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The Antarctic regional GPS network densification - status and results

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Corresponding Author:	Axel Rülke Federal Agency for Cartography and Geodesy Frankfurt/Main, GERMANY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Federal Agency for Cartography and Geodesy
Corresponding Author's Secondary Institution:	
First Author:	Axel Rülke
First Author Secondary Information:	
Order of Authors:	Axel Rülke
	Reinhard Dietrich
	Alessandro Capra
	E. D. Dong Chen
	Jan Cisak
	Trond Eiken
	Adrian Fox
	Larry D. Hothem
	Gary Johnston
	E. C. Malaimani
	Alexey J. Matveev
	Gennadi Milinevsky
	Hans-Werner Schenke
	Kazuo Shibuya
	Lars E. Sjöberg
	Andrés Zakrajsek
	Mathias Fritsche
	Andreas Groh
	Christoph Knöfel
	Mirko Scheinert
Order of Authors Secondary Information:	
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Axel Rülke · Reinhard Dietrich · Alessandro Capra · E. Dong Chen · Jan Cisak · Trond Eiken · Adrian Fox · Larry D. Hothem · Gary Johnston · E. C. Malaimani · Alexey J. Matveev · Gennadi Milinevsky · Hans-Werner Schenke · Kazuo Shibuya · Lars E. Sjöberg · Andrés Zakrajsek · Mathias Fritsche · Andreas Groh · Christoph Knöfel · Mirko Scheinert

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Axel Rülke
Federal Agency for Cartography and Geodesy, Frankfurt/Main, Germany, E-mail: axel.ruelke@bkg.bund.de

Reinhard Dietrich, Andreas Groh, Christoph Knöfel, Mirko Scheinert
TU Dresden, Institut für Planetare Geodäsie, Dresden, Germany, E-mail: reinhard.dietrich@tu-dresden.de

Alessandro Capra
Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Modena, Italy

E. Dong Chen
Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan, China

Jan Cisak
Instytut Geodezji i Kartografii, Warsaw, Poland

Trond Eiken
Department of Geosciences, University of Oslo, Oslo, Norway

Adrian Fox
British Antarctic Survey, Cambridge, U.K.

Larry D. Hothem
U.S. Geological Survey, Reston, VA, USA

Gary Johnston
Geoscience Australia, Canberra, Australia

E. C. Malaimani
National Geophysical Research Institute (NGRI), Hyderabad, India

Alexey J. Matveev
OAO Aerogeodezia, St. Petersburg, Russia

Gennadi Milinevsky
Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Hans-Werner Schenke
Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany

Kazuo Shibuya
National Institute of Polar Research, Tokyo, Japan

Lars E. Sjöberg
Royal Institute of Technology, Stockholm, Sweden

Andrés Zakrajsek
Instituto Antártico Argentino, Buenos Aires, Argentina

Mathias Fritsche
Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum GFZ, Potsdam, Germany

Abstract We report on the activities related to the IAG Subcommission 1.3f "Regional Reference Frame for Antarctica". Campaign-style GPS observations have been carried out since 1995. Based on the Bernese GNSS Software the latest analysis yields results for about 30 stations aligned to the terrestrial reference frame solution IGS08. The obtained station motions are discussed in the context of plate kinematics and glacial-isostatic adjustment. It is demonstrated that the activities are a valuable contribution both to the ITRF densification in Antarctica and to geodynamic research.

Keywords Reference frame · Antarctica · Crustal deformation · Euler pole · GIA

1 Introduction

In 1994, at the XXIII Meeting of the Scientific Committee on Antarctic Research (SCAR) in Rome it was decided to start geodetic GPS observations in Antarctica. GPS campaigns were carried out on an annual basis in order to realize and to densify the Antarctic GPS network and to link Antarctica to the global terrestrial reference frame (ITRF). For this purpose a project group was established. In 2003 the International Association of Geodesy (IAG) decided to establish subcommissions for regional reference frames. Concurrently to the SCAR affiliation the project group became Subcommission 1.3f within the IAG. Closely linked to the

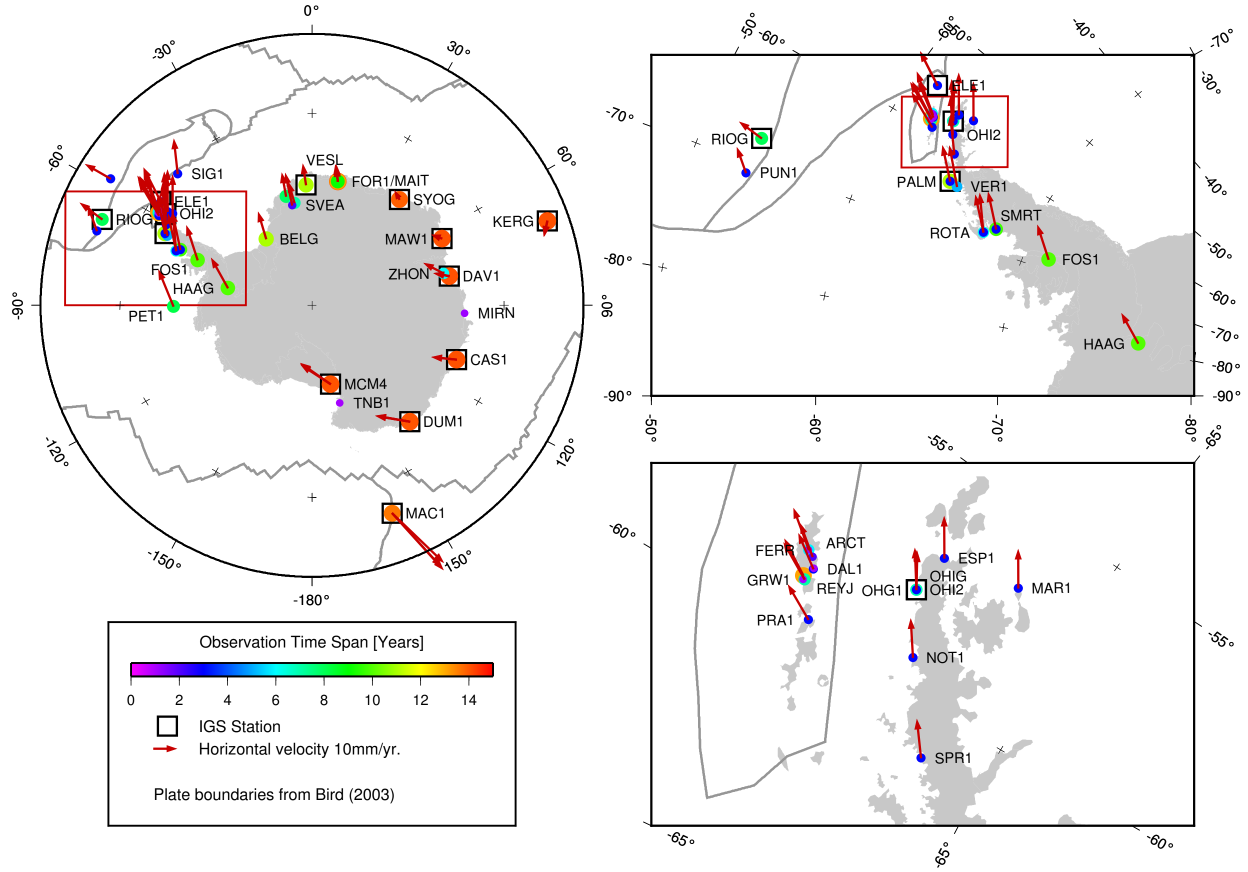

Fig. 1 Horizontal velocity field estimated for the Antarctic network. Only velocities from observation time spans of more than two years are shown here. Size and color of the circles depend on the time span covered by observations. The permanent IGS sites are marked by a black square. Right: Zoom of the areas marked by the red rectangles. Plate boundaries are taken from [4].

permanent GPS stations in Antarctica contributing to the International GNSS Service (IGS, [10]), over the years the campaign stations have been providing valuable geodetic information with a lot of significant geophysical implications [9]. On a regular basis reports were delivered both to SCAR and to IAG. In the following we summarize these activities related to GPS observations in Antarctica and present their major results and conclusions.

2 Campaign organization and observations

During the 1990ies, because of the shortage of permanent sites in Antarctica, the campaign observations were coordinated to take place between January 20 and February 10 each Antarctic summer. With an increasing number of permanent sites this coordinated schedule for the campaigns became obsolete. The number of participating stations increased rapidly. A total of about 30 stations contributed observations (Fig. 1, Table 1). The observational data as well as the corresponding meta data are archived within a database located at TU Dresden, Germany. To maintain consistency the observations of permanents sites used in this analysis are limited to the time spans covered by observations of the campaign sites.

3 Data analyses and results

The acquired data of the Antarctic GPS sites and of a selected number of permanent IGS stations in the Southern hemisphere were homogeneously analyzed using a modified version of the Bernese GNSS Software 5.0 [6]. Satellite orbits and Earth orientation parameters were taken from a homogeneous reprocessing [20]. A tropospheric model based on ECMWF weather data [23], higher-order ionospheric corrections [11], absolute antenna phase center corrections and ocean tide load-

Table 1 Estimated velocities of the Antarctic network sites. (Δ_T: time span covered by observations; v_n, v_e, v_u: estimated velocities in north, east and vertical directions. $\sigma_{n,e}$ and σ_u: respective uncertainties; v_u^{el}: vertical deformation caused by the elastic effect; v_u^{W12a} and v_u^{IJ05R2}: vertical rates predicted by the GIA model W12a [24] and IJ05R2 [14], resp., cf. Fig 4).

Station	Lat. [deg]	Lon. [deg]	ΔT [yrs]	v_n	v_e	v_u	$\sigma_{vn,e}$	σ_{vu} [mm/yr]	v_u^{el}	v_u^{W12a}	v_u^{IJ05R2}
ARCT 66016M001	−62.16	−58.47	2.1	12.7	8.8	7.9	2	5	0.4	1.3	−0.1
ART1 66017M001	−62.18	−58.90	13.1	15.9	8.6	−1.1	1	2	0.4	1.4	−0.1
BELG 66018M002	−77.87	−34.63	11.0	11.7	3.7	0.6	1	2	−0.2	0.1	1.3
CAS1 66011M001	−66.28	110.52	14.6	−10.4	2.5	2.1	1	2	0.8	2.4	0.7
DAL1 66019M001	−62.24	−58.68	3.1	14.1	9.0	5.6	2	4	0.4	1.4	−0.1
DALL 66019M002	−62.24	−58.66	1.1	18.8	8.0	−8.9	4	9	0.4	1.4	−0.1
DAV1 66010M001	−68.58	77.97	14.6	−6.2	−2.4	−0.1	1	2	0.5	0.7	1.0
DUM1 91501M001	−66.67	140.00	14.0	−11.7	9.2	1.1	1	2	0.2	1.3	1.6
EACF 66015M002	−62.08	−58.39	1.2	17.9	9.9	−4.7	4	9	0.4	1.3	−0.1
ELE1 66021M001	−61.48	−55.63	3.1	14.9	7.1	−0.6	2	4	0.2	1.0	−0.3
ESP1 66022M001	−63.40	−57.00	3.1	10.9	14.8	21.6	2	4	0.8	1.7	−0.2
FERR 66015M001	−62.09	−58.39	5.9	15.9	11.0	−10.5	1	2	0.4	1.3	−0.1
FOR1 66023M001	−70.78	11.83	14.0	6.9	−2.4	0.9	1	2	1.3	1.2	0.4
FOR2 66023M002	−70.77	11.84	13.2	6.9	−1.9	1.0	1	2	1.3	1.2	0.4
FOS1 66024M001	−71.31	−68.32	9.9	10.4	11.9	−1.7	1	2	−0.2	0.3	3.3
GRW1 66012M001	−62.22	−58.96	7.1	16.6	8.2	−3.7	1	2	0.4	1.4	−0.1
HAAG 66025M001	−77.04	−78.29	10.0	9.9	11.2	7.5	1	2	−1.2	5.6	4.3
KERG 91201M002	−49.35	70.26	14.2	−4.3	5.1	2.4	1	2	-	-	-
KOTA 66027M001	−74.30	−9.76	7.0	9.2	−1.0	0.6	1	2	−1.3	0.6	0.5
MAIT 66028M001	−70.77	11.74	9.1	6.0	−1.8	0.2	1	2	1.3	1.2	0.4
MAR1 66029M001	−64.24	−56.66	3.1	10.1	13.6	8.0	2	4	0.6	1.8	−0.2
MAW1 66004M001	−67.60	62.87	14.0	−3.4	−3.4	0.6	1	2	0.1	1.0	0.9
MCM4 66001M003	−77.84	166.67	14.0	−12.1	10.5	0.9	1	2	0.5	4.3	−0.1
MIRN	−66.55	93.01	1.2	−1.2	−0.8	29.2	4	9	−0.2	0.4	0.7
NOT1 66031M001	−63.67	−59.21	3.1	10.2	13.4	6.9	2	4	0.7	2.0	0.1
OHG1 66008M003	−63.32	−57.90	3.1	11.0	14.3	3.8	2	4	1.2	1.8	−0.1
OHI2 66008M005	−63.32	−57.90	7.0	9.7	14.1	4.8	1	2	1.2	1.8	−0.1
OHIG 66008M001	−63.32	−57.90	6.9	9.2	13.7	5.7	1	2	1.2	1.8	−0.1
PAL1 66005M001	−64.77	−64.05	3.1	11.4	15.4	4.5	2	4	1.6	2.0	0.5
PALM 66005M002	−64.78	−64.05	11.0	10.4	12.0	4.5	1	2	1.6	2.0	0.5
PET1 66032M001	−68.86	−90.43	8.1	6.9	15.9	2.2	1	2	0.4	0.0	−0.7
PRA1 66033M001	−62.48	−59.65	3.1	15.8	7.8	4.5	2	4	0.5	1.6	0.0
PUN1 41718M001	−53.63	−70.92	3.1	8.2	8.2	1.3	2	4	-	-	-
REYJ 66012M002	−62.20	−58.98	1.1	13.1	16.6	9.3	4	9	0.4	1.4	−0.1
RIOG 41507M004	−53.79	−67.75	8.0	11.8	2.4	2.8	1	2	-	-	-
ROT1 66007M001	−67.57	−68.13	3.1	8.4	15.0	3.8	2	4	1.2	2.0	0.8
ROTH 66007M003	−67.57	−68.13	6.1	9.8	13.3	2.9	1	2	1.2	2.0	0.8
SIG1 30607M001	−60.71	−45.59	3.1	12.5	8.9	1.6	2	4	0.1	0.0	−0.4
SMR1 66034M001	−68.13	−67.10	3.0	12.1	14.4	−0.6	2	4	2.2	1.5	1.5
SMRT	−68.13	−67.10	9.8	10.1	13.2	2.1	1	2	2.2	1.5	1.5
SPR1 66035M001	−64.30	−61.05	3.1	10.4	13.3	6.2	2	4	2.0	2.2	0.4
SVEA	−74.58	−11.23	3.0	14.2	−0.2	−3.9	2	4	−1.4	0.5	0.6
SYOG 66006S002	−69.01	39.58	13.9	1.7	−4.0	2.9	1	2	−0.3	1.1	0.8
TNB1 66036M001	−74.70	164.10	1.1	−15.0	11.7	6.1	4	9	1.1	1.8	−0.3
VER1 66038M001	−65.25	−64.25	5.1	11.4	14.0	3.1	2	3	2.5	2.1	0.6
VESL 66009M001	−71.67	−2.84	11.0	9.2	−0.9	2.2	1	2	0.5	1.4	0.4
WASA 66039M001	−73.04	−13.41	7.9	10.4	0.5	3.2	1	2	−1.2	1.3	0.7
ZHON 66030M001	−69.37	76.37	6.1	−7.5	−6.2	−4.7	1	2	1.0	0.7	1.5

ing corrections according to the FES2004 model were applied.

The daily solutions were combined at the normal equation level to estimate a set of station coordinates and velocities. In the analysis we considered inhomogeneities due to geophysical events such as earthquakes or due to antenna changes. In such cases new station coordinates were adopted. If possible, station velocities before and after the event were jointly estimated by introducing appropriate constraints [18]. The velocities of stations located close to each other were separately estimated, e.g. FOR1 and FOR2 or OHIG, OHG1 and OHI2. The final solution is aligned to the IGS08 reference frame by a minimum constraining condition on the IGS stations. The estimated station velocities are plotted in Fig. 1 and compiled in Table 1.

We computed daily coordinate solutions for each campaign. The averaged daily repeatability of all station coordinates is 6 mm for the vertical and 2 mm for the horizontal components. The assumption of a white noise error model for the daily coordinate solution and an average observation time span of 20 days for each campaign yields formal errors of 1.3 mm and 0.4 mm. A more realistic power noise model considers the correlations between the daily solutions and scales the error measures by a factor of 2 to 5 [27,15,25,26]. Thus, a factor of 4.5 results in error estimates of 6 mm for the vertical and 2 mm for the horizontal coordinate components for an individual campaign solution. Then, the station velocity error estimates are computed by error propagation. The effect of the reference frame realization noise adds another 1 mm/yr uncertainty to these values [8,2]. The individual error estimates are listed in Table 1.

Independent velocity errors are computed for individual points at co-located sites such as FOR1 and FOR2 or OHIG, OHG1 and OHI2. This enables a further check of the achieved uncertainties. However, it needs to be considered that station velocities may change over time in the Antarctic Peninsula region [21].

4 Geophysical implications

4.1 Horizontal motion and plate kinematics

From a geological point of view the Antarctic plate cannot be regarded as a homogeneous block. While East Antarctica consists of a stable craton, West Antarctica is considered to consist of a multitude of tectonic fractions entities which may move relatively to each other or with respect to East Antarctica [7]. Fig. 2 shows changes of the spherical distances between station pairs across the Antarctic Plate. The accuracy of these distance rates propagated from the accuracy of the horizontal station velocities (cf. Table 1) is estimated to be 1 to 2 mm/yr. The deformation rates in East Antarctica are small and do not exceed 1 mm/yr for most station pairs including the Kerguelen Islands. The majority of station pairs in West Antarctica also show small values of less than 1 mm/yr. This includes a coherent motion of Peter I. Island and the Antarctic Plate. The right subfigure of Fig. 2 clearly shows the opening of the Bransfield Strait between the Antarctic Peninsula and the South Shetland Islands. From our analyses we inferred a value of about 7 mm/yr for this opening rate. This result agrees with seismological evidence in that region which suggests an opening rate of less than 10 mm/yr [16].

A shortening of -2.8 mm/yr can be found for the baseline between O'Higgins (OHI2) at the northern tip of the Antarctic Peninsula and SANAE IV (VESL) in East Antarctica which is in good agreement with [1]. Fig. 3 displays the residual motions of the northern Antarctic Peninsula and its offshore islands after subtracting the plate motion of the Antarctic plate (red arrows). Knowledge of the tectonic activity in the Bransfield Strait helps to explain the shortening of the spherical distance between the Antarctic Peninsula and East Antarctica mentioned already by [17]. The residual motion of the observation sites in the Antarctic Peninsula are systematically directed eastwards. This suggests that the spreading process in the Bransfield Strait has an impact on the motion not only of the South Shetland Island block but also of the northern part of the Antarctic Peninsula. A relative Euler pole of this part with respect to the Antarctic Plate is located at $(67.1\pm15.5)^\circ$S and $(292.3\pm10.4)^\circ$E. The rotation rate is estimated to be $(0.20\pm0.19)^\circ$/Ma. The residuals of this Euler pole estimation are shown in Fig. 3 (in blue). Due to the small area the three components of the Euler pole are highly correlated resulting in large error estimates.

4.2 Vertical motion and glacial-isostatic adjustment

Past ice-mass changes in Antarctica are the cause a glacial-isostatic adjustment (GIA) of the solid Earth. Therefore, the vertical rates of the GPS sites contain valuable information about GIA and can be used to validate respective models. In Fig. 4 and in Table 1 (last columns) the observed rates are compared with those predicted by two recent GIA models [14,24]. For comparison the observed vertical rates have to be reduced by the elastic effect caused by present-day ice-mass changes. The elastic uplift is computed based on ICESat observations [12]. The GPS results and the GIA model predictions are related to the center of mass (CM) of the whole Earth system and the center of solid Earth (CE), respectively. However, this effect does not exceed 0.2 mm/yr and can be neglected here [21].

It can be seen that along the coast of East Antarctica there is a good agreement between both models and the observations. On the contrary, there are remarkable differences between both model predictions in the region of the Antarctic Peninsula. At some sites the GPS rates also reveal larger differences with the model predictions. More GPS sites can certainly help to provide further constraints to improve the GIA modeling.

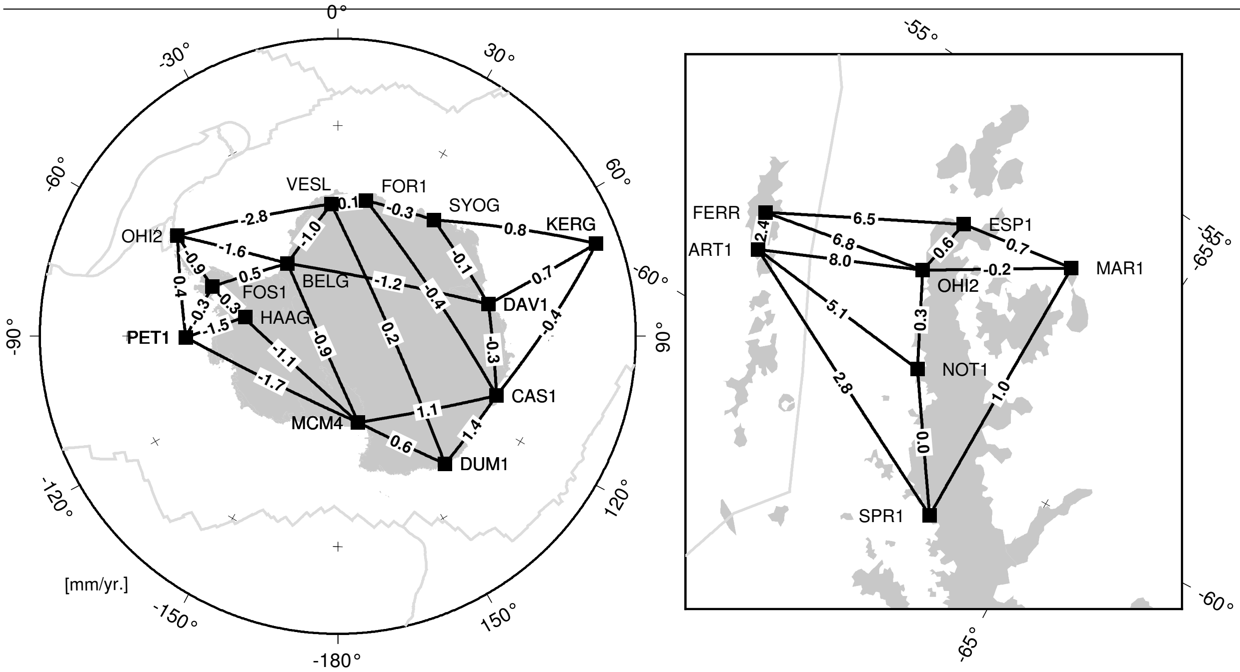

Fig. 2 Changes of spherical distance for selected station pairs in Antarctica [mm/yr]. The right figure depicts an enlargement of the northern tip of the Antarctic Peninsula, the Bransfield Strait and the South Shetland Islands.

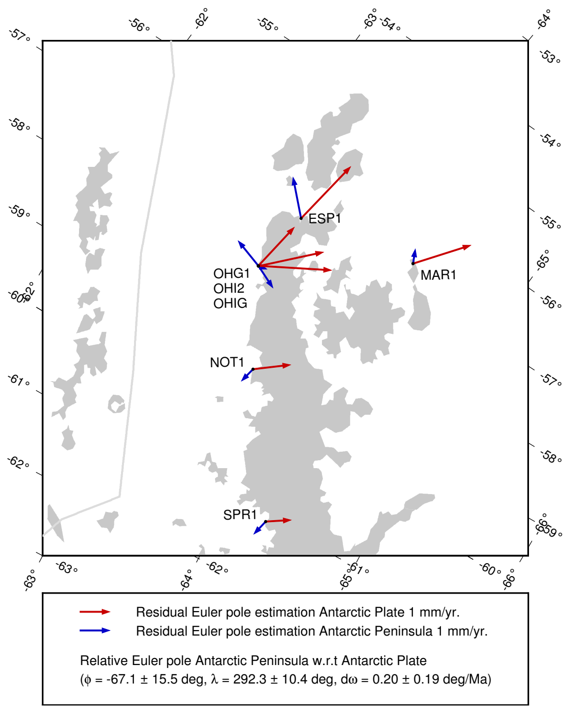

Fig. 3 Estimation of the Euler pole for the Antarctic Plate. The red arrows indicate the residuals of the Euler pole estimation. Additionally, an Euler pole of the northern tip of the Antarctic Peninsula was estimated. The respective residuals are indicated in blue.

5 Summary and outlook

We have shown that the SCAR GPS Campaigns provided valuable data for the ITRF densification in Antarctica. The geophysical interpretation of site motions in the context of plate kinematics and GIA demand highest accuracies. It has already been demonstrated that different software packages incorporating the same data may lead to small differences in the results [8]. Since there exist several national GNSS projects in Antarctica [3,5,13,19,22] it is a future challenge to generate homogeneous and consistent results with respect to the global reference frame in order to gain the most reliable information on the GIA in Antarctica. In our opinion, this forms also an important prerequisite to achieve improved estimates of the Antarctic ice-mass balance by means of satellite gravimetry [12,13].

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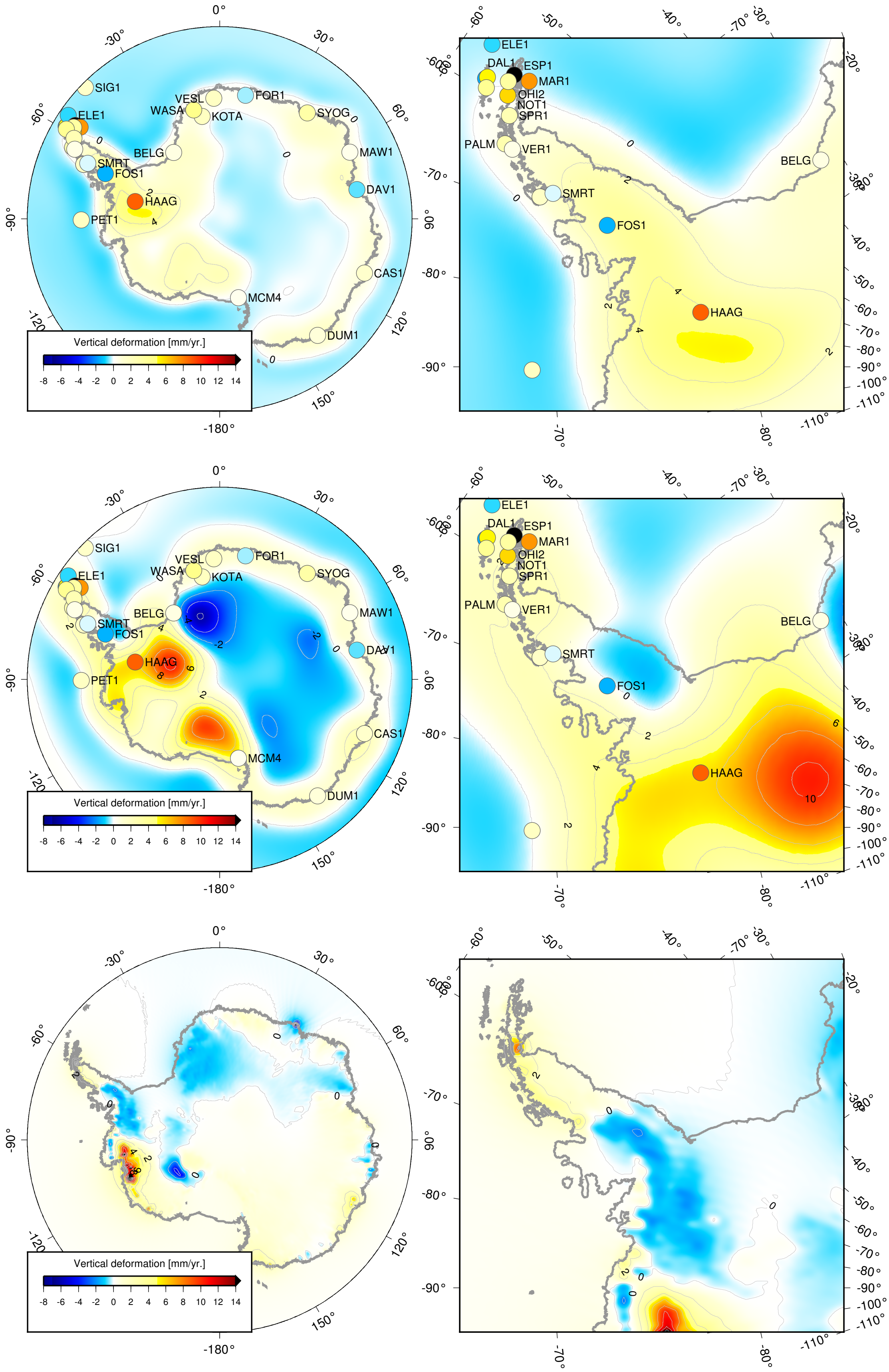

Fig. 4 Comparison of the vertical deformations observed by GPS and predicted by two GIA models. The GPS results have been reduced by the modeled elastic uplift effect and are plotted by color-coded circles. The respective GIA model prediction is shown in the background. Top: IJ05R2, 65 km lithospheric thickness (cf. [14], Fig. 5). Center: W12a [24]. Bottom: Elastic uplift effect caused by present-day ice mass changes [12].

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