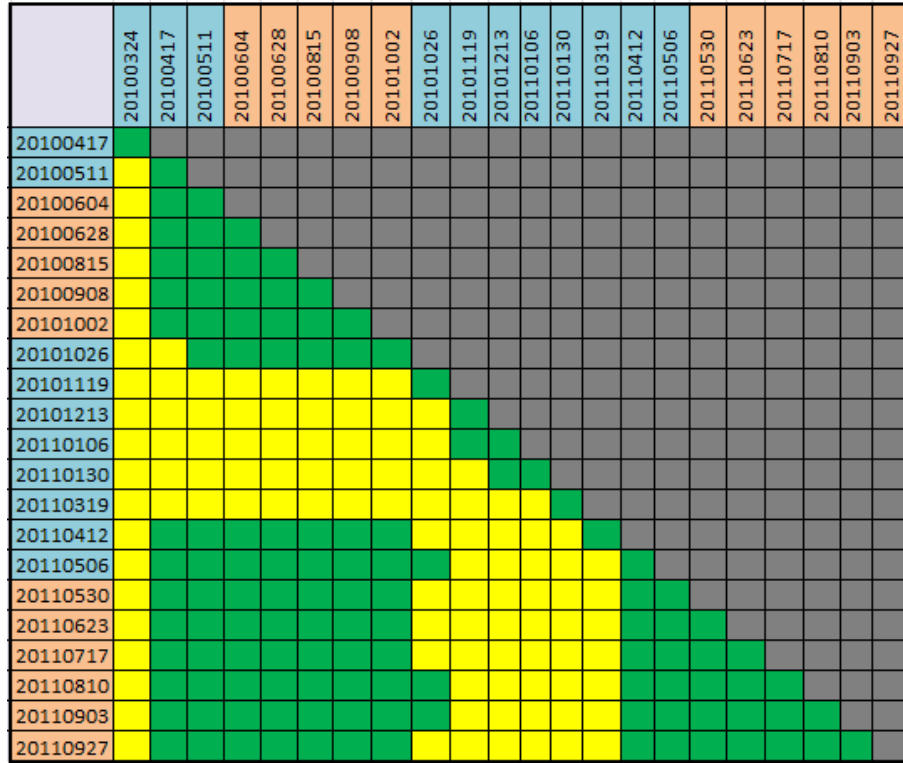


FIGURE 4.5: Selected interferograms. The X- and Y-axes are image dates, and the green boxes show the interferograms with average coherences that exceed 0.25. The yellow boxes show the interferograms with average coherence less than 0.25. The winter images (with snow) are marked in blue, and the summer images (without snow) are marked in orange.

4.3 Snow deposition on CRs

In high latitudes with long winters and heavy snowfall, CRs need a protective shield to prevent snow accumulation inside. Accumulating snow can cause structural damage or change in CR shape, and this could result in an operational failure. Also, the accumulated snow can introduce additional phase noise to the InSAR measurements.

In the Kiruna test site, CRs are equipped with a plastic snow shield. It was observed that there can be a thin snow layer (about 4-8 cm thick) on top of the snow cover in winter. Thin ice layers on top of the snow shield have also been observed. These observations have been made within few hours of the satellite overpass times. Figure 4.7, Figure 4.8 and Figure 4.9 show scenarios of snow and ice on a snow-shielded CR. The snow shield works well in case of vertical snowfall. However, if there is wind, snowfall can take place in a direction perpendicular to the snow shield and deposit there (Figure 4.10). This snow layer remains on the



FIGURE 4.6: Shielded CR installed in Kiruna without snow.

snow shield until the gravity pulls it down, or strong wind blows it off. The snow deposition is accelerated by the buildup of any ice particles on the shield surface due to snow melting (or wet snow).



FIGURE 4.7: Shielded CR with a snow layer on top of the shield.



FIGURE 4.8: Shielded CR with a ice layer on top of the shield.



FIGURE 4.9: CR with inhomogeneous snow cover on top of the shield; some of the snow has been blown off by wind.

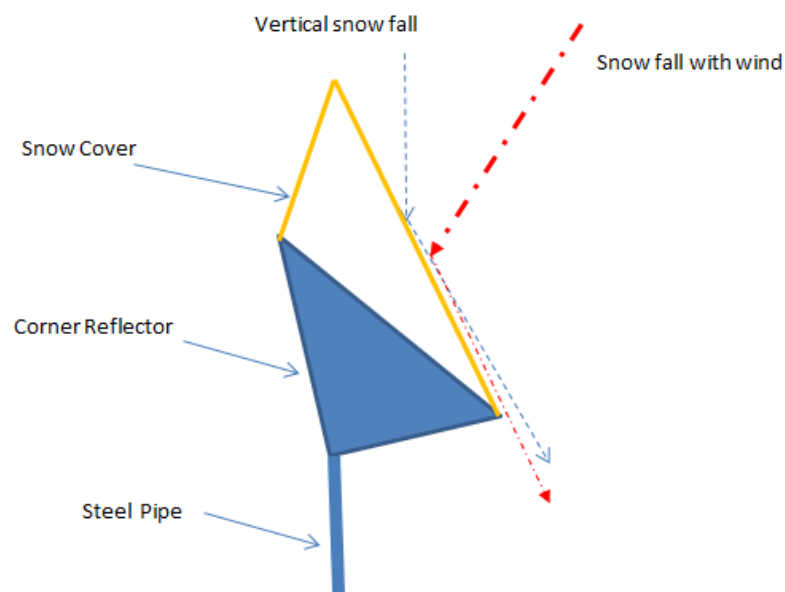


FIGURE 4.10: Function of the snow shield.

4.4 Methodology

4.4.1 Selection of comparable measurements

First, GPS-CR pairs suitable for comparison was manually identified. Twenty-six GPS-CR pairs were formed by selecting the closest GPS measurement point to each CR. Here the assumption was that the deformation signal was spatially smooth and did not varying significantly over a few tens of meters. Therefore, both techniques measure the same deformation signal. The distance between a GPS measurement point and CR (in a GPS-CR pair) ranged from 2 m to 60 m. Next, the temporally closest Radarsat-2 acquisition (CRInSAR measurement) to a GPS measurement was identified and formed GPS CRInSAR temporal pairs. The temporal difference between any GPS measurement and the closest CR measurement was less than 12 days (repeat cycle of Radarsat-2 is 24 days). Again, the assumption was that the temporal difference between a GPS measurement and the closest CRInSAR measurement was close enough to show the same deformation in both CRInSAR and GPS measurements for this comparison.

4.4.2 Converting GPS measurements into radar line-of-sight

To compare ground subsidence measurements between GPS and CRInSAR, a vector parallel to the Radarsat-2 line-of-sight (LOS) was calculated using the GPS East-West, North-South and Vertical vectors (Figure D.1 and D.2).

The calculation was performed as follows:

$$\overrightarrow{GPS}_{EWLOS} = (\cos(\alpha - \pi) * \cos(\frac{\pi}{2} - \theta)) * \overrightarrow{GPS}_{EW} \quad (4.1)$$

$$\overrightarrow{GPS}_{NSLOS} = (-\cos(\frac{3\pi}{2} - \alpha) * \cos(\frac{\pi}{2} - \theta)) * \overrightarrow{GPS}_{NS} \quad (4.2)$$

$$\overrightarrow{GPS}_{VTLOS} = (\cos\theta) * \overrightarrow{GPS}_{VT} \quad (4.3)$$

$$\overrightarrow{GPS}_{LOS} = \overrightarrow{GPS}_{EWLOS} + \overrightarrow{GPS}_{NSLOS} + \overrightarrow{GPS}_{VTLOS} \quad (4.4)$$

where GPS_{EW} is the GPS measurement in the East-West direction, GPS_{NS} is the GPS measurement in the North-South direction, GPS_{VT} is the GPS measurement in the Vertical direction, GPS_{EWLOS} is the line-of-sight component calculated from the East-West GPS measurement, GPS_{NSLOS} is the line-of-sight component calculated from the North-South GPS measurement, GPS_{VTLOS} is the line-of-sight component calculated from the Vertical GPS measurement, GPS_{LOS} is the vector calculated parallel to the Radarsat-2 LOS direction (CR_{LOS}), α is the heading angle of Radarsat-2 U6D beam (measured clockwise), and θ is the incidence angle of the U6D beam.

4.4.3 Double difference calculations, time series plots and scatter plots

As mentioned earlier, the GPS measurements (single difference GPS measurements that are taken relatively to the reference stations) date back to 2003, while the InSAR measurements are more recent (beginning in 2010). Therefore, only those GPS measurements temporally overlapping with CRInSAR measurements were considered, and the GPS double difference values were calculated by interpolating a GPS measurement value to the first CR measurement date. The interpolated value was subtracted from the rest of the GPS measurements and can be described as follows:

$$GPS_{LOSDD(i,k)} = GPS_{LOS(i,k)} - GPS_{LOS(1,k)} \quad (4.5)$$

where, $GPS_{LOSDD(i,k)}$ is the i^{th} LOS GPS double difference value at k^{th} GPS-CR pair, $GPS_{LOS(i,k)}$ is the i^{th} GPS LOS measurement of the k^{th} GPS-CR pair and $GPS_{LOS(1,k)}$ is the first GPS measurement (interpolated to the first CR measurement date) of the k^{th} GPS-CR pair.

The CRInSAR double difference calculations can be described as follows:

$$CR_{LOSDD(i,k)} = CR_{LOS(i,k)} - CR_{LOS(1,k)} \quad (4.6)$$

where, $CR_{LOSDD(i,k)}$ is the i^{th} CR double difference value at k^{th} GPS-CR pair, $CR_{LOS(i,k)}$ is the i^{th} CR LOS measurement of the k^{th} GPS-CR pair and $CR_{LOS(1,k)}$ is the first measurement of the k^{th} GPS-CR pair.

The time series plots were produced by using the double difference CR and GPS values. A scatter plot was produced using the CR and GPS double difference measurements, and the correlation coefficient was calculated.

4.4.4 CRInSAR and GPS velocity plots

By using the double difference GPS and CRInSAR values, the deformation velocities for the GPS and CRInSAR measurements were calculated as follows:

$$CR_{LOSV(n,j)} = \frac{CR_{LOSDD(n,j)}}{CR_{Date(n,j)} - CR_{Date(1,j)}} \quad (4.7)$$

where, $CR_{LOSV(n,j)}$ is the CR LOS velocity associated to n^{th} double difference of j^{th} GPS-CR pair $CR_{LOSDD(n,j)}$ is the n^{th} double difference of the CR measurement for j^{th} GPS-CR pair, $CR_{Date(n,j)}$ is the n^{th} CR measurement date at the j^{th} GPS-CR pair, and $CR_{Date(1,j)}$ is the first CR measurement date at j^{th} GPS-CR pair.

$$GPS_{LOSV(n,j)} = \frac{GPS_{LOSDD(n,j)}}{GPS_{Date(n,j)} - GPS_{Date(1,j)}} \quad (4.8)$$

where $GPS_{LOSV(n,j)}$ is the LOS GPS velocity associated to n^{th} double difference of j^{th} GPS-CR pair, $GPS_{Date(n,j)}$ is the n^{th} GPS measurement date of j^{th} GPS-CR pair, and $GPS_{Date(1,j)}$ is the first GPS measurement date of j^{th} GPS-CR pair. Here the assumption was that the deformation velocity rate is constant for this calculation.

4.4.5 Uncertainties of GPS and CRInSAR measurements

The GPS line-of-sight measurement uncertainty is a function of the GPS measurement uncertainties in the East-West, North-South and Vertical directions and can be described as follows:

$$\xi_{GPSLOS} = \xi_{GPSLOS}(\xi_{GPS_{EW}}, \xi_{GPS_{NS}}, \xi_{GPS_{VT}}) \quad (4.9)$$

where, $\xi_{GPS_{LOS}}$ is the measurement uncertainty in line-of-sight GPS measurements, $\xi_{GPS_{EW}}$ is the GPS measurement uncertainty in the East-West direction, $\xi_{GPS_{NS}}$ is the GPS measurement uncertainty in the North-South direction and $\xi_{GPS_{VT}}$ is the GPS measurement uncertainty in the Vertical direction.

The East-West, North-South and Vertical GPS measurements are affected by three error components: (1) GPS instrument related uncertainties, (2) operator errors (the improper fixing of the GPS antenna etc.) and (3) errors are due to an instability in the reference stations. These components can be described as follows:

$$\xi_{GPS(i)} = \xi_{MGPS(i)} + \xi_{RefGps} + \xi_{OpGps} \quad (4.10)$$

where $\xi_{GPS(i)}$ is the total uncertainty in GPS measurement in the direction i (East-West or North-South or Vertical), ξ_{OpGps} is the GPS operator error and ξ_{RefGps} is the error introduced due to the unstable reference stations. $\xi_{MGPS(i)}$ is the uncertainty stated in the GPS instrument for the direction i (East-West uncertainty is (ξ_{GPSEW}), North-South uncertainty is (ξ_{GPSNS}) and Vertical uncertainty is (ξ_{GPSVT}).

By combining Equation 4.9 and Equation 4.10 we obtain:

$$\xi_{GPS_{LOS}} = \sqrt{R_1 + R_2 + R_3} \quad (4.11)$$

where $R_1 = \left(\frac{\partial \xi_{GPS_{LOS}}}{\partial \xi_{GPSEW}} \cdot \delta \xi_{GPSEW} \right)^2$,

$R_2 = \left(\frac{\partial \xi_{GPS_{LOS}}}{\partial \xi_{GPSNS}} \cdot \delta \xi_{GPSNS} \right)^2$, and

$R_3 = \left(\frac{\partial \xi_{GPS_{LOS}}}{\partial \xi_{GPSVT}} \cdot \delta \xi_{GPSVT} \right)^2$. Here, the assumption is that the GPS reference points are on stable ground. Hence, $\xi_{RefGps} = 0$ and the GPS operator error are considered negligible ($\xi_{OpGps} = 0$). The 1σ LOS GPS uncertainty ($\xi_{GPS_{LOS}}$) that results from this calculation equal 5 mm.

CR measurements feature a degree of uncertainty due to the additional phase components (Equation 6.1) and the instability of the reference corner reflectors. This relationship can be described as follows:

$$\xi_{TotCr} = \xi_{Cr} + \xi_{RefCr} \quad (4.12)$$

where ξ_{TotCr} is the total uncertainty in the CR measurement, ξ_{Cr} is the measurement uncertainty provided by the InSAR software (after calculations) and ξ_{RefCr} is the uncertainty due to the instability in the reference corner reflectors. Here, the assumption is that the CR reference points are on a stable ground. Hence, $\xi_{RefCr} = 0$. The measurement uncertainty (1σ) provided by the software (ξ_{CR}) is 5 mm. Therefore, the CR uncertainty (ξ_{TotCr}) that results from this calculation equal 5 mm.

4.4.6 Mean error and Standard deviation of CRInSAR double difference measurements relative to the GPS double difference measurements

To calculate the mean error and standard deviation of the CR measurements (relative to GPS measurements), first, the $\xi_{D(i,j)}$ error vector was calculated by using all GPS-CR pairs and measurements. The ξ_D can be described as:

$$\xi_{D(i,j)} = CR_{LOSDD(i,j)} - GPS_{LOSDD(i,j)} \quad (4.13)$$

where, $\xi_{D(i,j)}$ is the i^{th} error of i^{th} CR_{LOS} measurement relative to i^{th} GPS_{LOS} measurement at j^{th} GPS-CR pair, $GPS_{LOSDD(i)}$ is the i^{th} double difference GPS_{LOS} measurement at j^{th} GPS-CR pair, $CR_{LOSDD(i)}$ is the i^{th} double difference CR_{LOS} measurement at j^{th} GPS-CR pair.

Then the mean and standard deviation (1σ) of the error vector was calculated. For this calculation, the assumption was that the GPS measurements were reflecting the ground truth. The calculated mean and standard deviations are presented in the results section (Table 4.2).

4.4.7 Mean error and Standard deviation of CRInSAR velocities relative to the GPS velocities

To calculate the mean error and standard deviation of the CR velocities (relative to GPS velocities), first the ξ_V error vector was calculated by using all GPS-CR pairs, and GPS and CR velocities. The ξ_V can be described as follows:

$$\xi_{V(i,j)} = CR_{LOS V(i,j)} - GPS_{LOS V(i,j)} \quad (4.14)$$

where, $\xi_{V(i,j)}$ is the i^{th} error of i^{th} CR_{LOS} velocity relative to i^{th} GPS_{LOS} velocity at j^{th} GPS-CR pair, $GPS_{LOS V(i,j)}$ is the i^{th} GPS_{LOS} velocity at j^{th} GPS-CR pair, $CR_{LOS V(i,j)}$ is the i^{th} CR_{LOS} velocity at j^{th} GPS-CR pair.

Then the mean and standard deviation (1σ) of the error vector was calculated. For this calculation, the assumption was that the GPS velocities are reflecting the ground truth. The calculated mean and standard deviations are presented in the results Section (Table 4.2).

4.4.8 Uncertainties of Static-GPS and CRInSAR velocities

To calculate the uncertainties of the Static-GPS and CRInSAR velocities, it is assumed that both measurements have constant mean displacement velocities. By using error propagation law, error calculations for the CRInSAR velocities can be described as follows:

$$\xi_{CR_{LOS V(n,j)}} = \sqrt{W_1 + W_2} \quad (4.15)$$

where $W_1 = \left(\frac{\xi_{TotCr}}{CR_{Date(n,j)} - CR_{Date(1,j)}} \right)^2$,

$W_2 = \left(\frac{-\xi_{TotCr}}{CR_{Date(n,j)} - CR_{Date(1,j)}} \right)^2$ and $\xi_{CR_{LOS V(n,j)}}$ is the uncertainty in n^{th} line-of-sight corner reflector velocity measurement of j^{th} GPS-CR pair.

Similarly, the error calculations for the Static-GPS can be described as follows:

$$\xi_{GPS_{LOS V(n,j)}} = \sqrt{U_1 + U_2} \quad (4.16)$$

where $U_1 = \left(\frac{\xi_{GPS_{LOS}}}{GPS_{Date(n,j)} - GPS_{Date(1,j)}} \right)^2$,

$U_2 = \left(\frac{-\xi_{GPS_{LOS}}}{GPS_{Date(n,j)} - GPS_{Date(1,j)}} \right)^2$ and $\xi_{GPS_{LOS V(n,j)}}$ is the uncertainty in n^{th} line-of-sight GPS velocity measurements of j^{th} GPS-CR pair, The calculated standard deviations were plotted in the velocity scatter plot (Figure 4.18).

4.4.9 Student's T test

A standard Student's T-test was used to investigate the statistical significance of the measurement bias of the CRInSAR and Static-GPS measurements. For this test, the Static-GPS and CRInSAR double difference measurements were used. Here the assumption is that both the Static GPS and CRInSAR measurements are normally distributed and the variance of both groups (Static GPS and CRInSAR) are close enough to perform Student's T-test (ξ_{GPSLOS} is 5 mm and ξ_{TotCr} is between 5 to 2 mm).

4.5 Results

TABLE 4.2: Correlation coefficient, Mean error and Standard deviation

Parameter	CRInSAR-SBAS-Corrected (CISC)	CRInSAR-SBAS (CIS)	CRInSAR-Sequential (CISQ)
Correlation coefficient (for double difference)	0.88	0.58	0.63
Mean error (for double difference) (mm)	1.1	17.9	37.8
Standard deviation (for double difference) (mm)	10.7	30.9	41.5
Correlation coefficient (for velocity)	0.77	0.43	0.53
Mean error (for velocity) (mm/year)	2.5	22.0	50.6
Standard deviation (for velocity) (mm/year)	17.8	42.6	57.5

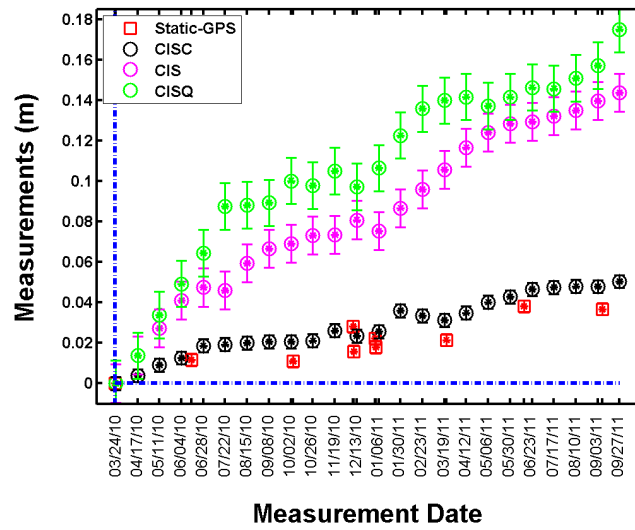


FIGURE 4.11: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-06 and GPS-L10.

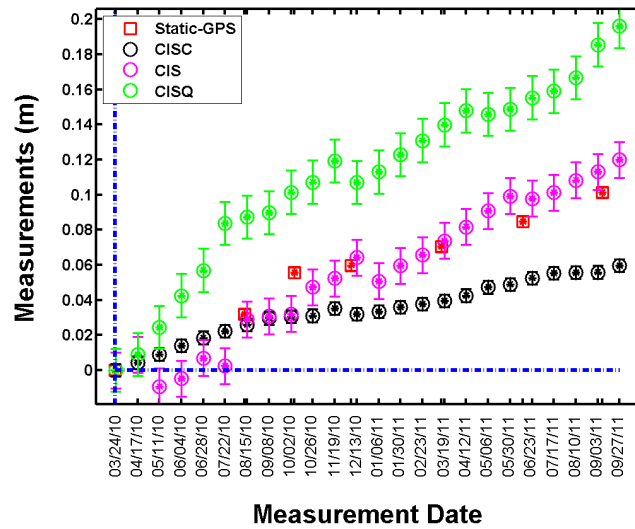


FIGURE 4.12: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-10 and GPS-H11.

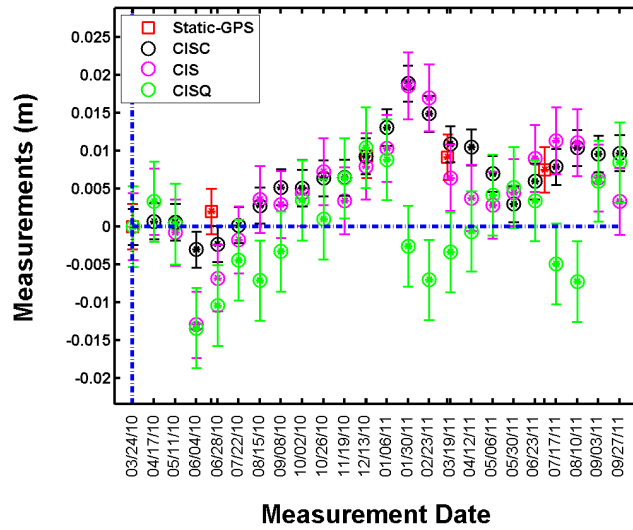


FIGURE 4.13: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-23 and GPS-T29.

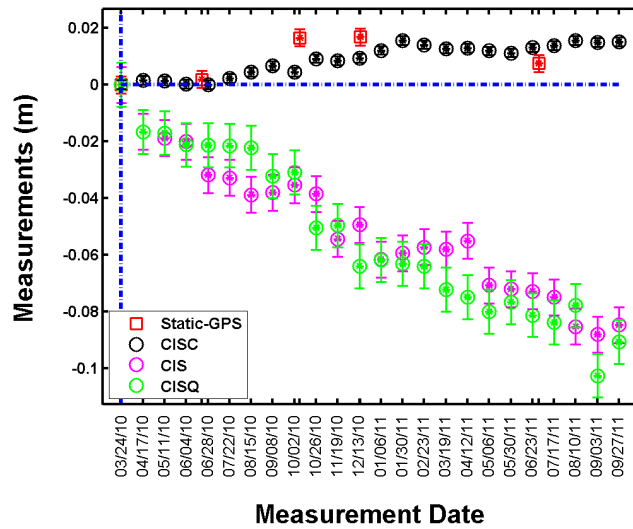


FIGURE 4.14: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-27 and GPS-D57.

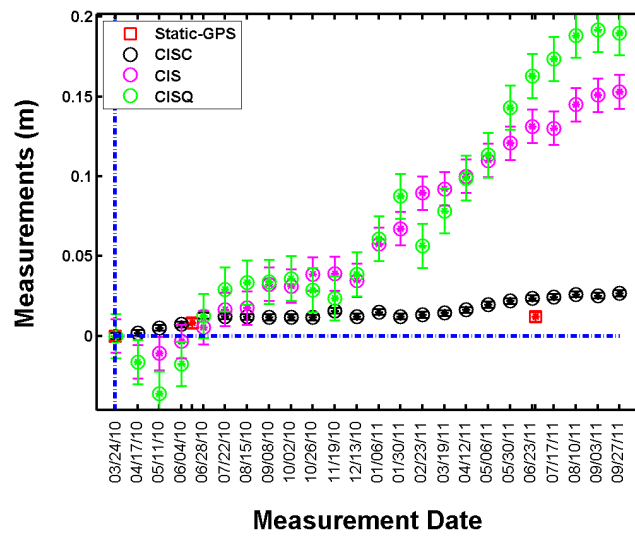


FIGURE 4.15: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-06 and GPS-L10.

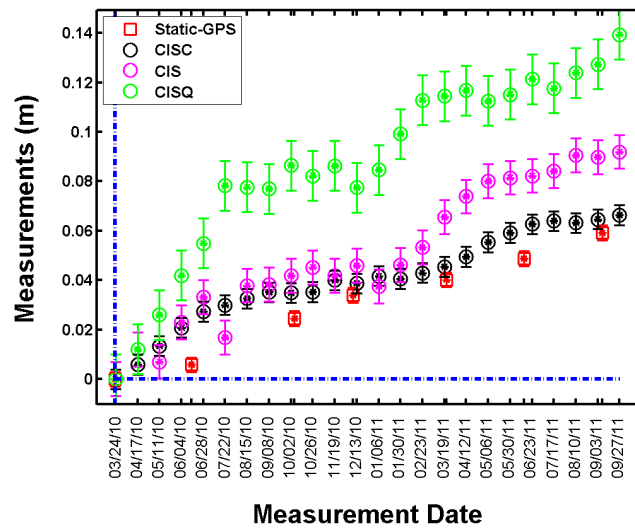


FIGURE 4.16: Time series plots of double difference CRInSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-2 and GPS-M7.

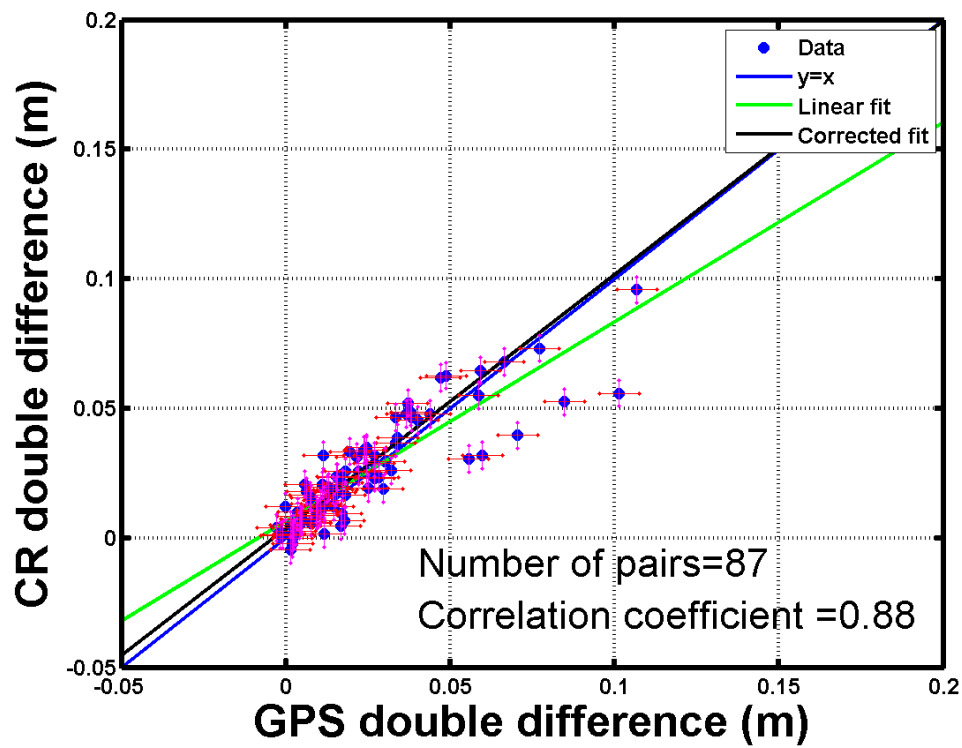


FIGURE 4.17: Double difference scatter plot of CISC Vs Static-GPS for the entire inter-comparison time period.

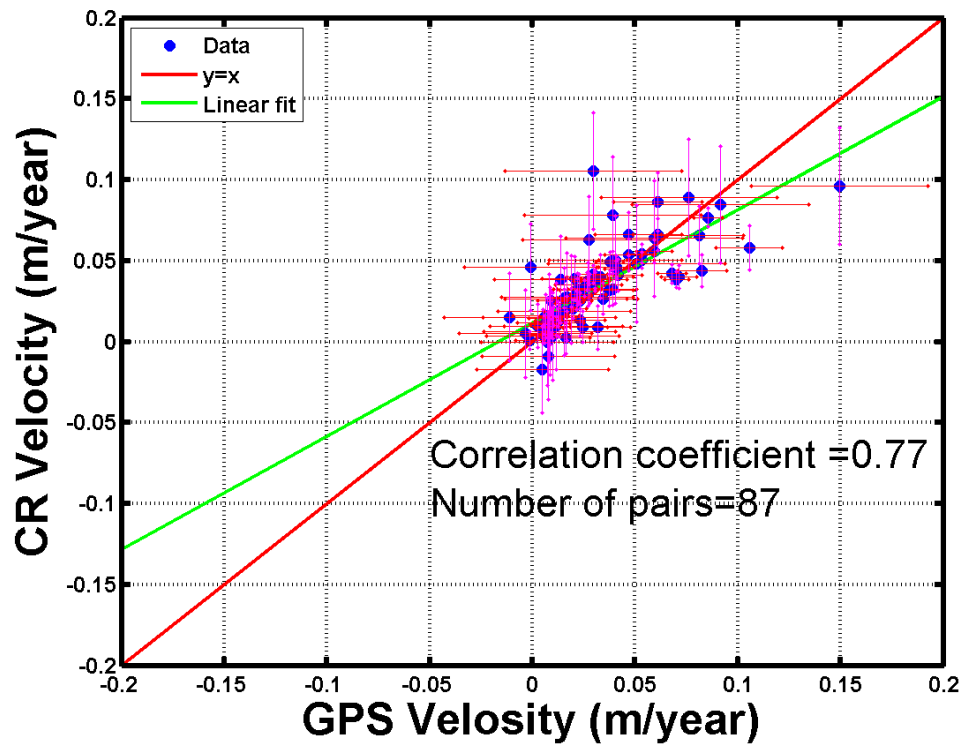


FIGURE 4.18: Velocity scatter plot of CISC Vs Static-GPS for the entire inter-comparison time period.

4.6 Discussion

In this study, the seasonal effects on the CRInSAR measurements were investigated.

4.6.1 Double difference GPS and CRInSAR time series plots

The double difference time series plots show the deformation measurements of CR-GPS pairs. Each plot shows the CR measurements derived from each processing technique (CISC, CIS and CISQ) and Static-GPS measurement. Figure B.6 shows the double difference time series plot of the CR-06. The time series plots of CR-02 to CR-09, CR-11 to CR-22 and CR-24 to CR-26 shows similar behaviour. The time series plot of CR-10 is shown in Figure B.23, CR-23 is shown in Figure B.10 and CR-27 is shown in Figure 4.14. The plots clearly show that the CISC technique gives the best agreement with the Static-GPS measurement results, whereas CISQ, shows the worst agreement. The CISQ values are 1-5 times higher than the CISC values, and the CIS technique sometimes showed values at least two-times higher than the CISC technique. The CISQ technique yielded the highest CRInSAR values during the summer and winter. These higher deformation values (Figure B.6, B.10) are due to the atmospheric effects and snow. Residual phase errors persisted even when using an APS to remove the atmospheric effects. The output of the CISC and CIS techniques influenced both the summer and winter measurements. The CISC technique used fewer winter measurements than the CIS technique. Hence, the output is biased towards the summer measurements and showed fewer snow-induced errors. Figure B.23 and 4.14 show the phase unwrapping errors in CR-10 and CR-27 measurements. In CR-10, the phase unwrapping error occurred in the CISC technique. Therefore, the estimated CR deformation values are lower than the Static-GPS values primarily because CR-10 experienced a higher rate of deformation compared to the previous months from August 2010 to October 2010. The CISC technique predicted this high value as noise and a correction was applied. However, when considering the CIS technique, the deformation rate between August 2010 and October 2010 (for CR-10) was not significantly different from its estimations for the previous months. Therefore, no correction was applied during the deformation estimations. In CR-27, the CIS and CISQ

techniques failed to distinguish the phase noise from the deformation signal. As a result, both techniques estimated an uplift of the ground instead of the ground deformation. The main reasons for the higher noise value in the CRInSAR measurement was the snow deposition on top of the CR shield and the ground snow layer. This error was not found in the CISC technique because it used fewer winter images. Therefore, this technique was biased towards the summer measurements.

4.6.2 Double difference GPS and CRInSAR scatter plots

The double difference scatter plots show that the agreement of each technique with Static GPS as a complete measurement system. Here, the Static GPS measurements were considered as the ground truth. For the entire inter-comparison period, the CISC (Figure 4.17) method gives the best agreement with a correlation of 0.88, mean error of 1.1 mm and a standard deviation of 10.7 mm. The other two techniques yielded low correlation values (0.58, 0.68), high mean errors (17.9 mm, 37.8 mm) and high standard deviations (30.9 mm, 41.5 mm). These high mean error values are due to the atmosphere- and snow-induced errors. Figure 4.17 shows that the slope of the regression line (green line) does not equal one, and the CISC estimations are lower than the GPS measurements. The main reason for this observation is the presence of outliers due to a phase unwrapping error in CR-10. The black line represents the regression excluding these outliers. The results are summarised in Table 4.2. The Students T-test was used to investigate the statistical significance of the mean error of the CISC estimations. The null hypothesis of this Student's T-test was that both Static GPS and CISC estimations belong to the same population or that they both reveal the same ground truth. According to the results, the null hypothesis cannot be rejected at 0.05α level. In other words, the GPS measurements and CISC estimations are consistent within the expected error levels for both techniques.

4.6.3 Velocity scatter plots

The velocity scatter plot (Figure 4.18) shows the relationship between the static GPS and CRInSAR annual velocities and the uncertainty of the measurements. The velocity plots, like the double difference scatter plots, also show that the CISC technique agrees best with the Static GPS measurements, yielding a correlation

coefficient of 0.77 and mean error of 2.5 mm/year. The other two techniques yielded higher mean errors (22 mm/year, 50 mm/year) than the CISC technique. The higher degrees of uncertainty in the measurement of some outliers is due to the close measurement dates between the GPS measurements. Table 4.2 shows the summary of all the results.

4.6.4 Snow induced phase errors and limitations of CISC technique

The large difference between the CISC and CIS estimations (Table 4.2) shows that the InSAR winter measurements have significantly larger phase errors than the summer measurements. The winter snow condition constitutes the main source of these phase errors in winter, when the temperature is below zero, and the amount of atmospheric column water vapour is low. This snow induced phase errors in two ways: The first type of error occurs in the baseline optimisation step of the InSAR processing, where spatial coherence is the input parameter to optimise the baseline. Because the ground snow layer directly affects the spatial coherence, it is not possible to determine the optimum baseline. The second type of error occurs because of snow layers on top of the protective shields of the corner reflectors. These snow layers introduce an additional phase to the measurements. So far, this additional phase error was corrected by using an adaptive deformation model. However, removing this error can be very difficult if CRs are experiencing non-linear deformation rates, and/or the thickness or density of the snow layer (on top of the protective shield) is high. This situation can induce phase unwrapping errors; Figure B.10 (CISC technique) shows such a scenario. This type of error is one of the limitations of the CISC technique.

By selecting the interferograms with high average coherence, the error due attributed to the incorrect baseline estimations which can be minimized. However, in doing so, a considerable number of interferograms were left out from the calculations and the final results will be biased towards summer measurements. Additionally, losing the entire set/sets of interferograms related to a particular image/images (a winter image/images) is possible, and this loss will lead to loss of measurements for a particular date/dates. In this case, it is needed either to lower the coherence threshold, which will lead to a higher phase errors in the measurements and more unwrapping errors or to obtain an interpolated value/values for

the (missing) particular date/dates, which will eventually bias the output towards the summer measurements. This restriction is another limitation of the CISC technique.

4.6.5 Assumption

In this study, we assumed that the temporal difference between a GPS measurement and the closest CRInSAR measurement was close enough to show the same deformation in both CRInSAR and GPS measurements. Since the GPS and CRInSAR measurements are reporting the same ground truth, we can say that our assumption was correct.

4.7 Conclusion

The Static-GPS and CRInSAR measurements were compared by calculating a GPS vector component (GPS_{LOS}) parallel to the corner reflector line-of-sight. The GPS_{LOS} was compared with the CRInSAR measurements (CR_{LOS}), which were estimated using the following techniques: (1) (CISC): Using the SBAS technique to process CRInSAR measurements and only using interferograms with a higher average spatial coherence (higher than 0.25), (2) (CIS): Using the SBAS technique to process CRInSAR measurements, and with (3) (CISQ): CRInSAR sequential measurements.

The results show that the CISC technique yielded the closest agreement with Static-GPS measurements, showing a 1.1 mm mean error and 10.7 mm standard deviation, while the other two techniques had higher mean errors (17.9 mm, 37.8 mm) and standard deviations (30.9 mm, 41.5 mm). Moreover, the same technique (CISC) yielded the highest correlation with Static-GPS measurements, which showed a correlation coefficient of 0.88 for the entire inter-comparison period. Conversely, the other two techniques showed lower correlation coefficient values (0.58 and 0.63). From this study, the arrived conclusions are that (1) snow conditions in high latitude regions will introduce an additional phase to CRInSAR measurements. However, this additional phase can be minimized by using only those interferograms with higher average spatial coherence values and the SBAS

techniques, which reduces the mean error more than 16-fold. (2) Both Static-GPS and CISC measurements report the same ground truth.

The limitations of the CISC technique are (1) phase unwrapping errors that can arise due to corner reflectors experiencing higher/non-linear deformations with a significant additional snow induced phase. (2) The possibility of losing entire sets of interferograms related to a particular image (a winter image) due to the removal of interferograms with lower average coherence. This loss will in turn lead to the loss of measurements for that particular date.

Although the overall measurement error due to snow was quantified, it was unable to differentiate the error contribution from the ground snow layer and from the snow layer on top of the corner reflector shield.

Chapter 5

Improving DInSAR measurements

5.1 Introduction

DInSAR is a well established and operational method for ground deformation measurements [48]. This technique has been used to monitor deformation around open pit mines as well as around underground mines [7, 9, 92]. The standard DInSAR technique has measurement accuracy of the order of a centimeter but requires a minimum of two satellite images. Sub-centimeter accuracies can be achieved with the use of InSAR time series techniques (e.g. PSInSAR, CTM). However, those techniques require more (about 15 or more) satellite images than DInSAR technique [46, 48]. The requirement of the large number of satellite images is one of the limitations of the InSAR time series techniques. In most cases, it is possible to get a prior understating of the areas affected by the mining activities (mining induce deformation) [12]. In this study, a model deformation (spatial) signal between two points in the ROI with a known deformation parameters were compared with the DInSAR deformation measurements (spatial) between those two points. There are a number of standard techniques (squares as a maximum likelihood estimator, Chi-square fitting, Singular value decomposition, etc.) to compare set of data with a model [93]. The basic approach in all those techniques are,

1. Designing or identifying the figure-of-merit function that measures the agreement between the model and the data for given parameters.

2. Adjusting the model parameters to achieve a minimum in the merit function, which gives the best-fit parameters.

In this study, a comparison was carried out by using (1) RMS error and (2) Correlation coefficient. If the correlation is high or, RMS error is low then the model has the best-fit parameters. Results from the simulations and validation show that RMS error fitting technique and Correlation coefficient can be used to improve the DInSAR measurement accuracies to sub-centimeter levels. In this study, a linear deformation model was used, and further studies are required to validate non-linear deformation models.

5.2 Methodology

In this section, the proposed methodology was presented.

5.2.1 Ground deformation between two points at the ROI (ground strain)

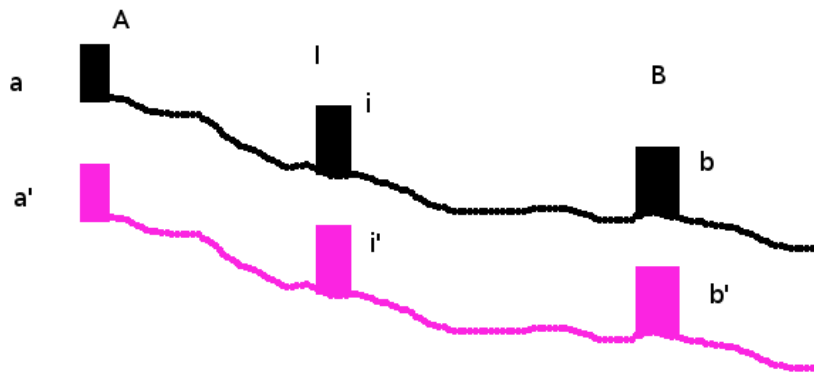


FIGURE 5.1: Ground deformation at the ROI. A and B are two points at the ROI. A is at point a , and B is at point b during the first satellite pass. Due to the ground subsidence A has moved to point a' and B has moved to point b' during the second satellite pass. I is a random point between point A and B . I is at i during the first satellite pass and at i' during the second satellite pass.

Figure 5.1 shows the ground subsidence at the ROI. A and B are two points at the ROI. A is at point a , and B is at point b during the first satellite pass and

due to the ground subsidence A is at point a' and B is at point b' during the second satellite pass. I is a random point between point A and B . I is at i during the first satellite pass and at i' during the second satellite pass. During the first and second satellite passes radar images were taken for the ROI and by using those images and an external DEM, a DInSAR interferogram was generated. Noise due to the baseline errors and atmospheric effects were removed by using baseline optimization technique and using atmospheric phase screen.

The Interferometric phase for any pixel of the interferogram can be written as:

$$\phi = \phi_{def(i)} + \phi_{noise(i)} \quad (5.1)$$

where, ϕ is the interferometric phase measured from the interferogram at pixel i , $\phi_{def(i)}$ is the phase related to the deformation at pixel i and, $\phi_{noise(i)}$ is the phase related to the noise at pixel i .

The ground subsidence at point B relative to the point A can be written as:

$$\phi_{AB} = \phi_{def(B)} + \phi_{noise(B)} - \phi_{def(A)} - \phi_{noise(A)} \quad (5.2)$$

where, ϕ_{AB} is the interferometric phase related to the ground subsidence at point B relative to the point A , $\phi_{def(A)}$ is the phase related to the deformation at point A , $\phi_{noise(A)}$ is the phase related to the noise at point A , $\phi_{def(B)}$ is the phase related to the deformation at point B and, $\phi_{noise(B)}$ is the phase related to the noise at point B .

The ground subsidence at any point between A and B (relative to point A) can be written as:

$$\phi_i = \phi_{def(i)} + \phi_{noise(i)} - \phi_{def(A)} - \phi_{noise(A)} \quad (5.3)$$

where, ϕ_i is the phase at point i relative to the point A , $\phi_{def(A)}$ is the phase related to the deformation at point A , $\phi_{noise(A)}$ is the phase related to the noise at point A . $\phi_{def(i)}$ is the phase related to the deformation at point i and, $\phi_{noise(i)}$ is the phase related to the noise at point i .

5.2.2 Deformation modeling

Now let's assume that the deformation phase at point A (relative to a stable ground point) is $\phi_{def(A)}$. Also, Let's assume that the model deformation phase at point A (relative to a stable ground point) as $\phi_{Pdef(A)}$. Therefore, the error of the model or the difference between the real deformation and model value can be written as:

$$\phi_{ePhase} = \phi_{def(A)} - \phi_{Pdef(A)} \quad (5.4)$$

where, $\phi_{def(A)}$ is the deformation phase at point A relative to a stable ground point at the ROI, $\phi_{Pdef(A)}$ is the model deformation phase at point A relative to a stable ground point at the ROI and, ϕ_{ePhase} is the error of the model or the difference between the real and model values.

To model the deformation closer to the real value or to achieve the best-fit parameters, the ϕ_{ePhase} should to be minimized.

5.2.3 Using Root Mean Square (RMS) error fitting to find the best-fit parameters

The RMS difference between real and model deformation for n number of pixels in the interferogram can be written as:

$$\phi_{rmsAePhase} = \sqrt{\frac{\sum_{i=1}^n (\phi_{def(i)} - \phi_{Pdef(i)})^2}{n}} \quad (5.5)$$

where, $\phi_{def(i)}$ is the deformation phase at point i , $\phi_{Pdef(i)}$ is the model deformation phase at point i . $\phi_{rmsAePhase}$ is the RMS difference of real and model values and, n is the number of pixels used.

Assuming the model parameters are not too off from the real values (assuming having a priori knowledge of the approximate deformation value), the minimum value of the $\phi_{rmsAePhase}$ will give the best-fit parameters.

Using Equation 5.1 and 5.5, RMS difference of real and model values can be written as:

$$\phi_{rmsAePhase} = \sqrt{\frac{\sum_{i=1}^n (\phi_{def(i)} + \phi_{noise(i)} - \phi_{Pdef(i)})^2}{n}} \quad (5.6)$$

where, $\phi_{def(i)}$ is the deformation phase pixel i , $\phi_{Pdef(i)}$ is the model deformation phase at pixel i . $\phi_{rmsAePhase}$ is the RMS difference of real and model values, $\phi_{noise(i)}$ is the noise at pixel i and, n is the number of pixels used.

5.2.4 Using linear deformation strain rates between two points at the ROI

In a two-pass interferogram, each pixel gives the ground deformation between the first satellite pass and second satellite pass. Let's take two points (two pixels) A and B in the interferogram. Now, the phase difference between A and B gives the ground strain between A and B during first and second satellite pass. Let's assume that there is a priori knowledge of the approximate value of the ground deformation between point A and B . Let's assume that the ground has a linear deformation strain between the point A and B , and there are n number of pixels between point A and B . The deformation strain between point A and B can be written as:

$$def_{rateAB} = \frac{def_B - def_A}{n} \quad (5.7)$$

where, def_{rateAB} is the linear deformation strain per pixel between point A and B , def_A is the deformation at point A (relative to the stable ground), def_B is the deformation at point B (relative to the stable ground) and, n is the number of pixels between point A and B .

By using the Equation 5.7, the deformation at point i can be written as:

$$def_i = (def_{rateAB} * i) + def_A \quad (5.8)$$

where, def_{rateAB} is the linear deformation strain rate per pixel between point A and B , def_A is the deformation at point A (relative to the stable ground), def_i is the deformation at pixel i (relative to the stable ground) and, i is the pixel number starting from point A towards point B .

Considering the Equation 5.8, The deformation at the point i (def_i) can be written as the deformation phase at point i :

$$\phi_{def(i)} = \frac{def_i * 4\pi}{\lambda} \quad (5.9)$$

where, $\phi_{def(i)}$ is the deformation phase at point i in radians (rad), def_i is the deformation at point i in millimeters (mm), λ is the radar wavelength in millimeters (mm) and, i is the pixel number starting from point A towards point B .

Using Equation 5.8 and 5.9 we can write the deformation at point i :

$$\phi_{def(i)} = \frac{((def_{rateAB} * i) + def_A) * 4\pi}{\lambda} \quad (5.10)$$

where, $\phi_{def(i)}$ is the deformation phase at point i in radians (rad), def_A is the deformation at point A in millimeters (mm), def_{rateAB} is the linear deformation rate per pixel between point A and B in millimeters, λ is the radar wavelength in millimeters (mm) and, i is the pixel number starting from point A towards point B .

The deformation at point i can be model by using a model deformation rate between points A and B (Equation 5.10):

$$\phi_{Pdef(i)} = \frac{((Pdef_{rateAB} * i) + def_A) * 4\pi}{\lambda} \quad (5.11)$$

where, $\phi_{Pdef(i)}$ is the model deformation phase at point i in radians (rad), def_A is the deformation at point A in millimeters (mm), $Pdef_{rateAB}$ is the model linear deformation rate per pixel between point A and B in millimeters (mm), λ is the radar wavelength in millimeters (mm) and, i is the pixel number starting from point A towards to the point B .

By using Equation 5.7 and 5.11, the $\phi_{rmsAePhase}$ can be calculated and by minimizing the $\phi_{rmsAePhase}$, the deformation between point A to B can be model closest to the real value.

5.2.5 Correlation coefficient between measurement and the model deformation

Linear correlation or the dependence between two variables X and Y is calculated by Pearsons correlation coefficient. The calculation provides a value between +1 and -1 inclusive, where 1 signifies a total positive correlation, 0 for no correlation, and -1 is a negative correlation. It is a widely used measure in the field of sciences as a measure of the degree of linear dependence between two experimental variables.

By using Pearsons correlation coefficient, the correlation of the measurement and model deformation between A and B can be calculated:

$$CRF = \frac{(\phi_{def(i)} - \phi_{def(Mean)}) * (\phi_{Pdef(i)} - \phi_{Pdef(Mean)})}{\sqrt{\sum_{i=1}^n (\phi_{def(i)} - \phi_{def(Mean)})^2 \sum_{i=1}^n (\phi_{Pdef(i)} - \phi_{Pdef(Mean)})^2}} \quad (5.12)$$

where, $\phi_{def(i)}$ is the measured deformation phase at pixel i in the interferogram, $\phi_{def(Mean)}$ is the mean measured deformation, $\phi_{Pdef(Mean)}$ is the mean model deformation, $\phi_{Pdef(i)}$ is the model deformation phase at pixel i and, n is the number of pixels between A and B .

Correlation coefficient will be maximum, when the model value (model deformation between A and B) is closest to the real value (real deformation between A and B).

5.3 Simulation

Matlab (version 2012 b) was used as the simulation tool.

5.3.1 Constructing the spatial deformation signals

First step of the simulation is to construct a deformation signal without noise. The constructed signal (without the noise) is used as the model deformation signal for the simulation. The Equation 5.10 was used to create the deformation signal. The distance between A and B is taken as 100 meters and in a Radarsat-2

interferogram this distance is approximately equal to 33 pixels. For this simulation, deformation signals were constructed with different linear deformation rates (def_{rateAB}) between 0.01 mm per pixel to 25 mm per pixel. Figure 5.2, 5.3 and 5.4 shows model deformation signal (in blue) with different deformation rates. wavelength of the model signal is a function of the deformation rate, and amplitude of the model signal is the pixel phase value. The simulated real measurements or the real deformation signal was constructed by adding a random noise to the model deformation signal. After adding the random noise, some of the pixels can show phase values higher than π . In that case, the pixel phase values were kept between π and $-\pi$, by subtracting $k\pi$ (k is an integer) from each pixel phase value. In the same way, if the pixels show phase values lower than $-\pi$, then the pixel phase values were kept between π and $-\pi$, by adding $k\pi$ (k is an integer) to each pixel phase value. Different real deformation signals were constructed from 0.1 SNR to 0.9 SNR. The SNR was defined by the ratio of signal and noise powers. The SNR thresholds were selected by assuming that the deformation strain between two points (100 meters apart from each other) can be represented by a noisy signal (SNR < 0.9) in a Kiruna summer interferogram. Figure 5.2, 5.3 and 5.4 shows the simulated deformation signal (in red) with different deformation rates and different SNRs.

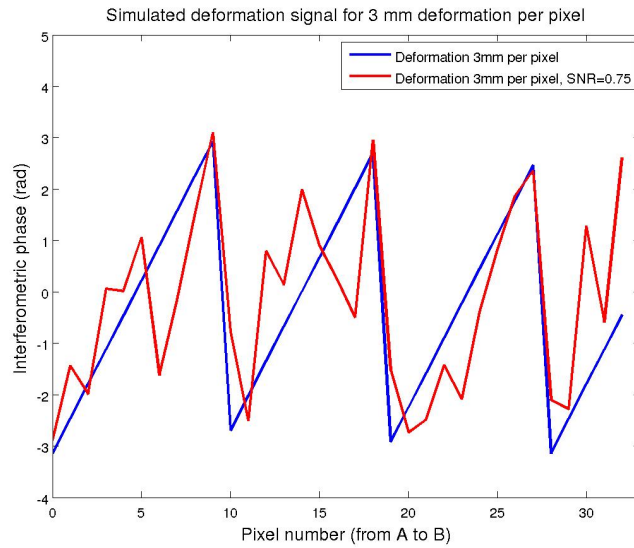


FIGURE 5.2: Simulated deformation signal with and without noise. The simulated deformation rate is 3 mm/pixel. SNR is 0.75

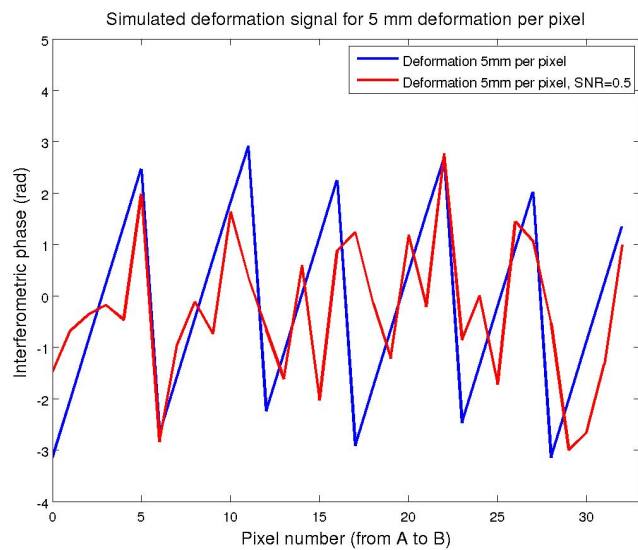


FIGURE 5.3: Simulated deformation signal with and without noise. The simulated deformation rate is 5 mm/pixel. SNR is 0.5

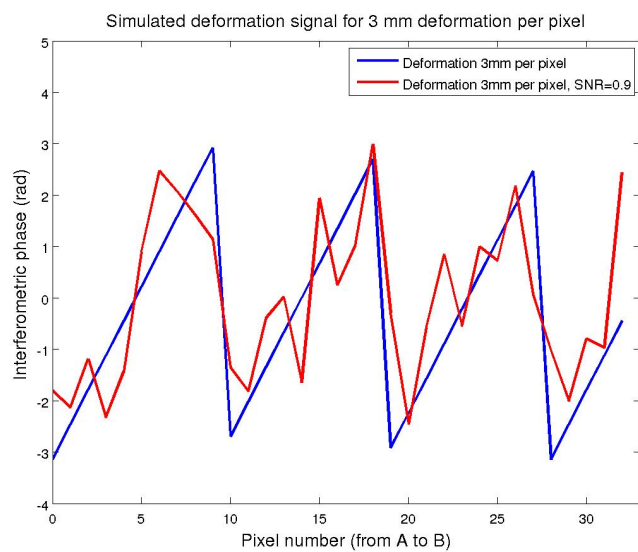


FIGURE 5.4: Simulated deformation signal with and without noise. The simulated deformation rate is 3 mm/pixel. SNR is 0.9

5.3.2 RMS error fitting simulation

For the RMS error fitting simulation, first a simulated deformation signal was constructed for a known deformation rate and known SNRs. The simulated deformation rate is chosen between 0.01mm per pixel to 25mm per pixel. The 25mm per pixel is used as the upper limit to the simulated deformation signal to avoid any wrap phase between two pixels. Then series of model deformation signals were constructed from deformation rate 0.01mm per pixel to 25mm per pixels. The deformation rate difference between two subsequent signals is 0.01mm per pixel.

Then the RMS error was calculated for each model signal with the simulated deformation signal and plot the graph RMS error Vs Predicted deformation rate. The minimum RMS error gives the best-model deformation rate for the simulated deformation rate.

5.3.3 Correlation coefficient simulation

For the Correlation coefficient method simulation, first a simulated deformation signal was constructed for a known deformation rate and known SNRs. The simulated deformation rate is chosen between 0.01mm per pixel to 25mm per pixel. The 25mm per pixel is used as the upper limit to the simulated deformation signal to avoid any wrap phase between two pixels. Then series of model deformation signals were constructed from deformation rate 0.01mm per pixel to 25mm per pixels. The deformation rate difference between two subsequent signals is 0.01mm per pixel.

The Correlation coefficient can be calculated using Equation 5.12 for each model signal with the simulated deformation signal and plot the Correlation coefficient Vs Predicted deformation rate graph. The Maximum Correlation coefficient gives the best-model deformation rate for the simulated deformation rate.

5.4 Validation methodology

For the validation of this proposed method, the DInSAR and CTM measurements that are produced for the Kiruna region were used.

5.4.1 Selection of the ROI

The ROI (Figure 5.5) was carefully selected to observe considerable deformation rates in the CTM measurements as well as in DInSAR measurements. Therefore, the buildings in the edge of the Kiruna city limits were selected for the validation. Since we are using DInSAR interferograms without phase unwrapping, we assumed that the deformation strain between two adjacent CTM targets inside the ROI is less than 28 mm for the selected period. For example, if we generate an interferogram by using one year apart images, then the strain rate between two adjacent CTM targets inside the ROI should be less than 28 mm/year.



FIGURE 5.5: Selected ROI for the validation. The selected area is marked in the blue box (image source: Google earth).

5.4.2 Selection of DInSAR interferogram and CTM targets

The CTM time series was generated by using 34 Radarsat-2 U6D beam mode (from March 2010 to September 2012) images. A external digital elevation model (DEM) was used as an input to the processing chain. EVInSAR was used for InSAR processing. 561 DInSAR interferograms were produced using the 34 images. 2010 June image was selected as the master image and the rest of the images, and the DEM was co-registered to this image. Raw interferograms were then produced for all possible image pair combinations. Topographic and flat earth phases from

the raw interferograms were removed by using the DEM and Radarsat-2 orbit information. Interferograms with low spatial coherence for the ROI (< 0.3) was removed from the interferogram stack. Optimization and correction of baseline errors were then performed. Atmospheric phase screens (APS) were generated and filtered out from the interferogram stack. The coherence threshold of 0.8 was used to identify the CTM targets. The reference phase was extracted from the stable CTM targets (CTM targets far away from the mine) and removed from the interferograms. Then CTM phase was unwrapped spatially. Then CTM time series measurements were produced for the ROI.

For the validation, a summer-to-summer interferogram generated from 2010-05-11 and 2012-05-24 images was selected. Summer-to-summer interferogram was selected to extract stable phase measurements from the ROI. An interferogram with two years time span was selected to achieve high deformation rate between point A and B .

5.4.3 Selection of points A and B

The points A , and B are selected in such a way that both A and B are visible in the CTM measurements, and both points A and B are subsidizing relatively to the stable grounds (areas away from the city). Also, the points A and B are about 100 meters away from each other. Since point B is closer to the mine compare to the point A , point B has higher deformation rate compare to point A . The Figure 5.6 shows the points A and B in the DInSAR interferogram.

5.4.4 Selection CTM points between A and B

For the validation, 6 CTM points between A and B (including points A and B) were selected. These CTM points were selected in such a way that they are equally spaced between points A and B . The CTM time series measurements were extracted for the selected CTM targets for the period 2010 May to 2012 May. The deformation from A to B (relative to A) can be written using CTM measurements as:

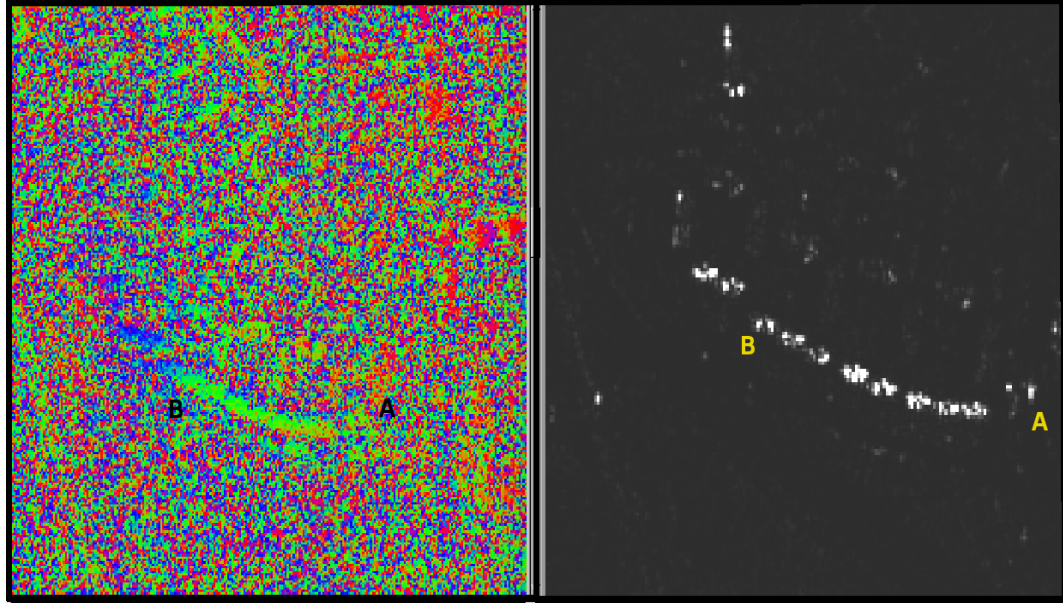


FIGURE 5.6: Points A and B : Interferogram is shown in the left, and the backscatter image is shown in the right image.

$$def_{CTM(i)} = def_{CTM(A)} - def_{CTM(A)}, \dots, def_{CTM(i)} - def_{CTM(A)}, \dots, def_{CTM(B)} - def_{CTM(A)} \quad (5.13)$$

where, $def_{CTM(i)}$ is the deformation extracted from CTM time series at point i relative to point A for the period 2010 May to 2012 May, $def_{CTM(A)}$ is the deformation extracted from CTM time series at point A for the period 2010 May to 2012 May and, $def_{CTM(B)}$ is the deformation extracted from CTM time series at point B for the period 2010 May to 2012 May.

5.4.5 Selection of pixels between A and B from the DInSAR interferogram

The 2010 May to 2012 May DInSAR interferogram was used to extract the phase from the selected pixels. Thirty two equally spaced pixels between points A and B were selected. Some of these pixels are bright pixels, and some of them were not that bright. Most of the pixels were not CTM points. A deformation signal from A and B for the selected 32 pixels can be written as:

$$\phi_{def} = \phi_{def(A)} - \phi_{def(A)}, \dots \phi_{def(i)} - \phi_{def(A)}, \dots \phi_{def(B)} - \phi_{def(A)} \quad (5.14)$$

where, $\phi_{def(i)}$ is the deformation phase at point i , $\phi_{def(A)}$ is the deformation phase at point A , $\phi_{def(B)}$ is the deformation phase at point B and, ϕ_{def} is the simulated deformation signal.

5.4.6 Validation

For the RMS validation, a deformation signal was constructed as described in the Section 5.4.5. Then series of model deformation signals were constructed starting rate from 0.01 mm per pixel to 25 mm per pixels. The deformation rate difference between two subsequent signals is 0.01 mm per pixel. Then the RMS error was calculated for each model signal with the deformation signal and plot the RMS error Vs Predicted (model) deformation rate graph. The minimum RMS error gives the best-model deformation rate.

In the same way, the Correlation coefficient (using Equation 5.12) was calculated for each model signal with the deformation signal and plot the Correlation coefficient Vs Predicted (model) deformation rate graph. The Maximum Correlation coefficient gives the best-model deformation rate. A manual optimization was carried out visualize the RMS error or Correlation coefficient for each model deformation rate.

5.5 Results

5.5.1 RMS error simulation

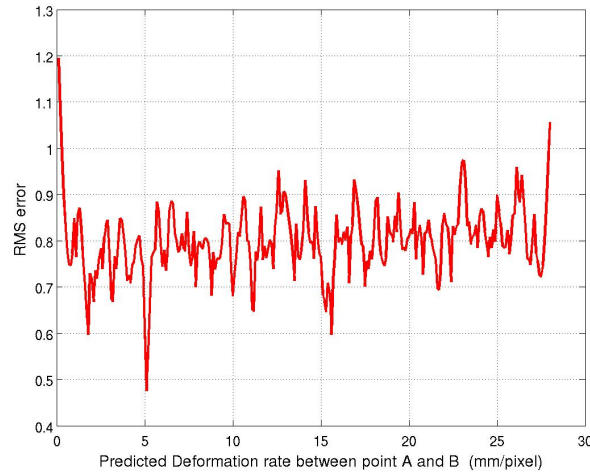


FIGURE 5.7: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 5 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

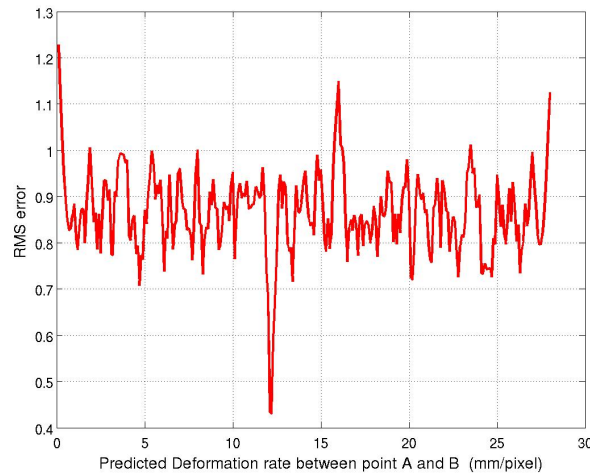


FIGURE 5.8: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 12 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

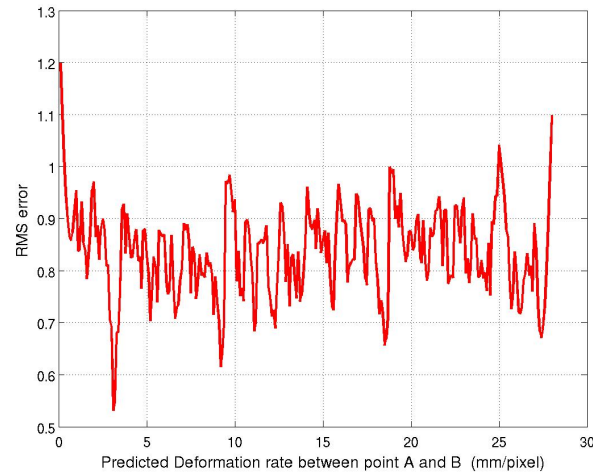


FIGURE 5.9: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 3 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

5.5.2 Correlation coefficient simulation

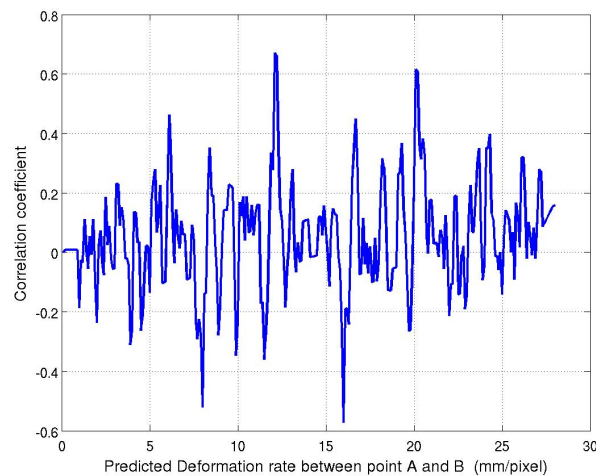


FIGURE 5.10: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 12 mm/pixel with 0.75 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

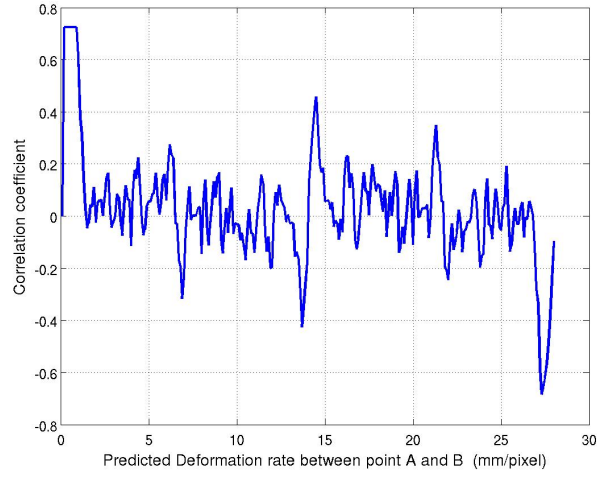


FIGURE 5.11: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 0.68 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

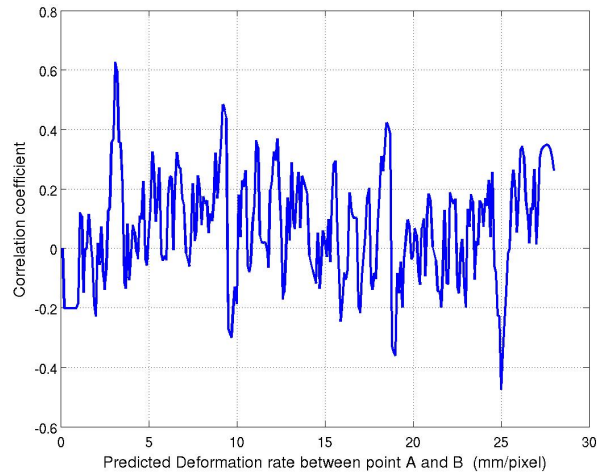


FIGURE 5.12: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 3 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

5.5.3 Validation results

The Figure 5.14 shows the best-model linear deformation rate from A to B as 0.41 mm per pixel or approximately 13 mm (for 32 pixels). The Figure 5.15 show linear deformation rate from A to B as 10 mm from the CTM measurements.

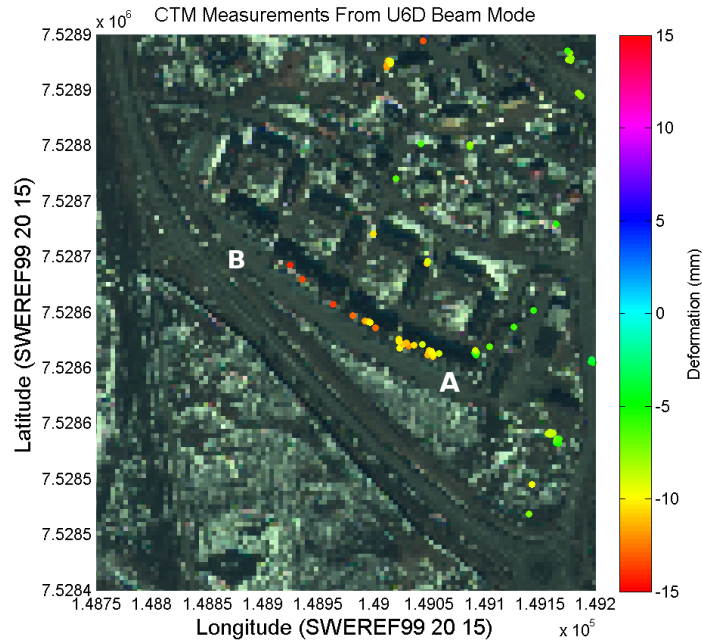


FIGURE 5.13: CTM points between A and B .

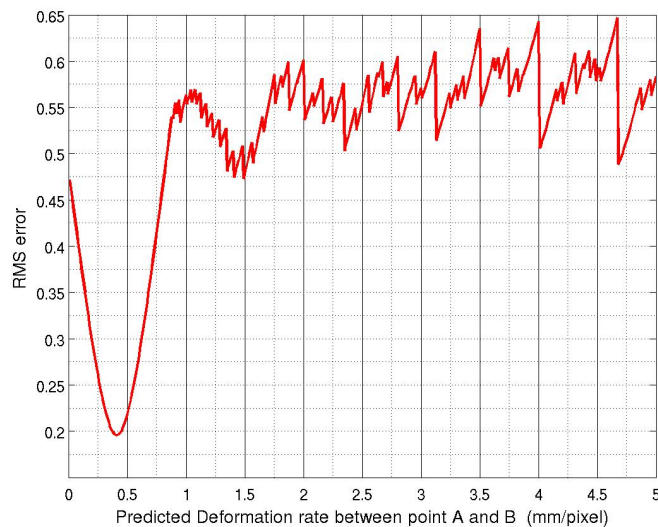


FIGURE 5.14: RMS error between real and model deformation signals. Minimum RMS value shows the closest model linear deformation rate from points A to B .

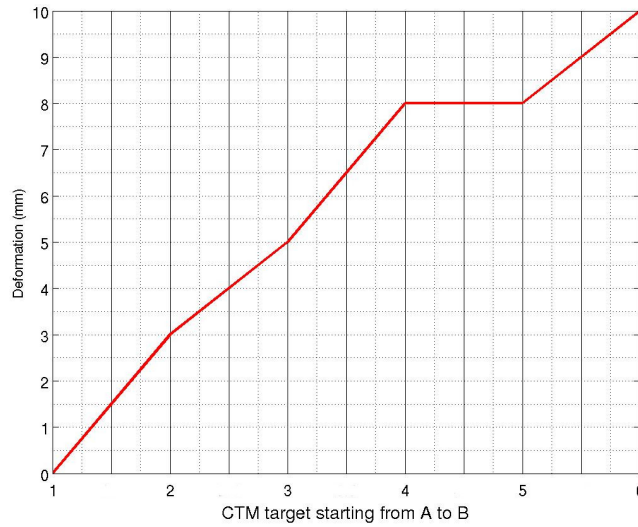


FIGURE 5.15: Deformation from A to B from CTM measurements. CTM point 1 is point A and the CTM point 6 is point B.

5.6 Discussion

The simulation result shows that by using the RMS error minimizing it is possible to predict the ground deformation more accurately. In the same way, the Correlation coefficient can be used to predict the deformation. Moreover, both RMS error minimizing and Correlation coefficient methods give same results for larger deformation rates. Correlation Coefficient shows slight variations (appears to be a constant value when rounding up to two decimal points) for small deformation rates (deformations less than 1 mm per pixel). Therefore for small deformation rates, it is not possible to identify a clear peak in the graph and failed to predict the correct value (5.11). The validation results show that, deformation estimated between point A and B from the CTM analysis is 10 mm and the deformation estimation from proposed RMS error minimizing is approximately 13 mm. There was only one area in the ROI that demonstrated this magnitude (10 mm deformation between two points) deformation with an approximate linear behaviour and which had CTM time series measurements. Therefore, only this data set is used for this validation, and this was one of the limitations of this validation. There are few limitations of this proposed technique. The first limitation is the requirement of prior information about the deformation patterns in the ROI. For mining induced deformation, most of the time this information is available and the highest deformation appears closer to the mine. Moreover, the deformation

magnitude decreases when moving away from the mine. However, if there are multiple mining areas in the ROI, the deformation pattern can be complex. In that case it is needed to use a non-linear deformation model. In this study, only the linear deformation model was used, and further studies are required to validate non-linear deformation models.

If our assumption was incorrect, then there will be wrap phase errors in the measurements. These wrap phase errors will lead to inaccurate estimations of the deformation, and that will result in failure in the validation. Since the CTM measurements and our predicted deformation values are close, we can say that our assumption is correct.

5.7 Conclusion

In this study, a model deformation signal between two points in the ROI with a known deformation parameters are compared with the DInSAR deformation measurements between those two points. The comparison was performed by using (1) RMS error and (2) Correlation coefficient. The best-fit model signal will give the least RMS error or the highest correlation to the measurement. The validation shows that the proposed technique can be used to improve the DInSAR deformation measurements up to sub-centimeter accuracies. Major limitation of this technique is the requirement of prior information about the deformation in the ROI. Simulations and validation (using CTM measurements) were carried out for linear deformation models, and further studies are required to validate non-linear deformation models.

Chapter 6

Improving North-South InSAR measurements

6.1 Introduction

This chapter presents a novel method to achieve accurate North-South measurements from repeat-pass InSAR by using compact active transponders (CAT). Standard InSAR techniques measure the ground movement only in the line-of-sight direction. Currently, operational SAR satellites have polar orbits, and the line-of-sight measurement contains only information from the vertical and horizontal (essentially East-West) change. The lack of robust measurements for North-South (NS) ground motion is observed as an impediment to the acceptance of InSAR as a complete measurement tool. This study was carried out to identify the basic requirement for a method, to achieve accurate NS measurements. An in-depth analysis of the functionality of CAT devices and fundamental InSAR equations were used for this purpose. The use of CAT devices enables the measurement of NS ground movement with the same level of accuracy as line-of-sight. In conclusion, the proposed method is workable but requires validation through field experiments.

6.1.1 Compact Active transponders (CAT)

A Compact Active transponder (CAT) is an electronic device which has the same function as a corner reflector. The device can receive radar signals from SAR

satellites and automatically transmit the received signals back to the satellite. In InSAR measurements CAT are used as stable backscattering targets [94]. Figure 6.1 shows a commercially available CAT device used for InSAR measurements [95] and figure 6.2 shows installed CAT devices in the field [96]. The device will only awake during the satellite passes and rest of the time the device will be in the sleep mode. The devices usually weigh a few kilograms, and battery lasts more than 12 months. After installation of the devices, there is no need for any manual labour unless there is a repair activity or to change the batteries. Figure 6.3 shows a simple block diagram of a CAT device. Use of CAT in InSAR measurements has been well documented, and CAT can provide sub-millimeter accuracies in the InSAR ground movement measurements [97]. By using a pulse encoding transponder design, it is possible to accurately locate the returns and process the phase change independently of any ground noise [98].



FIGURE 6.1: Commercially available CAT devices: The REFLEcX series of compact RF transponders. Developed by SEA company UK (image source: SEA [95]).

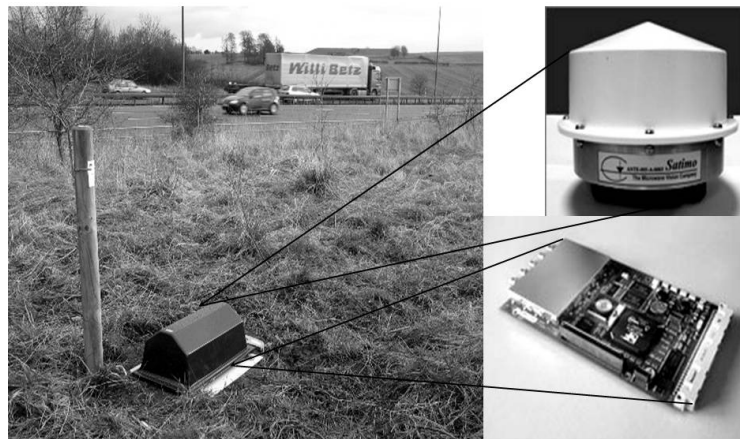


FIGURE 6.2: Commercially available CAT device installed at the field (image source: [96])

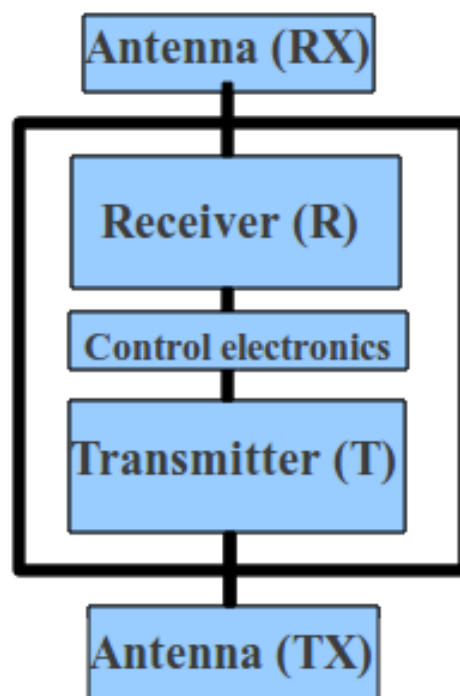


FIGURE 6.3: Simple block diagram of a CAT device

6.2 Proposed method

The proposed method requires a minimum of three CAT devices. The CAT devices are required to place on the ground as shown in Figure 6.4 to measure the North-South ground movement between point P2 and P1. CAT1 and CAT3 are placed on the point P2 and CAT2 is placed on the point P1. Line-of-sight visibility between CAT1 & CAT2, and between CAT2 & CAT3 is essential. This proposed method can be used to measure the changes in the line-of-sight distance (between CAT1 & CAT2 or between CAT2 & CAT3) distance (D_{NS}) between points P1 and P2. The receiver antenna from CAT1 is facing the satellite and the transmitter antenna from CAT1 is facing the receiver antenna of CAT2. The transmitter antenna of CAT2 is facing the receiver antenna of CAT3. The transmitter antenna of CAT3 should be facing the satellite. The frequency characteristic of the receiver from CAT1 and transmitter from CAT3 should match the satellite transmitter and receiver. The frequency characteristic of the transmitter from CAT1 and receiver of CAT2 should also match.

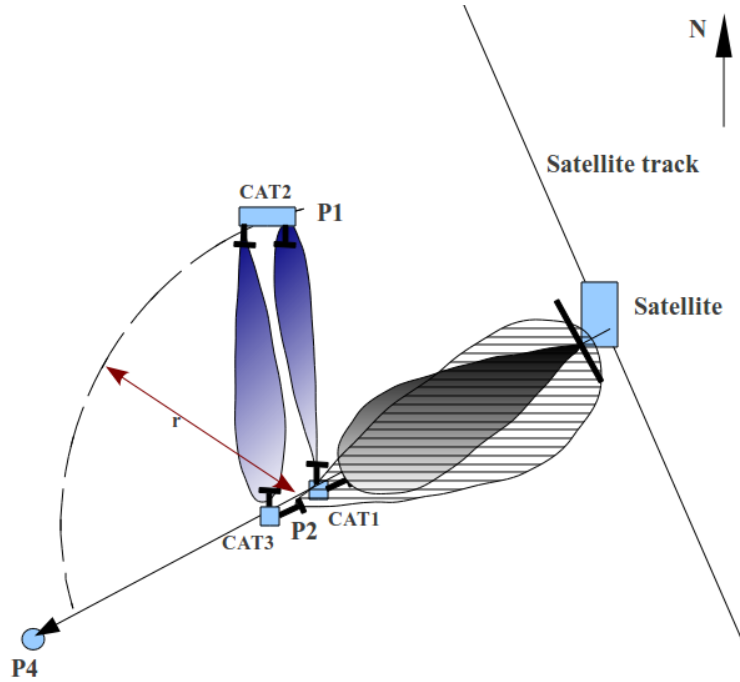


FIGURE 6.4: Proposed transponder placement in the field. The 'r' is the ground distance between point P1 and P2.

6.2.1 Theory

The interferometric phase can be written as [19]:

$$\Phi = \Phi_{\text{los}} + \Phi_{\text{topo}} + \Phi_{\text{orb}} + \Phi_{\text{atm}} + \Phi_{\text{noise}} \quad (6.1)$$

where Φ is the phase difference calculated from the interferogram, Φ_{los} is the phase difference due to the line-of-sight movement of the ground, Φ_{topo} is the topographic phase and flat earth phase, Φ_{orb} is the phase due to the incorrect baseline measurements, Φ_{atm} is the phase due to atmospheric water vapour and, Φ_{noise} is phase due to thermal noise in the system.

Equation 6.1 can be modified as follows for the proposed 3CAT method:

$$\Phi = \Phi_{\text{los}} + \Phi_{\text{NS}} + \Phi_{\text{topo}} + \Phi_{\text{orb}} + \Phi_{\text{atm}} + \Phi_{\text{noise}} + \Phi_{\text{CAT}} \quad (6.2)$$

where Φ_{los} is the phase difference due to line-of-sight (to the satellite) movement of ground at point P2, Φ_{NS} is the line-of-sight (between CAT1 & CAT2 or between CAT2 & CAT3) phase difference due to the North-South ground movement between point P2 & P1, and Φ_{CAT} is the phase difference due to the uncertainties in the response times (time delay between detection and emission of a radar pulse) of CAT1, CAT2 and CAT3.

6.2.2 Layover effect

In this proposed 3CAT method, the radar pulse transmitted from CAT3 will appear in the SAR image as a layover point. As shown in Figure 6.4, the backscatter signal from point (P4) will reach the satellite at the same time as of the transmitted signal from the CAT3. Therefore, there will be a bright pixel in the SAR image in the place where point P4 lies. The required time for the radar pulse to travel from the satellite to the layover point and return to the satellite is:

$$\tau_{\text{layover}} = \tau_{\text{LOS}} + \tau_{\text{NS}} + \tau_{\text{CAT}} \quad (6.3)$$

where τ_{layover} is the time required for a radar pulse to travel from the satellite to layover point and return to the satellite, τ_{LOS} is the total time required for an emitted radar pulse to reach the point P2 and travel back to the satellite, τ_{NS} is

the total time required for a radar pulse to travel from CAT1 (point P2) to CAT2 (point P1) and return to CAT3 (point P2), τ_{CAT} is the sum of the response times (internal delays) of CAT1, CAT2 and CAT3. The layover point(P4) will be in the far range direction away from point P2, and the line-of-sight distance between layover point and the satellite will be:

$$D_{\text{layover}} = \frac{\tau_{\text{layover}}}{2} * c \quad (6.4)$$

where D_{layover} is the line-of-sight distance to the layover point P4 from the satellite and c is the velocity of light. The North-South displacement between point $P1$ and $P2$ can only measure if the layover point lays inside the SAR image and for that, the following condition should be met:

$$\tau_{\text{layover}} < \tau_{\text{far}} \quad (6.5)$$

where τ_{far} is the time required for an emitted radar pulse to reach the far range and return to the satellite.

6.2.3 CAT response time requirement

The response time of a CAT device is crucial for this proposed method and in this section the time requirements were calculated. Here I define two types of CAT response time requirements. The first is the critical time requirement, which will define the critical condition for the CAT device. If a CAT device fails the critical time requirement, then it is not possible to use that CAT device in this proposed method. The second is the typical time requirement which will define the typical CAT device for the proposed method. The criteria for the typical time requirement calculation is that at least 90% of the area covered by the satellite image can be used for this proposed method, and to achieve that the distance between far-range and the point P1 should be less than 10% of the swath width. The distance between the points $P1$ and $P2$ will effect the distance between of $P2$ and $P4$. The distance between points $P1$ and $P2$, beam incident angle, satellite image swath width, satellite altitude are the other parameters which will effect to the CAT response time requirements.

angle (θ_n) for the Radarsat-2 U6 fine-beam mode image is 34.0277° and the far-range incident angle (θ_f) is 35.395° . The height of the satellite (h) is 802.43 km. Assuming a spherical earth model and using the cosine law, the far-range distance (D_f) and near-range distance (D_n) can be calculated. For these calculations we used the earth radius (R_e) as 6357 km.

$$R_e^2 = D_f^2 + (h + R_e)^2 - 2.D_f.(h + R_e).\cos(\theta_f) \quad (6.7)$$

$$R_e^2 = D_n^2 + (h + R_e)^2 - 2.D_n.(h + R_e).\cos(\theta_n) \quad (6.8)$$

Equation 6.7 can be rearrange as:

$$D_f^2 - [2.(h + R_e).\cos(\theta_f)].D_f + (h^2 + 2.R_e.h) = 0 \quad (6.9)$$

By solving Equation 6.9 the value for D_f can be calculated:

$$D_f = (h + R_e).\cos(\theta_f) - \sqrt{(h + R_e)^2.\cos^2(\theta_f) - (h^2 + 2.R_e.h)} \quad (6.10)$$

in same way the D_n can be calculated:

$$D_n = (h + R_e).\cos(\theta_n) - \sqrt{(h + R_e)^2.\cos^2(\theta_n) - (h^2 + 2.R_e.h)} \quad (6.11)$$

The Equation 6.6 can be rewrite using D_f , D_n and D_{NS} :

$$\tau_{CAT} < \frac{2.D_f}{c} - \frac{2.D_n}{c} - \frac{2.D_{NS}}{c} \quad (6.12)$$

By substituting Radarsat-2 U6 beam mode values to Equation 6.10 and 6.11, the D_f and D_n can be calculated. By substituting D_f , D_n and D_{NS} to Equation 6.12, following equation can be obtained:

$$\tau_{CAT} < 1.3338 * 10^{-4} \text{ s}$$

Assuming that CAT1, CAT2 and CAT3 have identical internal delays, the critical time requirement for an individual CAT device is one-third of τ_{CAT} :

$$\tau_{\text{critical}} < 4.4459 * 10^{-5} \text{ s}$$

6.2.3.2 CAT typical (recommended) response time requirement for Radarsat-2 U6 beam mode images

For the typical time requirement, Equation 6.6 can be modified as follows:

$$\tau_{\text{CAT}} < \tau_{\text{far}} - \tau_{\text{typical}} - \tau_{\text{NS}} \quad (6.13)$$

where τ_{typical} is the time required for an emitted radar pulse to reach point P1 (the distance between far-range and the point P1 is 10% of the swath width) and return to the satellite. The Equation 6.12 can be modified for the typical time requirement as:

$$\tau_{\text{CAT}} < \frac{2.D_f}{c} - \frac{2.D_{\text{typical}}}{c} - \frac{2.D_{\text{NS}}}{c} \quad (6.14)$$

where D_{typical} is the line-of-sight distance between the satellite and point P1. By using sine law (Figure 6.5) we can derive ψ_n and ψ_f :

$$\frac{\sin(\theta_n)}{Re} = \frac{\sin(\psi_n)}{Dn} \quad (6.15)$$

$$\frac{\sin(\theta_f)}{Re} = \frac{\sin(\psi_f)}{Df} \quad (6.16)$$

By using the cosine law, the D_{typical} can be derived as follows:

$$D_{\text{typical}} = \sqrt{Re^2 + (Re + h)^2 - 2.Re.(Re + h).cos(\gamma)} \quad (6.17)$$

where $\gamma = ((\psi_f - \psi_n) * 0.9) + \psi_n$ by using Equation 6.15, 6.16, 6.17 and 6.14 the τ_{CAT} can be calculated as:

$$\tau_{\text{CAT}} < 1.294 * 10^{-5} \text{ s}$$

Assuming that CAT1, CAT2 and CAT3 have identical internal delays and, therefore, the typical time requirement for an individual CAT device is one-third of τ_{CAT} :

$$\tau_{\text{typical}} < 4.3146 * 10^{-6} \text{ s}$$

6.3 Discussion

Although this proposed method can measure the North-South ground movement with the same measurement accuracies as the line-of-sight measurements, there are following limitations;

6.3.1 Requirement of Line-of-sight visibility between transponders

One of the limitations of the proposed method is the requirement of line-of-sight visibility between transponders (Figure 6.4; between CAT1 and CAT2 and between CAT3 and CAT2). This requirement can be fulfilled if points P1 and P2 are on barren flat regions. However, it can be challenging if the points (P1 and P2) are inside a forest or urban area where there are trees or buildings in between. For urban areas, the problem can be solved by placing the CATs on top of buildings. However, the multipath reflections from surrounding buildings or trees can interfere with the measurements and field tests are required to make any conclusions.

6.3.2 Layover effect

One of the limitations of the layover effect is that any bright targets in point P4 will interfere with the InSAR North-South measurements (Figure 6.4; between P1 and P2). Therefore, it is necessary to make sure that there are no bright targets in point P4. This goal can be achieved either (1) by selecting the distance between P1 and P2 in such a way that the layover point (P4) will appear on the area where there are no bright targets or (2) by removing any bright targets (if possible) from the point P4. Another limitation of this layover effect is that to achieve the North-South measurement (between point P1 and P2), P4 should be visible in the image. The placement of P1 (and P2) will depend on the response time of the Transponders (CATs), beam incident angle, satellite image swath width, satellite altitude are the other parameters which will effect the CAT response time requirements. The main advantage of this layover effect is that it can use to measure the North-South ground movement and the line-of-sight ground movement (at point P1) from a single satellite track. By placing proposed transponder arrangement in both

North-South and East-West directions, it is possible to achieve three-dimensional ground movements from a single satellite track.

6.3.3 CAT visibility in SAR image

Section 6.2.2 presents the layover effect. However, to find the exact location of the layover point, we need to treat the SAR processing as a two-dimensional problem. In the raw SAR data, the signal energy from a point target is spread not only in the range direction but also in the azimuth direction. In range direction, the signal is spread by duration the linear FM transmitted pulse. In azimuth direction, the signal is transmitted over the length of the synthetic aperture. Most of the SAR sensors use the range-Doppler algorithm to processes the collected SAR data into an image. When a point target passes through the azimuth antenna beam, range or the distance to the target will change. Because of this range variation, there will be a phase variation in the received signal that is a function of azimuth. This phase changes over the synthetic aperture complement to the Doppler bandwidth of the azimuth signal and allows the signal to be compressed in the azimuth direction [99].

Now when we place CAT device in the field, because of its response time delay, there will be a delay in the CAT transmitted signal compared to a backscatter from a stationary target. This time delay will lead to changes in the Doppler frequency chirp and Doppler shift. This problem is more analogs to a moving target in the ROI.

When a target is moving in the range direction, then the Doppler shift is changed compared with that from a stationary target. Moreover, when the target is moving along the aperture, the Doppler frequency chirp will change. As a result of above affect, moving targets will give significant position errors in azimuth and smearing effect in both range and cross-range [100]. Therefore when using a CAT device in the field, depending on the CAT response time, CAT device should show a significant position error (layover effect) in both azimuth and range directions in the image. Also because of the CAT time delays there will be defocusing effect and also smearing effect in both range and cross-range directions.

6.3.4 Replacing one transponder with a corner reflector

The proposed method requires a minimum of 3 transponder devices (3CATs). The proposed method can be modified to a 2CAT-CR method by replacing CAT2 with a corner reflector. In that case the frequency characteristic of the transmitter of CAT1 should be same as the frequency characteristic of CAT3 receiver. It is also important to avoid any direct emission from CAT1 to CAT3 since both transmitter and receiver frequency characteristic are the same. The advantage of this modification is that it can reduce the total delay time by one CAT device and therefore D_{layover} is less than for the proposed (3CAT) method. The disadvantage of this modification is that the backscattering/reflection of the surroundings of the CR can affect the measurement.

6.3.5 3D ground movement measurements by using a single satellite track

In this proposed method, CAT devices will redirect the radar waves in any direction and back to the satellite. Depending on the placement of the transponders, the proposed method can be used to measure the North-South ground movements, as well as East-West ground movements (or 3D ground movements) from a single track.

6.4 Conclusion

In this study, a novel method to improve the InSAR North-South measurements was investigated. This proposed method can deliver InSAR line-of-sight accuracies for the North-South measurements. The proposed method requires a minimum of three transponders (CAT devices) to measure the North-South ground movement between two points. The response times of the transponders are critical parameters for this method. The distance between selected ground points, beam incident angle, satellite image swath width, satellite altitude will determine the required CAT response times. For a Radarsat-2 U6 fine-beam mode image, the critical response time for a CAT device is 1.3338×10^{-4} s and the typical or recommended response time for a CAT device is 4.3146×10^{-6} s. The requirement on CAT devices, line-of-sight visibility between CAT devices and layover effects are identified

as limitations. Validation of the proposed method is an interesting topic for future work.

Chapter 7

InSAR measurements around Kiruna iron ore mine

7.1 Introduction

This chapter presents the result of a study carried out to identify the applicability of InSAR techniques for deformation measurements around Kiruna iron ore mine and Kiruna city area. For this study, EVInSAR software and its standard processing tools were used. Due to the underground mining activities ground deformation taking place around the Kiruna underground mine. With the continuous mining activities, the area affected by the mining induced ground deformations is spreading toward the Kiruna city. Therefore, it is important for LKAB to identify the affected areas. At present LKAB is using Static GPS technique to measure the deformation around the Kiruna iron ore mine and Kiruna city area. Currently, LKAB is exploring the possibility of using InSAR techniques for ground deformation measurements. For this study, images from Radarsat-2 U6D, U25D and U70D beam modes were used. The wide area deformation maps (DInSAR), CTM time series deformation maps and CRInSAR time series deformation maps were produced for the region of interest (ROI). The three-dimensional (3D) deformation vectors were calculated by using the U6D, U25A and U70D beam mode line-of-sight measurements. This study clearly shows that no individual technique can fully cover the ROI and best suitable option is to use all the techniques as a combination. Also, it has been noticed that most of the CTM points disappear due to the winter snow, and wide area deformation maps are only possible in summer

seasons. The study shows that accuracy of the North-South deformation measurements are poor due to the current orbit configurations of the SAR satellites.

7.2 Region Of Interest (ROI)

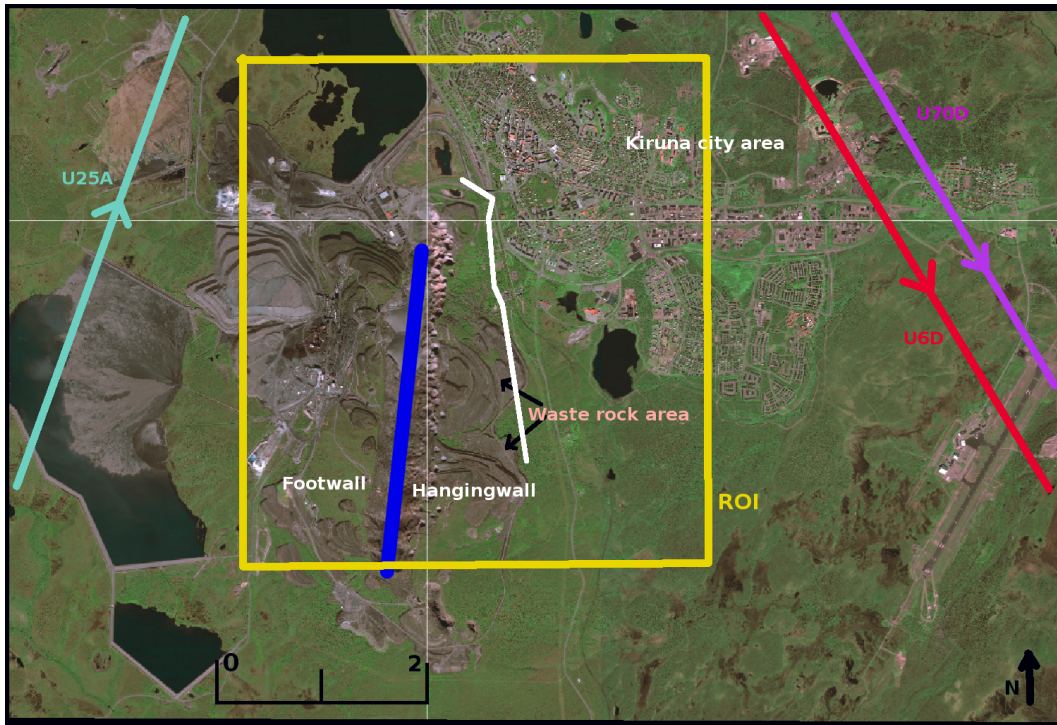


FIGURE 7.1: Kiruna city and the surroundings in summer (image source LKAB). ROI is marked in the yellow box. White line shows the Environmental criterion limit in 2014 (LKAB data was used for the plot). Used satellite track directions were marked in cyan line (U25A), red line (U6D), and magenta line (U70D).

The ROI (Figure 7.1) is located in northern Sweden ($67^{\circ}51' \text{ N}$, $20^{\circ}14' \text{ E}$) around Kiruna city and the Kiruna underground iron ore mine, which is owned by the Luossavaara Kiirunavaara Aktiebolag (LKAB) mining company. The mine is approximately 1 km (to the west side) from the Kiruna city. The ROI comprise with barren and flat waste rock areas, forest areas and Kiruna city area. Due to the underground mining the hangingwall wall side is experiencing ground deformation. The ROI is marked in the yellow box in the Figure 7.1.

7.3 Data

For this study, Radarsat-2 U25A (ascending), U6D (descending) and U70D (descending) beam modes were used. The characteristics of the selected beam modes were presented in the table D.1. For this study 33 images from U25A beam mode, 34 images from U6D beam mode, and 34 images from U70D beam modes were used. The Table D.2, D.3 and D.4 present the details of the used images. Image details are presented in the Appendix D.

7.4 Methodology

The Interferogram processing was carried out by using the EVInSAR processing software. The software contains separate processing chains for DInSAR, CTM, CRInSAR processing and three-dimensional (3D) deformation map generation.

7.4.1 DInSAR interferogram generation

EVInSAR DInSAR processing chain was used for the DInSAR Interferogram generation. As the first step, an image stack was prepared for each beam mode. U25A image stack was prepared using 33 images. U6D image stack was prepared using 34 images, and U70D image stack was prepared using 34 images. The 2010-03-24 image was selected as the master image (this was the first image acquired after CR installation) for the U6D beam mode, the 2010-03-18 image was selected as the master image (this was the first image acquired after CR installation) for the U25A beam mode, and the 2011-05-19 image was selected as the master image (this was the first image taken from the U70D beam mode) for the U70D beam mode. As the next step, images from each beam mode and an external DEM were co-registered to their respective master image. MDA provided the external DEM, and they have reported that the DEM was created by merging a Radarsat-2 DEM with an ASTER DEM. As the second step, three different image sub stacks were prepared for each beam mode (1) by keeping the original image stack (1 x 1 multi look), (2) by 4 x 4 multi looking for U6D and U25A and 4 x 2 multi looking for U70D beam mode and (3) by 10 x 10 multi looking. The original image stack was used for corner reflector InSAR processing, 4 x 4 and 4 x 2 multi look stacks were

used for the CTM InSAR processing and 10 x 10 multi look stacks were used for the wide area deformation maps. The main reason for this multi looking step is to reduce the spatial noise as well as the image size. Since the pixels are more rectangular shape in U70D beam mode (due to the steep incident angle) the 4 x 2 multi looking was used. As the next step 528 raw interferograms (for all possible image pair combinations) were produced for each sub stack for the U25A beam mode images, 561 raw interferograms (for all possible image pair combinations) were produced for each sub stack for the U6D beam mode, and 561 raw interferograms (for all possible image pair combinations) were produced for each sub stack for the U70D beam mode. The topographic and flat earth phases were subsequently removed from the raw interferograms by using an external DEM and Radarsat-2 orbit information. Then the average spatial coherence is calculated for each interferogram. The baseline errors were then optimized and corrected. The spatial coherence of the interferogram was used as an input parameter for the baseline optimization. The baseline optimization errors were identified when the average spatial coherence of the interferogram is less than 0.3. As the next step the 1 x 1, 4 x 2 and 4 x 4 interferograms were used to create a subset of interferograms by only selecting the ROI in the interferogram. This step is performed to reduce the size of the interferogram stack. A low-pass atmospheric phase screen (APS) was generated for each interferogram, with the deformation area masked out to prevent any loss of signal. The 10 x 10 multi look interferograms were used to generate the atmospheric phase screens (APS). APS was applied, and atmospheric phase noise was removed whenever the interferograms average spatial coherence was high enough to generate a valid APS. The next step was to use these interferograms to produce the DInSAR wide area deformation maps, CTM time series maps, and CRInSAR time series maps.

7.4.2 DInSAR wide area deformation maps

The 10 x 10 multi look image sub stack interferograms were used to produce the DInSAR wide area deformation maps. The interferograms that have higher spatial coherence (higher than 0.6 in the waste rock areas) were selected. The 0.6 coherence threshold is selected by trial and error method. The interferograms that have spatial coherence lower than 0.6 (in the waste rock areas) were showing higher unwrapping errors. Then the reference phase was calculated for each interferogram by using the stable areas in the ROI and the reference phase was removed. As

the next step, the low coherence areas in the interferograms were masked, and phase unwrapping was performed. The deformation maps were created by converting line-of-sight deformation to vertical and horizontal deformations. Finally, the deformation maps were geocoded to the SWEREF99 20 15 projection.

7.4.3 CTM time series maps

EVInSAR CTM processing chain was used for the CTM processing. For CTM processing U6D 4 x 4 multi look subset interferograms, U25A 4 x 4 multi look subset interferograms and U70D 4 x 2 multi look subset interferograms were used. As the first step, all the low spatial coherence interferograms were removed to exclude the interferograms with baseline optimization errors or faulty APS errors from the interferogram stack. Here used spatial coherence threshold was 0.3. The second step was to identify the CTM targets from the interferogram stack and extracts the CTM phase (line-of-sight). The targets that have higher coherence thresholds are identified as the coherent targets. Here coherence threshold of 0.8 was used. It was observed that, when the coherence threshold is higher than 0.8 the phase values of nearby CTM targets are spatially homogeneous but if the threshold is less than 0.7 then the phase values of nearby CTM targets are spatially heterogeneous which will lead to unwrapping errors. The next step was to decide the minimum required number of CTM targets for the ROI. For this study, I have decided the minimum required number of CTM targets as 5000 for the ROI. The next step was to process the interferogram stack and to check whether the minimum number of CTM targets can be achieved. If not, interferogram with the lowest spatial coherence was removed from the image stack and recheck the number of CTM targets, and this step was repeated until the number of CTM targets exceed 5000 for the ROI. The fourth step was spatially unwrapping the CTM phase. Then the reference phase was calculated from the stable CTM targets, and average reference phase was removed from the rest of the measurements. A network inversion (a maximum likelihood estimator of all (a maximum likelihood estimator of all possible measurements [101, 102] was used to provide the most robust measurement of the line-of-sight (LOS) change at each CTM targets. Finally, the deformation maps were geocoded to the SWEREF99 20 15 projection.

7.4.4 CRInSAR time series maps

EVInSAR CRInSAR processing chain was used for the CRInSAR processing. For CRInSAR processing U6D, U25A, U70D 1 x 1 multi look subset interferograms were used. As the first step, all the low spatial coherence interferograms were removed to exclude the interferograms with baseline optimization errors or faulty APS errors from the interferogram stack. Here, used average spatial coherence threshold was 0.3. The second step was to extract the CRInSAR phase (line-of-sight) from the interferogram stack. The third step was to unwrap the CRInSAR phase spatially. The phase unwrapping errors were corrected by using an adaptive deformation model based on sequential deformation. Then the reference phase was calculated from the stable corner reflectors and removed the average reference phase from the rest of the measurements. A network inversion (a maximum likelihood estimator of all (a maximum likelihood estimator of all possible measurements [101, 102] was used to provide the most robust measurement of the line-of-sight (LOS) change at each reflector. Finally, CRInSAR time series maps were geocoded to the SWEREF99 20 15 projection.

7.4.5 Three-dimensional (3D) time series map generation

EVInSAR three-dimensional vector separation processing chain was used for three-dimensional time series map generation. To generate 3D deformation maps for corner reflectors, the CRInSAR line-of-sight measurements from U6D, U25A and U70D were used. First the U6D beam mode was selected as the master beam mode. The U25A and U70D line-of-sight time series measurements were temporally interpolated to coincide with the U6D measurement dates. Then the 3D vectors (North-South, East-West and Vertical deformation vectors) were calculated for each corner reflector by using the beam incident and aspect angles. Finally, CRInSAR North-South, East-West and Vertical deformation maps were geocoded to the SWEREF99 20 15 projection.

To generate 3D deformation maps for CTM targets, the CTM line-of-sight measurements from U6D, U25A and U70D were used. First the U6D beam mode was selected as the master beam mode. The U25A and U70D CTM time series measurements were temporally interpolated to coincide with the U6D measurement dates. As the next step, the CTM line-of-sight measurements were geocoded to the

SWEREF99 20 15 projection. Then the CTM line-of-sight time series measurements were interpolated to a spatial grid. The distance between two consecutive grid points was selected as 50 m. Since most of the GPS points has a 50-100 m distance between each other, the 50 m grid spacing was used. Finally, the 3D vectors (North-South, East-West and Vertical deformation vectors) were calculated for each grid point by using the beam incident and aspect angles.

7.4.6 Small Baseline Subset network

Figure 7.2, 7.3 and 7.4 shows the image pairs used in the Small baseline subset network. The spatial (perpendicular baseline) and temporal baseline thresholds for image pair selection are 400 m and 180 days respectively. However, some image pairs were manually selected to omit low-coherence interferograms and to achieve well-connected network for each track.

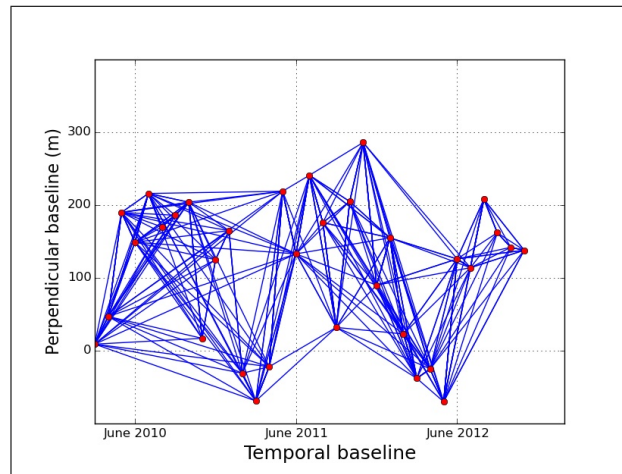


FIGURE 7.2: The network of the individual Small baseline subset (SBAS) interferograms for the U6D track. The red circles represent the images, and the blue lines show the image pairs of the generated interferograms.

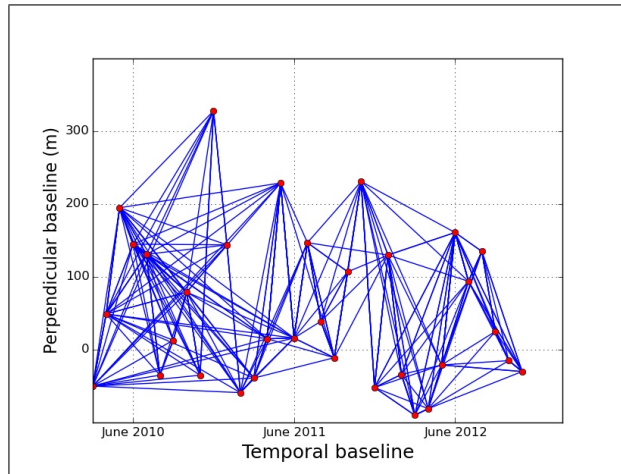


FIGURE 7.3: The network of the individual Small baseline subset (SBAS) interferograms for the U25A track. The red circles represent the images, and the blue lines show the image pairs of the generated interferograms.

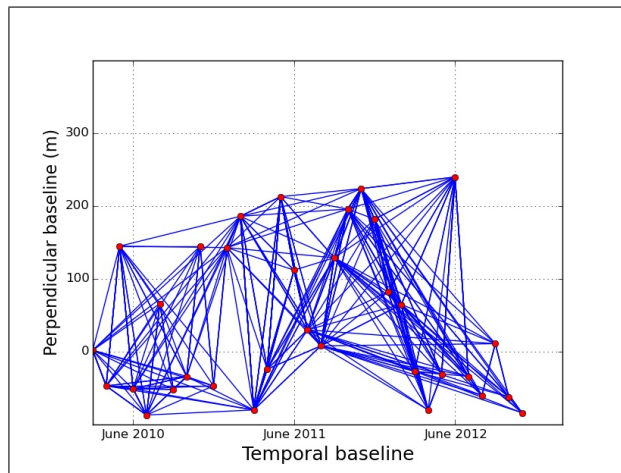


FIGURE 7.4: The network of the individual Small baseline subset (SBAS) interferograms for the U70D track. The red circles represent the images, and the blue lines show the image pairs of the generated interferograms.

7.5 Results

Figure 7.5 shows the summer-to-summer DInSAR interferogram generated from U6D, U25A and U70D beam modes for the Kiruna region. Figure 7.6 is the CTM map generated for the Kiruna region from 2010 March to 2012 May. Figure 7.7 is the CRInSAR map generated for the Kiruna region from 2010 March to 2012 May.

7.5.1 DInSAR interferograms

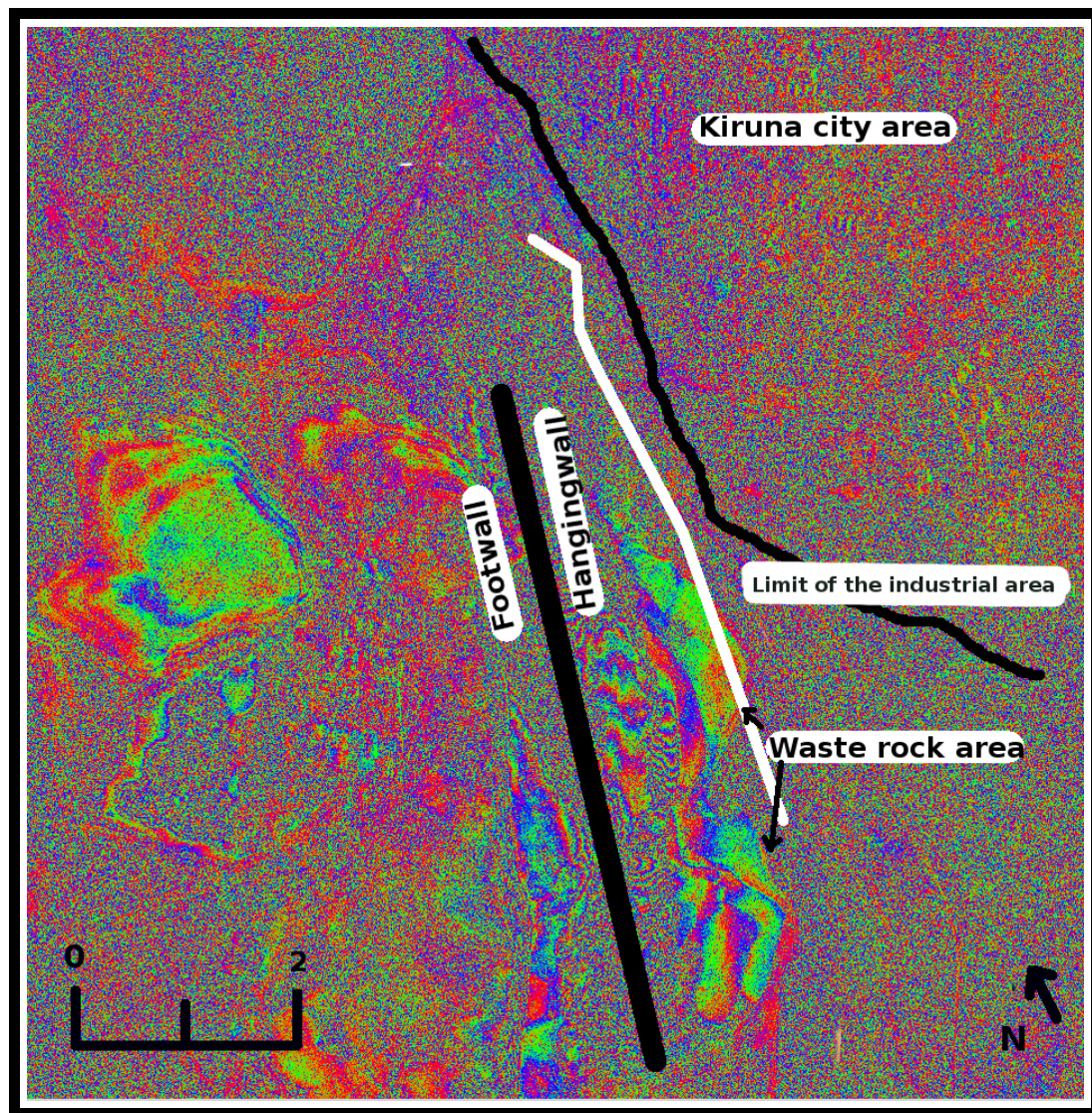


FIGURE 7.5: DInSAR summer-to-summer (2010-06-28 to 2010-08-15) interferogram from U6D beam mode for the ROI. White line shows the 2014 Environmental criterion limit (LKAB data was used for the plot). Thin blackline shows the line of the LKAB industrial area. Image scale is in kilometers.

7.5.2 CTM time series maps

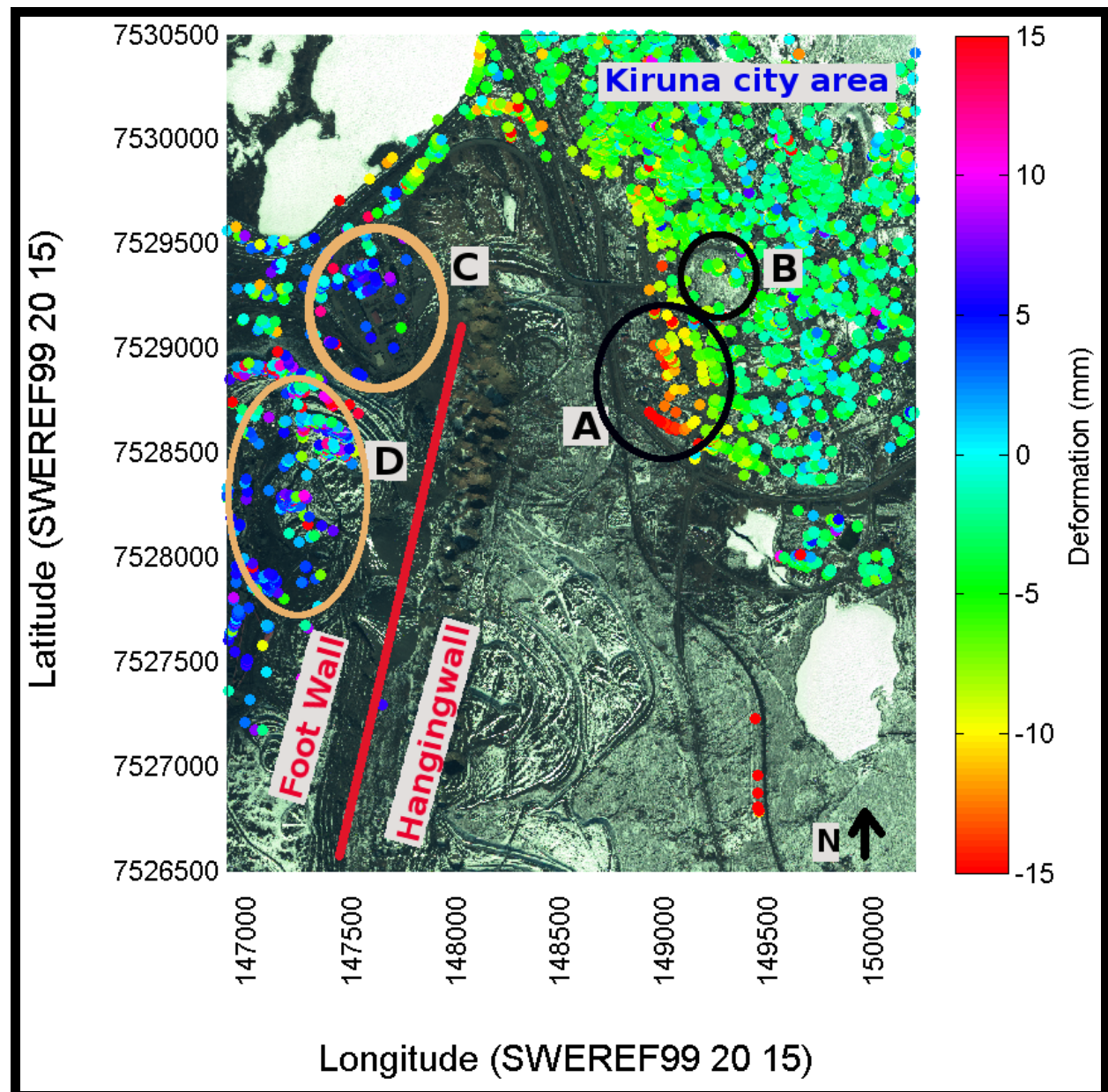


FIGURE 7.6: U6D line-of-sight CTM time series deformation measurements for Kiruna city and mine surrounding area from 2010 March to 2012 May. Ground movements towards to the satellite are positive, and ground movements away from the satellite are negative.

7.5.3 CRInSAR time series measurements

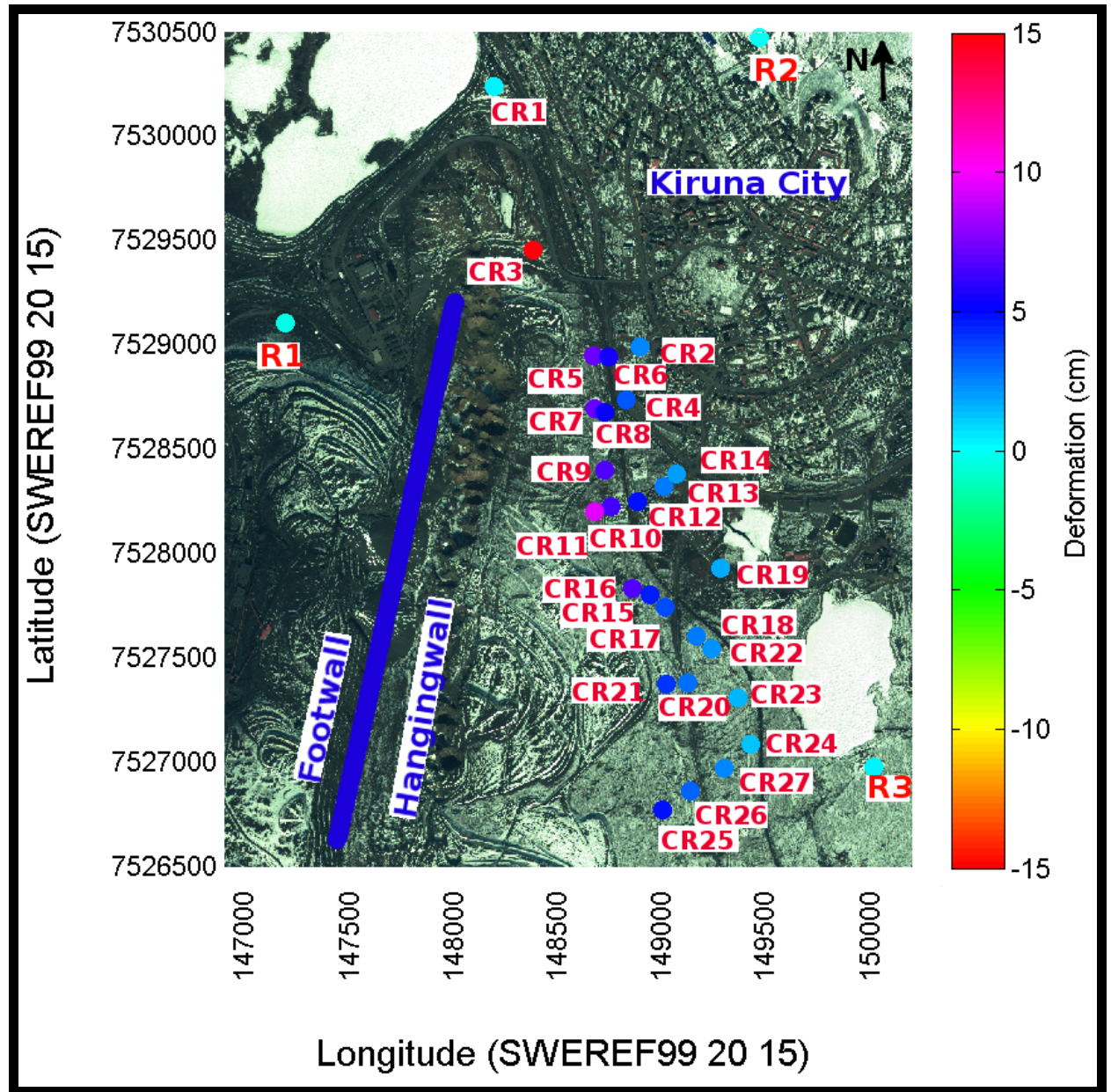


FIGURE 7.7: U6D line-of-sight CRInSAR deformation measurements for Kiruna CR network from 2010 March to 2012 May. Ground movements towards to the satellite are negative, and ground movements away from the satellite are positive.

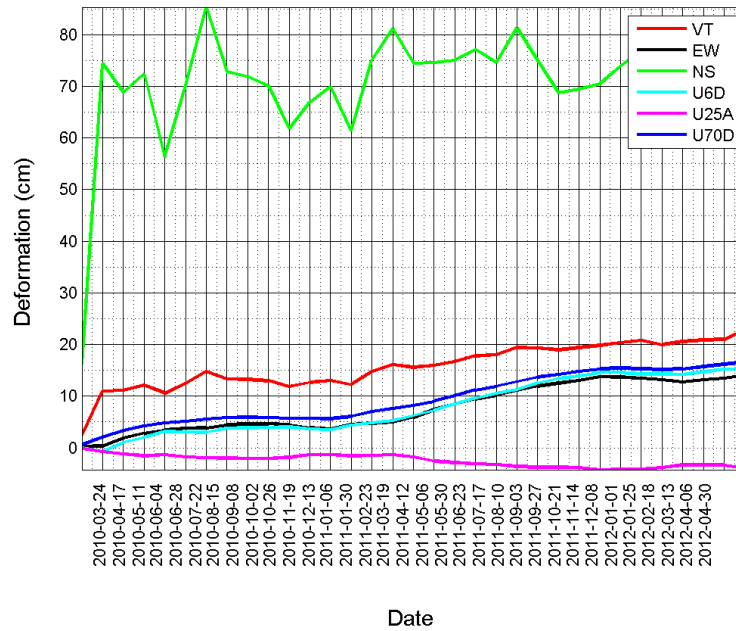


FIGURE 7.8: CRInSAR Time series from U6D, U25A, U70D beam modes and East-West, North-South and Vertical deformation components for CR3.

7.6 Discussion

In this study, DInSAR, CTM and CRInSAR techniques were used to measure the deformation around Kiruna iron ore mine and Kiruna city area. Each technique is successful in different areas in the ROI.

The waste rock areas have high spatial coherence, and therefore the DInSAR interferograms can be used to measure the ground movements in those areas. But DInSAR cannot be used in low spatial coherence areas such as city or areas with vegetation cover. The CTM technique shows a large number of CTM targets in the city area and few CTM targets in the waste rock area but there are no CTM targets in the areas of outside the city and waste rock. Corner reflectors are only available between city and waste rock and therefore the corner reflector measurements are limited to that part. Therefore neither technique can adequately cover the entire ROI. Therefore, it is necessary to use measurements of all these techniques to cover the entire ROI.

7.6.1 Seasonal effects in CTM measurements

The seasonal effects in the CTM targets are two-fold. The first is losing coherence due to the snow deposition on the targets. The second is losing spatial coherence in the interferogram due to the ground snow layer. Having a good spatial coherence is essential for a good APS. Also, spatial coherence is an input parameter to the baseline optimization step. Therefore, poor spatial coherence in the interferogram will add additional noise to the CTM measurements. If the winter interferograms used for CTM processing, then it is observed that the number of CTM targets for Kiruna city area dropping to less than 1000 targets. Because of this, the spatial density of the targets in the ROI is decreased. However, without the winter interferograms there are more than 8000 high coherence (0.8 or above) CTM targets. Therefore, the winter interferograms were removed from the CTM stack to achieve high spatial density of targets for the ROI. If the CTM coherence threshold was decreased slightly (0.6) then it is possible to increase the number of CTM targets (around 3000 CTM targets) in the ROI. However, it is observed that there are more phase unwrapping errors in the measurements. To achieve high CTM target density and also to minimize phase unwrapping errors, the winter interferograms were left out from the CTM processing.

7.6.2 DInSAR measurements around Kiruna iron ore mine

Waste rock area shows poor spatial coherence during the winter. The main reason for the low spatial coherence is the ground snow layer. However, during the summer the waste rock area shows high spatial coherence. Moreover, the annual deformation rate at the waste rock area varies from centimeter range to meter range. The highest deformation appears closer to the mining area. In the city area, there are some parts that exhibit high spatial coherence during the summer. However, the interferograms are too noisy to determine the deformation rate. During the winter, the city area exhibits poor spatial coherence. Therefore, the DInSAR measurements can only be used for summer interferograms and only for the waste rock area. Figure 7.5 shows the summer DInSAR interferogram generated from U6D beam mode for the Kiruna region.

7.6.3 Kiruna CTM time series measurements

Figure 7.6 shows the line-of-sight CTM time series measurements from U6D beam mode for the test site from 2010 March to 2012 May. All CTM time series measurement shows consistent deformation information for the Kiruna city area. Edge of the city (area *A*) shows the highest deformation rate in the CTM targets. The area *C* shows considerable ground movement in the footwall side. However, this ground movement was not captured by the LKAB GPS surveys. It is found that (information received from the MDA), the ground movements in the area *C* is a result due to a height error in the DEM. In InSAR processing, it requires removing the phase contribution from the topography from the interferograms. The DEM and information about the imaging geometry are used to approximate the topographic phase. The topographic phase is proportional to the perpendicular baseline of the interferogram. If we use a DEM with a height error, then our approximation of the topographic phase is not correct, and it leads to baseline-dependent phase residuals in the interferogram. In SBAS method, interferometric phases is used to estimate the DEM error and remove it from interferograms. However, from the results, it is visible that using only SBAS will not necessarily minimize the effect of DEM error. The area *D* also shows ground movement. However, the ground movements in the area *D* is due to the local industrial activities (movement of the waste rocks). Same deformation pattern is visible in the East-West CTM deformation vector, and East-West CTM deformation vector can be used to determine the LKAB Environmental criterion limit. However, because of the current satellite geometry, it is not possible to achieve three orthogonal line-of-sight measurements and therefore the North-South deformation vector is very noisy (about 10 cm standard deviation). Therefore, the North-South deformation vector cannot be used to determine the LKAB Environmental criterion limit. Moreover, the vertical CTM deformation vector is also somewhat noisy (about 1 cm standard deviation), but can be used to determine the LKAB Environmental criterion limit. The area *B* show that there are no CTM targets in that area.

7.6.4 Kiruna CRInSAR time series measurements

Figure 7.7 shows the line-of-sight CRInSAR time series measurements from U6D beam mode. All beam modes show consistent deformation patterns for the ROI.

The corner reflectors which installed closer to the mine exhibit the highest deformation rates (e.g., CR3), and the deformation rates decrease when they move away from the mine. Because of the current satellite geometry it is not possible to achieve three orthogonal line-of-sight measurements from any beam mode combination. Therefore, the North-South CRInSAR deformation vector is very noisy (Figure 7.8), and it cannot be used to determine the LKAB Environmental criterion limit. East-West vector is the least noisy deformation vector and suitable for determining the LKAB Environmental criterion limit. Although the vertical CRInSAR vector is also somewhat noisy, but it can be used to determine the LKAB Environmental criterion limit.

7.7 Conclusion

The InSAR deformation measurements around Kiruna iron ore mine show that neither single technique (DInSAR, CTM or CRInSAR) alone can fully cover the entire test site. The best suitable option is to use all the techniques as a combination. It has been noticed that most of the CTM points disappear due to the winter snow. The wide area deformation maps are only possible in summer seasons. The accuracy of the North-South deformation measurements are poor due to the current orbital configurations of the SAR satellites. The study shows that without the winter images still it is possible to achieve accurate CTM and CRInSAR time series estimations. Therefore, by omitting the winter images, the required number of images can be reduced by 50%. Moreover, the required number of images can be reduced further 30% by only using two beam modes instead of using three beam modes and still achieve the same accuracy levels in the CTM and CRInSAR time series measurements.

Chapter 8

Discussion

At the beginning of this study, it is known that the long winter season (with snow) will be the biggest challenge for the InSAR measurements. However, there were no prior InSAR monitoring studies for Kiruna region to understand the seasonal effects in the InSAR measurements. The general understanding was that the DInSAR measurements are vulnerable to seasonal effects, but CRInSAR and CTM measurements will be insusceptible to winter snow conditions. This research study shows that not only DInSAR but also CTM and CRInSAR techniques were affected by the winter snow conditions.

From this research, LKAB was expecting to get answers to the following questions:

1. What are the limitation of Kiruna InSAR measurements?
2. How to further improve Kiruna InSAR measurements (especially the winter InSAR measurements)?
3. Can InSAR use as an operational technique for Kiruna subsidence measurements?

The first step of this Ph.D. study was to quantify the seasonal effects in the InSAR measurements, which will provide answers to the above question 1 and 3. The second step was to identify techniques to improve the high latitude InSAR measurements, which will give answers to the above question 2.

8.1 Limitation of Kiruna InSAR measurements

This study shows that, neither single InSAR technique (DInSAR, CTM and CRInSAR) can cover entire ROI. DInSAR technique is only suitable for the waste rock areas, and CTM technique can cover only the Kiruna city area. Most part of the ROI is covered with forest area, and installation of a greater number of corner reflectors are needed to cover those areas. Therefore, requirement of large corner reflector network is one of the limitations in Kiruna InSAR measurements.

Since neither individual InSAR technique can cover entire ROI, Most suitable option is to use DInSAR, CTM and CRInSAR techniques as a combination to cover the entire ROI. However, since each InSAR technique (DInSAR, CTM and CRInSAR) has different measurement accuracy levels, each area in the ROI will have different measurement accuracies, and this is another limitation of Kiruna InSAR measurements.

The Kiruna mine surrounding area is exhibiting three-dimensional ground movements. Also, the “LKAB Environmental criterion limit” is defined as maximum allowed strain limit between two points on the ground. Since most of the ground movements are in East-West and vertical directions, at least, LKAB requires accurate deformation measurements in East-West and Vertical directions. However, InSAR provides line-of-sight deformation measurements. In this study, three different beam modes were used to separate the three-dimensional ground movement vectors. Because of the current satellite orbital parameters it is not possible to achieve accurate InSAR North-South ground movement vector, and this is another limitation of the Kiruna InSAR monitoring.

This research study shows that all used InSAR techniques (DInSAR, CTM and CRInSAR) were affected by the winter snow conditions, and this is another limitation of Kiruna InSAR measurements.

8.2 Improving Kiruna InSAR measurements

As the first step of this research study, the seasonal effects in InSAR measurements were quantified to identify the areas for improvements. The Chapter 2, 3 and 7 show how the DInSAR, CRInSAR and CTM measurements are affected by the

seasonal effects. The improvements of winter InSAR measurements were carried out by optimizing the InSAR processing scheme. This research study shows that by optimizing the InSAR processing scheme, manual inspection and quality control of each InSAR processing steps can minimize the errors and can improve both summer and winter InSAR measurements. Each Chapter presents the detailed description of the used methodologies.

Apart from optimizing the InSAR processing scheme, the Root Mean Square (RMS) error fitting technique was used to optimize DInSAR measurements. Since the Kiruna mining area has spatial deformation pattern, it was able to optimize the DInSAR measurement accuracies up to sub-centimeter levels.

Improving North-South InSAR measurements were a major challenge. One of the major contributions of this study is introducing a novel technique to measure North-South InSAR measurements. This technique is suitable for both high latitude and low latitude deformation measurements. The proposed technique will be most valuable for areas where Ground-based radar or manual surveying is not possible.

8.3 InSAR use as an operational technique for Kiruna subsidence measurements

To use InSAR as an operational technique for Kiruna subsidence measurement, the following conditions should be met.

1. InSAR measurements should provide required accuracy levels to measure the Environmental criterion limit.
2. InSAR measurements should be able to cover the entire ROI.

This study shows that only the CRInSAR and CTM line-of-sight, East-West and vertical measurements can provide the required measurement accuracies to measure the “Environmental criterion limit”. To comply with the current “Environmental criterion limit”, both vertical and horizontal deformation vectors need to be calculated. However, after the vector separation, the North-South measurement vector exhibits large noise levels. Since most of the ground movements are

in East-West and vertical directions, the East-West and, Vertical vectors are sufficient to calculate the ground strains. Also, in some corner reflectors, even the InSAR vertical vector has large noise levels. Only the East-west vector exhibits low noise levels in all measurements. Since the ground deformation around the mine is dominant by the East-West ground movements, current InSAR measurements can use to measure the LKAB current Environmental criterion limit. However, to use InSAR line-of-sight measurements to assess the “Environmental criterion limit”, it is required to apply appropriate correction factors to compensate the line-of-sight angle. The CTM technique provides adequate coverage (more than 5000 CTM points) for the Kiruna city area. However, the most of the current Environmental criterion limit lies between the waste rock area and the Kiruna city, and this area is covered only from 36 corner reflector points. Therefore, the least measurement density is available for the area where the current Environmental criterion limit lies. Moreover, part of the Environmental criterion limit lies on the waste rock area. However, at present, there are few CTM points (from U25A, and U70D track) cover that area, and there are no any corner reflector installations. Therefore, it is important to increase the number of installed corner reflectors in the area between Kiruna city and Kiruna iron ore mine.

8.4 High latitude InSAR processing challenges

Since LKAB already owned the software license, EVInSAR software was used for the InSAR processing. EVInSAR only has a CTM module and does not contain a PSInSAR module. Therefore, all the time series analysis were carried out using the CTM technique. EVInSAR software is a proprietary software and therefore there were no accessible details about the software code or used algorithms. One of the limitations of this research study is the use of a proprietary software. As an example, Graph 7.8 shows a shift in the InSAR North-South vector component. This behavior can be an adverse effect from the software code. However, since there is no accessible information about the software code or algorithms, it is difficult to rule out the negative contribution from the software code. In the EVInSAR software, baseline optimization and APS generation are two steps that use spatial coherence of the interferograms as an input parameters. In this study, it is observed that even a thin ground snow layer will effect to the spatial coherence of the interferograms. Therefore, baseline optimization and APS generation

steps will not work as expected. Having fault baseline values and fault APS will add more noise to the measurements than removing the noise, and this is one of the limitations of the current InSAR processing chain. Therefore during the InSAR processing, low coherence interferograms were removed from the interferogram stack before any baseline optimization or APS generation. The optimum coherence threshold was selected after performing manual inspection of the interferograms. The optimum coherence threshold was decided to keep all the possible interferograms for further processing. Manual inspection of the interferograms will not require for low latitude InSAR processing. For this study, Radarsat-2 definitive orbital information was used and the selected ROI also a small area (approximately $8 \times 8 \text{ km}^2$ area). Therefore, the error from the fault baseline is expected to be minimum. However, manual inspections were carried out to check the success of the baseline optimization step and if the optimization was failed, then only the available Radarsat-2 definitive orbital information were used. APS was generated by using a two-dimensional low-pass filter. However, when the spatial coherence of an interferogram is low, then the low-pass filter sometimes failed to capture the atmospheric effects. Therefore, manual quality control was performed, and any APS that has turbulent patterns was removed (it is highly unlikely to have turbulent atmospheric effects for the ROI). If the APS is faulty, then the interferogram was used without applying the APS. Extensive manual inspection and quality control measures will improve the InSAR measurement accuracies. However, a considerable amount of time is required for these manual inspection and quality control steps, and this is another limitation of current InSAR processing chain.

8.5 Required minimum number of satellite images for Kiruna InSAR measurements

In this study, it is found that the usefulness of the winter satellite images is very limited. Even the CRInSAR measurements are affected from winter snow conditions. By introducing winter interferograms to the CRInSAR and CTM processing the uncertainty of the measurement increases than decreasing. Therefore, the recommendation is to use only the summer (snow free) satellite images for the InSAR processing for the Kiruna region. Instead of using both summer and winter images (15 images from each beam mode per year), same measurement quality can be achieved by only using the summer (snow free) images (7-8 images per year).

Only using the summer images means 50% fewer images and possible saving image costs. However, by using only summer images means losing any available data in the winter images. Therefore it is recommended to use only the summer images if there is a requirement for image cost saving.

Apart for the Radarsat-2 satellite, TerraSAR-X, COSMO-SkyMed and Sentinel-1 satellites are also suitable for the ground deformation measurements at Kiruna.

The TerraSAR-X satellite is X-band (center frequency is 9.6 GHz) SAR satellite. The satellite has three beam modes, and the “spotlight” is the recommended mode for the LKAB ground deformation measurements. Spotlight mode has a 10 km x 5 km Swath and 1 m resolution. The satellite has a repeat cycle of 11 days. Therefore by using TerraSAR-X, LKAB can collect more images (about 15 images) in the summer (snow free period) compared to Radarsat-2.

COSMO-SkyMed is made up of four satellites called COSMO 1 - 4. These satellites are in a constellation, and each satellite has an X-band (center frequency is 9.6 GHz) SAR sensor. The satellite has three beam modes, and “spotlight-2” is the recommended beam mode for the LKAB ground deformation measurements. The spotlight-2 mode has a 10 km x 10 km Swath and 1 m resolution. The repeat cycle of a satellite is 16 days and using all four satellites LKAB can collect satellite images in every four days. Therefore by using COSMO-SkyMed satellite constellation, LKAB can collect more (about 40 images) images in the summer (snow free period) compared to Radarsat-2.

The sentinel-1 satellite has a C-band SAR sensor operating at a center frequency of 5.405 GHz. The satellite has four beam modes and “Interferometric Wide Swath (IW)” is the recommended mode for the LKAB ground deformation measurements. Interferometric Wide Swath (IW) mode has a 240 km swath, 5 m x 20 m resolution. The repeat cycle of a satellite is 12 days. Although the image resolution is lower than the Radarsat-2, LKAB can use this satellite to collect more frequent measurements during the summer.

8.6 Required minimum number of beam modes for Kiruna InSAR measurements

All DInSAR, CTM and CRInSAR measurements from all tracks shows consistent deformation patterns for the ROI. The main reason is to use three different beam modes is to measure the three-dimensional deformation. This study shows that due to the current satellite geometry, accuracy of the InSAR North-South vector component is very poor. Therefore, the recommendation is to use either a single beam mode or two different beam modes instead of three different beam modes. By only using two different beam modes, it is possible to separate the horizontal and vertical deformation vectors. The U70D and U25A beam modes will be the most suitable (from the current beam modes) for two-dimensional vector analysis. U70D has a steep beam incident angle, and the measurements will be biased (than U6D) to the vertical ground deformation. U25A has the highest incident angle and therefore U25A measurements will be biased (than U6D) towards to the horizontal ground measurements. By using two different beams modes instead of the three separate beam modes, the required number of satellite images for the data processing can be reduced by 33%.

8.7 CTM targets and new Corner reflector installations at Kiruna

At present, Kiruna city area has good CTM targets but the area between the mine and the city only have few CTM targets. Therefore, it is not possible to measure that area using the CTM technique. In coming years, it is expected that mining induced ground deformation will move towards to the Kiruna city area. All the infrastructure etc. has already been removed before the criterion is reached in the area. The corner reflectors can be used to replace the losing CTM targets but, it is challenging to install a large number of corner reflectors in a small area. Also to have continuous measurements for that area it is important to have CTM and CRInSAR overlapping measurements. Therefore, the recommendation is to perform a comprehensive CR network design and install the corner reflectors at least one year before removing the buildings. Having corner reflectors installed

one year before removing the buildings enables to collect 10-15 CRInSAR measurements alongside with the CTM measurements.

Chapter 9

Conclusion

9.1 Seasonal effects in DInSAR measurements

The parameter spatial coherence was used to quantify the seasonal variation in DInSAR interferograms. Even with a longer temporal baseline, the summer-to-summer interferograms for the barren and flat waste rock areas provide almost the same coherence. Therefore, the summer-to-summer interferograms are the most suitable for subsidence measurements in the waste rock area. Forest areas lose coherence with an increase in the temporal baseline and do not regain it seasonally. Urban areas show similar seasonal variation as that of barren and flat waste rock areas but with a lower magnitude of coherence. If the ground snow layer remains unchanged during two consecutive images, then high coherence can be achieved even with a ground snow layer. In spring, the coherence becomes very poor due to the melting snow and surface water, and in the autumn, the coherence is reduced due to leaf fall, shedding of the tree leaves due to wind, surface water from rain, and due to the first snow fall. Additionally this study showed that the winter Radarsat-2 U6D beam mode images are not suitable for DInSAR deformation measurements in flat waste rock areas in Kiruna and therefore, less than 50% of available Radarsat-2 U6D are suitable for Kiruna DInSAR measurements.

9.2 Seasonal effects in CRInSAR measurements

The corner reflectors provided by the MDA were covered with a protective shield to prevent the snow accumulation. However, it is observed that up to 8 cm snow layer can be accumulated on top of these shields during winter. The GPS vector component parallel to the corner reflector line-of-sight was compared with the CRInSAR line-of-sight measurements to quantify the seasonal variation in the CRInSAR measurements. The results show that by using SBAS technique and only using interferograms with a higher average spatial coherence (higher than 0.25) yielded the closest agreement with Static-GPS measurements, showing a 1.1 mm mean error, 10.7 mm standard deviation, and correlation coefficient of 0.88. However if the winter interferograms were added to the image stack then the mean error will climb up to 17.9 mm, standard deviations climb up to 30.9 mm, and correlation coefficient drops down to 0.58. The ground snow layer and the snow layer on top of the corner reflector shield are the main contributors to the CRInSAR measurement errors. However, these measurements errors can be minimized by using only those interferograms with higher average spatial coherence values and the SBAS techniques. However by doing so there is a possibility of losing entire sets of interferograms related to a particular image (a winter image) and this loss will in turn lead to the loss of measurements for that particular date. Although the overall measurement error due to snow was quantified, it was unable to differentiate the error contribution from the ground snow layer and the snow layer on top of the corner reflector shield. Since the ROI is a small area (approximately 8 x 8 km), the error contribution due to fault baseline and fault APS (due to ground snow layer) is minimum compared to the error contribution from the snow layer on top of the corner reflector shield.

9.3 Seasonal effects in CTM measurements

The seasonal effects in the CTM targets are two-fold. The first is losing coherence due to the snow deposition on top of the targets. The second is losing spatial coherence in the interferogram due to the ground snow layer. If the winter interferograms used for CTM processing, the number of CTM targets (coherence 0.8 or above) drops down from more than 8000 targets to less than 1000. The number of CTM targets can be increased from 1000 to 3000 by dropping down the coherence

threshold from 0.8 to 0.6. However, with 0.6 coherent threshold, it is observed that there are more phase unwrapping errors in the measurements. Therefore, to achieve high CTM target density in the ROI and to minimize phase unwrapping errors, the winter interferograms should be left out from the CTM processing. Removing winter interferograms from the image stack means there are no measurements for the winter period. Therefore this is the main disadvantage, and interpolation techniques can be used to mitigate this issue.

9.4 Improving DInSAR measurements

DInSAR deformation measurements can be improved by using the spatial deformation patterns in the ROI. For this study, a linear model signal was constructed by using known spatial deformation parameters between two points in the ROI. The actual deformation measurements were obtained from a summer-to-summer DInSAR interferogram. RMS error and/or Correlation coefficient was used to find the best-fit parameters for the model signal. CTM time series measurements were used to validate the results. Simulation and validation shows that the spatial deformation patterns in the ROI can be used to improve the DInSAR deformation measurements up to sub-centimeter accuracies. Major limitation of this technique is the requirement of prior information about the deformation to construct the model signal. Further studies are required to validate non-linear deformation models.

9.5 Improving North-South InSAR measurements

A novel method to improve the InSAR North-South measurements was investigated. This proposed method can deliver InSAR line-of-sight accuracies for the North-South measurements. The proposed method requires a minimum of three transponders (CAT devices) to measure the North-South ground movement between two points. The response times of the transponders are critical parameters for this method. The distance between selected ground points, beam incident angle, satellite image swath width, satellite altitude will determine the required CAT response times. For a Radarsat-2 U6 fine-beam mode image, the critical response time for a CAT device is 1.3338×10^{-4} s and the typical or recommended

response time for a CAT device is 4.3146×10^{-6} s. The requirement on CAT devices, line-of-sight visibility between CAT devices and layover effects are identified as limitations.

9.6 InSAR measurements around Kiruna iron ore mine

The InSAR deformation measurements around Kiruna iron ore mine show that neither single technique (DInSAR, CTM or CRInSAR) alone can adequately cover the entire ROI. The best suitable option is to use all the techniques as a combination. Also, it has been noticed that most of the CTM targets disappear due to the snow deposition, and wide area deformation maps (DInSAR maps) are only possible with summer images. Also, it has been noticed that the accuracy of the North-South deformation measurements is poor due to the current orbital configurations of the SAR satellites. Therefore, the North-South CRInSAR deformation vector is very noisy, and it cannot be used to determine the LKAB environmental criterion. The East-West vector is the least noisy deformation vector, and both East-West and vertical vectors can be used to determine the LKAB Environmental criterion limit.

The study shows that the accuracies of the CTM and CRInSAR time series estimations can be improved by minimizing the number of winter images in the image stack. Therefore, by omitting the winter images, required number of images for the InSAR processing can be reduced by 50%. Moreover, the required number of images can be reduced further 30% by only using two beam modes instead of using three beam modes and still, achieve the same estimation accuracies in the CTM and CRInSAR time series measurements.

9.7 Future work

To improve the accuracies of the high latitude InSAR measurements as well as the quality of LKAB InSAR monitoring program, following areas were identified as possible future research topics. One of the weaknesses of the LKAB InSAR monitoring program is the poor North-South InSAR measurement accuracy. Since

LKAB required measuring three-dimensional ground movements, it is important to continue future work in this topic. One possible approach is that using available GPS measurements to improve North-South InSAR vector. There are some previous studies related to this topic [81, 82]. However, future work is needed to optimize the number of GPS measurements required to improve the InSAR North-South accuracy and validate the technique for high latitude InSAR measurements. In Chapter 5, the theoretical calculation of the 3CAT method was presented. Validation of the technique by using field data is also a possible future research topic. Integration of 3CAT North-South measurements to improve the CRInSAR and CTM North-South vectors will be another research topic that need attention. The results from Chapter 3 shows that snow deposition on the CR shield will reduce the accuracy of the CRInSAR measurements. Therefore, it is needed to deploy snow shield that will prevent any snow deposition on top of them. Designing a snow shield for high latitude conditions will be another topic that need further research. Results from Chapter 3 shows that summer-to-summer DInSAR provide coherent measurements for the waste rock areas. However, because of the frozen ground condition, the top soil layer (less than 2 m from the top) can have local (not mining induced) movements. Therefore, it is important to carry out further studies to quantify the ground movements related to the frozen ground conditions. Chapter 5 show that the DInSAR measurements can be improved by using a deformation model. The simulations and validation were carried out for linear spatial deformation model. Further studies are required to validate non-linear deformation models. If the Radarsat-2 satellite need to be replaced by different satellite (e.g. Sentinel), then the corner reflector orientation has to be changed. In that case there will be new line-of-sight measurements from the new satellite data. Integration of current InSAR measurement with the new satellite InSAR measurements is an another topic for further research. Since the current InSAR measurements cannot deliver the accurate North-South ground movements measurements, the current Environmental criterion limit cannot use as it is with InSAR measurements. Therefore, if LKAB planning to use InSAR as an operational technique for ground deformation monitoring around Kiruna iron ore mine, then it is important to use InSAR line-of-sight measurements to calculate the Environmental criterion limit by compensating the line-of-sight angle. Calculating the Environmental criterion limit using InSAR line-of-sight measurements and validating it by using current GPS measurements is a topic for further study.

Bibliography

- [1] Tomás Fernando Villegas Barba. *Numerical Analyses of the Hangingwall at the Kiirunavaara Mine*. Licentiate thesis, Luleå University of Technology, 2008.
- [2] A E Rogers and R P Ingalls. Venus: Mapping the surface reflectivity by radar interferometry. *Science*, 165(3895):797–799, August 1969.
- [3] L C Graham. Synthetic interferometer radar for topographic mapping. *Proceedings of the IEEE*, 62(6):763–768, June 1974.
- [4] H A Zebker and R M Goldstein. Topographic mapping from interferometric synthetic aperture radar observations. *Journal of Geophysical Research*, 91(B5):4993–4999, April 1986.
- [5] A K Gabriel, R M Goldstein, and H A Zebker. Mapping small elevation changes over large areas: Differential radar interferometry. *Journal of Geophysical Research*, 94(B7):9183–9191, July 1989.
- [6] D Massonnet and F Adragna. A full-scale validation of radar interferometry with ERS-1: The Landers earthquake. *Earth Observation Quarterly*, 41, July 1993.
- [7] H Chang, L Ge, and C Rizos. Application of repeat-pass DInSAR and GIS for underground mine subsidence monitoring. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVII(B1):251–256, February 2008.
- [8] L Ge, H Chang, and C Rizos. Mine subsidence monitoring using multi-source satellite SAR images. *Photogrammetric Engineering & Remote Sensing*, 73(3):259–266, March 2007.

- [9] Z Perski, R Hanssen, A Wojcik, and T Wojciechowski. InSAR analysis of terrain deformation near the Wieliczka salt mine, Poland. *Engineering Geology*, 106(1-2):58–67, May 2009.
- [10] D Raucoules, C Maisons, C Carnec, S Le Mouélic, C King, and D Aubry. Monitoring of slow ground deformation by ERS radar interferometry on the Vayvert salt mine (France), comparison with ground based measurements. *Remote Sensing of Environment*, 88(4):468–478, December 2003.
- [11] T Villegas and E Nordlund. *Investigation of surface subsidence due to sub-level caving*, pages 181–188. Australian Centre for Geomechanics, 2010 edition, 2010. ISBN 978-0-9806154-1-8.
- [12] T Villegas, E Nordlund, and C Dahnér-Lindqvist. Hangingwall surface subsidence at the Kiirunavaara mine, Sweden. *Engineering Geology*, 121(12):18–27, 2011.
- [13] G W Stimson. *Introduction to Airborne Radar*. SciTech Publishing, 2 edition, 1998. ISBN 9781891121012.
- [14] I G Cumming and F H Wong. *Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation*. Artech House, 2005. ISBN 1580530583.
- [15] European Space Agency. Radar and SAR glossary, 2011. URL <https://earth.esa.int/handbooks/asar/CNTR5-2.html>. (Accessed 20 September 2015).
- [16] H Balzter. Forest mapping and monitoring with interferometric synthetic aperture radar (InSAR). *Progress in Physical Geography*, 25(2):159–177, June 2001.
- [17] ESA Earth Online. Remote sensing and SAR images processing. URL <https://earth.esa.int>. (Accessed 30 May 2017).
- [18] eoPortal. TSX (TerraSAR-X) mission. URL <https://directory.eoportal.org/web/eoportal/satellite-missions/t/terrasar-x#overview>. (Accessed 20 September 2015).
- [19] J Hoffmann, H A Zebker, D L Galloway, and F Amelung. Seasonal subsidence and rebound in Las Vegas valley, Nevada, observed by synthetic

- aperture radar interferometry. *Water Resources Research*, 37(6):1551–1566, June 2001.
- [20] P A Rosen, S Hensley, I R Joughin, F K Li, S N Madsen, E Rodriguez, and R M Goldstein. Synthetic aperture radar interferometry. *Proceedings of the IEEE*, 88(3):333–382, March 2000.
- [21] A Ferretti, C Prati, and F Rocca. Permanent scatterers in SAR interferometry. *Geoscience and Remote Sensing, IEEE Transactions on*, 39(1):8–20, January 2001.
- [22] V Poncos, S Mei, and V Singhroy. Point target interferometry for natural and artificial scatterers. In *Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International*, pages 2106–2109, July 2007.
- [23] P Blanco, F Pérez, A Concha, J Marturia, and V Palà. Operational PS-DInSAR deformation monitoring project at a regional scale in Catalonia (Spain). In *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International*, pages 1178–1181, July 2012.
- [24] D M Ugsang, K Honda, and G Saito. Assessment of small passive corner reflectors for geometric correction of Radarsat fine mode SAR data. In *22nd Asian Conference on Remote Sensing*, volume 5, page 9, 2001.
- [25] J Zhang and Q Qin. The research of difference interferometric SAR technique. In *Geoscience and Remote Sensing Symposium, 2003. IGARSS '03. Proceedings. 2003 IEEE International*, volume 6, pages 3827–3829, July 2003.
- [26] Peter Damoah-Afari, Xiao-li Ding, Zhong Lu, Zhiwei Li, and Makoto Omura. Magnitude and extent of six years of land subsidence in shanghai revealed by jers-1 sar data. In Pasquale Imperatore and Daniele Riccio, editors, *Geoscience and Remote Sensing New Achievements*, chapter 25. InTech, Rijeka, 2010. doi: 10.5772/9092. URL <http://dx.doi.org/10.5772/9092>.
- [27] Wenjian Ni, Zhiyu Zhang, Guoqing Sun, Zhifeng Guo, and Yating He. The penetration depth derived from the synthesis of alos/palsar insar data and aster gdem for the mapping of forest biomass. *Remote Sensing*, 6(8):7303–7319, 2014. ISSN 2072-4292. doi: 10.3390/rs6087303. URL <http://www.mdpi.com/2072-4292/6/8/7303>.

- [28] F K Li and R M Goldstein. Studies of multibaseline spaceborne interferometric synthetic aperture radars. *Geoscience and Remote Sensing, IEEE Transactions on*, 28(1):88–97, January 1990.
- [29] A K Gabriel and R M Goldstein. Crossed orbit interferometry: Theory and experimental results from SIR-B. *International Journal of Remote Sensing*, 9(5):857–872, 1988.
- [30] Q Lin, J F Vesecky, and H A Zebker. New approaches in interferometric SAR data processing. *IEEE Transactions on Geoscience and Remote Sensing*, 30(3):560–567, May 1992.
- [31] Z Weibao, L Yan, L Zhilin, and D Xiaoli. Improvement of the accuracy of InSAR image co-registration based on tie points: A review. *Sensors*, 9: 1259–1281, February 2009.
- [32] M Schäfer, D Walter, and W Busch. DInSAR ground movement monitoring in the rural environment of an open pit mining area. In *Proceedings of Envisat Symposium 2007, Montreux, Switzerland. ESA SP-636*, volume 1, July 2007.
- [33] Jos Claudio Mura, Muriel Pinheiro, Rafael Rosa, and Joo Roberto Moreira. A phase-offset estimation method for insar dem generation based on phase-offset functions. *Remote Sensing*, 4(3):745–761, 2012. ISSN 2072-4292. doi: 10.3390/rs4030745. URL <http://www.mdpi.com/2072-4292/4/3/745>.
- [34] A Ferretti, C Prati, and F Rocca. Multibaseline InSAR DEM reconstruction: The wavelet approach. *IEEE Transactions on Geoscience and Remote Sensing*, 37(2):705–715, March 1999.
- [35] G W Davidson and R Bamler. Multiresolution phase unwrapping for SAR interferometry. *Geoscience and Remote Sensing, IEEE Transactions on*, 37(1):163–174, January 1999.
- [36] B Fruneau and F Sarti. Detection of ground subsidence in the city of Paris using radar interferometry: Isolation of deformation from atmospheric artifacts using correlation. *Geophysical Research Letters*, 27(24):3981–3984, December 2000.

- [37] T Toutin and R Chenier. 3-D radargrammetric modeling of Radarsat-2 ultrafine mode: Preliminary results of the geometric calibration. *Geoscience and Remote Sensing Letters, IEEE*, 6(3):611–615, July 2009.
- [38] H S Jung, Z Lu, J S Won, M P Poland, and A Miklius. Mapping three-dimensional surface deformation by combining multiple-aperture interferometry and conventional interferometry: Application to the June 2007 eruption of kilauea volcano, hawaii. *Geoscience and Remote Sensing Letters, IEEE*, 8(1):34–38, January 2011.
- [39] A Hooper, H Zebker, P Segall, and B Kampes. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophysical Research Letters*, 31, December 2004.
- [40] P Lundgren, S Usai, E Sansosti, R Lanari, M Tesauro, G Fornaro, and P Berardino. Modeling surface deformation observed with synthetic aperture radar interferometry at Campi Flegrei caldera. *Journal of Geophysical Research: Solid Earth*, 106(B9):19355–19366, September 2001.
- [41] P Berardino, G Fornaro, R Lanari, and E Sansosti. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *Geoscience and Remote Sensing, IEEE Transactions on*, 40(11):2375–2383, November 2002.
- [42] O Mora, J J Mallorqui, and A Broquetas. Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 41(10):2243–2253, October 2003.
- [43] C Francesco. *The Small BAseline Subset technique: Performance assessment and new developments for surface deformation analysis of very extended areas*. PhD thesis, University of Cagliari, February 2009.
- [44] H Zebker, P Shankar, and A Hooper. InSAR remote sensing over decorrelating terrains: Persistent scattering methods. In *Radar Conference, 2007 IEEE*, pages 717–722, April 2007.
- [45] J J Sousa, A J Hooper, R F Hanssen, and L C Bastos. Comparative study of two different PS-InSAR approaches: DEPSI vs. Stamps. In *Advances in the Science and Applications of SAR interferometry, ‘FRINGE09’, Frascati, Italy, 30 Nov-4 Dec 2009*. ESA, 2010.

- [46] A Ferretti, A Fumagalli, F Novali, C Prati, F Rocca, and A Rucci. A new algorithm for processing interferometric data-stacks: Squeesar. *Geoscience and Remote Sensing, IEEE Transactions on*, 49(9):3460–3470, September 2011.
- [47] B M Kampes. *Radar Interferometry: Persistent Scatter Technique*. Springer, Dordrecht, The Netherlands, 2006. ISBN 978-1-4020-4723-7.
- [48] A Ferretti, G Savio, R Barzaghi, A Borghi, S Musazzi, F Novali, C Prati, and F Rocca. Submillimeter accuracy of InSAR time series: Experimental validation. *Geoscience and Remote Sensing, IEEE Transactions on*, 45(5): 1142–1153, May 2007.
- [49] M Van der Kooij, W Hughes, S Sato, and V Poncos. Coherent target monitoring at high spatial density: Examples of validation results. In *Fringe Workshop, European Space Agency*, 2005.
- [50] Peraya Tantikanuparp, Xuguo Shi, Lu Zhang, Timo Balz, and Mingsheng Liao. Characterization of landslide deformations in three gorges area using multiple insar data stacks. *Remote Sensing*, 5(6):2704–2719, 2013. ISSN 2072-4292. doi: 10.3390/rs5062704. URL <http://www.mdpi.com/2072-4292/5/6/2704>.
- [51] R Touzi, A Lopes, J Bruniquel, and P W Vachon. Coherence estimation for SAR imagery. *Geoscience and Remote Sensing, IEEE Transactions on*, 37(1):135–149, January 1999.
- [52] D J Weydahl. Analysis of ERS tandem SAR coherence from glaciers, valleys, and fjord ice on Svalbard. *Geoscience and Remote Sensing, IEEE Transactions on*, 39(9):2029–2039, September 2001.
- [53] H A Zebker and J Villasenor. Decorrelation in interferometric radar echoes. *Geoscience and Remote Sensing, IEEE Transactions on*, 30(5):950–959, September 1992.
- [54] H Behr and R Hanssens. Network adjustment of orbit errors in SAR interferometry. In *Fringe 2009 workshop*. ESA SP-677, 2010.
- [55] A L Gray, K E Mattar, and G Sofko. Influence of ionospheric electron density fluctuations on satellite radar interferometry. *Geophysical Research Letters*, 27(10):1451–1454, May 2000.

- [56] U Wegmüller, C Werner, T Strozzi, and A Wiesmann. Ionospheric electron concentration effects on SAR and INSAR. In *Geoscience and Remote Sensing Symposium, 2006. IGARSS 2006. IEEE International Conference on*, pages 3731–3734, July 2006.
- [57] M Shimada, M Minamisawa, and O Isoguchi. Correction of atmospheric excess path delay appeared in repeat-pass SAR interferometry using objective analysis data. In *International Geoscience and Remote Sensing Symposium, Sydney, Australia, 9–13 July 2001*, pages cdrom, 3 pages, 2001.
- [58] J Foster, B Brooks, T Cherubini, C Shacat, S Businger, and C L Werner. Mitigating atmospheric noise for InSAR using a high resolution weather model. *Geophysical Research Letters*, 33(16), August 2006.
- [59] B Puysségur, R Michel, and J P Avouac. Tropospheric phase delay in InSAR estimated from meteorological model and multispectral imagery. *Journal of Geophysical Research*, 112(B05419), May 2007.
- [60] V M Pinel, M Doin, S de la Cruz-Reyna, and A Hooper. Use of global meteorological model to correct for stratified tropospheric delays in SAR data: Application to active mexican stratovolcanoes. *American Geophysical Union, Fall Meeting Abstracts*, page C7, December 2008.
- [61] G Wadge, P W Webley, I N James, R Bingley, A Dodson, S Waugh, T Veneboer, G Puglisi, M Mattia, D Baker, S C Edwards, S J Edwards, and P J Clarke. Atmospheric models, GPS and InSAR measurements of the tropospheric water vapour field over Mount Etna. *Geophysical Research Letters*, 29(19):11/1–4, October 2002.
- [62] H A Zebker, P A Rosen, and S Hensley. Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps. *Journal of Geophysical Research*, 102(B4):7547–7563, April 1997.
- [63] R F Hanssen. *Radar Interferometry: Data Interpretation and Error Analysis*. Kluwer Academic Press, 2001. ISBN: 978-0-7923-6945-5.
- [64] N Fujii, S Kobayashi, T Sakurai-Amano, S Okubo, M Satomura, and A Mio. Crustal movement imaging by D-InSAR, reflector array, dense GPS, leveling and gravity changes in the plate convergent zone, at the Tokai region, central Japan. In *Geoscience and Remote Sensing Symposium, 1999. IGARSS '99 Proceedings. IEEE 1999 International*, volume 2, pages 797–799, 1999.

- [65] M D Henschel and B Lehrbass. Operational validation of the accuracy of InSAR measurements over an enhanced oil recovery field. In *Proceedings Fringe 2011*. ESA SP-697, January 2012.
- [66] M. C. Garthwaite, M. Hazelwood, S. Nancarrow, A. Hislop, and J. H. Dawson. A regional geodetic network to monitor ground surface response to resource extraction in the northern surat basin, queensland. *Australian Journal of Earth Sciences*, 62(4):469–477, 2015. doi: 10.1080/08120099.2015.1040073. URL <http://dx.doi.org/10.1080/08120099.2015.1040073>.
- [67] O. Sadiku and N. Matthew. Refractive index of snow at microwave frequencies. *Applied Optics*, 24(4):572–575, February 1985.
- [68] N Yankielun, W Rosenthal, and R E Davis. Alpine snow depth measurements from aerial FMCW radar. *Cold Regions Science and Technology*, 40:123–134, June 2004.
- [69] K Elder, J Dozier, and J Michaelsen. Snow accumulation and distribution in an Alpine Watershed. *Water Resources Research*, 27(7):1541–1552, July 1991.
- [70] A M Vázquez. *Snow cover monitoring techniques with GB-SAR*. PhD thesis, Joint Research Centre of the European Commission in Ispra (Italy), October 2008.
- [71] G Engen, T Guneriussen, and O Overrein. Delta-K interferometric SAR technique for snow water equivalent (SWE) retrieval. *IEEE Geoscience and Remote Sensing Letters*, 1(2):57–61, April 2004.
- [72] A Martinez-Vazquez, J Fortuny-Guasch, and U Gruber. Monitoring of the snow cover with a ground-based synthetic aperture radar. *EARSeL eProceedings*, 4(2):171–178, October 2005.
- [73] H C Jung and D Alsdorf. Repeat-pass multi-temporal interferometric SAR coherence variations with Amazon floodplain and lake habitats. *International Journal of Remote Sensing*, 31(4):881–901, February 2010.
- [74] P Budkewitsch, M A DIorio, P W Vachon, D T Andersen, and W H Pollard. Sources of phase decorrelation in SAR scene coherence images from Arctic environments. In *13th International Conference and Workshops on Applied Geologic Remote Sensing*, pages 1–3, January 1999.

- [75] L Liu, T Zhang, and J Wahr. InSAR measurements of surface deformation over permafrost on the North Slope of Alaska. *Journal of Geophysical Research: Earth Surface*, 115(F3), September 2010.
- [76] C Colesanti, A Ferretti, F Novali, C Prati, and F Rocca. SAR monitoring of progressive and seasonal ground deformation using the permanent scatterers technique. *Geoscience and Remote Sensing, IEEE Transactions on*, 41(7): 1685–1701, July 2003.
- [77] T J Wright, B E Parsons, and Z Lu. Toward mapping surface deformation in three dimensions using InSAR. *Geophysical Research Letters*, 31(L01607), January 2004.
- [78] J J Mohr, N Reeh, and S N Madsen. Accuracy of three-dimensional glacier surface velocities derived from radar interferometry and ice-sounding radar. *Journal of Glaciology*, 49(165):210–222, March 2003.
- [79] L Gray. Using multiple RADARSAT InSAR pairs to estimate a full three-dimensional solution for glacial ice movement. *Geophysical Research Letters*, 38(5), March 2011.
- [80] H Jung, J Won, and S Kim. An improvement of the performance of multiple-aperture SAR interferometry (MAI). *Geoscience and Remote Sensing, IEEE Transactions on*, 47(8):2859–2869, August 2009.
- [81] J Catalao, G Nico, R Hanssen, and C Catita. Merging GPS and atmospherically corrected InSAR data to map 3-D terrain displacement velocity. *Geoscience and Remote Sensing, IEEE Transactions on*, 49(6):2354–2360, June 2011.
- [82] S Samsonov and K Tiampo. Analytical optimization of a DInSAR and GPS dataset for derivation of three-dimensional surface motion. *Geoscience and Remote Sensing Letters, IEEE*, 3(1):107–111, January 2006.
- [83] P A Rosen, S Hensley, H A Zebker, F H Webb, and E J Fielding. Surface deformation and coherence measurements of Kilauea volcano, Hawaii, from SIR-C radar interferometry. *Journal of Geophysical Research*, 101(E10): 23109–23125, October 1996.

- [84] J Groot and M Otten. SAR imaging of corner reflectors larger than the spatial resolution. *Geoscience and Remote Sensing, IEEE Transactions on*, 32(3):721–724, May 1994.
- [85] G Xu. *GPS: Theory, Algorithms and Applications*. Springer, 2 edition, 2010. ISBN 9783642091810.
- [86] B Delouis, P Lundgren, J Salichon, and D Giardini. Joint inversion of InSAR and teleseismic data for the slip history of the 1999 Izmit (Turkey) earthquake. *Geophysical Research Letters*, 27(20):3389–3392, October 2000.
- [87] B Delouis, D Giardini, P Lundgren, and J Salichon. Joint inversion of InSAR, GPS, teleseismic, and strong-motion data for the spatial and temporal distribution of earthquake slip: Application to the 1999 Izmit Mainshock. *Bulletin of the Seismological Society of America*, 92(1):278–299, February 2002.
- [88] L Song and H Gong. Applications of GPS/InSAR integration in monitoring of land subsidence. In *Remote Sensing, Environment and Transportation Engineering (RSETE), 2011 International Conference on*, pages 1991–1993, June 2011.
- [89] S Stramondo, M Tesauero, P Briole, E Sansosti, S Salvi, R Lanari, M Anzidei, P Baldi, G Fornaro, A Avallone, M F Buongiorno, and G Franceschetti E Boschi. The September 26, 1997 Colfiorito, Italy, earthquakes: Modeled co-seismic surface displacement from SAR interferometry and GPS. *Geophysical Research Letters*, 26(7):883–886, April 1999.
- [90] R Bürgmann, M E Ayhan, E J Fielding, T J Wright, S McClusky, B Aktug, C Demir, O Lenk, and A Türkezer. Deformation during the 12 November 1999 Düzce, Turkey, earthquake, from GPS and InSAR data. *Bulletin of the Seismological Society of America*, 92(1):161–171, February 2002.
- [91] Leica Geosystems. Leica GPS1200+ series high performance GNSS system. URL http://www.leica-geosystems.com/downloads123/zz/gps/general/brochures/GPS1200_brochure_en.pdf. (Accessed 20 March 2015).
- [92] H Yue, G Liu, R Hanssen, R Wang, and X Zhong. Coal mine land subsidence monitoring using spaceborne InSAR data; A case study in Fengfeng, Hebei

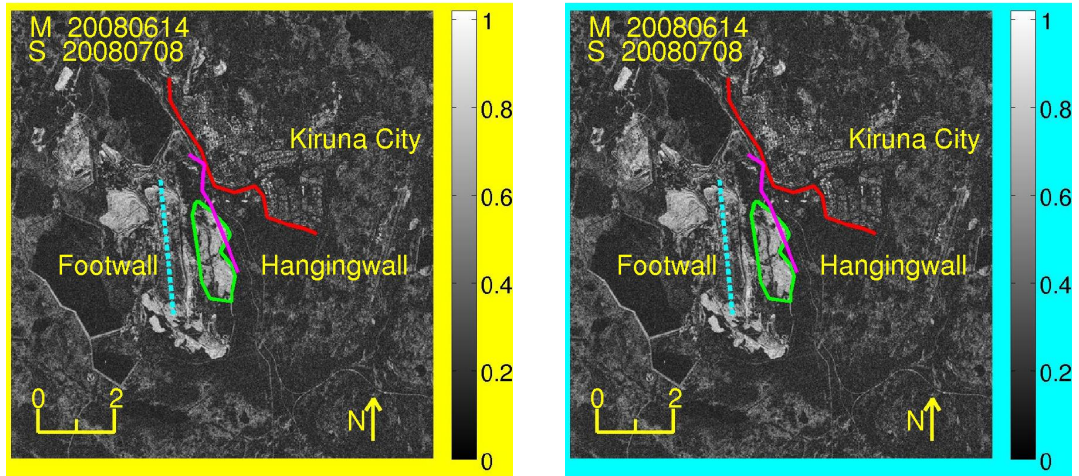
- province, China. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, XXXVII(B8):225–262, 2008.
- [93] W H Press, S A Teukolsky, W T Vetterling, and B P Flannery. *Numerical Recipes : The Art of Scientific Computing*. Cambridge University Press, New York, NY, USA, 3 edition, 2007. ISBN 978-0521880688.
- [94] J Hole, R Holley, G Giunta, G De Lorenzo, and A Thomas. InSAR assessment of pipeline stability using compact active transponders. In *Proceedings of FRINGE 2011 Workshop, Frascati, Italy*, volume 201. ESA SP-697, January 2012.
- [95] SEA. Reflex : A family of compact transponders. URL <https://www.sea.co.uk/docs/REFLEX%20DATASHEET%20rev%2029%201.pdf>. (Accessed 20 September 2015).
- [96] European Global Satellite Navigation System Agency. Integrated interferometry and GNSS for precision survey, . URL <http://www.gsa.europa.eu/integrated-interferometry-and-gnss-precision-survey>. (Accessed 10 August 2014).
- [97] P Mahapatra, H van der Marel, R Hanssen, R Holley, S Samiei-Esfahany, M Komac, and A Fromberg. Radar transponders and their combination with GNSS for deformation monitoring. In *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International*, pages 3891–3894, July 2012.
- [98] J P M Boncori and G Schiavon. Signal processing issues for the exploitation of pulse-to-pulse encoding SAR transponders. *Geoscience and Remote Sensing, IEEE Transactions on*, 46(4):1048–1057, April 2008.
- [99] European Space Agency. The ASAR user guide, . URL <https://earth.esa.int/handbooks/asar/CNTR2-6-1-2-3.html>. (Accessed 10 August 2015).
- [100] S Axelsson. Position correction of moving targets in SAR-imagery. In *SPIE-SAR Image Analysis, Modeling, and Techniques VI*, volume 5236, pages 80–92, January 2004.
- [101] P Shanker, F Casu, H A Zebker, and R Lanari. Comparison of persistent scatterers and small baseline time-series InSAR results: A case study of the

- San Francisco Bay Area. *Geoscience and Remote Sensing Letters, IEEE*, 8 (4):592–596, July 2011.
- [102] M S Seymour and I G Cumming. Maximum likelihood estimation for SAR interferometry. In *Geoscience and Remote Sensing Symposium, 1994. IGARSS '94. Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation., International*, volume 4, pages 2272–2275, August 1994.

Appendix A

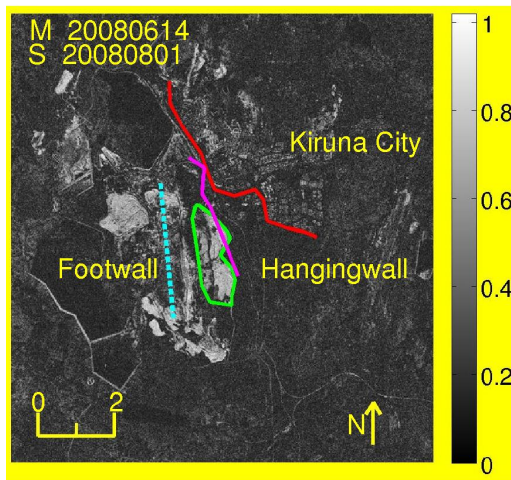
Coherence images for Kiruna test site

This annex lists the coherence images produced for the Kiruna test site. LKAB data was used to plot the Environmental criterion limit.

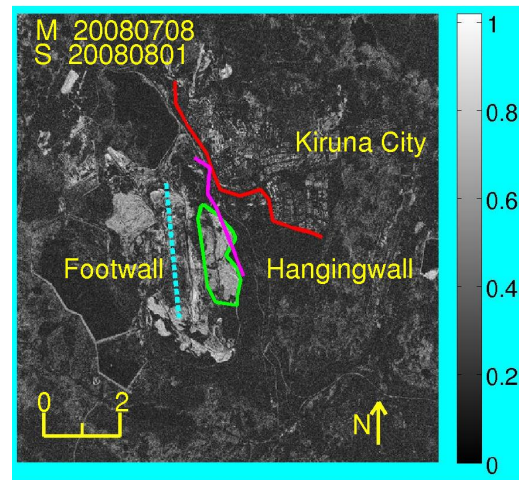


(a) Common master interferogram for the Kiruna test site. (b) Sequential interferogram for the Kiruna test site.

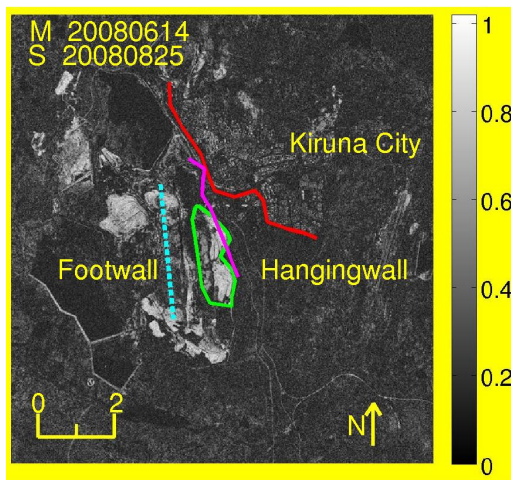
FIGURE A.1: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



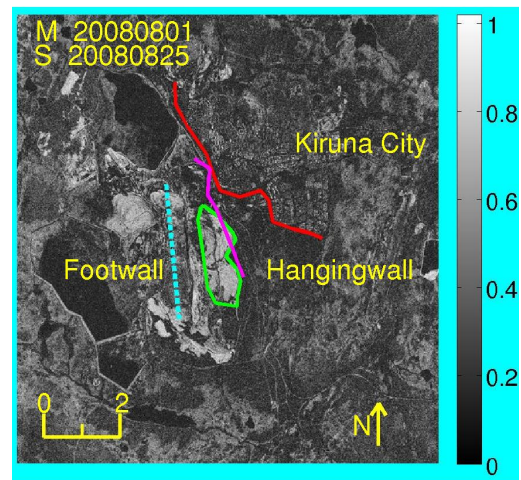
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

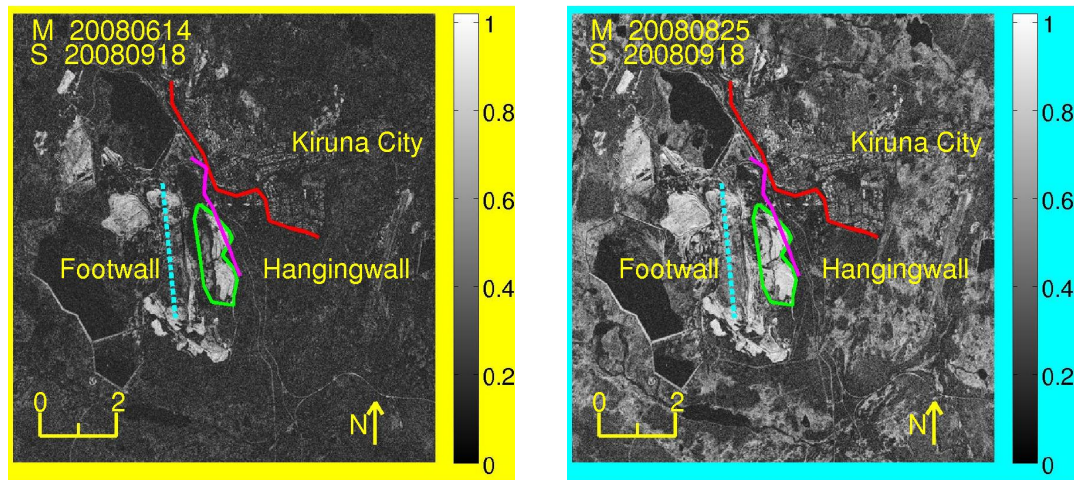


(c) Common master interferogram for the Kiruna test site.



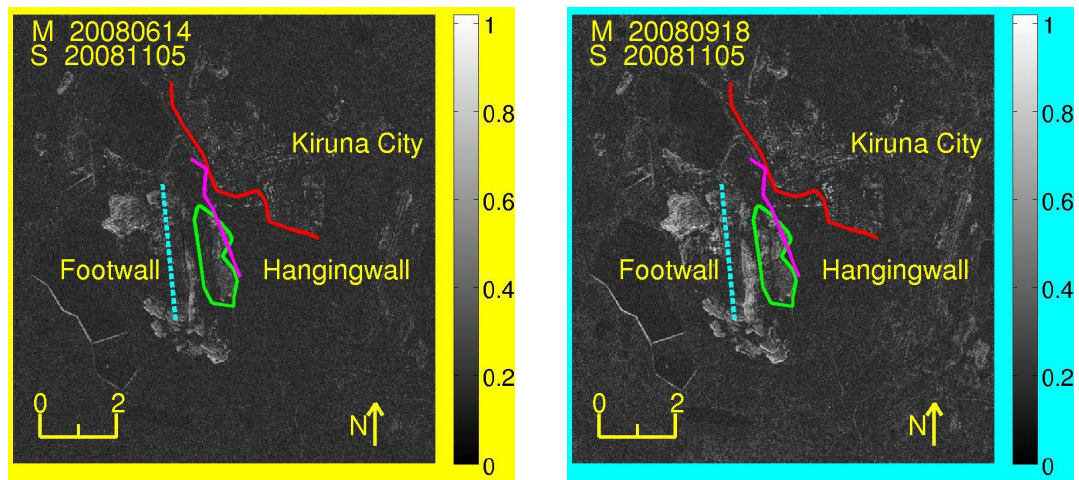
(d) Sequential interferogram for the Kiruna test site.

FIGURE A.2: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



(a) Common master interferogram for the Kiruna test site.

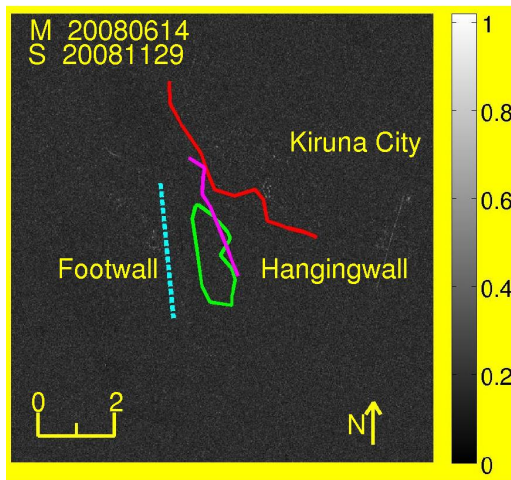
(b) Sequential interferogram for the Kiruna test site.



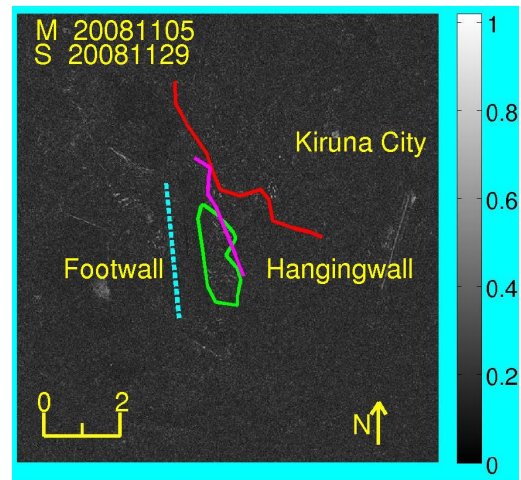
(c) Common master interferogram for the Kiruna test site.

(d) Sequential interferogram for the Kiruna test site.

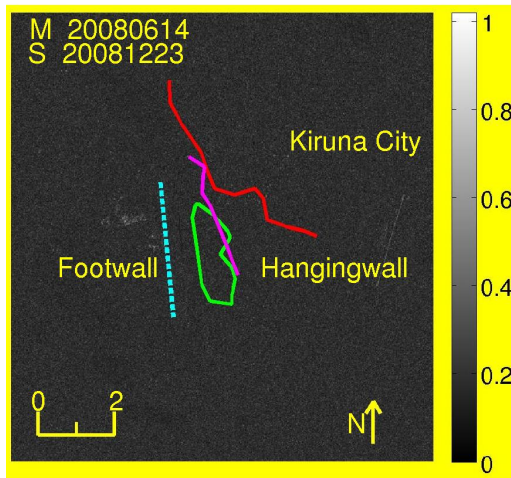
FIGURE A.3: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



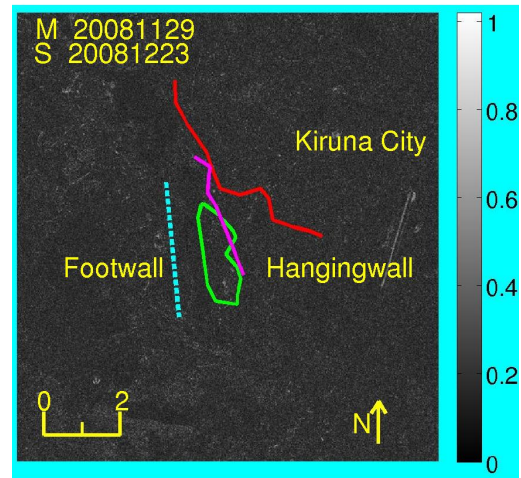
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

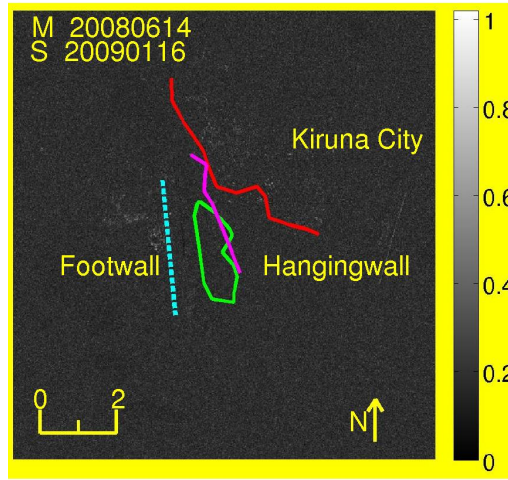


(c) Common master interferogram for the Kiruna test site.

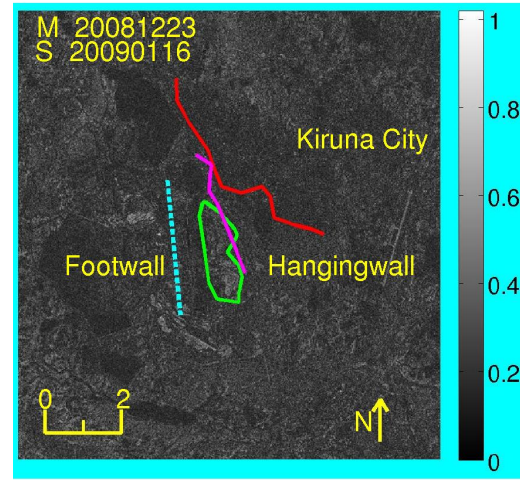


(d) Sequential interferogram for the Kiruna test site.

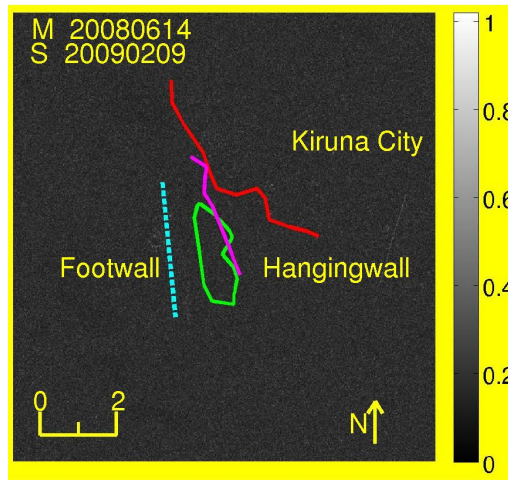
FIGURE A.4: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



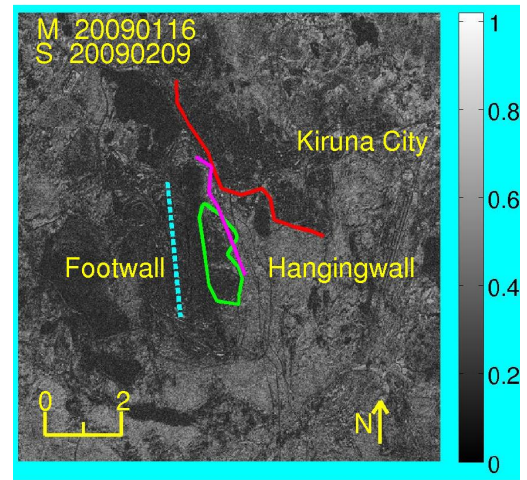
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

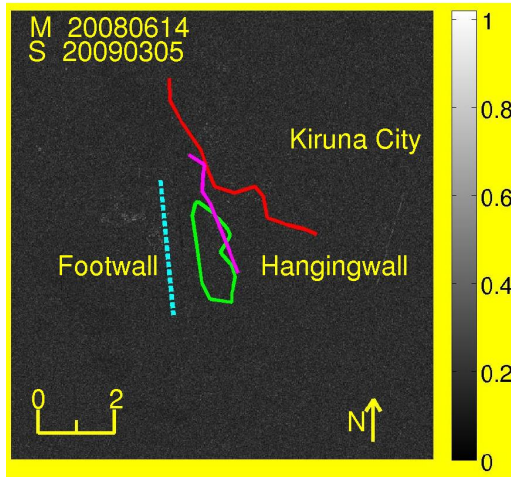


(c) Common master interferogram for the Kiruna test site.

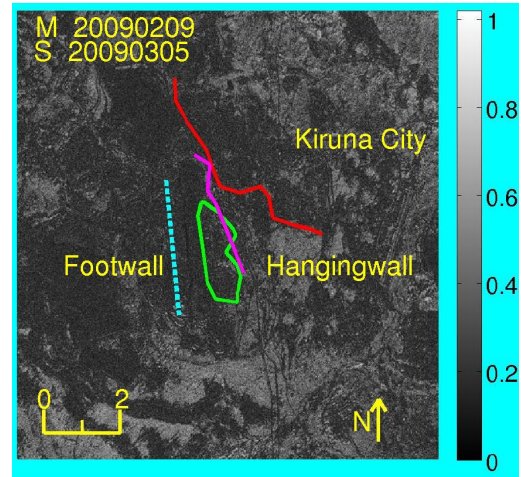


(d) Sequential interferogram for the Kiruna test site.

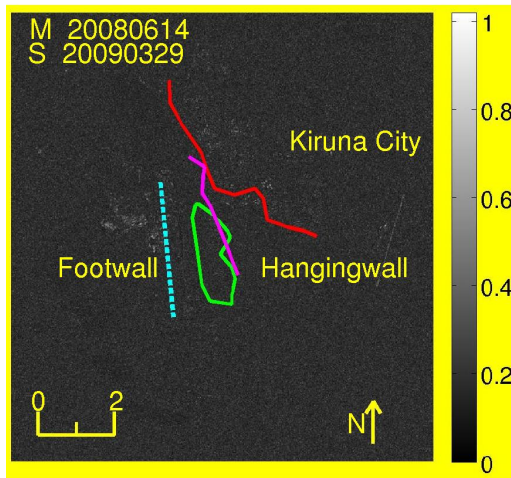
FIGURE A.5: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



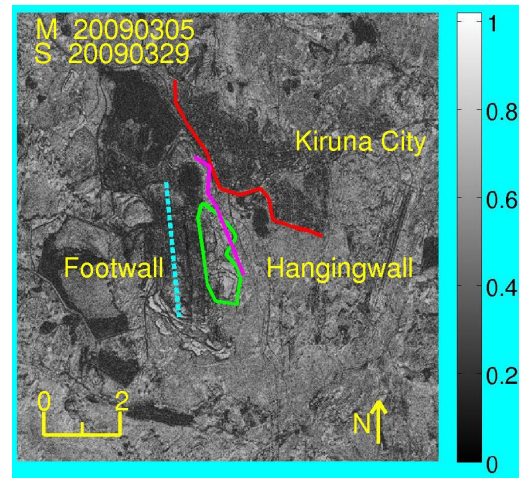
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

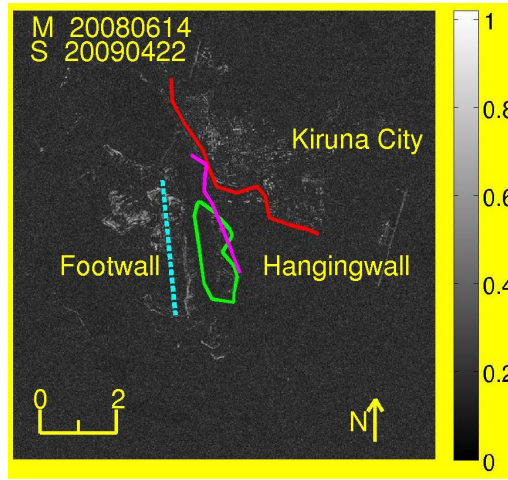


(c) Common master interferogram for the Kiruna test site.

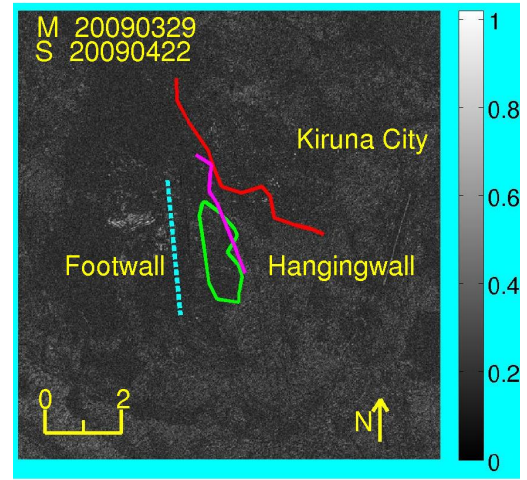


(d) Sequential interferogram for the Kiruna test site.

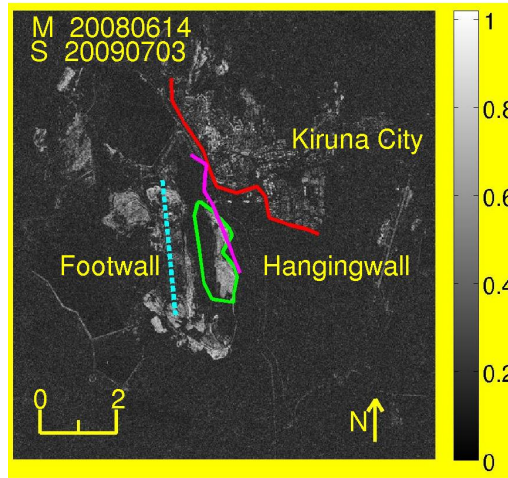
FIGURE A.6: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



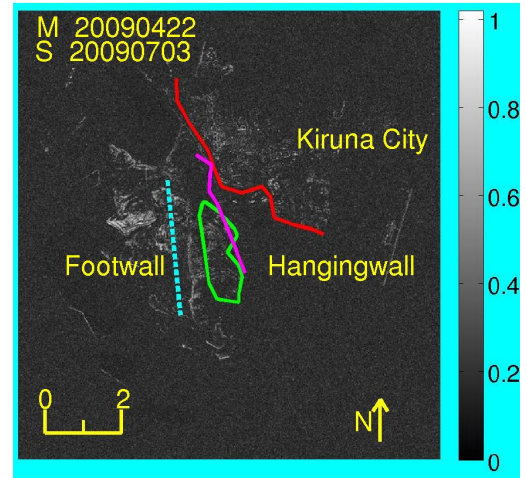
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

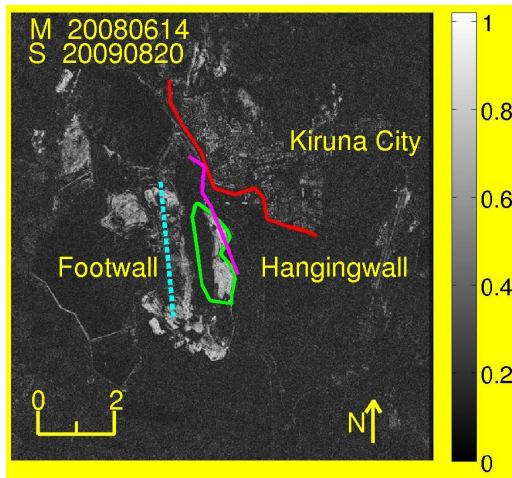


(c) Common master interferogram for the Kiruna test site.

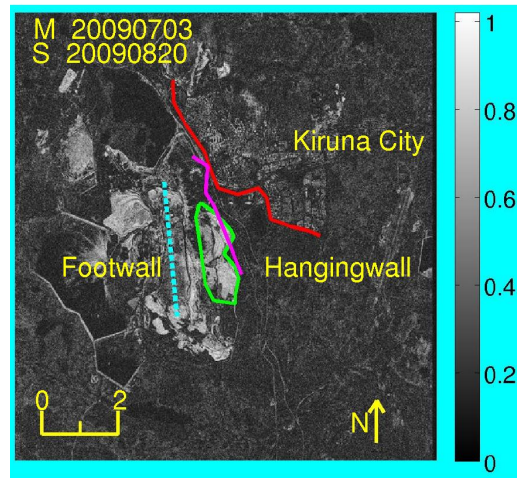


(d) Sequential interferogram for the Kiruna test site.

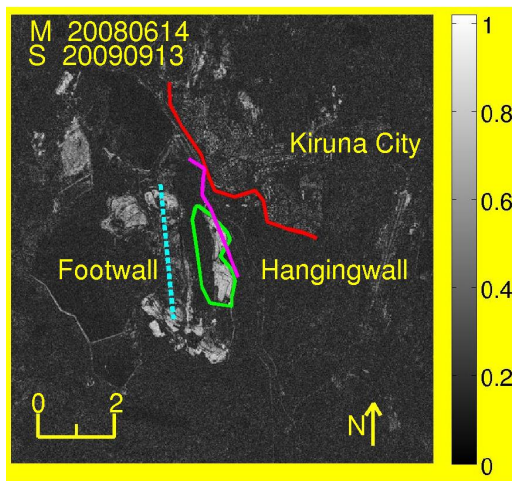
FIGURE A.7: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



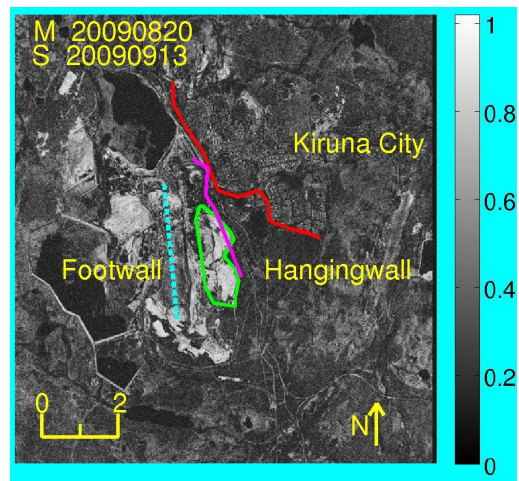
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

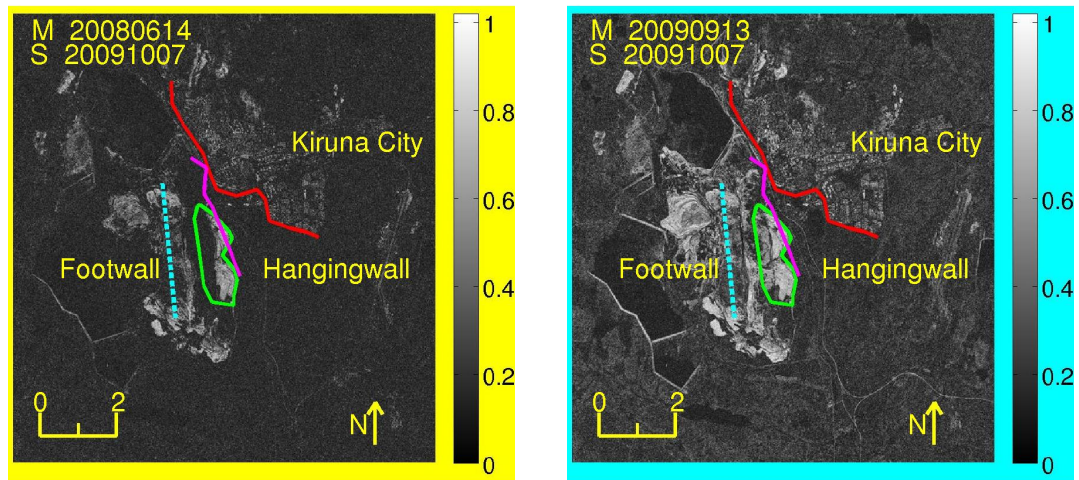


(c) Common master interferogram for the Kiruna test site.



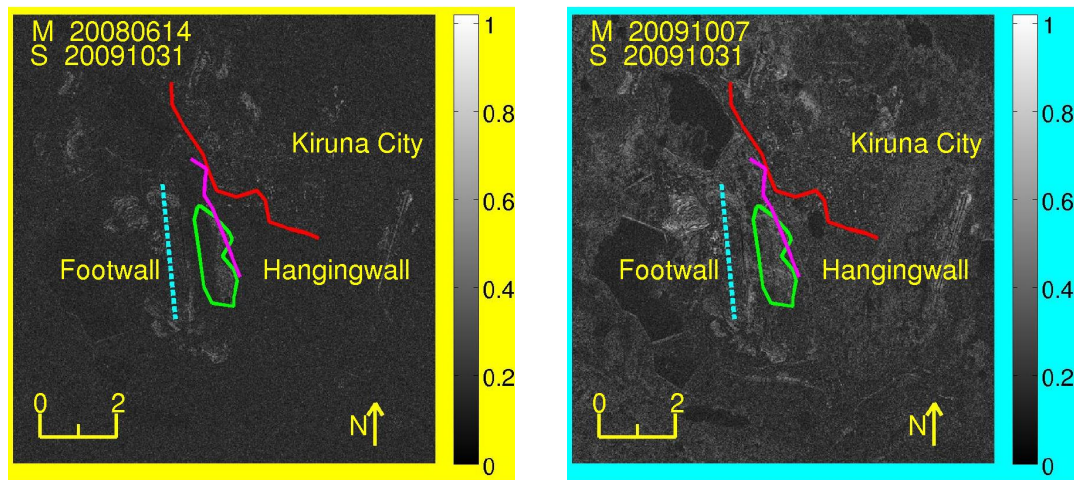
(d) Sequential interferogram for the Kiruna test site.

FIGURE A.8: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



(a) Common master interferogram for the Kiruna test site.

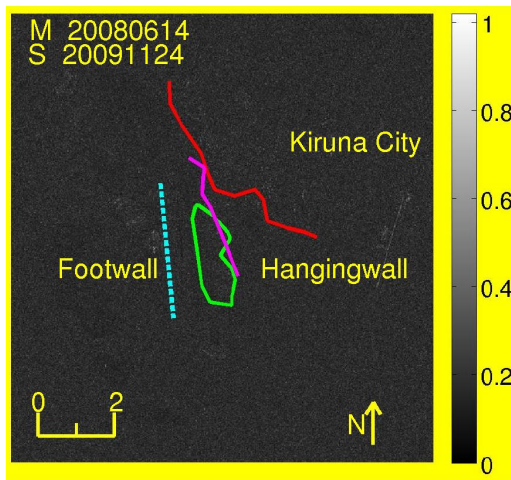
(b) Sequential interferogram for the Kiruna test site.



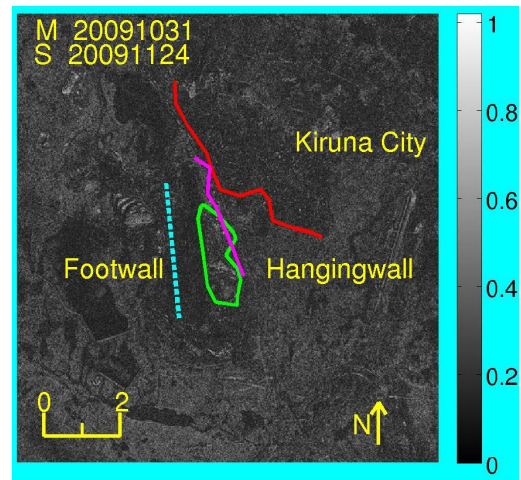
(c) Common master interferogram for the Kiruna test site.

(d) Sequential interferogram for the Kiruna test site.

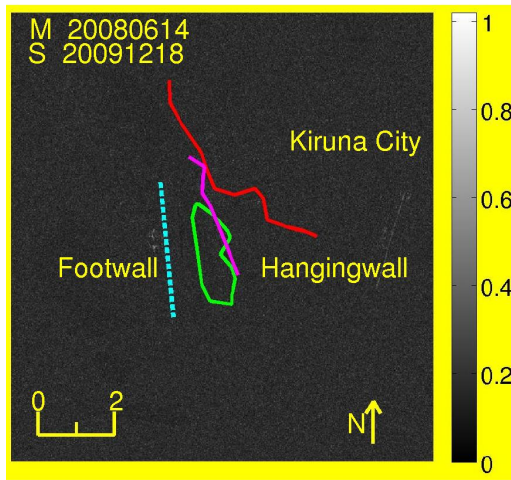
FIGURE A.9: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



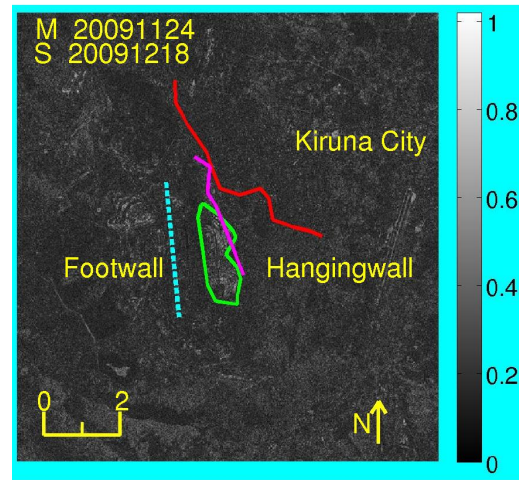
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

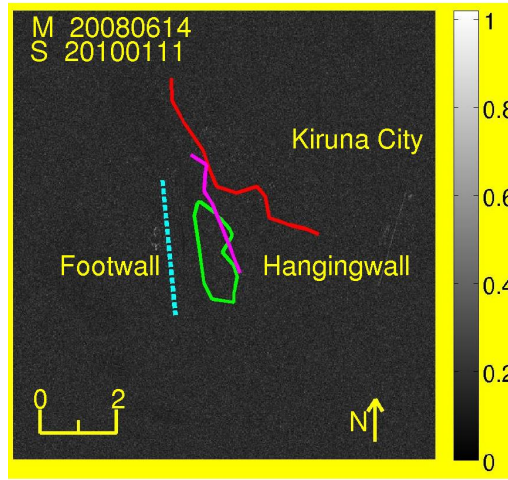


(c) Common master interferogram for the Kiruna test site.

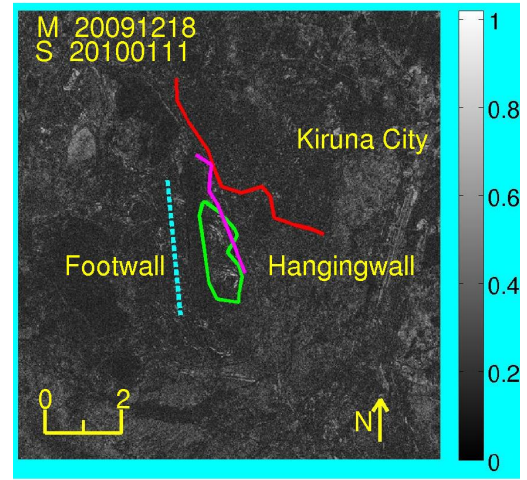


(d) Sequential interferogram for the Kiruna test site.

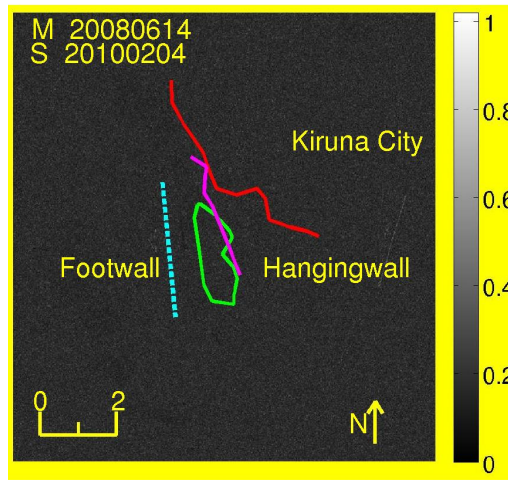
FIGURE A.10: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



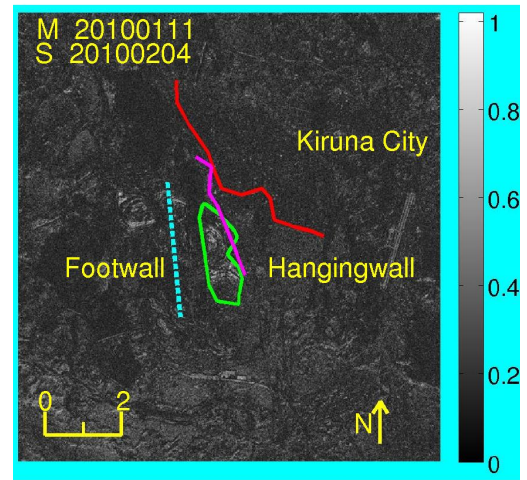
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

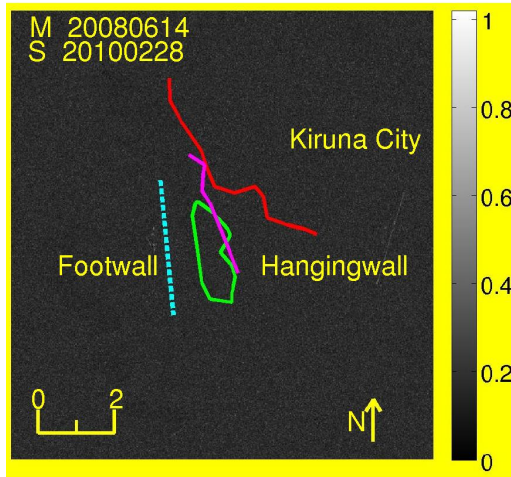


(c) Common master interferogram for the Kiruna test site.

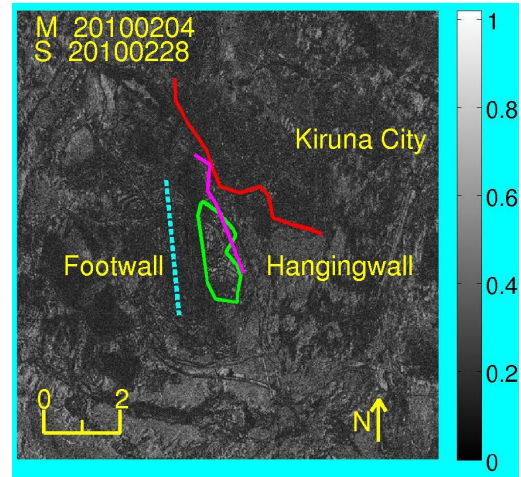


(d) Sequential interferogram for the Kiruna test site.

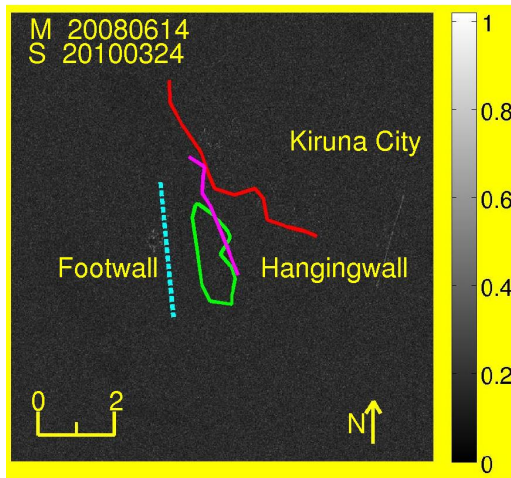
FIGURE A.11: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



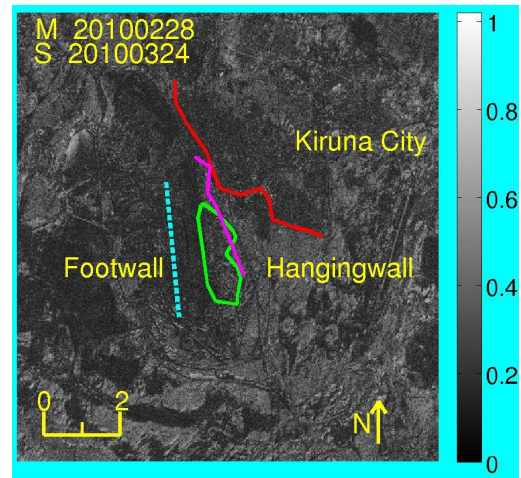
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

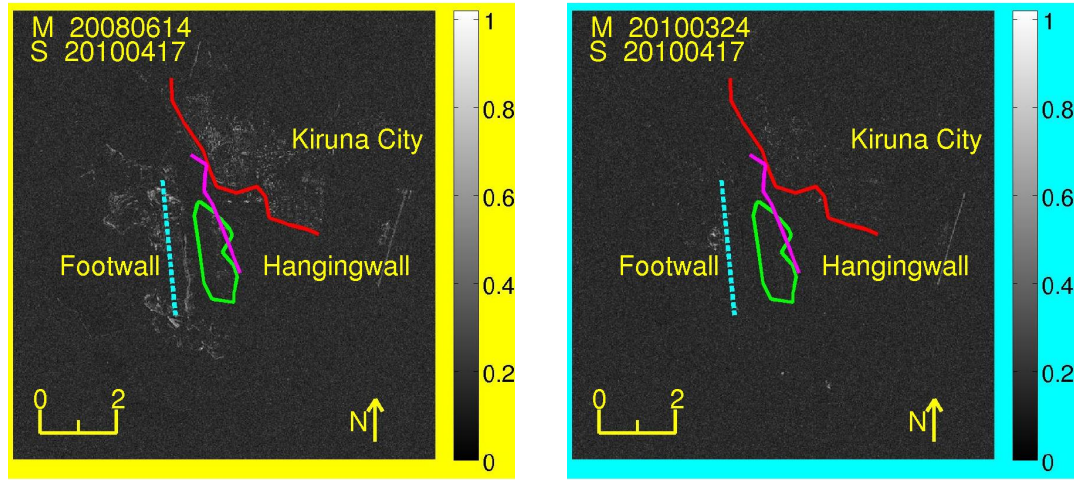


(c) Common master interferogram for the Kiruna test site.



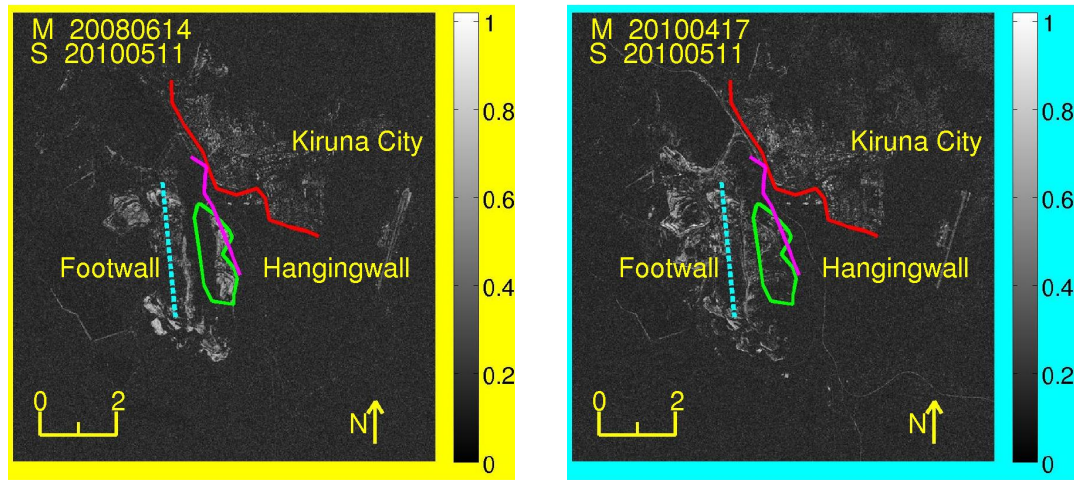
(d) Sequential interferogram for the Kiruna test site.

FIGURE A.12: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



(a) Common master interferogram for the Kiruna test site.

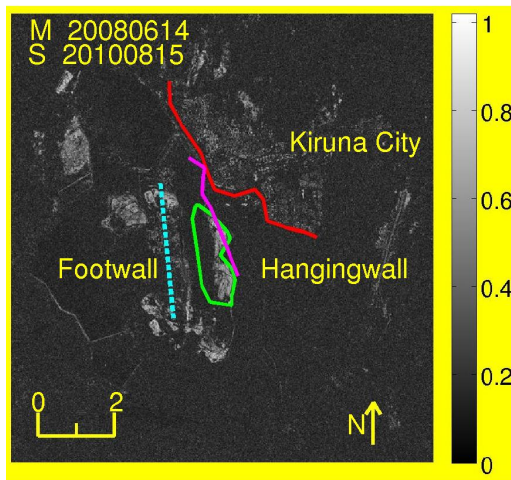
(b) Sequential interferogram for the Kiruna test site.



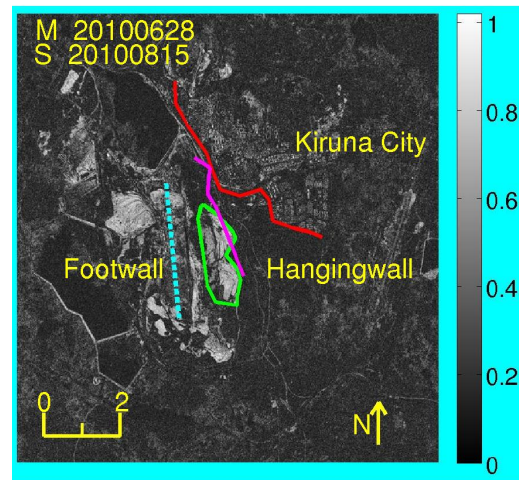
(c) Common master interferogram for the Kiruna test site.

(d) Sequential interferogram for the Kiruna test site.

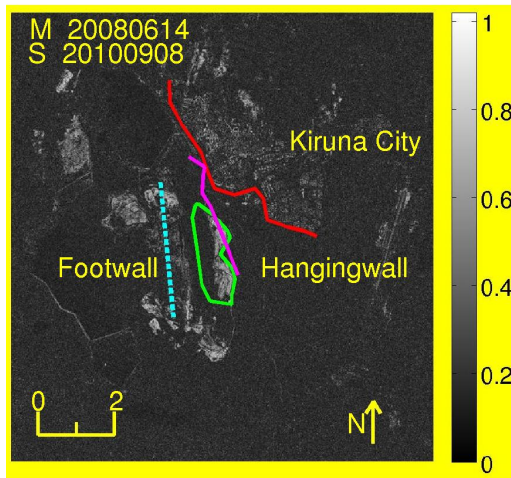
FIGURE A.13: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



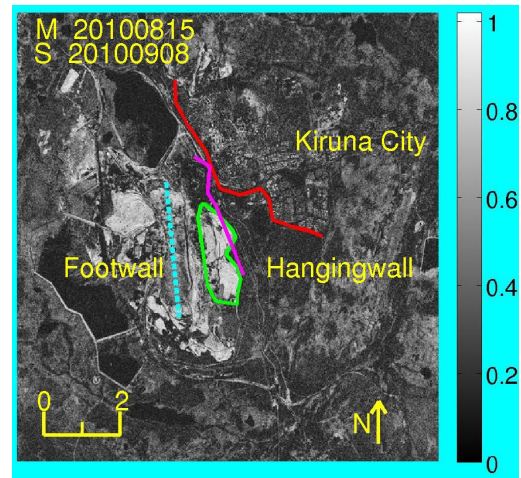
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.

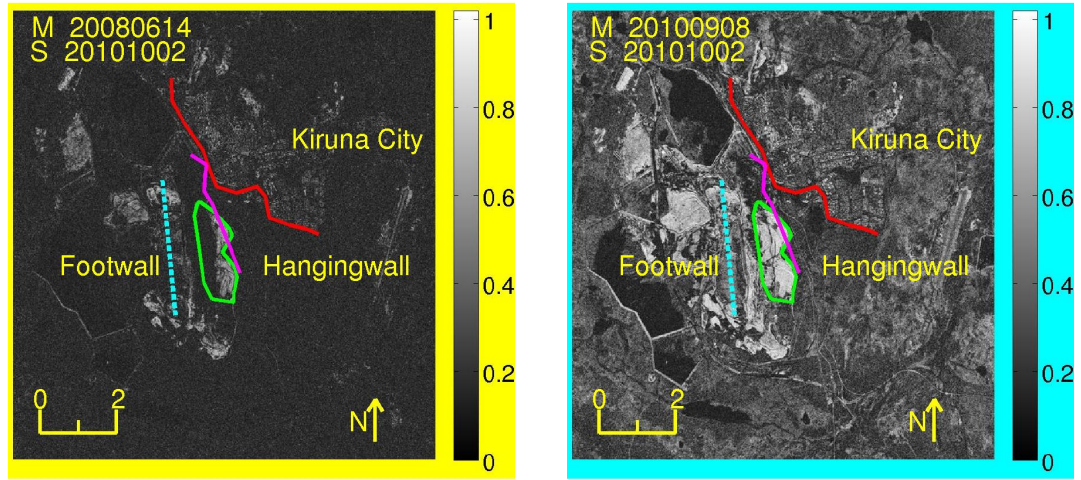


(c) Common master interferogram for the Kiruna test site.



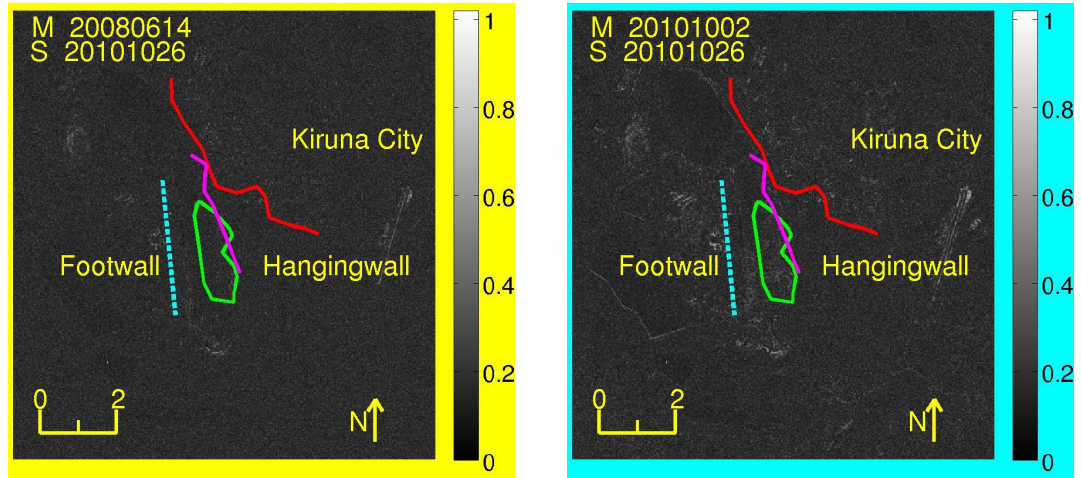
(d) Sequential interferogram for the Kiruna test site.

FIGURE A.14: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



(a) Common master interferogram for the Kiruna test site.

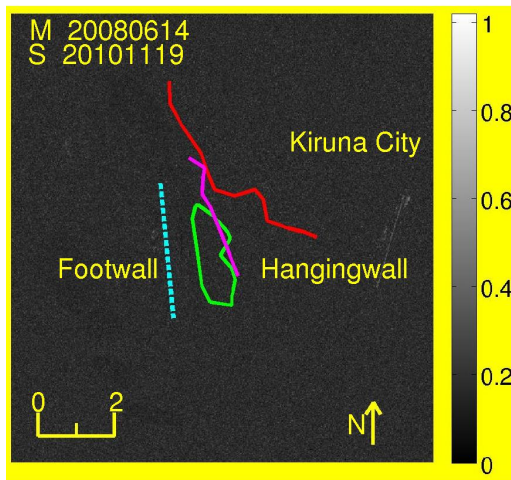
(b) Sequential interferogram for the Kiruna test site.



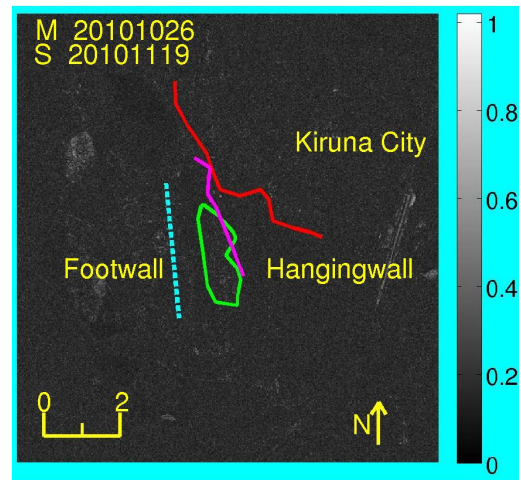
(c) Common master interferogram for the Kiruna test site.

(d) Sequential interferogram for the Kiruna test site.

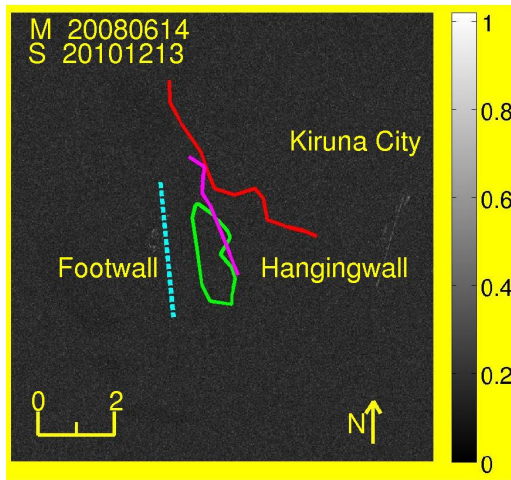
FIGURE A.15: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.



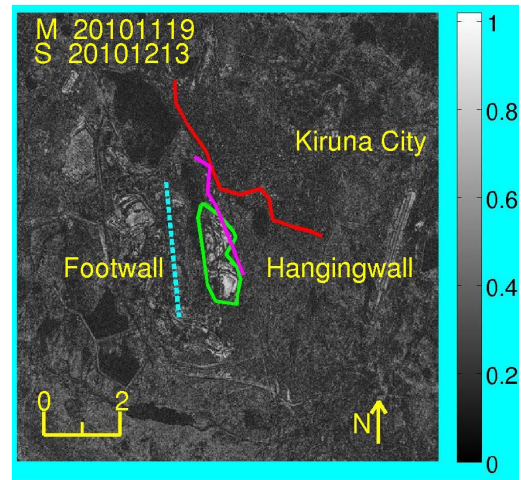
(a) Common master interferogram for the Kiruna test site.



(b) Sequential interferogram for the Kiruna test site.



(c) Common master interferogram for the Kiruna test site.



(d) Sequential interferogram for the Kiruna test site.

FIGURE A.16: M is the master image date in YYYYMMDD format. S is the slave image date in YYYYMMDD format. The red line is the Kiruna city limits. The magenta color line was the Environmental criterion limit in 2014. Waste rock area is marked in green color. The cyan-colored dashed line is the centerline of the open-pit.

Appendix B

Comparison of U6D CRInSAR and Static-GPS measurements

This annex lists the line-of-sight CRInSAR U6D beam mode time series measurements and Static-GPS Time series measurements produced for the Kiruna test site. EVInSAR software was used for the InSAR processing. LKAB Static-GPS measurement data were used in the plots.

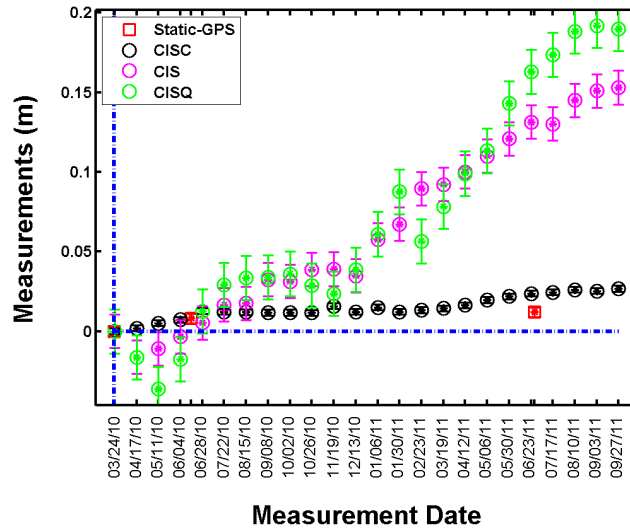


FIGURE B.1: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-02 and GPS-L14

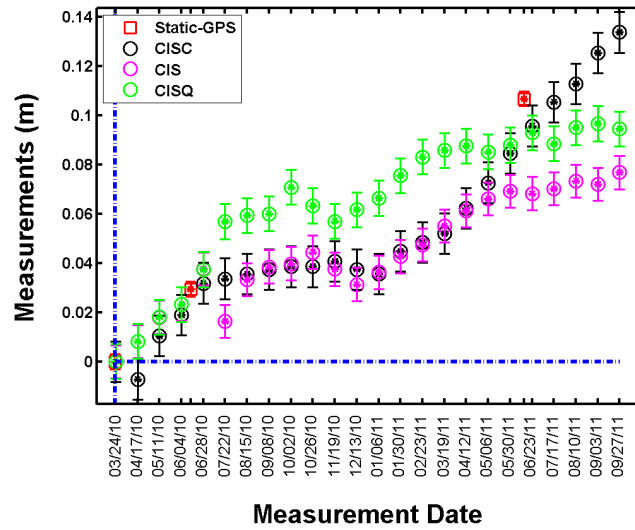


FIGURE B.2: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-3 and GPS-C8

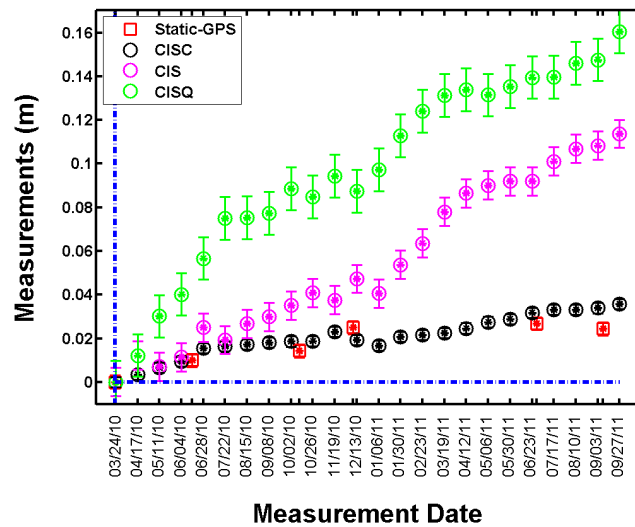


FIGURE B.3: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-4 and GPS-M12

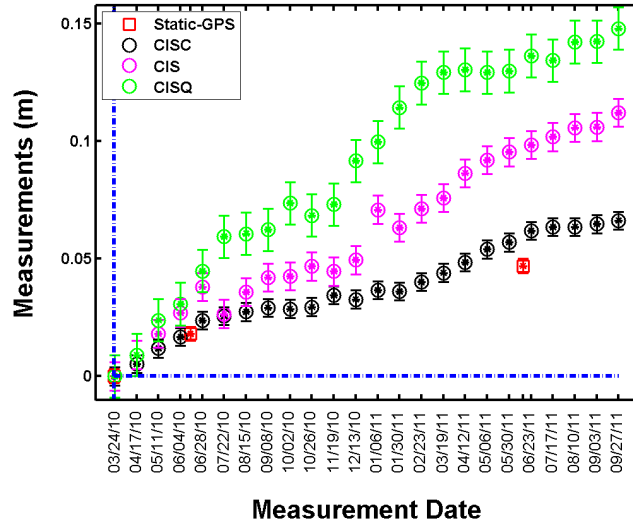


FIGURE B.4: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-5 and GPS-A8

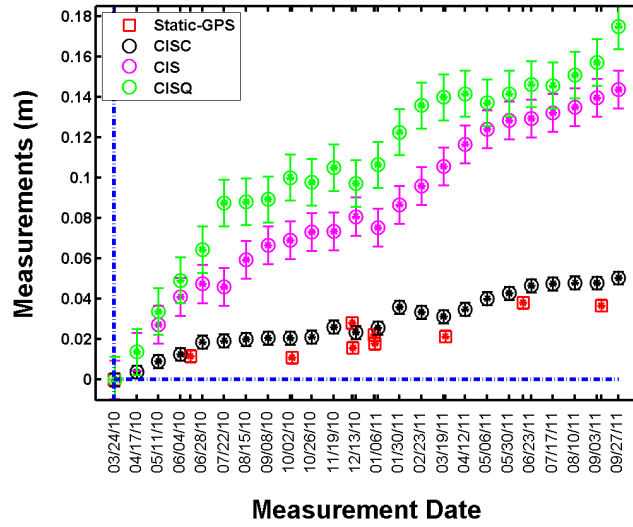


FIGURE B.5: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-6 and GPS-L10

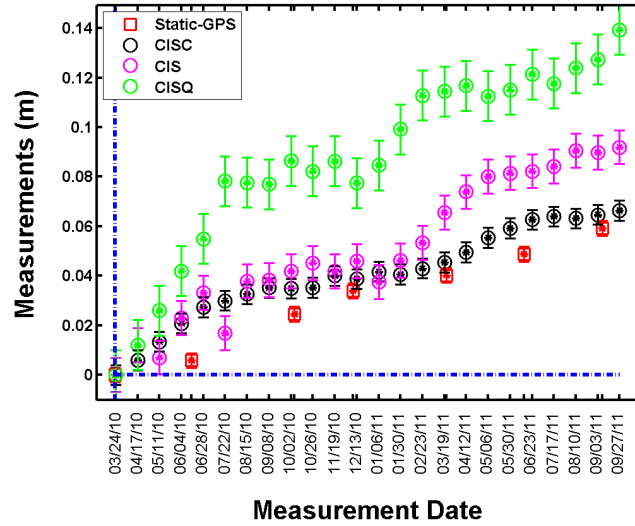


FIGURE B.6: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-7 and GPS-M7

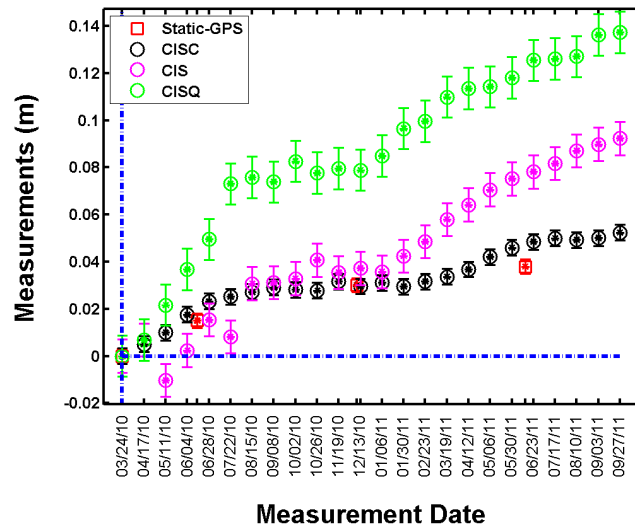


FIGURE B.7: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-8 and GPS-M8

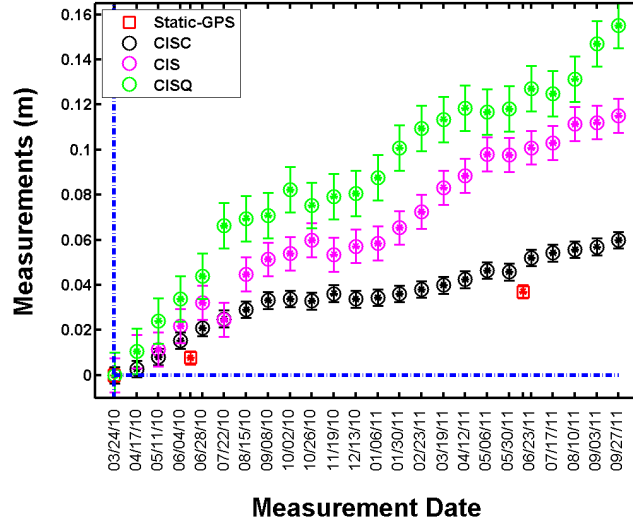


FIGURE B.8: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-9 and GPS-M1

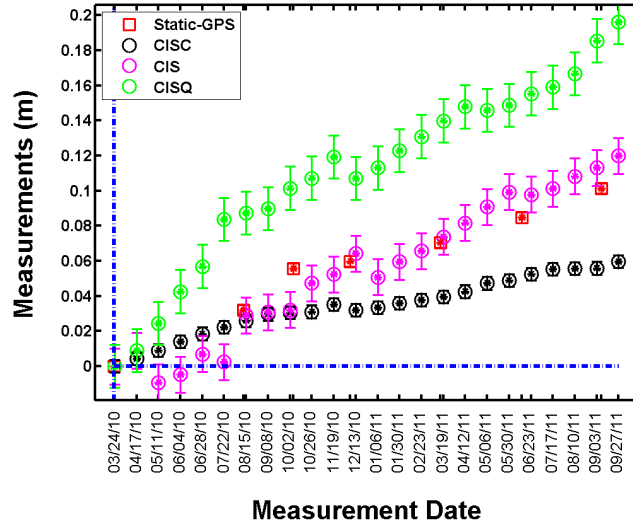


FIGURE B.9: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-10 and GPS-H11

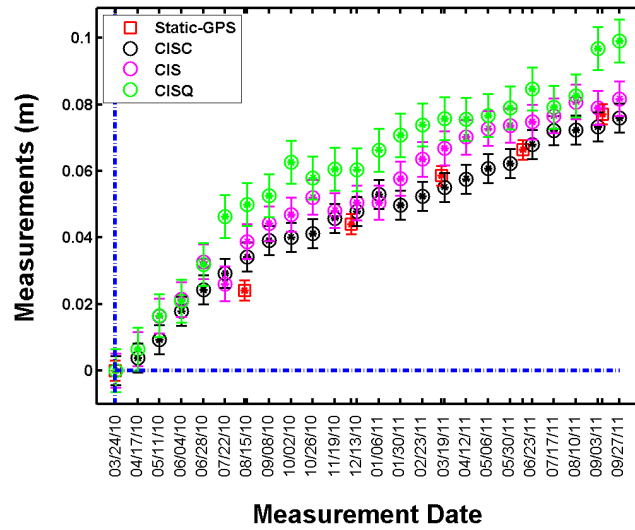


FIGURE B.10: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-11 and GPS-H13

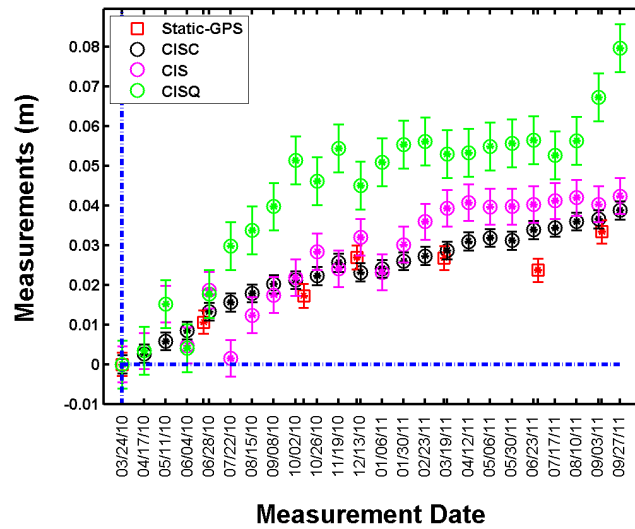


FIGURE B.11: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-12 and GPS-H16

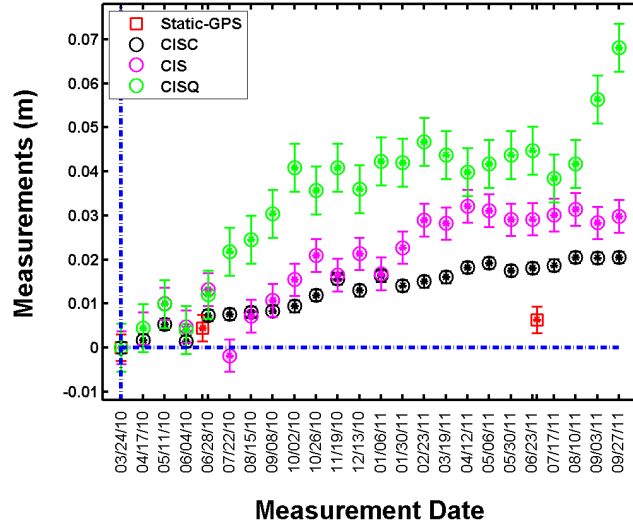


FIGURE B.12: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-13 and GPS-H18

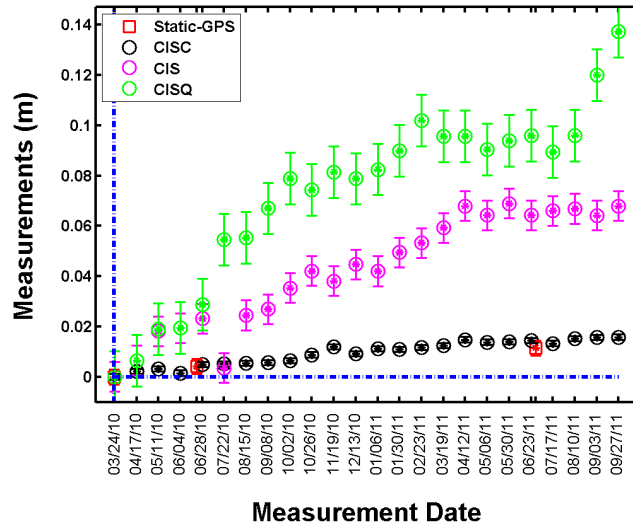


FIGURE B.13: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-14 and GPS-H32

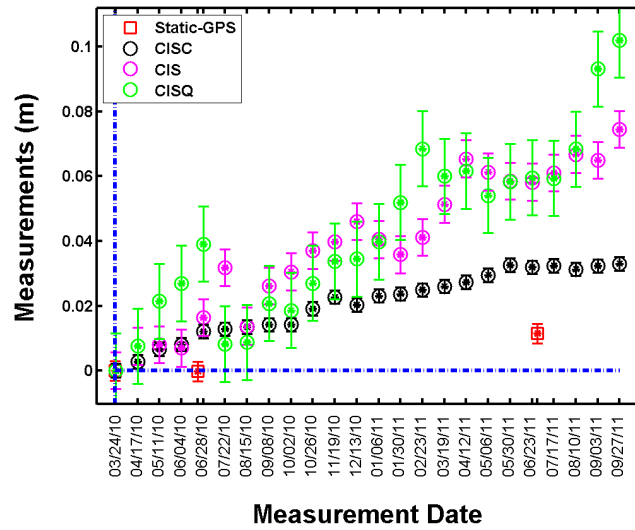


FIGURE B.14: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-15 and GPS-S10

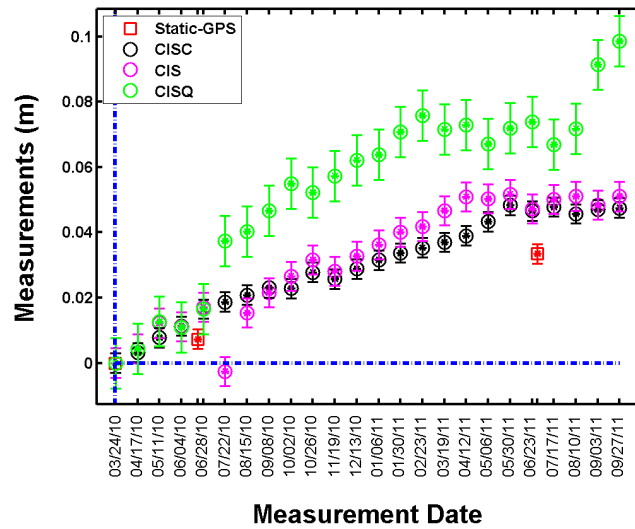


FIGURE B.15: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-16 and GPS-S8

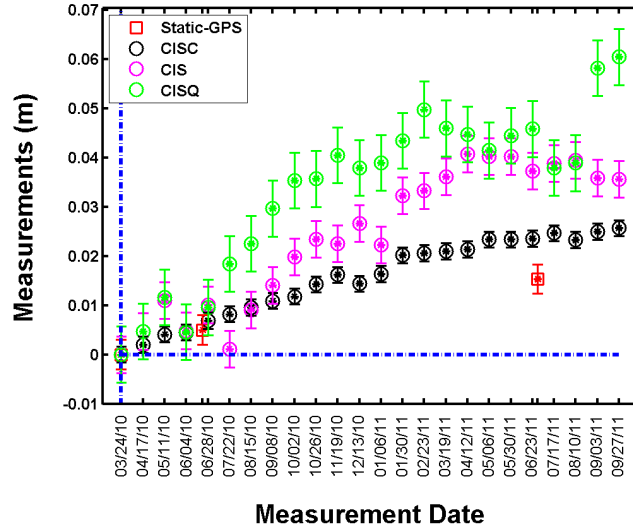


FIGURE B.16: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-17 and GPS-S11

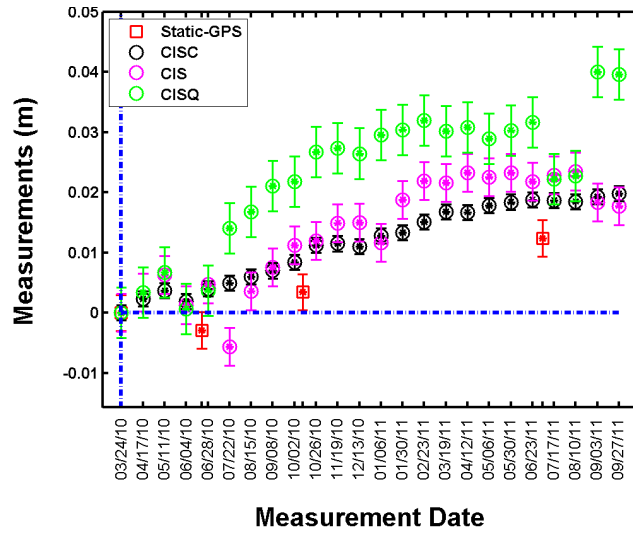


FIGURE B.17: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-18 and GPS-13

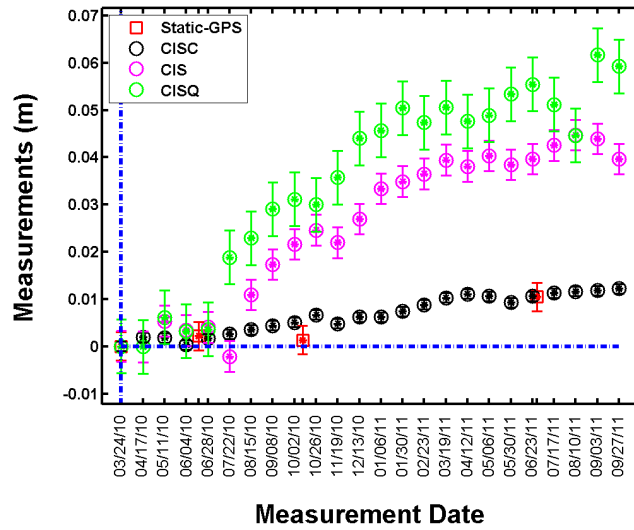


FIGURE B.18: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-19 and GPS-N51

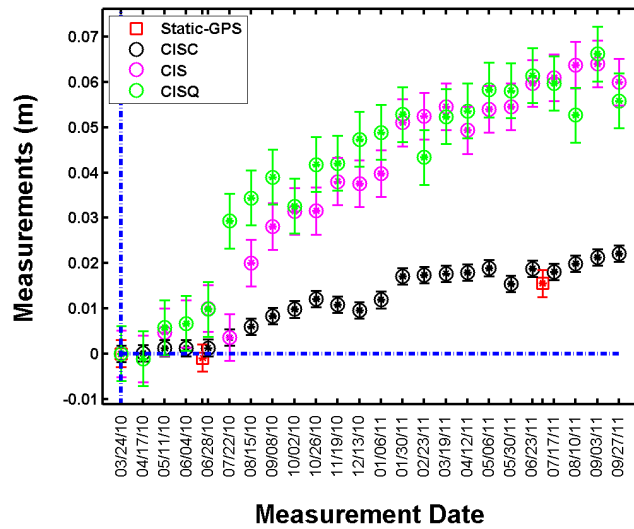


FIGURE B.19: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-20 and GPS-T25

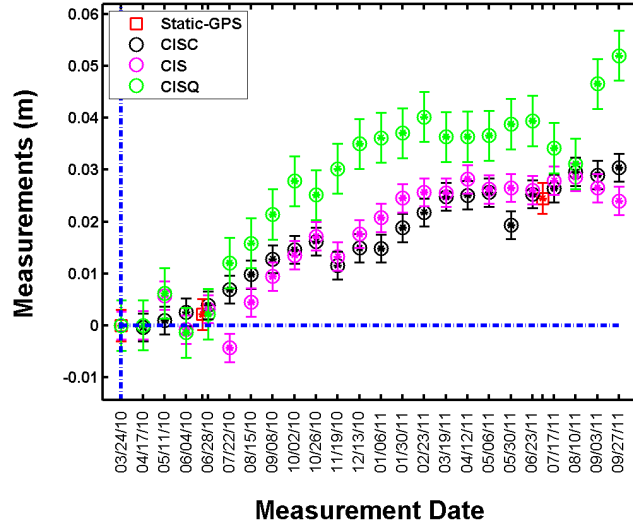


FIGURE B.20: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-21 and GPS-T23

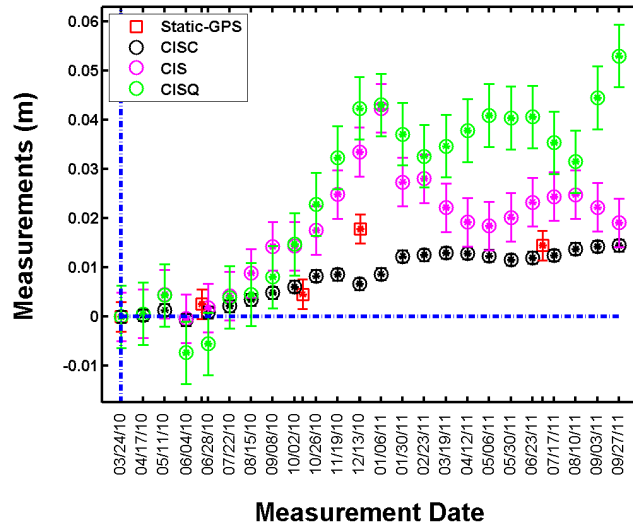


FIGURE B.21: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-22 and GPS-S15

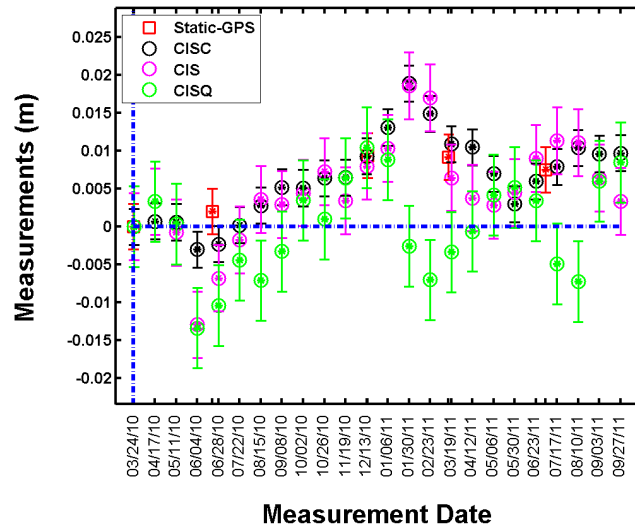


FIGURE B.22: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-23 and GPS-S29

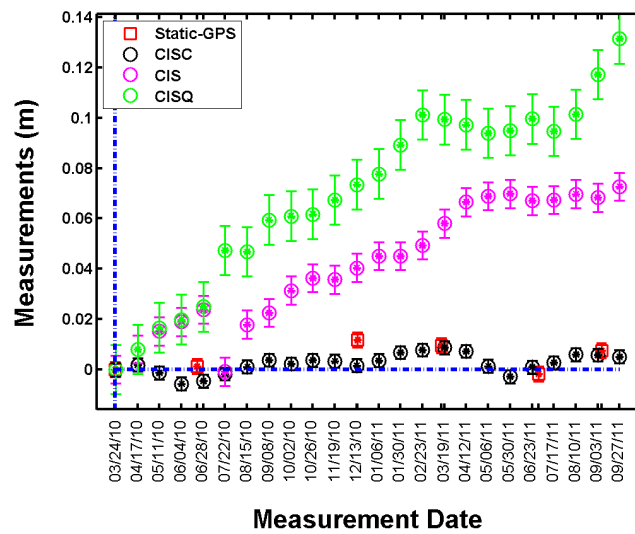


FIGURE B.23: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-24 and GPS-D60

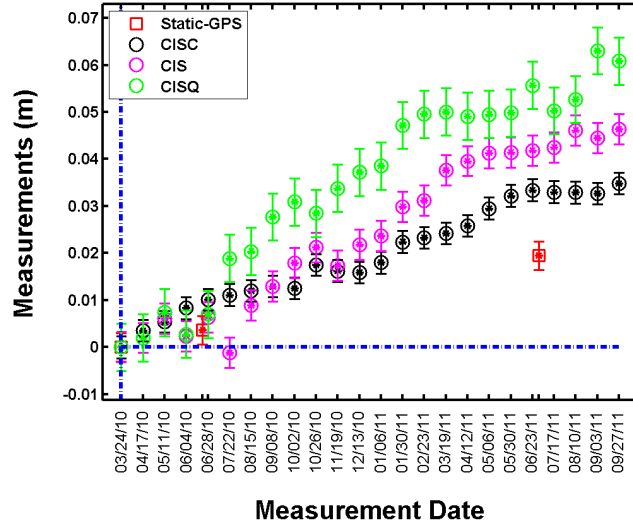


FIGURE B.24: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-25 and GPS-D50

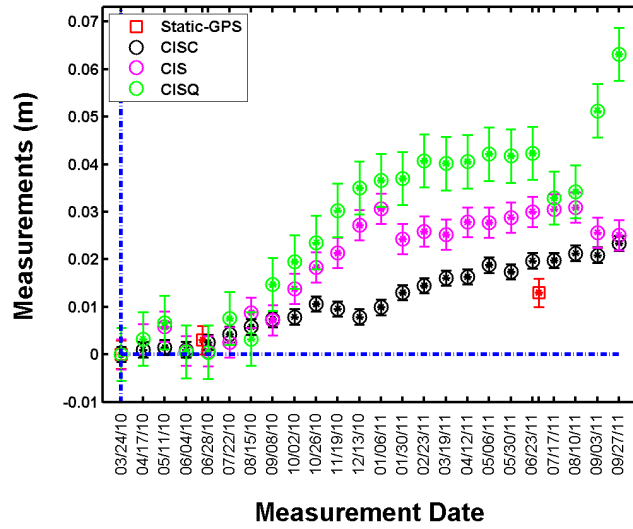


FIGURE B.25: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-26 and GPS-D53

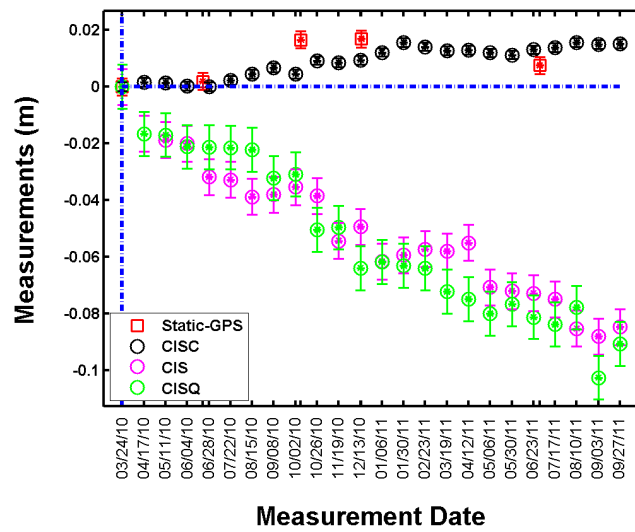


FIGURE B.26: Time series plots of double difference CR-InSAR measurements and double difference Static-GPS measurements. The CISC, CIS, CISQ and Static-GPS measurements are marked in black, purple and green circles, as well as red boxes. The cross point of the blue dotted lines is the starting point (zero) of the plots CR-27 and GPS-D57

Appendix C

Simulation plots

This annex lists the simulation plots. Matlab (R2012b) was used as the coding language and Matlab (R2012b) signal processing toolbox was used for the simulations.

C.0.1 RMS error plots for simulated signals

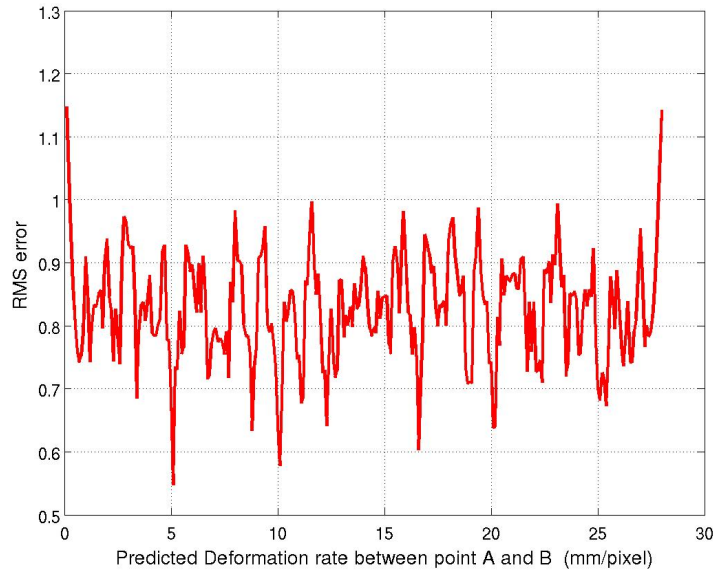


FIGURE C.1: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 5 mm/pixel with 0.75 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

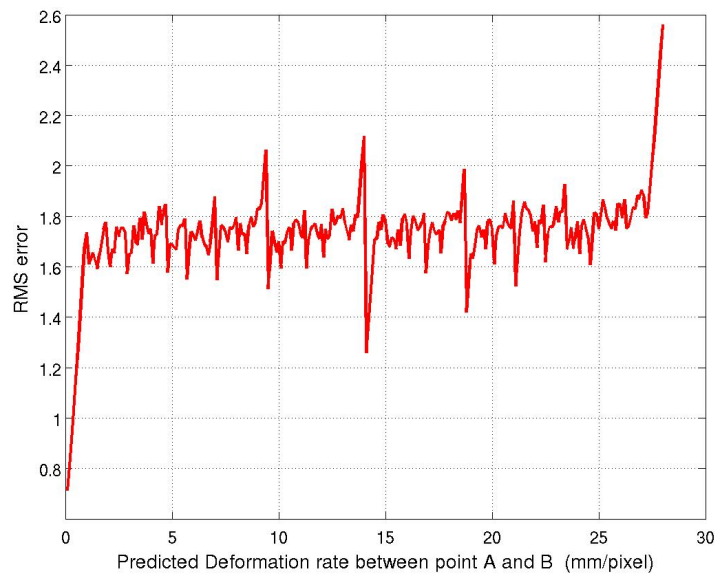


FIGURE C.2: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 0.2 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

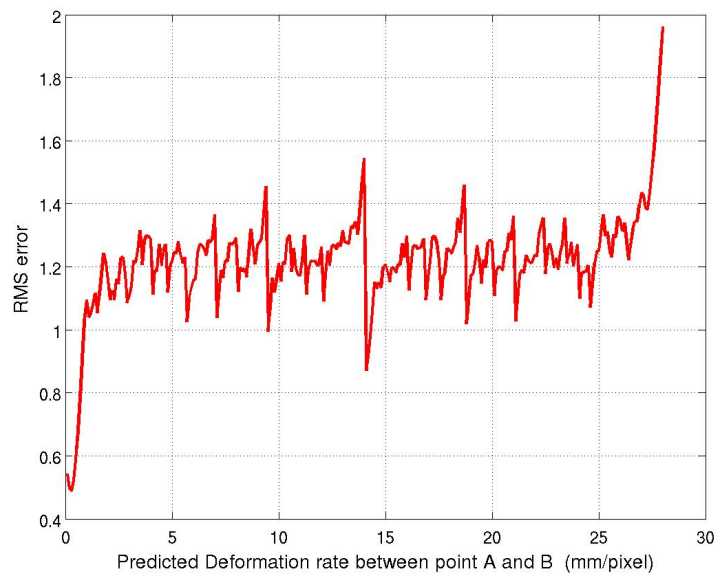


FIGURE C.3: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 0.7 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

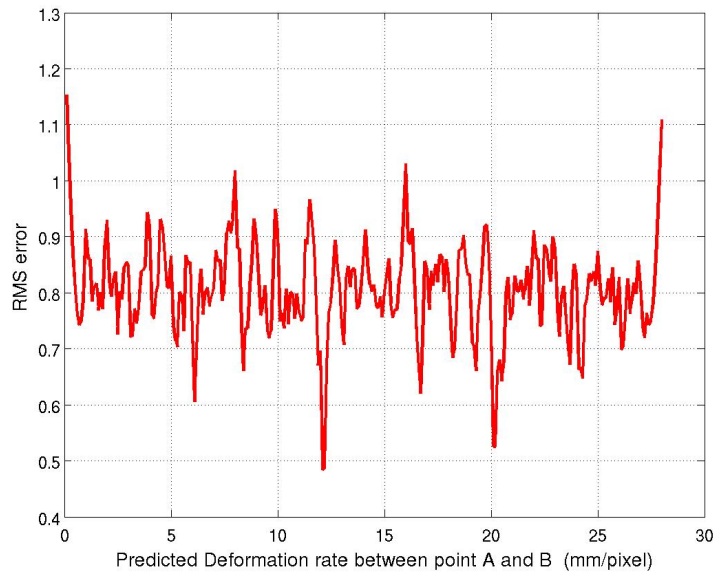


FIGURE C.4: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 12 mm/pixel with 0.75 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

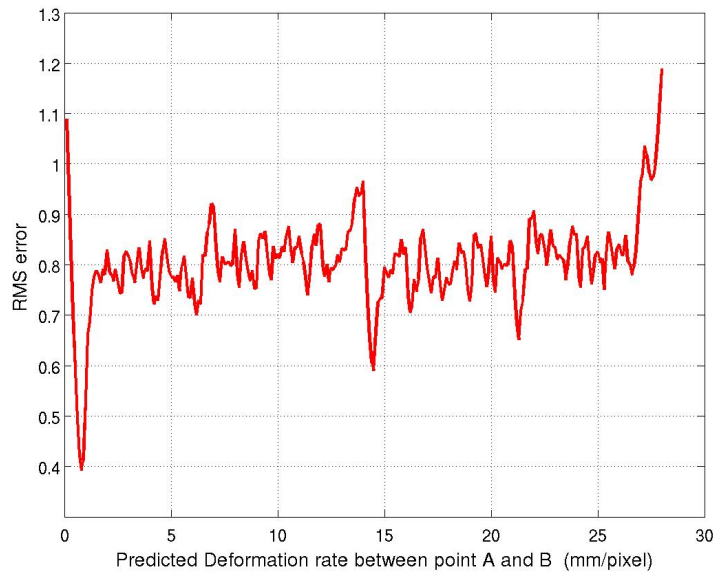


FIGURE C.5: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 0.68 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

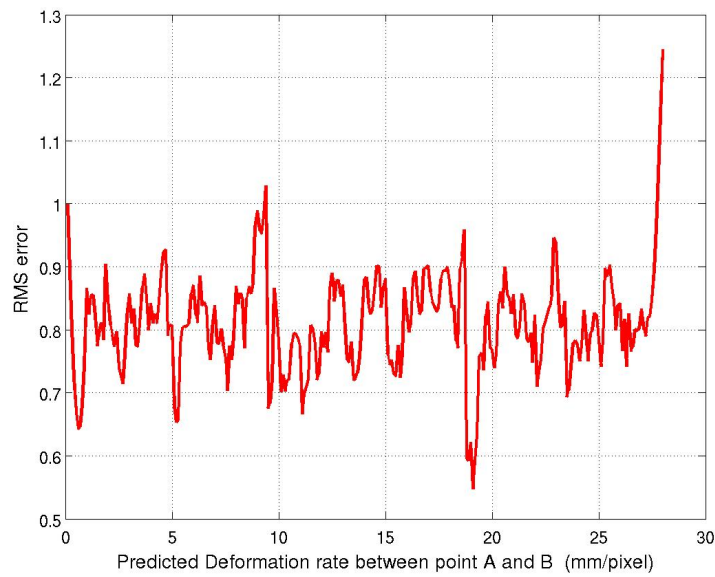


FIGURE C.6: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 19 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

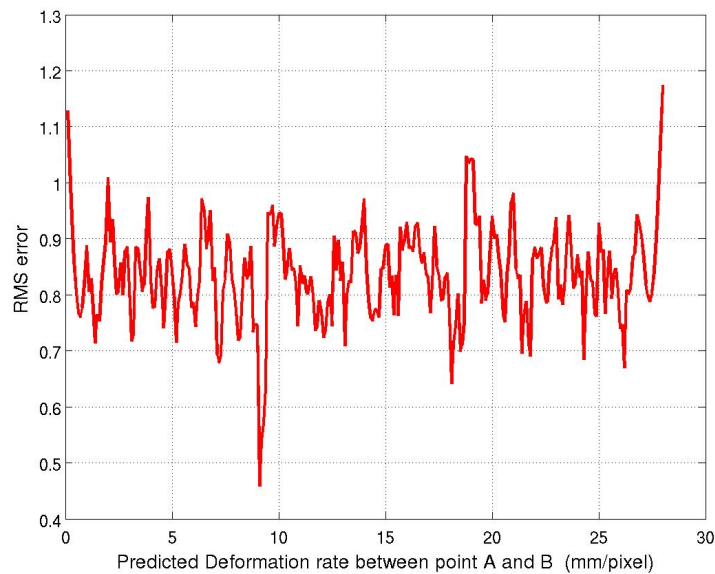


FIGURE C.7: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 9 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

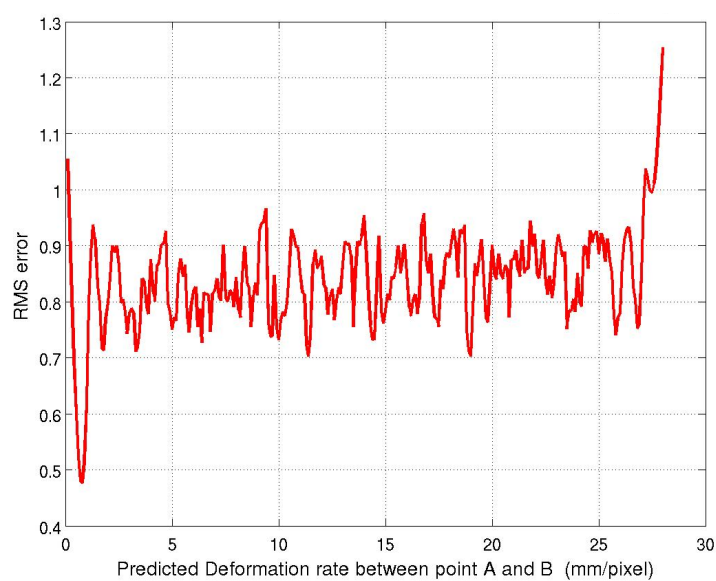


FIGURE C.8: RMS error between simulated ground deformation and model signal. The simulated ground deformation rate is 0.8 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is RMS error. Minimum RMS error gives the best-fit model (predicted) deformation rate.

C.0.2 Correlation coefficient plots for simulated signals

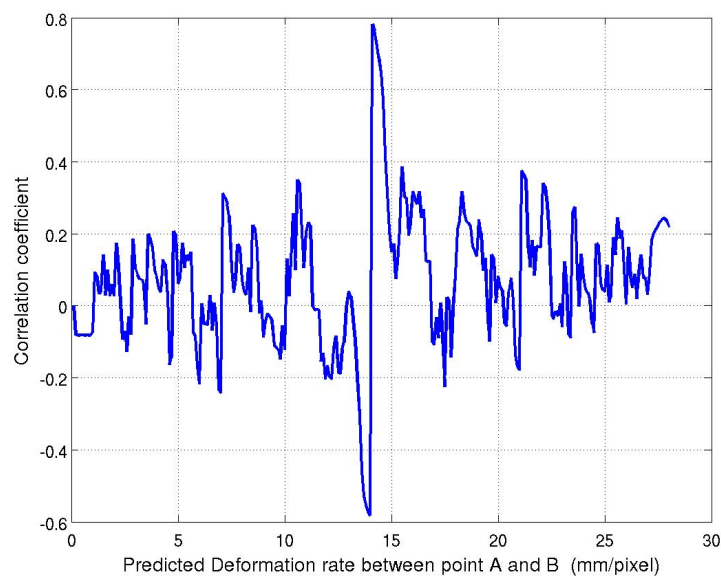


FIGURE C.9: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 14 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

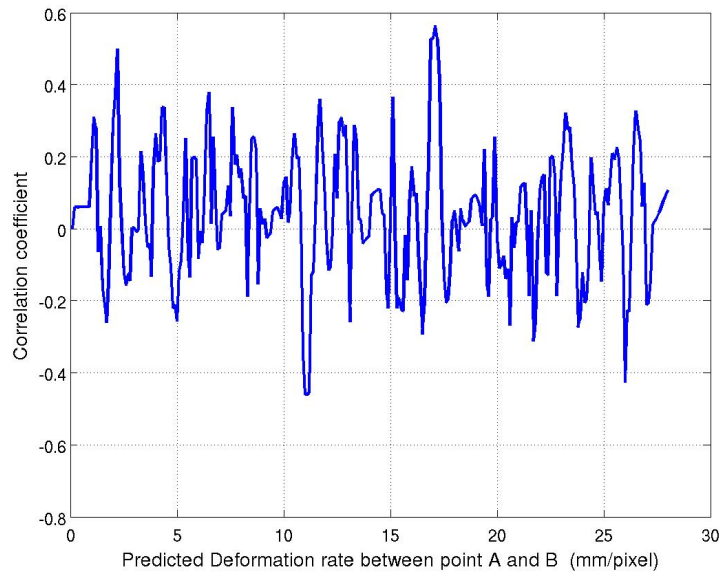


FIGURE C.10: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 17 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

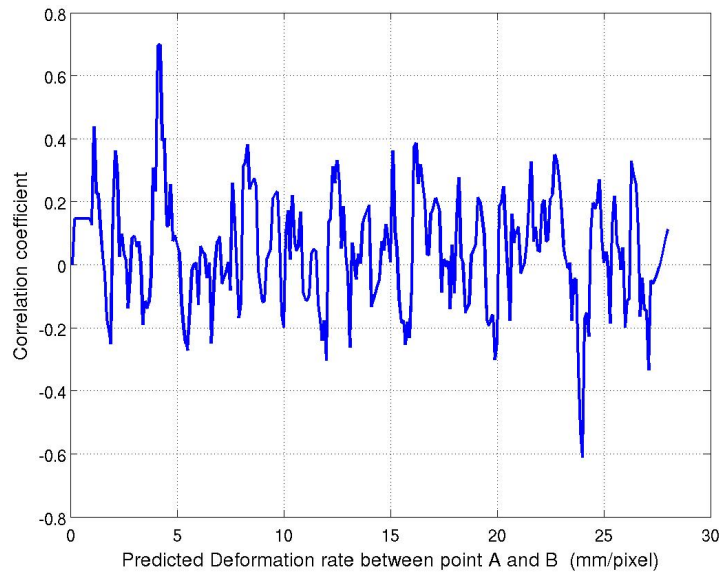


FIGURE C.11: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 4 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

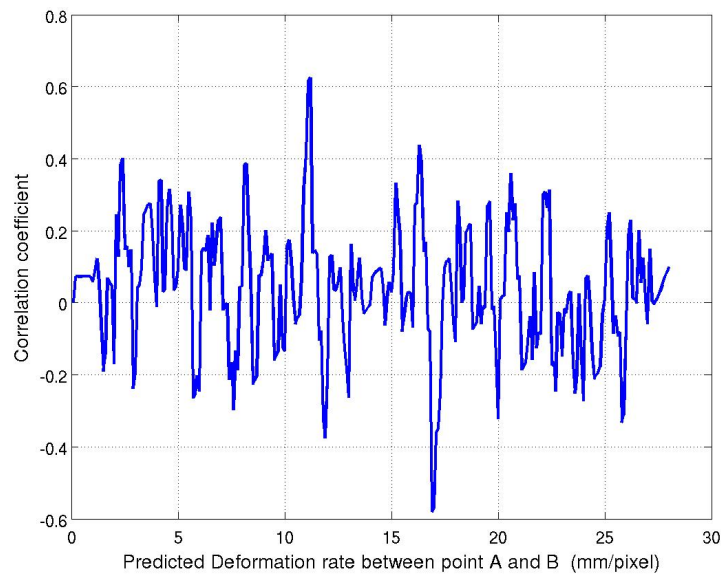


FIGURE C.12: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 11 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

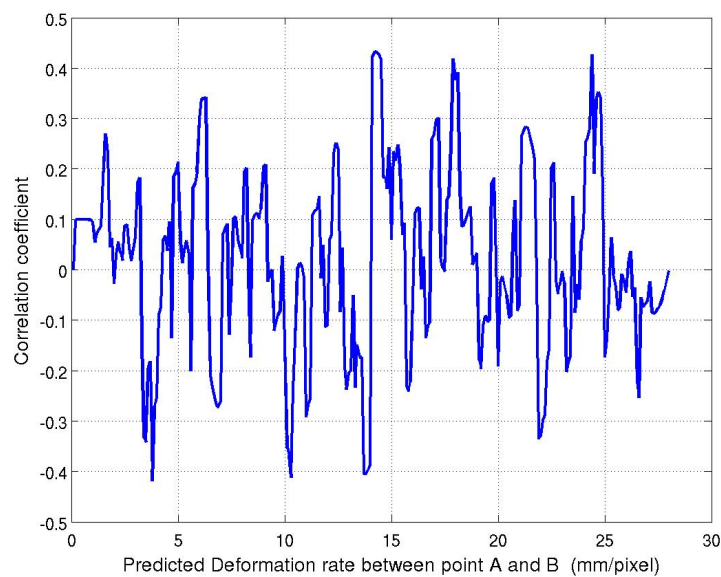


FIGURE C.13: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 14 mm/pixel with 0.9 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

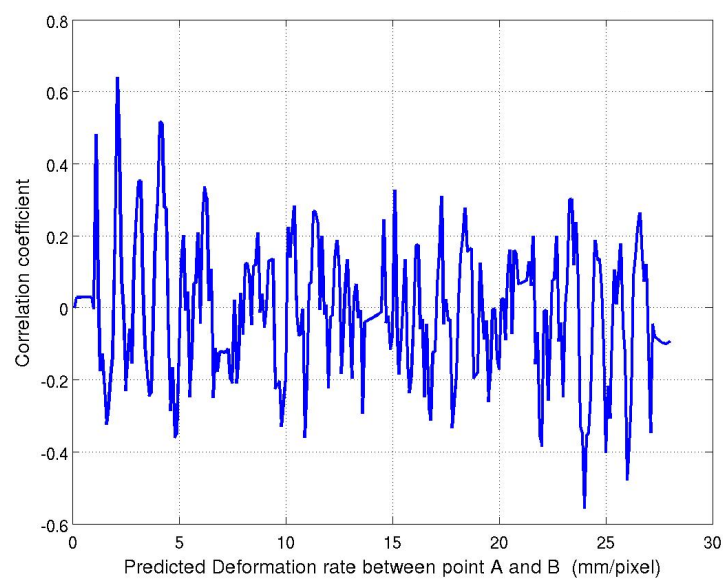


FIGURE C.14: Correlation coefficient between simulated ground deformation and model signal. The simulated ground deformation rate is 2 mm/pixel with 0.5 SNR. “X” axis is the Predicted (model) deformation rate (mm/pixel) and “Y” axis is Correlation coefficient. Highest Correlation coefficient gives the best-fit model (predicted) deformation rate.

Appendix D

Image data

This annex lists the used image data for InSAR processing in Chapter 7. EVInSAR software was used for the InSAR processing.

TABLE D.1: Beam characteristics of the selected tracks used for this study.

Track	Incident Angle Range (deg)	Nominal Resolution (m)	Orbit Direction	Heading Angle (deg)
U6D	34.0 - 35.3	2.8	Descending	194
U25A	47.4 - 47.7	2.1	Ascending	352
U70D	19.9 - 21.5	4.5	Descending	198

TABLE D.2: U6D beam mode images

Image Number	DATE	TIME (UTC)
1	2010-March-24	05:19
2	2010-April-17	05:19
3	2010-May-11	05:19
4	2010-June-04	05:19
5	2010-June-28	05:19
7	2010-August-15	05:19
8	2010-September-08	05:19
9	2010-October-02	05:19
10	2010-October-26	05:19
11	2010-November-19	05:19
12	2010-December-13	05:19
13	2011-January-06	05:19
14	2011-January-30	05:19
15	2011-February-23	05:19
16	2011-March-19	05:19
17	2011-April-12	05:19
18	2011-May-06	05:19
19	2011-May-30	05:19
20	2011-July-23	05:19
21	2011-July-17	05:19
22	2011-August-10	05:19
23	2011-September-03	05:19
24	2011-September-27	05:19
25	2011-October-21	05:19
26	2011-November-14	19:23
27	2011-December-08	05:19
28	2012-January-01	05:19
29	2012-January-25	05:19
30	2012-February-18	05:19
31	2012-March-13	05:19
32	2012-April-06	05:19
33	2012-April-30	05:19
34	2012-May-24	05:19

TABLE D.3: U25A beam mode images

Image Number	DATE	TIME (UTC)
1	2010-Mar-18	16:26
2	2010-Apr-11	16:26
3	2010-May-05	16:26
4	2010-May-29	16:26
5	2010-June-22	16:26
6	2010-July-16	16:26
7	2010-August-09	16:26
8	2010-September-02	16:26
9	2010-September-26	16:26
10	2010-October-20	16:26
11	2010-November-13	16:26
12	2010-December-07	16:26
13	2010-December-31	16:26
14	2011-January-24	16:26
15	2011-February-17	16:26
16	2011-March-13	16:26
17	2011-April-06	16:26
18	2011-April-30	16:26
19	2011-May-24	16:27
20	2011-June-17	16:27
21	2011-July-11	16:27
22	2011-August-04	16:27
23	2011-August-28	16:27
24	2011-October-15	16:27
25	2011-November-08	16:27
26	2011-December-02	16:27
27	2011-December-26	16:27
28	2012-January-19	16:27
29	2012-February-12	16:27
30	2012-March-07	16:27
31	2012-March-31	16:27
32	2012-April-24	16:27
33	2012-May-18	16:27

TABLE D.4: U70D beam mode images

Image Number	DATE	TIME (UTC)
1	2010-March-13	05:40
2	2010-April-06	05:40
3	2010-April-30	05:40
4	2010-May-24	05:40
5	2010-June-17	05:40
6	2010-July-11	05:40
7	2010-August-04	05:40
8	2010-August-28	05:40
9	2010-September-21	05:40
10	2010-10 October-15	05:40
11	2010-11 November-08	05:40
12	2010-12 December-02	05:40
13	2010-12 December-26	05:40
14	2011-01 January-19	05:40
15	2011-02 February-12	05:40
16	2011-03 March-08	05:40
17	2011-04 April-01	05:40
18	2011-04 April-25	05:40
19	2011-May-19	05:19
20	2011-June-12	05:40
21	2011-July-06	05:40
22	2011-July-30	05:40
23	2011-August-23	05:40
24	2011-September-16	05:40
25	2011-October-10	05:40
26	2011-November-03	05:19
27	2011-November-27	05:19
28	2011-December-21	05:40
29	2012-January-14	05:40
30	2012-February-07	05:40
31	2012-March-26	05:40
32	2012-April-19	05:40
33	2012-May-13	05:40
34	2012-June-06	05:40

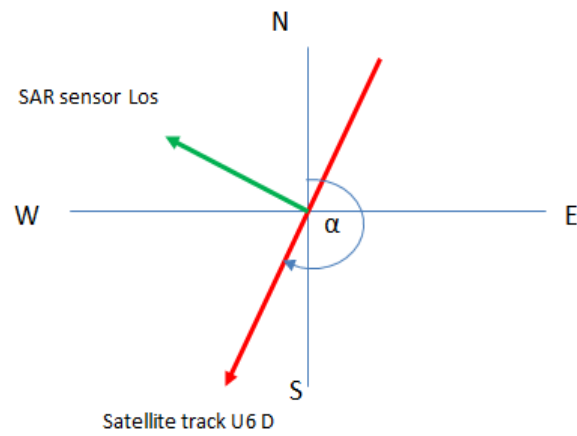


FIGURE D.1: U6D beam heading angle (α).

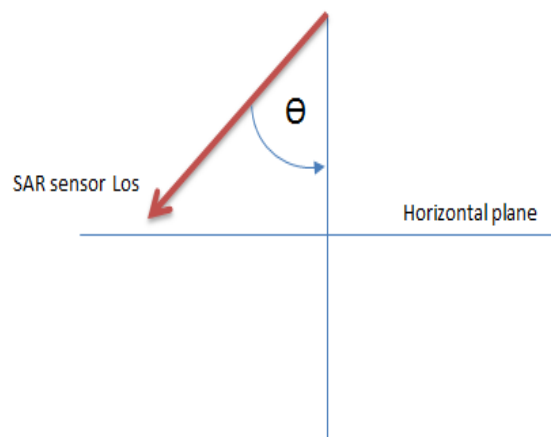


FIGURE D.2: U6D beam incident angle (θ).

