Crustal deformation studies in Krafla, Gjástykki, Bjarnarflag and Þeistareykir areas utilizing GPS and InSAR

Status report for 2012

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INTRODUCTION

Crustal deformation studies at Krafla, Þeistareykir, Gjástykki, and Bjarnarflag geothermal areas in the Northern Volcanic Zone (NVZ) were continued in 2012, utilizing Global Positioning System (GPS) geodesy and Interferometric Synthetic Aperture Radar (InSAR) analyses. Results from earlier studies include:

- **Krafla**: The most recent volcanic activity in the area was the Krafla rifting episode 1975-1984. Gradual uplift continued until 1989, five years after the last eruption, due to pressure increase in the shallow magma chamber under the center of the Krafla caldera. In 1989, the area began to subside at a fast rate of more than 5 cm/yr. The rate of subsidence decayed at an exponential rate. The estimated subsidence rate in 2006 was lower than 3 mm/yr [Sturkell et al., 2008].

  Following this development, the area of maximum rate of subsidence shifted 1.6 km SSE, from being directly above the shallow magma chamber, towards the array of boreholes in the Leirbotnar area. Similar subsidence has been observed around the array of boreholes at Bjarnarlag [Sturkell et al., 2008].

  A broad uplift signal has also been detected north and north-east of Krafla. Initially this was only detected during the 1990s, but recent processing results have shown that the signal persisted in the 2003-2010 period [Spaans et al., 2012]. Candidate explanations include magma accumulation near the crust/mantle boundary and/or post-rifting relaxation.

  Plate spreading across the NVZ and associated subsidence along the Krafla fissure swarm produce a clear deformation signal.

- **Þeistareykir**: Inflation of the area is observed from 2007-2008 suggesting magma intrusion [Metzger et al., 2011; Spaans et al., 2012].

- **Glacial isostatic adjustment needs to be considered as well, because ongoing retreat of ice caps in Iceland is influencing the area [Árnadóttir et al., 2009; Auriac et al., 2013].

The present report describes results from applying GPS and InSAR techniques in the Krafla and Þeistareykir areas. It describes both GPS campaign measurements carried out in 2012 as well as continuous measurements, including the installation of one new continuous GPS station in Bjarnarflag (Chapter 2). An overview is also presented on satellite synthetic aperture radar (SAR) data (Chapter 3) acquired 2009-2012 for the purpose of carrying out interferometric analysis (InSAR).
GPS campaign measurements were carried out in July, August, and late November 2012. A total of 79 stations were measured in Krafla, Gjástykki, Bjarnarflag, and Þeistareykir areas. Furthermore, a new continuous GPS station, named BJAC, was installed in Bjarnarflag, east of lake Myvatn.

GPS instruments used for the measurements are from the Institute of Earth Sciences (IES), UNAVCO, and King Abdullah University of Science and Technology (KAUST).

- Receivers: Trimble 5700, R7 and NET R9.
- Antennas: Trimble Zephyr Geodetic (TRM41249.00) and Trimble Zephyr Geodetic II (TRM57971.00).

Each campaign GPS station was measured for at least 24 hours, sampling data every 15 seconds.

The following people participated in the 2012 GPS measurements: From IES: Karsten Spaans, Sveinbjörn Steinþórsson, Vincent Drouin, Halldór Ólafsson, Karolina Michalczewska, Ásta Rut Hjartardóttir, Amandine Auriac, Freysteinn Sigmundsson, Sigrún Hreinsdóttir. From Gothenburg University, Sweden: Erik Sturkell

The data were analyzed at the University of Iceland using the GAMIT/GLOBK analysis software [Herring et al., 2010a; Herring et al., 2010b] using over 100 global reference stations to determine stations coordinates in the ITRF08 reference frame.

The resulting coordinates of the 79 GPS stations measured are presented in Table 2.2.
2.1 Summer 2012 GPS campaign

Figure 2.1: Map of measured GPS stations. Red diamonds show campaign GPS sites; red diamonds with blue core show continuous GPS sites. Map reference system: ISN93. Background map shows volcanic systems [Einarsson and Sæmundsson, 1987; Hjartardóttir et al., 2012]: fissure swarms (light brown), approximate extent of the Peistareykir, Krafla, and Fremri-Námar central volcanoes (dashed lines) and the Krafla caldera (comb line).
Table 2.2: 2012 GPS coordinates given in the ITRF08 reference system. Latitude and longitude are in decimal degrees. Height and cartesian coordinates are in meters. Date is in decimal year. Notice that BOTF is also known as BF15, HVRO as BF16 and HVFJ as BF17.
2.2 Continuous GPS stations

Continuous GPS measurements allow us to better quantify and understand time-dependent and secular deformation signals. In Iceland we have several sources of crustal deformation. Plate spreading, glacial isostasy, earthquakes, volcanic activity, and changes in geothermal fields (including changes due to utilization) are among different sources we can expect in the NVZ. In order to better understand and distinguish between the different sources and detect and understand transient signals we need to have both good spatial and time resolution of geodetic data. Campaign GPS and InSAR data provide us with good spatial resolution and the continuous GPS stations help resolve time dependent signals and improve accuracy of network solutions.

A new continuous GPS station, named BJA C, was installed in Bjarnarflag, on 25 October 2012 by Sveinbjörn Steinþórsson and Karsten Spaans from IES (Fig. 2.2). Time series of the data gathered since the installation are shown in Figure 2.3.

Figure 2.2: Picture of Bjarnarflag continuous GPS station (BJAC). It is supplied with both wind and solar energy.
2.2 Continuous GPS stations

Figure 2.3: GPS time series for Bjarnarflag GPS station. Displacements are presented in the ITRF08 reference frame subtracting velocities of 22.5 mm/yr, 0.8 mm/yr and 0.5 mm/yr in the north, east and up components. The time series are too short to evaluate BJAC velocity in ITRF08 so we assumed the values to be the same as for the nearest continuous GPS station, MYVA.
2.2 Continuous GPS stations

In addition, there are three other continuous GPS stations:

- **THR C**: Installed in Þeistareykir on 1 September 2011 by the Institute of Earth Sciences.

- **KRAC**: Installed in Krafla on 8 November 2011 by the Institute of Earth Sciences.

- **MYVA**: Installed near Myvatn on 31 August 2006 by Christof Völksen from the Commission for Geodesy and Glaciology, Bavarian Academy of Sciences and Humanities.

The data were analyzed at the University of Iceland using the GAMIT/GLOBK 10.4 analysis software using over 100 global reference stations to determine stations coordinates in the ITRF08 reference frame. We show detrended time series for the North, East and Up components. The trend of each component (East, North and Up) is computed (by minimizing the standard deviation) and subtracted from the time series. The trends give us the average velocities in each direction. When the average velocity is subtracted from the time series, it is flattened.

Detrended GPS time series from these sites are shown in Figs 2.4, 2.5 and 2.6. None of them is showing any significant deviations from the zero value that would relate to unusual deformation or displacements rate deviating from linear trends. The data from the continuous sites provides excellent reference to check for future irregularities of displacements that may arise from e.g. future utilization of the area.

The following velocities have been calculated for each continuous GPS station:

<table>
<thead>
<tr>
<th></th>
<th>North [mm/year]</th>
<th>East [mm/year]</th>
<th>Upp [mm/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>THRC</td>
<td>21.3 ± 0.3</td>
<td>-5.6 ± 0.3</td>
<td>3.1 ± 1.0</td>
</tr>
<tr>
<td>KRAC</td>
<td>23.1 ± 0.3</td>
<td>0.4 ± 0.3</td>
<td>-1.9 ± 1.4</td>
</tr>
<tr>
<td>MYVA</td>
<td>22.5 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>0.5 ± 0.3</td>
</tr>
</tbody>
</table>

Table 2.3: Station velocities in the ITRF08 reference system.
2.2 Continuous GPS stations

Figure 2.4: GPS time series for the Þeistareykir GPS station. Displacements are detrended using secular velocities of 21.3 mm/yr, -5.6 mm/yr and 3.1 mm/yr in the ITRF08 and annual and semi-annual terms estimated using time series analysis.
2.2 Continuous GPS stations

Figure 2.5: GPS time series for the Krafla GPS station. Displacements are detrended using secular velocities of 23.1 mm/yr, 0.4 mm/yr and -1.9 mm/yr in the ITRF08 and annual and semi-annual terms estimated using time series analysis.
2.2 Continuous GPS stations

Figure 2.6: GPS time series for the Myvatn GPS station. Displacements are detrended using secular velocities of 22.5 mm/yr, 0.8 mm/yr and 0.5 mm/yr in the ITRF08 and annual and semi-annual terms estimated using time series analysis.
2.3 Velocity field 2010-2012

A velocity field has been calculated based on the GPS data collected in 2010, 2011 and 2012 (Figs 2.7 and 2.8). Velocities were initially estimated in the ITRF08 reference frame. Then, using the ITRF2008 plate motion model [Altamimi et al., 2012], they are converted into velocities relative to the Eurasian plate or the North-American plate.

Velocities relative to a particular plate allow, in our case, the determination of the style of stretching across the NVZ and, furthermore, to check if other other deformation sources in addition to plate stretching are active. At the NVZ divergent plate boundary, the full relative plate velocity is 18.6 mm/yr according the NUVEL-1A model [DeMets et al., 1990; DeMets et al., 1994], with an azimuth of 105/285 degrees, depending on which plate is the reference.

Vertical velocities are independent of any reference plate. Detailed map of the vertical velocities for Krafla and Þeistareykir areas are available (Figs 2.10 and 2.13).

Only the GPS velocities with an uncertainty of 1 cm or better in the vertical component are shown in all the following figures.

2.3.1 North-American plate as reference

GPS stations near Húsavík show little velocity relative to stable North-American plate (Fig 2.7). However, there appears to be some effect of the Húsavík-Flatey fault, which is a right-lateral transform fault. GPS station south of Húsavík are moving north-west while GPS stations north of the village are moving north-east.

The whole data set shows well how eastward horizontal velocities increase gradually across the plate boundary, from west to east across the swarms marking the plate boundary. For example, the horizontal velocities are only few mm/yr near Húsavík but reach full plate velocities at the NOME benchmark to the east of the plate boundary.

Detailed maps of the horizontal velocities relative to the North-American plate for Krafla and Þeistareykir areas are shown in Figs 2.9 and 2.12.

2.3.2 Eurasian plate as reference

By changing the reference plate to Eurasia, the velocity field is “reversed”. Horizontal velocities now gradually increase towards the west.

The NOME station, the most easterly GPS station, is not showing any velocity in the horizontal component (Fig 2.8). It is following exactly the same motion as the Eurasian plate. This means the GPS benchmark is located on a stable part of the plate. On the other plate, near Húsavík the velocities are about 14-15 mm/yr.

Detailed map of the horizontal velocities relative to the Eurasian plate for Krafla and Þeistareykir areas are shown in Figs 2.10 and 2.13.
Figure 2.7: GPS velocities relative to stable North-American plate. Map reference system: ISN93. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.
Figure 2.8: GPS velocities relative to stable Eurasian plate. Map reference system: ISN93. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.
2.3.3 Velocities in the Krafla area

Figure 2.9: Horizontal GPS velocities in the Krafla area relative to stable North-American plate. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.

Figure 2.10: Horizontal GPS velocities in the Krafla area relative to stable Eurasian plate. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.
2.3 Velocity field 2010-2012

### 2.3.4 Velocities in the Þeistareykir area

Figure 2.12: Horizontal GPS velocities in the Þeistareykir area relative to stable North-American plate. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.
Figure 2.13: Horizontal GPS velocities in the Beistareykir area relative to stable Eurasian plate. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.

Figure 2.14: Vertical GPS velocities in the Beistareykir area. Background is same as Fig 2.1. Ellipses at arrow heads show 95% confidence intervals.
2.3.5 Interpolation of the 2010-2012 velocity field

Velocities have been interpolated using regularized spline with tension (RST). This is an interpolation method which aims to pass through (or close to) the input data points and at the same time make the resulting surface as smooth as possible [Cebecauer et al., 2002]. RST has been chosen instead of other methods because of our GPS velocities network: GPS benchmarks do not coincide with maximum displacements. The velocity field is also assumed to be a smooth surface with no ruptures in it as there was no known faulting events during the 2010-2012 time period.

The interpolation has been done with velocities relative to stable Eurasian plate. Zero velocity means then that the station is moving in the same manner as the stable interior of the Eurasian plate. The ITRF08-EURA velocity of a GPS station on the other side of the plate boundary, within the stable interior of the North American Plate would be 18.6 mm/yr in direction 285 degrees.

The interpolated velocity field shows well the overall gradients in velocities with respect to the East axis. Horizontal velocities are almost zero on the Eurasian plate, but about 14 mm/yr west and 4 mm/yr north on the North-American plate. This is in broad agreement with the NUVEL-1A prediction although the spreading is a bit too slow for stations on the North-American plate. This may relate to strain accumulation across the Húsavík-Flatey fault. The velocity of 18.6 mm/yr in direction 285 degrees anticipated from the NUVEL-1A model corresponds to 18.0 mm/yr in the east component, and 4.8 mm/yr in the north.

Figure 2.15: GPS velocities interpolation relative to stable Eurasian plate. Velocities are indicated in millimeters per year. Notice that the color scale is not the same between images. Central volcanoes are represented with hatched lines.
On the East velocities map, small anomalies, about 1-2 mm/yr, are noticeable in the following areas: Þeistareykir, Bjarnarlag, and NE of Krafla.

The North velocities also show an East-West gradient with anomalies in Þeistareykir, Bjarnarlag, and NE of Krafla.

The velocity field shows that Bjarnarlag is moving north and east relative to nearby areas and the area NE of Krafla is moving south and west. These kind of anomalies are generally caused by a subsurface pressure decrease located between the anomalies, related also to subsidence. In our case it means that they relate to ongoing pressure decrease around Leirbotnar in Krafla.

The vertical velocity field has three key aspects: Subsidence in Leirbotnar and Bjarnarlag, an important uplift centered on Gjástykki and a local subsidence at a station near the coast in the northwest.

The subsidence south of Krafla is consistent with observations in the area in previous years [Sturkell et al., 2008; Spaans et al., 2012]. The subsidence in Leirbotnar and Bjarnarlag caused by geothermal exploitation is still ongoing. However the broad deformation west of Þeistareykir seems to have changed in shape, now it is essentially an uplift concentrated on a smaller area.

The effect of glacial isostatic adjustment due to the retreat of ice caps in Iceland needs to be taken into account for the region [Árnadóttir et al., 2009; Auriac et al., 2013]. Model predictions indicate a uplift gradient from N-S: with 5 mm/yr uplift rate south of Krafla caldera to 2 mm/yr uplift rate in the Þeistareykir area. When taken into account it shows that the subsidence along the Krafla fissure swarm due to other processes than isostasy, both in the Krafla caldera and in Bjarnarlag, is about 6-7 mm/yr.
3.1 Technology overview

Until 2008, radar images from the ERS and Envisat satellites were acquired over Northern Iceland. Now that these programs have ended, we have acquired radar data from the TerraSAR-X satellite of the German Space Agency. The satellite signals are of different wavelength:

- ERS: the signal wavelength is about 5.6 cm.
- TerraSAR-X: the signal wavelength is about 3 cm.

Two sets of data are obtained from a radar signal:

- the amplitude image that measures the strength of the signal reflection
- the phase image that contains the signal phase.

Interferometric Synthetic Aperture Radar (InSAR) analysis use two or more radar images and to measure the difference in phase. The images obtained, called an interferogram, show with fringes displacements in the line of sight (LOS) of the satellite between the two acquisitions. Each fringe represent a displacement of half the satellite wavelength.

At the beginning of the processing we have the following signal components:

\[ \Phi_{interferogram} = \Phi_{image1} - \Phi_{image2} \]
\[ \Phi_{interferogram} = \Phi_{deformation} + \Phi_{atmospheric} + \Phi_{topographic} + \Phi_{orbital} + \Phi_{noise} \]

When using InSAR for geophysical purposes, only the deformation component has interest. All other components, except the atmospheric one, can be removed when processing a single interferogram.

This atmospheric signal cannot be removed except by methods using the redundancy in the dataset of images, like time series analysis. Interferograms with this signal may show fringes correlated to topography because of atmosphere stratification, and other patterns due to atmospheric turbulences.

Time between the acquisitions has an effect on the amount of displacements that can be measured but also on the image quality, the "coherence". If too large changes occur on the ground during the time between acquisitions, like change in vegetation or erosion, the interferograms may show entire areas only made of noise.
3.2 Data

Since 2009, 14 TerraSAR-X images, distributed in 4 different tracks, have been acquired over Krafla, Gjástykki, Bjarnarflag and Þeistareykir. Four of them have been acquired in 2012. Interferograms can be formed by combining these images (work in progress).

The current TerraSAR-X dataset does not include enough images to do time series analysis. Individual interferograms can though be inspected to evaluate if atmosphere turbulence is likely to be causing unwanted fringes on our interferograms.

Once interferograms are checked, they will be geocoded and displacements in the line of sight (LOS) of the satellite will be inferred.

Amplitude images of two radar acquisitions are shown in Figs 3.3 and 3.4, but interferograms are needed to evaluate the deformation over North Iceland (work in progress).

Figure 3.1: TerraSAR-X acquisitions since 2009.
Figure 3.2: Map of the TerraSAR-X images coverage. Map reference system: ISN93. Background is same as Fig 2.1.
Figure 3.3: TerraSAR-X amplitude image in radar geometry for the track T49 Krafla. See geographical coverage in Figure 3.2
Figure 3.4: TerraSAR-X amplitude image in radar geometry for the track T56 Þeistareykir. See geographical coverage in Figure 3.2
ACKNOWLEDGEMENTS

We like to thanks all people who participated in collection of geodetic data, as listed on page 4.

Necessary GPS instruments for this study were provided by Institute of Earth Sciences (IES), UNAVCO and King Abdullah University of Science and Technology (KAUST).

Figures were produced using GRASS, Quantum GIS, and GMT public domain software. GPS data was process using GAMIT/GLOBK software.
References


