GPS network measurements in the Krafla area in 2009

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1 Introduction

Crustal deformation has been studied in the Krafla area in collaboration between the Institute of Earth Sciences, University of Iceland, and Landsvirkjun. Results of these efforts from 2005 and earlier years are summarized by *Sturkell et al.* (2008). The aim of the measurements is to provide constraints on, and understanding of, the processes causing deformation in the area. These processes include geothermal utilization, magma movements and pressure changes within the magmatic plumbing systems of Krafla and Þeistareykir volcanic systems. Plate spreading and post-rifting adjustment of the crustal stresses after the Krafla rifting episode (*Pedersen et al.*, 2009). The measurement efforts in the area include GPS geodetic measurements, satellite radar interferometric observations using synthetic aperture radar images acquired by satellites (InSAR), and optical levelling. This report summarizes GPS measurements and preliminary results from the 2005, 2006, 2007 and 2008 surveys previously reported by *Ófeigsson et al.* (2009), as well as new measurements conducted in 2009 as a part of the collaborative efforts of the Institute of Earth Science and Landsvirkjun.

2 GPS-measurements

In 2009, a network of 24 stations was measured in the area (Figure 1, Table 1 in Appendix A). A subset of this network has been measured in 2005, 2006, 2007 and 2008 (Tables 2-5 in Appendix A). The measurements in 2009 were conducted in August, 2009. A total of 22 GPS-instruments were used. They include: 7 pairs of Trimble 5700 receivers and (Zephyr Geodetic) TRM41249.00 antennas, 10 pairs of Trimble 5700 receivers and (Zephyr Geodetic 1/2) TRM41249.00/TRM55971.00 antennas and 5 pairs of Trimble NETRS receivers and (Zephyr Geodetic) TRM41249.00 antennas. The GPS-data from 2005-2008 have been analyzed with version 5.0 of the Bernese GPS software (*Dach et al.*, 2007) in a similar manner as described by *Ófeigsson* (2008). The data were analyzed together with data from the following international continuous GPS stations: REYK, HOFN, ALGO, ALRT, WES2, ONSA, TROM and MADR. The following continuous GPS stations in Iceland were used in the analysis: AKUR, ARHO, RHOF, SKRO, HOFN, REYK, ISAK and VMEY (see Figure 2 and Appendix B).

3 Results

Time series of inferred three-dimensional displacements at each individual station are given in Appendix C. Map views of inferred horizontal and vertical displacements are shown in Figures 3-12. The horizontal displacements are all shown 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 NUVEL-1A velocity of ideal station at the other side of the plate boundary (on the North American Plate, i.e. close to AKUR), would move at velocity of 18.6 mm/yr in direction 285°. Inferred horizontal displacements are small, but a change in direction of velocities is suggested in the area Gjástykki area north

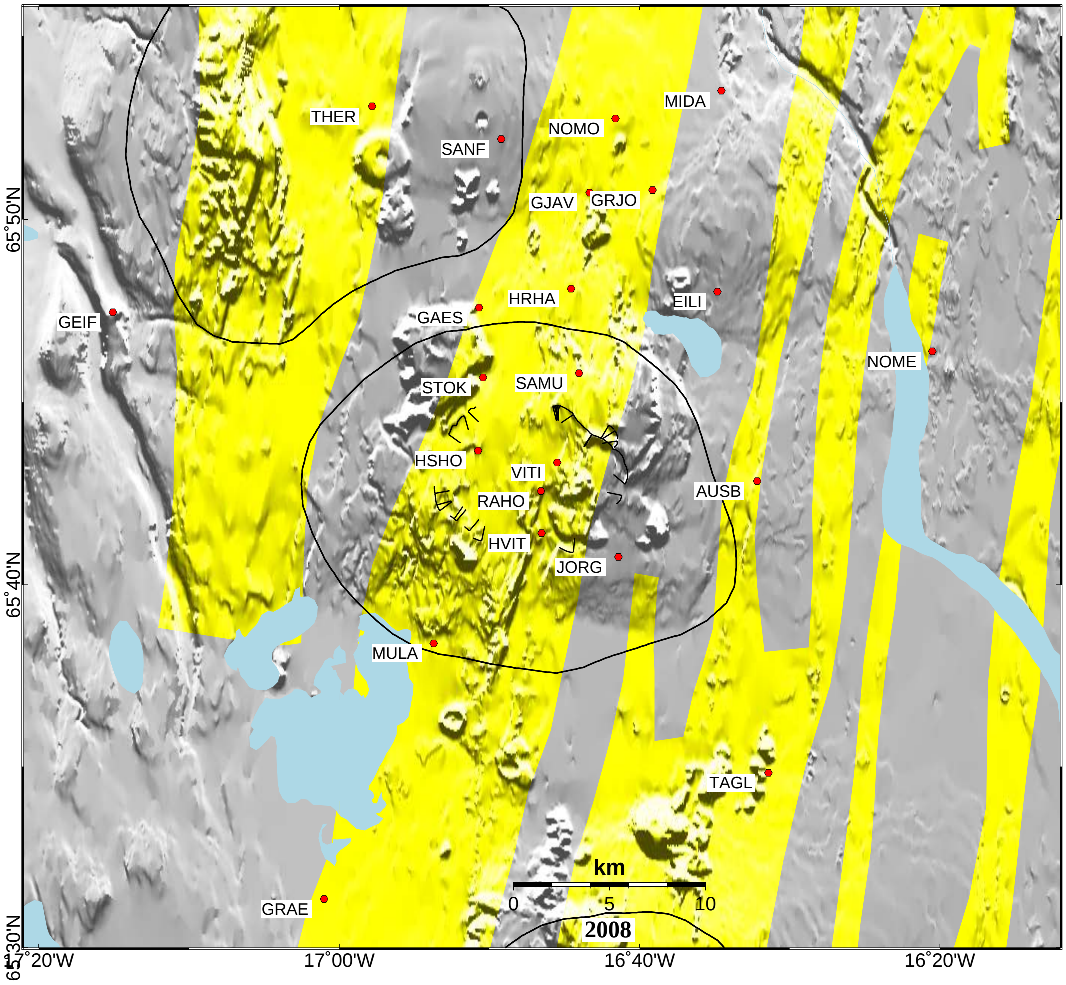

Figure 1: Benchmarks measured in the Krafla 2009 GPS-campaign.

of Krafla between THER and MIDA stations, in the 2005-2009 period. In the 2005-2006 period the predominant direction of velocities is such that stations within the Krafla fissure swarm move westward, at a rate comparable to half the spreading rate. Such displacement pattern is consistent with the Krafla fissure swarm being close to the central axis of the plate boundary deformation zone. About one half of the plate stretching was accordingly accommodated east of the Krafla fissure swarm, and the other to the west. In 2007 the focus of measurements was on the area north of Krafla. The 2006-2007 displacements suggest that the westward velocity relative to the Eurasian plate decrease in this period. For 2007-2008, a small eastward displacement is suggested for stations north of Krafla. This change in directions is observed quite well at stations SANF, HRHA, GJAV, NOMO and MIDA. This pattern of small eastward velocities north of Krafla continues for 2008-2009 at similar rates. EILI, GJAV, MIDA and NOMO show relatively stable eastward or close to zero velocities since 2006, suggesting an ongoing continuous process that began in 2006.

The inferred vertical pattern of displacement is irregular (Figures 8-12). In the 2005-2006 period the pattern is dominated by uplift of stations in the northern part of the network, and subsidence of a station HVIT in Hvíthólaklif, at the southern boundary of the Krafla caldera. For 2006-2007 subsidence of the northern stations is suggested, and rapid uplift in 2007-2008. For 2008-2009 the vertical rates are small. The most notable results are the high uplift rates in 2007-2008 at the stations north of Krafla. Both vertical and horizontal rates indicate that onset of a process after the summer of 2006 producing whidespread deformation. InSAR (Interferometric synthetic aperture radar) images of the area suggest a broad inflation centered on Þeystareykir. A likely cause is considered to be magma injection beneath the center of the Þeistareykir volcanic system.

Continuing work in the area includes InSAR data analysis of images from the ENVISAT satellite that can be compared to the indicated deformation pattern from GPS. This, together with longer time series of GPS-measurements will form a good database for crustal movements that can be utilized to explore crustal processes associated with geothermal utilization, magma movements and pressure changes, and extension across the plate boundary in North Iceland in the period since 2005.

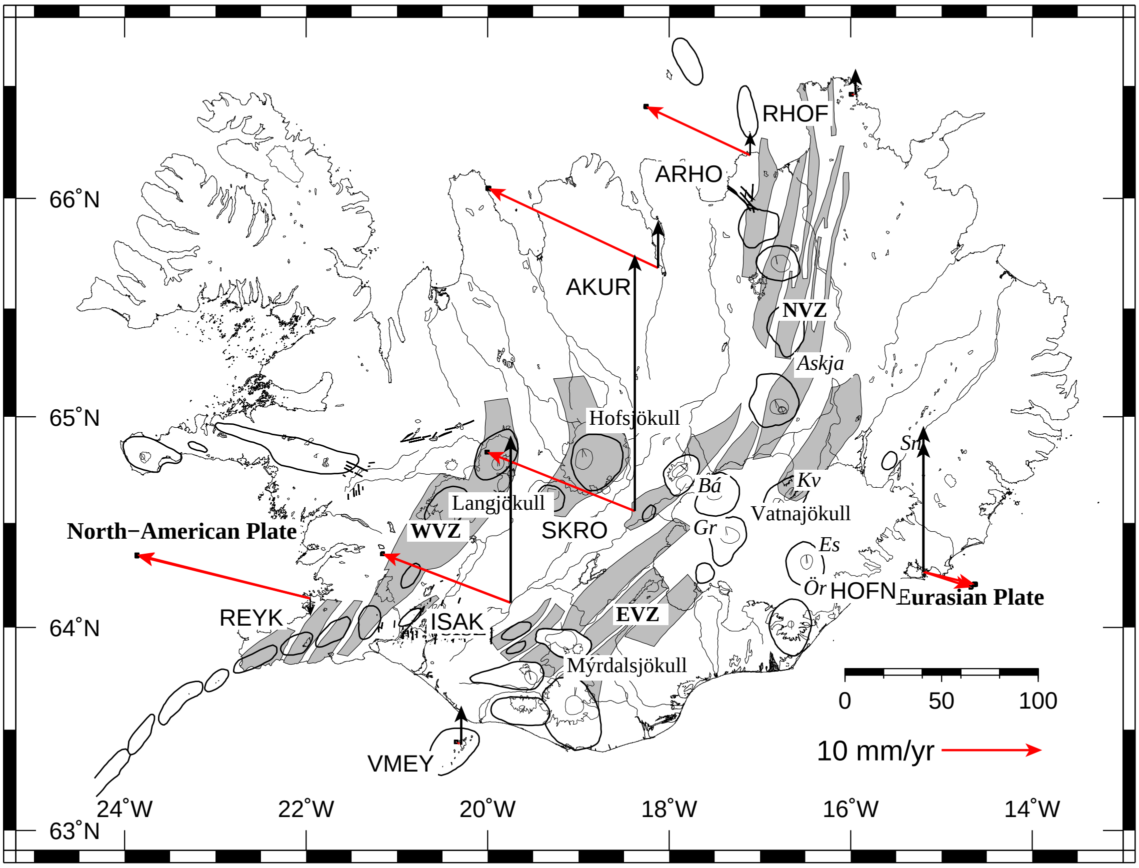

Figure 2: Velocities of some continuous GPS-stations processed with the Krafla GPS-campaign (for time series of these stations see Appendix B). These are the mean velocities from 2001 - 2009 and are in a reference frame of the Eurasian plate (see Appendix B). The red arrows show the horizontal velocities and the black arrows show the vertical velocities

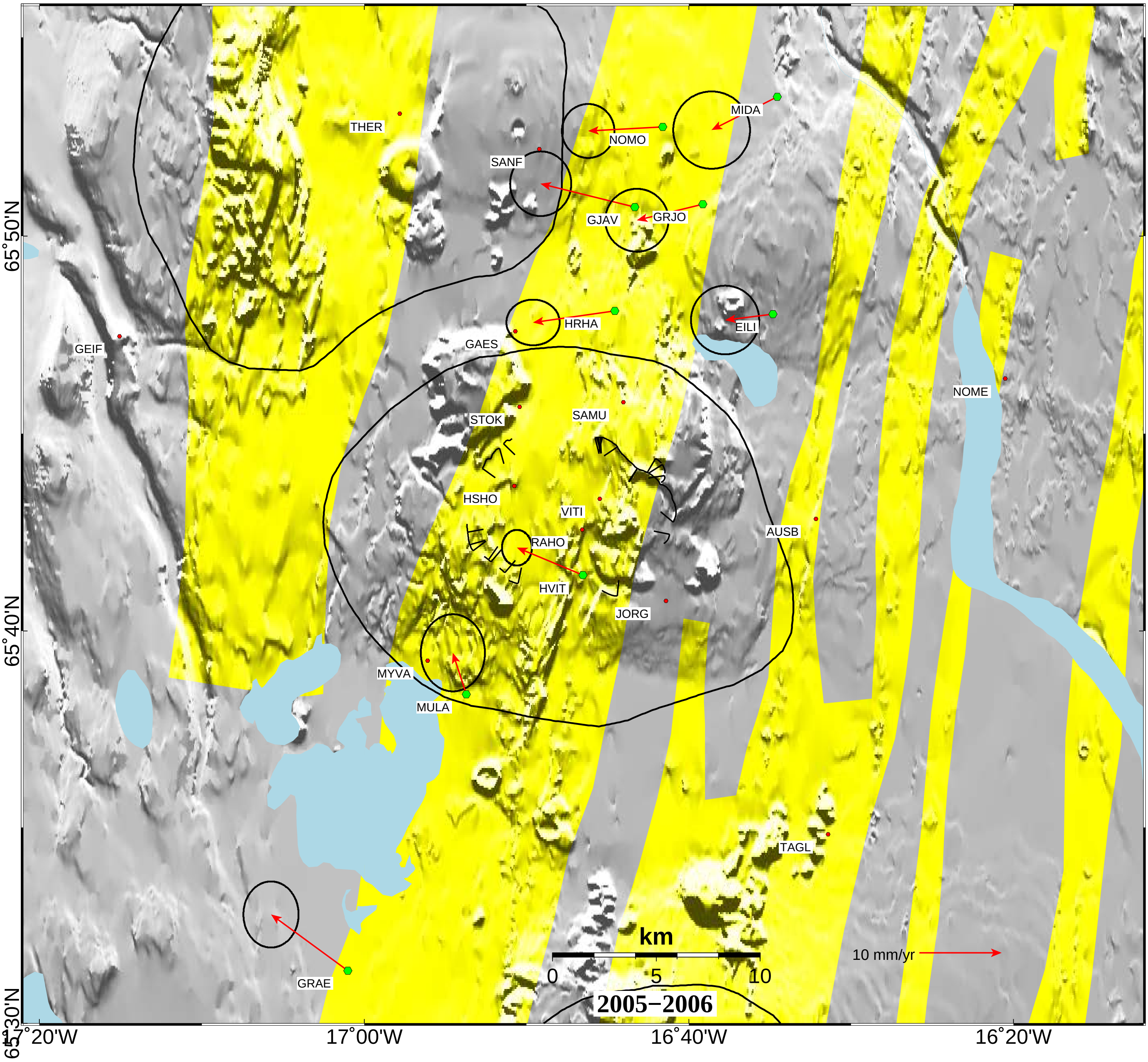

Figure 3: Horizontal velocities derived from the 2005 and 2006 GPS-campaigns, relative to stable Eurasian plate. The ellipses show 1 σ confidence interval.

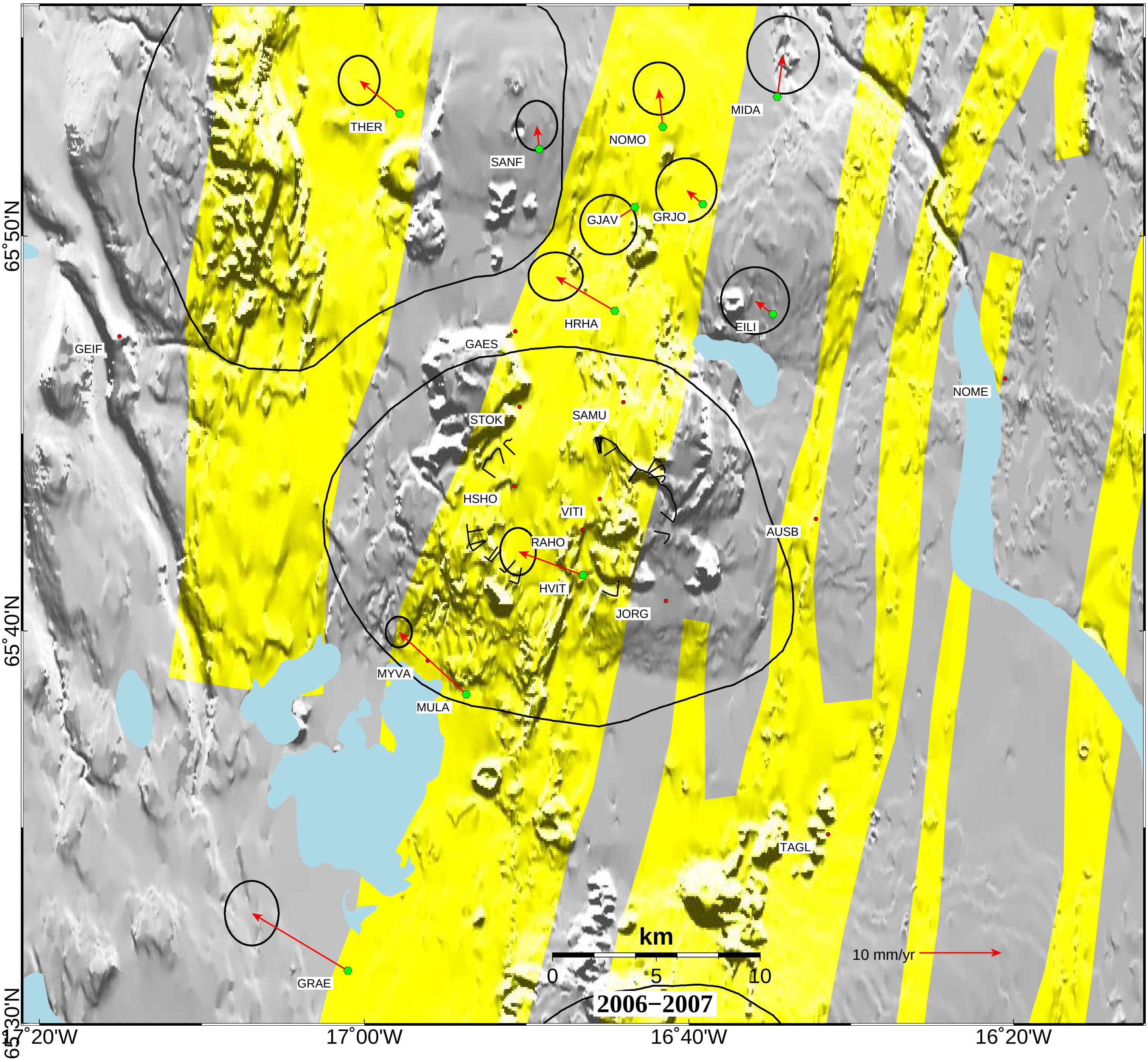

Figure 4: Horizontal velocities derived from the 2006 and 2007 GPS-campaigns, relative to stable Eurasian plate. The ellipses show $1\,\sigma$ confidence interval.

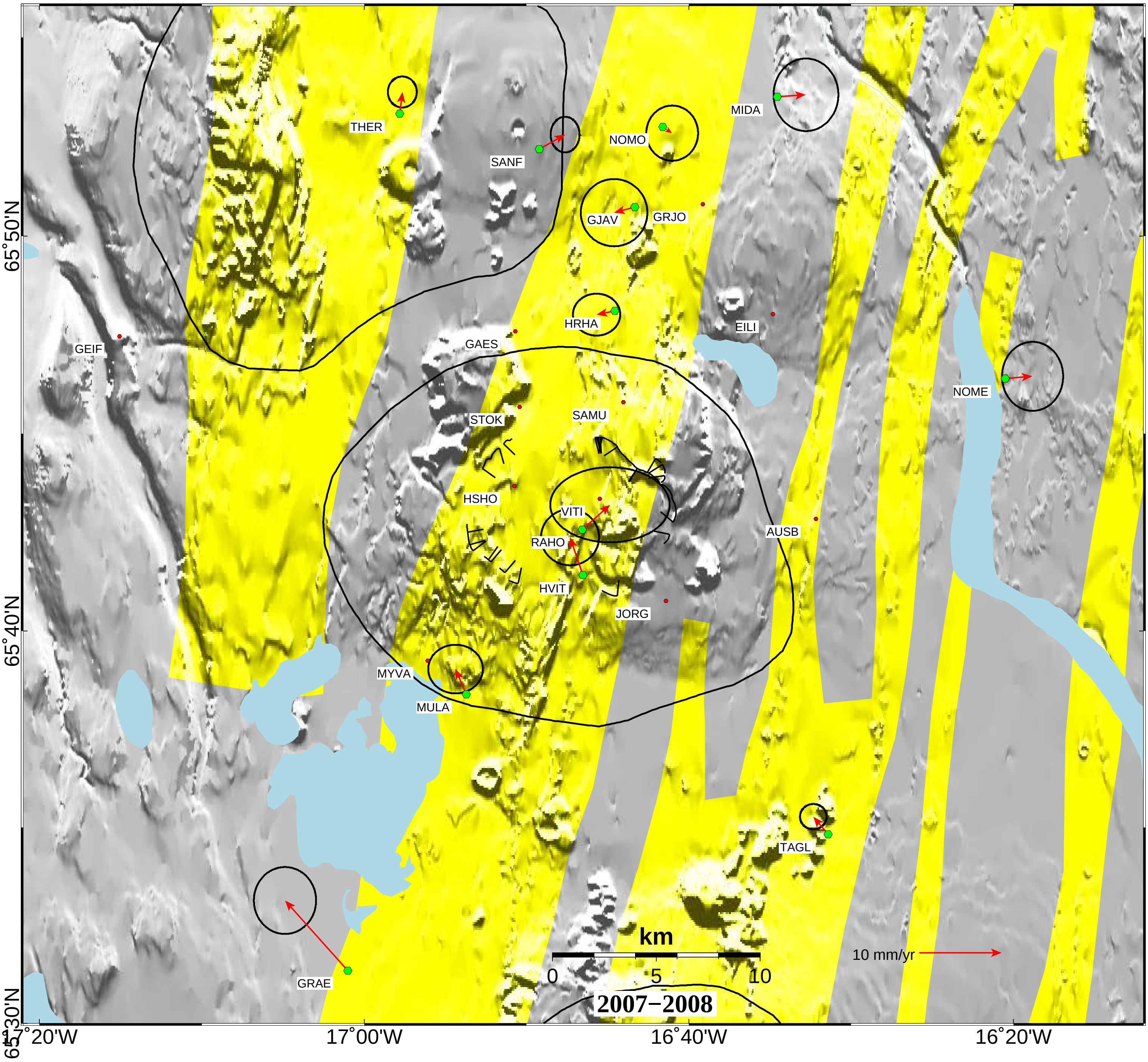

Figure 5: Horizontal velocities derived from the 2007 and 2008 GPS-campaigns, relative to stable Eurasian plate. The ellipses show $1\,\sigma$ confidence interval.

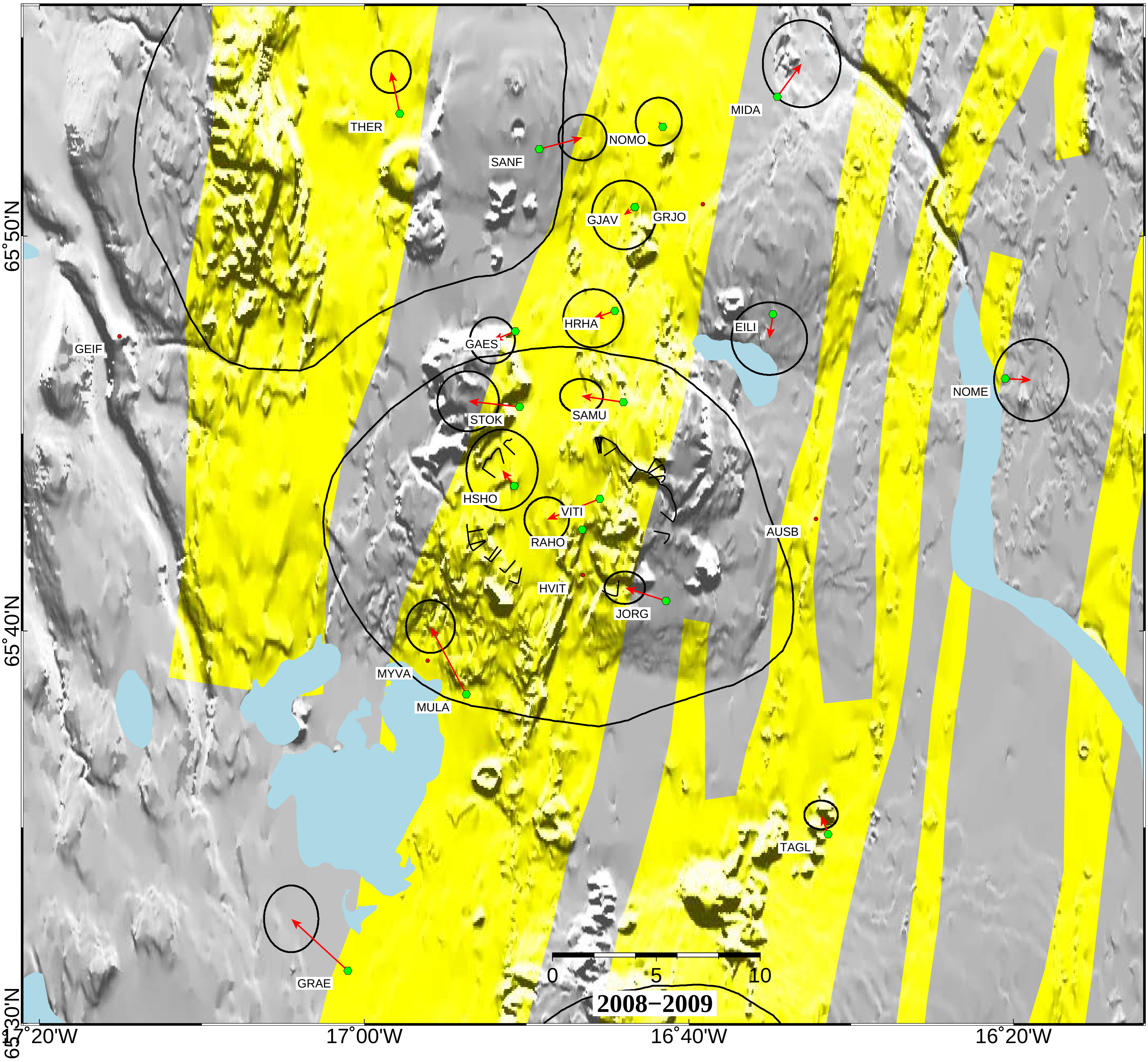

Figure 6: Horizontal velocities derived from the 2008 and 2009 GPS-campaigns, relative to stable Eurasian plate. The ellipses show $1\,\sigma$ confidence interval.

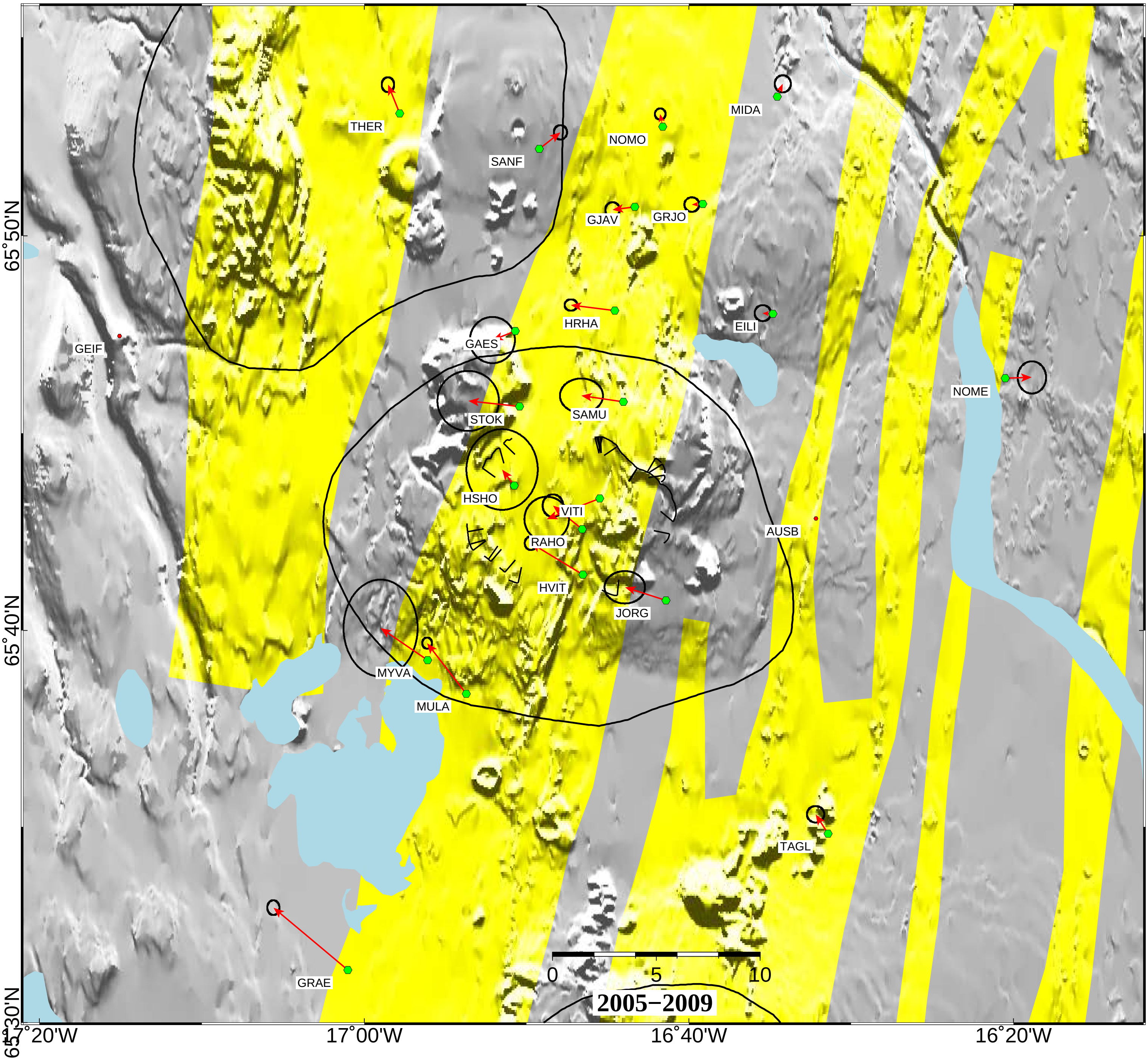

Figure 7: Average horizontal velocities derived from the 2005, 2006, 2007, 2008 and 2009 GPS-campaigns, relative to stable Eurasian plate. The ellipses show $1\,\sigma$ confidence interval.

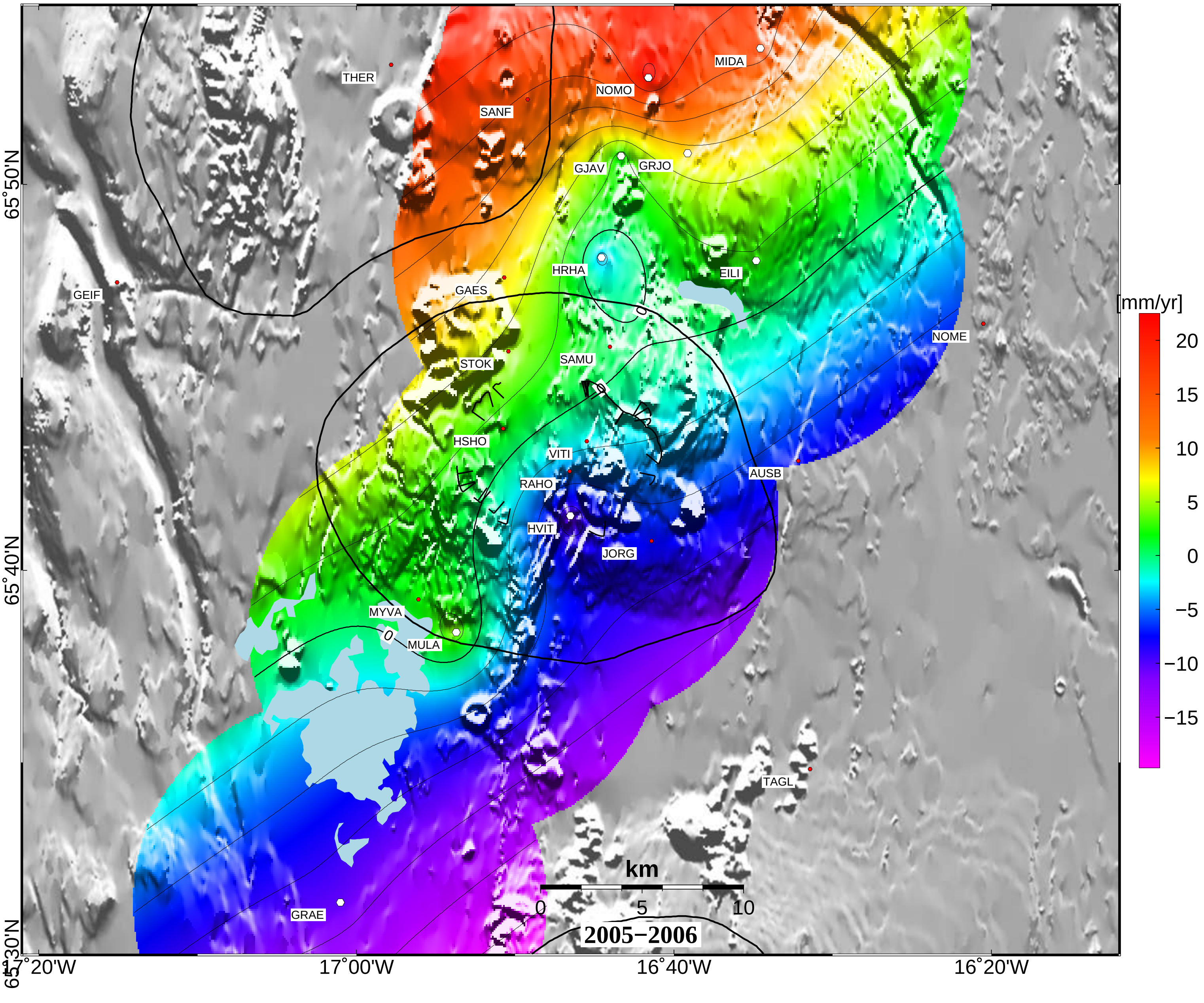

Figure 8: Vertical velocities derived from the 2005 and 2006 GPS-campaigns. The white hexagons show the stations used to derive the velocity field.

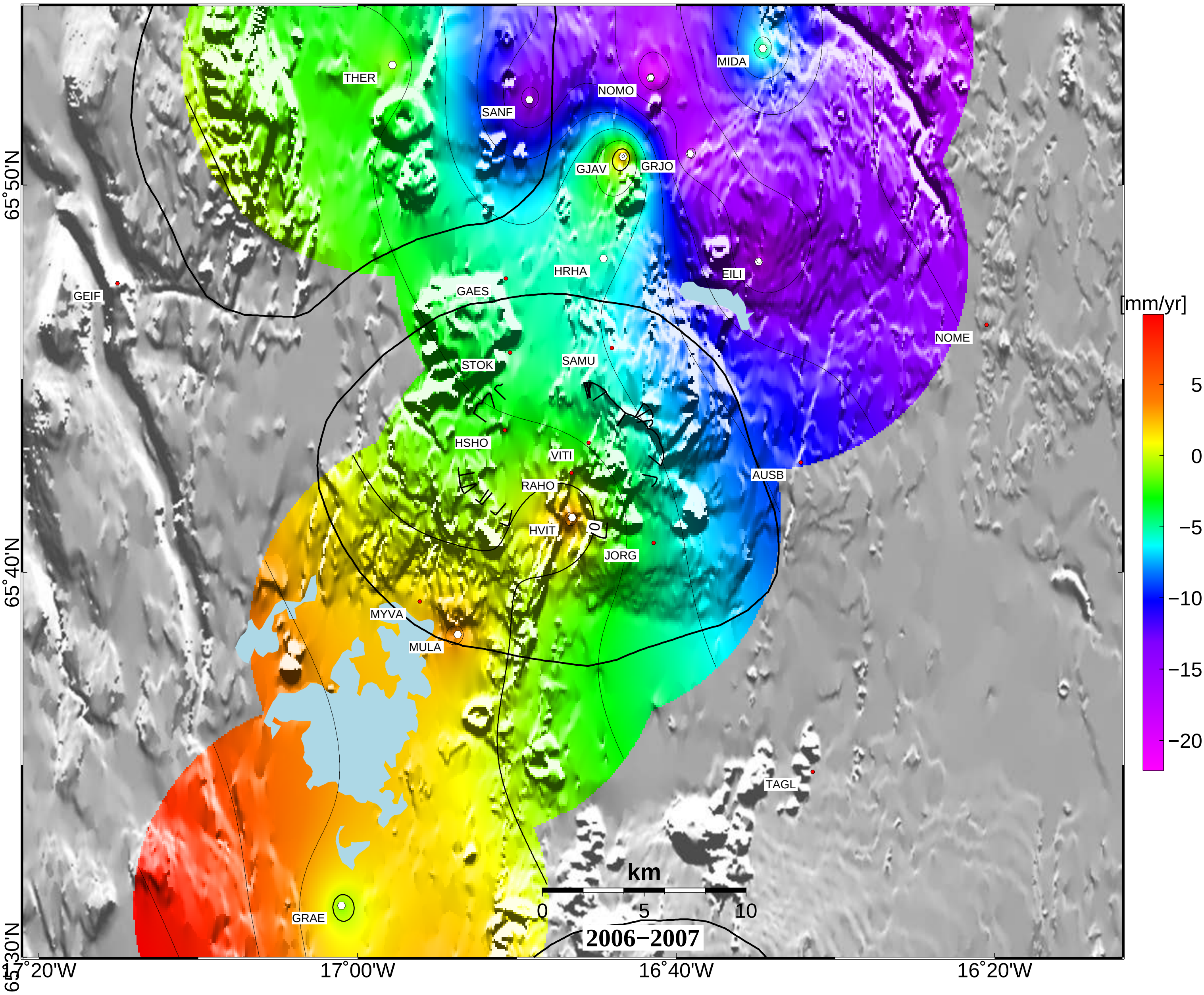

Figure 9: Vertical velocities derived from the 2006 and 2007 GPS-campaigns. The white hexagons show the stations used to derive the velocity field.

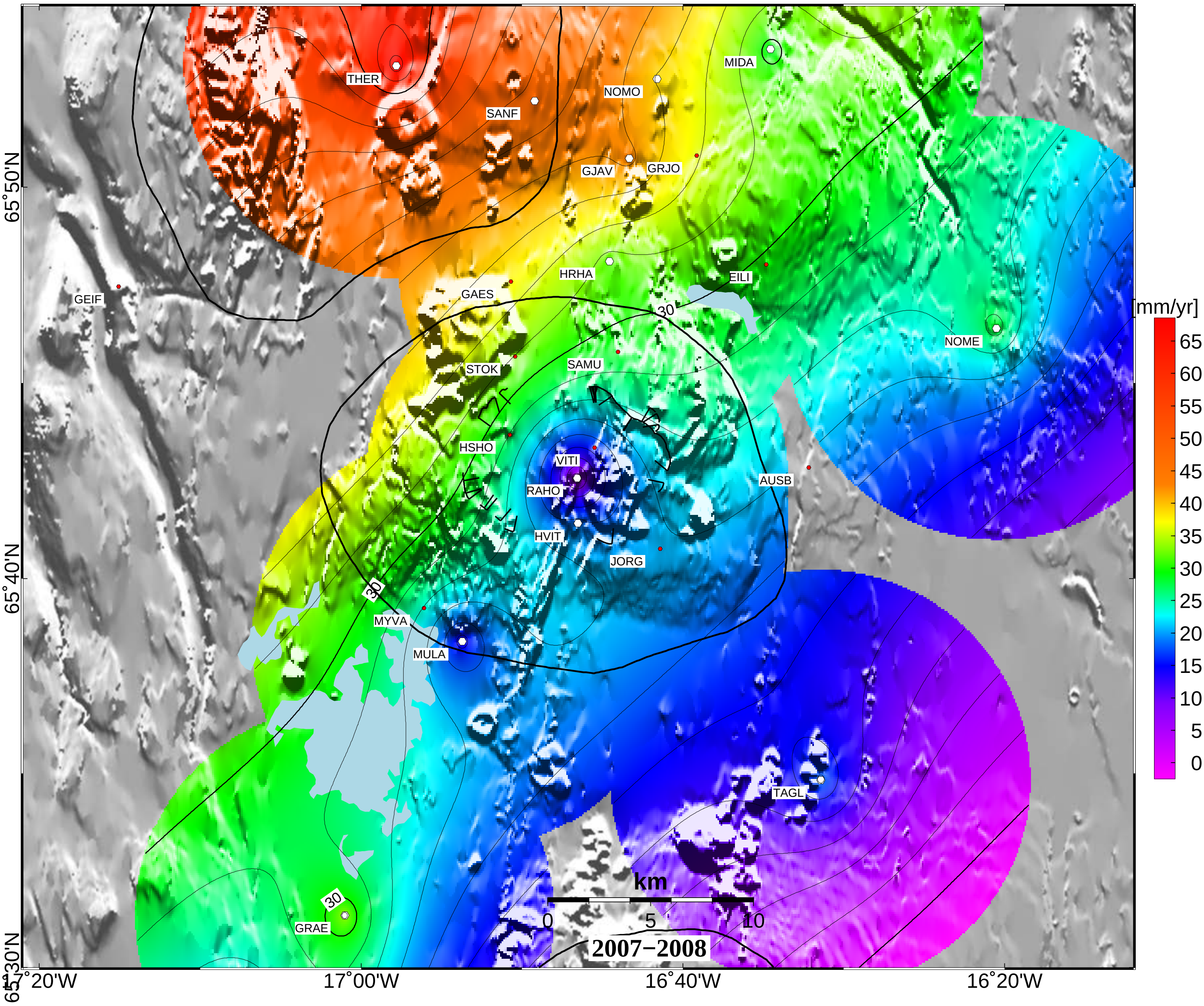

Figure 10: Vertical velocities derived from the 2007 and 2008 GPS-campaigns. The white hexagons show the stations used to derive the velocity field.

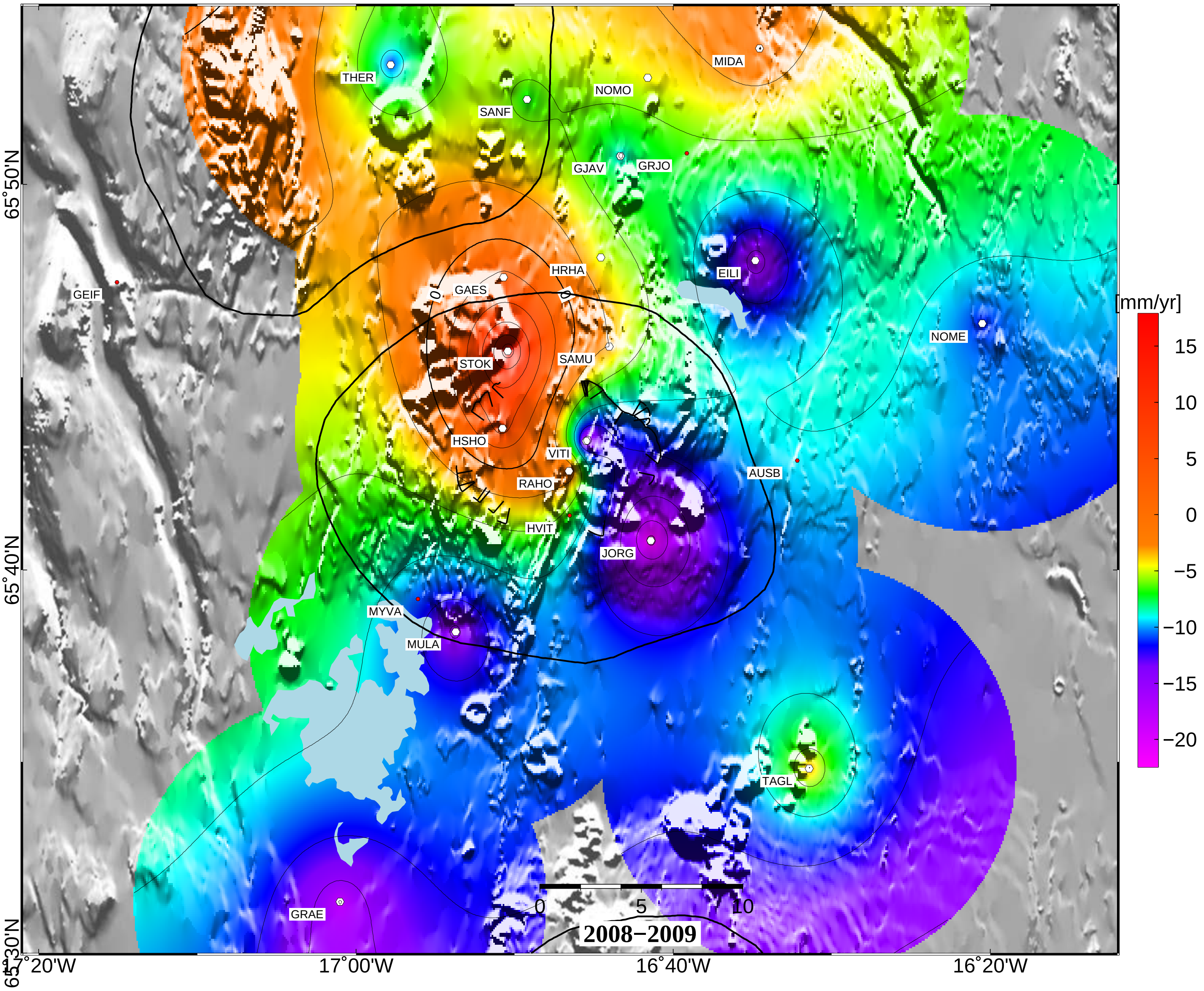

Figure 11: Vertical velocities derived from the 2008 and 2009 GPS-campaigns. The white hexagons show the stations used to derive the velocity field.

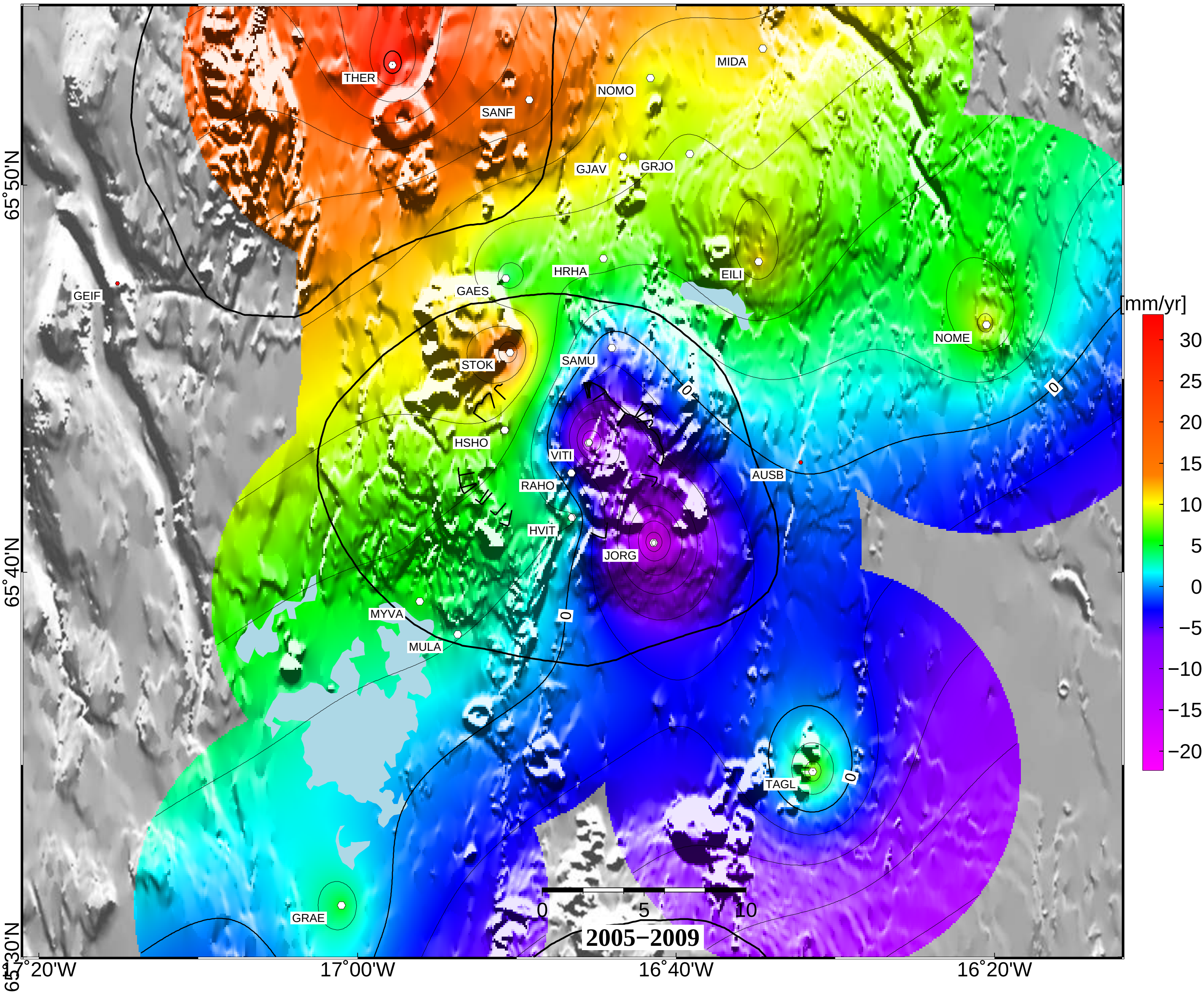

Figure 12: Average vertical velocities derived from the 2005, 2006, 2008 and 2009 GPS-campaigns (in mm/yr). The white hexagons show the stations used to derive the velocity field. The results from 2007 are not included in this velocity field. Also, measurements at Þeistareykir are not used.

References

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Appendix

A Coordinates

Table 1: Estimated geocentric coordinates (in ITRF2005 reference system) from 2009.

Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
EILI	2512994.5022	0.0017	-748211.0708	0.0012	5795327.6361	0.0035
GAES	2510234.8873	0.0021	-760031.2336	0.0014	5795038.8849	0.0046
GJAV	2506739.2527	0.0037	-753103.5698	0.0021	5797351.5889	0.0075
GRAE	2534174.0324	0.0022	-775587.6899	0.0015	5782405.3049	0.0048
GRAF	2569386.5806	0.0025	-741131.7639	0.0018	5771646.3076	0.0047
GRJO	2507528.2820	0.0017	-750015.2979	0.0013	5797392.2497	0.0036
HRHA	2510756.8485	0.0025	-755295.1524	0.0016	5795438.8896	0.0054
HSHO	2516591.8211	0.0019	-762006.6397	0.0014	5792103.7050	0.0040
HVIT	2521168.1062	0.5428	-760000.8351	0.5437	5790280.5313	0.5341
JORG	2523371.4923	0.0023	-756581.5468	0.0016	5789830.9903	0.0049
KRME	2550578.4325	0.0021	-739068.9491	0.0015	5780142.7687	0.0041
MIDA	2504102.7752	0.0017	-745353.7668	0.0013	5799374.1657	0.0035
MULA	2524416.1394	0.0018	-766736.3514	0.0013	5787827.8907	0.0035
NOME	2518718.3079	0.0024	-738513.5786	0.0016	5794009.4935	0.0054
NOMO	2503827.3295	0.0022	-750864.0299	0.0014	5798882.4947	0.0049
SAMU	2514677.2857	0.0019	-756056.6199	0.0014	5793804.3645	0.0040
SANF	2503118.6436	0.0029	-756697.7397	0.0027	5798583.4316	0.0062
STOK	2513409.6931	0.0028	-760783.4076	0.0015	5793603.8821	0.0056
TAGL	2535144.4090	0.0019	-752088.9149	0.0013	5785182.6840	0.0039
THER	2499694.2176	0.0018	-762498.8128	0.0013	5799073.0868	0.0039
VITI	2518298.0771	0.0018	-758313.5999	0.0013	5791867.2548	0.0036

Table 2: Estimated geocentric coordinates (in ITRF2005 reference system) from 2005.

Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
EILI	2512994.5379	0.0038	-748211.1028	0.0024	5795327.5845	0.0082
GJAV	2506739.2957	0.0043	-753103.5933	0.0026	5797351.5446	0.0088
GRAE	2534174.1211	0.0034	-775587.6994	0.0019	5782405.2571	0.0075
GRJO	2507528.3170	0.0037	-750015.3278	0.0024	5797392.1942	0.0077
HRHA	2510756.8962	0.0024	-755295.1678	0.0018	5795438.8470	0.0050
HVIT	2521170.6891	0.0023	-759999.7270	0.0017	5790283.9881	0.0049
MIDA	2504102.8093	0.0038	-745353.8059	0.0023	5799374.0986	0.0080
MULA	2524416.2144	0.0032	-766736.3824	0.0017	5787827.8442	0.0071
NOMO	2503827.3702	0.0037	-750864.0641	0.0023	5798882.4322	0.0083
RAHO	2519323.0875	0.0023	-759488.3313	0.0015	5791265.8614	0.0046

Table 3: Estimated geocentric coordinates (in ITRF2005 reference system) from 2006.

Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
EILI	2512994.5261	0.0021	-748211.0994	0.0014	5795327.5938	0.0045
GJAV	2506739.2772	0.0023	-753103.5954	0.0013	5797351.5530	0.0049
GRAE	2534174.0944	0.0022	-775587.6960	0.0013	5782405.2576	0.0045
GRJO	2507528.3071	0.0024	-750015.3289	0.0014	5797392.2069	0.0050
HRHA	2510756.8813	0.0021	-755295.1688	0.0014	5795438.8481	0.0044
HVIT	2521170.6671	0.0022	-759999.7235	0.0013	5790283.9878	0.0044
MIDA	2504102.8065	0.0027	-745353.8080	0.0016	5799374.1172	0.0059
MULA	2524416.1982	0.0019	-766736.3721	0.0012	5787827.8576	0.0039
NOMO	2503827.3641	0.0031	-750864.0675	0.0017	5798882.4608	0.0066
SANF	2503118.6693	0.0021	-756697.7857	0.0013	5798583.3831	0.0042
THER	2499694.2415	0.0028	-762498.8352	0.0016	5799073.0036	0.0059
RAHO	2519323.0839	0.0203	-759488.3252	0.0079	5791265.9008	0.0402

Table 4: Estimated geocentric coordinates (in ITRF2005 reference system) from 2007.

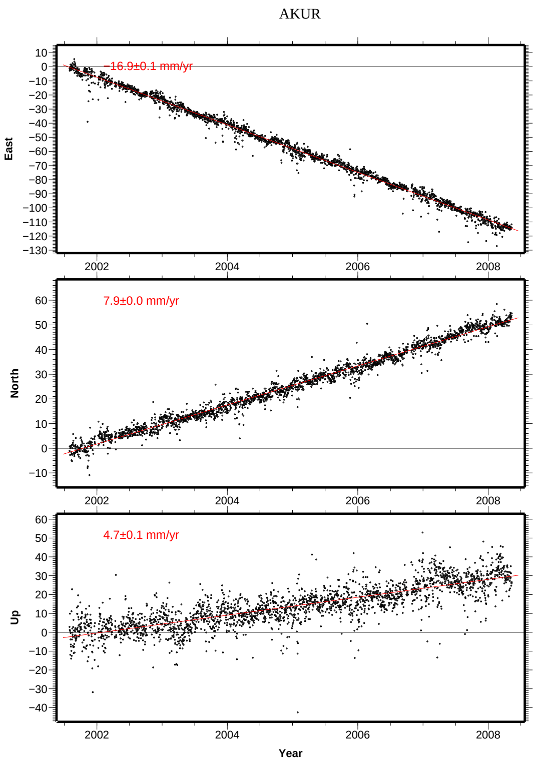
Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
EILI	2512994.5058	0.0025	-748211.0891	0.0014	5795327.5846	0.0056
GJAV	2506739.2691	0.0020	-753103.5899	0.0012	5797351.5619	0.0044
GRAE	2534174.0712	0.0018	-775587.6967	0.0010	5782405.2659	0.0037
GRAF	2569386.6062	0.0016	-741131.7905	0.0010	5771646.2973	0.0034
GRJO	2507528.2868	0.0019	-750015.3181	0.0011	5797392.1976	0.0043
HVIT	2521170.6519	0.0020	-759999.7221	0.0011	5790283.9986	0.0041
KRME	2550578.4495	0.0017	-739068.9699	0.0011	5780142.7401	0.0035
MIDA	2504102.7889	0.0018	-745353.7948	0.0011	5799374.1228	0.0039
MULA	2524416.1778	0.0019	-766736.3692	0.0011	5787827.8704	0.0041
NOME	2518718.3215	0.0025	-738513.6060	0.0015	5794009.4633	0.0056
NOMO	2503827.3394	0.0025	-750864.0533	0.0016	5798882.4509	0.0054
SANF	2503118.6489	0.0028	-756697.7730	0.0015	5798583.3762	0.0065
TAGL	2535144.4315	0.0018	-752088.9330	0.0011	5785182.6513	0.0038
THER	2499694.2247	0.0020	-762498.8294	0.0012	5799073.0114	0.0042
RAHO	2519323.0552	0.0018	-759488.3166	0.0011	5791265.8748	0.0039

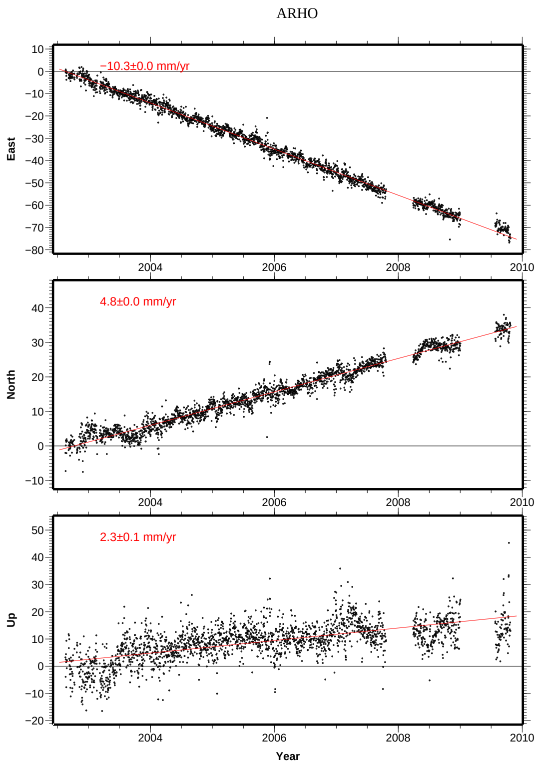
Table 5: Estimated geocentric coordinates (in ITRF2005 reference system) from 2008.

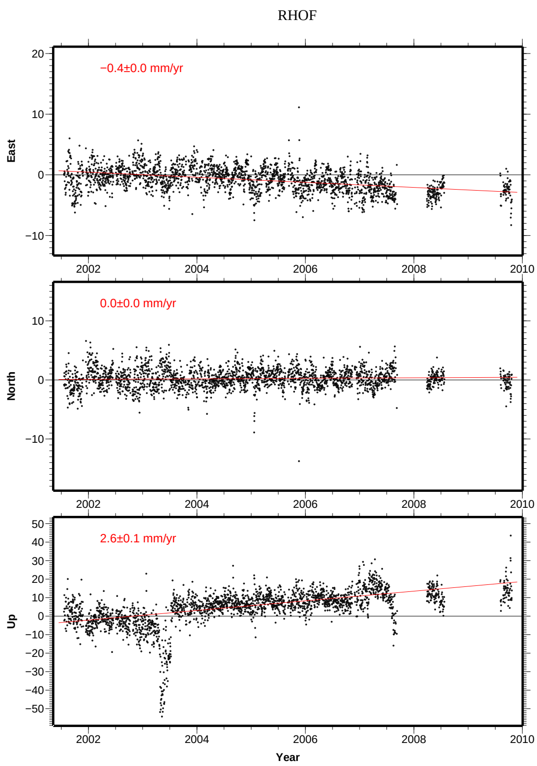
Point	x [m]	σ_x [m]	y [m]	σ_y [m]	z [m]	σ_z [m]
AUSB	2521974.7914	0.0193	-748782.0651	0.0242	5791345.1858	0.0314
EILI	2512994.5335	0.0233	-748211.0886	0.0239	5795327.6772	0.0379
GEIF	2504969.4243	0.0018	-777878.1223	0.0013	5794899.1872	0.0038
GJAV	2506739.2895	0.0233	-753103.5873	0.0239	5797351.6332	0.0379
GRAE	2534174.0410	0.0140	-775587.6391	0.0168	5782405.2588	0.0230
GRAF	2569386.5889	0.0091	-741131.7585	0.0110	5771646.2887	0.0151
GRJO	2507528.3157	0.0233	-750015.3141	0.0239	5797392.2928	0.0379
HRHA	2510756.8792	0.0233	-755295.1673	0.0239	5795438.9198	0.0379
HSHO	2516591.8318	0.0030	-762006.6480	0.0019	5792103.6919	0.0067
HVIT	2521170.6234	0.0137	-759999.6556	0.0168	5790283.9761	0.0224
JORG	2523371.5011	0.0107	-756581.5107	0.0129	5789830.9611	0.0176
KRME	2550578.4354	0.0092	-739068.9414	0.0110	5780142.7361	0.0152
MIDA	2504102.7890	0.0020	-745353.7815	0.0014	5799374.1577	0.0043
MULA	2524416.1488	0.0140	-766736.3036	0.0168	5787827.8427	0.0230
NOME	2518718.3218	0.0034	-738513.5922	0.0024	5794009.4983	0.0084
NOMO	2503827.3599	0.0233	-750864.0467	0.0239	5798882.5212	0.0380
SAMU	2514677.2955	0.0103	-756056.6269	0.0125	5793804.3436	0.0176
SANF	2503118.6557	0.0021	-756697.7624	0.0015	5798583.4312	0.0046
TAGL	2535144.4141	0.0092	-752088.9068	0.0110	5785182.6510	0.0154
THER	2499694.2377	0.0021	-762498.8245	0.0015	5799073.0873	0.0046
VITI	2518298.1321	0.0175	-758313.6101	0.0130	5791867.3494	0.0289
RAHO	2519323.0111	0.0194	-759488.2212	0.0244	5791265.8053	0.0309
STOK	2513409.7004	0.0025	-760783.4081	0.0015	5793603.8605	0.0051
GAES	2510234.8970	0.0017	-760031.2385	0.0013	5795038.8760	0.0037

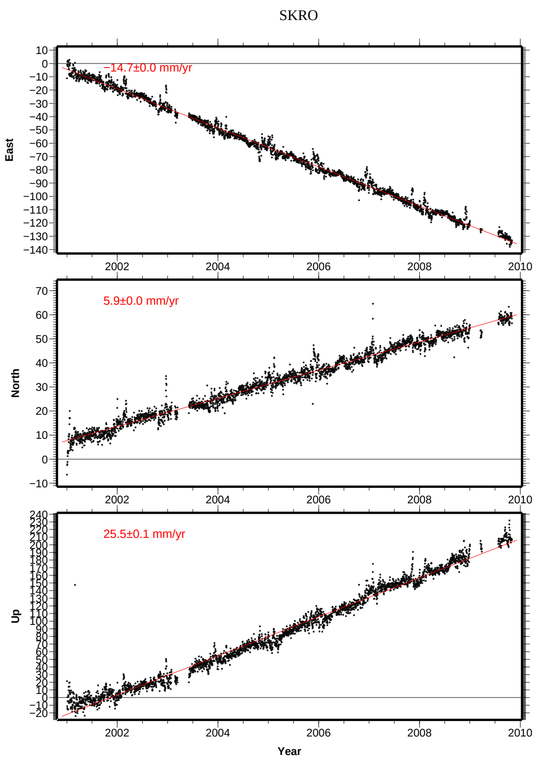
B Time series of continuous GPS data

Time series of the continuous GPS-stations shown in Figure 2. An annual component of the time series has been estimated and removed. The the plate velocity of the eurasian plate (ITRF05 reference frame) has been subtracted from the time series. The rotation pole of Eurasia in ITRF05 reference frame is (56.330 deg,-95.979 deg,0.261 deg/my) as published by *Altamimi et al.* (2007). The red lines show the least square linear fit (LSQ) of the time series and the red labels show the value of the LSQ with the 2σ uncertainties.

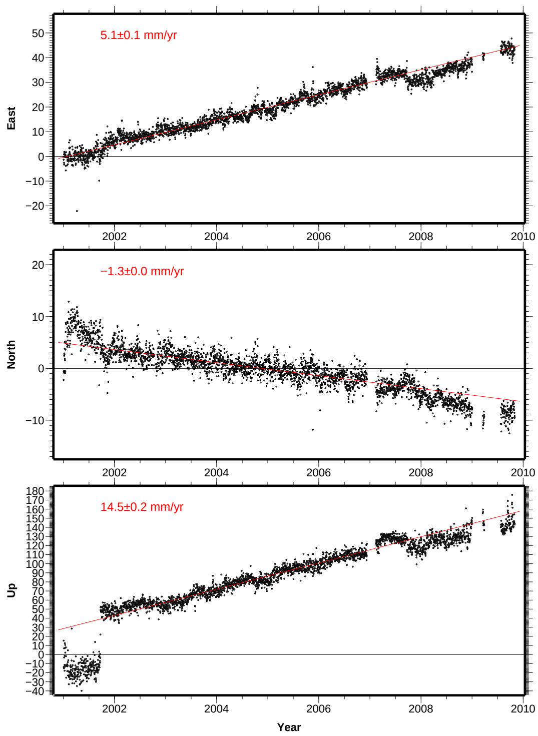

AKUR
East
−16.9±0.1 mm/yr
North
7.9±0.0 mm/yr
Up
4.7±0.1 mm/yr
Year


ARHO
East
−10.3±0.0 mm/yr
North
4.8±0.0 mm/yr
Up
2.3±0.1 mm/yr
Year

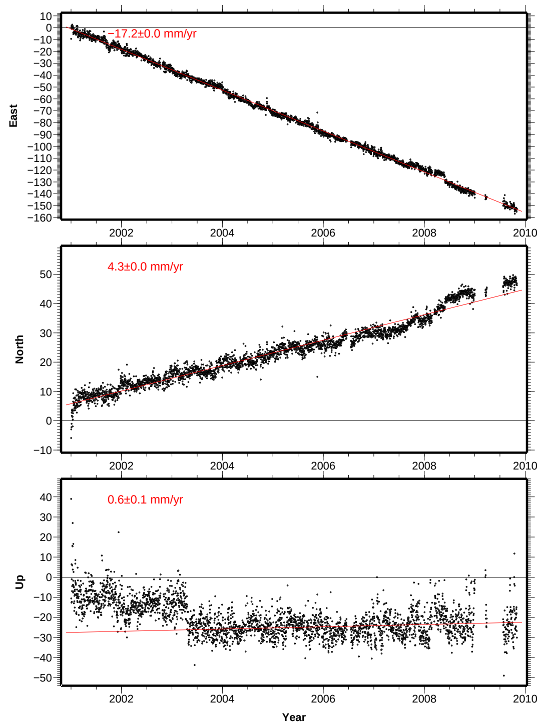

RHOF
East
−0.4±0.0 mm/yr
North
0.0±0.0 mm/yr
Up
2.6±0.1 mm/yr
Year


SKRO
East
−14.7±0.0 mm/yr
North
5.9±0.0 mm/yr
Up
25.5±0.1 mm/yr
Year

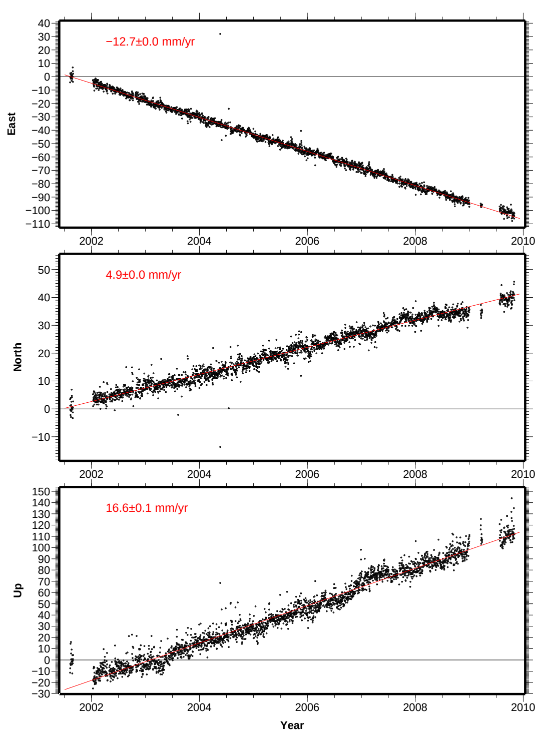
HOFN



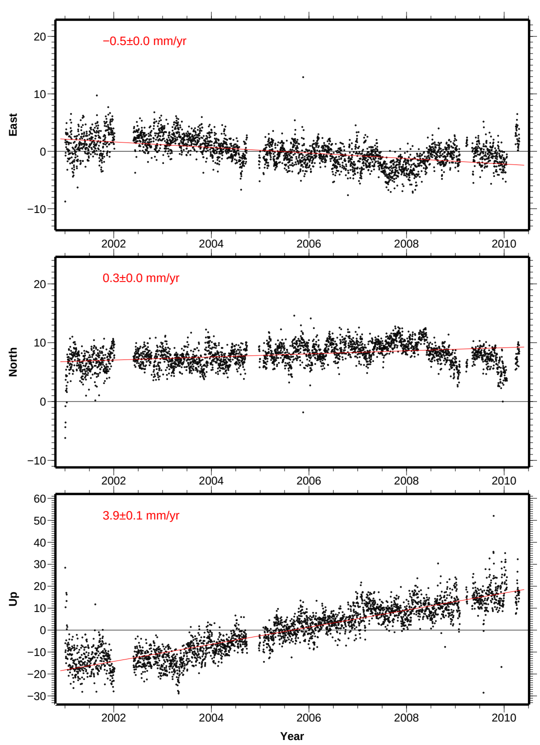
REYK



ISAK



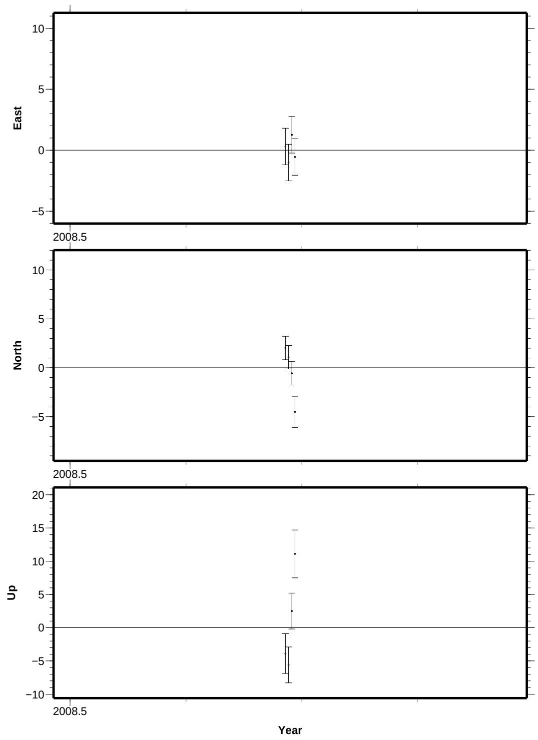
VMEY



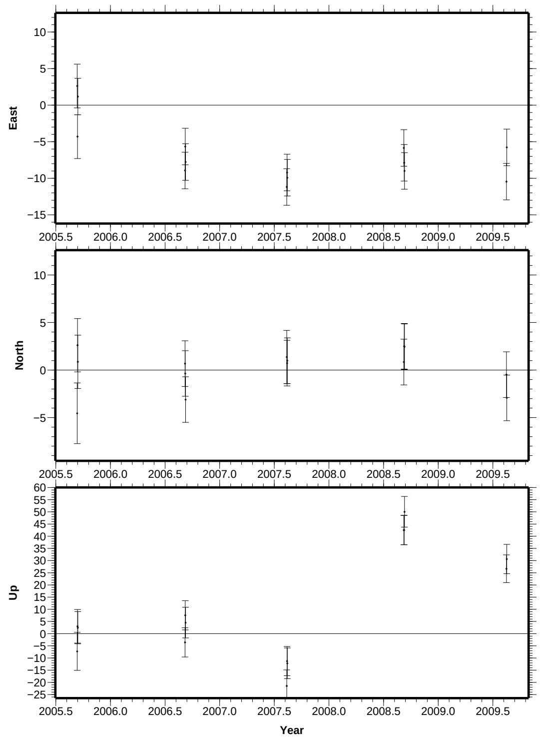
C Time series of GPS-campaign data

The following figures show the time series of displacements from 2005-2008. The the plate velocity of the eurasian plate (ITRF05 reference frame) has been subtracted from the time series. The rotation pole of Eurasia in ITRF05 reference frame is (56.330 deg,-95.979 deg,0.261 deg/my) as published by *Altamimi et al.* (2007).

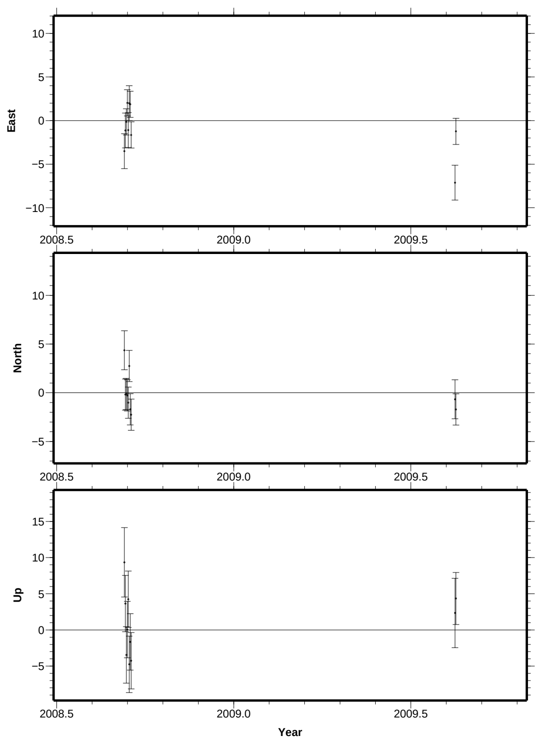
AUSB



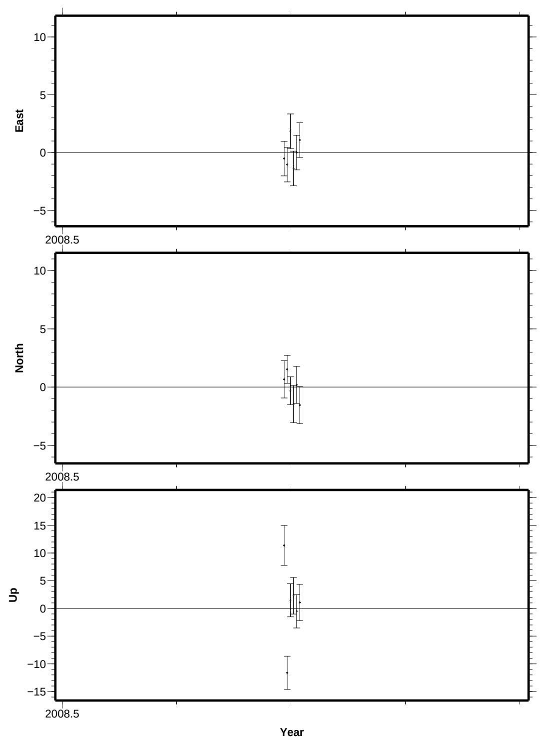
EILI



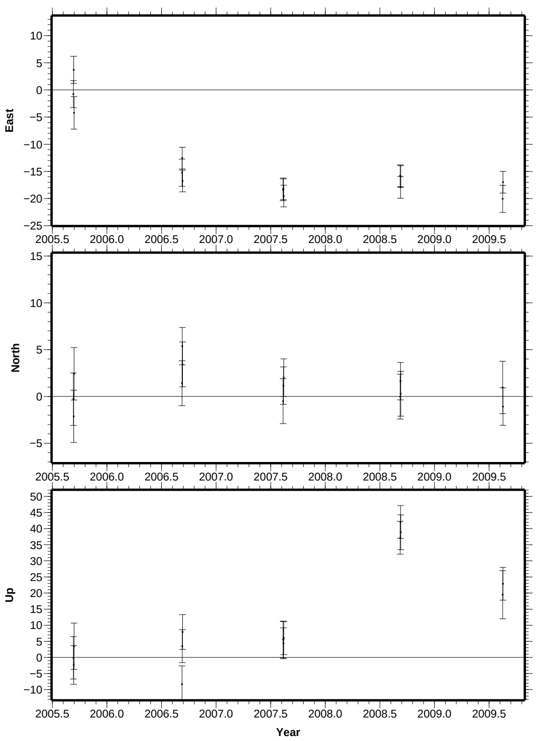
GAES



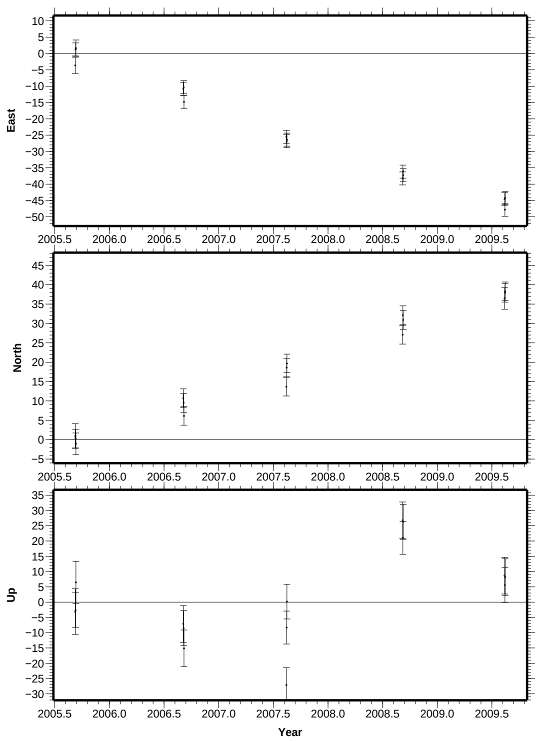
GEIF



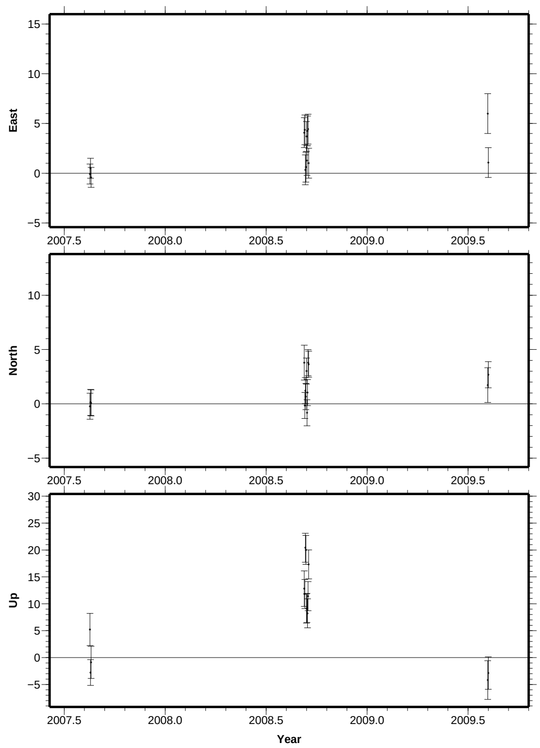
GJAV



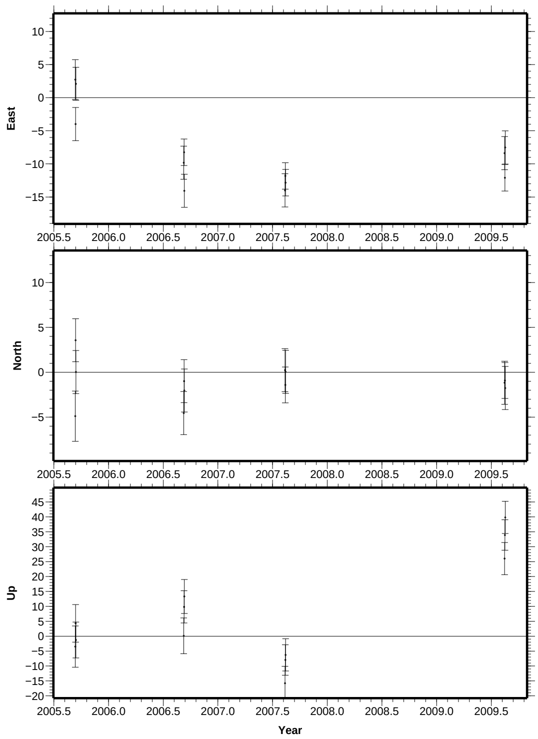
GRAE



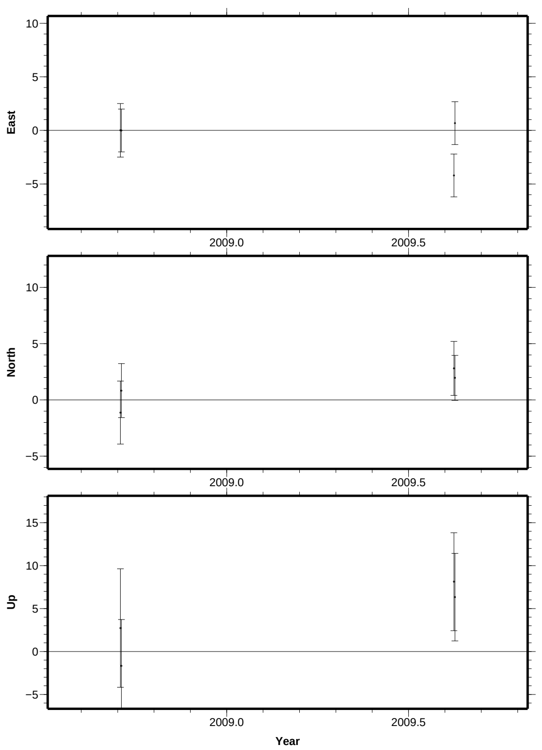
GRAF



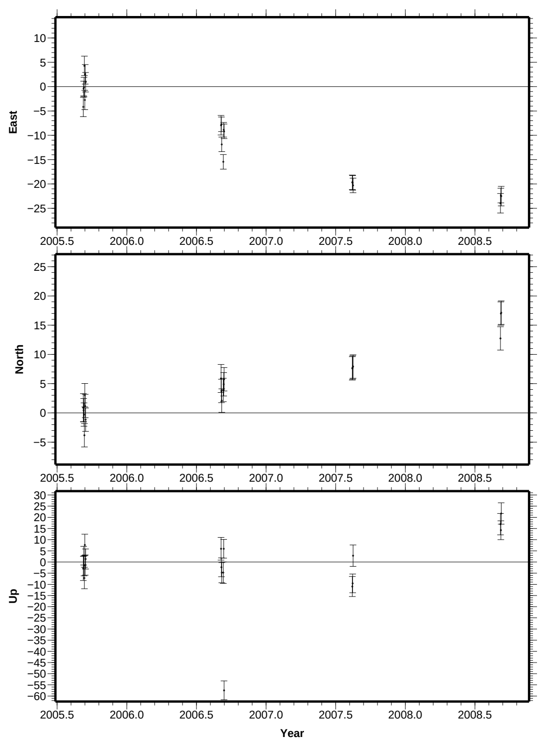
GRJO



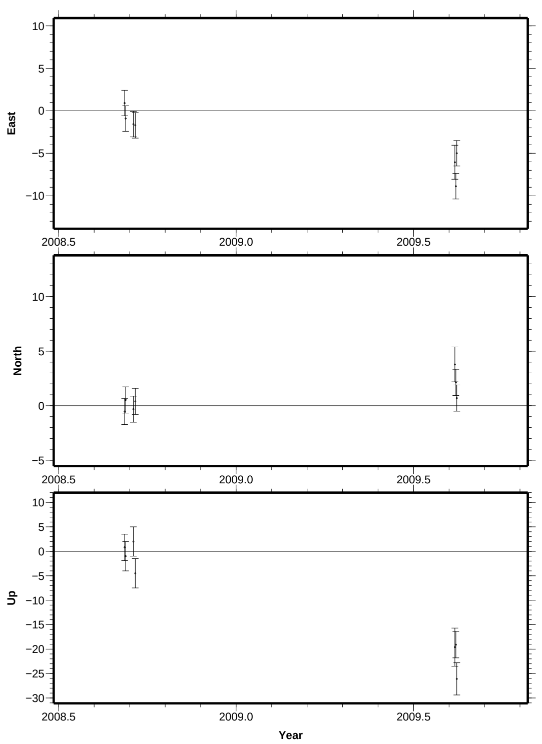
HSHO



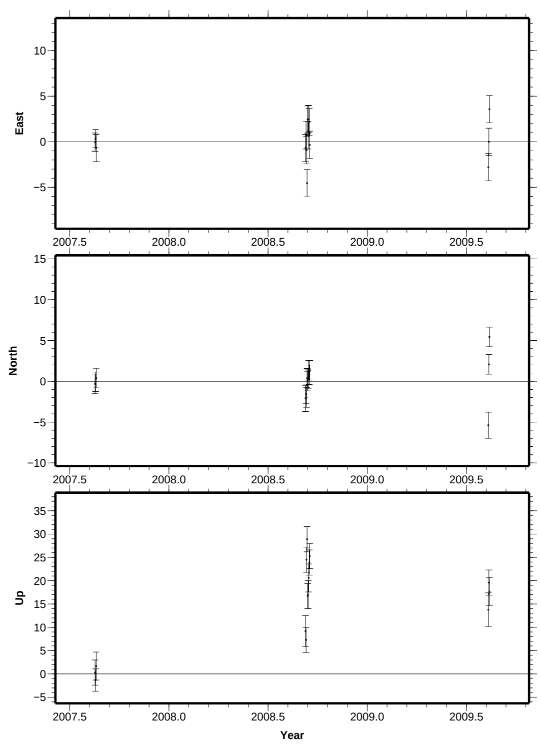
HVIT



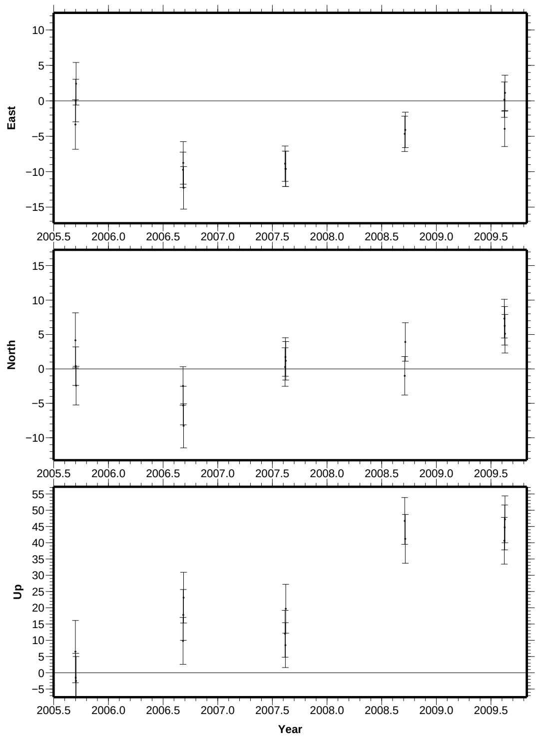
JORG



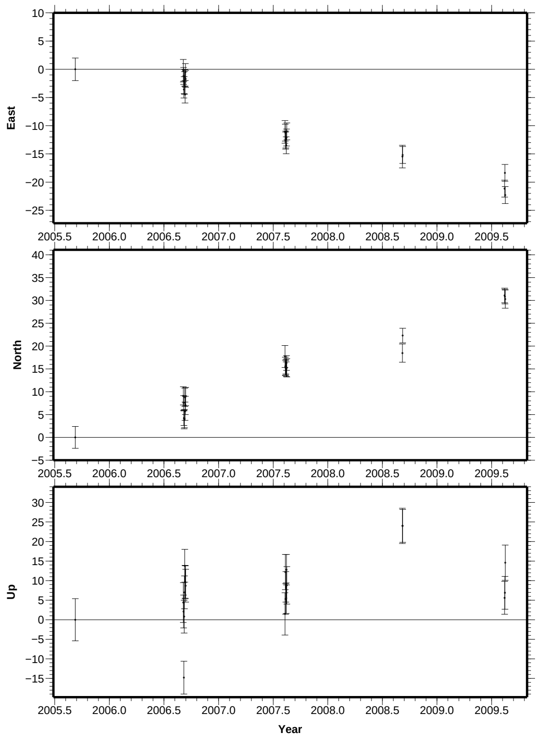
KRME



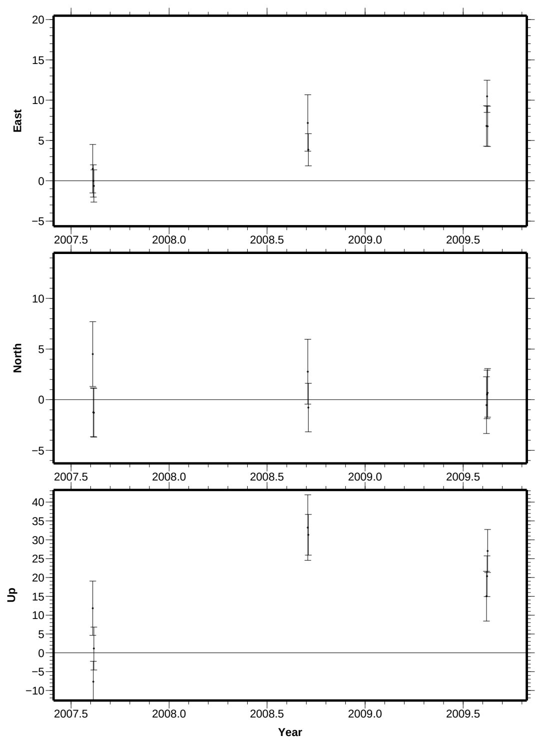
MIDA



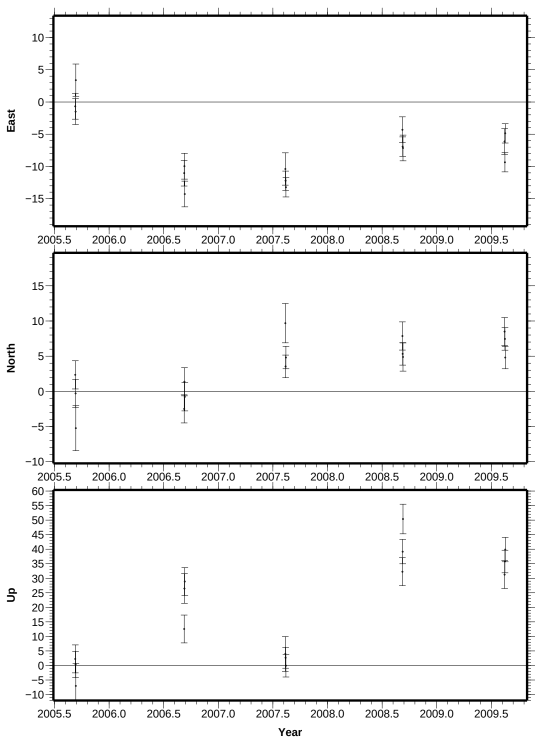
MULA



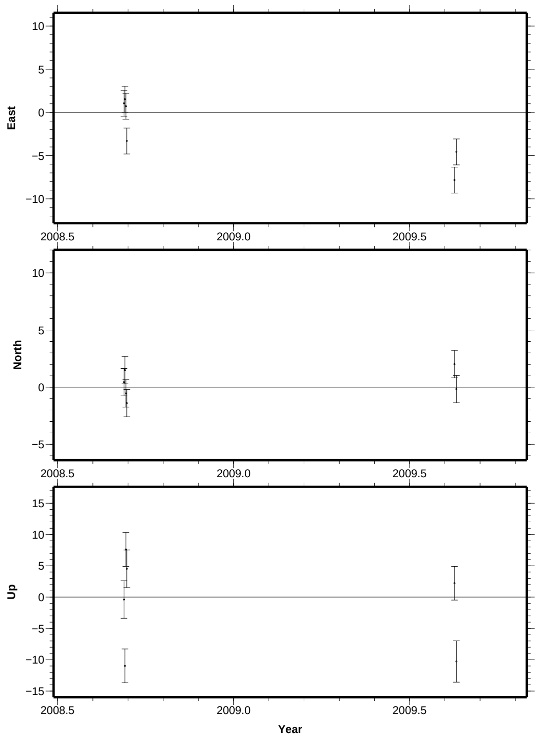
NOME



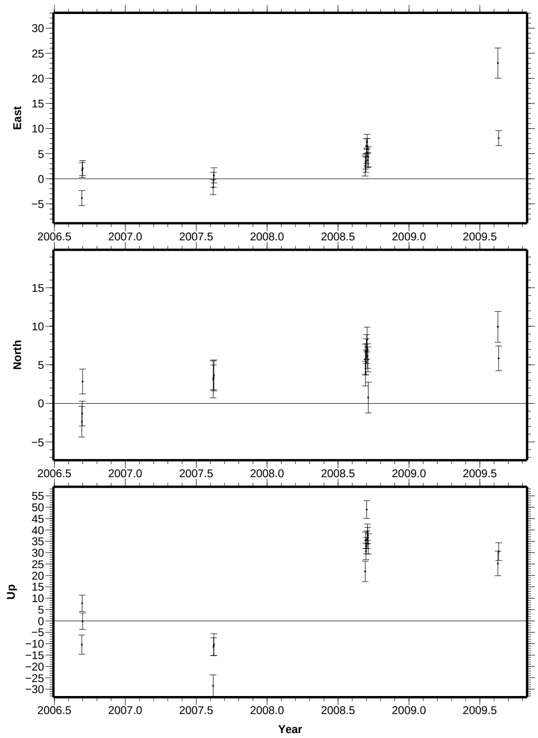
NOMO



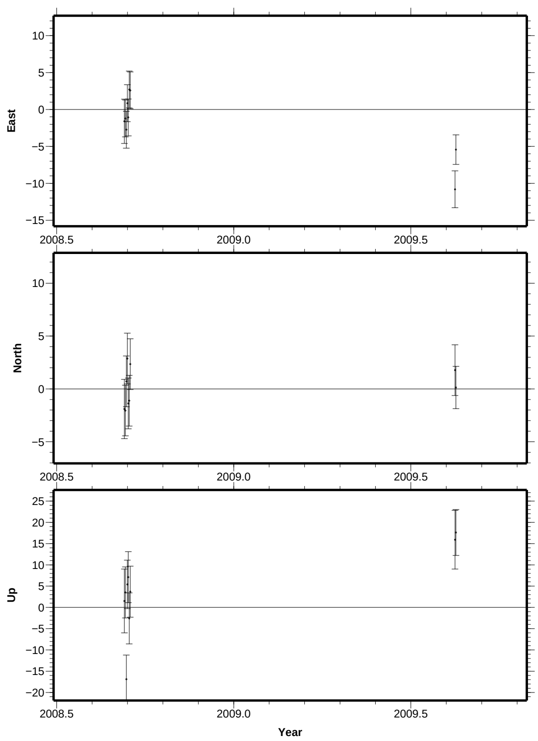
SAMU



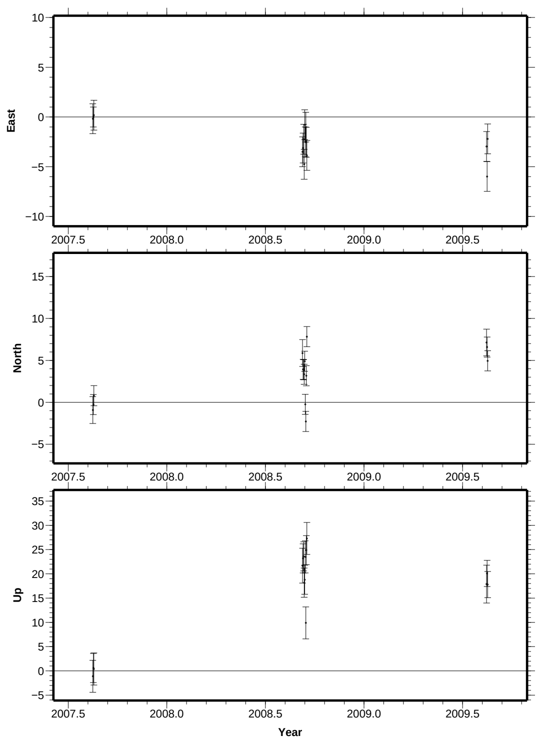
SANF

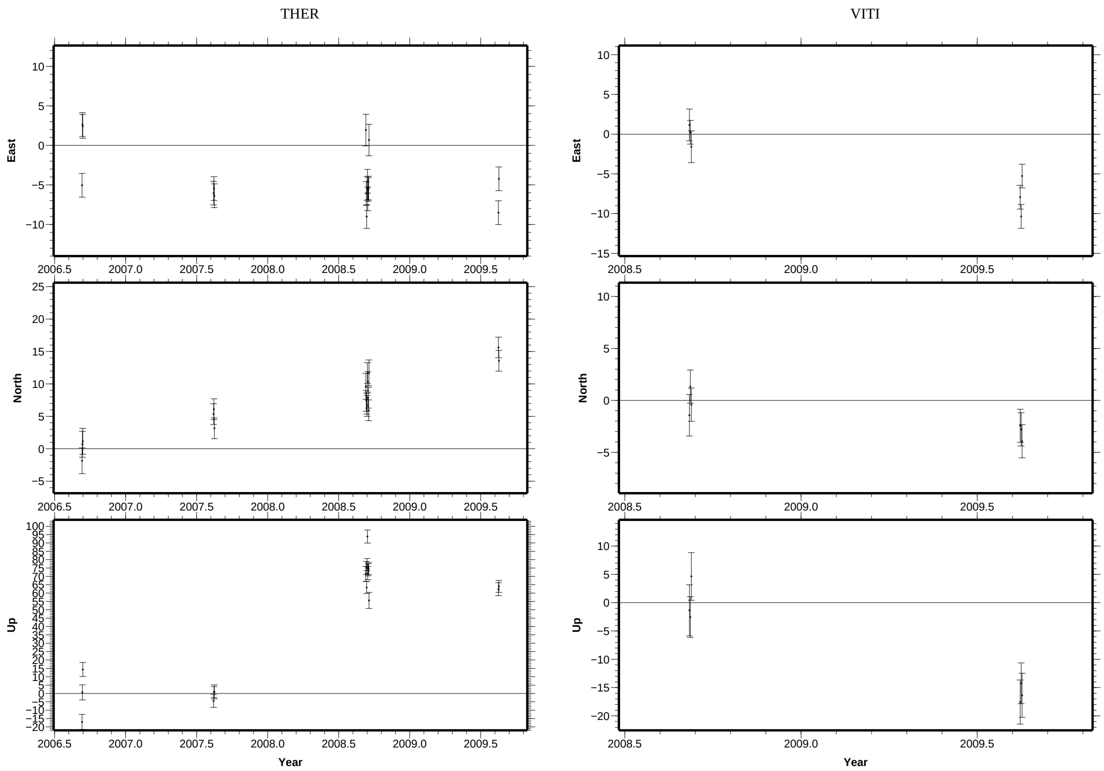


STOK



TAGL

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