



HAL
open science

Present day geodynamics in Iceland monitored by a permanent network of continuous GPS stations

Christof Völksen, Thóra Árnadóttir, Halldór Geirsson, Guðmundur Valsson

► To cite this version:

Christof Völksen, Thóra Árnadóttir, Halldór Geirsson, Guðmundur Valsson. Present day geodynamics in Iceland monitored by a permanent network of continuous GPS stations. *Journal of Geodynamics*, 2009, 48 (3-5), pp.279. 10.1016/j.jog.2009.09.033 . hal-00594416

HAL Id: hal-00594416

<https://hal.science/hal-00594416>

Submitted on 20 May 2011

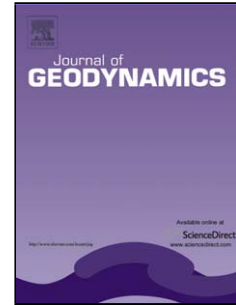
HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Title: Present day geodynamics in Iceland monitored by a permanent network of continuous GPS stations

Authors: Christof Völksen, Thóra Árnadóttir, Halldór Geirsson, Guðmundur Valsson



PII: S0264-3707(09)00100-8
DOI: doi:10.1016/j.jog.2009.09.033
Reference: GEOD 927

To appear in: *Journal of Geodynamics*

Please cite this article as: Völksen, C., Árnadóttir, T., Geirsson, H., Valsson, G., Present day geodynamics in Iceland monitored by a permanent network of continuous GPS stations, *Journal of Geodynamics* (2008), doi:10.1016/j.jog.2009.09.033

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 **Present day geodynamics in Iceland monitored by a permanent network of**
2 **continuous GPS stations**

3 Christof Völksen ^{a,*}, Thóra Árnadóttir ^b, Halldór Geirsson ^c, Guðmundur Valsson ^d

4 ^a Bayerische Kommission für die Internationale Erdmessung; Alfons-Goppel-Str.11, D-80539
5 München, Germany

6 ^b Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, Sturlugata 7 ,
7 101 Reykjavík, Iceland

8 ^c Icelandic Meteorological Office, Bústaðavegur 9, 150 Reykjavík, Iceland

9 ^d National Land Survey of Iceland, Stillholt 16-18, 300 Akranes, Iceland

10

11 **Abstract:**

12

13 Iceland is located on the Mid-Atlantic Ridge and thereby offers a rare opportunity to study
14 crustal movements at a divergent plate boundary. Iceland is not only characterized by the
15 divergence of the Eurasian and North American Plates, as several active volcanoes are located on
16 the island. Moderate size earthquakes occur in the transform zones, causing measurable crustal
17 deformation. In 1999 the installation of a permanent network of continuous GPS stations
18 (ISGPS) was initiated in order to observe deformation due to unrest in the Hengill volcanic
19 system and at the Katla volcano. The ISGPS network has been enlarged over the years and
20 consists today of more than 25 CGPS stations. Most of the stations are located along the plate
21 boundary, where most of the active deformation takes place. Uplift due to post-glacial rebound
22 due to the melting of the largest glacier in Europe, Vatnajökull, is also detected by the ISGPS

1 network. This study presents results from analysis of nine years of data from the ISGPS network,
2 in the global reference frame PDR05, which has been evaluated by the Potsdam-Dresden-
3 Reprocessing group with reprocessed GPS data only. We thus determine subsidence or land
4 uplift in a global frame. The horizontal station velocities clearly show spreading across the plate
5 boundary of about 20 mm/a. Stations in the vicinity of the glacier Vatnajökull indicate uplift in
6 the range of 12 mm/a, while a station in the central part of Iceland shows uplift rates of about 25
7 mm/a. Tide gauge readings in Reykjavik and current subsidence rates observed with CGPS agree
8 also quite well.

9

10 Keywords: Iceland, Plate boundary, Geodetic space techniques, PDR05, Sea level

11

12 *Corresponding author.

13 E-Mail address: voelksen@bek.badw.de (Christof Völksen)

14

15 **1. Introduction**

16

17 The primary purpose of geodetic networks is the realization of a reference frame by providing a
18 set of coordinates for several sites. The coordinates are either realized in a local, regional or
19 global scale. There is a long tradition for using geodetic networks to monitor crustal deformation
20 in Iceland, since Wegener's theory of continental drift in the 1930's. The first GPS survey was
21 carried out in 1986 to estimate precise coordinates for a number of sites in Iceland (Foulger et
22 al., 1987). This initial effort has continued and the networks were expanded and densified. In
23 northeast Iceland, several campaign style surveys were performed in 1987, 1990, 1992 and 1995
24 (Heki et al., 1993; Hofton and Foulger, 1996; Völksen, 2000). Likewise, in southwest Iceland
25 (e.g. Sigmundsson et al., 1995; Hreinsdóttir et al., 2000, Árnadóttir et al., 2006), the east of

1 Iceland (Jónsson et al., 1997, LaFemina et al., 2005) and several local networks have been
2 maintained at active volcanoes, such as Askja, Hekla, Krafla, Katla and Grímsvötn (e.g. Sturkell
3 et al., 2006).

4
5 The installation of continuous GPS (CGPS) stations started in November 1995 in the capital
6 Reykjavik (REYK), followed by a second site at the geodetic Laboratory of the National Land
7 Survey of Iceland in Höfn (Southeast Iceland) in May 1997. The purpose of these two sites was
8 at first to take part in the realization of a global terrestrial reference system. Therefore data were
9 processed within the community of the International GNSS Service (Dow et al. 2005) and used
10 for the realization of a global terrestrial reference system, such as the International Terrestrial
11 References System (ITRF). Due to their location on the North American and Eurasian plates,
12 respectively, they have also provided important data for estimating the spreading rates between
13 these two plates. In 1999 the first seven CGPS sites of the ISGPS network were installed in the
14 southwestern part of Iceland (Geirsson et al., 2006) with a focus on the Hengill volcanic system,
15 where intensive seismicity was observed, and around the Katla volcano. This network has been
16 increased over the past ten years and consists today of more than 25 sites. In addition to the
17 ISGPS network stations have also been installed by the National Land Survey of Iceland, the
18 University of Savoie, France and the Bayerische Kommission für die Internationale Erdmessung
19 (BEK), Germany. These sites also supply valuable data for crustal deformation studies.

20

21 Figure 1:

22

23 The tectonic setting is outlined in Fig. 1. The divergent part of the plate boundary across Iceland
24 consists of several volcanic zones, namely the Northern (NVZ), the Eastern (EVZ) and the
25 Western Volcanic Zone (WVZ). Each zone consists of a number of central volcanoes, with

1 associated fissure swarms. In the southern part of Iceland most of the spreading occurs in the
2 EVZ, while the activity in the WVZ is decreasing. The South Iceland Seismic Zone (SISZ), is an
3 E-W transform zone, connecting the WVZ and the EVZ in the south, while the Tjörnes Fracture
4 Zone (TFZ) translates the spreading between the NVZ and the offshore Kolbeinsey Ridge. The
5 transform zones are characterized by high seismic activity.

6
7 Crustal deformation in Iceland is thus caused by a range of geodynamic phenomena such as (i)
8 plate spreading, (ii) earthquakes, (iii) volcanism and (iv) glacial isostatic adjustment due to the
9 rapid melting of the largest glaciers. The CGPS sites are not evenly distributed over Iceland.
10 Most of the station locations were selected to monitor specific areas. A number of sites are
11 located in southern Iceland near the Hengill triple junction, in the SISZ, and close to
12 Mýrdalsjökull and Eyjafjallajökull. Other sites are located in the northeastern part of Iceland in
13 order to monitor the active spreading, while the last group of sites is located in central Iceland
14 and around Vatnajökull, which is the largest glacier in Europe (see Fig. 1).

15

16 **2 Data Analysis**

17

18 This paper presents data analysis done at the BEK. The Icelandic Meteorological Office (IMO)
19 and also the Nordic Volcanological Center (NVC) analyze the data as well, applying either a
20 different strategy or software. Routine processing is carried out by IMO using the CGPS station
21 REYK in Reykjavik as reference site: the data of one day are processed near real time with
22 predicted orbits from the Centre of Orbit Determination for Europe (CODE) (Geirsson et al.,
23 2006). This kind of analysis is subject to changes due to the reference frame realization, different
24 correction models and new analysis strategies. Therefore the estimated coordinates are usually
25 not consistent in time. It also has the disadvantage that changes in the coordinates of the site

1 REYK will be reflected in the coordinate time series of all the other sites. The present study
2 pursues another strategy. Instead of keeping one site fixed, data from 11 IGS sites surrounding
3 the North Atlantic were used to constrain the coordinates of the sites in Iceland. Sites were
4 selected along the east coast of North America, Greenland, Svalbard and along the west coast of
5 Europe from Scandinavia to Belgium. Therefore, individual position changes at REYK do not
6 affect the coordinates of the other sites in Iceland.

7 Another aim of this processing was to apply identical and well-accepted correction models (e.g.
8 ocean loading, antenna phase center variation (PCV) etc.), the same analysis strategy (e.g.
9 ambiguity fixing) and use consistent orbits and earth rotation parameters (ERP) that realize the
10 reference frame for the entire period of nine years.

11 Especially the correction of the phase center variations (PCV) for the GPS antennas changed
12 dramatically in the last years. It is now possible to estimate the absolute phase center variations
13 of GNSS antennas. A major breakthrough has been reached by an automated robot calibration of
14 the antennas that is highly precise and that also allows for the first time the efficient estimation
15 of the true PCV of the antennas (Wübbena et al., 2000). Today a new compiled set of antenna
16 correction models is available for most GNSS receiving and transmitting antennas and has
17 become a standard within the IGS community (Schmid et al., 2007). These models with type
18 specific absolute antenna corrections were applied in this study. As a consequence it was also
19 mandatory to use GPS orbits and ERPs that were also processed following this standard.
20 Reprocessing of the global IGS network has been carried out by a research group from the GFZ
21 Potsdam, the TU Dresden and the TU München (Steigenberger et al., 2006). Data from 1994
22 until 2005 were re-analysed in order to estimate a consistent set of orbits, ERPs and coordinates
23 based on absolute PCV. These orbits and ERPs were made available to the BEK in order to
24 reprocess GPS networks on a regional scale. Therefore, these products were used to reprocess the
25 ISGPS network.

1 Site specific parameters for the troposphere were estimated based on the wet Niell mapping
2 function for each hour and gradients were calculated once per day. The deformation of the crust
3 caused by ocean loading was corrected with the FES2004 model (Letellier, 2004). The model
4 parameters for each site were provided by the ocean tide loading provider (Scherneck, 1991;
5 <http://www.oso.chalmers.se/~loading>).

6 Data from January 1, 1999 until June 30, 2008 were processed using Bernese 5.0 (Dach et al.,
7 2007), based on these standards and products. Almost 3500 daily solution files were generated
8 and stored as BERNESE normal equation files and in SINEX (Solution INdependent EXchange)
9 format. These files are the basis for the estimation of the velocity field of the individual sites and
10 also to detect coseismic deformation.

11

12 **3 Velocity estimation**

13

14 The velocity estimation was carried out in two steps. In a first approach the normal equation files
15 of the daily solutions were processed using the tool ADDNEQ2, which belongs to the BERNESE
16 GNSS analysis software. Coordinates for a specific epoch and linear velocities were calculated
17 for each site based on the daily solutions. The daily coordinate residuals were then screened for
18 outliers and inconsistencies, such as jumps, were detected. Outliers were simply eliminated while
19 the size of the jumps had to be estimated. Inconsistencies were usually connected to changes in
20 the equipment of the CGPS site, which were well documented, or to single events like
21 earthquakes. Inconsistencies caused by equipment changes are much more frequent. Obviously
22 the antenna characteristics are also a question of the setup around the antenna: tripods, tribrachs
23 and environment seem to cause a systematic bias in the position (Wübbena et al., 2006).

24 In a final processing step the coordinates and velocities for all sites were estimated for a specific
25 epoch. Sites, which experienced jumps, were given two pairs of coordinates: one pair valid until

1 the appearance of the jump and another set used after the jump. Velocities for these sites were
2 constrained, so that the velocity before and after the event was identical. The coordinates and
3 velocities of the 11 IGS sites surrounding the North Atlantic were constrained in the PDR05
4 (Potsdam–Dresden- Reprocessing 2005) (Rülke et al., 2008) using a minimum constraint
5 condition. Therefore the coordinates and velocities are also dependent on the selection of
6 reference sites realizing a global reference frame. Comparisons of the PDR05, which is solely
7 derived with GPS, with the ITRF2000 and ITRF 2005 have shown generally a good agreement,
8 also in the vertical station velocities. The PDR05 has been chosen for this study because it has
9 been estimated by a homogeneously processed global reference network, which was entirely
10 based on absolute phase center variations for the GPS antennas as this study does.

11 Several time series of the position residuals of the individual sites show a significant seasonal
12 behavior as it has been reported already by Geirsson et al. (2006). In this study the time series
13 were analyzed with TSVIEW, which is a Matlab tool (Herring, 2003) and can be used for the
14 estimation of linear trends, annual and semi-annual velocity components and offsets. It also gives
15 a more realistic estimation of the error components for the velocities that can be used to rescale
16 the uncertainties of the velocities estimated with Bernese to more realistic values. Generally
17 standard deviations in the range of 0.2 to 0.3 mm/a were achieved. A typical example of a time
18 series showing the position changes is given in figure 2. The large uplift rate at this site is clearly
19 visible beside the typical motion of the American plate.

20

21 Figure 2:

22

23 **4 The velocity field**

24

25 Figure 3 shows the horizontal and vertical velocities of the ISGPS network. The horizontal

1 velocities are expressed relative to the stable part of the Eurasian plate. The figure displays also
2 for comparison the horizontal rates of the NUVEL-1A model (DeMets et al., 1994) for selected
3 sites on the North American plate. Only sites with a history of at least two years were considered
4 for the velocity estimation. Sites on the Eurasian plate in East Iceland have small horizontal
5 velocities. This agrees well with the assumption of two rigid plates moving apart. Sites on the
6 North American plate at larger distances from the plate boundary (REYK) show in general a
7 good agreement with velocities predicted by the NUVEL-1A plate motion model. However, sites
8 closer to the plate boundary (MYVA, ARHO) move at a slower rate than the NUVEL-1A model
9 prediction. This indicates these sites are located within the plate boundary zone. In the SISZ the
10 stations are affected by post-seismic deformation following two Mw6.5 earthquakes in June
11 2000. Another interesting feature can be seen at Mýrdalsjökull (MY). The velocity vectors of the
12 CGPS sites are pointing away from the center of the sub-glacial volcano Katla. This signal has
13 been interpreted as evidence for magma inflow into a shallow magma chamber beneath Katla
14 (Pinel et al., 2007). The vertical uplift of 10 mm/a monitored at these three CGPS sites supports
15 this assumption.

16 Therefore, not only the horizontal motion in Iceland is of great interest but also the vertical. Two
17 sites (KARV, HOFN) close to the eastern vicinity of Vatnajökull show large uplift rates in the
18 order of 12 mm/a. Figure 3 discloses the largest uplift rate in the center of Iceland with up to 24
19 mm/a at the site SKRO (compare also Fig. 2), which is located between the glaciers Vatnajökull
20 und Hofsjökull. Most of the uplift observed in central and southeast Iceland can be explained by
21 glacial isostatic adjustments due to the melting of the largest glaciers in Iceland since 1890
22 (Árnadóttir et al., 2009). Sites in the north of Iceland do not show any significant vertical signal
23 apart from the CGPS site AKUR in Akureyri. The southwestern corner of Iceland shows a
24 different vertical velocity pattern. Generally the stations around the volcano Hengill are
25 indicating slight subsidence at a rate of approx. 5-6 mm/a. The site REYK in Reykjavik shows

1 subsidence in the range of 1.7 mm/a. It is worth noting that a second GPS/GLONASS site
2 (REYZ), located about 1 m from REYK, has been operated in parallel until it was abandoned in
3 September 2007. This site did maintain the same antenna type for the entire time of operation.
4 The GPS data of this site were included in this analysis and subsidence of 2.3 mm/a was
5 estimated.

6

7 Figure 3

8

9 The primary national geodetic network of Iceland - ISNET - was installed and surveyed in 1993.
10 The network consists of 120 sites and the survey was repeated in 2004 (Valsson et al., 2007) in
11 order to update the coordinates of the sites due to the continuous deformation processes. The
12 survey of 1993 was re-processed using orbits and coordinates of the IGS stations realized in the
13 IGB00 (Ray et al., 2004), which is very similar to the PDR05, in the same manner as the survey
14 of 2004. Figure 4 displays the vertical deformation in Iceland as it is estimated from these two
15 campaigns for the entire island.

16

17 Figure 4:

18

19 Figure 4 shows significant uplift in the central part of Iceland with two maxima and agrees well
20 with uplift rates estimated with the ISGPS network. The eastern maximum is centered around a
21 GPS site located on the rim of the sub-glacial volcano Grimsvötn and therefore most likely due
22 to magma accumulation. The subsidence on Reykjanes is caused by just one site on the tip of the
23 peninsula that appears to have gone down by more than 8 cm in 11 years. This high subsidence
24 rate is not fully understood, but may be linked to the Svartsengi geothermal area. The uplift
25 signals in the NVZ, north of the Krafla volcano, evident in the ISNET measurements agree with

1 synthetic aperture radar interferometry (InSAR) observations spanning 1993–1999 (de Zeeuw-
2 van Dalfsen et al., 2004). The coastal region of Iceland displays generally no distinct vertical
3 changes. There is also no clear indication of large subsidence signal in Reykjavik according to
4 this analysis.

5 The analysis of the ISGPS network reveals a small signal of subsidence in Reykjavik: REYK
6 shows 1.7 mm/a and REYZ 2.3 mm/a of subsidence, in both cases with a standard deviation of
7 0.2 mm/a. The difference is mainly caused by the different treatment of the time series and also
8 reflects the accuracy for the vertical velocity estimation in general. Annual tide gauge readings
9 from Reykjavik provided by the *Permanent Service for Mean Sea Level* (PSMSL
10 <http://www.pol.ac.uk/psmsl>) of the last 50 years (1957-2007) indicate sea-level rise relative to
11 the local tide gauge on the order of 2.4 mm/a with a standard deviation of 0.4 mm/a. This
12 demonstrates a good agreement between tide gauge readings and crustal deformation, although
13 they cover different periods in time. This, however, does not take the mean sea level rise in the
14 region of Reykjavik due to global warming into account. The change of the mean sea level has
15 been estimated with data collected between 1993 and 2004 with the altimeter TOPEX (Bosch,
16 2008). For the sea around Iceland the change of the mean sea level rise ranges between 0 and
17 2 mm/a, with larger values in the west of Iceland. Altimeter readings from the ocean can be used
18 up to distances between 5 to 10 km from the coast, but they are generally noisier due to
19 insufficient models of the local tides and the more complex return signal caused by different
20 reflections of the coastline. An extrapolation of the sea level rise observed offshore to the tide
21 gauge in the harbor is therefore quite complicated. Since the observed values for tide gauge
22 readings, crustal deformation and sea level rise from TOPEX are small and cover different
23 periods of time it is still not possible to verify the individual values at the 1 mm/a level.

24

25 **5 Conclusions**

1

2 This study shows that the spreading rates in Iceland agree well with velocities predicted by the
3 NUVEL-1A plate motion model. It also proves that stations located within the volcanic zones of
4 Iceland do not move at the full spreading rate, indicating that the spreading is accommodated
5 over the total width of the zone rather than in a narrow zone of a few kilometers.

6 Horizontal velocities in the southern part of Iceland are generally more complex due to the active
7 volcanoes and moderate size earthquakes that occurred during the study period. Two sites close
8 to the volcano Hengill indicate subsidence (5-6 mm/a), while around Katla volcano the
9 horizontal and vertical velocity rates indicate uplift due to inflow of magma into the volcanic
10 system. Vertical rates around the volcano are very similar and in the range of 9 to 11 mm/a. A
11 part of the vertical signal might be connected to GIA.

12 Two sites at the eastern side of the glacier Vatnajökull also demonstrate uplift in the range of
13 12 mm/a. The largest vertical velocity can be observed in the center of Iceland: uplift rates of
14 24 mm/a can be seen. A part of this signal can be attributed to GIA due to recent melting of the
15 ice caps but the source for the remaining uplift is still unknown and needs further investigations.

16 This study demonstrates that precise determination (< 1 mm/a) of vertical velocities in a global
17 reference system using CGPS sites is still very difficult. A combination of crustal deformation,
18 sea level rise and tide gauge readings in Reykjavik disagree at the level of 1-2 mm/a. Even
19 though almost a decade of GPS data has been processed in this study, the vertical resolution is
20 still limited due to the use of the setup of the station (e.g. change of equipment), realization of
21 the reference frame, selection of reference sites and the standards and correction models used for
22 the data processing.

23 Studies of sea level changes with altimetry, CGPS and tide gauges at the coast of Iceland would
24 help to constrain the vertical component in many places in Iceland within a global frame. The
25 ISGPS network covers only specific parts of the island, while many other interesting places are

1 still left out. To cover all active processes in Iceland it would be necessary to enlarge the network
2 even further. Additional CGPS sites in the center of Iceland and on the tip of Reykjanes
3 Peninsula would greatly aid in determining the vertical velocity field in Iceland.

4

5 **Acknowledgements.** Thanks are expressed to Martin Lidberg and an unknown reviewer for their
6 constructive comments. This work has been supported by the Federal Republic of Germany by
7 the *Akademienprogramm*.

8

9 **References:**

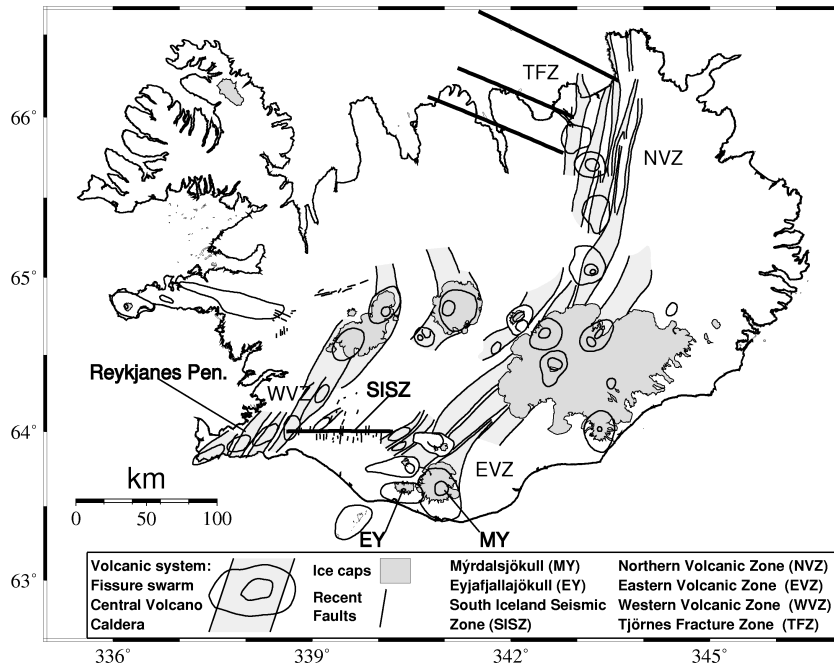
- 10 Árnadóttir, Th., Lund, B., Jiang, W., Geirsson, H., Björnsson, H., Einarsson, P., Sigurdsson, Th.
11 (2009). Glacial rebound and plate spreading: Results from the first countrywide GPS
12 observations in Iceland. *Geophys. J. Int.*, 177(2), 691-716, doi: 10.1111/j.1365-
13 246X.2008.04059.x, 2009.
- 14 Árnadóttir, Th., Jiang W., Feigl K. L., Geirsson H., Sturkell E.(2006), Kinematic models of plate
15 boundary deformation in southwest Iceland derived from GPS observations, *J. Geophys. Res.*,
16 *III*, B07402, doi:10.1029/2005JB003907.
- 17 Dach, R., Hugentobler U., Fridez P., Meindl M. (2007). BERNESE GPS Software Version 5.0.
18 Astronomical Institute, University of Bern.
- 19 DeMets, C., Gordon R.G., Argus D.F., Stein S. (1994). Effect of recent revisions to the
20 geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, 21,
21 2191-2194.
- 22 de Zeeuw-van Dalssen, E., Pedersen, R., Sigmundsson, F., Pagli, C. (2004). Satellite radar
23 interferometry 1993–1999 suggests deep accumulation of magma near the crust-mantle boundary
24 at the Krafla volcanic system, Iceland, *Geophys. Res. Lett.*, 31, L13611, doi

- 1 10.1029/2004GL020059.
- 2 Dow, J.M., Neilan R.E., Gendt G. (2005). The International GPS Service (IGS): Celebrating the
3 10th Anniversary and Looking to the Next Decade, *Adv. Space Res.* 36 vol. 36, no. 3, pp. 320-
4 326, 2005. doi:10.1016/j.asr.2005.05.125.
- 5 Foulger G.R., Bilham R., Morgan W.J., Einarsson P. (1987). The Iceland GPS geodetic field
6 campaign 1986. *Eos Trans. AGU*, 68, 1236.
- 7 Geirsson, H., Arnadóttir Th., Völksen C., Jiang W., Sturkell E., Villemin Th., Einarsson P.,
8 Sigmundsson F., Stefánsson R. (2006). Current plate movements across the Mid-Atlantic Ridge
9 determined from 5 years of continuous GPS measurements in Iceland. *J. Geophys. Res.*, 111,
10 doi:10.1029/2005JB003717.
- 11 Heki, K., Foulger G.R., Julian B., Jahn C.-H. (1993). Plate dynamics near divergent plate
12 boundaries: Geophysical implications of post-rifting crustal deformation in NE Iceland.
13 *J. Geophys. Res.* 98, 14279-14297.
- 14 Herring, T. (2003). MATLAB Tools for viewing GPS velocities and time series. *GPS Solutions*,
15 Volume 7, Number 3, Springer, 194-199.
- 16 Hofton, M.A., Foulger G.R. (1996). Post-rifting anelastic deformation around the spreading plate
17 boundary, north Iceland. 1. Modeling of the 1987–1992 deformation field using a viscoelastic
18 Earth structure, *J. geophys. Res.*, 101(B11), 25 403–25 422.
- 19 Hreinsdóttir, S., Einarsson P., Sigmundsson F. (2000). Crustal deformation at the oblique
20 spreading Reykjanes peninsula, SW Iceland: GPS measurements from 1993 to 1998. *J. Geophys.*
21 *Res.*, 106, 13803-13816.
- 22 Jónsson, S., Einarsson P., Sigmundsson F. (1997). Extension across a divergent plate boundary,
23 the Eastern Volcanic Rift Zone, south Iceland, 1967-1994, observed with GPS and electronic

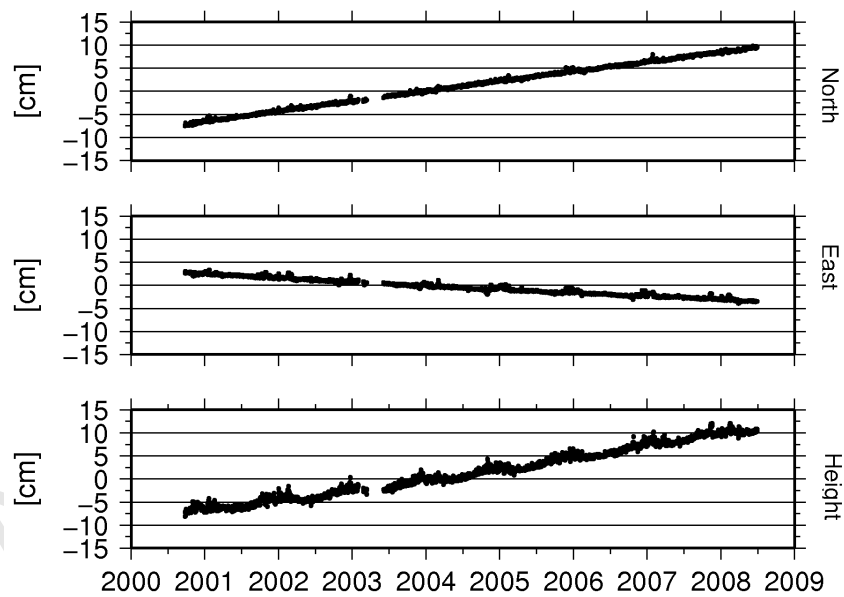
- 1 distance measurements, *J. Geophys. Res.*, 102, B11913-11929, 1997.
- 2 LaFemina, P.C., Dixon T.H., Malservisi R., Árnadóttir Th., Sturkell E., Sigmundsson F.,
3 Einarsson P. (2005). Geodetic GPS measurements in south Iceland: Strain accumulation and
4 partitioning in a propagating ridge system, *J. Geophys. Res.*, 110, B11405,
5 doi:10.1029/2005JB003675, 2005.
- 6 Letellier, T. (2004). Etude des ondes de marée sur les plateaux continentaux. Thèse doctorale,
7 Université de Toulouse III, Ecole Doctorale des Sciences de l'Univers, de l'Environnement et de
8 l'Espace.
- 9 Pinel, V., Sigmundsson, F., Sturkell, E., Geirsson, H., Einarsson, P., Gudmundsson, M. T.,
10 Högnadóttir, T. (2007). Discriminating volcano deformation due to magma movements and
11 variable surface loads: application to Katla subglacial volcano, Iceland. *Geophys. J. Int.*, 1, 393–
12 411.
- 13 Ray, J., Dong D., Altamimi Z. (2004). IGS reference frames: status and future improvements,
14 *GPS Sol.*, 8(4), 251 – 266, doi:10.1007/s10291-004-0110-x.
- 15 Rülke, A., Dietrich, R., Fritsche, M., Rothacher, M., Steigenberger, P. (2008). Realization of the
16 Terrestrial Reference System by a reprocessed global GPS network. *Journal of Geophysical*
17 *Research*, Vol. 113, doi: 10.1029/2007JB005231.
- 18 Scherneck, H-G. (1991). A parametrized solid Earth tide model and ocean loading effects for
19 global geodetic base-line measurements. *Geophys. J. Int.*, 106(3): 677-694.
- 20 Schmid R., Steigenberger P., Gendt G., Ge M., Rothacher M. (2007). Generation of a consistent
21 absolute phase center correction model for GPS receiver and satellite antennas. *Journal of*
22 *Geodesy*, Vol. 81, No. 12, pp 781-798, DOI: 10.1007/s00190-007-0148-y, December 2007.
- 23 Sigmundsson, F., Einarsson P., Bilham R., Sturkell E. (1995). Rifttransform kinematics in south

- 1 Iceland: Deformation from Global Positioning System measurements, 1986 to 1992. *J. Geophys.*
2 *Res.*, 100, 6235-6248.
- 3 Steigenberger, P., Rothacher, M., Dietrich, R., Fritsche, M., Rülke, A., Vey, S. (2006).
4 Reprocessing of a global GPS network. *J. Geophys. Res.*, Vol. 111, No. B5, B05402
5 10.1029/2005JB003747.
- 6 Sturkell, E., P. Einarsson, F. Sigmundsson, H. Geirsson, R. Pedersen, E. Van Dalssen, A. Linde,
7 S. Sacks, R. Stefánsson (2006). Volcano geodesy and magma dynamics in Iceland. *J. Volc.*
8 *Geothermal Res.*, 150, 14-34.
- 9 Valsson, G. T., Sigurdsson, T., Völksen, C., Rennen, M., (2007). ISNET2004. Results from a
10 resurvey of the Icelandic geodetic reference network (in icelandic with an english summary),
11 Tech. rep., National Land Survey of Iceland, Akranes, Iceland.
- 12 Völksen, C. (2000). Die Nutzung von GPS für die Deformationsanalyse in regionalen Netzen am
13 Beispiel Islands, Ph. D. thesis, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen
14 der Universität Hannover, Nr. 237, Hannover, Germany.
- 15 Wübbena, G., M. Schmitz, F. Menge, V. Böder, G. Seeber (2000). Automated Absolute Field
16 Calibration of GPS Antennas in Real-Time. Proceedings of the 13th International Technical
17 Meeting of the Satellite Division of the Institute of Navigation, ION GPS-2000, Salt Lake City,
18 Utah, September 19-22. 2000, pp. 2512-2522.
- 19 Wübbena, G., M. Schmitz, G. Boettcher (2006). Near-field Effects on GNSS Sites: Analysis
20 using Absolute Robot Calibrations and Procedures to Determine Corrections. Submitted to
21 Proceedings of the IGS Workshop 2006 Perspectives and Visions for 2010 and beyond, May 8-
22 12, ESOC, Darmstadt, Germany.

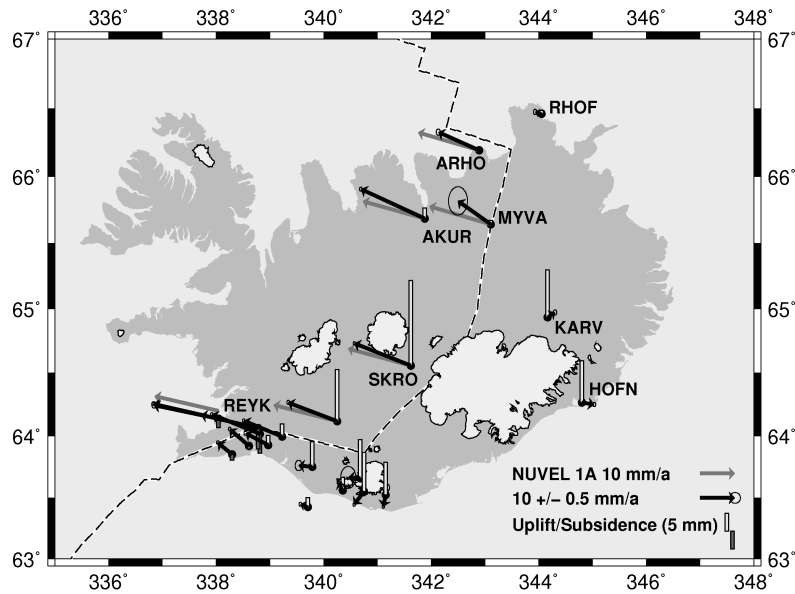
1
2
3
4
5
6
7
8
9
10



11 Figure 1: Tectonic setting in Iceland with the Neovolcanic Zone that represents the plate
12 boundary in Iceland.



13 Figure 2: Position changes of the station Skrokkalda (SKRO) for the north, east and up
14 component. Outliers are already removed. The large vertical signal is clearly visible.



1 Figure 3: Horizontal and vertical velocities for the CGPS sites in Iceland. Light grey bars
 2 indicate uplift while dark grey bars show subsidence. The scale is identical for horizontal and
 3 vertical velocities.

4

5

6

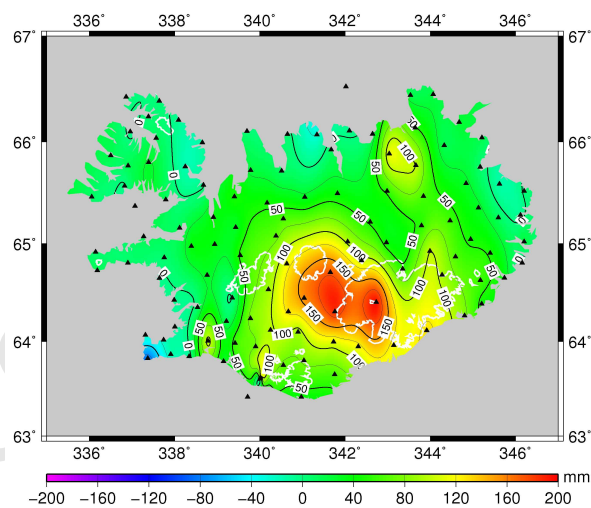
7

8

9

10

11



12 Figure 4: Vertical changes in Iceland estimated by two GPS campaigns in 1993 and 2004 in the
 13 IGB00 reference frame. Black triangles indicate the locations of ISNET sites. The glaciers are
 14 outlined with white lines. High uplift rates are observed in the center of Iceland as well as
 15 subsidence on the Reykjanes Peninsula. Uplift is also observed in the NVZ.