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Combining Satellite and Terrestrial Interferometric Radar Data to Investigate Surface Displacement in the Storfjord and Kåfjord Area, Northern Norway

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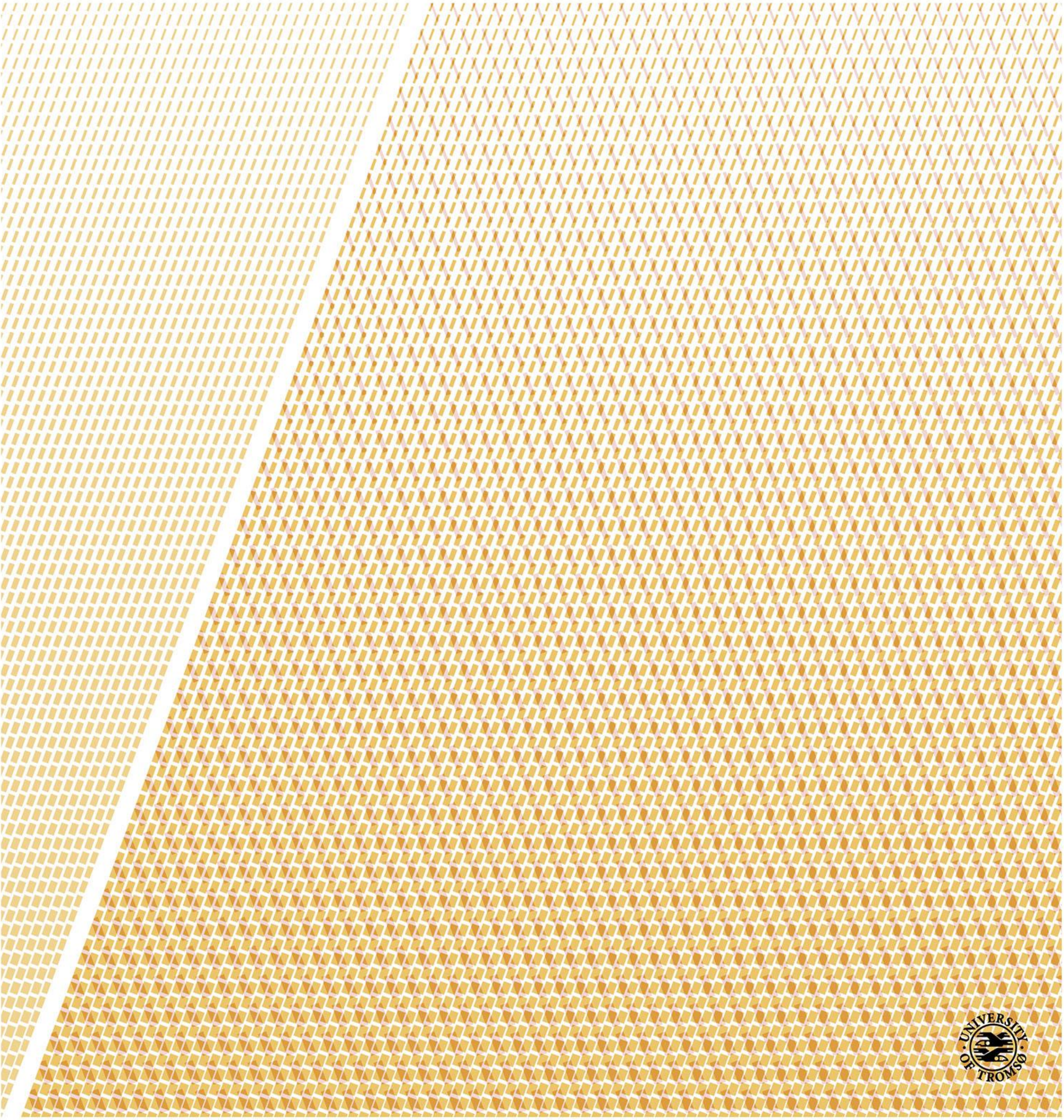

ABSTRACT

Due to their all-weather all-day capabilities and increased availability, synthetic aperture radar (SAR) interferometric displacement datasets have gained popularity in a variety of scientific disciplines. Both satellite and ground-based platforms are used. Satellite-based radar instruments cover large areas on a regular basis without the need for in-situ instrumentation. As with all measuring techniques, radar has its limitations. One intrinsic property is its ability to only observe displacement along the Line-Of-Sight (LOS) direction, thus displacement components diverging from the LOS-direction are underestimated, which limits interpretation of displacement processes. Being portable, the LOS-direction of ground-based radars can be selected. However, as with the satellite-based instruments, ground-based radars still suffer from underestimation of displacement that arises due to divergence from the instrument's LOS-direction.

In this project, we have combined multi-geometrical radar datasets from ground- and satellite-based radar to form two-dimensional (2D) and three-dimensional (3D) surface displacement vectors, creating new ways to interpret surface deformation. By plotting the resulting 2D and 3D surface displacement vector datasets in map and cross-sections, we interpret displacement at the landform- and landscape-scale.

Using 2D surface displacement vectors produced from scenes acquired by the TerraSAR-X satellite in ascending and descending orbits we have studied rockslides, rock glaciers and solifluction lobes at the landform scale. In addition, we have investigated the use of periglacial landform-specific displacement rates as a tool for geomorphological mapping at the landscape-scale. By also including data from ground-based radar we have calculated 3D surface displacement vectors for the Jettan rockslide. In contrast with single radar datasets, using 2D and 3D surface displacement vectors together with topography enables us to calculate different kinematic diagnostic parameters that can be used as tools for interpretation of displacement patterns. Variations in kinematic diagnostic parameters such as combined displacement velocity, azimuth, dip/plunge, displacement into and out of the slope (subsidence/ uplift), compression/extension (strain rate) and horizontal and vertical components, when plotted in cross-sections, enables us to discuss the processes and, factors controlling observed deformation patterns. The 2D and 3D surface displacement vector datasets produced in this work act as an important contribution together with geomorphological, structural and field data for proposing geological models.

PREFACE

This research was supported, as part of a PhD program by, Troms County Council, project number 217720 and grant number RDA12/165.

During this PhD, approximately 2 weeks of field work each summer from 2013 to 2016 have been used for mapping of localities presented in this thesis. This includes instrumentation of about 80 temperature loggers in air, ground fractures/talus, plus several time-lapse cameras and snow depth measurements from the Gamanjunni 3 rockslide (unpublished material) and Ádjet rock glacier.

I have attended several courses including AG-830 Permafrost and Periglacial Environments (UNIS), Low-arctic permafrost and periglacial processes (UIO), Ground based SAR For Deformation Monitoring Data Analysis (Institut de Geomatica, www.IdeG.es) and Rock-slope failures: Geology, hazard and monitoring (UiT) in addition to an oral presentation at the IAEG XII Congress (Eriksen et al., 2015).

ORGANIZATION OF THESIS

This thesis is organized as follows. Chapter 0 describes the background of the project, followed by a description of the study area, summary of papers, and last other contributions of the author. Chapter 2 gives an overview of methods used and a short discussion of limitations. Chapter 3 describes the datasets used. Chapter 4 gives the rationale for and description of combining multi-geometrical radar dataset into 2D and 3D surface displacement vectors. Chapter 5 discusses implication for investigations of surface displacement using combined radar dataset. The manuscripts presented in chapters 6–9 form the foundation of this thesis. Finally, conclusions are drawn and future research possibilities mentioned in Chapter 10.

ACKNOWLEDGEMENTS

Without the good will, hospitality and cooperation of many people, this project would never be accomplished.

I would like to thank my supervisor Professor Steffen G. Bergh for this good guidance and endless patience during the writing process. I have been fortunate to learn from his geological knowledge during enthusiastic field campaigns.

I acknowledge my co-supervisor Geoffrey D. Corner for introducing me to his long lasting interest in geomorphology, rockslides, and especially for directing my attention to the Ádjet Mountain in Skibotn. I value his comments on manuscripts and for supporting this project with time-lapse cameras and temperature loggers.

I am grateful for the contribution by my co-supervisor Tom Rune Lauknes. Under his guidance, I have learned some of the wonders and pitfalls of InSAR. He has had an essential role in all stages of this PhD project. Firstly, for forming the initial ideas and designs, then applying for and securing the necessary funding, followed by collecting long time series of satellite data, and for contributing so that Norut would buy a ground based radar, giving the necessary datasets for this PhD. Lastly I am thankful for his constructive feedback and patience during the written process. The TerraSAR-X data used, have been provided through the German Aerospace Centre (DLR) TerraSAR-X AO projects #GEO0565, GEO0764 and Geo2497.

I would like to thank Lars Harald Blikra and Ingrid Skrede for good discussions and educational days in field in Kåfjord and Skibotn.

I would like to thank Pål Tengesdal and the rest of the gang in the Tromsø Astronomy Association for letting us stay in their comfortable Skibotn Observatory during fieldwork campaigns.

This thesis would never have been possible without the help in field by a number of people. I am grateful for Ole Patrick Larsen’s good humor and persistency, we managed to get things done and have fruitful conversations even in high winds and wet foggy weather. I want to acknowledge Iselin Bakkhaug and Hannah Nopper for setting out temperature loggers and for their thorough work in the unforgiving terrains of the Ádjet Mountain. I would like to thank Line Rouyet, Marie Bredal, Markus Eckerstorfer, and Aleksander Amundsen for the helping out during field cam-

paigns. I am grateful for Trond Eiken's good spirit and for helping out with GNSS-data processing a number of times. I appreciate the times we spent in Manndalen together with Reginald Hermanns and Martina Böhme during Geological Survey of Norway (NGU) yearly field campaigns. I thank Stein Rune Karlsen for supplying us with tripods used with the time lapse cameras and temperature instrumentation. The fieldwork done and number of in-situ instrumentation set out during this PhD would have been highly reduced without help with logistics from NGU. I am grateful for the good humor and hospitality of Roald Elvenes and the rest of the guys at Nordnorsk fjellovervåking, now Norwegian Water Resources and Energy Directorate (NVE), in Manndalen. Their supplied me with essential tips and tricks regarding instrumentation and safety in the field. Thanks to their snowmobiles, ATWs and high-class accommodation I have had good days in the field. I acknowledge Bjørn Barstad in Terratec AS for all his help and his steady hand during the orthorectifying process of the aerial photographs used in this project. I am very thankful to Øyvind Ørnebakk who cleared the forest in Skibotn making the ground-based radar campaigns possible. He is by far the best fit person compared to age that participated in this project. I thank Hannah Vickers for thorough copyediting of this manuscript.

I have been fortunate to attend some interesting courses during this PhD. I would like to thank Ole Humlum and Hanne Christiansen at UNIS for sharing their knowledge during the Permafrost and Periglacial Environments course in the unforgettable surroundings of Svalbard archipelago. I would also like to thank Bernd Etzelmüller and Jan Hjort for good times and educational field trips during the UIO-course on Low-arctic permafrost and periglacial processes in Troms and Kilpisjärvi.

I am utterly thankful for the support and good advice given during my ups and downs in this PhD-project from my wonderful, caring and hardworking wife Anita. None of this could have been accomplished without your great scheduling skills. Being a father of three wonderful children is more demanding than finishing a PhD. You have pulled my share of the load regarding housework, follow-ups and holding the family at a steady course in a caring and firm way. All this simultaneously while you are finishing your own PhD. I am thankful for all help from the family, especially to my Mother stepping in weeks at a time.

CONTENTS

LIST OF ACRONYMS

2D – Two-dimensional

3D – Three-dimensional

DEM – Digital Elevation Model

DLR – German Aerospace Centre

ERS – European remote sensing satellite

ESA – European Space Agency

GNSS – Global Navigation Satellite System

InSAR – Interferometric Synthetic Aperture Radar

LGM – Last Glacier Maximum

LOS – Line Of Sight

A.S.L. – Above Sea Level

NGI – Norwegian Geotechnical Institute

NMA – The Norwegian Mapping Authority

Norut – Northern Research Institute

NVE – Norwegian Water Resources and Energy Directorate

SAR – Satellite synthetic Aperture Radar

SB – Small Baseline method

UIT – Arctic University of Norway

1 INTRODUCTION

In this thesis, we combine multi-geometrical datasets from ground- and satellite-based radar instruments, and investigate how the resulting 2D and 3D surface displacement vectors can be used for interpretation of slope displacement such as rockslide kinematics, thaw related displacement in permafrost landforms (rock glaciers) and creep of solifluction. In advance, we present a first attempt to compare 2D surface displacement rates and geomorphological field mapping at landform scale of a periglacial landscape.

1.1 BACKGROUND

The collaborative project "ROS Fjellskred i Troms" between the Geological Survey of Norway (NGU), UiT-The Arctic University of Norway (UiT) and the municipalities of Tromsø, Kåfjord, Storfjord, Kvænangen, Nordreisa and Lyngen have paved the way for awareness of rockslides and unstable slopes in the northern part of Troms County, Norway. Results from the ROS-project forced higher awareness of the local threat posed by slope processes. The project also launched and intensified research activities regarding rockslides and unstable slopes in the region. These initiatives have so far resulted in several peer-reviewed articles, book chapters, a PhD thesis (Lauknes, 2010), reports, conference contributions and several master theses (Bakkhaug, 2015; Bredal, 2016; Eriksen, 2013; Hannus, 2012; Hernes, 2014; Husby, 2011; Larsen, 2014; Nopper, 2015; Nystad, 2014; Rasmussen, 2011; Skrede, 2013).

Surface displacement datasets from Norut (Northern Research Institute) based on satellite interferometric synthetic aperture radar technique (InSAR) have proven vital for the mapping of unstable slopes and rockslides. As part of a national initiative, the Geohazards project (2005–2016) with participants from Norut, the Norwegian Space Centre (NSC), NGU, Nordnorsk fjellovervåking and Åknes/Tafjord Beredskap IKS, now Norwegian Water Resources and Energy Directorate (NVE), and the Norwegian Geotechnical Institute (NGI) developed remote sensing techniques for mapping and monitoring of rockslides. Later, the resulting InSAR data supported NGU to successfully discover multiple rockslides in the region, some later classified as high-risk objects. This PhD project is inspired by the mentioned work.

This project present results from using various remote sensing methods and tools achieved by combining surface deformation measured by satellite- and ground-based radars to form two-dimensional (2D) and three-dimensional (3D) surface deformation vector datasets. On the land-form scale, combined radar datasets serve as a basis for interpretation of surface displacement processes, and are responsible for controlling factors such as structural and geomorphological elements. On the landscape-scale, comparison of combined surface displacement and geomorphological classes show relation between topography (slope/elevation) and surface displacement.

Lately, strong efforts in the remote sensing community have been made to map and monitor displacement phenomena such as rockslides/landslides (Berardino et al., 2003; Lauknes et al., 2010; Tarchi et al., 2003), earthquakes, glacier flow (Goldstein et al., 1993), volcano deformation (Massonnet et al., 1995) and subsidence (Chaussard et al., 2014; Strozzi et al., 2001). Remote sensing by radar instruments is a useful tool due to it's all-day all-weather capability and no requirement for in-situ instrumentation. Radar instruments are sensitive to displacement in their LOS-direction. By making repeated acquisitions and using appropriate processing algorithms, displacement measurements with sub-millimeter accuracy in the instrument's LOS direction is made possible. Radar instruments can be deployed on both space- and ground-based platforms, each having their own advantages and drawbacks (Caduff et al., 2015a; Massonnet and Feigl, 1998; Monserrat et al., 2014; Prati et al., 2010). Ground-based radars have proven useful for studying displacement phenomena ranging from landslides (Barla et al., 2010; Lowry et al., 2013), snowpack (Caduff et al., 2015b), glaciers (Riesen et al., 2011), rock glaciers (Strozzi et al., 2009) and infrastructures (Pieraccini, 2013). Compared with space-borne SAR instruments, ground-based radars cover smaller areas, but have the advantages of being portable making possible a selection of the best LOS direction for observing ground surface displacement and having customizable temporal frequency (temporal sampling), increasing capability for observing surface process deformation with different velocities.

Earlier InSAR studies have significantly increased knowledge of hazards and factors controlling rockslide and rock glaciers in the study area (Böhme et al., 2016b; Dehls et al., 2012; Dehls et al., 2014; Eriksen et al., 2012; Eriksen et al., 2015; Frauenfelder et al., 2008; Henderson et al., 2011; Lauknes et al., 2010; Rouyet et al., 2015). However, satellite InSAR techniques have known displacements of the order of mm to cm yr^{-1}, underestimating fast moving landforms. Furthermore, the ability to combine ground and satellite-based radar datasets have not been fully exploited, resulting in low sensitivity for displacements with components orthogonal to radar LOS-direction. Satellite-based radars regularly cover large areas, but the temporal sampling is fixed and the selection of LOS direction is limited. Surface displacement with direction oblique to the instruments LOS direction will therefore be underestimated. Due to this LOS-ambiguity, interpretation of single radar datasets can be challenging. At worst case, if the displacement direction is orthogonal to the LOS, no displacement can be observed.

The present thesis aims to fill this gap by combining multi-geometrical radar datasets.

Studies combining remote sensing data often tend to focus on methods applicable for observing processes where the deformation signal is large e.g. during earthquakes (Fialko et al., 2005; González et al., 2009), glacial flow (Gudmundsson et al., 2002), deformation related to volcanic activity (Jung et al., 2011), deformation taking place at high latitudes (Gray, 2011) or areas with a high number of and large spatial distribution of Global Navigation Satellite System (GNSS) stations (Samsonov et al., 2008), where the surface-parallel flow is assumed (Joughin et al., 1998). We combine multi-geometrical radar datasets to study landforms that deform at a rate of mm to 10s' m yr^{-1} in a periglacial environment.

We report on research which attempts to provide solutions by (1) combining two satellite-based radar datasets into 2D surface displacement vector datasets, and (2) combining two satellite-based radar datasets with one ground-based radar dataset into 3D surface displacement vector datasets. The main goal has been to improve interpretation of kinematics and give new insight into ongoing slope deformation processes using remote sensing data. By synthesizing kinematic diagnostic parameters from 2D and 3D surface displacement vectors such as combined displacement velocity, azimuth, dip/plunge, displacement into and out of slope (subsidence/uplift), compression/extension (strain rate), and horizontal and vertical components in cross-sections, landforms as rockslides, solifluction lobes and rock glaciers have been studied.

In addition to adding new tools to the remote sensing toolbox, this study also provides insight into the state of rockslides and permafrost landforms that may be subject to future collapse caused by climate warming.

1.2 STUDY AREA

The bedrock geology of the study area is part of the Caledonian nappe sequence thrusted over Precambrian basement rocks during the closure of the Iapetus ocean and the following Caledonian orogeny during the Silurian period (Roberts, 2003; Zwaan, 1988). Most rocks have a well-defined, gently SE-dipping foliation that provides a favorable fabric for rock sliding. In addition, the bedrock is overprinted by numerous post-Caledonian brittle faults that formed during successive stages of rifting (extension) during the late Paleozoic, Mesozoic and early Cenozoic time periods, i.e. processes that culminated with the opening of the North Atlantic margins (Osmundsen et al., 2002). Remains of rift-margin brittle faults and fracture sets are widespread in coastal and central parts of Troms County, and these faults have exerted a major controlling effect on late-Cenozoic landscape, uplift-subsidence and glacial erosion, as well as enabled the location of scarps and unstable cliffs sustainable for rockslides and avalanches. Most fjords and valleys in Troms region follow the trends of the rift-margin faults (Bergh et al., 2007; Hansen and Bergh, 2012; Hansen et al., 2008; Indrevær et al., 2013), where the most dominant ones strike in directions NNE-SSW and NE-SW, sub-parallel to the rift margins and are linked by NW-SE striking transfer zones (Hansen, 2009).

The alpine high–relief topography with mountain peaks well above 1000 m in the study area formed during a series of glaciations during the Quaternary period (2.5 Ma – present) (Corner, 2005). During the last 600 000 years, the area has experienced larger glaciations with a frequency of ~100 000 years (Vorren and Mangerud, 2007). After the last glacial maximum (LGM), about 18 000 – 20 000 C14 years ago, the ice shield re-advanced several times during cold periods (Vorren and Mangerud 2007, with the highest areas piercing through the ice-sheet as nunataks. The most prominent glacial formations and moraines in the region are from the longer colder period called the Younger Dryas (Tromsø-Lyngen event) lasting from between 11,000 to 10,000 years before the present time (Vorren and Mangerud, 2007).

The state of permafrost from borehole data from northern Norway indicates a rise in ground temperature and an increase in thickness of the active layer (Christiansen et al., 2010). Permafrost is found in discontinuous patches as low as 550 m above sea level (a.s.l.) in the inner part of the northern Scandinavian mountains, and above 990 m a.s.l. at the coast (Christiansen et al., 2010). For the study area the climate is subarctic, and there are indications of patches of permafrost in open spaces (fractures/tallus) in colluvium even close to sea level (Blikra and Christiansen, 2014).

Recent surface displacement in the study area is the result of many factors. On the large scale the landscape of the Norwegian coast has been formed and is being actively reshaped due to uplift from isostatic rebound and tectonic uplift components (Fjeldskaar et al., 2000). In the study area this is associated with active normal faulting and anomalous clusters of landslides (Osmundsen et al., 2009). On a local scale, high concentrations of avalanche paths, rock-avalanche fronts, rock-slides, ridges, rock glaciers, talus cones, debris flow levees, pro-talus ramparts and faults document ongoing mass movement (Corner, (in prep.); Tolgensbakk, 1988).

The study area has a high density of rock glaciers, both active (Frauenfelder et al., 2008; Rouyet et al., 2015) and inactive (Lilleøren and Etzelmuller, 2011; Tolgensbakk, 1988), solifluction lobes (Hjort et al., 2014) and unstable rock slopes and rockslides (Blikra et al., 2015; Braathen et al., 2004; Bunkholt et al., 2013a; Böhme et al., 2016a; Hermanns et al., 2013; Nordvik et al., 2010). Some of these may be controlled by regional geological structures (Bunkholt et al., 2013b) while others are most likely controlled by permafrost (Blikra and Christiansen, 2014).

1.3 SUMMARY OF PAPERS

One published paper and three manuscripts are the result of this PhD-project. The focus has mainly been on combining remote sensing datasets for visualizing slope displacement, discussing controlling factors for displacement, including climatic forcing, and using combined remote sensing datasets for characterization of geomorphological landforms. Papers included in the PhD are:

Paper 1: Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Corner, G. D., Bergh, S. G., Dehls, J., and Kierulf, H. P., 2017, Visualizing and interpreting surface displacement patterns on unstable slopes using multi-geometry satellite SAR interferometry (2D InSAR): *Remote Sensing of Environment*, v. 191, p. 297-312., DOI: dx.doi.org/10.1016/j.rse.2016.12.024

The aim of this paper was to show how combined 2D InSAR surface displacement gives new opportunities for interpreting ongoing slope displacement processes. It describes the advantages and limitations of the 2D InSAR technique using deforming landforms commonly found in periglacial environment such as solifluction lobes and rockslides. By combining TSX data from ascending and descending satellite orbit, 2D displacement vectors are calculated. In addition, the link between 2D InSAR surface displacement and local geomorphological elements and geological structures are investigated by plotting 2D InSAR displacement vector data in cross-sections, giving new opportunities for interpretation of remote sensing data.

Main conclusions:

- 2D InSAR displacement vectors in map and cross-section are a powerful tool for visualizing surface displacement.
- Combining InSAR dataset to 2D InSAR vectors allows us to investigate the vertical and horizontal components, dip and magnitude of combined surface displacement vectors.
- Spatial variation of dip of 2D InSAR vectors in areas with small variation in magnitude, may provide information of subsurface processes controlling displacement, such as glide surfaces.

- Variations in 2D InSAR vectors enable postulation of kinematics of landforms, such as areas having extension/compression and areas moving into or out of the slope (subsidence/uplift).
- 2D InSAR data reduce the complexity related to LOS-ambiguity which is often challenging when interpreting single InSAR datasets where dip and direction of surface displacement must be considered.

Paper 2: Eriksen, H. Ø., Lauknes, T. R., Rouyet, L., Berthling, I., Isaksen, K., Hindberg, H., Larsen, Y., & Corner, G. D., Abrupt Increase in Permafrost Creep Rates Following Climate Change (manuscript draft)

The focus of this paper has been to use a multi-disciplinary, remote sensing approach to learn more about the decadal, yearly and seasonal displacement pattern of a rock glacier in Skibotn valley, Northern Norway.

Significant acceleration and even collapse of rock glaciers related to a warmer climate has been documented from the European Alps, but few examples exist from elsewhere. In this work we provide evidence of recent acceleration on a rock glacier in northern Norway based on 62 years of remote sensing data.

We document the displacement evolution of the rock glacier from 1954 until present using historical orthophotos, a diversity of satellite and ground-based radar datasets and processing techniques, local climate evolution from modelled data and the present ground thermal regime.

Using remote sensing data we infer changes in spatial deformation patterns across the rock glacier, and interpret position of shear zones separating the upper parts of rock glacier from the lower part. In addition, we identify areas having subsidence and uplift and their temporal variation, by combining TSX offset tracking data from 2009-2015 to form 2D surface displacement vectors.

Our findings are important when it comes to understanding impacts of global warming related to degrading permafrost. This is a contribution to improve forecasting of future geohazards and ensure reliable risk management in mountainous environments due to climate warming.

Paper 3: Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Rouyet, L., Corner, G. D., Bergh, S. G., Skrede, I., Relating 3D surface displacement from satellite- and ground-based InSAR to structures and geomorphology of the Jettan rockslide. (manuscript draft)

The focus of this work has been to combine one ground-based dataset with two satellite based InSAR datasets to form 3D surface displacement vectors for the Jettan rockslide, Troms, northern Norway. We show how 3D surface displacement vectors relate to geological structures and topography, and give new insights into the kinematics of slope movements within a complex field rockslide classified as a high-risk object. Using 3D displacement vectors, topography and simple calculations we attempt to link displacement patterns to bedrock structures and geomorphological elements, thus indicating structural and topographic control on rockslide kinematics.

Remote sensing of surface displacement may in this way contribute to examine controlling geological regime at depth.

The main conclusions of the paper are that the 3D inversion method depends on the orientation of LOS-direction of the input datasets. For the 3D inversion to produce trustworthy results, the LOS-direction of the ground-based radar must differ from the plane formed by the two satellite based radars' LOS-directions. If the LOS directions are parallel, 3D inversion results in ill-conditioned displacement vectors. For the Jettan rockslide, caution must be taken in the northernmost area where LOS of the ground-based radar approaches the plane made by the LOS directions of the TSX instrument in both ascending and descending orbits.

By plotting 3D displacement vectors in cross-sections we found a combined topographic and structural control on displacement in the northern area, where azimuth directions of 3D displacement seem to be structurally controlled. Opening of fractures in an oblique manner may be explained by sets of increasing velocity from north to south. Furthermore, a repeated stepping pattern in the northern area may indicate a complex fault geometry with several stepped and discontinuous slide surfaces. In the south, displacement patterns are more homogenous and this may be due to the concentration of displacement along more continuous fault geometries at depth.

The observed displacement patterns are consistent with other sources that indicate internal backward-rotational movement along steep fractures curving to low-angle detachments at depth. Another explanation can be that internal zones of compression and extension result in stacking of blocks in thrust-imbricated zones.

The technique described is applicable for investigation of other displacement processes observed by three individual radar datasets.

Paper 4: Eckerstorfer, M., Eriksen, H. Ø., Rouyet, L., Christiansen, H. H., Lauknes, T. R., Blikra, L. H., Comparison of geomorphological field- and 2D InSAR mapping of the periglacial landscape at Nordnesfjellet, Northern Norway (manuscript draft)

We present 2D InSAR data based on 2009-2014 TerraSAR-X datasets from ascending and descending orbits and geomorphological mapping of aerial imagery validated in the field. Using this data, we show that 2D InSAR correctly depicts displacement rates that can be associated with typical deformation patterns for flat-lying or inclined landforms, within and below the regional permafrost limit for both wet and dry areas.

1.4 OTHER CONTRIBUTIONS BY AUTHOR

In this PhD research, the author has contributed to several publications and presentations, not included in the thesis.

Books and book chapters

Böhme, M., Bunkholt, H. S. S., Oppikofer, T., Dehls, J. F., Hermanns, R. L., Eriksen, H. Ø., Lauknes, T. R., and Eiken, T., 2016, Using 2D InSAR, dGNSS and structural field data to understand the deformation mechanism of the unstable rock slope Gamanjunni 3, northern Norway, *Landslides and Engineered Slopes. Experience, Theory and Practice*, CRC Press, p. 443-449.

Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Dehls, J. F., Grydeland, T., and Bunkholt, H., 2015, Satellite and Ground-Based Interferometric Radar Observations of an Active Rockslide in Northern Norway, in Lollino, G., Manconi, A., Guzzetti, F., Culshaw, M., Bobrowsky, P., and Luino, F., eds., *Engineering Geology for Society and Territory - Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation:* Cham, Springer International Publishing, p. 167-170.

Dehls, J. F., Lauknes, T. R., Hermanns, R. L., Bunkholt, H., Grydeland, T., Larsen, Y., Eriksen, H. Ø., and Eiken, T., 2014, Use of Satellite and Ground Based InSAR in Hazard Classification of Unstable Rock Slopes, in *Landslide Science for a Safer Geoenvironment*, Springer, p. 389–392.

Dehls, J.F., Lauknes, T., Blikra, L.H., Kristensen, L., Christiansen, H., and Eriksen, H. Ø., 2012, Extensive InSAR observations of the Jettan rockslide in northern Norway, using Radarsat-2, TerraSAR-X, and corner reflectors: *AGU Fall Meeting Abstracts*, v. 1, p. 1101.

Conference contribution

Rouyet, L., Eriksen, H. Ø., Lauknes, T. R., Hindberg, H., Larsen, Y., Eckerstorfer, M., Blikra, L. H., and Werner, C., 2015, Ground-based and Satellite Interferometric Observations of a Fast Moving Rock Glacier Complex (Ádjet mountain, North Norway), in *Proceedings Fringe 2015*, presentation only.

Böhme, M., Bunkholt, H. S. S., Dehls, J., Eiken, T., Eriksen, H. Ø., Gosse, J., Hermanns, R. L., Kristensen, L., Molina, F. X. Y., and Oppikofer, T., 2014, Understanding the deformation mechanism of the unstable rock slope Gamanjunni 3, northern Norway, for hazard and risk assessment, *3rd Slope Tectonics conference* – Program and abstract book, NGU rapport 2014.030, Trondheim, Norway.

Eriksen, H. Ø., Lauknes, T. R., Corner, G. D., Larsen, Y., and Eckerstorfer, M., 2014, Rock glacier displacement patterns measured using ascending and descending TerraSAR-X InSAR data, in *Proceedings ESA DUE Permafrost Meeting*, presentation only.

Lauknes, T.R., Larsen, Y., Eriksen, H.Ø., Grydeland, T. and Dehls, J.F., 2013, Deformation patterns at the Jettan rockslide in northern Norway observed using high-resolution TerraSAR-X, Radarsat-2 and corner reflector InSAR data. 5th TerraSAR-X Science Team Meeting, Oberpfaffenhofen: *5th TerraSAR-X Science Team Meeting*, Oberpfaffenhofen, Germany, 10-12 June, presentation only.

Lauknes, T. R., Grydeland, T., Dehls, J., and Eriksen, H. Ø., 2013, Ground and satellite based interferometric Radar Observations of an Active Rockslide in Northern Norway, in *Proceedings Living Planet Symposium, ESA 2013*, presentation only.

Eriksen, H. Ø., Lauknes, T. R., Dehls, J. F., Larsen, Y., and Corner, G. D., 2012, A Detailed View of Rockslide Deformation Patterns in Northern Norway Using Both Ascending and Descending High-Resolution TerraSAR-X Satellite InSAR Data: *AGU Fall Meeting Abstracts*, v. 1, p. 1594, poster.

Böhme, M., Bunkholt, H., Dehls, J. F., Oppikofer, T., Hermanns, R. L., Dalsegg, E., Kristensen, L., Lauknes, T. R., and Eriksen, H. Ø., 2016, Geologisk modell og fare- og risikoklassifisering av det ustabile fjellpartiet Gamanjunni 3 i Manndalen, Troms. NGU rapport 2016.031, (in norwegian), p. 64.

Reports

Böhme, M., Bunkholt, H., Dehls, J. F., Oppikofer, T., Hermanns, R. L., Dalsegg, E., Kristensen, L., Lauknes, T. R., and Eriksen, H. Ø., 2016, Geologisk modell og fare- og risikoklassifisering av det ustabile fjellpartiet Gamanjunni 3 i Manndalen, Troms. *NGU rapport 2016.031*, (in norwegian), p. 64.

Eriksen, H. Ø., Lauknes, T. R., Hindberg, H., and Larsen, Y., 2015, Bakkebaserte radarmålinger i etterkant av leirskredet i Sørkjosen 10.5.2015. *Norut Report nr. 13/2015*, (in norwegian), p. 21.

2 DEFORMATION MAPPING USING SYNTHETIC APERTURE RADAR (SAR) IMAGING

This chapter starts by establishing the basic concepts of synthetic aperture radar (SAR) and the interferometric synthetic aperture radar (InSAR) and offset-tracking techniques. The LOS-ambiguity and other limitations of SAR instruments and the InSAR technique are then described.

2.1 INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

A synthetic Aperture Radar (SAR) is an active imaging instrument which has proven capabilities for measuring earth properties (Bamler and Hartl, 1998). First, electromagnetic radiation is transmitted in pulses from the SAR-instrument, then pulses hitting objects on the ground are scattered in all directions and a small part of the pulses are reflected to the receiver antenna on the SAR-instrument. The received signal is complex, meaning that it contains a phase and amplitude component (Hanssen, 2001).

Interferometric SAR (InSAR) displacement data are a product of combinations of SAR scenes, acquired from an altitude of 514 km. By comparing the phase signal from repeat-pass SAR acquisitions and applying different filtering techniques, the surface displacement between the passes can be found (Gabriel et al., 1989). Estimates are accurate to within a fraction of the wavelength of the sensor. The difference in phase between two SAR scenes are called an interferogram. Phase difference ($\Delta\phi$) in an interferogram is measured in radians from 0 to 2π and it is a result of contribution from surface deformation ($\Delta\phi_{\mathrm{Displ}}$), difference in atmospheric path delay ($\Delta\phi_{\mathrm{APS}}$), topography ($\Delta\phi_{\mathrm{Topo}}$) and other noise contributions ($\Delta\phi_{\mathrm{decorr}}$):

$$\Delta\phi = \Delta\phi_{\mathrm{Topo}} + \Delta\phi_{\mathrm{Displ}} + \Delta\phi_{\mathrm{APS}} + \Delta\phi_{Decorr} \quad (1)$$

In order to find the surface deformation component ($\Delta\phi_{\mathrm{Displ}}$) of the total phase difference in an interferogram ($\Delta\phi$), topographic contributions ($\Delta\phi_{\mathrm{Topo}}$) are removed using a Digital Elevation Model (DEM) and the contribution from the atmosphere ($\Delta\phi_{\mathrm{APS}}$) is removed by filtering techniques using the small baseline (SB) method (Berardino et al., 2002), persistent scatterer interferometry (PSI) method (Prati et al., 2010) or by averaging or stacking (Peltzer et al., 2001). The resulting phase component is converted to mm displacement during the time span of the interferogram. The topography component ($\Delta\phi_{Topo}$) is proportional to the distance between the two orbits (perpendicular baseline, $B_{\perp}$). Interferograms with small perpendicular baselines are therefore preferable to minimize sensitivity to topography. Other noise effects ($\Delta\phi_{decorr}$) stem from changes of geometrical or dielectric properties of surface cover (temporal decorrelation) and phase contributions caused by difference in baseline (spatial baseline decorrelation) (Lauknes, 2010).

If the surface displacement between to two neighboring pixels in the SAR-scenes is more than 2π, or half the wavelength of the SAR-instrument, ambiguity arises because phase will wrap around to 0. Phase ambiguity can be resolved by phase unwrapping (Chen and Zebker, 2001). The amount of time covered by the interferogram, or temporal baseline, is important for the resulting InSAR data's sensitivity to displacement. Depending on the wavelength of the SAR-instrument used or temporal baseline selected, resulting InSAR data will be sensitive to different ranges of surface velocities. Using a high temporal baseline with an interferogram spanning periods of years, displacement of the order of mm to cm can be observed. Consequently, with low temporal baseline with interferograms spanning days (minimum 11 days for the TSX satellite), displacement of the order of cm to 10s' of cm can be observed. Therefore, the SAR-instrument and temporal baseline of interferograms must be selected in accordance with the deformation expected to be observed.

2.2 SAR OFFSET TRACKING

Contrary to the InSAR technique, offset tracking is a technique that estimates surface velocity both along the satellite's flight direction and the satellite's LOS-direction. The offset tracking technique estimates displacement by comparing and tracking patterns (speckle-tracking) based on the amplitude part of the received complex backscattered signal, and it is usually applied to observe glaciers (Rignot et al., 2011; Strozzi et al., 2002; Sund et al., 2014). The lowest detectable deformation using offset tracking is between 1/10-1/20 of the resolution (Casu et al., 2011).

2.3 LIMITATIONS

SAR, and hence InSAR and offset tracking, have some intrinsic limitations that are vital to understand when combining multi-geometrical radar datasets to 2D and 3D surface displacement vectors.

2.3.1 InSAR coherence

Landforms in a periglacial environment deform with highly different surface velocities. Changes from scene to scene and in some cases high velocity of surface deformation, affects the quality or coherence of the interferogram. If there is a large change in the backscatter reflectivity between acquisitions, the quality or coherence of the interferograms is reduced and decorrelation occurs. The time before decorrelation occurs depends on the SAR-instrument's wavelength, and surface properties in the scene. Water, vegetated areas (grass, trees with leaves etc.) decorrelate within seconds and minutes, while bedrock and outcrops will remain coherent for years (Barboux et al., 2014; Monserrat et al., 2014). Therefore, the surface cover must be considered when selecting sensor and temporal baseline.

2.3.2 Geometrical effects

Due to the SAR-instrument's perspective and the concentric nature of radar waves, some geometric effects reduce the spatial extent that can be observed. The factors that are especially active in steep topography are: (1) foreshortening, (2) layover and (3) shadow. Foreshortening is a geometrical effect caused by compression of radar pulses on terrain dipping towards, and stretching of pulses in terrain dipping away from the instrument. Compression results in lower resolution and stretching results in higher resolution. Layover occurs when a radar echo returns from the top of a steep slope before the echo from the bottom of the slope. Foreshortening and layover results in very high intensity of backscattered radar pulses. Radar shadow occurs in areas invisible to the instrument, also due to steep topography. When mapping mountainous terrain from a satellite-based radar, slopes facing the satellite suffer from compression and layover, and slopes facing away from the satellite suffer from stretching and shadow. In steep terrain this effectively reduces the common areas, and thus the spatial extent of 2D and 3D combined data using datasets from polar orbiting satellites.

2.3.3 Unwrapping errors

Phase unwrapping, or the process of restoring the correct multiple of 2π of the interferometric phase signal, may introduce errors due to high surface deformation or sparse phase signal due to temporal decorrelation (water, vegetation etc.) or steep topography.

2.3.4 Common calibration point

The InSAR technique is relative, meaning that the dataset must be calibrated to a spatial point with known velocity. Often an area with outcropping bedrock, assumed stable is used, but any area with known velocity can be utilized. Before combining datasets to 2D and 3D surface displacement, all input datasets must be referenced to the same area. If the assumed displacement in the reference area differs from the actual displacement, the resulting combined data will be affected.

3 AVAILABLE DATASETS

This chapter gives the rationale for, and description of datasets included in this project.

Inside the study area in northern part of Troms County, Norway, TSX datasets and data from ground-based radar campaigns were used to compute 2D and 3D surface displacement vectors. In Paper 1, we used snow-free TSX satellite (2009–2014) scenes from ascending and descending orbit using a maximum temporal baseline of 55 days to produce InSAR data. By combining ascending and descending InSAR data to form 2D InSAR surface displacement vectors for (1) the Jettan rockslide on the Nordnes Peninsula; (2) the Gámanjunni 3 rockslide in Manndalen; (3) the Njárgavárri rockslide in Kåfjorddalen; and (4) solifluction landforms at the tip of the Nordnes Peninsula (Fig. 2), we have been able to study displacement patterns in rockslides and solifluction lobes of the order of mm yr^{-1} to 10s' of cm yr^{-1}.

In Paper 2, we apply a multi-disciplinary approach, including study of surface displacement patterns from InSAR, offset-tracking, orthophoto-comparison, terrestrial radar interferometry (TRI) of ground based radar data, and 2D surface displacement vectors, to study slow (~mm yr^{-1}) to high deformation (~15 cm day^{-1}) on and around an accelerating permafrost landform (rock glacier). During two campaigns in the summer of 2014 (09.–31.08) and spring of 2015 (20.05–20.06) we used the Norut owned Gamma Portable Radar Interferometer (GPRI) (Fig. 1) (Werner et al., 2012; Werner et al., 2008) to observe a rock glacier in the SW slope of the Ádjet Mountain in the Skibotn valley (locality 5 in Fig. 2). The surroundings were observed using the InSAR technique on TerraSAR-X scenes (2009-2014, 2016). Further investigations of the rock glacier was performed by combining the range (along LOS-direction) components of offset tracking data of TSX from ascending and descending satellite orbit to make 2D displacement vectors using the approach described in Paper 1. To gain insight into the long time displacement trend of the rock glacier we used InSAR displacement data from the European Space Agency (ESA) European Remote Sensing (ERS) satellites 1 and 2 in tandem mission in 1995 (22.–23.07) and orthophotos from 1954, 1977, 2006 and 2014.

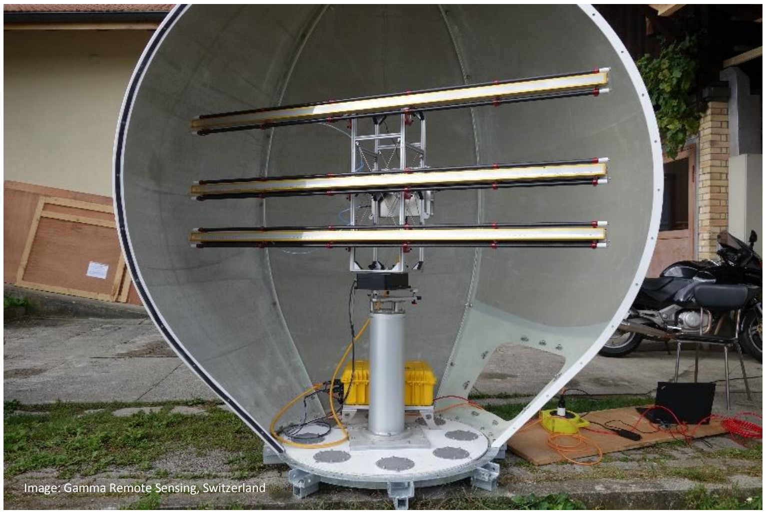

Fig. 1 – Gamma Portable Radar Interferometer (GPRI) with extra dome for weather protection.

In Paper 3, we resolve 3D displacement vectors of the order of mm yr^{-1} to 10s' of cm yr^{-1} for the Jettan rockslide, by combining TRI data collected by the Norwegian Water Resources and Energy Directorate (NVE) using an instrument from Ellegri (LiSALab) (Kristensen, 2013), and TSX InSAR data from ascending and descending orbits.

In Paper 4, we combine TSX interferograms from ascending and descending orbits having a maximum temporal baseline of 55 days, into 2D InSAR displacement data covering a study area of approximately 8 km^2 on the Nordnes peninsula (Fig. 2). By comparing 2D InSAR displacement data with geomorphological mapping from photogrammetric aerial image interpretation that have been verified with field observations, landscape-scale displacement patterns and rates of six geomorphological classes and their relation to topographical factors including slope angle and elevation are discussed.

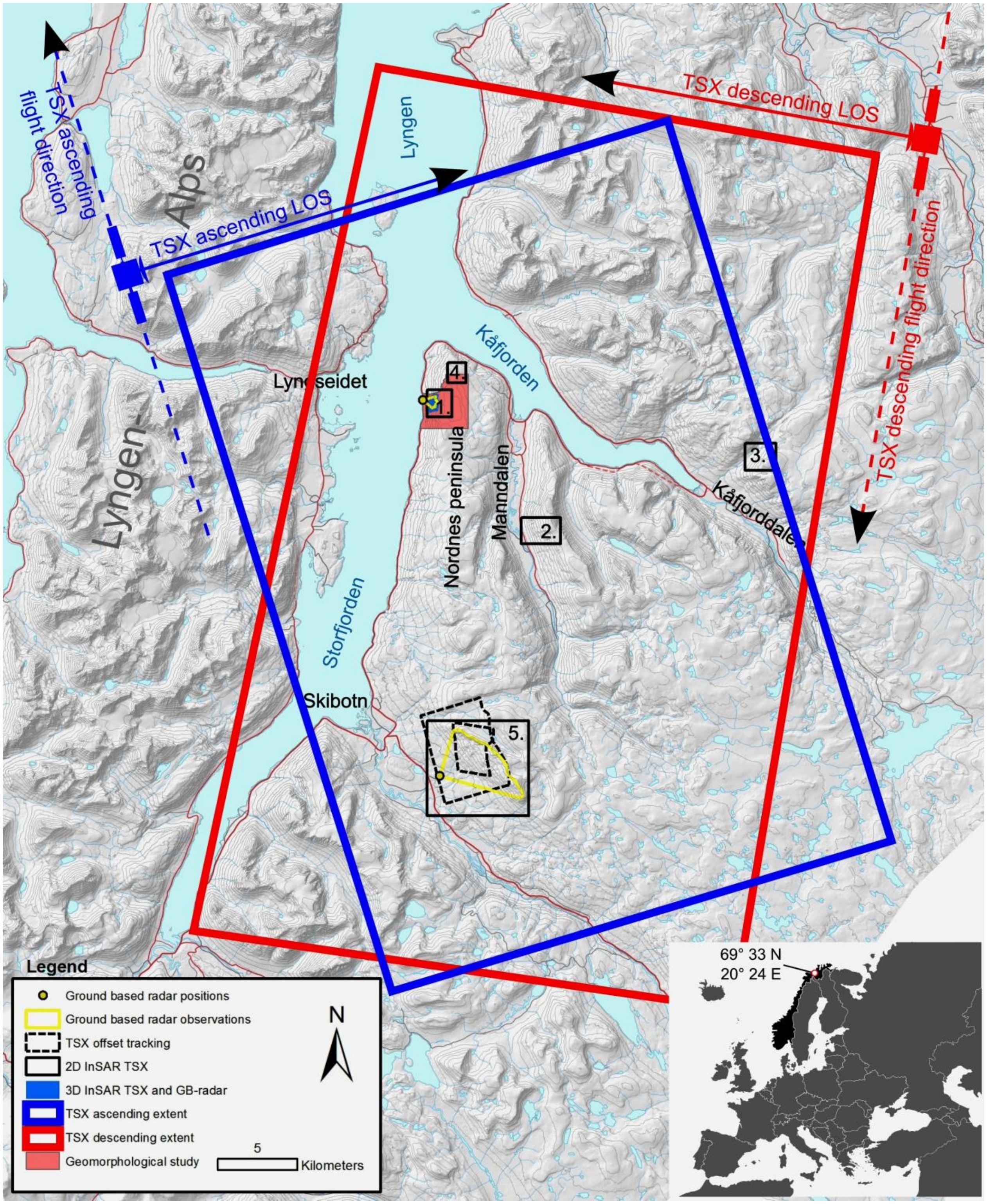

Fig. 2 – Overview of the locations included in the PhD project from the northern part of Troms County in northern Norway. The extent of datasets and processing techniques used are marked: (1) Jettan rockslide on the Nordnes Peninsula, (2) Gámanjunni 3 rockslide in Mann-

dalen, (3) Njárgavárri rockslide in Kåfjorddalen, (4) solifluction landforms at the tip of the Nordnes Peninsula, (5) Ádjet Mountain in Skibotn and (6) Geomorphological mapping compared to 2D InSAR at the Nordnes Peninsula.

4 COMBINING RADAR DATASETS TO 2D AND 3D DISPLACEMENT

Single InSAR datasets can only observe displacement in the sensor LOS-direction (red and blue dashed lines in Fig. 3). Because of this LOS-ambiguity, surface displacement diverging from the LOS-direction will be underestimated, such as deformation in Scenario 1 or it will be parallel to the blind plane and thus not detected at all, as illustrated for the satellite in ascending orbit observing deformation scenario 2 (Fig. 3). On the other hand, both deformation scenarios are observable for a satellite in descending orbit, though the sensitivity to displacement is best in Scenario 2.

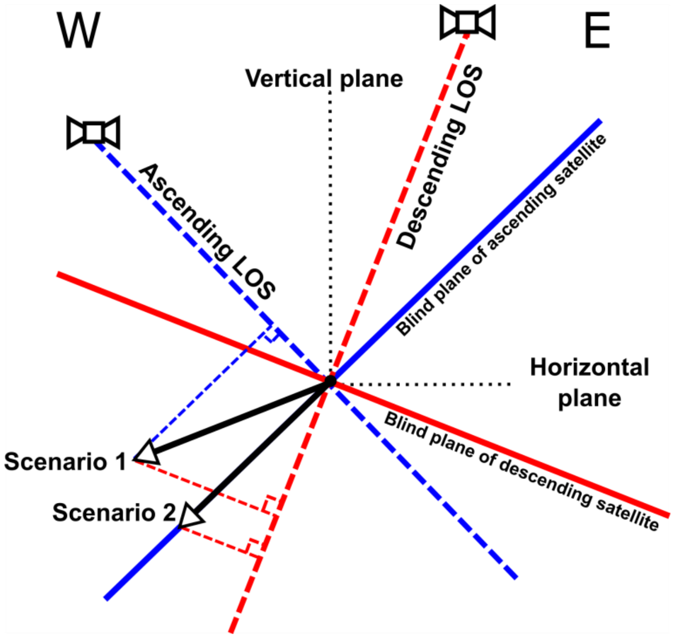

Fig. 3 – Up-Down West-East plot of TSX satellite in ascending and descending orbits and the different sensitivity to deformation in two displacement scenarios. The blind plane for the satellite in ascending orbit is marked with a blue solid line, and the blind plane for the satellite in descending orbit is marked with a red solid line. Figure from Paper 1.

Recently, several successful approaches have been taken to mitigate the LOS-ambiguity by calculating 2D and 3D displacement vectors (Hu et al., 2014). A method for resolving 2D surface velocity vectors referred to by Hu et al. (2014) as “Neglect of the N–S displacement component”, is applicable for resolving displacement in areas where the North-South component can be assumed zero. This is the case in mountainous terrain with North-South trending ridges. By combining displacement observed along the LOS-direction from the satellite in ascending and descending orbits, a combined displacement vector in the LOS-plane (Fig. 4) oriented close to the East-West Up-Down plane can be calculated, as described in Paper 1. This 2D combination is possible in areas covered by two spatially and temporally overlapping datasets. 2D surface displacement vectors are not able to observe surface displacement orthogonal to the plane made by the ascending and descending LOS-direction, the LOS-Plane (Fig. 4).

If a third radar dataset is available, an inversion resulting in 3D surface displacement vectors can be performed for areas (pixels) covered by all three datasets:

$$A * x = b$$

$$x = inv(A) * b \qquad \text{(Eq. 1)}$$

The resulting vector x is the combined 3D deformation for each pixel in the common areas of the three radar displacement datasets. A is a matrix representing the LOS unit vectors of the input datasets, and b is a vector representing deformation along the LOS-direction for the input datasets, as described in Paper 3. The quality (sensitivity) of 3D inversion, or the ability to reproduce surface displacement, depends on the orientations of LOS-directions of the input datasets with respect to each other. The more aligned the LOS-directions of the input datasets are, the more numerically unstable (ill-conditioned) the 3D inversion will be. Because the LOS-direction of the GB-radar varies across the scene, the sensitivity will also vary over the study area. The sensitivity approaches zero when the displacement direction approaches orthogonal to the aligned LOS-direction of the input datasets. In case of the Jettan rockslide, the North-South component in the northern part must be handled with caution (Fig. 4). However, the West-East and Up-Down components from the 3D inversion are still reliable in these areas.

From the resulting 2D and 3D surface displacement vectors, bi-products such as the horizontal and vertical components and dip of surface displacement vectors can be derived. Using 2D and 3D surface displacement vectors in combination with digital elevation model, additional diagnosing kinematic parameters such as displacement into or out of slope (subsidence/uplift), and strain rate (compression/extension) can be found.

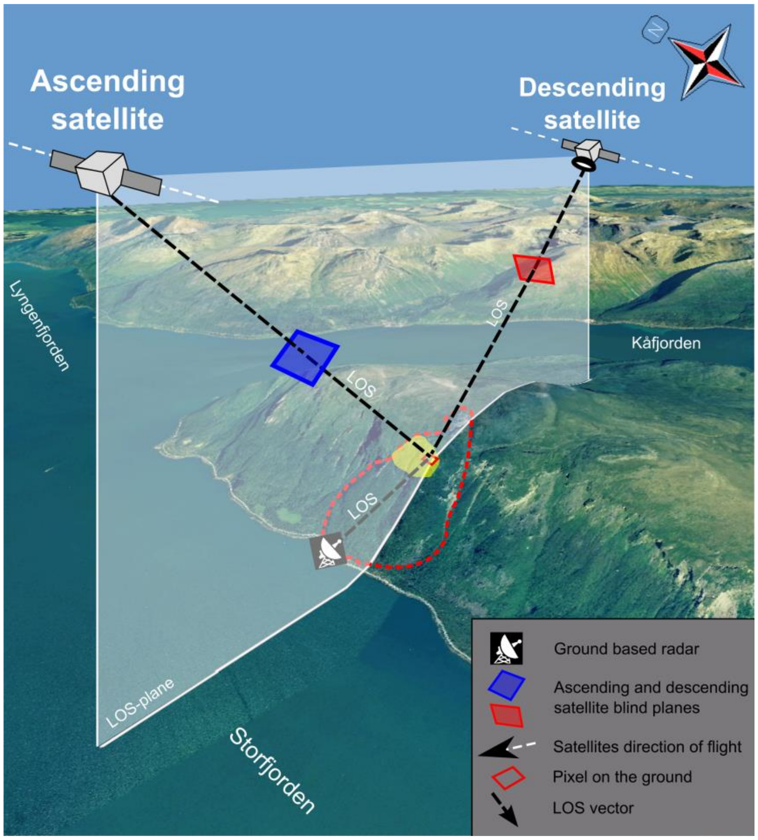

Fig. 4 – Orthophoto draped on DEM showing the Nordnes peninsula with the Jettan rock-slide (red dashed line) pinpointed by the LOS vectors of the GB-radar and TSX satellite in ascending and descending orbits.) Blind planes from Fig. 3 marked with red and blue squares. 2D surface displacement vectors from combination of ascending and descending TSX data are constrained to the LOS-plane defined by LOS-directions illustrated with white transparent color. Common area for all datasets (yellow) gives the extent of the 3D surface displacement vectors. Figure modified from Paper 1.

5 INTERPRETATION OF DISPLACEMENT PATTERS FROM 2D AND 3D SURFACE DISPLACEMENT

New opportunities for understanding processes are created by comparing 2D and 3D surface displacement vectors and related bi-products with topography, mapped geological structures and geomorphological elements/classes. In the following, diagnostic kinematic parameters supporting interpretation of displacement patterns are presented: (1) Combined displacement velocity, (2) Dip/plunge of displacement, (3) Displacement into and out of slope (subsidence/uplift), (4) Strain rate, (5) Horizontal and vertical components, and (6) Azimuth of displacement.

5.1 COMBINED DISPLACEMENT VELOCITY

Using single InSAR datasets, the sensitivity to displacement varies due to LOS-direction and surface displacement direction. By combining displacement datasets, areas with displacement direction that are not detectable in one input dataset due to LOS-ambiguity, may be observable in another (Fig. 3). For the Jettan rockslide the mean displacement direction from GNNS is between WNW and WSW, plunging down towards the fjord (Blikra et al., 2015). This is a direction close the blind plane for the TSX-satellite in ascending orbit, thus low sensitivity using this dataset can be expected for displacement parallel to the slope. Nevertheless, the ascending dataset contributes to the combined displacement by its sensitivity to displacement directions out of the slope and into the slope. On the other hand, the TSX-satellite in descending orbit is sensitive to the surface-parallel flow. By combining datasets, both geometries complement each other. In this project, combined displacement velocity has been used for interpreting rockslides, rock glaciers and solifluction (Paper 1 and 3). For example, we show that spatial variations in velocity from 3D surface displacement vectors inside the Jettan rockslide, show sections with repeated pattern of increasing surface velocity (Paper 3), which support field observations of oblique trends in structural and geomorphological elements made by Skrede (2013). This includes greater opening of the northern part than the southern part of fractures. The same pattern could explain that terraces are more developed and scarps are higher in their southern parts than in northern parts.

In addition, in Paper 4, combined displacement velocities are used on the landscape-scale to give evidence of a highly active periglacial landscape in the study area of the Nordnes Peninsula. The highest velocities are found in the Jettan rockslide found in steep low-elevation terrain composed of rockfall colluvium and fractured bedrock. Combined displacement velocity is lower in the gentler high elevation permafrost areas containing mostly weathered material that has undergone solifluction.

5.2 DIP/PLUNGE OF DISPLACEMENT

In addition to, and in combination with spatial variation in velocity, variations in dip/plunge of combined 2D and 3D surface displacement are very useful for interpretation of surface displacement. The dip of displacement for the Gámanjunni 3 rockslide gives a clear indication of a large-scale rotational movement into the slope in the upper part and out of the slope in the middle part (Paper 1). Variations in dip of displacement further permit interpretation of rockslide kinematics, possibly dividing the rockslide material into slide compartments. Some of these have been identified as slide scarps in field observations. In this way, the dip of displacement has proven useful as a kinematic parameter, even in areas with subtle variations in surface velocity. Some of the same pattern was observed for the Njárgavárri rockslide where dip of displacement indicates surface displacement out of the slope in the lower parts (Paper 1). Here, lobes or slide blocks could be stacked on top of each other, explaining observed internal variations. Also, we may infer the position of outcropping sliding surfaces or shear zones only from remote sensing data.

For the Jettan rockslide, we compare the plunge of 3D displacement vectors between the northern and southern part (Paper 3). Findings suggest a shallower and spatially discontinuous plunge in the north, compared with the steeper and spatially more continuous plunge in the south. Variations in combined displacement velocity are interpreted as a combined topographic and structural control on displacement in the northern area. Steepening of 3D displacement velocity plunge in the southern part of the rockslide may be controlled by steeply plunging fractures in the vicinity. Within the southern area, velocity increases downslope while plunge of 3D displacement vectors follow a concave curvature, with steep plunge in the upper part and shallower plunge in the lower part. Together with field observations, this indicates a structural controlling mechanism where step fractures curve to low-angle (listric) detachments giving back-rotation of blocks at depth, possibly combined with zones of compression and extension and stacking blocks in thrust-imbricated zones.

On the large scale, dip of 2D displacement indicates an overall settlement resulting in an overall net lowering of the surface of the landscape of the Nordnes Peninsula during the snow-free period (Paper 4).

5.3 DISPLACEMENT INTO AND OUT OF SLOPE (SUBSIDENCE/UPLIFT)

Another useful diagnostic parameter is the ability to distinguish between areas having displacement into and out of the slope (subsiding and uplifting). These are found by comparing dip of surface displacement with slope of topography. For the Gámanjunni 3 rockslide we find a backward-rotational movement around a pivot point in the middle, with displacement into the slope subsidence in the upper part and out of the slope in the lower part (Paper 1). The same 2D approach was used for the Ádjet rock glacier, where areas with displacement into the slope (thinning) and out of the slope (thickening) (Paper 2) were found. By combining range component from offset-tracking of ascending and descending TSX scenes from individual years (2009-2016), we observed that the position of thinning and thickening areas were relatively constant over time. We hypothesize that the observed pattern may be due to ongoing transverse ridge formation and development of depressions.

Also for the Jettan rockslide, displacement into and out of the slope give insight into surface displacement kinematics, which again can guide interpretation of sub-surface controlling structures. The observed displacement into the slope in the upper part, and out of the slope in the lower part of the northern area, could be a result of steep planar fractures that are becoming curved (listric) gliding surfaces towards depth, resulting in back-rotation of blocks (Paper 3). In addition, variations in displacement into and out of slope indicated a forward rotational movement possibly related to an ongoing toppling-process.

5.4 STRAIN RATE

Strain rate, or downslope acceleration and deceleration from combined 2D and 3D surface displacement have been used as a diagnosing kinematic parameter. This is the case in particular for localization of the possible shear zone that separates the lower part from the upper part of the Ádjet rock glacier. In Paper 2 we show how spatially averaged offset-tracking data obtained over 7 years, documents annual variation in strain rate. The most noticeable strain rate signal from this landform is related to the convex middle part. Here, variations in strain rate point towards an irreversible and positive feedback process, indicating a separation of the upper and the lower part, possibly preconditioned by climatic forcing and sustained by gravitational forces.

5.5 HORIZONTAL AND VERTICAL COMPONENTS

Horizontal and vertical components of 2D surface displacement vectors have proven most valuable during the study of solifluction lobes at the tip of the Nordnes Peninsula (Paper 1). At this location, solifluction landforms can be detected in areas with increased horizontal velocity components. The most active parts of the landforms were visible as peaks in the horizontal data. These variations, which are not easily identifiable in the input ascending and descending TSX InSAR data, stand out more when studied using 2D combined datasets. This is an example where the ascending and descending input data, combined through the 2D procedure complement each other, resulting in higher sensitivity to surface displacement. For the same location, vertical components show steeper dip of displacement into the slope at gentle terraces than in solifluction areas. This pattern is possibly related to more water-saturated ground on the leveled terraces, giving greater thaw subsidence here than on the steeper and more drained solifluction areas.

On the landscape-scale, decomposition of 2D surface displacement vectors show that the vertical components dominate for all six of the mapped geomorphological classes on the Nordnes Peninsula. The distribution of the horizontal component shows a correlation with aspect e.g. solifluction lobes on eastern slopes have high eastward horizontal components in addition to vertical downward components (Paper 4).

5.6 AZIMUTH OF DISPLACEMENT

From 3D surface displacement, the azimuth direction can be found. 3D azimuth direction and plunge relationship can be investigated and used to understand controlling factors. In the Jettan rockslide we use this diagnostic kinematic parameter to document a change from displacement towards WNW in the northern part, to NW in the southern part (Paper 3). This trend is confirmed by displacement direction of GNSS-stations.

A similar trend for the Jettan rockslide shows that a greater north component in the azimuth direction is linked to a steeper plunge of the displacement. This is observed in the southern part where steeply dipping NE-SW fractures control the displacement pattern. We also document a clockwise rotation of azimuth direction from the upper parts to the lower parts of the northern area of the rockslide. This turning trend is also observed in the azimuth direction of mapped geological structures by Skrede (2013), indicating structural control on the displacement. However, some caution must be taken because the North-South component of the 3D inversion varies more in the northern part of Jettan due to alignment of the TSX-satellites LOS-plane and the LOS-directions of the GB-radar. Azimuth direction of 3D surface displacement vectors can also be used in advance to infer the degree of topographic control on displacement. This is done by comparing azimuth of 3D displacement with aspect of the topography.

5.7 SYNTHESIZING DATA IN GEOLOGICAL CROSS-SECTIONS

The use of cross-sections has been important for interpretation of displacement patterns, and has increased the conceptual understanding of active displacement processes (Paper 1-3). By plotting combined 2D and 3D surface displacement vectors, diagnostic kinematic parameters, mapped geological structures, and geomorphological elements in geological cross-sections, new opportunities for understanding processes arise. For example, by synthesizing available data for the Gámanjunni 3 rockslide in a cross-section, we could propose a geological model with overall downslope acceleration and extension of masses in the upper part, and deceleration and compression in the toe-zone along sub-horizontal thrust planes (Paper 1). Another example is how the use of cross-section contributes to increased understanding of the relation between convex topography and increased strain rates for the Ádjet rock glacier (Paper 2). And finally, without the use of data from cross-sections we would not be able to track the pattern of internal backward-rotational movement along steep fractures that curve to low-angle detachments at depth for the Jettan rockslide (Paper 3).

We would like to stress the fact that, with the exception of the Jettan rockslide, and GNSS measurements on the Gamanjunni 3 rockslide and Ádjet rock glacier, the rest of the landforms studied in this PhD have no in-situ data describing displacement and no information of structures at depth. However, using detailed spatial variations and for the Ádjet rock glacier, temporal variations of surface displacement in cross-sections and map view, we are able to deduce simple, yet descriptive conceptual geological models and discuss controlling factors.

10 CONCLUSIONS

This project set out to investigate if and how combined multi-geometrical datasets from ground- and satellite based radar instruments, can support interpretation of slope displacement process at the landform- and landscape-scale. The present work found that combined datasets can contribute in a number of ways. For example by opening up a new toolset of kinematic diagnostic parameters (azimuth direction, dip/plunge, displacement into and out of slope (subsidence/thinning and uplift/thickening), compression/extension (strain rate), and horizontal and vertical components), one may acquire greater information when compared with traditional interpretation using single InSAR datasets that give one dimensional information along the line-of-sight direction.

Interpretation of displacement patterns from radar datasets is also made easier, since combined data from different geometries and different LOS complement each other by reducing the LOS-ambiguity. At sites with varied topography, the user does not have to consider to the same extent as with single geometry datasets, the instrument's LOS and how much of the surface displacement component is possible to measure.

Kinematic diagnostic parameters have enabled us to discuss factors controlling displacement in rockslides and rock glaciers by comparing combined displacement to geological structures, geomorphological elements and topography in map and in particular cross-sections.

The capability of the technique to remotely observe ground surface displacement patterns over large areas makes it suitable as an important supporting material when mapping and monitoring any displacement phenomena that are spatially and temporally covered by two or more radar datasets.

These findings could be of interest to organizations concerned with mapping and monitoring of subsidence and unstable slopes such as NGU and NVE. Increased information about ground displacement from combined datasets, would benefit organizations in the building sector, or those that are responsible for infrastructure such as roads, railways, power lines etc. in steep terrain (Mesta, Statens Vegvesen, Bane NOR), or entrepreneurs/consulting engineers (e.g. Sweco, Consto, Multiconsult) working with projects where the state and evolution of ground stability are vital for the safety of personnel and project cost.

Knowledge of 2D and 3D displacement patterns for thawing permafrost landforms may prove important as supportive information for future predictions of slope stability response to climate change.

We have also discussed use of combined satellite-based InSAR datasets in quantifying periglacial landform-specific displacement rates as a tool for geomorphological mapping. Our results show that 2D InSAR datasets have limited value as a standalone dataset for large-scale geomorphological mapping, and should be treated as an additional input in for example, geostatistical modeling of a landscape.

The use of remote sensing data is expected to increase in the future. The launch of the Sentinel-1A and -1B satellites is a good example of this. Together they will cover the globe every six days. With increased availability of datasets, an increased number of users is expected. Many of the new users will lack previous knowledge of the limitations of the InSAR technique, thus an application that can mitigate LOS-ambiguity of single datasets will be welcome. The possibilities created by the kinematic diagnostic parameters presented in this work may provide inspiration to develop applications and services that combine remote sensing data, enabling experts in various fields to investigate displacement patterns and processes in new ways.

10.1 FUTURE RESEARCH

As a result of this study, further research might well be conducted on investigating the role of pre-, syn-, and post-collapse of rock glaciers, or landforms controlled by or susceptible to degrading permafrost as climatic proxies. By comparing diurnal/seasonal annual variations recorded by cost effective in-situ instrumentations (temperature loggers (air/fractures/talus/surface/ground), time-lapse cameras (snow depth/distribution)) with variations in kinematic diagnostic parameters from combined surface displacement from ground- and satellite-based radar (2D and 3D), controlling/forcing factors can be studied.

By producing time-series from ground- and satellite-based radar datasets, 4D InSAR datasets can be produced. This will show 3D displacement evolution over time for areas covered in time and space by the input datasets.

Furthermore, increased understanding of the link between surface displacement, geological structures, geomorphological elements and landscape processes, some due to changing climates, can be established in the future. This could be done by comparing field observations and geophysical data from high-risk objects and other high-priority areas with kinematic diagnostic parameters from 2D and 3D, and perhaps even 4D InSAR datasets in cross-section and map-view.

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