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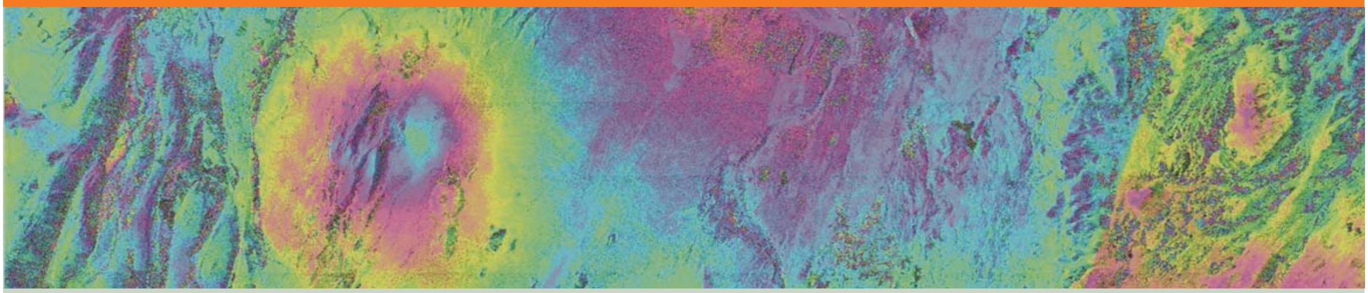

# Crustal deformation in the Krafla, Gjástykki and Þeistareykir areas inferred from GPS and InSAR techniques

Status report for 2011

**Key Page**

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**Title:** Crustal deformation in the Krafla, Gjástykki and Þeistareykir areas inferred from GPS and InSAR techniques


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**Prepared for:** Landsvirkjun

**Co operators:**


**Abstract:** Crustal deformation is measured by Global Positioning System (GPS) geodesy and interferometric analysis of synthetic aperture satellite radar images (InSAR) in the Krafla - Gjástykki - Þeistareykir area. The research is a collaboration between Institude of Earth Sciences, University of Iceland, Þeistareykir and Landsvirkjun. This status report describes the 2011 GPS campaign, installation of two new continuous GPS stations , as well as preliminary results from InSAR analysis.



**Keywords:** Þeistareykir, Krafla, Gjástykki, GPS, Crustal deformation, InSAR, GNSS

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Theodór Theodórsson

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# Crustal deformation in the Krafla, Gjástykki and Þeistareykir areas inferred from GPS and InSAR techniques

Status report for 2011

Institute of Earth Sciences Report 1201
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Mars 2012

# Contents

# Chapter 1

# Introduction

Ground deformation in north-east Iceland has been extensively studied in the last few decades, with particular attention on Þeistareykir, Gjástykki and especially the Krafla region. Recent peer-reviewed studies include a combination of levelling and Global Positioning System (GPS) measurements by *Sturkell et al.* [2008] and an Interferometric Synthetic Aperture (InSAR) study by *de Zeeuw-van Dalfsen* [2004]. Results from GPS campaign measurements in 2010 are described by *Ófeigsson et al.* [2010].

In the last two decades, the area around Krafla caldera has been subsiding due to pressure decrease in the shallow magma chamber and movements are occurring in relation to the geothermal exploitation in the area. To the north of Krafla, a widespread uplift signal has been observed since the early 1990's. It remains unclear whether this signal is related to deep magma accumulation under the area, or due to post-rifting adjustment. Finally, between the summer of 2007 and the summer of 2008, an uplift signal of 7-8 centimeters was detected in the Þeistareykir area, indicating a relatively shallow magma intrusion.

In the last two decades, satellite based geodetic measurement techniques have to some extent replaced terrestrial based techniques. GPS and InSAR techniques are the two main satellite based techniques to measure deformation of the Earth's surface. Both techniques allow millimeter level accuracies, and require either no fieldwork (InSAR) or less fieldwork (GPS) than terrestrial based measurements. The techniques are also complimentary: GPS allows absolute deformation measurements in three spatial dimensions with dense sampling in time, but lacks dense sampling in space; InSAR on the other hand allows dense sampling of deformation measurements in space over large areas, but only provides measurement in the radar Line-of-Sight and is limited by the satellite revisit time in terms of temporal sampling. Combining results from both techniques can yield a complete picture of deformation patterns in time and space.

This report describes results from applying GPS and InSAR techniques on the Krafla and Þeistareykir areas. It includes results from the 2011 GPS campaign, described in Chapter 2. In the summer of 2011, two new continuous GPS stations were installed, as described in Chapter 3. Finally, Chapter 4 presents preliminary results from an analysis of radar data using current InSAR techniques, providing a look back in time of the evolution of ground deformation all the way to 1993.

# Chapter 2

# 2011 GPS campaign and data analysis

The 2011 GPS campaign in the Þeistareykir and Krafla region consisted of two phases. During the first phase in the beginning of August, 39 new Þeistareykir benchmark points were installed in cooperation with ISOR, and 55 benchmarks in total were measured in Krafla and Þeistareykir. During the second phase in the beginning of September, several points in Þeistareykir were remeasured for an extended period of time, and several additional points in Krafla were measured to complete the spatial coverage.

The measurements were performed using a tripod setup, centered over a fixed benchmark. The antennas used were all Trimble Zephyr geodetic antennas, and the receivers used were Trimble 5700 and Trimble R7. The stations were measured for a time span ranging from half a day to several days, depending on the site. Some sites were measured to provide accurate coordinates for the gravity measurements performed by ISOR. These stations were typically only measured for 12-24 hours. The stations which either have had measurements in previous years, or are considered to be important for future time series were measured for at least 48 hours.

Fig. 2.1 and 2.2 show maps of the location of the measured points during the 2011 campaign points. The newly installed and measured benchmarks in Þeistareykir result in this area being the most densely measured area in Iceland by GPS.

The data collected during the campaign was analysed using the GAMIT/ GLOBK software [*Herring et al.*, 2010], using several continuous stations throughout Iceland and abroad to obtain precise coordinates for each station in the ITRF2005 reference frame. The resulting coordinates are given in Appendix A.

Fig. 2.3 shows the time series for the THER station at Þeistareykir,

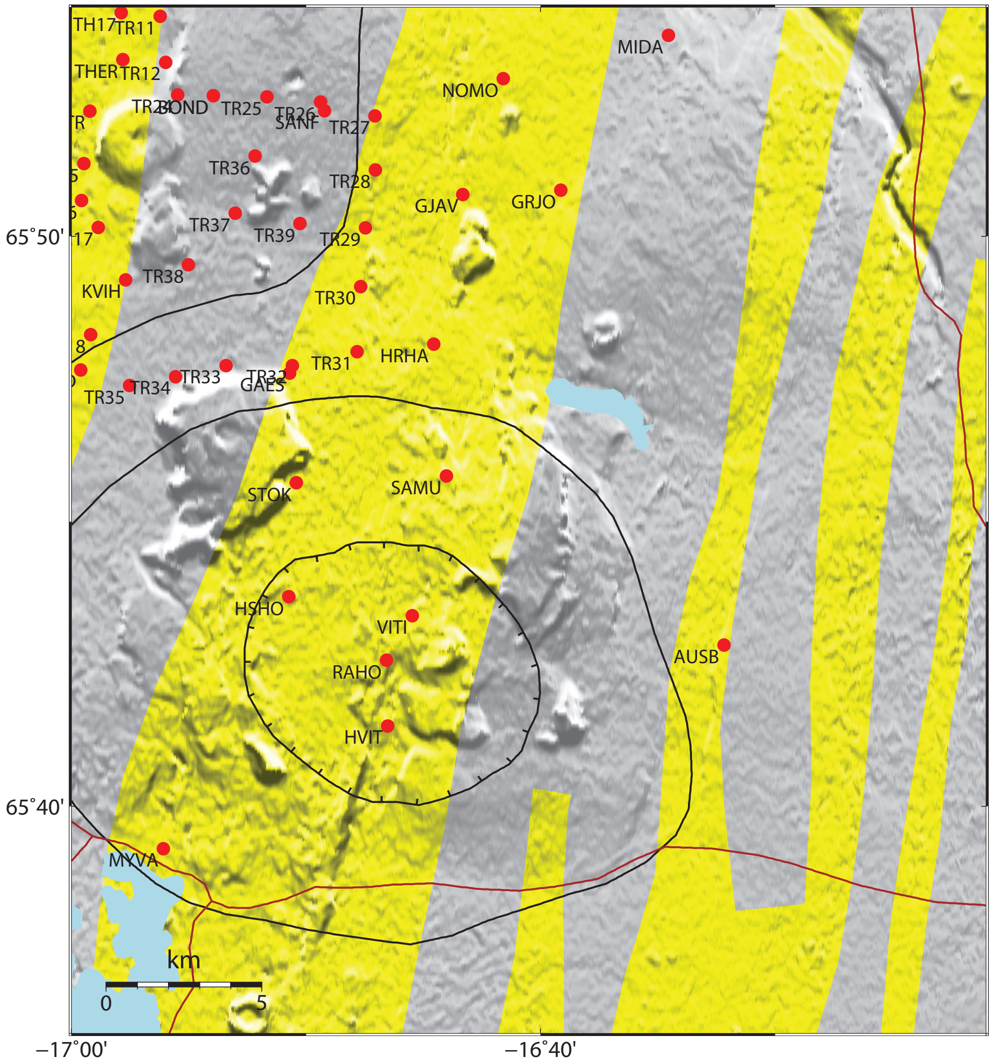



Figure 2.1: Map of the Krafla and Gjástykki area, showing the 2011 campaign stations.

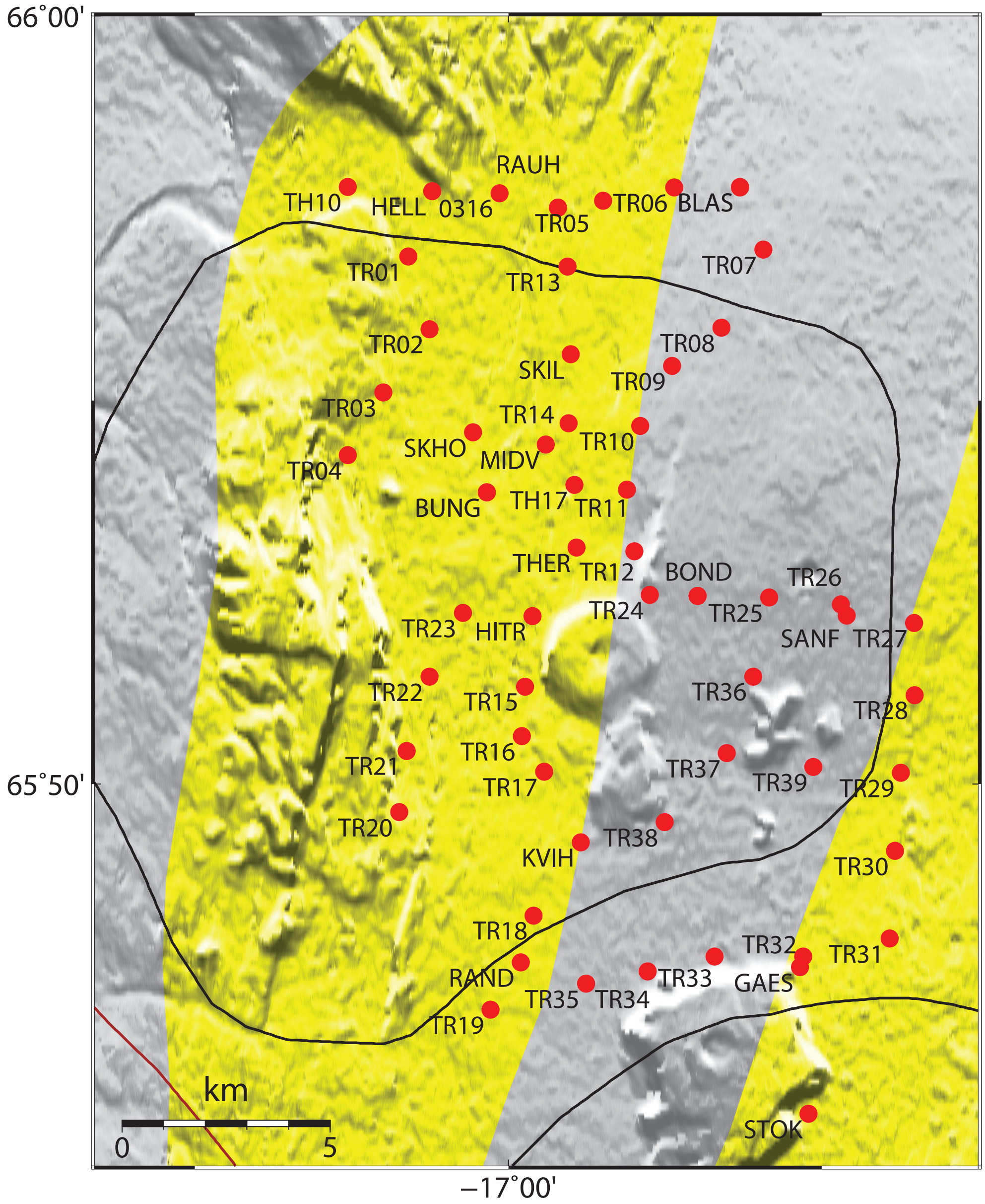



Figure 2.2: Map of the Þeistareykir area, showing the 2011 campaign stations. Th points with ID's starting with TR followed by 2 numbers are the newly installed points.

utilizing data from all the campaigns performed between 1997 and 2011. Interesting to note is the eastward shift of the station this year. The station was measured both in the August and the September 2011 trip, and both independent measurements show the shift. Data from other stations in Þeistareykir which have measurements in previous years are currently being analysed using the new software, and results from them should follow in the near-future. This will provide more insight in the overall deformation pattern in the area.

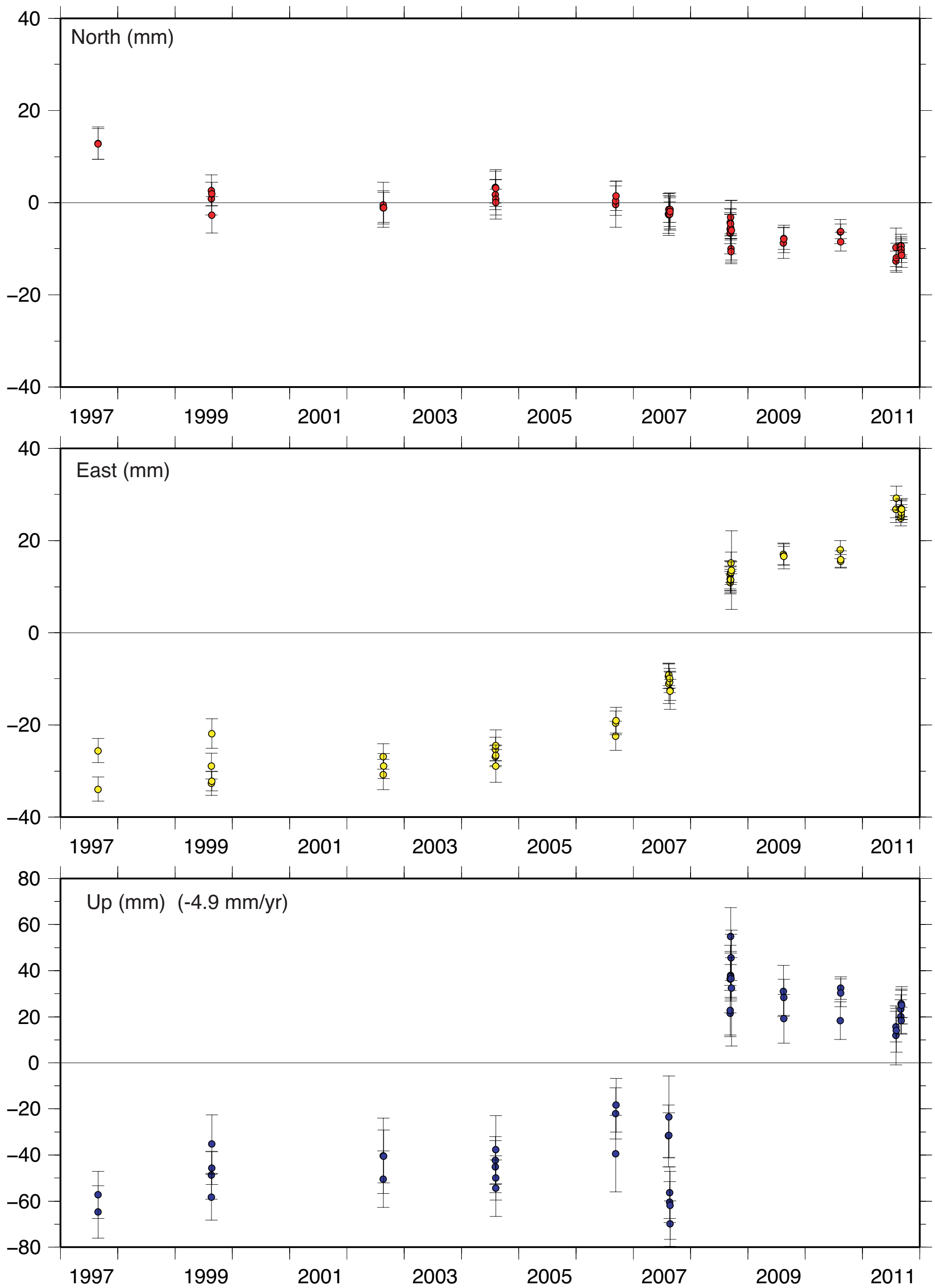



Figure 2.3: Detrended time series results in north, east and up components of station THER between 1997 and 2011.

# Chapter 3

# Continuous GPS stations KRAC and THRC

In the summer of 2011, Landsvirkjun provided funding for two new continuous GPS stations. In early September, the THRC station was installed by Sveinbjörn Steinþorsson and Karsten Spaans, about 3 meters away from the campaign benchmark BUNG in the Þeistareykir area. This station is located close to the center of uplift resulting from the 2007-2008 intrusion in the area. In early November, the second continuous station, KRAC, was installed in the Krafla area by the same team. The station is located about 750 meters south of the geothermal energy plant in Krafla, and about 6 meters away from a meteorological station operated by Landsvirkjun. Fig. 3.1 shows the location of the two new stations.

Both stations are equipped with a Trimble Zephyr Geodetic antenna mounted on a steel quadripod bolted to bedrock. They utilize Trimble receivers, a NetRS for THRC and a NetR9 for KRAC. Due to the close proximity to the meteorological station of KRAC, electricity was available from Landsvirkjun to power that station. The much more remote THRC station is equipped with a solar panel and a windmill to charge its battery. The collected data can be downloaded from the instrument using GSM connections to routers installed at the stations, allowing daily monitoring of the deformations. Fig. 3.2 and 3.3 shows photographs of the THRC and KRAC station setups, respectively.

After installation, both THRC and KRAC stations have been logging data continuously. Fig. 3.4 and Fig. 3.5 show time series results for THRC and KRAC, respectively. Websites were created for both stations, where an overview of the stations, including daily updates of the time series, can be found. The websites are:
http://strokkur.raunvis.hi.is/∼sigrun/THRC.html

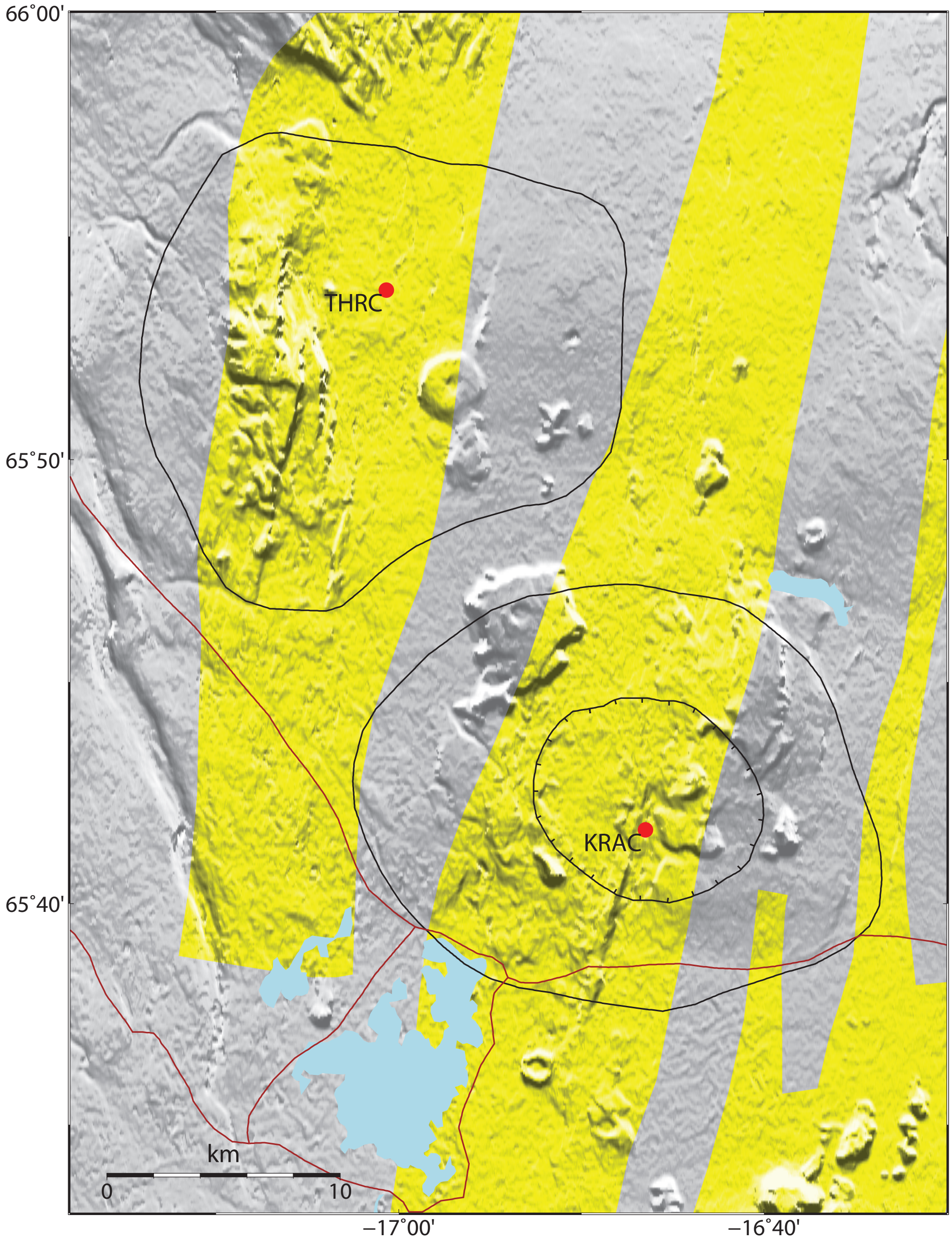
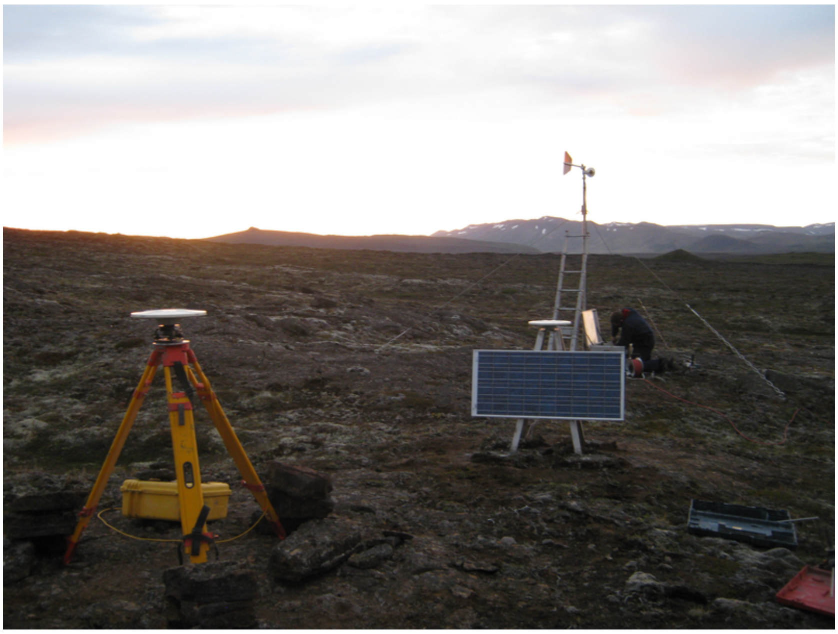
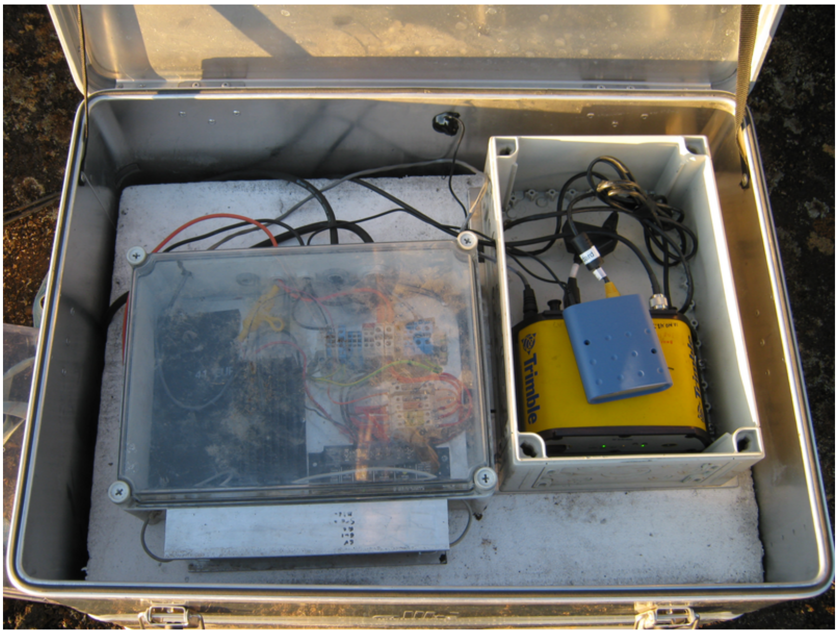



Figure 3.1: Map of the Krafla and Þeistareykir area, showing the locations of the new continuous GPS sites KRAC and THRC. The black lines indicate the central volcanoes of Krafla and Þeistareykir, and the hatched line shows the Krafla caldera. The brown lines show main roads. The yellow areas give the locations of fissure swarms in the area. The background is shaded relief, generated using a DEM.

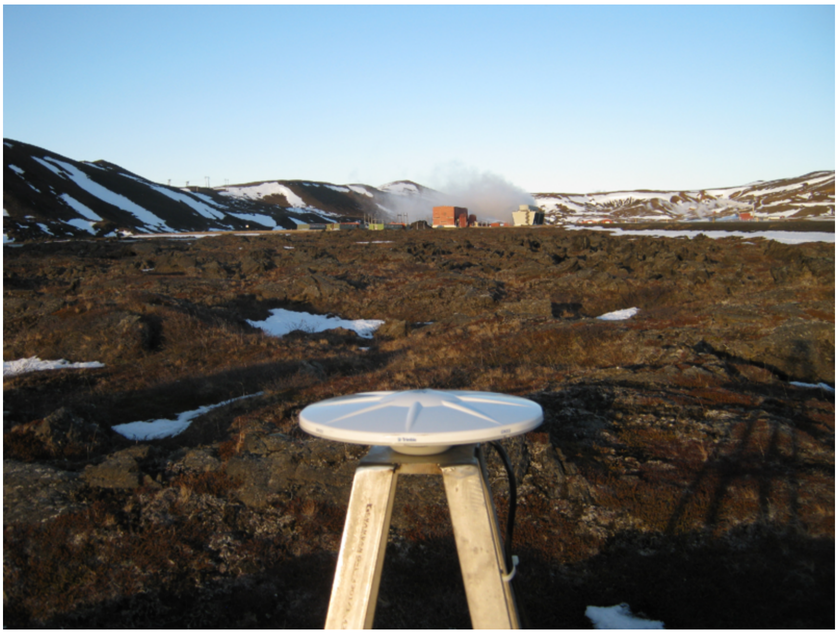


(a)

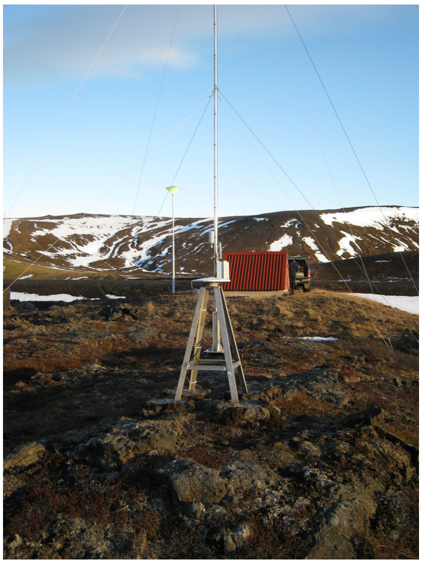



(b)

Figure 3.2: Photographs of THRC continuous station: a) Campaign station BUNG running together with THRC; b) Boxes containing the receiver and router (right) and electrical systems (left).



(a)



(b)

(c)

Figure 3.3: Photographs of KRAC continuous station: a) The antenna mounted on the steel quadripod, with the Krafla power plant on the background ; b) View from the quadripod to the meteorological station. The GPS receiver is located inside the little hut in the background; c) Boxes holding the receiver (left) and the router plus electrical systems (right).

http://strokkur.raunvis.hi.is/∼sigrun/KRAC.html

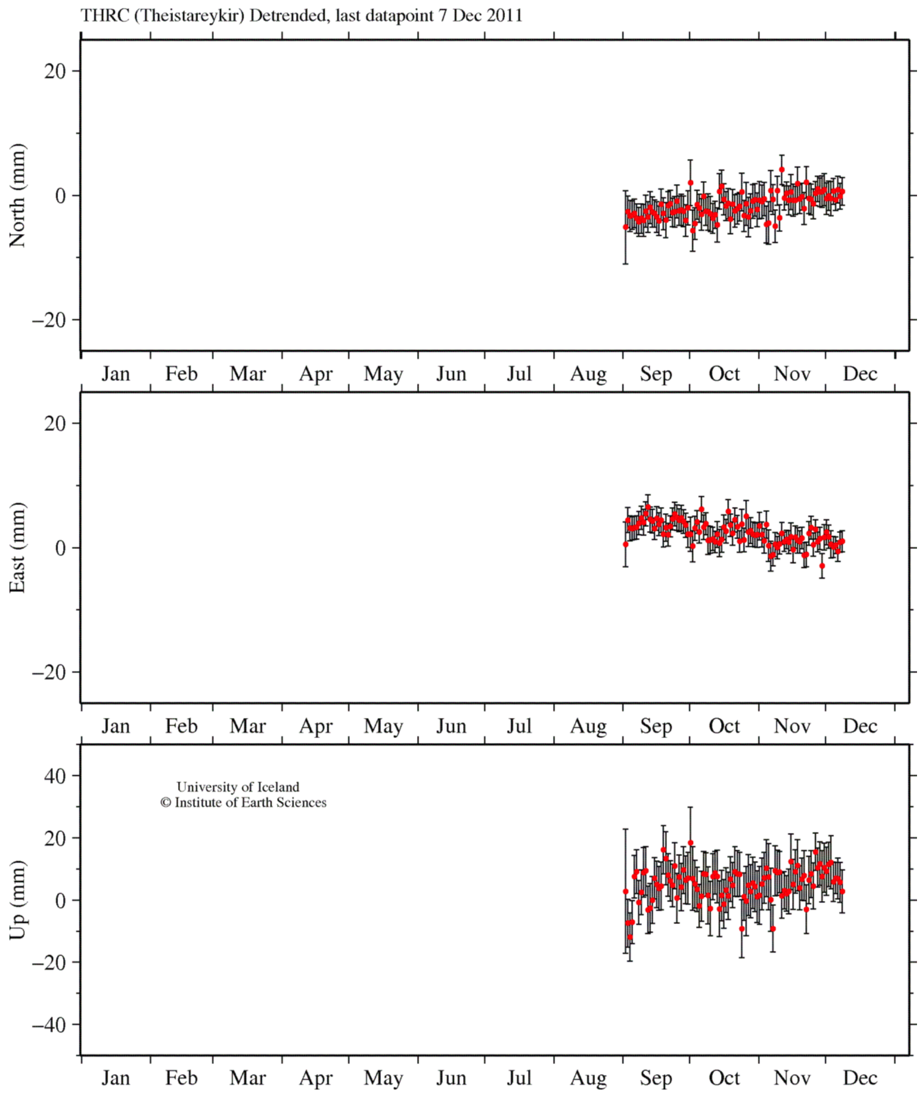



Figure 3.4: Time series plot showing deformation of station THRC in north, east and up components. Data collection started on September 1st 2011, the graph was extracted on December 7th 2011.

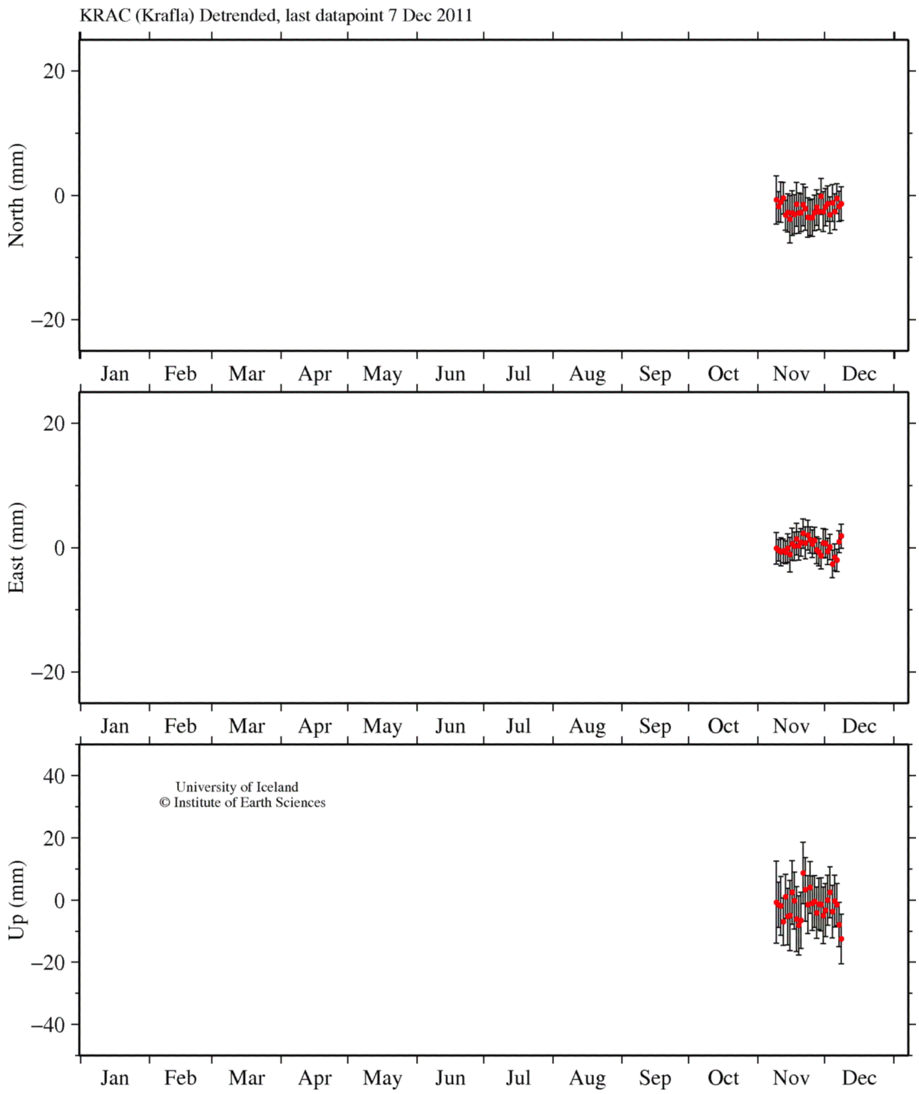



Figure 3.5: Time series plot showing deformation of station KRAC in north, east and up components. Data collection started on November 8th 2011, the graph was extracted on December 7th 2011.

# Chapter 4

# InSAR study

Radar data collected since 1993 by the ERS missions and since 2003 by the Envisat mission provides a valuable look back in time. Using the current processing techniques, based on time series analysis to select high signal-to-noise ratio points [*Hooper et al.*, 2007], we are able to extract accurate deformation measurements. Radar can only resolve for deformations in its line-of-sight (LOS), which for radar satellites is slightly off vertical, with an average angle of 23 degrees from vertical for the satellites used in this report. Furthermore, the satellites are located in a near-polar orbit, which makes the heading of the satellite ground track at Iceland's latitude 340 degrees (north-north west) in the ascending and 160 degrees (south-south east) in the descending track. Using this information, correcting for effects related to the curvature of the Earth, we can define the LOS deformation as:

$$d_{LOS} = \begin{bmatrix} d_U & d_N & d_E \end{bmatrix} \begin{bmatrix} u_U \\ u_N \\ u_E \end{bmatrix},$$

where $d_U$, $d_N$ and $d_E$ are the deformations in up, north and east directions, respectively, and $[\ u_U \quad u_N \quad u_E\ ]^T$ is the unit vector in LOS direction. The unit vector varies over the scene, but on average has values of$[\ 0.93 \quad -0.1 \quad -0.35\ ]^T$ for ascending and $[\ 0.93 \quad -0.1 \quad 0.35\ ]^T$ for descending tracks. This clearly results in a high sensitivity to vertical deformations, but also some sensitivity to deformations in east-west direction. Furthermore, deformations in east-west direction can be distinguished from deformations in the vertical (and, to a small extent, in north-south direction) by making linear combinations of ascending and descending tracks.

The radar data presented here consists of three tracks. ERS track 9 is a descending track, in which we have 23 radar images in the period September 1992 until July 2002. For Envisat we have track 9 available as well, which provides 13 radar images between September 2003 until October 2008. Finally, Envisat track 230 is an ascending track, in which we obtained 14 images spanning July 2004 until August 2010. For every track, we generated conventional interferograms of every image with respect to a single master using the DORIS software [*Kampes*, 1999], and performed our time series analysis to select high quality points using the StaMPS software [*Hooper et al.*, 2007].

Fig. 4.1, 4.2 and 4.3 show initial results from these analyses. It must be noted that there is a difference in colour bar scales for the ERS tracks and the two Envisat tracks. The velocity plots shed more light on some of the processes previously identified. The wide uplift pattern to the north of Krafla seems to be still ongoing in the 2003-2010 period at a reduced rate, which was previously unsure. Also, from the difference between the ascending Envisat track 230 (4.3) and the descending Envisat track 9 (4.2), we can deduce that there is a significant horizontal component present in the signal. This suggests a complicated deformation process that needs to be evaluated further. The LOS change associated with the inferred 2007-2008 intrusion at Þeistareykir can clearly be seen on the Envisat plots. It must be noted that the velocities here are not representative for the true velocities, as this was a relatively short event, and the velocities are estimated over the full timespan. The campaign GPS results described in *Ófeigsson et al.* [2010] show that the deformation between 2007 and 2008 was 7-8 cm.

A persistent deformation pattern along the central part of the Krafla fissure swarm can be seen, in both the ERS and Envisat velocity results. The subsidence inside the caldera seems to have significantly reduced in the latter plots. The subsidence at the Bjarnarflag geothermal field however seems to continue at a relatively steady rate throughout the entire period.

These initial InSAR time series provide important information on deformation, especially on its spatial pattern. Further work is required to extract all the information available. The next steps include obtaining an ascending ERS track to complete the picture for the period 1993-2002. Also, combining the two tracks for each satellites into the linear combinations to distinguish vertical deformation from east-west motion will have a high priority in the near future.

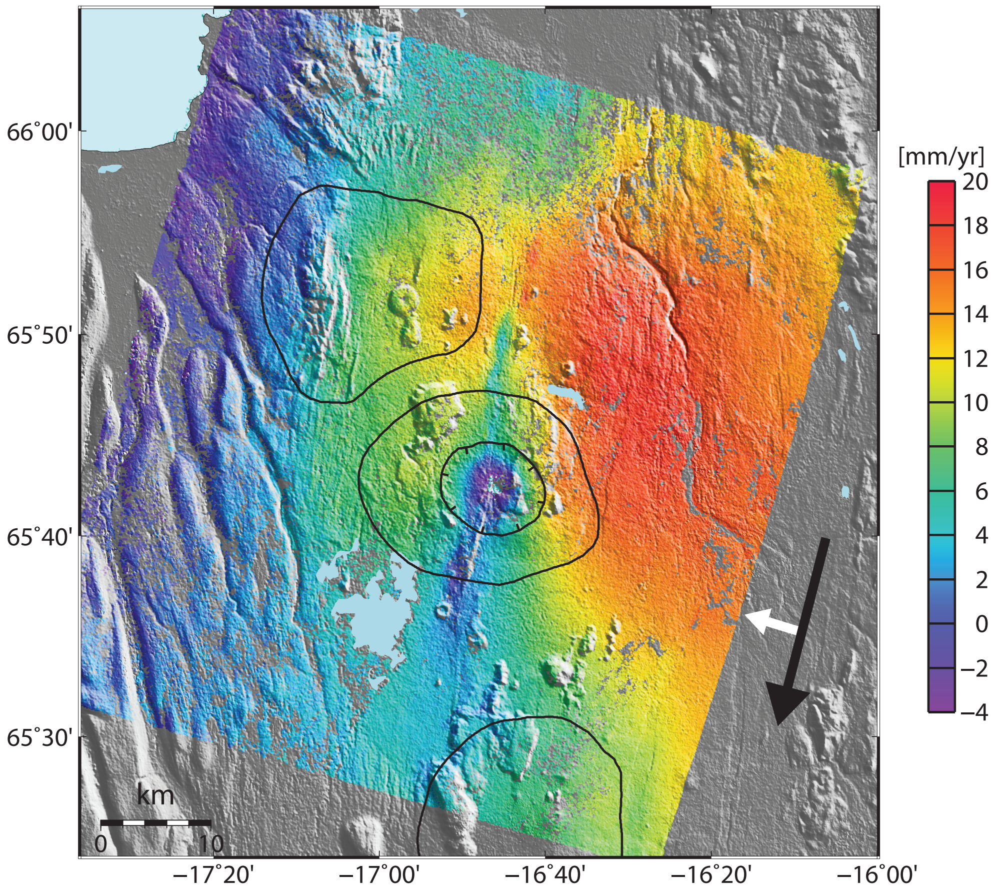



Figure 4.1: Average LOS velocity estimate for descending ERS track 9, spanning the period 1993-2002. The black arrow shows the flight direction, while the white arrow shows the projection of the look direction on the horizontal plane.

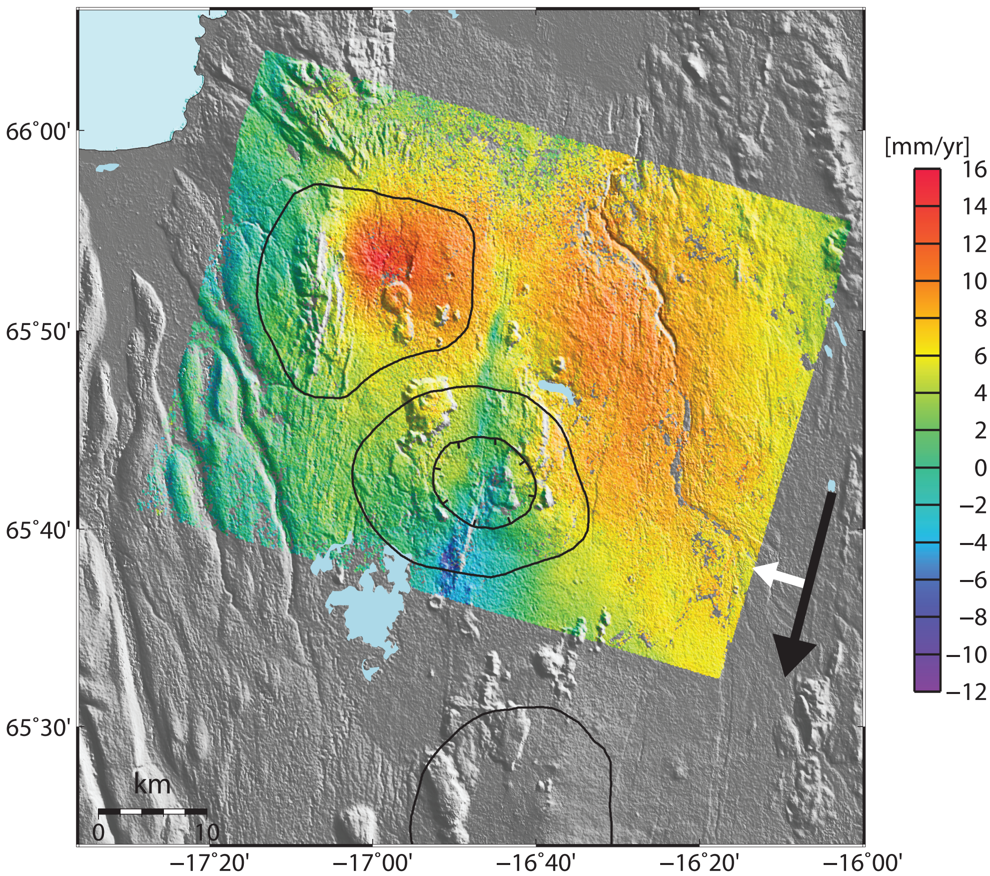



Figure 4.2: Average LOS velocity estimate for descending Envisat track 9, spanning the period 2003-2010. The black arrow shows the flight direction, while the white arrow shows the projection of the look direction on the horizontal plane.

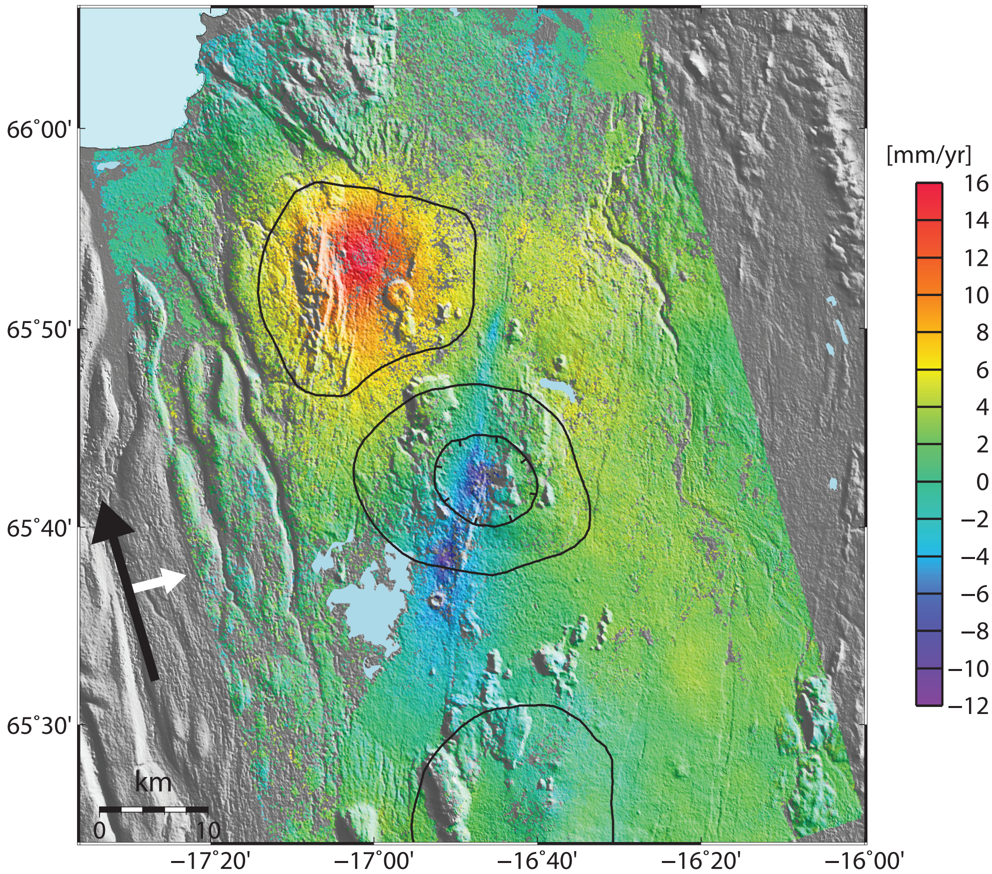



Figure 4.3: Average LOS velocity estimate for ascending Envisat track 230, spanning the period 2003-2008. The black arrow shows the flight direction, while the white arrow shows the projection of the look direction on the horizontal plane.

# Appendix A

# GPS campaign sites

In the table below, the coordinates of the measured campaign sites in Þeistareykir and Krafla, as well as several continuous GPS stations spread around Iceland, can be found. The coordinates are referenced to ITRF2005.

| Station ID | Decimal date | Latitude [deg] | Longitude [deg] | Height [m] |
|---|---|---|---|---|
| 0316 | 2011.595 | 65.961648133 | -17.004799613 | 341.1244 |
| 5699 | 2011.695 | 65.650189716 | -16.791942091 | 427.2426 |
| AKUR | 2011.694 | 65.685425870 | -18.122481740 | 134.2048 |
| ARHO | 2011.714 | 66.193072490 | -17.109042735 | 123.9504 |
| AUSB | 2011.697 | 65.714115949 | -16.536316429 | 478.4565 |
| BLAS | 2011.666 | 65.962930824 | -16.876845729 | 332.1158 |
| BOND | 2011.651 | 65.874200795 | -16.899340637 | 564.9916 |
| BUNG | 2011.656 | 65.896734598 | -17.011343238 | 373.4740 |
| GAES | 2011.597 | 65.793249388 | -16.844892930 | 555.0102 |
| GJAV | 2011.603 | 65.845487618 | -16.721926168 | 474.5496 |
| GRAE | 2011.678 | 65.522417225 | -17.016807512 | 351.5771 |
| GRAN | 2011.703 | 65.918659423 | -17.578607980 | 86.8345 |
| GRJO | 2011.605 | 65.846708532 | -16.652208929 | 458.0450 |
| HELL | 2011.593 | 65.962031887 | -17.040406998 | 339.6114 |
| HITR | 2011.588 | 65.869774529 | -16.987100047 | 392.4337 |
| HOFN | 2011.722 | 64.267292831 | -15.197918645 | 82.8041 |
| HRHA | 2011.604 | 65.801825072 | -16.742531916 | 563.7258 |
| HSHO | 2011.698 | 65.728012911 | -16.845950170 | 611.4689 |
| HVIT | 2011.609 | 65.690218282 | -16.775283475 | 517.1941 |
| KRAC | 2011.860 | 65.694499773 | -16.774914221 | 521.9348 |
| KVIH | 2011.588 | 65.820575981 | -16.961511663 | 466.0240 |
| LV20 | 2011.694 | 65.632824391 | -16.844924260 | 398.8184 |
| MIDA | 2011.604 | 65.891746157 | -16.575795885 | 379.9188 |

| | | | | |
|---|---|---|---|---|
| MIDV | 2011.671 | 65.907081680 | -16.979979386 | 372.4959 |
| MYVA | 2011.618 | 65.642320506 | -16.891352741 | 370.6131 |
| MYVN | 2011.694 | 65.654046474 | -16.934799081 | 358.3896 |
| NOME | 2011.676 | 65.773226764 | -16.341668143 | 430.5354 |
| NOMO | 2011.605 | 65.879193989 | -16.693278117 | 467.8018 |
| RAHO | 2011.676 | 65.709505867 | -16.776232746 | 623.3761 |
| RAND | 2011.590 | 65.794362075 | -16.993403710 | 463.9286 |
| RAUH | 2011.588 | 65.958510245 | -16.973718055 | 347.9955 |
| REYK | 2011.723 | 64.138785369 | -21.955487248 | 93.0377 |
| SAMU | 2011.676 | 65.763315437 | -16.733800198 | 703.0264 |
| SANF | 2011.597 | 65.869886562 | -16.820171456 | 604.9466 |
| SAVI | 2011.707 | 65.993185752 | -17.376103728 | 135.4053 |
| SKHO | 2011.593 | 65.909729624 | -17.018837488 | 356.7736 |
| SKIL | 2011.588 | 65.926663101 | -16.966766810 | 361.7632 |
| STOK | 2011.698 | 65.761337751 | -16.840527029 | 582.4803 |
| TH10 | 2011.589 | 65.963010762 | -17.085464730 | 349.3468 |
| TH17 | 2011.595 | 65.898335784 | -16.964854312 | 389.7983 |
| THER | 2011.657 | 65.884703115 | -16.963636916 | 401.5755 |
| THRC | 2011.764 | 65.896770533 | -17.011335199 | 374.2065 |
| TR01 | 2011.595 | 65.947926145 | -17.053164057 | 338.3420 |
| TR02 | 2011.593 | 65.932172478 | -17.041779928 | 337.3272 |
| TR03 | 2011.589 | 65.918433236 | -17.066531443 | 359.7371 |
| TR04 | 2011.590 | 65.904748483 | -17.085273283 | 380.3353 |
| TR05 | 2011.600 | 65.959963982 | -16.949608948 | 320.5869 |
| TR06 | 2011.597 | 65.962843253 | -16.911944878 | 334.8619 |
| TR07 | 2011.595 | 65.949348179 | -16.864324906 | 382.1212 |
| TR08 | 2011.595 | 65.932503927 | -16.886636588 | 423.5837 |
| TR09 | 2011.595 | 65.924168452 | -16.912897784 | 431.5617 |
| TR10 | 2011.592 | 65.911152880 | -16.929767945 | 437.4516 |
| TR11 | 2011.589 | 65.897312095 | -16.936959894 | 422.1717 |
| TR12 | 2011.596 | 65.883980177 | -16.933038965 | 414.9616 |
| TR13 | 2011.592 | 65.945735271 | -16.968584454 | 350.9375 |
| TR14 | 2011.663 | 65.911661274 | -16.967955177 | 379.4697 |
| TR15 | 2011.595 | 65.854493858 | -16.991167462 | 398.2604 |
| TR16 | 2011.587 | 65.843715849 | -16.992833827 | 415.8297 |
| TR17 | 2011.587 | 65.835924750 | -16.981051061 | 447.1987 |
| TR18 | 2011.591 | 65.804620657 | -16.986410967 | 461.0459 |
| TR19 | 2011.603 | 65.784058942 | -17.009436963 | 460.0747 |
| TR20 | 2011.589 | 65.827163190 | -17.057997954 | 458.9087 |
| TR21 | 2011.589 | 65.840545004 | -17.054181509 | 408.0731 |
| TR22 | 2011.592 | 65.856698116 | -17.042058543 | 387.3518 |

| | | | | |
|---|---|---|---|---|
| TR23 | 2011.593 | 65.870473874 | -17.024201494 | 379.3485 |
| TR24 | 2011.600 | 65.874431939 | -16.924726467 | 543.4332 |
| TR25 | 2011.600 | 65.873897201 | -16.861175628 | 586.4956 |
| TR26 | 2011.599 | 65.872397162 | -16.823090636 | 581.7503 |
| TR27 | 2011.600 | 65.868343506 | -16.784332172 | 537.0538 |
| TR28 | 2011.599 | 65.852645951 | -16.784087692 | 512.5885 |
| TR29 | 2011.600 | 65.835730203 | -16.791262670 | 496.5019 |
| TR30 | 2011.600 | 65.818664752 | -16.794556194 | 511.9706 |
| TR31 | 2011.600 | 65.799581890 | -16.797114168 | 573.8137 |
| TR32 | 2011.599 | 65.795579078 | -16.843219347 | 535.9734 |
| TR34 | 2011.599 | 65.792366509 | -16.925965060 | 489.7817 |
| TR35 | 2011.602 | 65.789726169 | -16.958663297 | 468.3139 |
| TR36 | 2011.603 | 65.856703546 | -16.869736406 | 564.7766 |
| TR37 | 2011.599 | 65.840013503 | -16.883806172 | 499.1940 |
| TR38 | 2011.597 | 65.824974382 | -16.916935696 | 502.0153 |
| TR39 | 2011.599 | 65.836963158 | -16.837778935 | 515.4464 |
| VITI | 2011.676 | 65.722515326 | -16.758175643 | 628.5559 |

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