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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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The Antarctic regional GPS network densification - status and results

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 2 Federal Agency for Cartography and Geodesy, Frank-3 furt/Main, Germany, E-mail: axel.ruelke@bkg.bund.de 4
Reinhard Dietrich, Andreas Groh, Christoph Knöfel, Mirko ₅ Scheinert TU Dresden, Institut für Planetare Geodäsie, Dresden, Ger- ⁶ many, E mail: reinhard dietrich@tu dresden do.
Alessandro Capra ⁸ Department of Engineering "Enzo Ferrari", University of ⁹ Modena and Reggio Emilia, Modena, Italy ¹⁰
E. Dong Chen ¹¹ Chinese Antarctic Center of Surveying and Mapping, Wuhan ¹² University, Wuhan, China ¹³
Jan Cisak Instytut Geodezji i Kartografii, Warsaw, Poland
Trond Eiken Department of Geosciences, University of Oslo, Oslo, Norway ¹⁴
Adrian Fox ¹⁵ British Antarctic Survey, Cambridge, U.K. ¹⁶
Larry D. Hothem ¹⁷ U.S. Geological Survey, Reston, VA, USA ¹⁸
Gary Johnston 19 Geoscience Australia, Canberra, Australia 20
E. C. Malaimani National Geophysical Research Institute (NGRI), Hyder-22 abad, 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

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 \cdot Antarctica \cdot Crustal deformation \cdot Euler pole \cdot 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

Royal Institute of Technology, Stockholm, Sweden

Andrés Zakrajsek Instituto Antártico Argentino, Buenos Aires, Argentina Mathias Fritsche

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



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].

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permanent GPS stations in Antarctica contributing to44 27 the International GNSS Service (IGS, [10]), over the₄₅ 28 years the campaign stations have been providing valu-46 29 able geodetic information with a lot of significant geo-47 30 physical implications [9]. On a regular basis reports₄₈ 31 were delivered both to SCAR and to IAG. In the fol- $_{49}$ 32 lowing we summarize these activities related to GPS₅₀ 33 observations in Antarctica and present their major re-34

³⁵ sults and conclusions.

ble 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.

about 30 stations contributed observations (Fig. 1, Ta-

⁵¹ 3 Data analyses and results

³⁶ 2 Campaign organization and observations

During the 1990ies, because of the shortage of per-54 manent sites in Antarctica, the campaign observations were coordinated to take place between January 20 and February 10 each Antarctic summer. With an increas-57 ing number of permanent sites this coordinated sched-58 ule for the campaigns became obsolete. The number of participating stations increased rapidly. A total of 60 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).

a a									-	-	
Station	Lat. [deg]	Lon. [deg]	ΔT [yrs]	v_n	v_e	v_u	$\sigma_{vn,e}$ [r	σ_{vu} nm/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	-19	1.0	1	2	1.3	1.2	0.4
FOS1 66024M001	-71.31	-68.32	9.9	10.4	11.0	-1.7	1	2	-0.2	0.3	3.3
GBW1 66012M001	-62.22	-58.96	71	16.4	8.2	-3.7	1	2	0.2	14	-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	1.2	-	-
KOTA 66027M001	-74.30	-9.76	7.0	4.0 0.2	_1.0	0.6	1	2	_13	0.6	0.5
MAIT 66028M001	-70.77	11.74	0.1	6.0	_1.0	0.0	1	2	1.0	1.2	0.0
MAR1 66020M001	-64.24	-56.66	3.1	10.1	13.6	8.0	2	4	0.6	1.2	-0.2
MAW1 66004M001	-67.60	-50.00	14.0	-3.4	-3.4	0.6	1	-4	0.0	1.0	-0.2
MCM4 66001M003	-07.00 -77.84	166 67	14.0	-12.4	-3.4 10.5	0.0	1	2	0.1	1.0	-0.1
MIRN	-66 55	03.01	1 9	_1.1	-0.8	20.2	1	0	-0.2	4.5	0.1
NOT1 66031M001	-63.67	-50.01	2.1	-1.2 10.2	-0.8 13.4	6.0	2	3	-0.2	2.0	0.1
OHC1 66008M003	-63 32	-57.00	3.1	11.0	14.3	38	2		1.2	1.0	-0.1
OHI2 66008M005	62 22	-57.90	7.0	0.7	14.0	1.0	2 1	4	1.2	1.0	-0.1
OHIC 66008M003	-63.32	-57.90 -57.00	6.0	9.7	14.1 13.7	4.0 5.7	1	2	1.2	1.0	-0.1
DAL 1 66005M001	-03.32 64.77	-51.90	2.1	9.2 11.4	15.7	4.5	1	4	1.2	1.0	-0.1
DALM 66005M001	-04.11	-04.05	11.0	10.4	10.4	4.5	2 1	4 9	1.0	2.0	0.5
DET1 66022M001	-04.10	-04.03	0 1	6.0	12.0	4.0	1	2	1.0	2.0	0.5
PDA1 66022M001	-00.00	-90.45	0.1 2.1	15.9	15.9	2.2 4.5	1	2 4	0.4	0.0	-0.7
DUN1 41718M001	-02.40 52.62	-59.05	2.1	10.0	1.0	4.0	2	4	0.5	1.0	0.0
DEVI 66010M002	-00.00	-70.92	0.1 1 1	0.2	0.4 16.6	1.0	4	4	-	-	-
REIJ 00012M002	-02.20 52.70	-36.96	1.1	10.1	10.0	9.5	4	9	0.4	1.4	-0.1
DOT1 66007M004	-00.19	-07.75	0.0 9.1	11.0 0 1	2.4	2.0	1	4	- 1 0	-	-
ROTI 66007M002	-07.57	-08.13	5.1 6 1	0.4	10.0	0.0 0.0	2 1	4	1.2	2.0	0.8
SIC1 20607M001	-07.57	-08.13	0.1	9.0 19.5	13.3	2.9 1.6	1	2 4	1.2	2.0	0.8
SIG1 5000710001 SMD1 66024M001	-00.71	-45.59	3.1	12.0	0.9	1.0	2	4	0.1	0.0	-0.4
SMAI 00054M001	-08.15	-07.10	3.0	12.1	14.4	-0.0	2 1	4	2.2	1.0	1.5
SMRI	-08.13	-07.10	9.8	10.1	13.2	2.1	1	2	2.2	1.0	1.5
SPRI 00035M001	-04.30	-61.05	3.1	10.4	13.3	0.2	2	4	2.0	2.2	0.4
SVEA	-74.08	-11.23	3.0	14.2	-0.2	-3.9	2	4	-1.4	0.5	0.0
SIUG 00000S002	-09.01	39.58	13.9	1.7	-4.0	2.9	1	2	-0.3	1.1	0.8
INBI 00030M001	-14.70	104.10	1.1	-15.0	11.7	0.1	4	9	1.1	1.8	-0.3
VERI 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

⁶¹ ing corrections according to the FES2004 model were⁶⁸ ⁶² applied.

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The daily solutions were combined at the normal₇₁ equation level to estimate a set of station coordinates₇₂ and velocities. In the analysis we considered inhomo- $_{73}$ geneities due to geophysical events such as earthquakes₇₄ 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 are²⁴
plotted in Fig. 1 and compiled in Table 1.

We computed daily coordinate solutions for each₂₆ 77 campaign. The averaged daily repeatability of all sta-127 78 tion coordinates is 6 mm for the vertical and 2 mm fon $_{28}$ 79 the horizontal components. The assumption of a white29 80 noise error model for the daily coordinate solution and 30 81 an average observation time span of 20 days for each³¹ 82 campaign yields formal errors of 1.3 mm and 0.4 mm₁₃₂ 83 A more realistic power noise model considers the corre-133 84 lations between the daily solutions and scales the erron₃₄ 85 measures by a factor of 2 to 5 [27, 15, 25, 26]. Thus, a³⁵ 86 factor of 4.5 results in error estimates of 6 mm for the₃₆ 87 vertical and 2 mm for the horizontal coordinate com-137 88 ponents for an individual campaign solution. Then, the³⁸ 89 station velocity error estimates are computed by erron³⁹ 90 propagation. The effect of the reference frame realiza-140 91 tion noise adds another 1 mm/yr uncertainty to these₄₁ 92 values [8,2]. The individual error estimates are listed in₄₂ 93 Table 1. 143 94

Independent velocity errors are computed for in-44
dividual points at co-located sites such as FOR1 and 45
FOR2 or OHIG, OHG1 and OHI2. This enables a fur-46
ther check of the achieved uncertainties. However, it⁴⁷
needs to be considered that station velocities may changes
over time in the Antarctic Peninsula region [21]. 149

¹⁰¹ 4 Geophysical implications

¹⁰² 4.1 Horizontal motion and plate kinematics

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From a geological point of view the Antarctic plate can¹⁵³ 103 not be regarded as a homogeneous block. While East¹⁵⁴ 104 Antarctica consists of a stable craton, West Antarctica⁵⁵ 105 is considered to consist of a multitude of tectonic frac¹⁵⁶ 106 tions entities which may move relatively to each other¹⁵⁷ 107 or with respect to East Antarctica [7]. Fig. 2 shows⁵⁸ 108 changes of the spherical distances between station pairs⁵⁹ 109 across the Antarctic Plate. The accuracy of these dis¹⁶⁰ 110 tance rates propagated from the accuracy of the hori-161 111 zontal station velocities (cf. Table 1) is estimated to be⁶² 112 1 to 2 mm/yr. The deformation rates in East Antarc¹⁶³ 113 tica are small and do not exceed 1 mm/yr for most sta-164 114 tion pairs including the Kerguelen Islands. The major-165 115 ity of station pairs in West Antarctica also show small⁶⁶ 116 values of less than 1 mm/yr. This includes a coher-167 117 ent motion of Peter I. Island and the Antarctic Plate¹⁶⁸ 118 The right subfigure of Fig. 2 clearly shows the opening⁶⁹ 119 of the Bransfield Strait between the Antarctic Penin¹⁷⁰ 120 sula and the South Shetland Islands. From our analyses⁷¹ 121 122 we inferred a value of about 7 mm/yr for this opening⁷² rate. This result agrees with seismological evidence in⁷³ 123

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 ± 15.5) °S and (292.3 ± 10.4) °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 residuals⁹⁶ are indicated in blue.

174 **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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