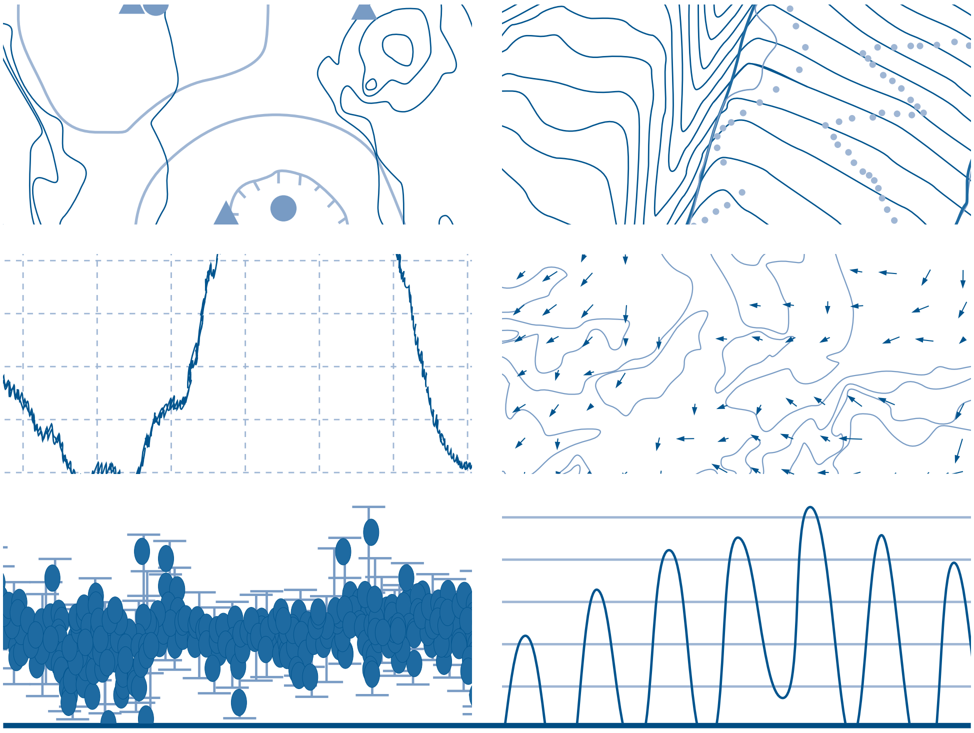
Icelandic
Meteorological Office

Veðurstofa
Íslands



A Survey of Active Slope Movements in Central-North Iceland from Satellite Radar Interferometry

Sigurjón Jónsson, ETH Zürich

Skýrsla
VÍ 2009-002

Icelandic
Meteorological Office

Veðurstofa
Íslands

A Survey of Active Slope Movements in Central-North Iceland from Satellite Radar Interferometry

Sigurjón Jónsson, ETH Zürich

Veðurstofa Íslands
Bústaðavegur 9
150 Reykjavík

+354 522 60 00
+354 522 60 01
vedur@vedur.is

Skýrsla
VÍ 2009-002
ISSN 1670-8261

Veðurstofa Íslands

Lykilsíða

Skýrsla nr.:	**Dags.:**	**Dreifing:** Opin ☒ Lokuð ☐
VÍ 2009-002	Júní 2009	**Skilmálar:**

Heiti skýrslu / Aðal- og undirtitill:	**Upplag:**
A survey of active slope movements in Central-North Iceland from satellite radar interferometry	26
	Fjöldi síðna: 78
Höfundar: Sigurjón Jónsson, ETH Zürich	**Verkefnisstjóri:** Þórður Arason
Gerð skýrslu/Verkstig: Lokaskýrsla	**Verknúmer:** 2341-0-0002

Unnið fyrir:
Ofanflóðasjóð

Samvinnuaðilar:

Útdráttur:
Lýst er könnun á notagildi bylgjuvíxlmælinga úr ratsjárgervitunglum til að mæla örlitlar hreyfingar á lausum jarðefnum í fjallshlíðum, sem geta verið aðdragandi skriðufalla. Aðferðin hentar vel til að kortleggja virkar skriður í heilum landshlutum og finna a.m.k. 100–200 m stór svæði í fjallshlíðum sem hníga fram um 1–5 cm/ári. Fjallað er um mælingar á slíkum hreyfingum í fjallshlíðum á Mið-Norðurlandi. Höfundur hefur áður gefið út niðurstöður svipaðrar rannsóknar fyrir Austurland í greinargerð Veðurstofunnar 07004.

Lykilorð:	**ISSN númer:**
Bylgjuvíxlmælingar, InSAR, Hreyfingar á lausum jarðefnum	1670-8261
	Undirskrift verkefnisstjóra:
	Yfirfarið af: ÞA

Summary

Knowledge of a few unstable slopes near towns in East and North Iceland led to the initiation of this project that has the following two primary objectives: To assess the monitoring capabilities of Synthetic Aperture Radar Interferometry (InSAR) from satellites on these known slopes and to survey large areas in East and Central-North Iceland to search for other moving slope deposits that may exist. Here I report on the results from North Iceland, while the East Iceland results have already been published in another report [*Jónsson,* 2007].

I ordered and processed radar data from the European Space Agency's archives that were collected by the ERS-1 and ERS-2 satellites during 1995-2000. I also requested new data acquisitions from the Envisat satellite during summers in 2004 and 2005. A total of 30 interferograms were processed of Central-North Iceland and they have variable time-spans from one day to over two years. Some problems were encountered in the data processing, which were mainly due to an inaccurate digital elevation model (DEM), but no adequate high-resolution DEM was available for the project, and due to high-elevation snow cover in several of the images, which corrupts the signal. However, my results indicate that while inter-annual interferograms often provide only limited information, single- and multi-month summer interferograms are very useful to study unstable slopes in Iceland.

Prior to the start of this project, the main known unstable slopes in Central-North Iceland were the deposits along the road to Siglufjörður, in an area known as Almenningur. This area is seen actively moving in almost all of the processed interferograms with two main sites active, in Almenningsnöf and in Höðnuvík. The lowermost part of these actively moving slopes, which includes the road crossing the deposits, is moving so fast that the slopes appear decorrelated in interferograms that span one year or more. Interferograms spanning 1-2 months, on the other hand, reveal details about the borders of the moving deposits and about their complicated displacement pattern.

In my search for other active slope movements I found more than 20 sites of previously unknown creep. The search extended from Skagafjörður in the west to Skjálfandi in the east. The largest of these sites is the Víkurhólar deposits in Eyjafjörður. The movement at this site is rather slow and at a non-steady rate during the observation period. Other locations where moving deposits were detected include Fnjóskadalur, three sites in Höfðahverfi, Hrafnagilshraun and Hesthraun in Þorvaldsdalur, Kirkjufjall in Öxnadalur, Tungudalur near Stífluvatn Lake, and several other locations.

The results of this project from East and Central-North Iceland show that InSAR is a useful technique to both search for and monitor active slope movements in Iceland that are larger than 1-200 m in aerial extent. A better DEM of Iceland is needed to improve the quality of the data processing and to allow for meaningful analysis of more interferograms. Radar data acquisitions in most of Iceland are neither regular nor frequent and the 2004-2005 data exist only because of my request to European Space Agency. Therefore, a slope-monitoring policy and an observation plan for Iceland is needed to secure future data acquisitions.

Contents

List of Figures

Abbreviations

ALOS	Advanced Land Observing Satellite
DEM	Digital Elevation Model
DLR	German Aerospace Center
CSA	Canadian Space Agency
ERS	European Remote Sensing Satellite
ESA	European Space Agency
GPS	Global Positioning System
IMO	Icelandic Meteorological Office
InSAR	Interferometric Synthetic Aperture Radar
JPL	Jet Propulsion Laboratory
LOS	Line of sight
m.a.s.l.	meters above sea level
NASA	National Aeronautics and Space Administration
NLSI	National Land Survey of Iceland
ROI_PAC	Repeat Orbit Interferometry Package
SAR	Synthetic Aperture Radar
SLC	Single-Look Complex
SNR	Signal to Noise Ratio
SRTM	Shuttle Radar Topography Mission
UTM	Universal Transverse Mercator
WGS	World Geodetic System

1 Introduction

Debris flows and snow avalanches mainly occur in three regions of Iceland: The Eastern Fjords, the central part of North Iceland, and the Western Fjords [*Jóhannesson and Arnalds,* 2001]. These areas are geologically the oldest parts of Iceland and consist of valleys and fjords bounded by steep sided mountains, a landscape shaped by glaciers during the past ice ages. Two snow avalanches in the Western Fjords in 1995 caused 34 fatalities and led to a complete revision of laws and regulations related to hazard and risk evaluation for debris flows and snow avalanches in Iceland. To fulfill these new laws and regulations many projects have been initiated to study, catalogue, map, and evaluate past debris flows and snow avalanches near towns, mostly in these three regions. In addition, a recent discovery of unstable slopes near the towns of Seyðisfjörður and Neskaupstaður in eastern Iceland has also prompted extra efforts to assess if a catastrophic event could occur. These efforts include mapping and geodetic observations of the slope movement. GPS measurements of the Þófi site in Seyðisfjörður and in Urðarbotn above Neskaupstaður, have shown displacement rates of up to 33 and 138 cm/year, respectively [*Jensen and Jóhannesson,* 2002; *Jensen and Hjartarson,* 2002].

The results of the Seyðisfjörður and Neskaupstaður GPS measurements, among other things, led to the initiation of a new project focussing on using satellite radar interferometry (InSAR) to study active slope movements in Iceland. This project started in 2003 and it was decided to focus on East Iceland and the central part of North Iceland. The project has three main goals:

1. To investigate the feasibility of satellite radar interferometry (InSAR) to detect and monitor active slope movement in Iceland.
2. To use InSAR to measure creeping motion at sites that are known to be active, such as the Þófi site in Seyðisfjörður, Urðarbotn above Neskaupstaður, and the sites along the road to Siglufjörður in North Iceland, and to compare InSAR results with ground based measurements.
3. To survey both East and North Iceland to search for other locations where creeping slopes are present.

In this report I present the results from North Iceland, while the results from East Iceland have already been summarized in another report [*Jónsson,* 2007] and at several conferences [e.g. *Jónsson and Ágústsson,* 2004, 2007]. I begin by discussing general conditions of InSAR and the satellite radar data availability for the region. Next I discuss the general results of the measurements in North Iceland and then move on to describe results at the different sites, starting with the known instable slopes near Siglufjörður, then summarizing the results in the east around Eyjafjörður and ending by describing the results in the west in Skagafjörður.

Some of the locations where active slope movement has been detected in the processed interferograms correspond to "landslides" that have been described geomorphologically, e.g.

by *Jónsson* [1976]. The origin of these deposits has been a subject of a considerable debate during the past decades where many have agreed with *Jónsson's* [1976] interpretation that they originate from sudden catastrophic slope failures or rock avalanches. In resent years, however, another interpretation has been gaining ground which links these deposits to active and inactive rock glaciers [*Guðmundsson,* 2000]. The history of past morphological investigations and interpretations has been summarized by *Guðmundsson* [1995]. In this report I describe the InSAR observations and the sites were displacements are detected, but refrain from attempting to explain what is causing the slope movements. I use several terms to describe these sites, e.g. "unstable slopes", "creeping landslides", or simply "landslides", and also to describe the observed movement, such as "active landslide displacements", "mass-waste movement", or simply "slope movement". Therefore, the term "landslide" should not necessarily be understood here as deposits resulting sudden rock avalanches, but rather rather where deposits are actively seen creeping in the interferograms.

2 Data Availability and Data Processing

The satellite radar data used in this project are from the ERS-1, ERS-2, and Envisat satellites operated by the European Space Agency (ESA). ERS-1 was launched in 1991 and was operated for nine years or until 2000. ERS-2 and Envisat were launched in 1995 and 2002, respectively, and both are still in operation. However, the precise pointing of the ERS-2 radar antenna failed in 2001 and since then only some ERS-2 images can be used for radar interferometry. All these satellites transmit radar signals at C-band (wavelength ≈ 5.6 cm) that interact with and reflect from objects on the ground that have roughness of a similar dimension. The ERS-1 and ERS-2 radar wavelengths are identical and data from these two satellites can be combined to form interferograms. The Envisat radar, on the other hand, operates on a slightly different wavelength so Envisat data cannot easily be interferometrically combined with ERS data. Other radar data of Iceland exist, including data from the Japanese L-band (wavelength ≈ 23.5 cm) JERS-1 satellite (1992-1998) and the Canadian C-band Radarsat-1 (launched in 1995 and still in operation). However, these data were not investigated in this project. Other recent radar missions include the Japanese L-band ALOS satellite (launched in 2006), the Canadian Radarsat-2 (launched in 2007), and the German TerraSAR-X mission (launched in 2007) .

My investigation focussed on two classes of data. First, I surveyed what data have been acquired in the past and exist in the ESA archives, which include primarily ERS-1 and ERS-2 data from the 1990s, and selected several of these scenes for this study. Second, I requested new Envisat radar acquisitions above North Iceland during summers of 2004 and 2005.

In this section I first discuss how the rough topography of North Iceland limits satellite radar observations, then I report on the ERS-1/ERS-2 data availability and baselines of the different satellite tracks that cover the study area, and finally I describe what data were collected during summers of 2004 and 2005 that I requested as a part of this project.

2.1 Limitations due to the Radar Viewing Geometry

Radar imaging is fundamentally different from conventional passive remote sensing techniques that typically acquire near-nadir photographs in the visible or near-visible bands. Radar imaging is an active remote sensing technique where radar pulses are transmitted and the ground reflections of these pulses are collected again by the same antenna (see e.g. *Hanssen* [2001] for a review). The primary advantage of this technique over other remote-sensing techniques is that radar imaging is not limited to daylight acquisitions nor to cloud-free conditions, and in addition it can be used to detect ground displacement. The ERS-1/2 satellites cover in each pass a swath that is about 100 km wide and the incidence angle varies from about 19° to about 26° across the swath (Figure 1). The Envisat satellite can be operated in several different modes with different incidence angles. However, the data requested for North Iceland were acquired in the IS-2 mode, which is similar to the ERS mode.

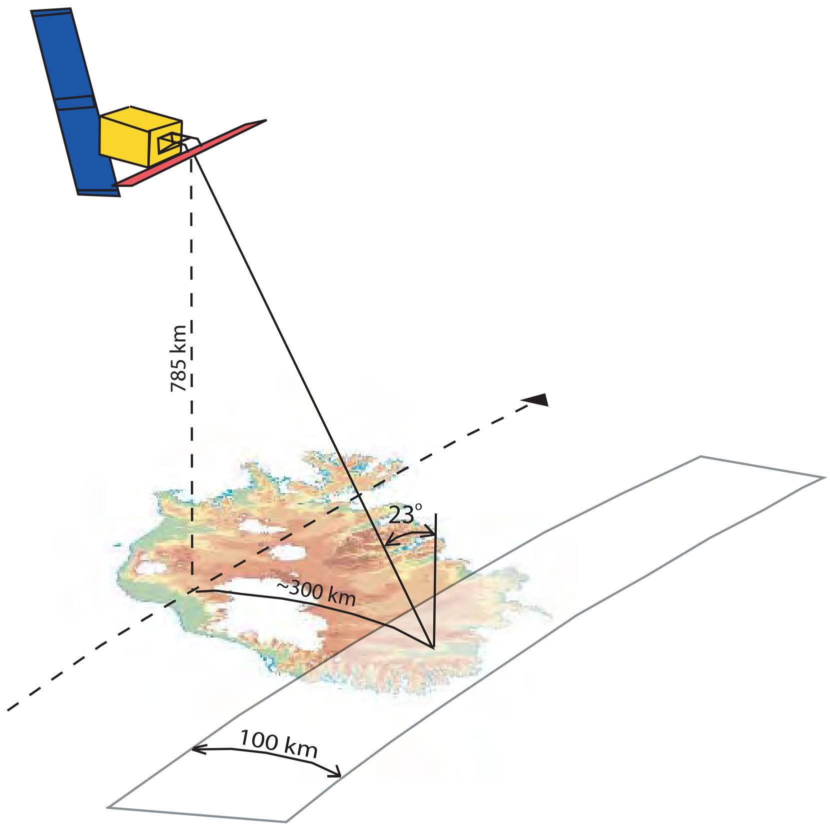


Figure 1. *Schematic figure of an ERS-2 ascending pass covering East Iceland. The incidence angle is 23° in the middle of the 100 km wide swath the satellite covers in each pass. The viewing direction during ascending passes is about N78°E for ascending passes and N78°W for descending passes.*

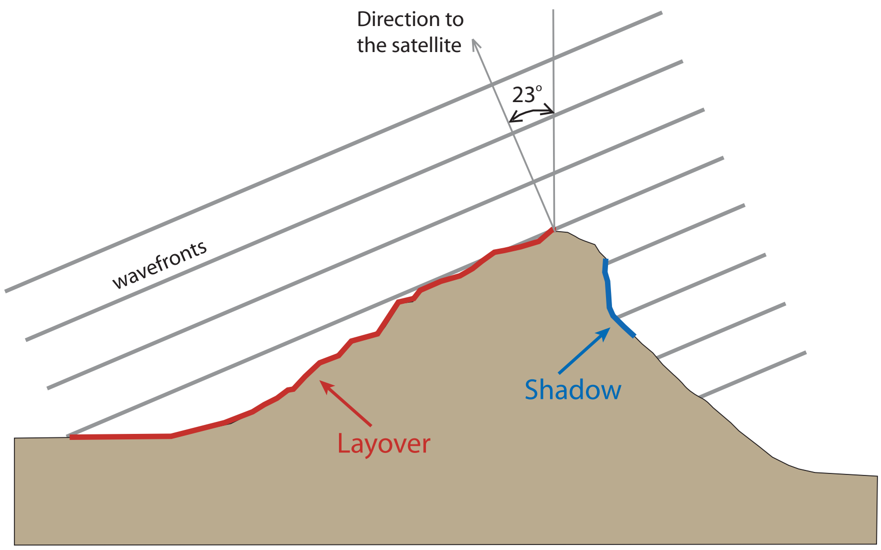


Figure 2. *Schematic figure showing shadowing and layovers in radar imaging. The gray straight lines indicate incoming wavefronts from a radar satellite looking down from the left. When slopes facing the satellite are steeper than 23° reflected signals from the top of the mountain return before reflections from further down the slope, resulting in a "layover". Slopes facing away from the radar are better imaged, although shadowing can occur on very steep slopes.*

The average incidence angle of 23° has limitations and it means that slopes tilting away from the radar and are steeper than 67° are in a 'shadow' and cannot be imaged by the radar satellite (Figure 2). However, not many slopes are so steep. More important is the imaging limitation of slopes that incline towards the radar look direction. When the tilt of these slopes exceeds 23°, radar returns from the top of the mountain will arrive at the same time or before radar reflections from further down the slope, which makes it impossible to distinguish between these signals (Figure 2). This phenomena is called a 'layover' and is much more limiting than shadowing, as it excludes virtually all significant slopes facing the radar look direction. Fortunately, radar satellites can acquire radar data from approximately opposite directions, i.e. during ascending and descending passes, so most slopes can be imaged using one of these two viewing directions.

The topography of Central-North Iceland is relatively rough with steep-sided valleys and fjords and with mountains exceeding 1200 m in elevation (Figure 3). A large part of the area consists of slopes exceeding 23° and some slopes even exceed 67°. Figure 4a-b shows a map of predicted layovers near the town of Akureyri in Central-North Iceland the ascending and descending viewing directions, assuming the average ERS incidence angle of 23°. The steep topography clearly limits the capability of the radar imaging at many slopes, showing that slopes facing ESE result in a layover during descending passes and WSW slopes cannot be imaged during ascending passes.

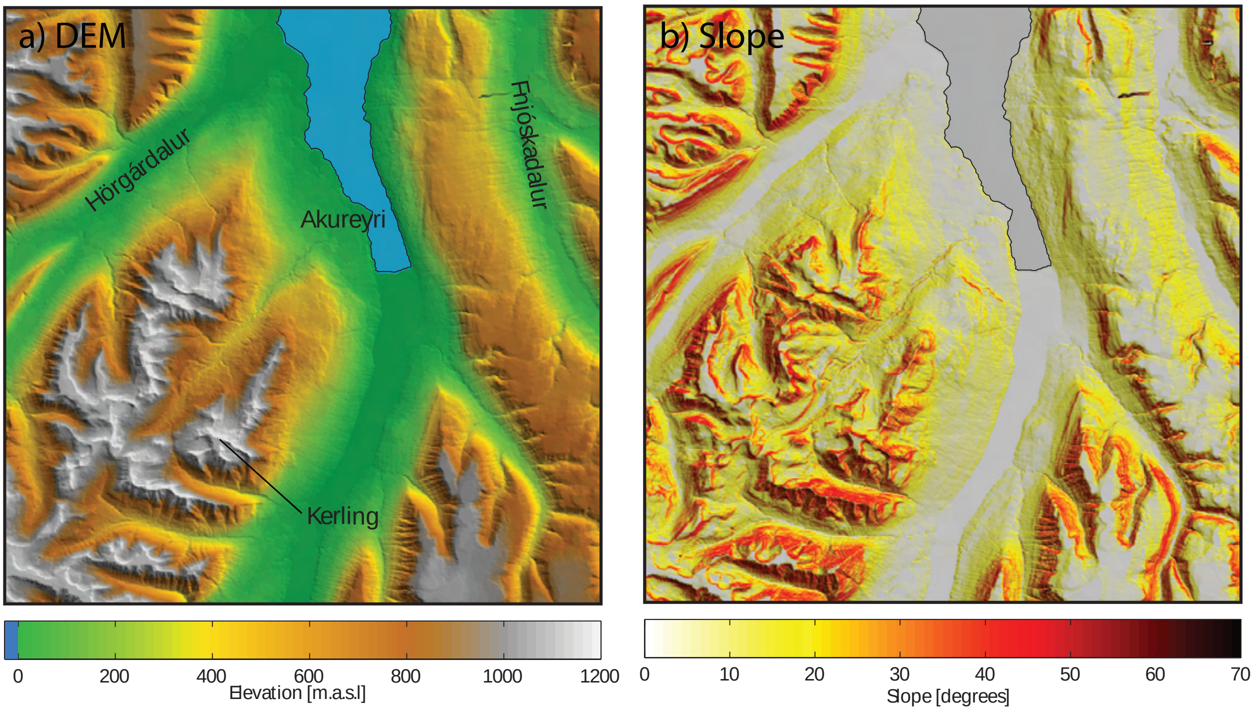


Figure 3. *An example of the topography (left) and slopes (right) near Akureyri in North Iceland. The topography of the North Iceland is typically rough with many steep slopes. The colorscale in a) is saturated at 1200 m.a.s.l., but the highest mountain on this map is Kerling (1534 m.a.s.l.).*

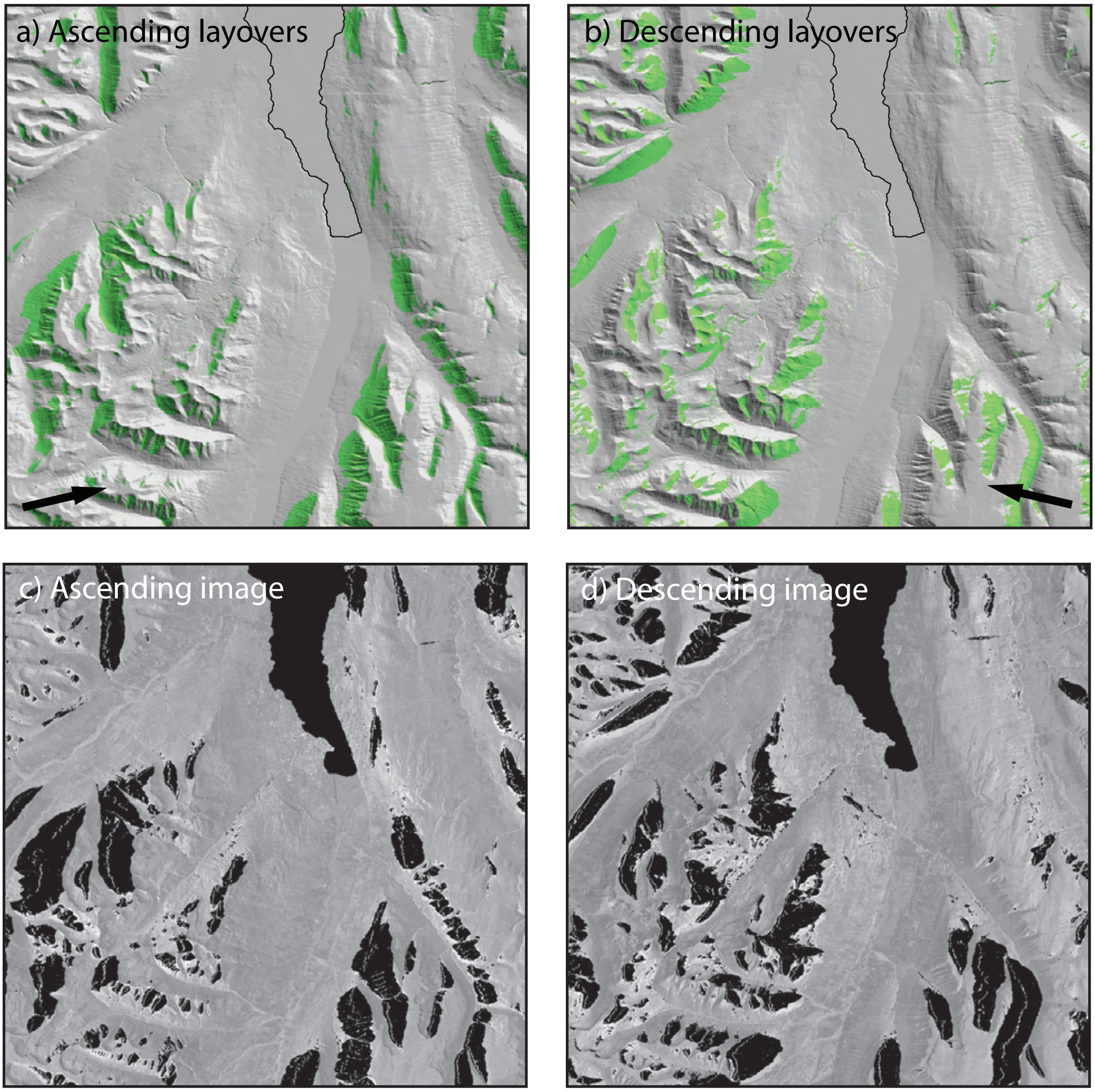


Figure 4. *Map of ERS-1/2 layovers (shown as green) from the a) ascending and b) descending viewing directions for the same area as in Figure 3. Black arrows indicate the look direction of the satellite. The figures show clearly that many slopes cannot be imaged using only one look direction. c-d) show the corresponding geocoded amplitude images with layover areas masked out.*

2.2 ERS-1 and ERS-2 Data Availability and Baselines

Thousands of ERS-1 (1991-2000) and ERS-2 (1995-) radar images have been acquired over Iceland since 1991 with multiple acquisitions for any given location from several different tracks and from both the ascending and descending directions. The repeat time of these satellites is 35 days, which means that they orbit along the same track every 35 days. The revisit time is shorter, as any given point on ground can be imaged more frequently, i.e. from overlapping tracks and from ascending and descending tracks. Although many acquisitions of Iceland exist, most of these data have been acquired during descending passes. Other limitations include a gap in ERS-1 data from Dec. 1993 to April 1995, when the satellite was operated in different orbits. After the launch of ERS-2 in 1995 the satellite trailed ERS-1 by only a day, providing an opportunity to form one-day (tandem) interferograms that have been extensively used to generate digital elevation models and to study glacier motion. However, after 1997 ERS-1 was only used as a backup for ERS-2 until its operation was stopped in 2000. In addition, the precise pointing capabilities of ERS-2 failed in early 2001 and after that time ERS-2 data are of limited use for interferometry, although some scenes can be used for the purpose [e.g. *Jónsson,* 2008].

I searched the ESA data archives for ERS-1/2 data of Central-North Iceland from four parallel ascending tracks (tracks: 87, 316, 44, and 273) and four parallel descending tracks (tracks: 367, 95, 324, and 52, see Figure 5). All of these tracks cover parts of Central-North Iceland as there is almost 70% overlap between adjacent tracks at this latitude. The amount of existing ascending data from 1991 to 2007 is 42-74 radar images for each of the four tracks (See Appendix A, Figures 32-33). The perpendicular baseline information for these datasets reveals that several small-baseline image pairs exist that span less 1-2 years. Within this project I ordered only four ascending ERS images (from track 44) and from them formed four interferograms (Figure 6a). The data are from 1997-1998 and the interferograms span in time from one day to 14 months and have perpendicular baselines between 31 m and 185 m.

The amount of acquired descending data is larger, especially for tracks 324 and 52 (Figures 34-35). The spatio-temporal baseline distribution indicates that many potentially usable interferograms can be formed using data from any of the four descending tracks. Due to the better spatial coverage of track 324, compared to track 52, data from this track were ordered for this project. The ordered data were acquired mainly during summers of 1995-2000 (Figure 6b), but a few additional scenes were ordered 2002-2003, which turned out to be unusable due to the ERS-2 steering problem. The data were selected based on acquisition date (summer) and the possibility to combine multi-month and multi-year scenes with a relatively small perpendicular baseline ($<$200 m) due to the steep topography in North Iceland. In addition, two one-day tandem pairs (one ascending and one descending) were ordered to generate a high-resolution DEM of the area. However, in the end a 25 m DEM of North Iceland was used in the data processing. From the descending images I generated 12 interferograms with variable perpendicular baselines from 10 m to 400 m and with temporal baselines from one day to two years (Figure 6b).

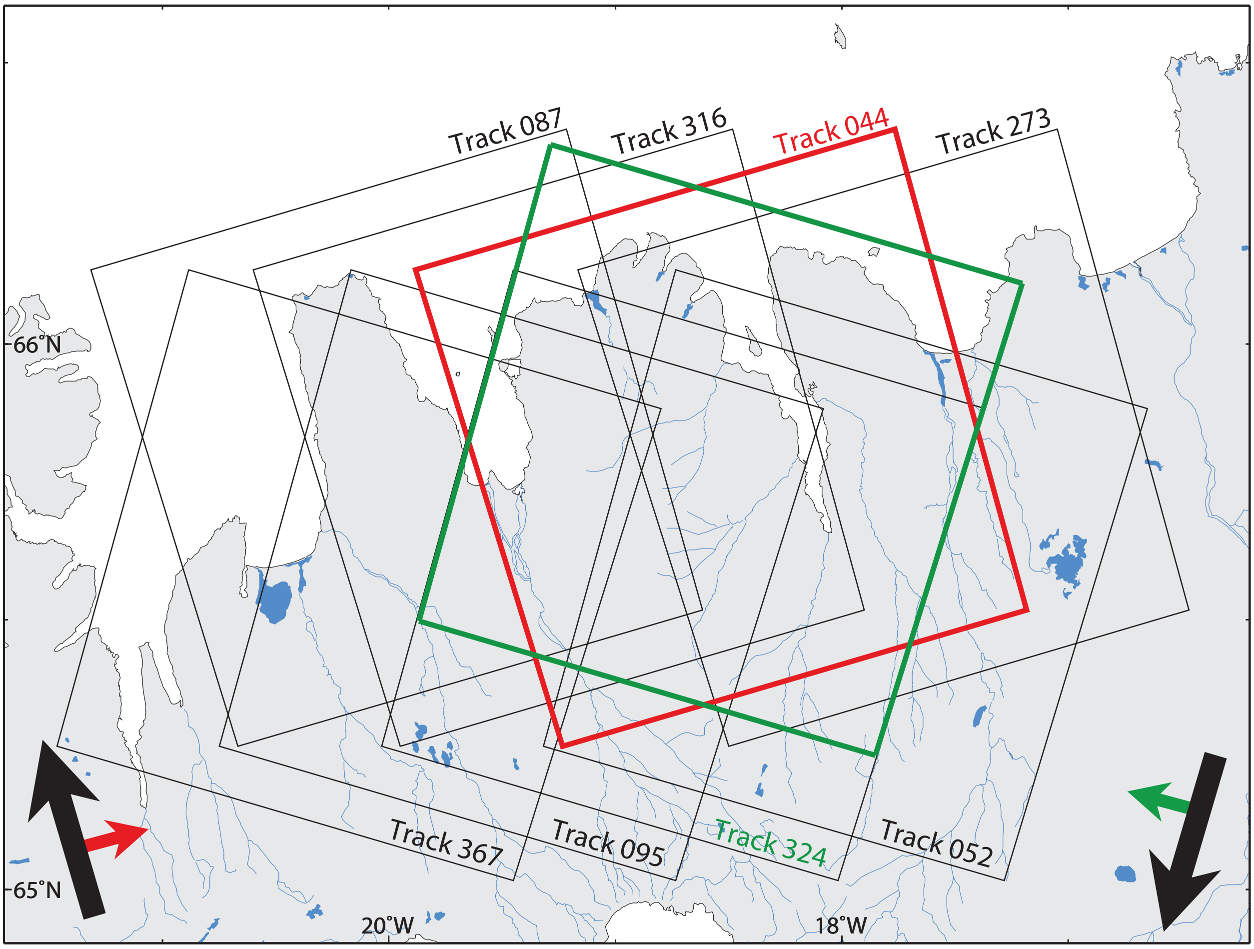


Figure 5. *Map of North Iceland showing the coverage of four ascending tracks (87, 316, 44, and 273) and four descending tracks (367, 95, 324, and 52), for the standard ascending frame 1323 and descending frame 2277. I ordered ERS-1/2 ascending data from track 44 (red rectangle) and descending data from track 324 from a shifted frame (2272) as indicated by the green rectangle. The large black arrows show the ascending and descending satellite flying directions and indicate into what direction the right-looking radar antenna is pointing (colored arrows). The Envisat data used in this project are from ascending track 2044 and descending track 2324 and these data cover approximately the same area as indicated by the red and green rectangles.*

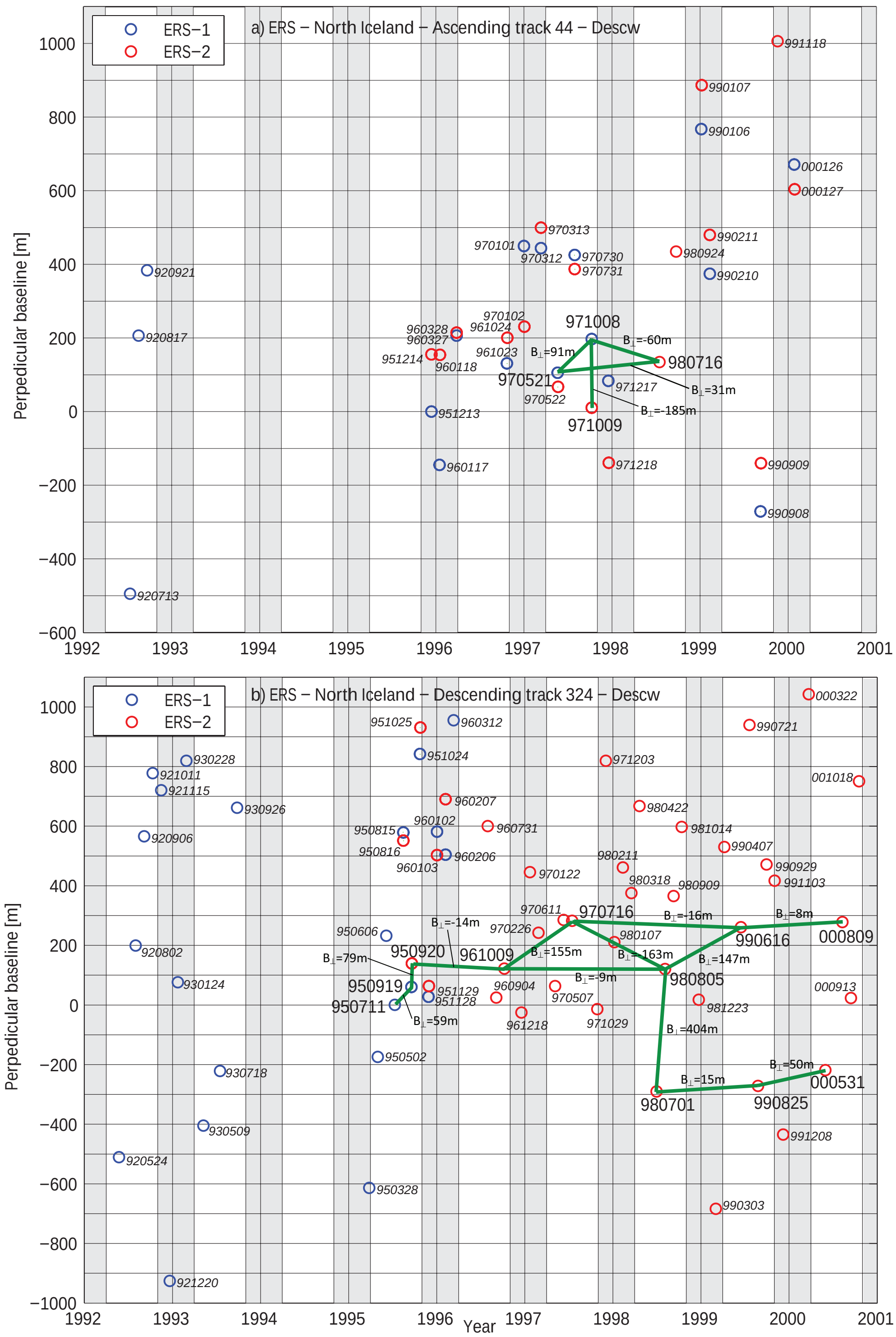


Figure 6. *Spatio-temporal baseline information for ERS ascending track 44 and descending track 324 for the time period 1992-2001. The information comes from ESA's Descw database. Scenes labeled in non-italic were ordered for the project and green lines indicate the interferograms formed. Also shown is the perpendicular baseline ($B_\perp$) as calculated from the precise Delft orbital information.*

2.3 Envisat Acquisitions and Baselines

Within this project I submitted requests to ESA for Envisat acquisitions above East and North Iceland during summers 2004 and 2005. The Envisat satellite has also a revisit time of 35 days, which makes 10-11 acquisitions possible each year of any given area from a certain track. However, to avoid potential problems due to snow cover I only asked for acquisitions from May to early October. My request included 3-5 image acquisitions from one ascending and one descending track each summer, or a total of 16 North Iceland acquisitions during the 2 years. Unfortunately, there is limited prior knowledge about how the satellite orbit is going to be during each pass and thus outlier scenes are acquired that are not well suited for interferometry. In addition, the perpendicular baseline information for Envisat satellite in ESA's Descw catalogue appears to be significantly poorer than the baseline information for the ERS-1 and ERS-2 satellites. This is demonstrated by the comparison of Descw baselines and baselines calculated from precise orbits in Figures 7.

For ascending track 2044 I requested three acquisitions in 2004 (from 20 May to 29 July) and five acquisitions in 2005 (from 5 May to 22 September). The perpendicular baseline distances between the passes show a range of about 1000 m (Figure 7a). The baseline distribution is not very favorable resulting in only one possible interferogram with less than a 100 m perpendicular baseline. Most of the formed interferograms have baselines of 150-250 m and one has about 400 m (Figure 7a).

I requested 8 acquisitions from descending track 2324 in 2004-2005, four in each year. However, data from only two acquisitions were reported available for 2005 (Figure 7b). The baseline distribution for these acquisitions is fairly favorable with many possible interferograms with a baseline smaller than 200 m. Only the image acquired in September 2004 is an outlier (Figure 7b). I formed 6 different interferograms from these images that have baselines ranging from 2 m to over 700 m.

2.4 Data Processing Steps

The data in this project were processed using the Gamma software package from the Gamma Remote Sensing in Switzerland. This is a different software package than was used in processing the East Iceland landslide data [*Jónsson*, 2007], when the ROI_PAC software, developed by the Jet Propulsion Laboratory (JPL) in Pasadena, California [*Rosen et al.,* 2004]. In my data processing I followed a typical 2-pass processing procedure using a simulated interferogram to remove the effects of topography [e.g. *Massonnet and Feigl,* 1998; *Hanssen,* 2001]. The simulation was formed using a 25 m Digital Elevation Model (DEM) of Iceland provided by the Iceland Meteorological Office.

The data processing of each interferogram consists of the following steps:

1. Directory structure is set up on a Linux computer and "zero-level RAW" radar data from ESA are uploaded from CDs. Precise satellite orbit information is downloaded from the Technical University of Delft, The Netherlands [*Scharroo et al.,* 1998].

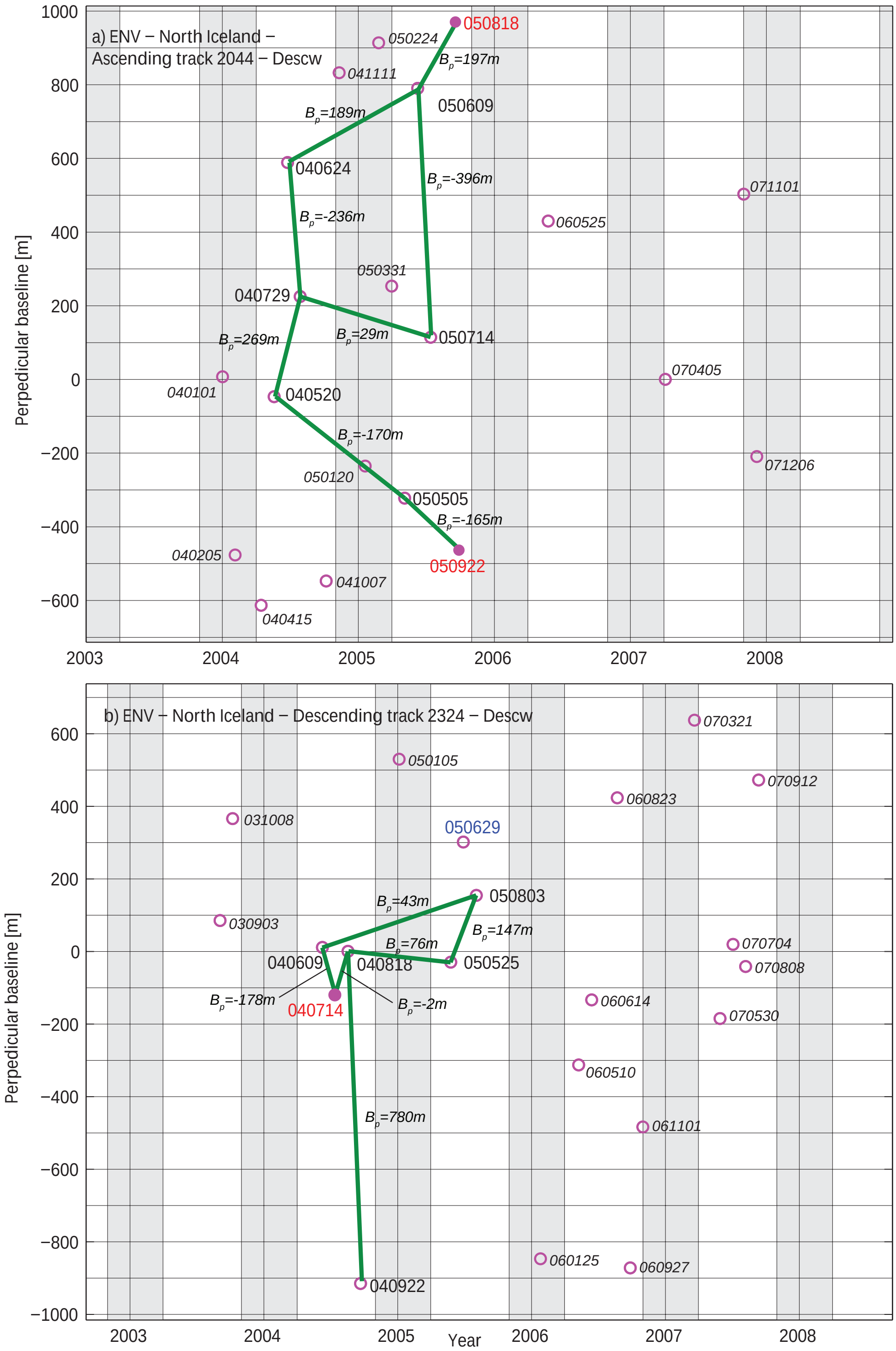


Figure 7. *A spatio-temporal baseline diagram for Envisat radar data acquired along ascending track 2044 and descending track 2324. Green lines show which interferograms were formed. Scenes in italic script exist, but were not ordered for this project. Scenes labelled in red exist, but are missing in ESA's Descw catalogue, while the scene in blue (29 June 2005) is listed in the Descw, but does not exist.*

2. Single-look complex (SLC) radar images are generated from the RAW data.
3. One of the SLC images is selected as a master image and the offsets of other images (slave images) are estimated relative to the master image. The offset-fields is estimated from cross-correlations of small sub-images across the images.
4. The slave images are resampled according to the offset estimations.
5. Interferograms are calculated for small-baseline image pairs. The phase caused by Earth's curvature is removed resulting in a 'flattened' interferograms that contain phase signatures due to topographic heights and deformation.
6. The Digital Elevation Model (DEM) is projected into radar coordinates and a simulated back-scatter image is formed.
7. The offset-field between the simulated back-scatter image and the master amplitude image is estimated and the simulated image is resampled accordingly.
8. The DEM, in radar coordinates, is converted to simulated unwrapped phase using information about the perpendicular baseline. The topographic phase signature in the interferogram is removed by subtracting the simulated unwrapped image from the processed interferogram. The result is a differential interferogram that only should contain phase signals caused by ground deformation (plus errors).
9. The wrapped differential interferogram is filtered to reduce high frequency noise.
10. The interferograms are geocoded, i.e. projected from the radar geometry of interferograms to geographical WGS-84 coordinates.
11. The raw differential interferograms are visually inspected for possible landslide motion and sub-sets of the interferograms are selected for the report.

3 General Results

In this Chapter I discuss the general results of the project by describing the quality of the processed interferograms and by listing briefly where deformation is detected within them.

3.1 General Interferogram Results

I processed a total of 30 interferograms in this project of which 4 and 12 are from ascending and descending ERS-1/2 data, respectively, acquired in 1995-2000, and 14 are from Envisat data acquired in 2004-2005 (8 from descending orbits and 6 from ascending orbits). The time span of the interferograms varies from one day to over two years and the perpendicular baselines vary from 0 m to 700 m. Information about the interferograms is listed in Tables 1-2 and the spatio-temporal baseline information is displayed graphically in Figures 6-7.

Several of the processed interferograms are of good quality with nearly a constant interferometric phase in non-deforming areas while exhibiting details about ground movements in several places. This said, however, many other interferograms proved to be not usable due to interferometric decorrelation and due to topographical artifacts in the data. The decorrelation is primarily caused by snow or changes in the surface characteristics [*Zebker and Villasenor,* 1992], e.g. due to vegetation growth or erosion. Topographical artifacts result primarily from inaccuracies in the DEM, which are up to 40-50 m in many cases, and effectively exclude reliable deformation analysis of interferograms with perpendicular baseline larger than about 200 m. Despite the problems of decorrelation and topographic artifacts, the short-baseline interferograms provide useful results for the area and many details can be extracted from these interferograms.

The ascending data are primarily useful to image slopes that face to the east and northeast, while all southwest tilting slopes will disappear in layovers. The ERS and Envisat interferograms made from ascending data span time periods in 1997-1998 and 2004-2005, and therefore only provide snap-shots of the ongoing deformation in the area during the past two decades. Interferograms during both years are of good enough quality to study landslide motion in the area, although the Envisat interferograms all have a rather large perpendicular baseline, which gives rise to topographical artifacts. The main site where landslide displacement was discovered in the ERS data is near Möðrufellsfjall in Eyjafjarðardalur. Other sites are Kvarnárdalur, just to the north of Möðrufellsfjall, Unadalur in the Höfðaströnd area, and Dalsmynni near the northern end of Fnjóskadalur. These results are discussed in more detail in Chapter 4. In the Envisat data from 2004-2005 a small amount of deformation can be seen on the Möðrufellsfjall landslide in interferograms spanning about one year, but not in the shorter time-span interferograms. Otherwise, the only other site where deformation could be detected in these data was at the neighboring Kvarnárdalur site.

Many other locations with active surface deformation were discovered in the 12 ERS and 6 Envisat descending interferograms (Table 2). The ERS data span various different time intervals during 1995-2000 and the Envisat data 2004-2005, and the descending data

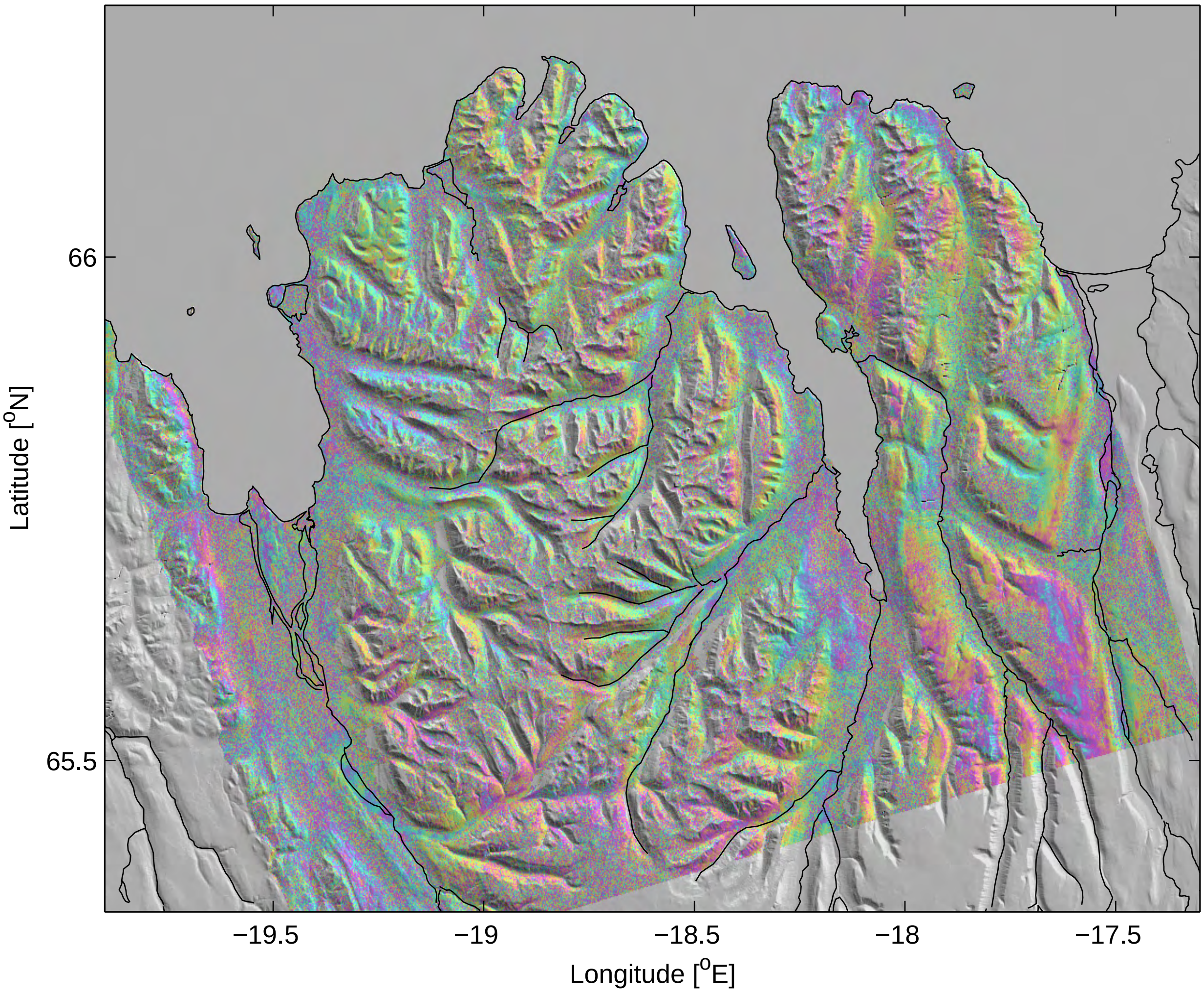


Figure 8. *Example of a geocoded ascending Envisat interferogram of North Iceland (9 June - 18 August, 2005). The displayed area is too large to see any details in the data. However, one can see that the interferogram is decorrelated at the lowest elevations, due to vegetation growth and agricultural activities, and at the highest elevations too, presumably due to snow. The main phase variations are from atmospheric effects that correlate with the topography in some places. ©ESA.*

No.	Data set	$B_\perp$ (m)	Δt days	Coherence	Möðrufellsfjall	Kvarnárdalur	Other places
	ERS-1/2						
1	970521-971008	91	140	Poor	No	No	No
2	970521-980716	32	421	Poor	Yes	Yes	No
3	971008-971009	-186	1	Excellent < 800 m	No	No	No
4	971008-980716	-60	281	Fair	Yes, 2 cm	No	Dalsmynni, Unadalur
	ENVISAT						
5	040520-040729	269	70		No	Yes	-
6	040520-050505	-171	350	Poor	Yes	Yes	No
7	040624-040729	-237	35	Good	No	Yes	No
8	040624-050609	189	350	Fair	Yes	Yes	No
9	040729-050714	29	350	Good, bad atmo	Yes	Yes	Þorvaldsdalur
10	050505-050922	-165	140	Fair, at low elev.	No	No	No
11	050609-050714	-397	35	Good, bad baseline	No	No	-
12	050609-050818	197	70	Fair	No	No	No

Table 1. *Information about the 4 ERS and 8 Envisat ascending interferograms and detected deformation in North Iceland. The second column lists what dates were involved in each interferogram, and the next three columns show information about the perpendicular baseline $B_\perp$, the time-span Δt in days, and the interferogram coherence. The last three columns provide information about whether or not deformation was detected on the Möðrufellsfjall landslide, in Kvarnárdalur, or at other locations. The dash (last column) denotes cases where no measurement was possible.*

therefore provide a more complete picture of the active landslide movement in the region in comparison to the ascending data, as well as providing information on west-facing slopes, instead of east-faceing slopes. The most spatially most extensive mass movements were detected along the road to Siglufjörður in Almenningur, on Víkurhólar in Eyjafjörður, in Tungudalur near Stífluvatn, and on Kirkjufell in Öxnadalur. Many other smaller landslides were detected, e.g. in Fnjóskadalur, Höfðahverfi, Þorvaldsdalur, Svarfaðadalur, Sléttuhlíð, and Skagafjörður. Many of these sites correspond with deposits that were catalogued from geomorphological and geological investigations by *Jónsson* [1976].

Degradation in interferometric coherence or interferometric correlation, usually simply referred to as decorrelation [*Zebker and Villasenor,* 1992], is one of the main limitation of using InSAR to measure ground deformation. The coherence is a measure of the consistency of neighboring phase values and is calculated for a small moving window (often 7×7 pixels in size) across the image and is bounded within the interval [0,1]. There are many factors that cause a loss of coherence. The most important is temporal decorrelation which results from changes in the surface scattering characteristics during the time between the two radar acquisitions. Such changes can be caused by many different processes, including vegetation growth, erosion by water and wind, agricultural activities, and snow. Many of the processed images show poor coherence due to high-elevation snow or due to vegetation growth (Tables 1-2). I discussed this limitation in more detail in the East Iceland report [*Jónsson,* 2007] and the same coherence conclusions also apply for North Iceland. They are that snow-free interferograms that span less than six months can be used for detailed analysis of small landslides. Longer time-spans of up to one year or even several years can be used for measuring and monitoring some sites and large landslides, which do not require detailed pixel-to-pixel analysis.

Another limitation described in the East Iceland report was the inaccurate DEM avail-

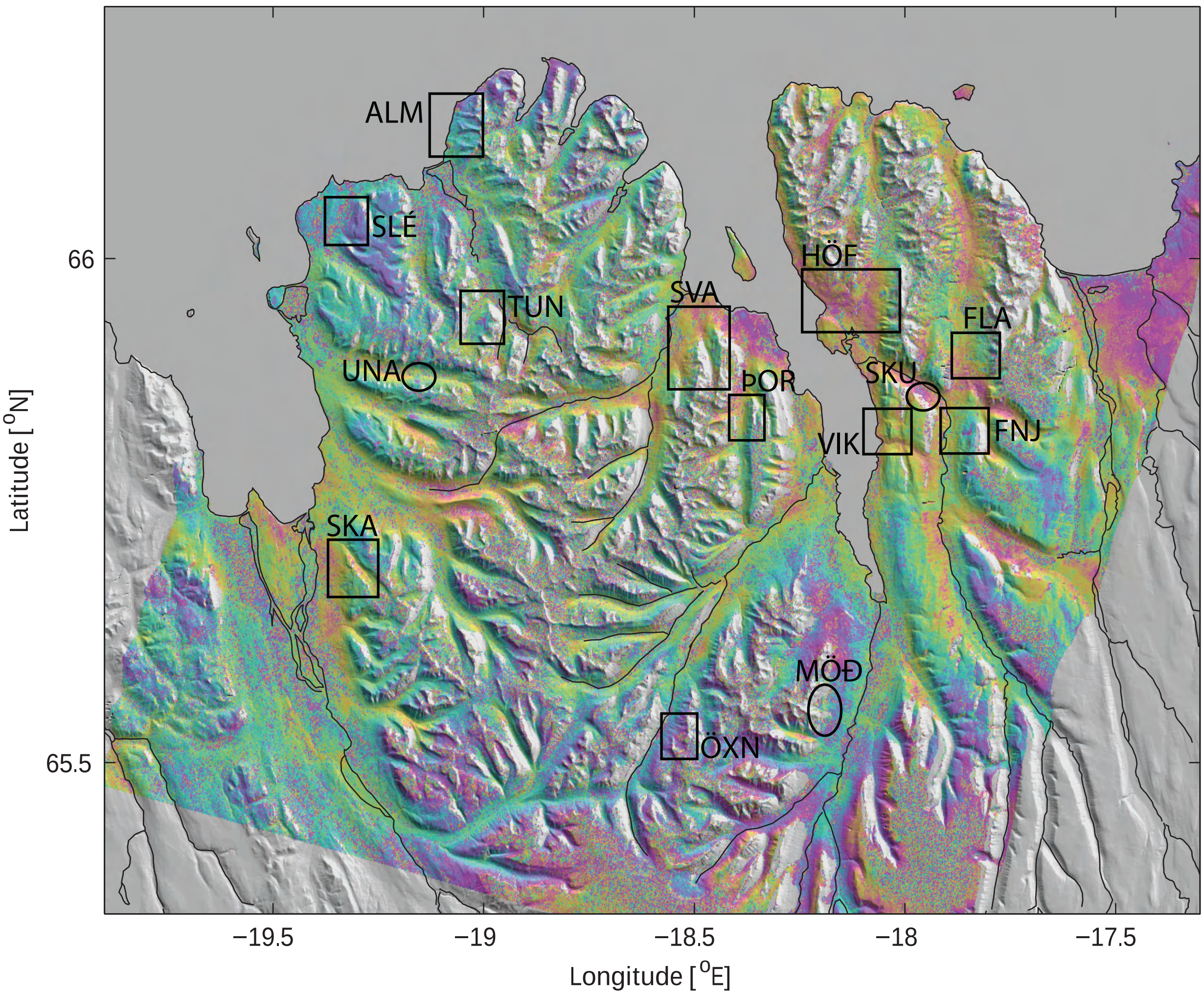


Figure 9. *Descending ERS interferogram of North Iceland (11 July - 19 September, 1995) showing locations where deformation was detected (in this and/or in other interferograms), see Chapter 4 for details. ALM - Almenningur, SLÉ - Sléttuhlíð, TUN - Tungudalur, UNA - Unadalur, SKA - Gljúfurárdalur in Skagafjörður, SVA - Svarfaðardalur, ÞOR - Þorvaldsdalur, HÖF - Höfðahverfi, FLA - Flateyjardalsheiði, SKU - Skuggabjörg, VIK - Víkurhólar, FNJ - Fnjóskadalur, MÖÐ - Möðrufellshraun, ÖXN - Öxnadalur.* ©*ESA.*

No.	*Data set*	*$B_\perp$ (m)*	*Δt days*	*Coherence*	*Siglufjarðarvegur*	Víkurhólar	*Other places*
	ERS-1/2						
13	950711-950919	59	70	Very good at all elevations	Yes	no	many locations
14	950919-950920	79	1	Excellent at all elevations	no	no	no
15	950920-961009	-14	385	Poor	Yes	1-2 cm	Sléttuhlíð
16	961009-970716	155	280	Rather poor	∼1 cm	2 cm	Sléttuhlíð, Höfðahverfi
17	961009-980805	-9	665	Poor	-	yes	Sléttuhlíð
18	970716-980805	-164	385	Fair	-	0-1 cm	several locations
19	970716-990616	-16	700	Bad	-	yes	-
20	980701-980805	404	35	Fair	-	-	-
21	980701-990825	15	420	Fair	yes	3 cm	Fnjóskadalur etc.
22	980805-990616	147	315	Poor	-	yes	-
23	990616-000809	8	420	Poor	-	∼3 cm	-
24	990825-000531	50	280	Rather poor	-	∼3 cm	Sléttuhlíð
	ENVISAT						
25	040609-040714	-178	35	Good below ca. 800 m	yes	no	Several locations
26	040609-050803	43	420	Fair	yes	yes	A few locations
27	040714-040818	-2	35	Very good	no	no	many locations
28	040818-040922	-778	35	Very poor	-	-	-
29	040818-050525	77	280	Bad above 2-300 m	yes	yes	a few locations
30	050525-050803	147	70	Poor	no	no	-

Table 2. *Same as Table 1, except for the 18 descending interferograms.*

able, which is the same as we have for North Iceland. This DEM has a resolution of 25 m $\times$ 25 m and was generated by interpolating digitized 20 m contours of 1:50000 maps from the National Land Survey of Iceland. Differential interferometric analysis revealed significant topographic residuals in the interferograms when the baselines were longer than about 300 m. A 30 m DEM error will result in a 1-fringe error in a 300 m baseline interferogram and although one would expect better accuracy from interpolating 20-m contour lines one needs to bear in mind that the contour lines themselves also contain errors. Therefore, I concluded that interferograms with baselines exceeding 200 m include too many topographical artifacts to be reliable for deformation measurements. This is a pity, because this excludes several of the processed interferograms, many of which may include valuable information if the topography could be correctly removed. But until a better DEM becomes available, this will remain a problem.

4 Observed Slope Displacements

In this Chapter I describe the observed deformation at the various locations in central-North Iceland. I begin by reporting my findings at the previously known Almenningur landslides, near Siglufjörður, and then move on to describe the results at other locations, first east of Eyjafjörður in Fnjóskadalur, Höfðahverfi, and in Víkurhólar, then west of Eyjafjörður, in Þorvaldsdalur, in Svarfaðadalur and at other locations, and finally further west in Sléttuhlíð and in Skagafjörður.

Only small subsets of the full interferograms are presented, focussed in each case on the area of interest, as it is impossible to display in this report format all the details of the full resolution interferograms that typically are about 5000×5000 pixels in size. Therefore, each interferogram was carefully examined using a high resolution monitor and any detected evidence for displacement was documented (Tables 1-2 and Appendix B). Then I extracted interferogram subsets with the focus on known landslide areas, such as in Almenningur, and on other areas where I detected displacements.

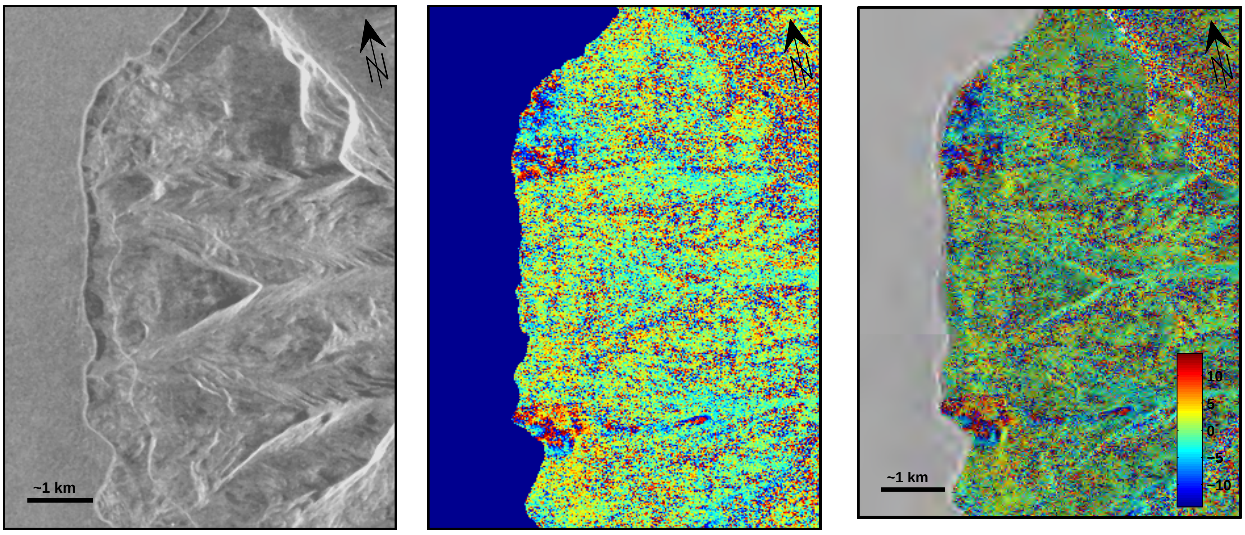


Figure 10. *Display example of an interferogram from Almenningur near Siglufjörður. The displayed image includes a SAR amplitude image (left) as a background shading for the interferometric phase observation (middle) and the result is a shaded interferogram (right).* ©*ESA.*

The results in the subsequent sections are mostly displayed in their original radar geometry (or radar coordinates) rather than in geographical coordinates. This is to keep the data as original as possible and to avoid losing signal details when the data are projected into geographical coordinates (geocoding), as it results in significant modifications of the data. To locate the observed signals the interferometric phase is overlain on a SAR amplitude image that shows strength of the radar returns, which is primarily a function of the surface roughness and the local slope. The resulting interferogram is a shaded color phase-image, where

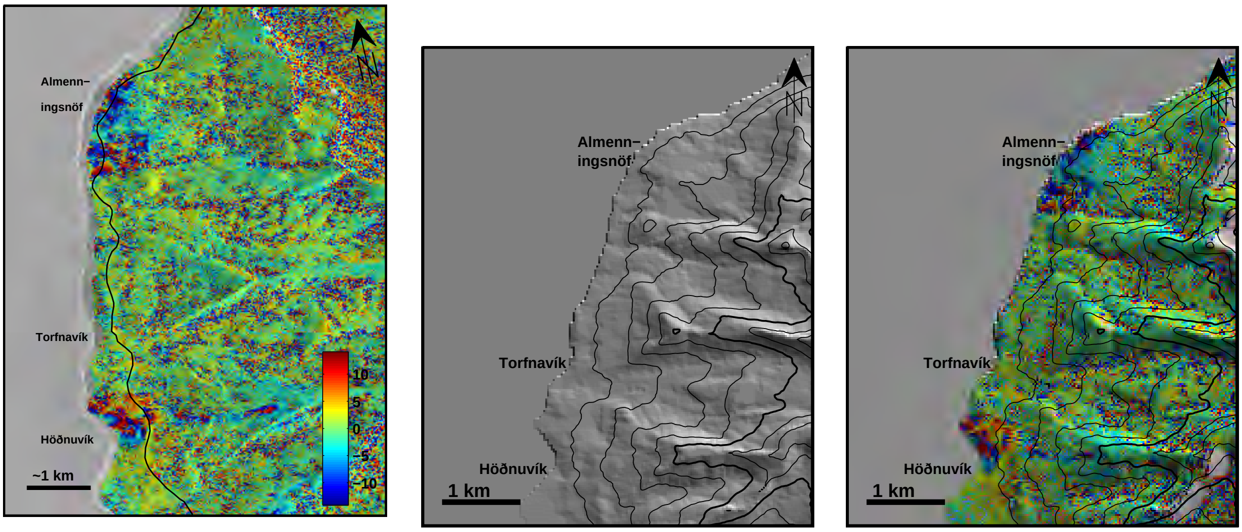


Figure 11. *Example of the postprocessing of an interferogram from Almenningur near Siglufjörður: Filtered interferogram (left), shaded relief map (middle), and a geocoded interferogram (right). ©ESA.*

the shading helps to put a reference to where displacements are taking place (Figure 10). Although I like to keep the data as original as possible, most of the subset interferograms displayed in the following sections have been somewhat post-processed. The post-processing involved adaptive filtering to reduce high-frequency noise in the interferograms as well as masking of ocean areas and sometimes other areas that were interferometrically completely decorrelated. Also, in some cases I geocode the interferograms to pin down the exact location of the detected deformation. Figure 11 shows an example from Almenningur (300×400 pixels) of the post-processing of an interferogram subset that is filtered, then geocoded and overlain on a shaded relief map (200×250 pixels). The geocoding projection of radar data from radar coordinates to geographical coordinates (Latitude/Longitude or UTM) involves significant interpolations and modifications of the radar data, especially in areas that are topographically rough like Central-North Iceland. However, most of the InSAR results in the following sections were not geocoded, but displayed as filtered and masked interferogram subsets in the original radar coordinates, i.e. like the left image in Figure 11.

The differential interferograms in this report are displayed wrapped with phase values in the range $[-\pi, \pi]$. This means for a half-wavelength of 56.6/2=28.3 mm (for ERS and similar for Envisat) the corresponding LOS displacement range is [-14, 14] mm, which is the color scale I use in the figures. The scale is defined as LOS displacement, rather than range change, meaning that a positive trend (green-red-blue) represents movement of the ground towards the radar (range decrease), i.e. uplift towards the radar, and a negative trend (green-blue-red) represents LOS displacement away from the satellite (range increase). In all interferograms the master scene is the image acquired on the earlier date, while the slave image is from a later date, and therefore the wrapped phase showing e.g. positive LOS displacement represents positive LOS displacement with time.

4.1 Almenningur near Siglufjörður

The deposits in Almenningur have been known to be actively moving for some time as signs of movements are clear in the area. Repeated repairs of the road to Siglufjörður have been needed in the past decades, especially after periods of significant precipitation. Figure 12 shows one of the locations along the road exhibiting meter-scale landslide movement since the surface of the road was last paved. These deposits have been described in great detail by *Guðmundsson* [2000].

Figure 12. *Looking south along the road from Siglufjörður town in Almenningur exhibiting meter-scale displacement of a portion of the road since its surface was paved.*

The Almenningur deposits are well imaged from descending orbits and clear signs of movement are detected along the road in most of the processed interferograms. Figure 13 shows three examples of interferograms of Almenningur. Two of the interferograms, one spanning 70 days in 1995 and the other 35 days in 2004, show clearly two main areas of active landslide displacement, one to the north in an area known as Almenningsnöf and the other on the north side of Höðnuvík inlet. The Almenningsnöf landslide appears to be almost 2 km wide along the coast, but narrower at higher elevations. Its maximum displacement appears to be near its southern and well defined edge (see close up in Figure 14). The pattern of displacement of the Höðnuvík landslide appears to be almost identical in these two interferograms, at least below the road (Figure 14). A notable difference, however, is that the 1995 interferogram also shows movement high up on Breiðafjall mountain. The middle interferogram in Figure 13 spans a much longer time period than the other two, or 420 days from 1 July 1998 to 25 August 1999. The lower portions of the Almenningsnöf and Höðnuvík landslides are decorrelated in this interferogram, almost certainly because the displacements are simply too large and chaotic. More subtle displacements, however, are visible higher on the Almenningsnöf landslide and possibly on the Höðnuvík landslide too, in areas where no visible movement was seen in the shorter-term interferograms. This indicates that the different portions of these two large landslides are moving at a different rate.

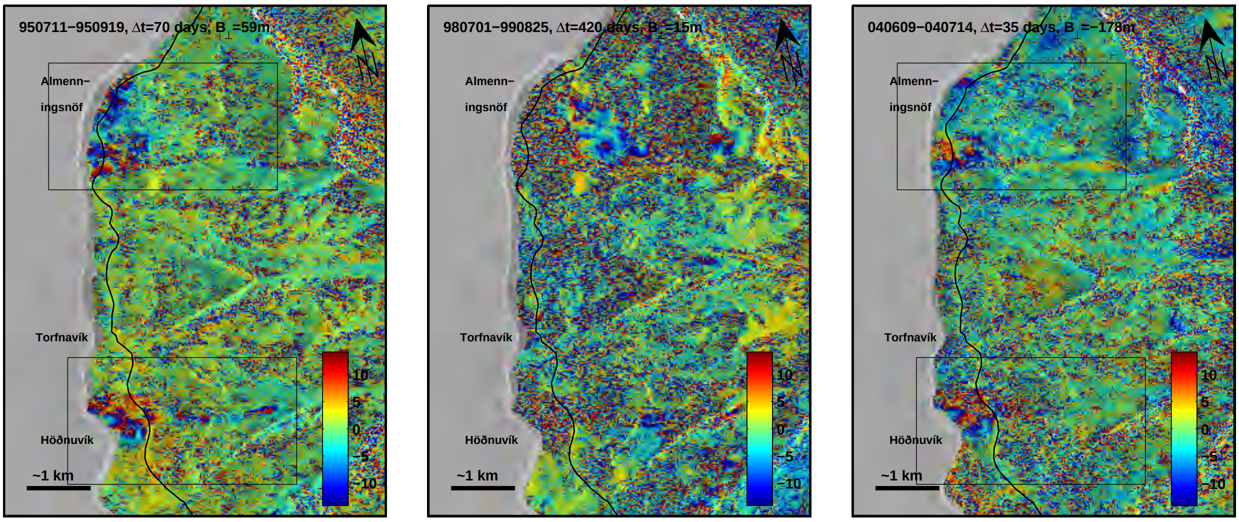


Figure 13. *Three interferograms of Almenningur spanning two months in 1995 (left), one year from 1998 to 1999 (middle) and one month in 2004 (right). The Siglufjörður road is marked as a black line.* ©*ESA.*

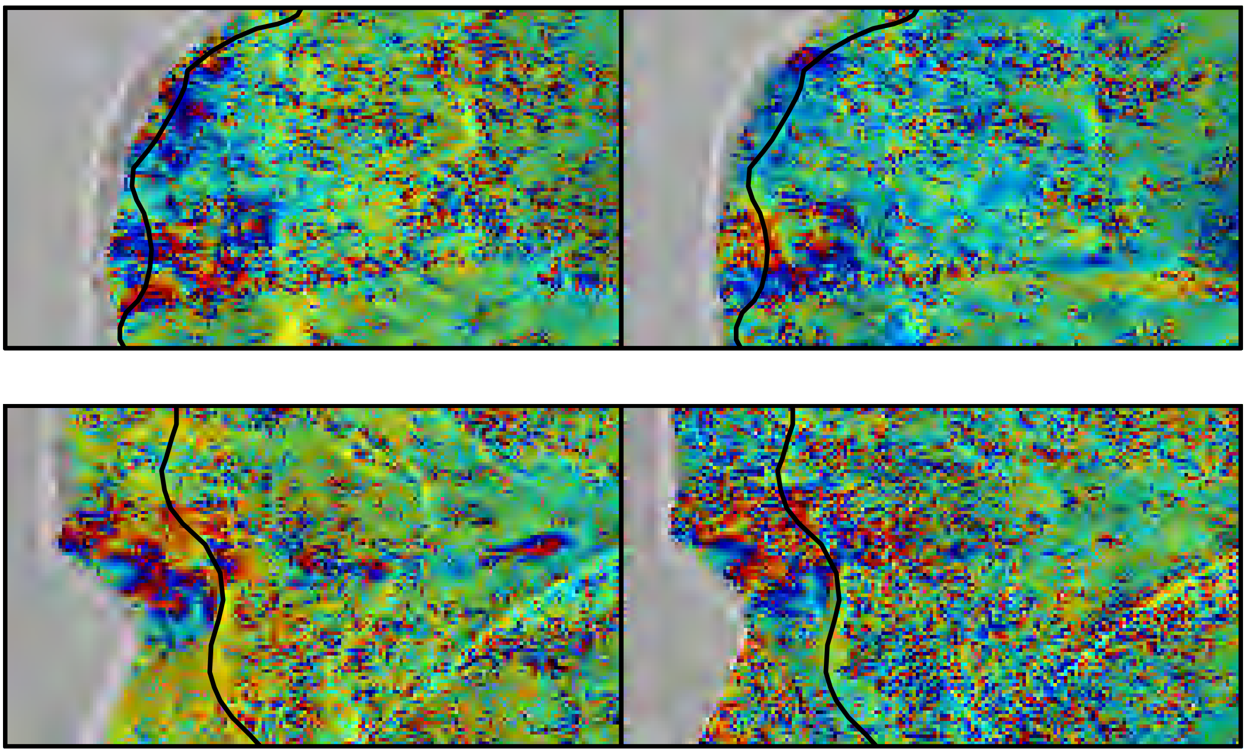


Figure 14. *Close-ups of the interferograms shown in Figure 13 showing Almenningsnöf (top panels) and the Höðnuvík site (lower panels). The interferograms span July-September 1995 (left) and June-July 2004 (right).* ©*ESA.*

In addition, it is clear that the motion of these deposits is not at a steady rate, because no significant displacements are found in the 35-day interferogram (July-Aug. 2004, not shown here) that follows the one shown to the right in Figure 13.

The extent of the two areas that are actively seen moving in the interferograms matches very well with the investigations of *Guðmundsson,* [2000, page 155], where he maps locations of "recent movement". In addition to the Almenningsnöf and Höðnuvík sites *Guðmundsson* [2000] maps signs of recent movements of a smaller area below Torfnakambur in Torfnavík (or Selvík). This site is not found to be moving in the 1-2 month interferograms but the one-year interferograms are mostly decorrelated at this location, which possibly is due to too much deformation.

4.2 Flateyjardalsheiði and Fnjóskadalur

Flateyjardalsheiði is a high valley or a pass connecting Flateyjardalur and Fnjóskadalur valleys. The Kinnarfjöll mountains on the east side of Flateyjardalsheiði rise up to 1200 m.a.s.l. and clearly exhibit loose deposits below the highest and steepest slopes (Figure 15). The most prominent deposits appear to be below and north of Uxaskarðsöxl and below the summits of Vigga and Sigga.

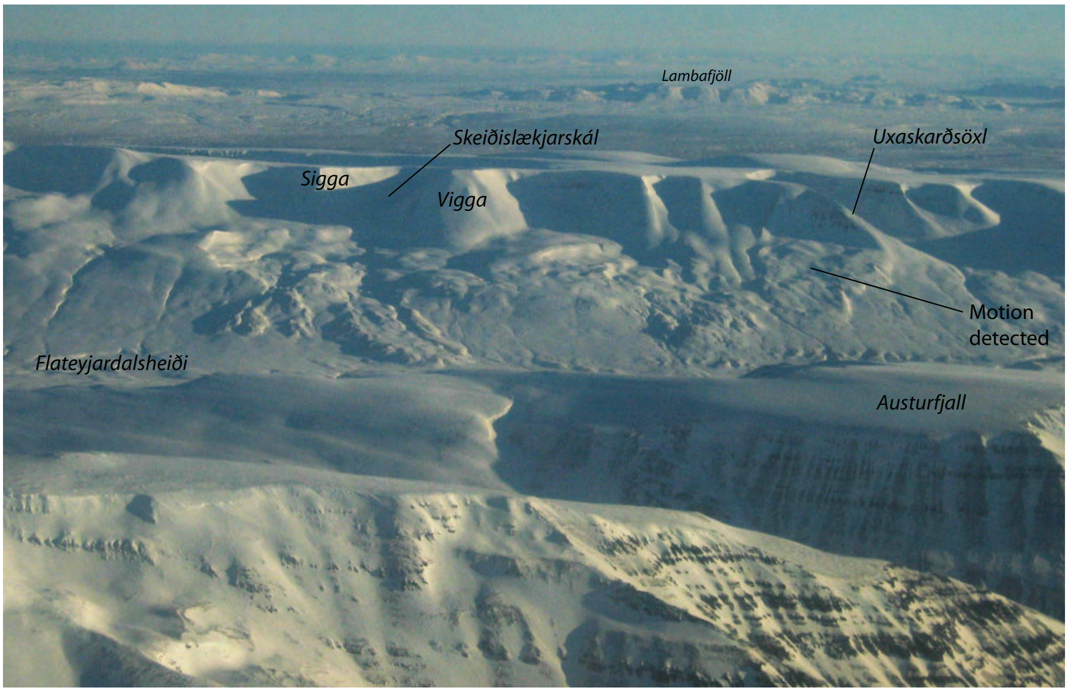


Figure 15. *Photograph taken from an airplane looking east to the slopes above Flateyjardalsheiði. In the foreground is Austurfjall, north of Dalsmynni. Several deposits can clearly be seen below Sigga and Vigga and near the Uxaskarðsöxl ridge. Surface displacements were only detected on the deposits farthest to the south under Uxaskarðsöxl.*

Several interferograms show motion of the deposits near Uxaskarðsöxl while the deposits further north appear stable. A 70-day interferogram spanning July-September 1995 shows clear movement of up to 2 cm (Figure 16) and a similar signal is seen during June-July 2004 (not shown here). Interestingly, however, no displacement is found on the landslide during the following month July-August 2008 (Figure 16). One-year interferograms are rather noisy in this area and usually provide only limited information, although signs of movement near Uxaskarðaöxl is seen in many of them. The clearest example of these one-year interferograms is shown in Figure 16 and it spans the time period from July 1997 to August 1998. This interferogram clearly shows displacements on the site near Uxaskarðsöxl although it is hard to judge the amount the displacement amplitude, but it is at least 3 cm. The extent of the moving area seems somewhat larger than in the 70-day interferogram from 1995.

The other locations where clear loose deposits exist, i.e. under Sigga and Vigga mountains do not appear to be moving during the the time periods the different interferograms span, despite that these deposits appear fresh looking and similar to the unstable deposits below Uxaskarðsöxl (Figure 15).

Landslide deposits above the farm of Böðvarsnes in Fnjóskadalur, about 5 km south of the Uxaskarðsöxl site, can be seen in a photograph taken in February 2007 (Figure 17), although the upper part of the deposits are in a shadow. A few interferograms show displacement at this site, including the example in Figure 18 spanning one-year from 1998 to 1999. This interferogram is rather noisy due to the long time-span, but still shows that the upper part of the landslide appears to move by 1-2 cm and the lower part possibly more, although that part of the landslide is mostly decorrelated. This site exhibits movements during summer of 1995, while no visible motion is seen in 1997-1998 and 2004-2005.

The Böðvarsnes landslide is described in detail by *Jónsson* [1976, page 203]. He reports that the deposits look very fresh in some places that cracks can be seen at the various locations as well, which he interprets as being clear signs of recent or ongoing movement. He also reports that the farmer in Böðvarsnes farm had often found new cracks and realized that old ones had closed, a further indication of active movement. The clearest sings of movement in the interferograms is found rather high on the landslide, where the slope is relatively gentle (Figure 18) and higher than where *Jónsson* [1976] described fresh looking cracks. However the lower parts of the landslide are decorrelated in most of the interferograms, possibly due to fast displacement rates on this part of the deposits.

4.3 Höfðahverfi

Höfðahverfi is the area near the village of Grenivík on the eastern side of Eyjafjörður. Three locations of active surface deformation were detected in this area in several short-term interferograms. One location is above the farm of Hléskógar, below a ridge called Benidiktskambur, and appears to be moving by as much as 5 cm in a 70-day interferogram from summer of 1995 (Figure 19). The movement appears somewhat chaotic with the largest amount of movement near the top of the deposits, at an elevation of 400-500 m, with a tongue extend-

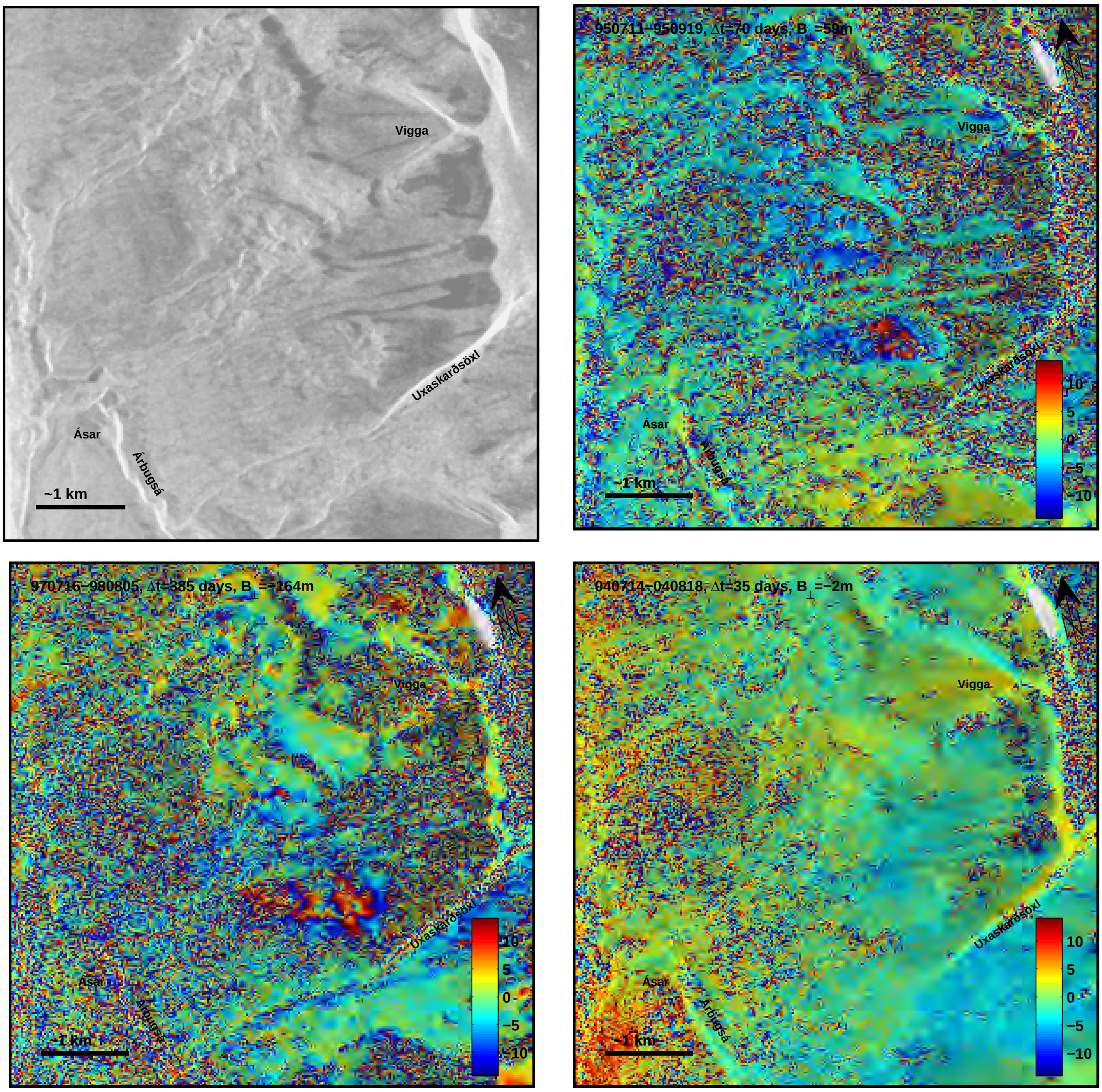


Figure 16. *A radar amplitude image (top left) and three interferograms of Flateyjardalsheiði. The 70-day interferogram from 1995 (top right) shows clear signs of displacements near Uxaskarðsöxl, while the 35-day interferogram from 2004 (bottom right) exhibits no measurable deformation. The one-year interferogram from 1997-1998 (bottom left) is noisier due to the longer time-span but clearly shows deformation below Uxaskarðsöxl ©ESA.*

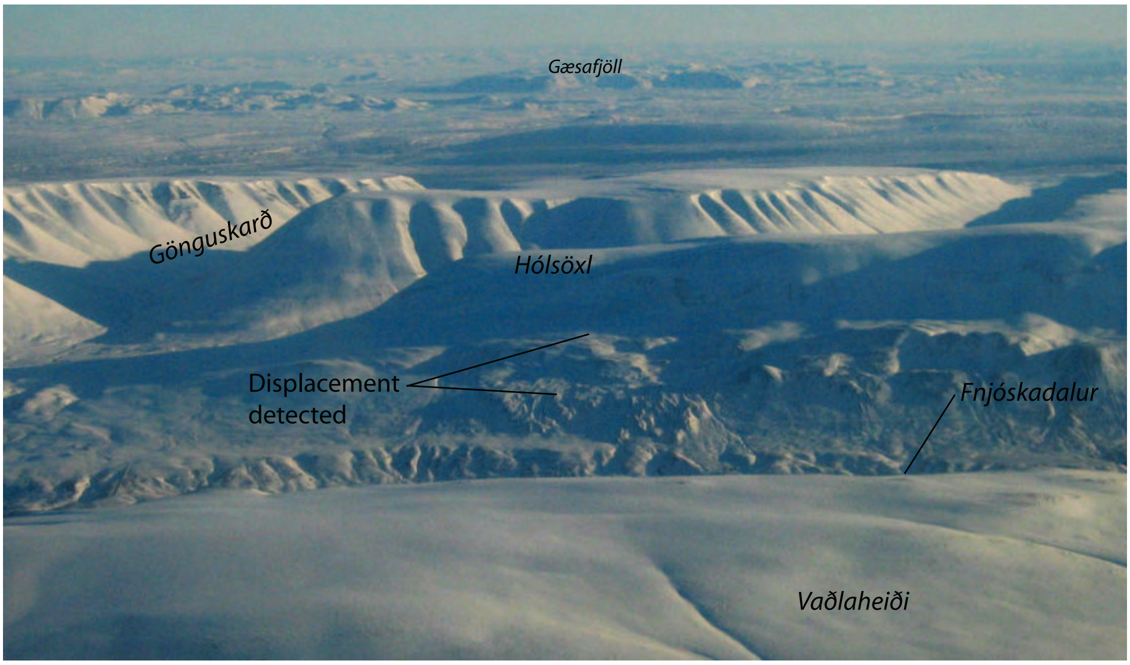


Figure 17. *Looking east over Vaðlaheiði towards Hólsöxl on the east side of Fnjóskadalur valley. Loose deposits can be seen under Hólsöxl, above and north of the farm Böðvarsnes, and they appeared to be moving in some of the processed interferograms.*

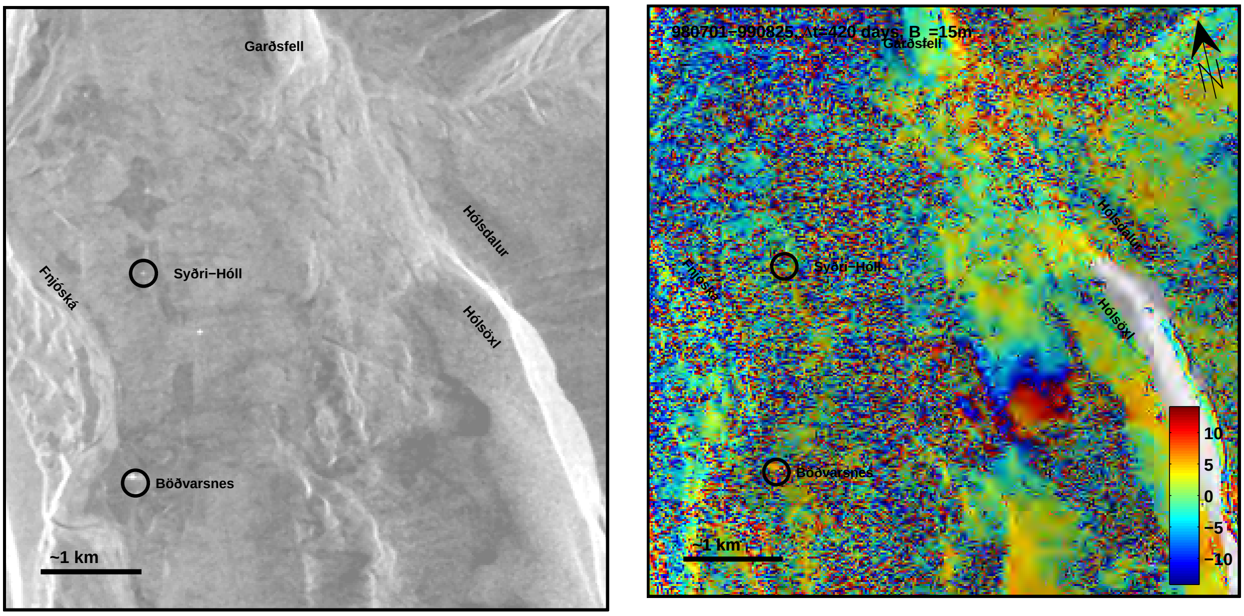


Figure 18. *SAR amplitude image (left) and a one-year interferogram of Hólsöxl in Fnjóskadalur. This 1998-1999 interferogram shows displacements above the Böðvarsnes farm.* ©*ESA.*

ing to the southwest to elevations of about 200 m.a.s.l. This site is seen moving in most of the processed descending interferograms, e.g. clearly in the two 35-day interferograms from 2004.

Another location is on Leirdalsheiði, above an area called Grásteinsmóar. This area appears fairly large, or about 1 km wide and is moving as much as 2-3 cm in the July-September 1995 interferogram (Figure 19). These deposits exhibit movements in some of the longer-term interferograms, e.g. in 1998-99, but appear to be moving in fewer interferograms than the ones under Benidiktskambur. For example, they do not show any significant surface displacements in the interferograms from summer of 2004. The altitude of the area is between 400 and 600 meters.

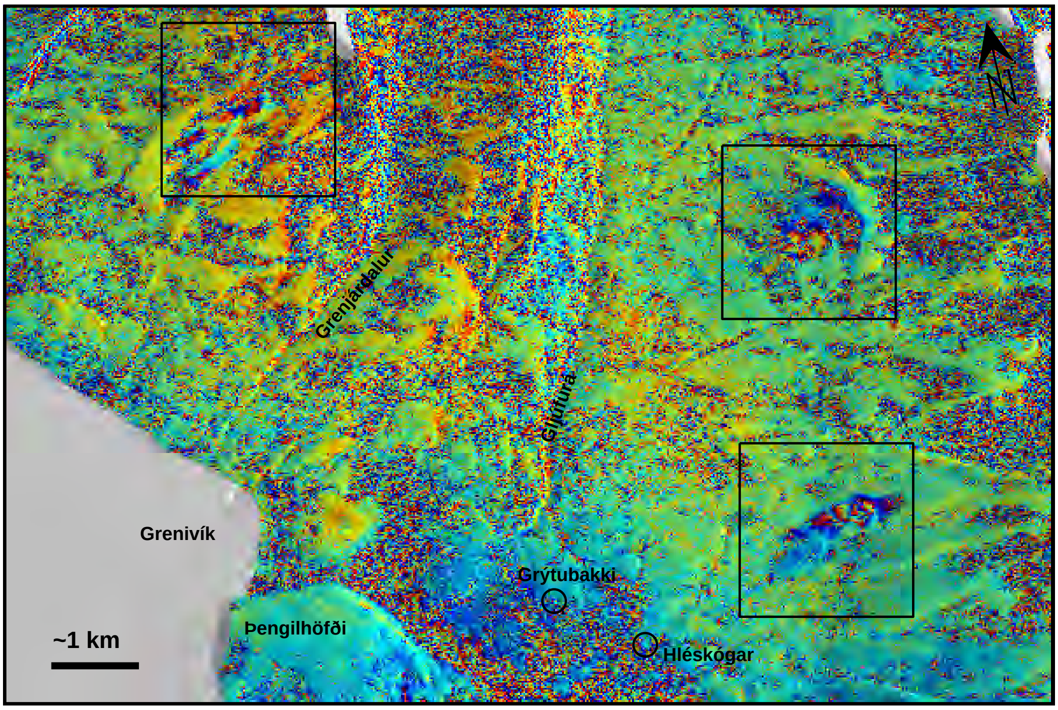


Figure 19. *Interferogram (July-Sept. 1995) from Höfðahverfi showing movement at three locations: Above Hléskógar (bottom right), on Leirdalsheiði (top right) and Kaldbakur (left).*

The third location that exhibits surface displacement in many of the interferograms is high on Kaldbakur mountain, north of Grenivík village and Grenjardalur gully, above two small lakes called Leynitjörn and Lýsistjörn. This signal is somewhat unclear in the interferogram from 1995 (Figure 19). However, signs of movements are seen in all processed interferograms that are coherent in this area, which lies relatively high, or between 600 m and 1000 m.a.s.l. The displacement pattern is particularly clear in an interferogram spanning July to August 2004 (not shown here), showing a narrow band of movement, only about 500 m wide and more than 1 km long. The maximum amount of displacement appears to be about 2 cm during that month.

4.4 Víkurhólar in Eyjafjörður

The Víkurhólar hills are deposits on the eastern shore of Eyjafjörður, just north of the Víkurskarð pass. This site can clearly be seen from the other side of the fjord or from the Víkurskarð road, as the deposits are remarkably distinct, extending from a bowl on Ystuvíkurfjall mountain down to the sea, where they form an arcuate shoreline into the fjord (Figure 20). The geomorphology of these deposits has been detailed by *Jónsson* [1976] and he estimated its area to be 2.5 km^2 and its volume 50×10^6 m^3. High cliffs on the Ystuvíkurfjall mountain mark the bowl and Jónsson [1976] describes clear cracks on the top of the mountain, near the edge of the cliffs. One of these cracks is 450-500 m long and only 15-60 m from the edge. *Jónsson* [1976] believes the cause of the instability of this landslide is related to a fault that runs through Ystavíkurfjall mountain and can be seen on the south side of the Kræðufjall mountain to the north of the Víkurhólar landslide. The fact that the deposits reach into the fjord has caused some concern that they could potentially generate a tsunami, threatening Akureyri and other towns in Eyjafjörður [*Davíðsdóttir,* 2008].

Figure 20. *Photograph looking east towards the Víkurhólar deposits. The road across the deposits can be clearly seen as well as the road up to the Víkurskarð pass on the right.*

Víkurhólar hills are seen moving in several interferograms that span one year or more. Shorter-span interferograms, e.g. 35 or 70-day interferograms, do not exhibit visible displacements in Víkurhólar (Figure 21, top), showing that these large deposits are moving at a slower rate than many other sites described in this report. Interferograms spanning about one year, i.e. from one summer to the following summer, show displacements of up to 3 cm on the Víkurhólar deposits. The pattern of displacement is similar from one year to another and shows that the northern half of the landslide is moving faster than the southern half, with the southernmost part of the deposits not moving at all. The northern edge of the moving area is very well defined and can be seen as a straight line in many of the interferograms (e.g. Figure 21, bottom-middle panel). The southern boundary of the moving area, on the other hand, appears irregular and is not as clearly detectable as in the north. The maximum displacement rate is usually found above the road crossing the landslide and it seems to fluctuate somewhat from one year to another. The maximum rate is 1-2 cm/year in 1995-96, around 2 cm/year in 1996-97, less than 1 cm/year in 1997-98, but around 3 cm/year in 1998-2000 (Figure 21). The rate revealed by the Envisat interferograms shows again slower rate for 2004-05, or about 1 cm/year. These results are summarized in Table 2.

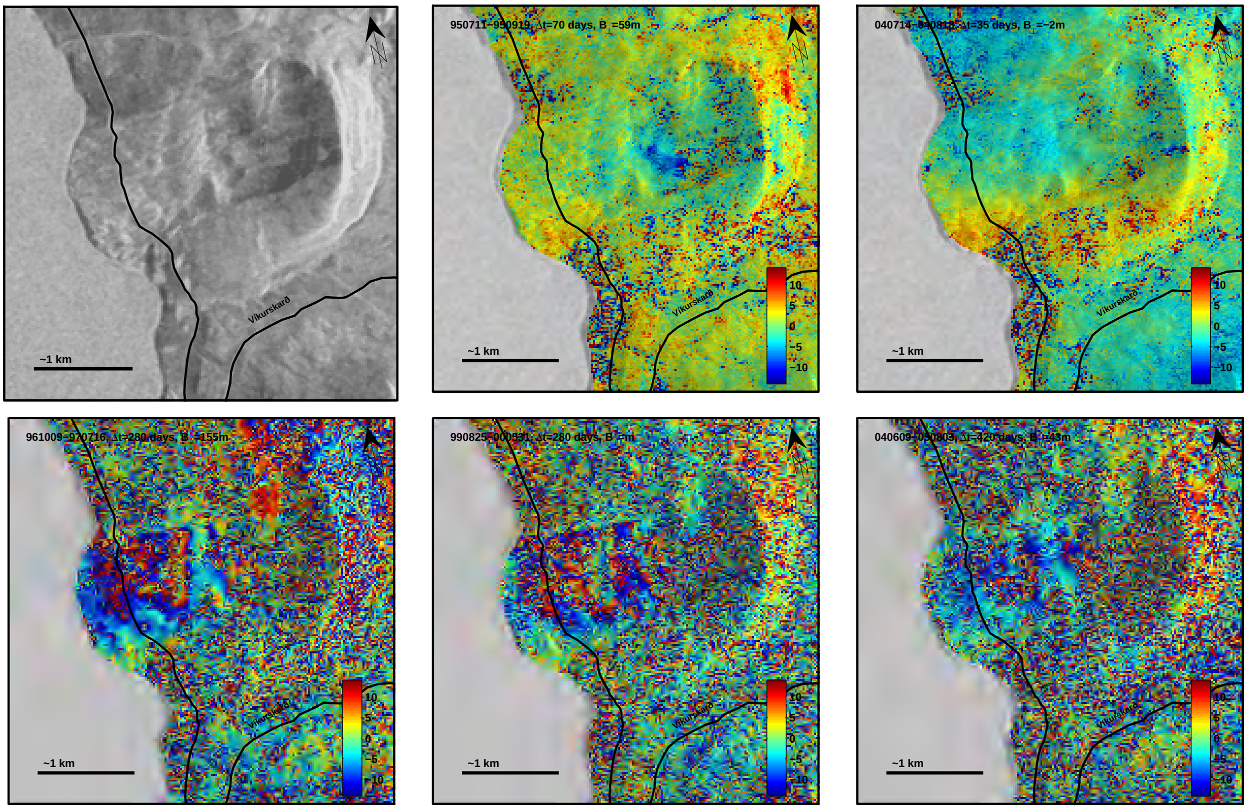


Figure 21. *SAR amplitude image (top left) and five interferograms of Víkurhólar in Eyjafjörður, two spanning only 70 and 35 days (top middle and right) and three spanning about a year in 1998-99, 1999-2000, and 2004-05 (bottom).* ©*ESA.*

It is interesting to compare this pattern of movement to the geomorphological description by *Jónsson* [1976]. He states that the northern edge of the landslide is marked by a relatively straight and well defined gravel ridge, while the southern edge is not as clearly defined. He also mentions that the total displacement of the southern part of the landslide is clearly not as large as the northern part. This description agrees very well with the current displacement pattern, that shows more displacement in the north and a clearly defined northern boundary of the moving part of the deposits.

4.5 Kirkjufjall in Öxnadalur

One site of mass movement was detected in Öxnadalur valley under the mountain of Kirkjufjall. This site is south of the farms Hraun and Engimýri, above an abandoned farm called Fagranes. High on the Kirkjufjall mountain some displacements can be seen in the shorter-term descending interferograms spanning 1-2 months. The area that is moving is under the high summit of Kirkjufjall (1274 m.a.s.l) at elevations between 800 m and 1100 m, just north of a small tributary valley called Kirkjufjallsdrag (Figure 22). The pattern of displacement shows two tongues of movement; the southern tongue is larger and moving about 1 cm in this image, the northern tongue is smaller but appears to be moving faster, with a maximum displacement of at least 2-3 cm. The interferogram is decorrelated on the top of Kirkjufjall and at elevation above 1100 m to the south of the summit. Otherwise the west-facing slopes of Kirkjufjall are nicely coherent, but do not exhibit any other detectable movement.

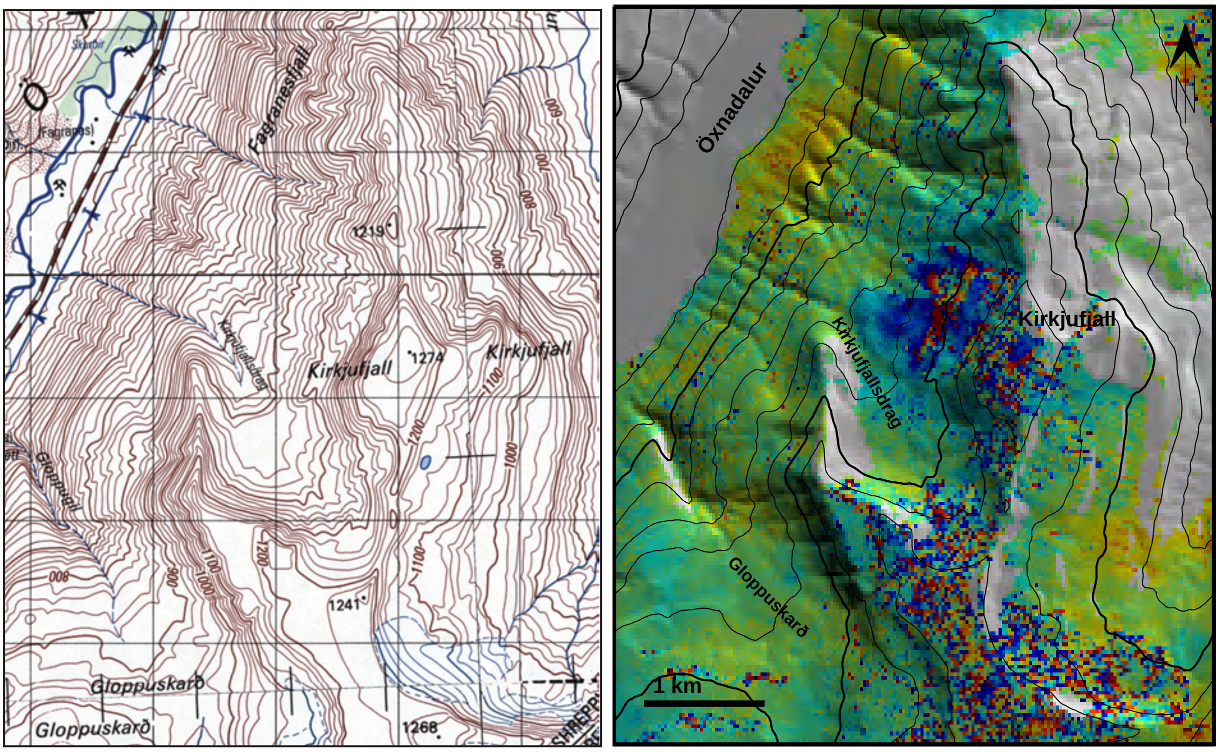


Figure 22. *Map and a geocoded interferogram (July-August, 2004) of Kirkjufjall in Öxnadalur showing deformation near Kirkjufjallsdrög with 2-3 cm maximum LOS displacement. Both 100 m and 500 m (thick) elevation contour lines are shown. ©NLSI and ESA.*

Radar amplitude image of this area in radar coordinates shows that rough surface materials exist at the site of the detected movement resulting in relatively strong backscatter (Figure 23). When the July-August (2004) interferogram, which is shown in map geometry in Figure 22, is inspected in the more detailed radar geometry, one can see that the maximum displacement in this image may exceed 3 cm and may exceed two fringes locally, or

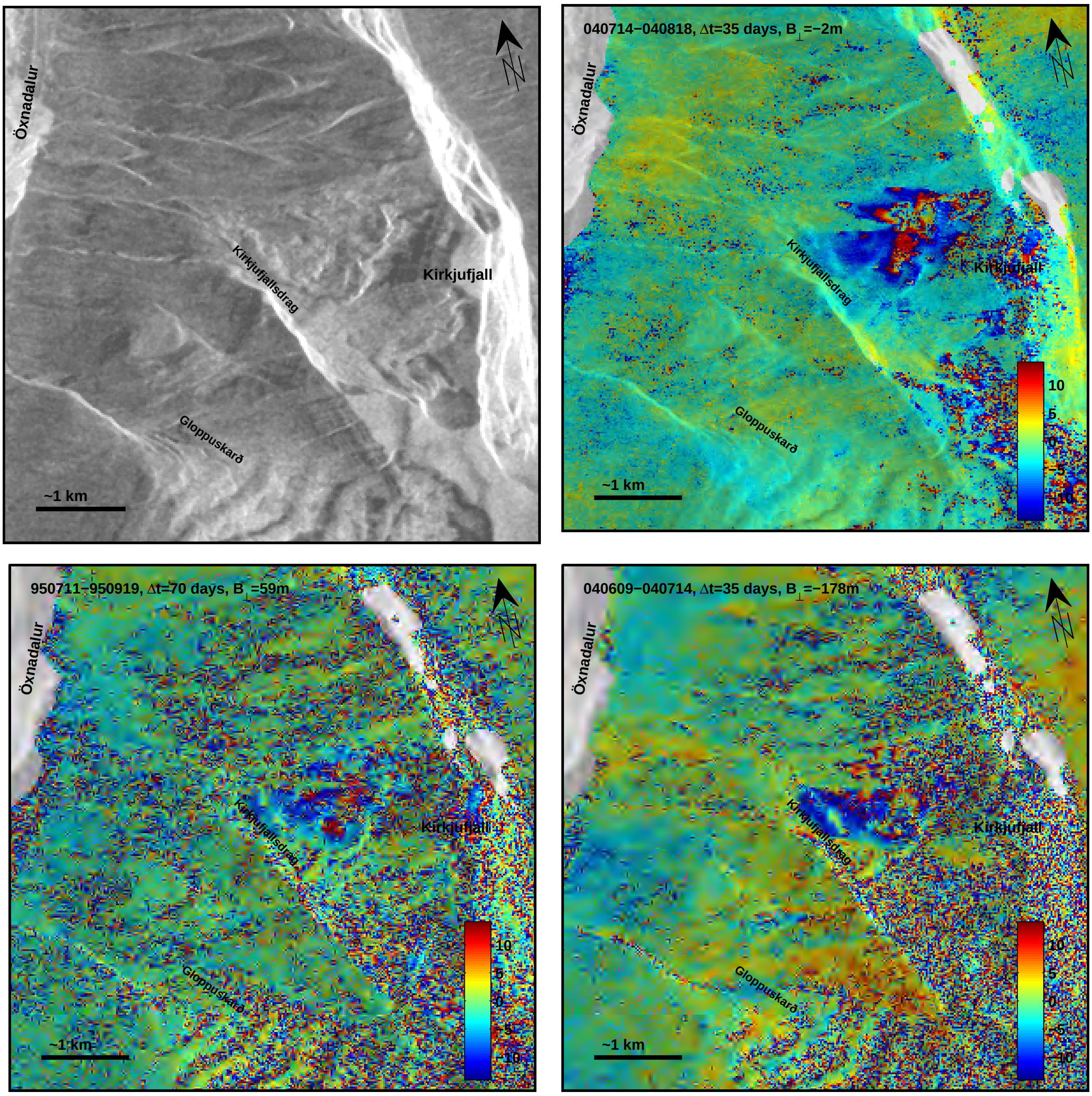


Figure 23. *Amplitude image and interferograms of Öxnadalur. A 35-day interferogram (July-August, 2004) shows deformation in Kirkjufellsdrög in the radar-geometry (same as in Figure 24). Two other interferograms spanning 70 days in 1995 (bottom left) and June-July 2004 (bottom right) also show displacements at this site.* ©*ESA.*

about 6 cm. Two other shorter-term interferograms also show displacements in this area, although their quality is lower. The 70-day interferogram from 1995 shows a similar pattern of movement as the July-August 2004 interferogram, depicting the two tongues of the moving deposits. The June-July interferogram from 2004 also shows displacements on the landslide, but the upper parts of the deposits and Kirkjufjall mountain are decorrelated, presumably due to high-elevation snow. Many of the one-year interferograms also show displacements in this area but most of these interferograms are too incoherent to provide useful information.

4.6 Þorvaldsdalur

Þorvaldsdalur is an uninhabited valley on the west side of and parallel to Eyjafjörður, connecting Hörgárdalur valley in the south and Árskógssandur in the north. The valley is a home to several deposits that have been described in the catalogue of *Jónsson* [1976] and among these are Hrafnagilshraun and Hesthraun (Figure 24) on the east side of the valley on Vatnshlíðarfjall mountain (*Jónsson,* 1976, pages 265-274). Hrafnagilshraun, in particular, is seen moving in several short-time spanning interferograms (Figure 25). An interferogram from July-August 2004 shows clearly localized movement on this landslide with an amplitude of about 2 cm during the 35 days the interferogram spans. The geocoded version of this interferogram shows that the deformation is concentrated at an elevation of about 400 m, or some 200 m above the valley floor (Figure 24), but not at the lower parts of the deposits. Two other interferograms, spanning 70 days in 1995 and June-July in 2004 also show clear signs of movement on this landslide (Figure 25, bottom) and in these cases the moving area is larger and the amplitude of movement as well. However, the displacement pattern on the landslide appears chaotic in both cases, showing that the landslide deposits are not moving in a coherent fashion like a one large block, but rather that different parts of the landslide are moving at a different rate. The 1995 interferogram also suggest a small amount of deformation on the Hesthraun deposits further to the south (Figure 25, top right).

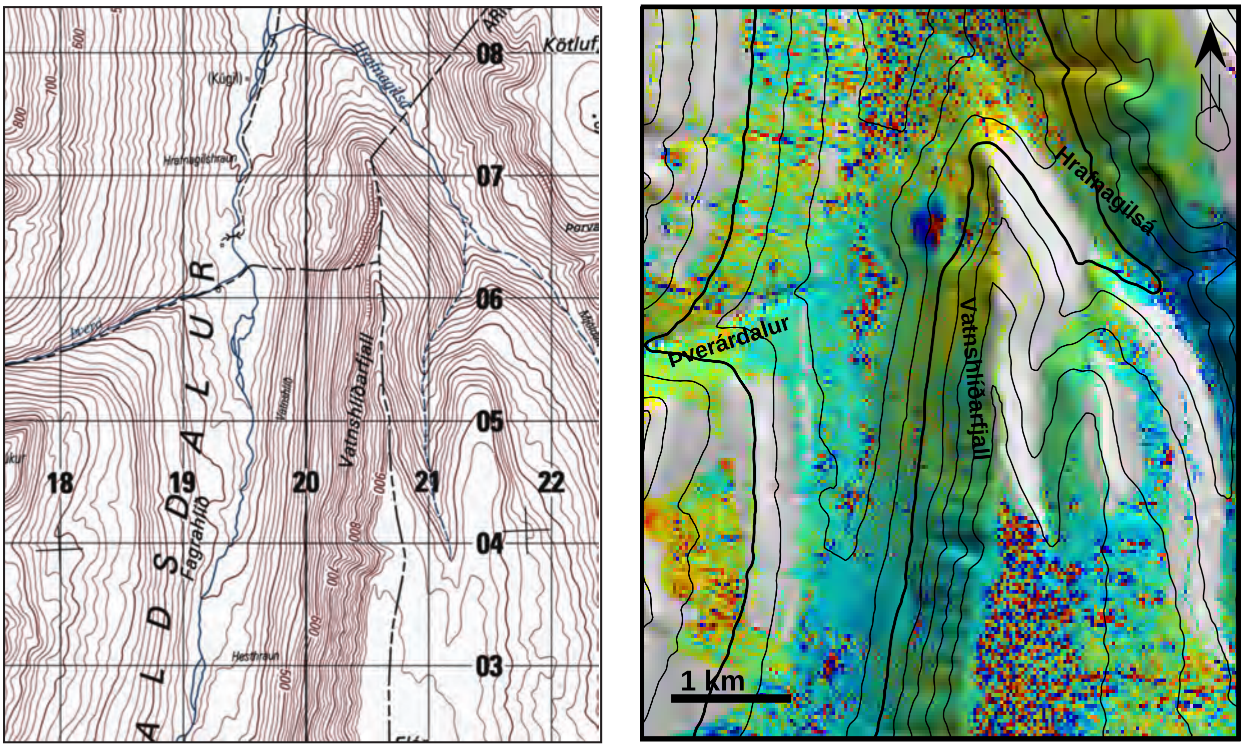


Figure 24. *Map and a geocoded interferogram of Þorvaldsdalur. The 35-day interferogram (July-August, 2004) shows deformation of Hrafnagilshraun. The interferogram has 100 m contour lines with the 500 m line displayed thick. ©NLSI and ESA.*

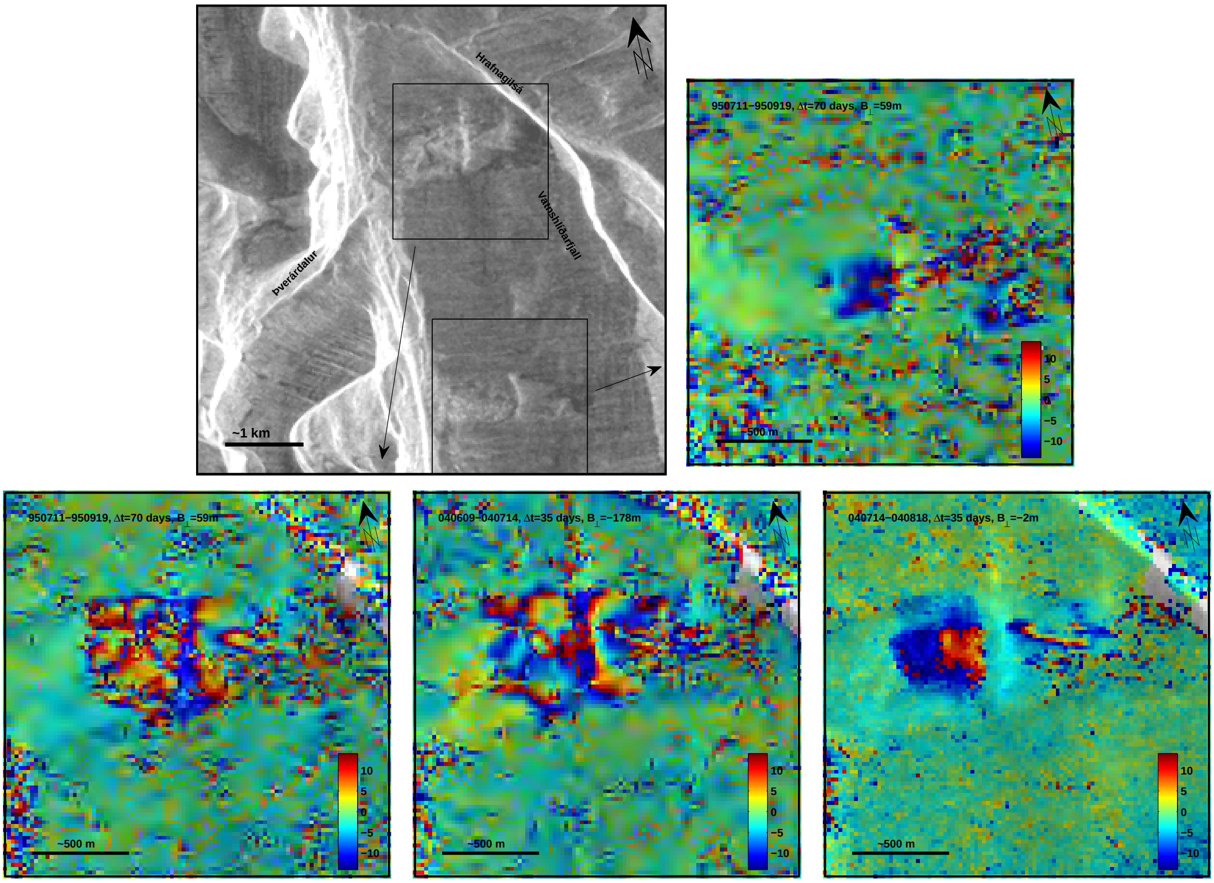


Figure 25. *Amplitude image and interferograms of Þorvaldsdalur. The July-August (2004) interferogram is here shown in radar coordinates (it is in map coordinates in Figure 24) and it shows clear deformation on Hrafnagilshraun (bottom right). Two other interferograms spanning 70 days in 1995 (bottom left) and June-July 2004 (bottom middle) show stronger displacements at the same site as well as hint of displacement further south near Hesthraun (top right). ©ESA.*

4.7 Svarfaðardalur

Svarfaðardalur valley is on the western side of Eyjafjörður, extending to the southwest from the sea near the village of Dalvík. *Jónsson* [1976] has documented numerous deposits in Svarfaðardalur and its tributary valleys and some of them are quite large, e.g. the so called Hvarfið, between the farms of Ytra-Hvarf and Syðra-Hvarf. Despite the many deposits that exist in this valley, I have only detected movement on sites in Hálsdalur and Hofsdalur, two tributary valleys on the east side of Svarfaðardalur, near its northern end.

The shorter-term (35 or 70 day) interferograms show a reasonable degree of coherence at these sites when conditions are snow free, but most inter-annual interferograms are two noisy for extracting useful information about the movement at these sites. The July-August (2004) Envisat interferogram proves here to be the least noisy example, as in many of the other cases in this report, showing a clear displacement signal at one site (possibly two) in Hálsdalur (Figure 26, top left). The same interferogram is also shown in map coordinates to localize where these signal are seen and there one can see that the most prominent landslide motion is takes place between 600 and 800 m.a.s.l. The very different appearance between the geocoded interferogram and the one in radar coordinates is in this case a result of the dramatic topography in and around Svarfaðardalur. Two other interferograms hint at displacements in Hólsdalur, although these data sets are more noisy than the one from July-August 2004 (Figure 26). *Jónsson* [1976] describes large deposits near the northern end of Hálsdalur that are called Ripplar. However, the detected displacements in the interferograms do not correspond to the Ripplar site, as movement is found higher and further south.

The interferograms also exhibit mass movement in Hofsdalur, which is another tributary valley to the southwest of Hálsdalur. While limited displacements are seen in the July-August (2004) interferogram, the July-September (1995) data shows displacements at two locations (Figure 26). One location is to the north in a small bowl, right below the summit of Dagmálahnjúkur, while no displacements are seen in the more prominent Hofsskál bowl, which is one of the three sites in Hofsdalur that was documented by *Jónsson* [1976]. The other two sites he describes are Hraunskál on the eastern side of the valley and Hofsárhraun on the western side (not imaged in the descending viewing geometry). The southern location in Hofsdalur, where movements are seen in the July-September interferogram, seems to correspond to the Hraunskál site documented by *Jónsson* [1976]. The displacement signal is quite noisy, but it must be about 2-3 cm of LOS displacement in an area that is 500-800 m wide (Figure 26, bottom left).

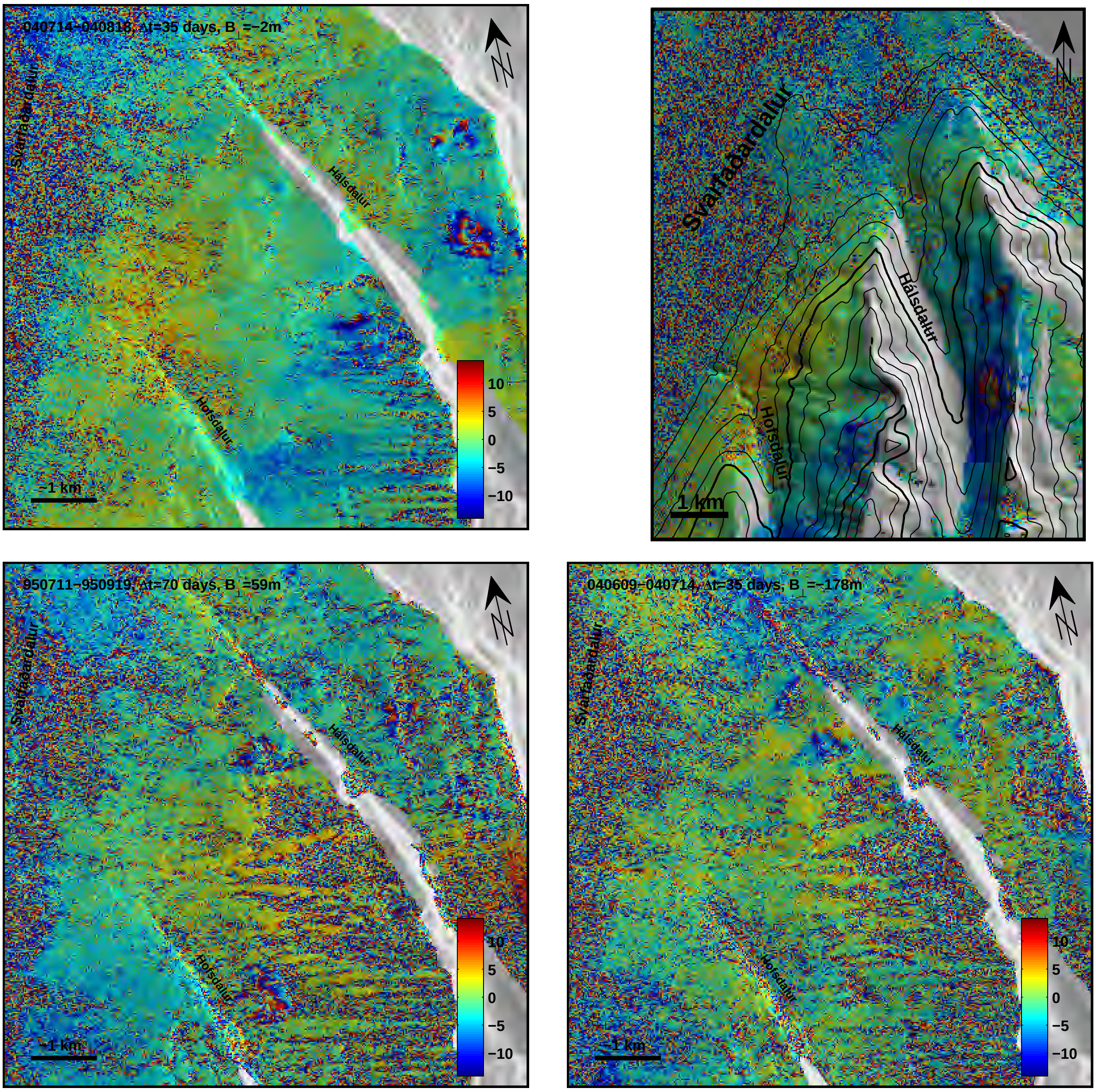


Figure 26. *Interferograms of Svarfaðardalur. A 35-day interferogram (July-August, 2004), both in geographic and in radar coordinates (top). Two other interferograms spanning 70 days in 1995 (bottom left) and June-July 2004 show the same area in radar coordinates (bottom).* ©*ESA.*

4.8 Tungudalur

Tungudalur is a small uninhabited tributary valley southwest of Stífluvatn Lake in the Fljót district. The valley is only 5-6 km long and surrounded by 1000 m high mountains and it opens out to the lake. Large deposits dam the main valley in front of Stífluvatn and these deposits have their origin from Hvammshnjúkur mountain [*Jónsson,* 1976]. No measurable deformation was detected in the processed interferograms on these extensive deposits in front of the lake. However, motion was seen on the east side of Tungudalur Valley in many interferograms, under the mountains of Hrafnahnjúkur and Lambahnjúkur. Extensive deposits cover this slope and they exhibit complicated and variable movement patterns [*Guðmundsson,* 2000].

Figure 27 shows a map of Tungudalur Valley and a 35-day interferogram from 2004 in mapping coordinates to localize the deformation well. It shows a small deformation signal at an elevation of 600 m below and between the two summits. The same interferogram is shown in Figure 28 where this small deformation signal is seen a bit better, indicating about 2 cm of LOS displacement during this month. A much larger area is seen moving in the other two short-term interferograms (Figure 28, bottom), with large area moving about 1 cm but a localized area moving as much as 2 cm in both cases. The displacement patterns are quite similar between these two interferograms, but the noise level is higher than in the first interferogram presented at this site.

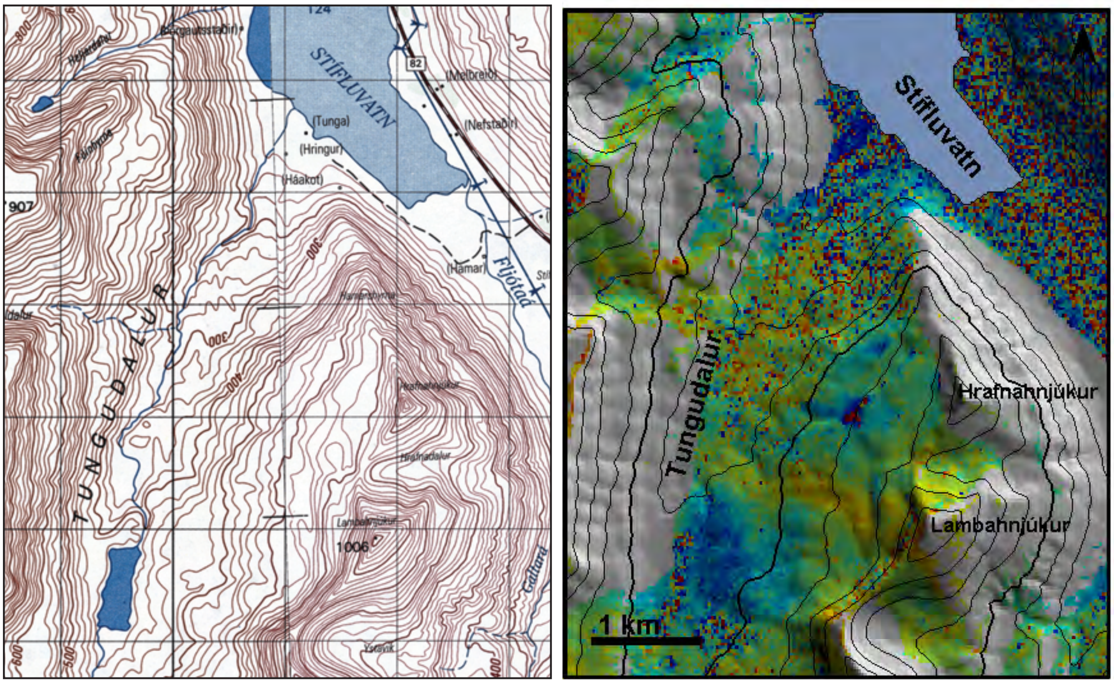


Figure 27. *Map and a geocoded interferogram (July-August, 2004) of Tungudalur near Stífluvatn showing deformation below Hrafnahnjúkur at 600 m.a.s.l. The interferogram has 100 m contour lines with the 500 m line displayed thick.* ©*NLSI and ESA.*

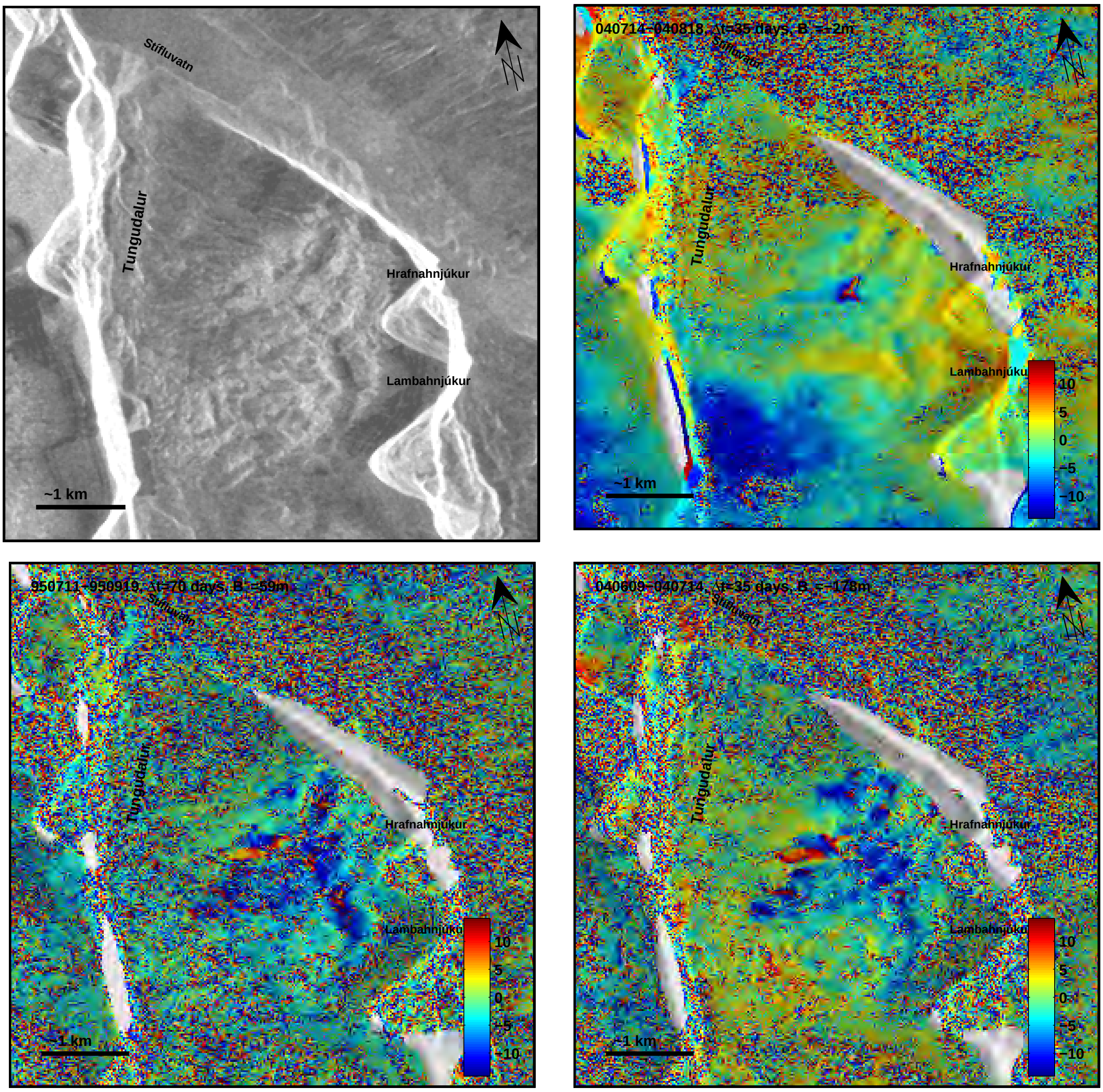


Figure 28. *SAR amplitude image and interferograms of Tungudalur. The 35-day interferogram (July-August, 2004) is the same as in Figure 27, except it is here in radar coordinates. Two other interferograms spanning 70 days in 1995 (bottom left) and June-July 2004 (bottom right) show stronger displacements a the same site. ©ESA.*

4.9 Sléttuhlíð

Sléttuhlíð is on the east side of Skagafjörður, between the Fljót district and the village of Hofsós. East of Sléttluhlíðarvatn Lake and above a farm called Hraun are large deposits, below a mountain called Hraunsöxl or Hyrna. These deposits were described by *Jónsson* [1976] and he estimated their area to be 2.4 km^2 and the volume 50×10^6 m^3. Figure 29 shows a map of the area and a geocoded one-year interferogram as well (2004-2005). The interferogram appears coherent in many places but almost completely decorrelated between the lake and Hraunsöxl mountain. The same interferogram in radar coordinates, however, shows a clear localized signal southeast of the lake, indicating about 3 cm of LOS displacement on this part of the deposits during the whole year (Figure 30, bottom right). The spatial extent of this signal is a bit difficult to determine precisely because the one-year interferograms at this location are widely incoherent. However, it is clear that only a small part of the large Sléttuhlíð deposits are moving, as they extend over a much larger area.

This part of the deposits is also seen moving in several other one-year interferograms, e.g. in 1997-98 (Figure 30, bottom left), with a similar displacement pattern and displacement magnitude. Shorter term interferograms, on the other hand, like the the 70-day interferogram from 1995 (Figure 30, top right), exhibit little or no displacement. The large areas that are completely decorrelated in the 70-day interferogram probably correspond primarily to agricultural fields that were worked during the observation period.

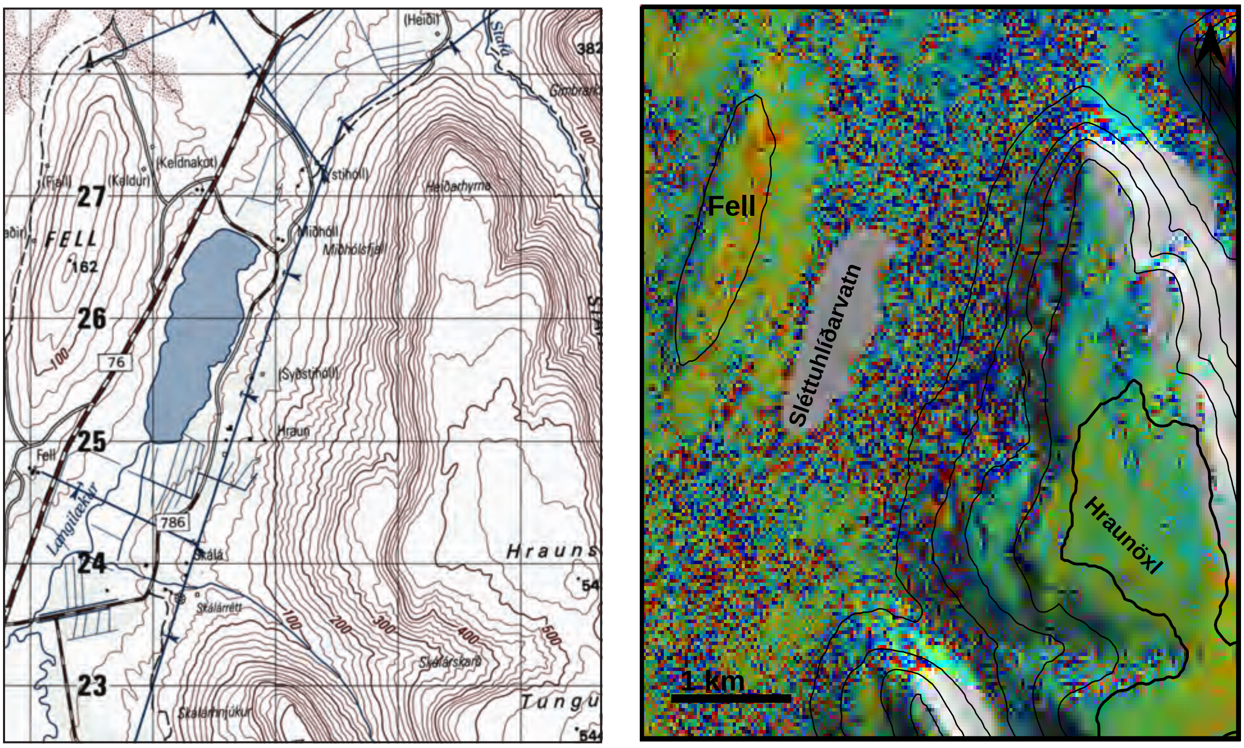


Figure 29. *Map and a geocoded one-year interferogram (2004-2005) of Sléttuhlíð.* ©*NLSI and ESA.*

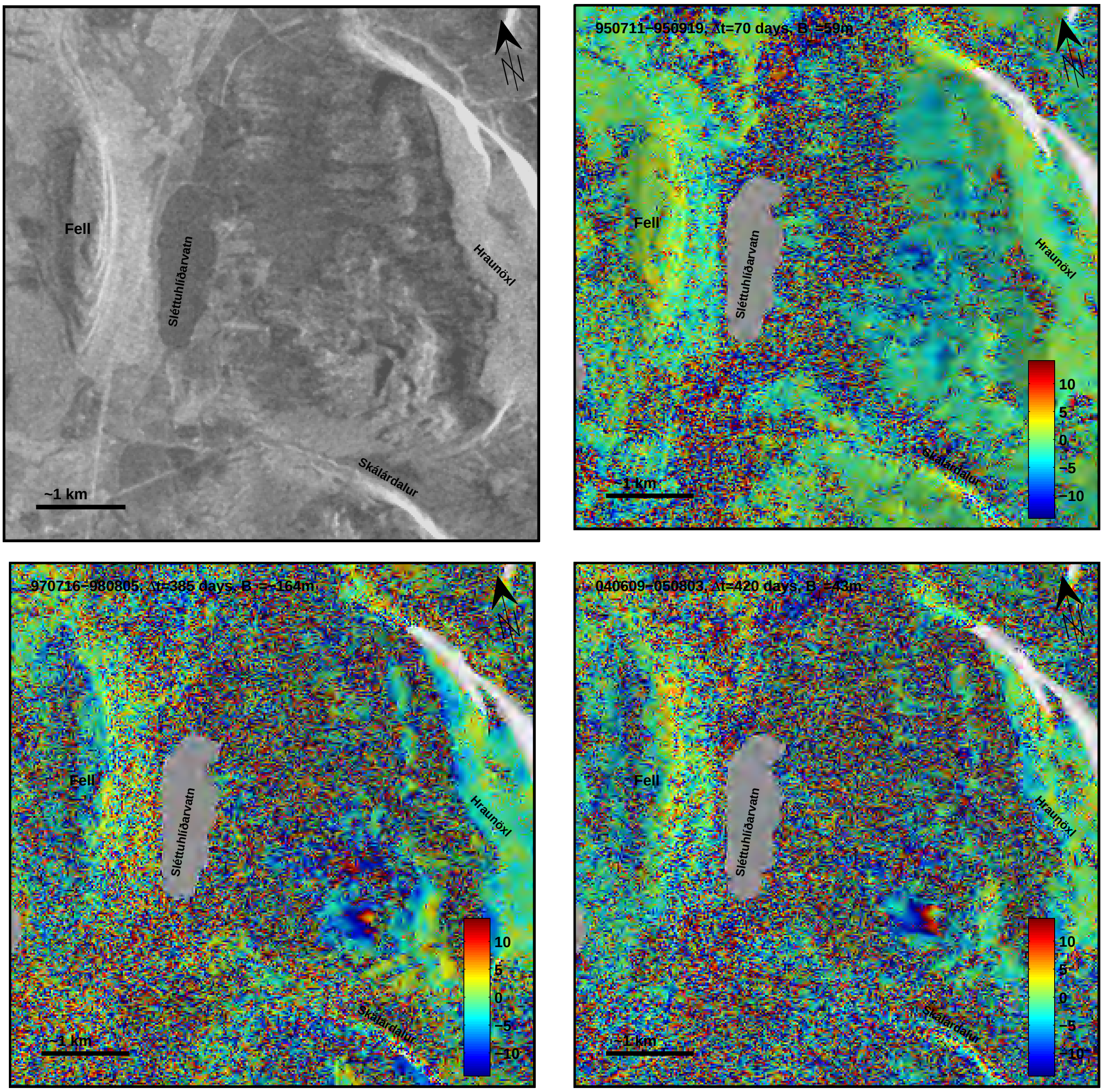


Figure 30. *SAR amplitude image and interferograms of Sléttuhlíð in radar coordinates. The 70-day interferogram (July-Sept. 1995, top right) exhibits little or no deformation, while the one year interferograms (bottom) from 1997-1998 and 2004-05 show up to 3 cm of displacements on part of the deposits. ©ESA.*

4.10 Gljúfurárdalur in Skagafjörður

Two sites with some surface displacement were detected on the east side of Skagafjörður, just south of of Hjaltadalur. These two locations are near a small tributary valley, Gljúfurárdalur, that extends to the southeast from the main Skagafjörður valley. One of the sites is just north of Gljúfurárdalur at an elevation of about 800 m. It is only about 200 m wide, but consistently shows about 2-3 cm deformation (Figure 31, middle row). The spatial extent of this signal is so small that if it would have been detected in only one interferogram, it probably would have gone undetected.

The other site is to the south of Gljúfurárdalur at an elevation of about 700 m. This moving deposits also have limited spatial extent and the pattern of movement appears somewhat different from one interferogram to another (Figure 31, bottom row). The interferograms show narrow streaks of unrest that are hard to draw any useful conclusions from, except that some material movement is going on at this location.

4.11 Other Locations

Active deformation was detected at several other locations in the interferograms from Central-North Iceland. One of these sites is the Möðrufellshraun deposits, below Möðrufellsfjall mountain in Eyjafjörður valley. These deposits are geomorphologically a very clear feature and with well defined boundaries, and one of the sites detailed in the catalogue by *Jónsson* [1976]. He estimated its area to be 1.5 km^2 and its volume 40×10^6 m^3. These deposits are on a east-facing slope and can therefore only be imaged from ascending radar look directions. The processed ascending interferograms span time periods during two years, i.e. 1997-1998 and 2004-2005. Some deformation is seen on these deposits during both periods, e.g. about 1-2 cm in an interferogram spanning Oct. 1997 to July 1998.

Some deformation is also visible in several interferograms in Kvarnárdalur, which is some 5 km to the north of Möðrufellshraun. This site is under Þríklakkar mountain and high above the farms of Hranastaðir and Merkigil. Many interferograms are decorrelated at this location as it is relatively high on the mountain and often affected by snow. The clearest signal was found in an interferogram spanning May 1997 - July 1998, which shows 1-2 cm surface displacement.

A small area of unrest was discovered in Dalsmynni pass, which connects Fnjóskadalur Valley to Eyjafjörður. This site is below a gully on Skuggabjargahnjúkur mountain and above an abandoned farm called Skuggabjörg. One of the interferograms (Oct. 1997 - July 1998) shows 1-2 cm movement on this site that has a very limited spatial extent.

Unadalur Valley is on the east side of Skagafjörður near Hofsós Village. The valley is mostly uninhabited and extends about 15 km inland from the sea. On the south side of the valley are clear deposits that are called Selhólar [*Jónsson,* 1976, page 344]. A hint of some movements was found on these deposits in the interferogram spanning Oct. 1997 - July 1998.

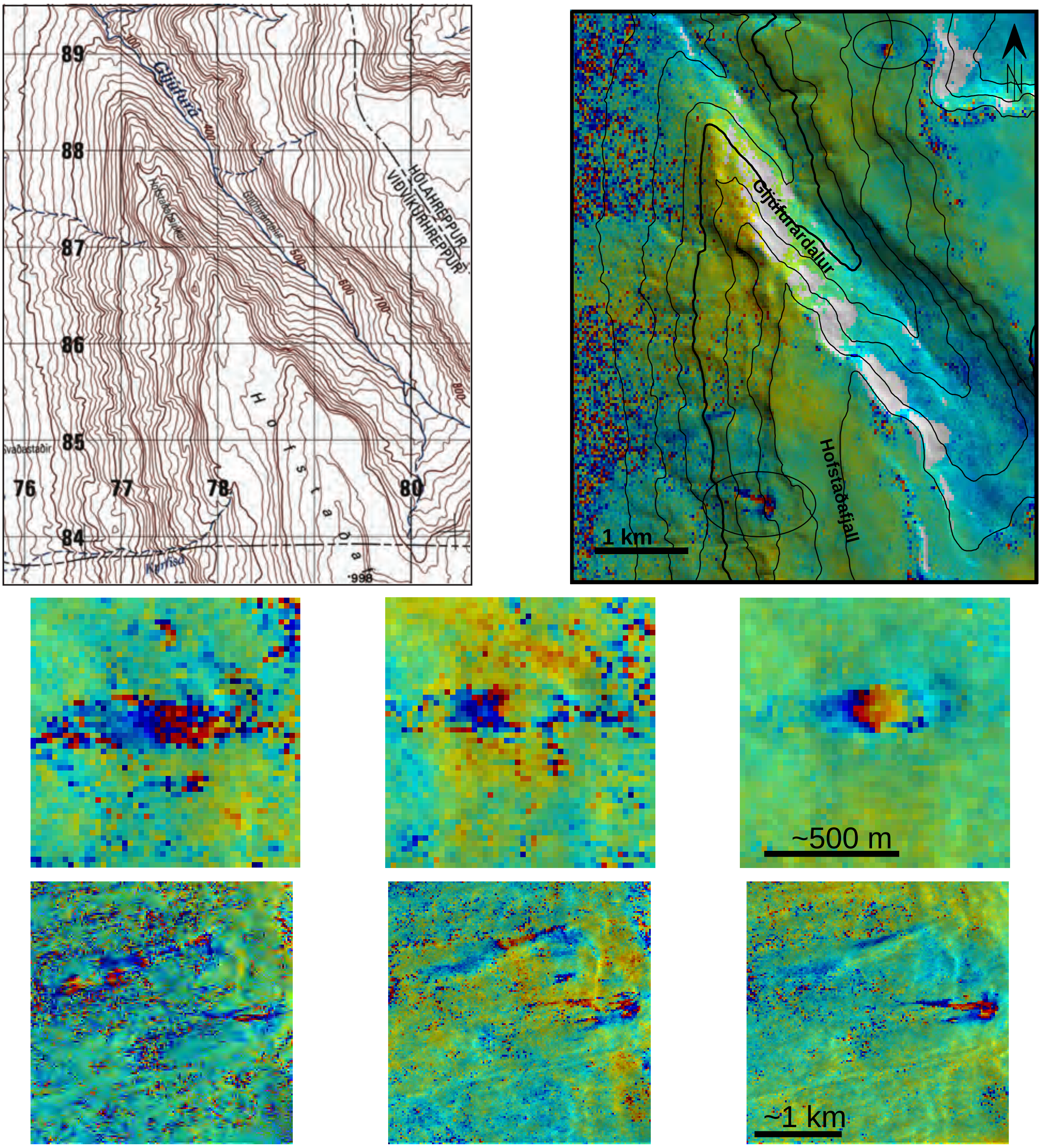


Figure 31. *Map and interferograms from Skagafjörður. The map shows a small area around Gljúfurárdalur, at the eastern side of Skagafjörður, just south of Hjaltadalur. The geocoded interferogram (top right) shows two small locations of unrest marked by ellipses. These two sites are to the north and south of Gljúfurárdalur and are shown in close-ups in radar coordinates (middle row and bottom row, respectively) in three different interferogram (July-Sept. 1995, June-July 2004, and July-August 2004). ©NLSI and ESA.*

5 Conclusions

Within this project I processed 30 radar interferograms of Central-North Iceland to investigate the capabilities of the InSAR technique for slope-movement detection and monitoring in this part of Iceland. I used the interferograms to study both the previously known sites in Almenningur near Siglufjörður and by surveying large areas in search for active slope displacements. The radar data that I used were ERS data from 1995-2000 and Envisat data from 2004-2005. The conclusions from Central-North Iceland can be summarized as follows:

1. The coherence of C-band radar interferometry is generally good enough for single- and multi-month observations during summers in Central-North Iceland. Inter-annual observations can also provide useful information on larger deposits, but not on the smaller sites as some filtering is generally required, which prevents small-scale pixel-to-pixel analysis. The main InSAR measurement problems in North Iceland are the same as in East Iceland, i.e. the lack of a digital elevation model of adequate quality, which prevents analysis of long-baseline interferograms, and second, the frequent high-elevation snow cover, which often limits the use of spring and autumn images.

2. The previously known unstable slopes along the road to Siglufjörður in Almenningur are seen moving in almost all of the processed interferograms. The deposits are quite extensive and are primarily active in two areas, in Almenningsnöf and in Höðnuvík. At both locations the deposits are moving so fast that they appear completely decorrelated in interferograms spanning one year or more. 35-day and 70-day interferograms provide useful information about the extent of the moving deposits and about the displacement pattern, which appears somewhat chaotic and difficult to quantify.

3. Around 20 locations of previously unknown slope-creep were discovered in Central-North Iceland in the processed interferograms. In some cases the locations of observed creep correspond to deposits that have been geomorphologically documented, such Víkurhólar hills, and in Sléttuhlíð and Þorvaldsdalur. The extent of some of the deposits is quite small, e.g. in Skagafjörður, on Kaldbakur, and in Dalsmynni, while other moving areas are relatively extensive, even exceeding 1 km^2, e.g. in Tungudalur and Víkurhólar.

4. The results of this project from Central-North Iceland and from East Iceland [*Jónsson,* 2007] show that InSAR is a useful technique to both search for and monitor slope movement in these regions. However, radar data acquisitions of these areas are neither regular nor very frequent and the 2004-2005 data exist only because of my request to European Space Agency. Therefore, a slope-movement monitoring policy and an observation plan for Iceland would be needed to secure more data acquisitions in the future.

Acknowledgements

I thank Kristján Ágústsson (Iceland GeoSurvey (ISOR)) and Þórður Arason (Icelandic Meteorological Office (IMO)) for their support and discussions throughout this project. I also thank the various scientists who attended several project meetings at the IMO for their comments and advise. This project was supported by the Icelandic Avalanche Fund and all satellite data were provided by the European Space Agency through Category-1 project #2424.

References

Davíðsdóttir, M., Víkurhólar in Eyjafjörður, Iceland: A rock avalanche into the sea and a potential resulting tsunami, M.Sc. thesis, University of Iceland, 2008.

Guðmundsson, Á., Landslides or rock glaciers? (in Icelandic), *Náttúrufræðingurinn, 64,* 177-186, 1995.

Guðmundsson, Á., Frerafjöll og Urðarbingir á Tröllaskaga, M.Sc. thesis, University of Iceland, 310pp, 2000.

Hanssen, R. *Radar interferometry - data interpretation and error analysis*, Kluwer Academic Press, Dordrecht, The Netherlands, 308 pp, 2001.

Jóhannesson, T., and Th. Arnalds, Accidents and economic damage due to snow avalanches and landslides in Iceland, *Jökull, 50,* 81-94, 2001.

Jensen, E. H., and T. Jóhannesson, *Assessment of landslide risk in Seyðisfjörður, eastern Iceland: first measurement results (in Icelandic),* IMO document ÚR-EHJ-2002-03, 10pp, 2002.

Jensen, E. H., and A. Hjartarson, *Field investigation of the 27 June 2002, Neskaupstaður landslide (in Icelandic),* IMO document ÚR-EHJ-2002-02, 11pp, 2002.

Jónsson, Ó., *Landslides (in Icelandic),* Ræktunarfélag Norðurlands, Akureyri, 623pp, 1976.

Jónsson, S., *A Survey of active Landslide Movement in East Iceland from Satellite Radar Interferometry*, Report 07004, The Icelandic Meteorological Office, 85pp, 2007.

Jónsson, S., Importance of post-seismic viscous relaxation in southern Iceland, *Nature Geoscience*, 1, 136-139, doi:10.1038/ngeo105, 2008.

Jónsson, S., and K. Ágústsson, Landslides in Iceland studied using SAR interferometry, *Proc. to the Envisat Conference,* European Space Agency, Salzburg, 2004.

Jónsson, S., and K. Ágústsson, Episodic landslide movement in Iceland studied using SAR Interferometry, *Proc. to the Envisat Symp.,* European Space Agency, Montreux, 2007.

Massonnet, D., and K. L. Feigl, Radar interferometry and its application to changes in the earth's surface, *Rev. Geophys., 34*, 441-500, 1998.

Rosen, P. A., S. Henley, G. Peltzer, and M. Simons, Update repeat orbit interferometry package released, *EOS Trans. AGU, 85,* p47, 2004.

Scharroo, R., P. N. A. M. Visser, and G. J. Mets, Precise orbit determination and gravity field improvement for the ERS satellites, *J. Geophys. Res., 103,* C4, 8113-8127, 1998.

Zebker, H. A., and J. Villasenor, Decorrelation in interferometric radar echoes, *IEEE Geosci. Remote Sensing, 30*, 950-959, 1992.

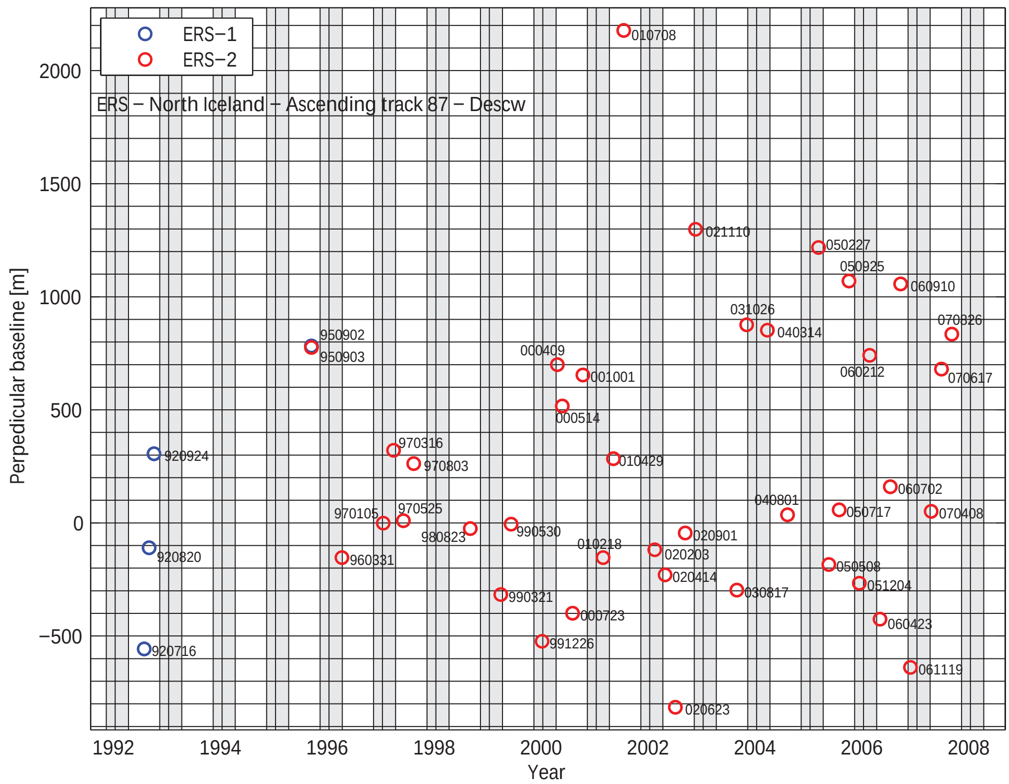
A Baseline Information for ERS and Envisat

Here I provide information about ERS-1, ERS-2, and Envisat radar data that have been acquired above Central-North Iceland from the different parallel ascending and descending tracks. The archive information and baselines numbers were extracted from the ESA's stand-alone Descw catalogue. The data are presented graphicly for each track with perpendicular baseline (with respect to a certain scene) as a function of acquisition date. Each image acquisition is labeled by its acquisition date and winter months from November through March are shown with gray shades. The ERS-1 and ERS-2 data are presented together as they can be combined to form interferograms while the Envisat data are displayed separately. By displaying the data in this way, one can quickly judge e.g. how many small-baseline interferograms can be formed using summer acquisitions from a certain track.

A.1 Spatio-Temporal Baselines Information for ERS

The ERS-1 and ERS-2 data that have been acquired above Central-North Iceland are primarily from four ascending and four descending tracks. The spatial coverage of the standard frames (1323 for ascending, and 2277 for descending) is shown in Figure 5. The ERS-1 data are from 1992-2000 and the ERS-2 data from 1995-2007.

The number of acquired ascending scenes is 43 and 74 for tracks 87 and 316, respectively (Figure 32), and 42 and 57 radar images for ascending tracks 44 and 273 (Figure 33). The amount of acquired descending data even greater, or 50 and 55 scenes from tracks 367 and 95, respectively (Figure 34), and 131 and 123 radar images from tracks 324 and 52 (Figure 35).



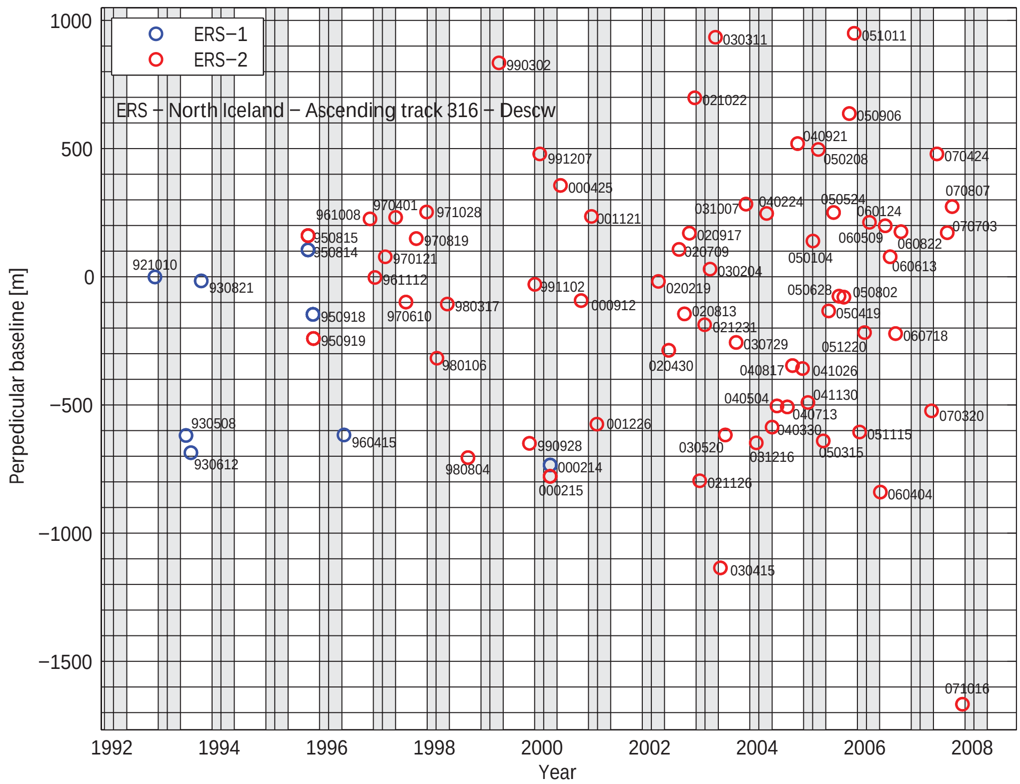


Figure 32. *Spatio-Temporal baseline information for ERS-1/2 radar data of Central-North Iceland acquired from ascending tracks 87 and 316. The information was extracted from ESA's Descw database.*

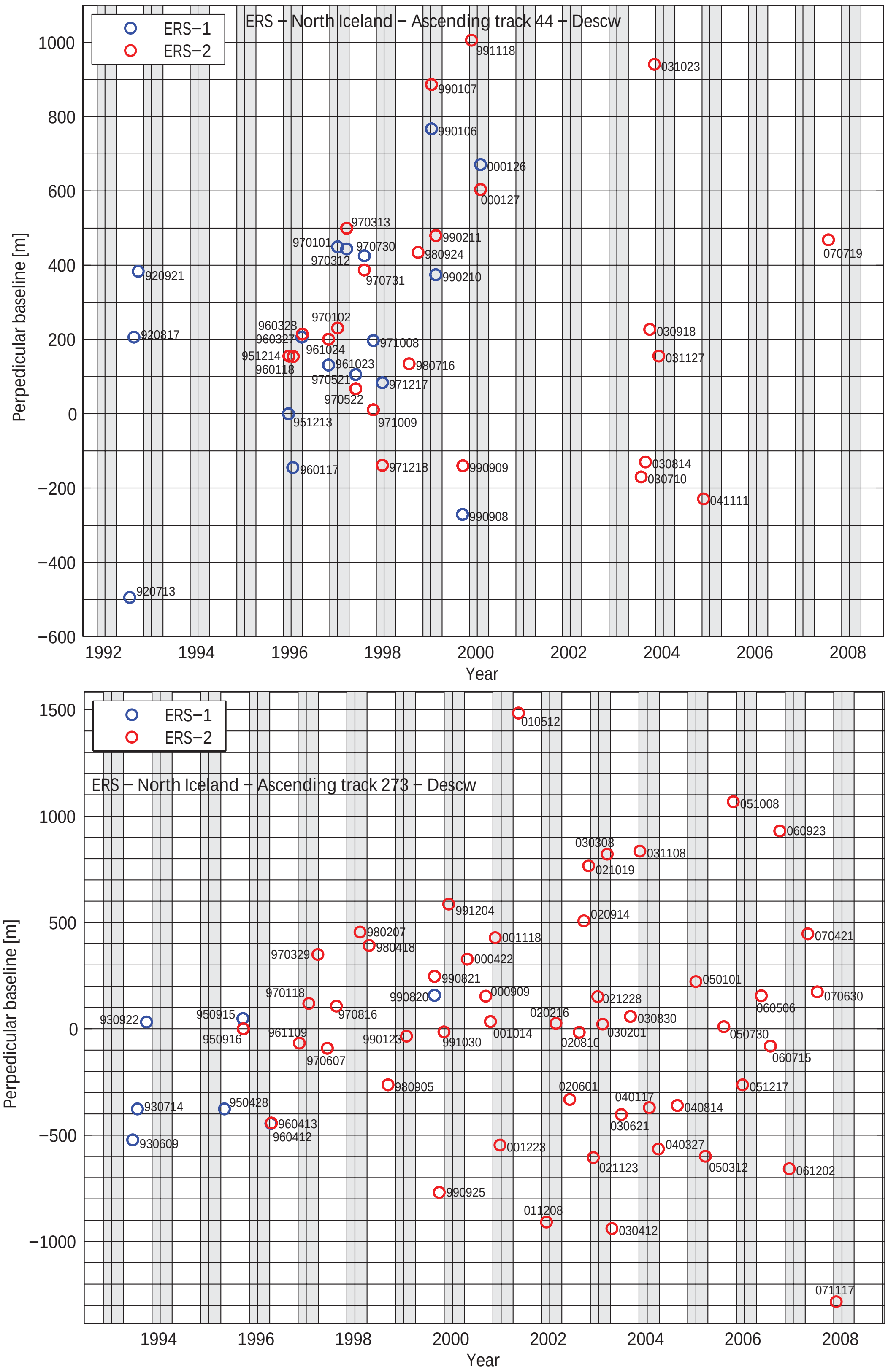


Figure 33. *Same as Figure 32, except for ascending tracks 44 and 273.*

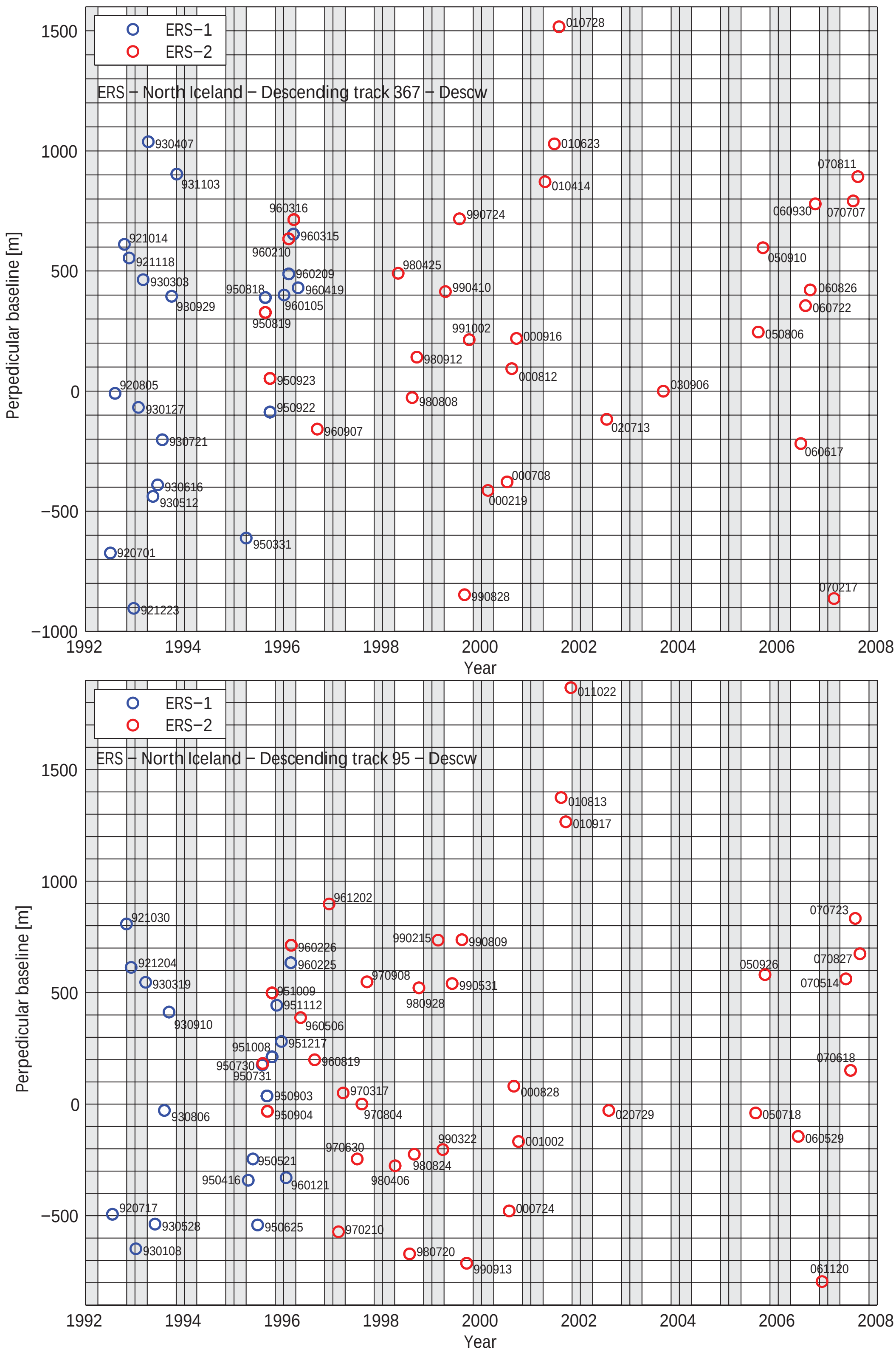


Figure 34. *Same as Figure 32, except for descending tracks 367 and 95.*

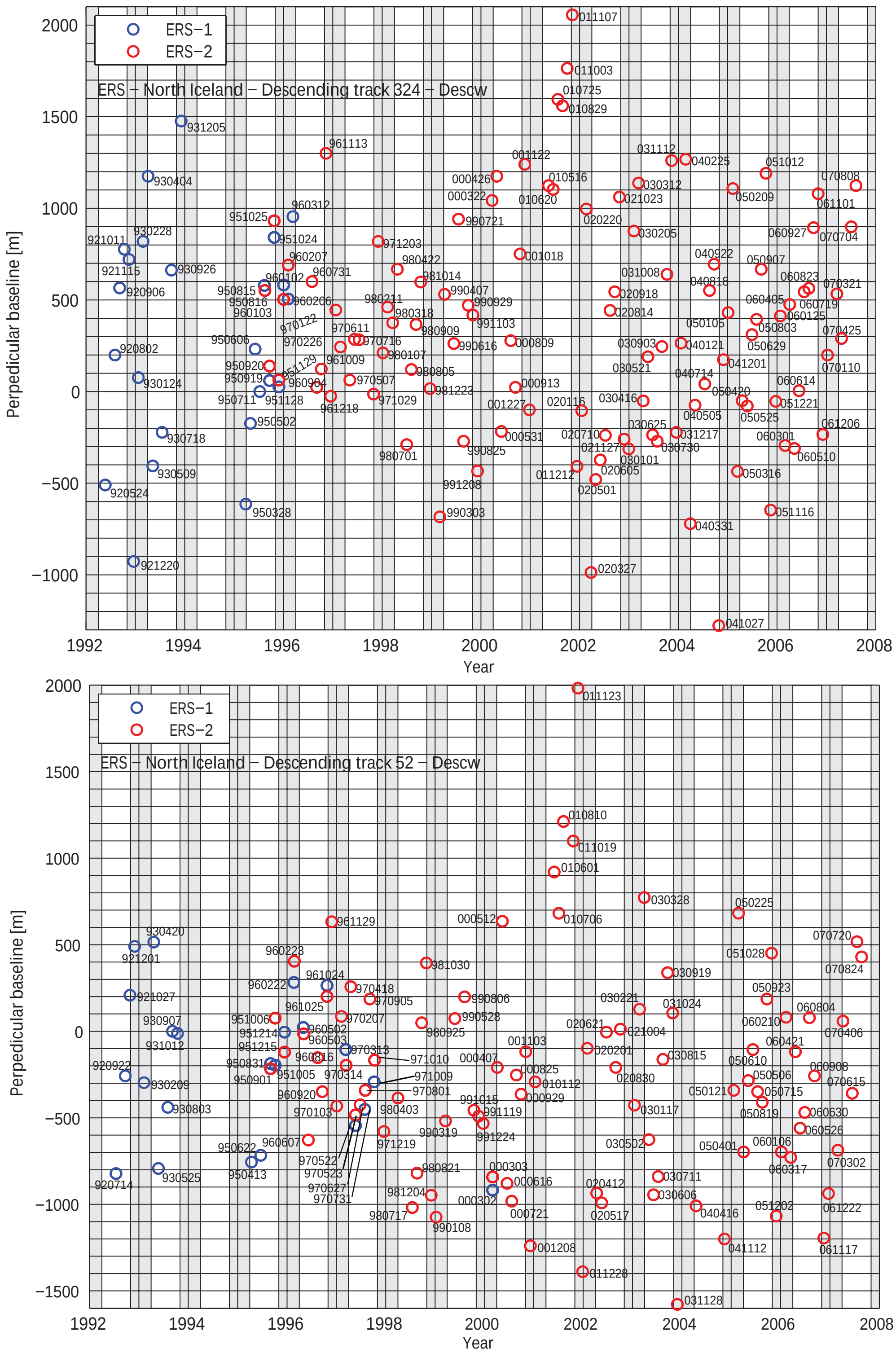


Figure 35. *Same as Figure 32, except for descending tracks 324 and 52.*

A.2 Spatio-Temporal Baselines Information for Envisat

The Envisat tracks are similar to the ERS tracks, but the numbering is a little bit different, with e.g. track 324 now numbered 2324, indicating image-mode number 2 (IS-2). The coverage of standard frames is similar to the ERS frames shown in Figure 5. Along ascending orbits, 9, 10, 18 and 10 scenes have been acquired from tracks 2087, 2316, 2044, and 2273, respectively (Figure 36-37), as of December 2007. From descending orbits the number of acquired scenes is 11, 7, 20, and 13, from tracks 2367, 2095, 2324, and 2052, respectively (Figures 38-39).

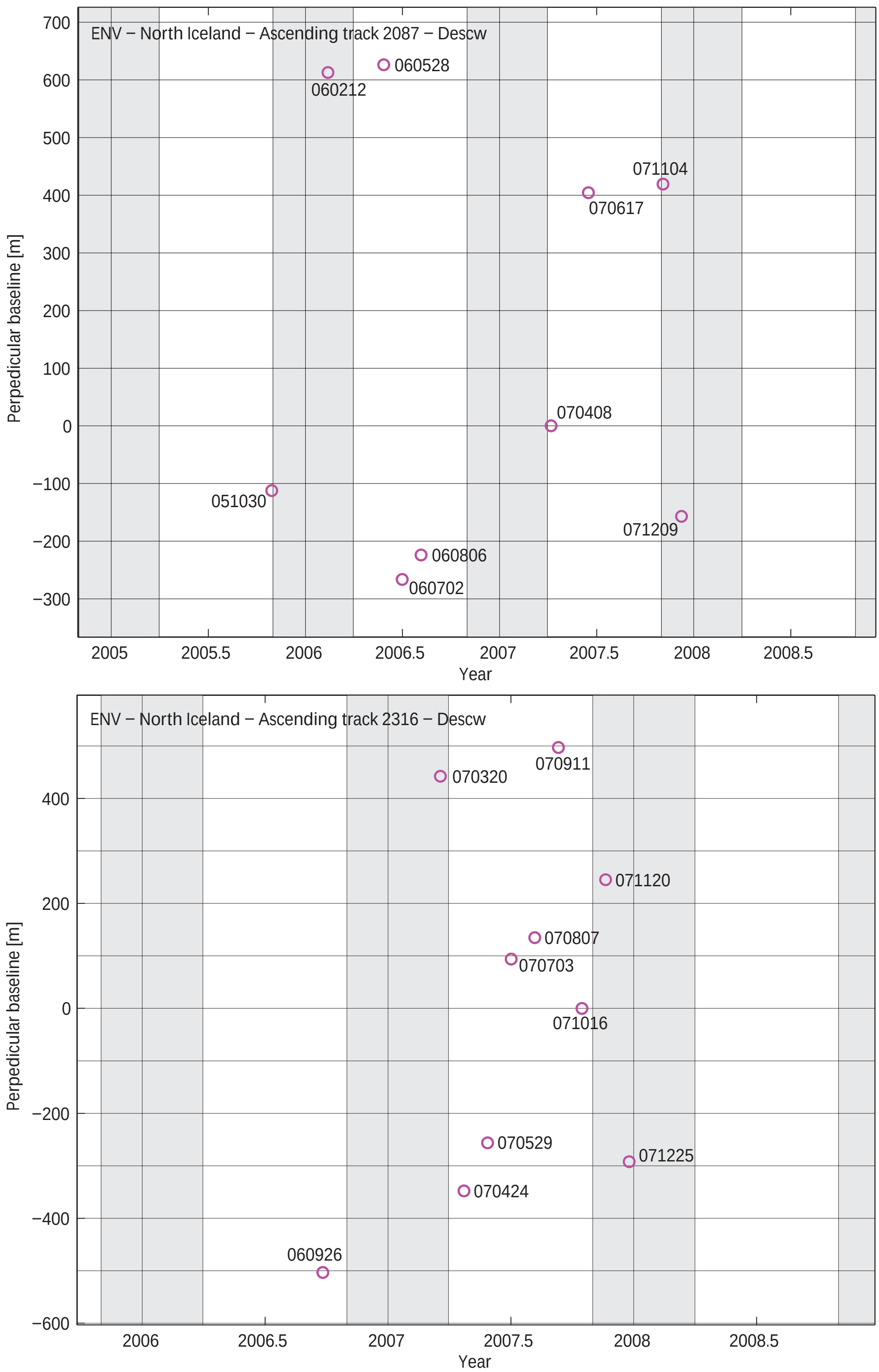


Figure 36. *Spatio-Temporal baseline information for Envisat radar data of Central-North Iceland acquired from ascending tracks 2087 and 2316, mode IS-2. The information was extracted from ESA's Descw database.*

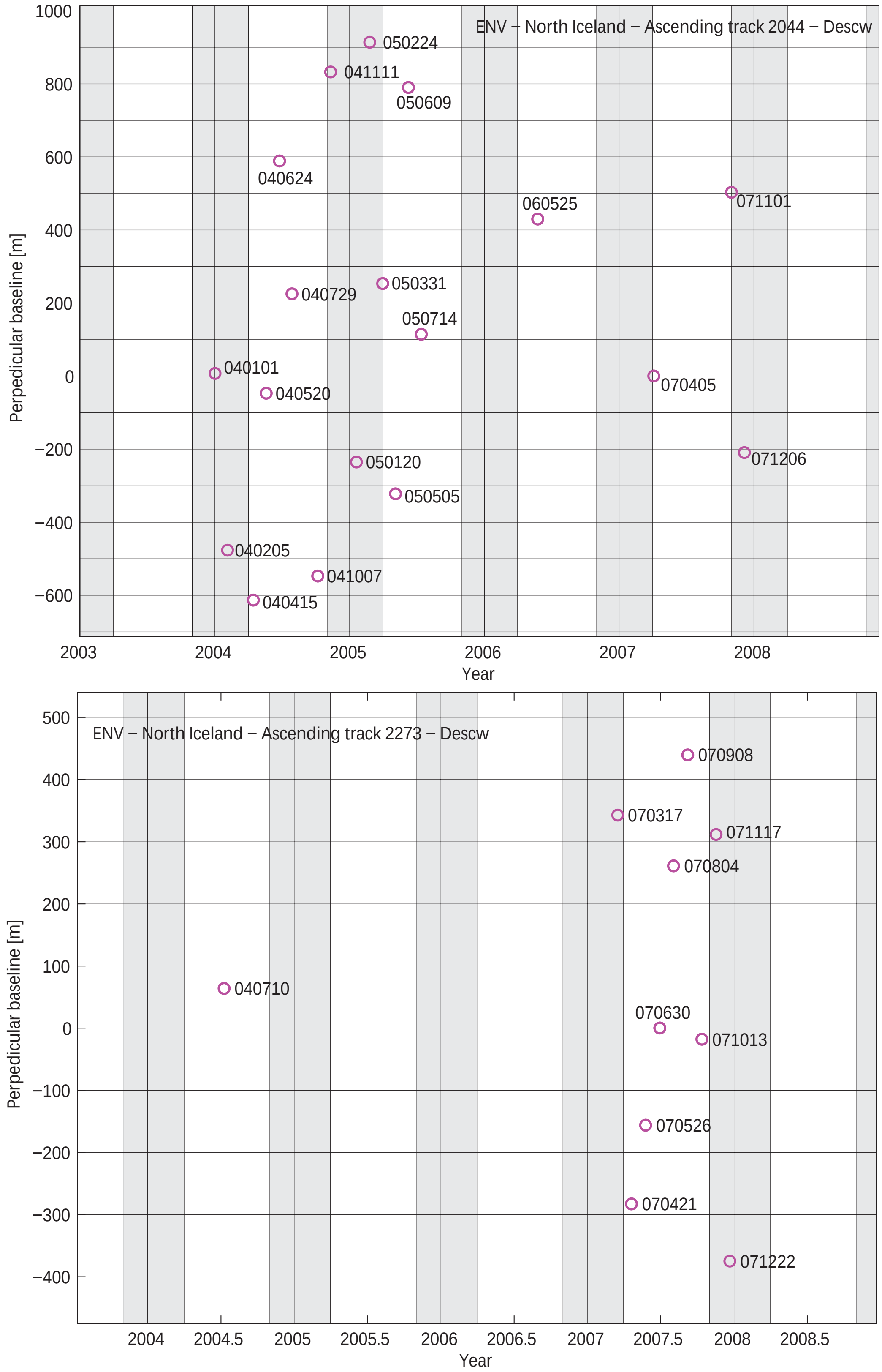


Figure 37. *Same as Figure 36, except for ascending tracks 2044 and 2273.*

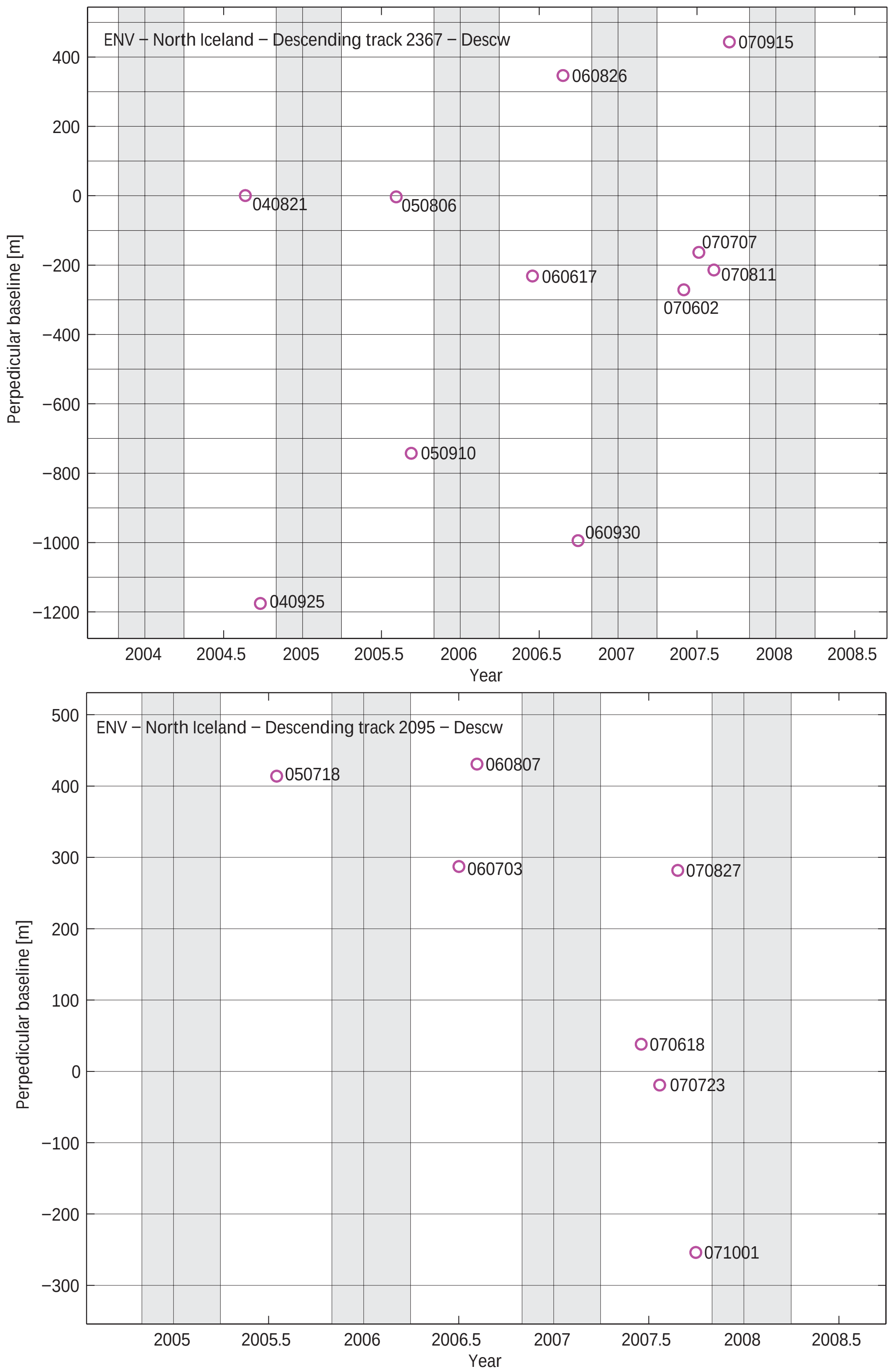


Figure 38. *Same as Figure 36, except for descending tracks 2367 and 2095.*

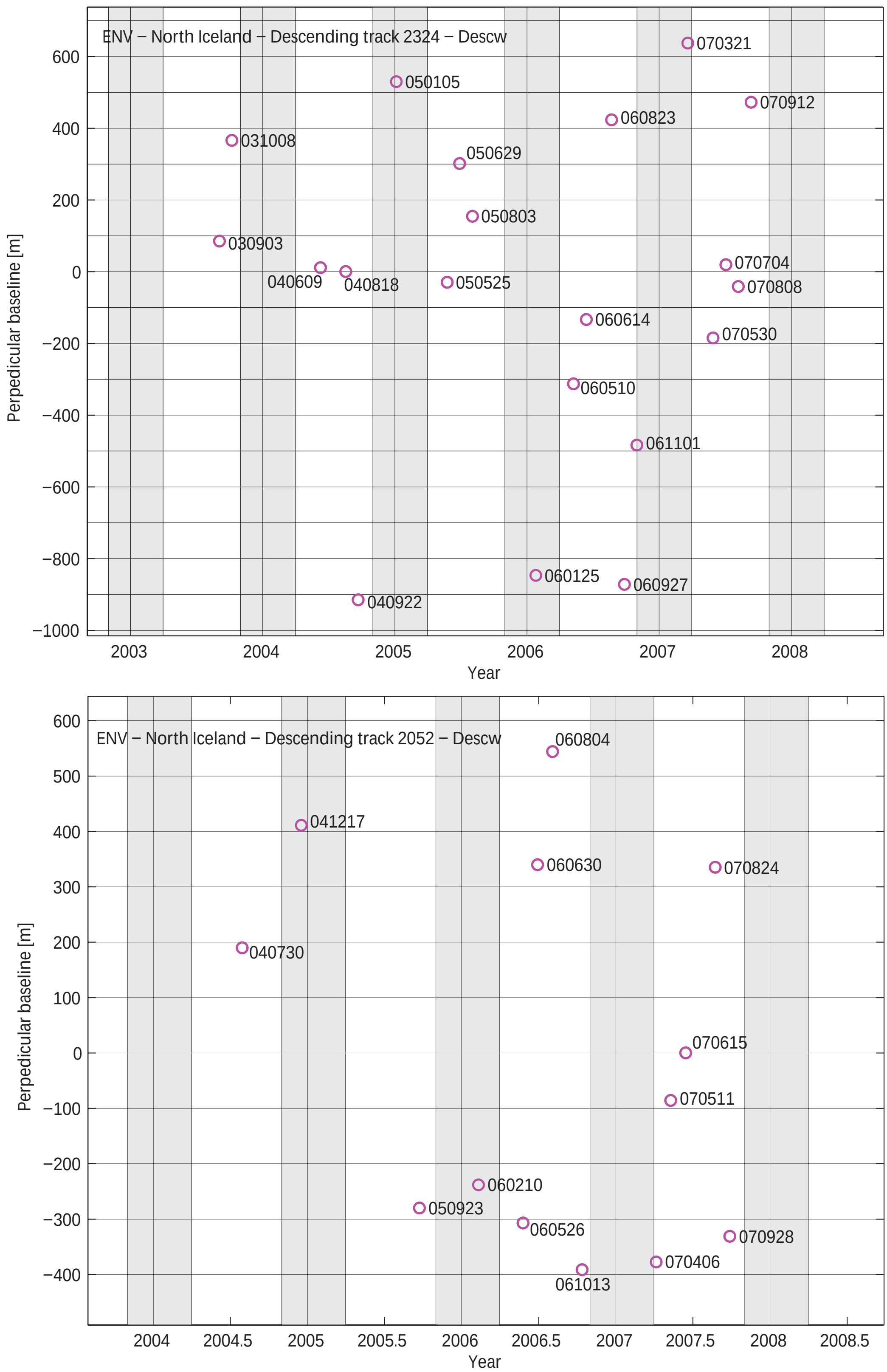


Figure 39. *Same as Figure 36, except for descending tracks 2324 and 2052.*

B Information about the Individual Interferograms

B.1 Ascending interferograms from ERS-1/2 data 1997-1998

Here I provide information about the four ERS-1/2 ascending interferograms that were processed within this project and about what can be seen in these data.

970521-971008

This 4.5 month interferogram has a perpendicular baseline of 91 m, but its correlation is rather poor. Snow is clearly the cause of decorrelation at the higher elevations, probably during spring of 1997. However, the correlation at the lower elevations is not very good either and the reason remains unexplained. Poor coregistration does not seem to be a problem, as some small areas within the interferogram remain highly correlated. Möðrufellsfjall is nicely correlated, but does not show any signs of movement in this interferogram. The overall low quality of this interferogram, with most slope poorly correlated, makes small-scale deformation analysis difficult. However, no larger deformation sources were detected within this interferogram either.

970521-980716

This 420-day interferogram has a small perpendicular baseline of only 32 m, but also exhibits poor interferometric correlation, presumably in part due to snow in May 1997. In fact, the correlation is so poor here that it prevents any deformation detection on most slopes. However, the Möðrufellshraun site is nicely coherent and the center part of it exhibits clear movement of 1-2 cm. Another sign of deformation is seen further north in Kvarnárdalur, under a mountain called Þríklakkar, far above the farms Hranastaðir and Merkigil.

971008-971009

This 1-day tandem interferogram has a baseline of 186 m and shows excellent coherence, except at highest elevations in the eastern part of the image, where snow fall or snow melting clearly seems to have affected the correlation. The differential interferogram shows many phase signatures, primarily related to DEM errors but also due to atmospheric artifacts. The DEM errors are often small scale, sharp, and somewhat correlated with the topography or topographical edges, while the inferred atmospheric signals are much smoother and of larger spatial extent. The idea behind ordering this tandem data was to produce a high-resolution DEM or to improve the existing DEM. Unfortunately, the decorrelation within the interferogram due to snow prevents that this can be achieved for the whole image, although some parts of the interferogram could be used to improved the pre-existing DEM locally. Within this project, I only used this image to verify that the deformation seen in interferograms 970521-980716 and 971008-980716 was real, but not due to topographical artefacts.

971008-980716

This 260-day interferogram has a 60 m baseline and is the best deformation interferogram of the three ascending ERS interferograms processed within this project. However, the interferogram is largely decorrelated at the higher elevation and exhibits only a fair amount of correlations elsewhere. Möðrufellshraun shows clearly a 1-2 cm LOS displacement in this interferogram. The site in Kvarnárdalur, on the other hand, is decorrelated in this interferogram and there no movement is detectable. Two other locations were found with visible movement. The first one is in Dalsmynni, a localized movement of 1-2 cm, and then there are large deposits in Unadalur, called Selhólar, of which the center part appears to move slightly.

B.2 Ascending interferograms from Envisat data 2004-2005

In this section I provide information about the eight Envisat ascending interferograms that were processed within this project and span the various time intervals in 2004 and 2005.

040520-040729

This 70-day interferogram from summer of 2004 has a baseline of 269 m and is clearly affected by both topographic problems and very strong atmospheric artifacts. These factors basically prevent any meaningful deformation analysis in this interferogram. That said, however, one can see clear evidence of displacement in Kvarnárdalur and that nothing is happening at Möðrufellshraun.

040520-050505

This 1-year interferogram has a perpendicular baseline of 170 m and is completely decorrelated at the higher elevations due to snow. At low elevation the correlation is poor, providing only very limited information. That said, however, signals of movement can be seen both on Möðrufellshraun and in Kvarnárdalur. The former site exhibits a signal that is less than one interferometric fringe, while the amount of deformation at the latter site is not possible to quantify.

040624-040729

This one-month interferogram has good correlation but a long perpendicular baseline of 236 m, resulting in numerous topographical errors. In addition, the interferogram appears to have very strong tropospheric signals, presumable related turbulent conditions on 29 July 2004. The Möðrufellsfjall site exhibits no movement in this interferogram, but a small localized deformation can be seen in Kvarnárdalur, a bit further downslope than in other interferograms showing deformation at this location.

040624-050609

This one-year interferogram is rather incoherent and noisy, but is still good enough to survey many slopes for possible landslide movement. The perpendicular baseline is 189 m so the topographic artifacts are visible in some places, but not really too problematic. Some movement is seen at both Möðrufellsfjall and Kvarnárdalur sites, but no other displacements were detected.

040729-050714

This one-year interferogram has a perpendicular baseline of only 29 m and it exhibits very good coherence at both low and high altitudes. The problem, however, is that it show exceptionally turbulent troposphere with many signals correlated with topography and others signals that are more like spatially long wavelength ripples. Despite this problem, most slopes can be carefully examined for possible deformation. A sign of movement is detected on Möðrufellsfjall and Kvarnárdalur sites, although the signatures are not clear. No other signals could be found, except maybe two small round like signals in Þorvaldsdalur, hinting at some minor mass movement.

050609-050714

This 35-day interferogram has rather high degree of coherence, but with almost 400 m perpendicular baseline it shows nothing but a numerous topographical artifacts due to inaccuracies in the DEM. It is therefore not useful in searching for possible deformation. However, no sign of deformation is seen at the usual sites of Möðrufellsfjall and Kvarnárdalur.

050609-050818

This interferogram spans 70 days and has a smaller baseline of about 200 m. The level of coherence is in many places good, except at the highest elevations (still covered with snow in the June image) at low elevation in many valleys (agricultural activity). The best coherence is usually found at intermediate elevations, including on many of the slopes that might have active slope movement. However, no signs of deformation were found in this interferogram.

B.3 Descending interferograms from ERS-1/2 data 1995-2000

This section provides information about the 9 descending interferograms processed using data from the ERS-1 and ERS-2 satellites during 1995-2000.

950711-950919

This 70-day interferogram from 1995 has a baseline of 59 m and is of excellent quality. Numerous clear signs of mass movement can be seen in this interferogram. Starting from the east, then there are clear signs of mass movements at two locations on the east side of Fnjóskadalur. One location it is high above Böðvarsnes farm in Hólsöxl mountain and the other is further north, just north of Uxaskarðsá. In both cases, a rather large area appears moving about 1-2 cm. Further west in Höfðahverfi there are three locations showing movement in this interferogram. One location is above the farm Hléskógar and another site is further north on Leirdalsheiði, north of a creek called Strjúgsgil. The third location is north of the Grenivík village on Látraströnd, high on the Kaldbakur mountain, above two small lakes called Leynitjörn and Lýsistjörn. In all three cases it is hard to determine the amount of displacement, as the motion is not spatially extensive and a bit chaotic, however, in all cases it appears to exceed 2 cm. The Víkurhólar hills are not seen moving in this interferogram, nor other deposits east of Eyjafjörður, apart from possible small-scale displacement near the north end of Látrastönd.

West of Eyjafjörður there are many locations showing mass movement. A large area is seen moving on the east side of Öxnadalur, high on Kirkjufjall mountain, in a small Valley called Kirkjufjallsdrag. Mass movement is seen at two locations on the east side of Þorvaldsdalur, one location is just north of Nautárdalur in Hesthraun and the other is further north, just south of Hrafnagilsá, possibly where it is called Hrafnagilshraun. In both cases it is hard to quantify the amount of LOS displacement. In the neighboring Svarfaðardalur there are 3-4 locations showing sings of movement, these area again on the eastern side of the Valley (as the western side is invisible due to layover in these descending interferograms), more specifically in two small tributary valleys called Hálsdalur and Hofsdalur. In all cases the displacements are small-scale, hard to quantify, and appear to correlate to deposit-like features in the amplitude images, just like in Þorvaldsdalur. There is also a relatively large area moving in Tungudalur, a tributary valley near Stífluvatn Lake. The unstable slopes in Almenningur, where the road to Siglufjörður is, show clear displacements in this interferogram. There are primarily two areas that are active during this period, one to south in Höðnuvík where the track over Siglufjarðarskarð pass starts, and the other further north in Almenningsnöf. In both cases the displacements appear somewhat chaotic and hard to quantify but are likely several cm and the areas that are active are relatively large and extend into the ocean. In addition to these two areas there is possible small scale movement further north in Engidalur, high above the road. In addition to all these locations, two small-scale mass wastes appear to be moving slightly in Skagafjörður, in Hofstaðafjall, one high on the mountain near Kyrfisá creek, the other one in a tributary valley called Gljúfurárdalur.

950919-950920

This one-day tandem interferogram has a 79 m baseline and exhibits excellent correlation at all altitudes. The baseline is a bit too short to use this interferogram to correct the DEM for the numerous DEM errors that are visible in all interferograms with baselines over 200 m. However, this tandem image can be used to help distinguishing between DEM artifacts and real LOS displacement in in some other interferograms.

950920-961009

This one-year interferogram has rather disappointing coherence and is very noisy, despite its very small perpendicular baseline of only 14 m. Snow in October 1996 is a likely explanation for the poor coherence. Despite the noise, movement is seen in Víkurhólar, Sléttuhlíð and in Almenningur (primarily in Almenningsnöf). The amount of displacement is about one fringe (3 cm) in Sléttuhlíð, 1-2 cm in Víkurhólar, but difficult to quantify in Almenningur.

961009-970716

The coherence of this one-year interferogram is rather poor (baseline 155 m), although clear displacements can be seen in Víkurhólar (2 cm), in Almenningur near Almenningsnöf (1 cm), and in Sléttuhlíð (3 cm). The Sléttahlið site is above a farm called Hraun, near Sléttahlíðarvatn lake. The deposits above the Hléskógar farm appears to be showing displacement as well.

961009-980805

Despite its small baseline of 9 m, this two-year interferogram is so noisy that it prevents any general search for or detection of landslide motion in the region. The Sléttuhlíð site is seen moving and Víkurhólar as well, although it is hard to quantify the movement. In addition, there is a hint of displacement in Hofstaðafjall mountain in Skagafjörður.

970716-980805

This one-year interferogram has a rather long baseline of 165 m and exhibits DEM artifacts in many places, although not too severe. The coherence is rather good in many places but poor in other, e.g. at the lowest elevations due likely to agricultural activity. One of the two sites seen moving in 950711-950919 in Fnjóskadalur, the one further north, is shows movement of 1-2 cm in this interferogram, while the other one appears to be stable. Víkurhólar show here only a little bit of displacement at the center of the deposits above the road. In addition to these the Tungudalur mass waste is clearly moving in this interferogram, as well as a smaller area in an neighboring tributary valley Klaufabrekknadalur on the Lágheiði pass. The sléttahlíð site is also moving in this interferogram, as usual.

970716-990616

The perpendicular baseline of this two-year interferogram is only 16 m but the coherence is very poor. The Víknahólar hills seem to be moving, but otherwise not much information can be drawn from this interferogram.

980701-980805

This 35-day interferogram exhibits a reasonably good coherence but has a perpendicular baseline of over 400 m and is therefore full of DEM artifacts. The residual DEM signals are so strong that no useful information can be taken from this interferogram about deforming hill sides.

980701-990825

This one-year interferogram has a small baseline of 15 m and shows a reasonably good coherence at the higher altitudes, but is noisier at the lowest elevations, probably due to more vegetation growth and agriculture. Several displacement signals can be seen in the interferogram. Three of them are in Fnjóskadalur, above Böðvarsnes and north of Uxaskarðsá, as before (950711-950919), and the third one is just a bit further north, near the second landslide. There is also a mass movement on Leirdalsheiði, at a similar location as seen in interferogram 950711-950919. Víkurhólar move as well, probably around 3 cm or so, with most of the landslide mass moving from high on the mountain to the sea, from the northern sharp boundary towards the south, although the southernmost part of this mass is not moving here, rather than in other interferograms. Clear movements are seen across a large area in Tungudalur near Stífluvatn lake. Both Sléttuhlíð and Almenningur exhibit movement as well, but the amount is hard to quantify.

980805-990616

The baseline of this one-year interferogram is about 150 m and it is quite noisy, especially at the higher elevations. It covers more or less the same time period as the interferogram above, but is much noisier, and thus does not provide any additional information.

990616-000809

This 420-day interferogram has a perpendicular baseline of only 8 m, but still it shows very limited correlation. The signal is a bit better in the east, than in the west, where the interferogram is completely decorrelated. The reason for the poor signal quality is unknown. The Víkurhólar site is clearly active during this period, showing around 3 cm displacement on most of the deposits, except the southernmost part. Otherwise, any reliable detection of mass movement is hindered by the decorrelation.

990825-000531

This interferogram also spans 1999-2000, but the time span is shorter (280 days) and the baseline is longer (50 m). The quality is not very good and the interferogram is quite noisy, especially at the higher elevations. The Víkurhólar hills are clearly moving, showing displacements up to 3 cm, and the usual very sharp displacement boundary to the north, but a diffuse boundary to the south. Active movement is also seen in Sléttuhlíð, but not at other locations.

B.4 Descending interferograms from Envisat data 2004-2005

In this final section I provide information about the six descending Envisat interferograms that were processed within this project and span the various time intervals in 2004 and 2005.

040609-040714

This one-month interferogram has baseline of almost 200 m and does show quite a bit of DEM artifacts, although these are not too strong. The coherence is quite good, except at the highest elevation, presumably due to remaining winter snow in June 2004. Both the Hléskógar and Kaldbakur sites are seen moving in this interferogram, as well as the one in Fnjóskadalur, north of Uxaskarðsá, while no movement is seen on Víkurhólar hills. Of the usual suspects west of Eyjafjörður, Almenningur, Tungudalur, and one of the Þorvaldsdalur sites (Hrafnagilshraun) are seen moving, while the Sléttuhlíð deposits appear stable. In addition, movement is detected on Kirkjufell in Öxnadalur. In most cases it is rather difficult to detect the amount of displacements, but it is often around one fringe, or 3 cm.

040609-050803

This one-year interferogram has a rather small baseline of 43 m, but the coherence is not very good in many places. The Víkurhólar hills are moving, maybe 1-2 cm during this time period. In addition, movement can be seen in Fnjóskadalur, Almenningur, Tungudalur, and in Sléttuhlíð. In these cases on can detect that something is going on but the details are hard to extract from the interferogram, due to noise. Many slopes are completely decorrelated, providing no information about possible mass movements.

040714-040818

This 35-day interferogram has practically no perpendicular baseline and exhibits fantastic quality almost everywhere. The Fnjóskadalur and Víkurhólar sites are clearly not moving during this time period, while movement can be seen on the Hléskógar and Kaldbarkur sites. The displacement of the Hléskógar deposits is up to 3 cm. Some movement is also seen in

Flateyjardalur, which is not seen in other interferograms, and the location is high on the slope, just south of where it is called Stóraskriða. Movement is detected on Hrafnagilshraun in Þorvaldsdalur, like in many other interferograms, and at two locations in the neighboring Hálsdalur, which also saw movement in the high-quality interferogram 950711-950919. Very limited or no movement is seen in Almenningur, Tungudalur, nor in Sléttuhlíð during these 35 days, but clear displacements are visible in Klaufabrekknadalur on Lágheiði and on Kirkjufell in Öxnadalur. Small-scale displacements are also visible on Hofsstaðafjall in Skagafjörður.

040818-040922

This 800 m baseline interferogram is of no use, it has very poor coherence and is full of DEM artifacts.

040818-050525

This 9-month interferogram has a baseline of 77 m and exhibits very poor coherence above ca. 2-300 m. That said, however, the sites in Víkurhólar, Hléskógar, Almenningur, Sléttuhlíð, and Hofstaðafjall can be seen moving. Other usual locations are completely decorrelated.

050525-050803

This interferogram has a baseline of 147 m and spans only 70 days during the summer of 2005. Despite this relatively good configuration, the coherence is poor in most location, particularly at the higher elevations. There is not much information that one can draw from this interferogram, except that the Víkurhólar, Almenningur, and Sléttuhlíð deposits do not appear to be moving during this time period, while the Hléskógar site shows a sign of movement.