SPECIAL SECTION: 10 YEARS OF AGGO / SECCIÓN ESPECIAL: 10 AÑOS DE AGGO

Absolute gravimetric observations in southern Patagonia

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Abstract This article presents the GRAVPATAGONIA project, a research effort conducted in close cooperation between Argentine and German geodesists. It aims at the determination of gravity-change rates in southern Patagonia as an independent geodetic observable of the response of the solid Earth to mass changes of the Patagonian Icefields. For this purpose, repeated observations with a FG5 absolute gravimeter are conducted and complemented by auxiliary geodetic measurements. The present work focuses on the geodynamic motivation of the project, on the methods and procedures applied in the measurements, as well as on documenting the fieldwork and logistic efforts accomplished in two gravimetric campaigns in 2020 and 2022. Since the observations are not completed yet, the article does not pretend to present conclusive results.

Keywords absolute gravimetry, glacial isostatic adjustment, Patagonian Icefields.

Observaciones gravimétricas absolutas en la Patagonia austral

Resumen El artículo presenta el proyecto GRAVPATAGONIA, un proyecto de investigación llevado a cabo en cooperación entre geodestas argentinos y alemanes. Aspira a la determinación de tasas de cambio de gravedad en la Patagonia austral en calidad de un observable geodésico independiente de la respuesta de la Tierra sólida a cambios de masa de los Campos de Hielo Patagónicos. Para este fin se efectúan observaciones con un gravímetro absoluto FG5 y se complementan con mediciones geodésicas auxiliares. El presente trabajo se concentra en la motivación geodinámica del proyecto, en los métodos y procedimientos aplicados en las mediciones, así como en la documentación de los trabajos y el esfuerzo logístico realizados en dos campañas gravimétricas en 2020 y 2022. Como las observaciones aún no han finalizado, este artículo no pretende presentar resultados concluyentes.

Palabras clave gravimetría absoluta, ajuste glacioisostático, Campos de Hielo Patagónicos.

INTRODUCTION

The foundation of the Argentine-German Geodetic Observatory (AGGO) in 2015 entailed also the long-term presence of the FG5-227 absolute gravimeter in Argentina. This instrument, property of the German Bundesamt für Kartographie und Geodäsie (BKG), is fundamental for the regular calibration of AGGO's superconducting gravimeter SG038 and for providing the geodetic fundamental station with a continuous gravity reference.

The Patagonian Icefields represent the largest glacial system of the southern hemisphere outside Antarctica. The Northern (NPI) and Southern Patagonian Icefield (SPI) have been experiencing intense, and likely accelerating, ice-mass loss over the last decades (Richter et al., 2019; Braun et al., 2019; Malz et al., 2018; Aniya et al., 1996). An accurate quantification of ongoing ice-mass changes is crucial for guiding a sustainable local development, projecting freshwater availability and understanding sea-level changes. GRACE and GRACE Follow-On satellite gravity field missions allow the determination of ice-mass change time series (Richter et al., 2019). However, an accurate isolation of ice-mass

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induced gravity changes requires a correction for the gravimetric effect of mass displacements within the solid Earth due to glacial-isostatic adjustment (GIA). Space geodetic observations have revealed unusually intense uplift centered on the northern part of the SPI, attributed to the regional response of the solid Earth to mass changes of the Patagonian Icefields (Dietrich et al., 2010; Lange et al., 2014; Richter et al., 2016a; Russo et al., 2022; Lenzano et al., 2023).

The GravPatagonia project aims at a precise determination of local gravity-change rates as an independent geodetic observable of Patagonian GIA. Several Argentine and German geodetic research institutions have joined this effort: AGGO, Facultad de Ciencias Astronómicas y Geofísicas of Universidad Nacional de La Plata (UNLP), Estación Astronómica Río Grande (EARG), Instituto Geográfico Nacional (IGN), BKG and the Chair of Geodetic Earth System Research at Technische Universität Dresden (TUD). The project has been funded by the German Research Foundation (DFG).

This article gives an overview of this project in progress. In the following Section, the response of the solid Earth to regional ice-mass changes is briefly described, outlining the geodynamic motivation for the GravPatagonia project. The third section presents the geodetic requirements to the gravity-change rate determination as GIA observable. Section 4 gives an overview over the fieldwork conducted in southern Patagonia in the scope of the GravPatagonia project. The following section summarizes the data processing methods and some preliminary results. The concluding remarks in Section 6 close the paper. With this introduction of the GravPatagonia project, the article highlights the importance and potential of AGGO as hub for international, multidisciplinary research in Argentina.

MOTIVATION: GLACIAL ISOSTATIC ADJUSTMENT IN PATAGONIA

The solid Earth responds to a persistent surface load through deformations which comprise two mechanisms: an elastic, quasi-instantaneous compression of the lithosphere, and a lateral flow of viscous mantle material in pursuit of a new isostatic equilibrium with the load. The latter mechanism is referred to as glacial isostatic adjustment (GIA). The viscosity of the mantle delays the GIA response with respect to the application of the load. The surface expression of the load-induced mantle displacement is modulated by the elastic bending of the overlying lithosphere, hence this mechanism describes a viscoelastic deformation. Thus, the viscoelastic GIA deforms the lithosphere “from beneath” (mantle), whereas the elastic mechanism refers to the lithosphere deformation from above (surface). Another crucial difference between the two mechanisms is that the viscoelastic mechanism involves a mass displacement in the Earth’s interior, locally perceived as a loss or gain of mass; while the elastic mechanism does not. The modelling of loading effects requires the introduction of a load model, which describes the mass distribution of the load in space and time, and an Earth model. GIA models employ a viscoelastic Earth model that quantifies the deformation in response to a unit load as a function of distance and time. Its principal parameters are the mantle viscosity and the effective lithospheric thickness.

Early GIA models of Ivins and James (1999) and Ivins and James (2004), still lacking geodetic constraints, identified the Patagonian Icefields as a locus of exceptionally intense bedrock uplift composed of an elastic lithosphere decompression due to ongoing mass wasting and the reflow of mantle material beneath the icefields displaced by glacial loading in the past. Key to understand the intensity of the ice-load induced deformation in this area is the unusually low viscosity of the mantle beneath the icefields. NPI and SPI are located above the Patagonian Slab Window (Breitsprecher & Thorkelson, 2009), which opens as a consequence of the subduction of the Chile Ridge beneath the South American plate at the Chile Triple Junction, just northwest of the NPI (Figure 1). The slab window gives way to upwelling, hot mantle material of a viscosity as low as 10^{18} Pa s (Mark et al., 2022; Russo et al., 2022). Such an extremely low viscosity entails viscoelastic relaxation times much shorter than in other studied GIA regions. In fact, it implies that any GIA effect of the deglaciation following the Last Glacial Maximum (roughly 20,000 years ago) has faded long ago in Patagonia, and that the GIA uplift observable today is produced by much younger ice-mass changes after the Little Ice Age (LIA, less than 200 years ago).

Dietrich et al. (2010) provided the first geodetic evidence of bedrock uplift at the SPI, with a rate of

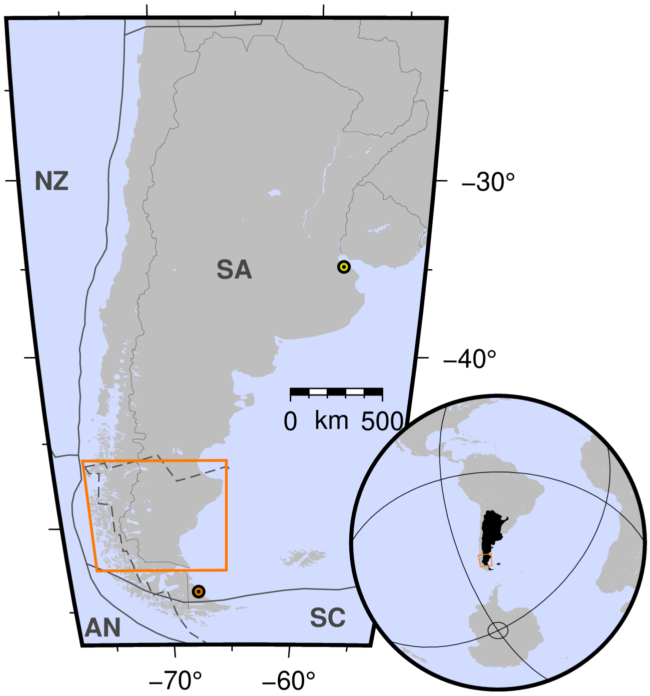

Figure 1. *Overview map of the location of southern Patagonia and its plate tectonic setting. Solid dark lines: boundaries of the tectonic plates: South America (SA), Nazca (NZ), Antarctica (AN) and Scotia (SC) according to Bird (2003); dashed dark line: boundary of the Patagonian Slab Window according to Breitsprecher and Thorkelson (2009); yellow dot: AGGO; orange dot: EARG. The orange polygon shows the map extent in Figure 2. The inset shows the location of Argentina (black shaded) and the region under investigation (orange outline).*

39 mm/a derived from repeated GNSS observations, qualitatively confirming the predictions of Ivins and James (2004). Lange et al. (2014) extended the GNSS observations over the Chilean part of the SPI, including sites on top of the icefield observed as early as 1996. The derived uplift rates were used to adjust viscoelastic Earth-model parameters adopting a suite of load models that represent alternative, plausible ice-mass evolutions since the LIA maximum. However, the search in the two-dimensional parameter space (mantle viscosity vs. lithosphere thickness) yields two endmember GIA models (termed “A” and “B”), with practically equivalent fit to the observed uplift rates, but implying different ice-load evolutions and mantle viscosities. The extension of the GNSS observations to the Argentine part of the SPI (Richter et al., 2016a) allowed to establish a preference for the GIA model “A”. However, the most recent stage of the ice-load evolution assumed by the other GIA model (“B” in Lange et al. (2014)) fits regional ice-mass loss rates derived from GRACE satellite gravimetry (Richter et al., 2019) much better. Russo et al. (2022) present results of GNSS observations at the NPI and propose a marked viscosity contrast at 49°S to explain the large uplift rates derived at those sites. This density contrast was confirmed by a seismic tomography that mapped an anomaly of very low SV wave velocities, and thus viscosities, in the northern part of the slab window (Mark et al., 2022).

The regional GIA models published so far for the Patagonian Icefields area manifest inconsistencies with the available geodetic and geophysical evidence which call for a new generation of GIA models. At the same time, the international community dedicated to GIA research has been making significant advances. One major paradigm shift GIA modelling has faced in recent years is the replacement of the Maxwell theory, which assumes a discrete separation between the instantaneous elastic response and a long-term viscoelastic deformation described by constant viscosity, by more sophisticated Earth models, such as the Extended Burgers Model, that account for transient deformations by describing the mantle viscosity as a function of frequency (Ivins et al., 2020). Another paradigm shift concerns the implementation of a 3D viscosity structure in viscoelastic Earth models which account for lateral and radial variations within regions as narrow as southern Patagonia. These innovations in regional GIA modelling formalism imply an urgent need for geodetic observations of GIA effects in order to constrain the expanded set of viscoelastic Earth model parameters and to evaluate the performance of competing Earth model descriptions.

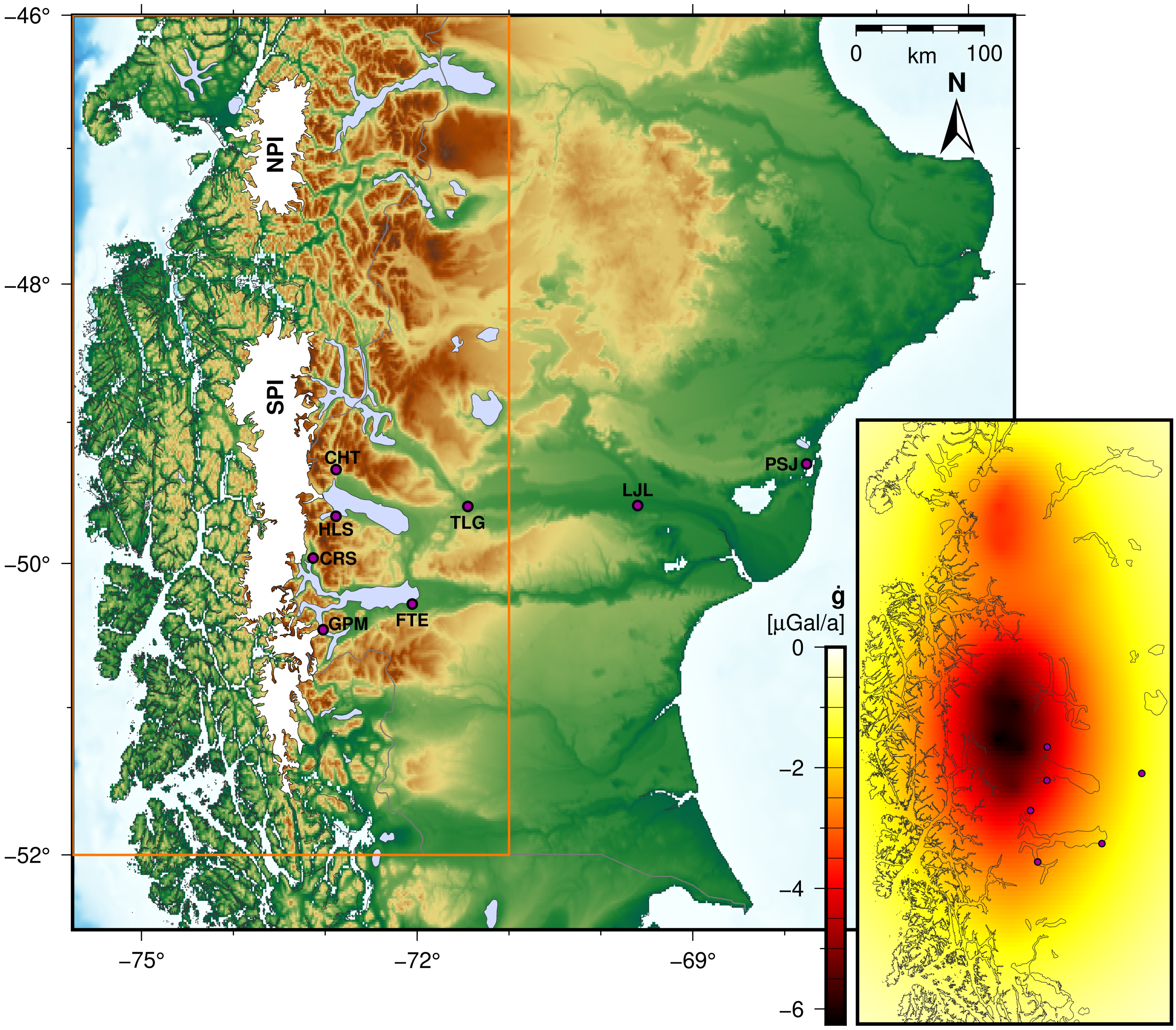

Figure 2. *Map of the region under investigation. Purple dots show the location of the GravPatagonia absolute gravimetry network sites. NPI: Northern Patagonian Icefield; SPI: Southern Patagonian Icefield; orange outline: map domain of the inset; topography: ETOPO1 (Amante & Eakins, 2009). Inset: Tentative estimation of the gravity-change rates $\dot{g}$ expectable from glacial isostatic adjustment according to the regional GIA model B by Lange et al. (2014). Purple dots: GravPatagonia absolute gravimetry sites.*

Southern Patagonia represents an ideal natural laboratory to explore the solid-Earth response to ice-mass changes. The area of the Patagonian Icefields is characterized by:

- intense crustal deformation;
- rapid present-day ice-mass loss, confined to within the narrow icefields, which implies significant contributions from both elastic and the viscoelastic mechanisms;
- extremely low viscosity, which makes the contribution of transient deformations especially relevant;
- a complex viscosity structure imposed by subduction tectonics, an active slab window and vigorous mantle dynamics (Ben-Mansour et al., 2022).

The GIA correction needed to improve the accuracy of GRACE(FO)-derived ice-mass change rates in Patagonia requires a separation between the elastic and viscoelastic contributions to the observed bedrock deformation (Richter et al., 2019). GNSS observations alone are unable to discriminate between the contributing mechanisms. In order to isolate the GIA contribution, another independent observable is needed, that ought to be sensitive to mass changes. Within the repertoire of geodetic observation techniques, the determination of local gravity-change rates promises the greatest discriminatory power between elastic and viscoelastic deformation contributions, quantifying the mantle mass accretion that accompanies the GNSS observed uplift.

ABSOLUTE GRAVITY DETERMINATION

The objective of the GravPatagonia project is the determination of accurate rates of local gravity change in southern Patagonia, to be compared with uplift rates derived from collocated GNSS observations. Relative gravimeters are usually unable to reliably determine gravity change rates, because their inherent drift cannot be separated from long-term gravity variations. Absolute gravimetry yields local gravity values, free of time-variable drift effects. Hence, absolute gravimeter observations repeated over several years allow to derive local gravity change rates. In geodesy, at least three observation epochs are usually required to determine rates of change. It also requires an exact reproduction of the gravimeter setup during all measurement epochs at a site. This calls for a permanent marking of the site's center and a thorough documentation of the observation conditions.

Among the currently available absolute gravimeters, the Micro-g LaCoste FG5 and FG5X models (Niebauer et al., 1995; Niebauer et al., 2011) offer the highest accuracy. It is a free-fall gravimeter, with a prismatic optical mirror as test mass. The prism is dropped in a vacuum chamber, and the change of its vertical position during the fall is accurately measured by a Mach-Zehnder laser interferometer. A superspring system ensures the stability of the trajectory reference. The interferometric distance measurements are combined with high-accuracy timing using an atomic rubidium clock. Gravimeters of this type are usually operated under laboratory conditions, for example in long-term installations at geodetic observatories. A common objective is the calibration of superconducting gravimeters. At BKG, the FG5 observations are usually conducted in hourly sets of 100 drops each. At one site and epoch, 24 sets are measured during 24 hours, afterwards the azimuthal instrument orientation is turned by 180°, and additional 12 hourly sets are acquired in this second setup. The extension of the primary observation session over 24 hours serves to average out residual tidal effects, for example due to imperfect ocean-tidal loading corrections; and the reassembly in the opposite orientation reduces systematic effects (Křen et al., 2018). Under these conditions, and by averaging the results of all accepted sets and drops, absolute values of the local gravity acceleration are usually determined with an uncertainty of typically 2.5 μGal (1 μGal = 10 nm/s^2) (Křen et al., 2020).

GravPatagonia's endeavour to determine gravity-change rates at the highest possible accuracy under the particular conditions of southern Patagonia poses a true challenge to the FG5-227 instrument, its operators and the campaign logistics. The primary tasks assigned to this gravimeter, the regular calibration of the superconducting gravimeter SG038 and providing an absolute gravity reference at AGGO, allow only campaign-style measurements at each site in Patagonia. The transportation of the instrument from AGGO to the region under investigation, and between the measurement sites there, has to cope with seemingly interminable distances, rugged gravel roads and ship navigation across a choppy Lago Argentino. Rough climatic conditions, with Patagonia's notorious winds and broad daily air temperature amplitudes during the southern summer, call for an efficient isolation. The need of mechanical stability throughout the rate determination over several years, and the hope for usefulness in future gravimetric works beyond the project, require the location of the absolute gravimetric sites within solid buildings with concrete foundations. Another criterion for the choice of the sites is the availability of 220 V power supply. The scarce infrastructure in southern Patagonia, especially in the vicinity of the icefield where we expect the best detectability of the investigated geodynamic signal, seriously restricts the selection of gravimetric sites according to our criteria.

Since the project focuses on the loading effect of the SPI and, in particular, its remarkable gradient in intensity from South to North, the network design comprises an E-W profile, perpendicular to the icefield axis, down to the Atlantic coast, and a N-S profile along the eastern boundary of the SPI (Figure 2). Both profiles encompass four gravimetric sites and shall allow the determination of spatial gradients in the gravity-change rates. The latitude of the E-W profile was chosen close to that of the maximum uplift rate in the northern part of the SPI, and its extension to the coastal town Puerto San Julián provides the network with a reference site where ice-load effects are not to be expected. The network is complemented by a regional reference site of easy access at El Calafate International Airport. An integral component of the gravity determinations in Patagonia consists in FG5-227 absolute gravimeter observations at AGGO before and after each campaign. These observations at the well-established reference site at AGGO, next to the continuously recording superconducting gravimeter, allow to detect or discard any systematic bias the absolute gravimeter might suffer before or during the campaign.

At a site close to the icefield, if the ambient mass distribution can be considered unchanged between the measurement epochs, the expected gravity-change rate results from the superposition of two effects. First, the uplift of the Earth's surface causes a vertical movement of the gravimeter and, thus, reduces the measured gravity. The vertical position change alone can be approximated by applying the normal gravity gradient ($\approx$ -0.3 μGal/mm). Second, the GIA-driven mass redistribution in the mantle and the accompanying solid-Earth deformation beneath the gravimetric site increase the measured gravity. Theoretically, this contribution could be approximated based on representative values for the density of the mantle material and the lithospheric thickness. The observable gravity-change rate represents the sum of the two effects, which lets us expect intermediate values between the purely geometrical free-air case and the rigid mantle-mass case (Wahr et al., 1995; Wahr et al., 2001; De Linage et al., 2007). The relation between the gravity-change rate $\dot{g}$ and the local uplift rate $\dot{u}$ is indicative of the proportion of the contributions from the elastic and the viscoelastic response mechanisms. Thus the determination of the ultimately interpretable ratio $\dot{g}/\dot{u}$ requires the collocation of gravimetric and GNSS observations. For example, in Fennoscandia, Olsson et al. (2019) derived a $\dot{g}/\dot{u}$ ratio of -0.168 μGal/mm from 688 absolute gravity observations at 59 stations (1976-2015). Bilker-Koivula et al. (2021) report ratios between -0.206 $\pm$ 0.017 and -0.227 $\pm$ 0.024 μGal/mm from observations spanning 43 years at 12 stations in Finland. In central North America, Mazzotti et al. (2011) derived a ratio of 0.17 $\pm$ 0.01 μGal/mm at eight sites (1995-2010). In SE Alaska, a GIA region more akin to southern Patagonia, Naganawa et al. (2022) determined local gravity-change rates between -2.05 and -4.4 μGal/a, and a $\dot{g}/\dot{u}$ ratio of -0.16 $\pm$ 0.030 μGal/mm. In the inset of Figure 2 we show a preliminary estimation of the gravity-change rates published GIA models let us expect in our region under investigation. This rough approximation is derived by multiplying uplift rates according to the regional GIA model "B" by Lange et al. (2014) with a constant $\dot{g}/\dot{u}$ ratio of -0.16 μGal/mm as determined by Naganawa et al. (2022) from absolute gravimeter observations in Alaska.

In practice, the mass distribution around the gravimetric sites varies between and during the absolute gravity measurements. The sites close to the icefield are affected by the gravity effect of ice-mass changes. Several sites are located close to the shores of Lago Argentino and Lago Viedma, where gravity changes due to water mass variations in the lakes. The mean annual lake-level cycle in Lago Argentino has an amplitude of 1.2 m, for Lago Viedma it is slightly smaller (Richter et al., 2016b). In Puerto San Julián ocean tides and sea-level variations affect the gravity determination. In the determination of gravity-change rates, the impact of these ambient mass changes has to be corrected based on observations or validated models. Time series of ice-mass change in southern Patagonia are derived with monthly resolution from GRACE and GRACE Follow-On satellite gravimetry data (Romero et al., submitted manuscript), and form the basis for the ice-mass change correction. Ocean-tidal loading is routinely corrected in absolute gravity determinations applying global models. However, an ICESat-2 laser altimetry analysis suggests a differentiated tidal regime within the Bahía San Julián compared to the open Atlantic, not adequately represented by the FES2014b global ocean tide model (Suad Corbetta et al., 2023). Therefore, water-level observations within the bay, simultaneous with the gravity determinations, are needed to account for its loading effect through a local model. Likewise, lake-level observations are needed simultaneously and close to the gravimetric observations at Lagos Argentino and Viedma. Another uncertainty arises from continental water storage changes that are typically dominated by a seasonal signal of up to 10 μGal (Naujoks, 2008; Boy & Hinderer, 2006; Antokoletz et al., 2020).

This means that a series of complementary geodetic observations have to accompany the absolute gravity measurements. Water-level observations are needed in Puerto San Julián and at the sites close to the lakes. Moreover, all the gravimetric campaigns are scheduled for the same time of the year (February) in order to minimize disturbing impacts of seasonal signals, such as hydrological variations.

Table 1. *Sites of the GravPatagonia absolute gravimetry network. Approximate site coordinates are given relative to the WGS84 ellipsoid.*

ID	Latitude [° S]	Longitude [° W]	Height [m]	Place	Remark
FTE	50.284	72.053	198	El Calafate	Airport, workshop
CHT	49.337	72.881	394	El Chaltén	National Park Visitors Center, exhibition room
GPM	50.462	73.023	185	Perito Moreno glacier	NP Volunteers house, garage
HLS	49.667	72.883	257	Estancia Helsingfors	Huemul observation hut
PSJ	49.299	67.772	19	Puerto San Julián	University property, Rock Mechanics lab
TLG	49.599	71.448	227	Tres Lagos	Church, back quarters
TLGc	49.599	71.445	230	Tres Lagos	Administration office, entrance hall
CRS	49.962	73.131	184	Estancia Cristina	“Old” house, entrance hall
LJL	49.591	69.600	83	Estancia La Julia	Main house, living room

February corresponds to late summer in the region under investigation, when snow cover is minimum and lake-levels and river discharge maintain at their maxima. GNSS observations are needed to complement the gravity-change rates with uplift rates. High-precision levelling connects the GNSS antenna reference point with the gravimetric site center, verifying the local stability of the site. Relative gravimetry is employed at each absolute gravimetric site to determine vertical gravity gradients and to connect eccentric markers. Some of the eccenters are nearby sites of the RAGA network, IGN's official absolute gravity network *Red Argentina de Gravedad Absoluta* (Instituto Geográfico Nacional, n.d.). Other eccenters were established in close vicinity of the absolute gravity sites to provide easy access to an accurate gravimetric reference. The observational determination of local gravity gradients shall allow the use of the absolute gravimetric sites with different gravimeter types, with different heights of the instrumental gravity reference point, without loss of accuracy. The vertical gradients are not expected to change with time, despite the uplift and mantle mass change.

FIELDWORK IN SOUTHERN PATAGONIA

The importance of the network design and site selection, considering the challenging conditions in southern Patagonia, motivated the realization of a reconnaissance campaign at an early stage of the project. This campaign achieved the step forward from an ideal network sketch on a map based upon theoretical considerations to a set of precisely defined site locations with verified access, measurement conditions and agreement from the hosts. Two experienced researchers from BKG and one from UNLP joined this effort during the second half of October 2019. The experiences and insights gathered in that journey were crucial for the preparation and planning of the subsequent gravimetric campaigns.

The first gravimetric campaign of the project took place in January and February 2020. The activities in Patagonia extended from January 27 to February 24. For the participants who traveled from Germany, the entire campaign, including the reference observations at AGGO, lasted from January 22 to February 28. In the field work participated one researcher from BKG, AGGO, TUD and EARG, and two from UNLP. All the team and equipment were transported over land in two vehicles from AGGO to the work area, between the Patagonian sites, and back to AGGO. With base quarters set up in El Calafate, the team moved from there to each site. During that campaign, six of the absolute gravimetric sites envisaged in the GravPatagonia network were established and observed for the first time, complemented by local geodetic measurements. The sites are summarized in Table 1, shown in Figure 2, and the observation dates of the absolute gravity measurements are summarized in Table 2. In addition, this campaign was used to explore an additional gravimetric site at Estancia La Julia (LJL).

At all of these sites, the gravimetric site center was marked by a screw in the floor. Within a short

Table 2. *Overview of the amount and accuracy of absolute gravity measurements with the FG5-227 gravimeter at the GRAVPATAGONIA network sites. The FG5 observation date, the number of sets per gravimeter setup, the uncertainty of the absolute gravity value σ_g, and the local vertical gravity gradient dg/dh derived from relative gravimetric observations are shown for each site and measurement epoch.*

	2020				2022			
Site	Date	Sets/setup	σ_g [µGal]	dg/dh [µGal/m]	Date	Sets/setup	σ_g [µGal]	dg/dh [µGal/m]
FTE	09/02	11 + 22	1.89	-306.9 ± 3.6	12/02	24 + 24	1.96	-310.9 ± 4.4
	16/02	12 + 12	1.93		04/03	20	1.95	
CHT	14/02	14 + 6 + 12	1.94	-258.9 ± 3.0	23/02	15 + 17	1.89	-253.7 ± 2.9
GPM	11/02	14 + 22	1.89	-234.1 ± 1.5	20/02	21 + 23	1.87	-234.4 ± 3.3
HLS	07/02	12 + 8 + 14	1.93	-280.4 ± 2.8	16/02	18 + 14	1.99	-284.1 ± 4.0
PSJ	20/02	24 + 18	1.94	-309.3 ± 3.6	03/02	24 + 24	2.03	-306.7 ± 4.3
TLG	05/02	4 + 20 + 12	1.91	-283.3 ± 2.5	08/02	13 + 24	1.88	-282.9 ± 1.8
TLGc					10/02	22 + 19	1.90	-297.6 ± 2.3
CRS					27/02	23 + 23	1.95	-262.3 ± 3.0
LJL					06/02	12 + 16	1.93	-312.9 ± 1.6
AGGO	25/01	14+12	1.89		28/01	7	1.88	
	25/02	20	1.90		28/03	12	1.90	

distance from the building hosting the gravimetric center, local GNSS markers were installed that provide for forced centering of the GNSS antenna during campaign observations simultaneous with the absolute gravity determinations. Additional, eccentric gravimetric markers were emplaced outside the buildings hosting the gravimetric centers of FTE, TLG, HLS, GPM and PSJ. At our sites CHT and PSJ, the IGN's RAGA network site centers CHAL and RIGA, respectively, served as eccenters. In Tres Lagos, the RAGA site TLAG had been affected by structural alterations at the entrance to the *Comisión de Fomento* building. A new eccenter was established at this place, pursuing a collocation with the former RAGA center as exact as possible with the information at hand. Site descriptions were prepared for each network site.

The absolute gravity measurements at the Patagonian sites strived for an implementation of the BKG standard procedure as close as the local conditions allowed. The FG5-227 measurements were carried out in hourly sets of 100 drops every 10 s each. At least two independent instrument setups were realized at each site. Both installations were made with the same instrument orientation (North). The session duration of each setup was chosen in a way to cover at least a whole tidal cycle at each site. Thermal stability turned out to be a difficulty at various sites, forcing superspring resetting or abortion of measurement sessions due to low laser fringe amplitudes at HLS and CHT. Strong winds outside increased the drop scatter at CHT, PSJ and FTE (second occupation). Information on the amount and accuracy of the FG5-227 measurements acquired at each site are summarized in Table 2.

Usually in between the absolute gravimetric sessions, gravimetric measurements were carried out with BKG's Scintrex CG-5M S/N 81240496 on the site centers at sensor heights of 25 and 125 cm to determine vertical gravity gradients. The results of the gradient determinations are included in Table 2. Additional relative gravimeter measurements were carried out to determine gravity differences between the absolute gravimetry centers and the eccenters or RAGA sites. The measurements were performed in sets of three (gradient determination) or five (eccenter differences) 1 min cycles each. Depending on the dispersion of the readings and time availability, between three and seven sets were acquired. Sudden small jumps in the gravity readings complicated several of these measurements.

Height differences between the local GNSS markers and gravimetric sites, including the absolute gravity markers and the eccenters, were determined by two-way precise levelling. The GNSS markers, and most of the gravimetric eccenters, are located less than 100 m away from the absolute gravimetric sites. However, the RAGA sites in El Chaltén and Tres Lagos are located further apart from our FG5 sites. Thus, the longest levelling loop, at CHT, totals about 1 km. AGGO's Leica LS15 digital level along with a pair of 2 m invar levelling staffs were used. Staff tripods were essential for ensuring a high precision despite the wind. Complete loops were measured with a back-fore-fore-back sight sequence, with equal distances between back and fore sights, keeping sight distances below 25 m.

The GNSS observations were extended over several complete GNSS days to provide for an accurate positioning. Geodetic GNSS receivers and antennas (Trimble Microcentered with groundplane) were used. The choice of the GNSS locations prioritized short distances to the gravimetric centers. This may imply suboptimal conditions for crustal deformation determinations, such as markers placed on top of buildings and structures in urbanized environments (FTE, PSJ, CHT, TLG). These local sites are used to link the gravimetric sites with the geodynamic GNSS network observed since 2010 (Richter et al., 2016a). For this reason, selected, nearby geodynamic GNSS sites were observed simultaneously with the local GNSS markers at the gravimetric sites. A GNSS buoy was employed to determine water-surface heights at FTE and GPM (Lago Argentino), HLS (Lago Viedma) and PSJ (Bahía San Julián). Multi-system, dual-frequency GNSS code and phase data were recorded at a 1 Hz sampling rate. The autonomy of the battery mounted onto the buoy restricted continuous observations to 4 h or less.

Prior to the GravPatagonia campaign, the FG5-227 gravimeter had been linked in Germany to the International Terrestrial Gravity Reference System (ITGRS) (Wziontek et al., 2021) by several simultaneous measurements: in 2016 with FG5-301 in the Geodetic Observatory Wettzell and in 2017 with FG5-101 at the Gravity Reference station Bad Homburg. In AGGO, during the days before the departure to Patagonia, the bubble levels of the dropping chamber were readjusted using the x-y detector, and the gravimeter's rubidium frequency standard was compared with the AGGO time standard, yielding a rubidium frequency of 10 000 000.0053 Hz. In addition, the collimation unit of FG5-227 has been exchanged before the campaign for a new, fix-collimation unit with a triplet lens system which minimizes diffraction. A change of the collimation unit can potentially introduce a systematic bias in measured gravity values at the μGal level. However, as the same collimation unit has been used in all GravPatagonia campaigns, this has no effect on our determination of gravity changes in Patagonia.

Reference measurements were carried out immediately before departure to and after return from the GravPatagonia campaign on pillar AA in the AGGO gravity laboratory with the FG5-227. Both reference measurements agree within the expected accuracy, and also with the SG038 time series, documenting the stability and reliability of the absolute gravity observations in Patagonia. During the preparations at AGGO before the departure to the south, a tilt calibration and a drift determination of the Scintrex CG-5M relative gravimeter was carried out. The LS15 digital level was also checked and its spirit level readjusted.

The first GravPatagonia gravimetry campaign and the return of the German colleagues concluded a few days before restrictions due to COVID-19 were implemented. Throughout the following year, the pandemic prevented any gravimetric activity in Patagonia. Finally, the second gravimetric campaign was carried out between January and March 2022, still under the memorable circumstances of the pandemic, for example, regulations requiring the use of face masks and regular COVID-19 rapid tests. For the colleagues from Germany, this campaign extended from January 24 to March 14; the activities in Patagonia took place between January 30 and March 7. One researcher from AGGO and TUD, two researchers from BKG and three researchers from UNLP joined this campaign. Again, the transportation of the team and equipment throughout the campaign was accomplished using two vehicles, and El Calafate served as base quarters during most of the fieldwork in Patagonia. Figure 3 conveys some impressions from the fieldwork.

During the campaign, the six absolute gravimetric sites established in 2020 were reobserved with the FG5-227. Also all the complementary geodetic measurements were repeated, including gravity gradient and eccenter determinations with the relative gravimeter, GNSS observations on the local markers and selected sites of the geodynamic GNSS network, high-precision levelling connections, and water-level observations. This time, GNSS interferometric reflectometry (Larson et al. 2017) was employed in parallel to the buoy deployments for the water-level determination. In all the measurements, identical instruments (absolute and relative gravimeters, digital level, GNSS buoy, and GNSS antennas)

Figure 3. *Impressions from the fieldwork in southern Patagonia.* ***a)*** *FG5-227 absolute gravimeter in operation at site CHT;* ***b)*** *Relative gravimetric observations for gravity gradient determination at GPM;* ***c)*** *Levelling at site CHT;* ***d)*** *Transportation of the gravimeter equipment to the remote CRS site;* ***e)*** *Installation of the FG5-227 gravimeter at site GPM;* ***f)*** *Reflectometric water-level monitoring in Lago Argentino, close to FTE site;* ***g)*** *GNSS buoy operated in Lago Viedma at HLS site. All pictures were taken during the 2022 campaign, except g) (2020).*

were used as in 2020, thus reducing systematic biases. In addition to the six pre-existing sites, two new gravimetric sites were established and observed for the first time. With these new sites, LJL and CRS, the planned network design was completed. The CRS site implies particular logistic challenges, as the remote Estancia Cristina is accessible only by ship across Lago Argentino. Furthermore, in Tres Lagos a second absolute gravimetric marker was observed with the FG5-227 in addition to the marker established in 2020. As in the first campaign, at the regional reference site at El Calafate airport, two absolute gravimetric observations were carried out.

The FG5-227 measurements followed a similar procedure as in 2020, with a few minor modifications based on the experience gathered in the first campaign and detailed examination of the instrument. At each site, two independent setups were carried out, with an average of 20 hourly sets per setup. The nominal number of drops per set was increased from 100 to 120. In 2022, the instrument was turned by 180° (south orientation) during the second setup. A tent was used, along with an electric heater, to stabilize the instrument temperature during the measurements. The number of drops per set was adapted at each site to the local ambient conditions, especially wind intensity, allowing to extend sets to up to 300 drops when needed to achieve the required set precision. Particular care was devoted to the stability of the laser iodine line.

At the time of writing (December 2025), the project team is preparing a third gravimetric campaign with the aim to repeat the gravity determinations and auxiliary observations at all sites of the GravPatagonia network. This will allow to derive the first gravity change rates in southern Patagonia and a tentative geodynamical interpretation in terms of GIA.

ANALYSIS & PRELIMINARY OUTCOME

The FG5-227 absolute gravity measurements acquired in both campaigns were analyzed by BKG, using the "g" software, version 9 (Micro-g LaCoste, 2012). As a result, absolute gravity values are obtained, along with their uncertainties, for each site and measurement epoch. A first analysis was carried out after the first campaign, that allowed to conclude on the success of the first measurements and the achievable accuracy. After the second campaign, the measurements of the first campaign were reprocessed within a thorough analysis of the complete dataset acquired in both campaigns. These determinations include standard corrections, i.e. for solid-Earth tides, ocean-tidal loading (based on the FES2004 ocean tide model), polar motion (using IERS pole coordinate time series), and atmospheric pressure variations (applying an empirical factor of 0.3 μGal/hPa). Figure 4 summarizes graphically the analysis of the FG5-227 measurement data for the example of the FTE site. The corrections for environmental mass change effects, in particular for ice-mass changes and water-mass changes in Lago Argentino, Lago Viedma and Bahía San Julián, are in progress. The relative gravimeter measurements were analyzed at TUD. The instrument settings during the observations included corrections for tides, tilt, automatic outlier rejection and a seismic filter. In the data analysis an air-pressure correction was applied. Final gravity differences, gradients, and their uncertainties were derived by a least-squares adjustment.

The GNSS data of the local markers are processed jointly with the complete GNSS dataset of the geodynamic network in southern Patagonia. This ensures consistency in linking the crustal deformation determination to the gravimetric sites, in particular, for accurate uplift rate estimates $\dot{u}$ at each absolute gravimetry site. The GNSS data processing is performed at UNLP, using the Bernese GNSS Software version 5.4 and the Precise Point Positioning with Ambiguity Resolution (PPP-AR) technique (Mendoza et al., 2021). The positioning yields daily 3D site coordinates referenced to the ITRF2020 terrestrial reference frame (Altamimi et al., 2023). The Hector software (Bos et al., 2012) is used to co-estimate coordinate-change rates and noise magnitude combining multiple stochastic models. The levelling measurements were also analyzed at UNLP. The analysis confirms an adequate accuracy of the height difference determinations, with loop misclosures below 0.6 mm in all cases. The height differences between the absolute gravimetry center and the local GNSS marker agree among the measurements in 2020 and 2022 usually within 0.5 mm. The consistency of the levelling results is well within our accuracy requirements, as a height difference of 0.5 mm would imply a negligible gravity change of 0.15 μGal.

The water-level determinations were analyzed at TUD (Burkhardt, 2023) and UNLP (Maciel & Richter, 2025). The GNSS buoy data were processed in kinematic PPP-AR mode, yielding time series of 3D coordinates each second describing the trajectory of the buoy's antenna. These time series are filtered to eliminate the height dispersion introduced by waves. The GNSS reflectometry data was processed

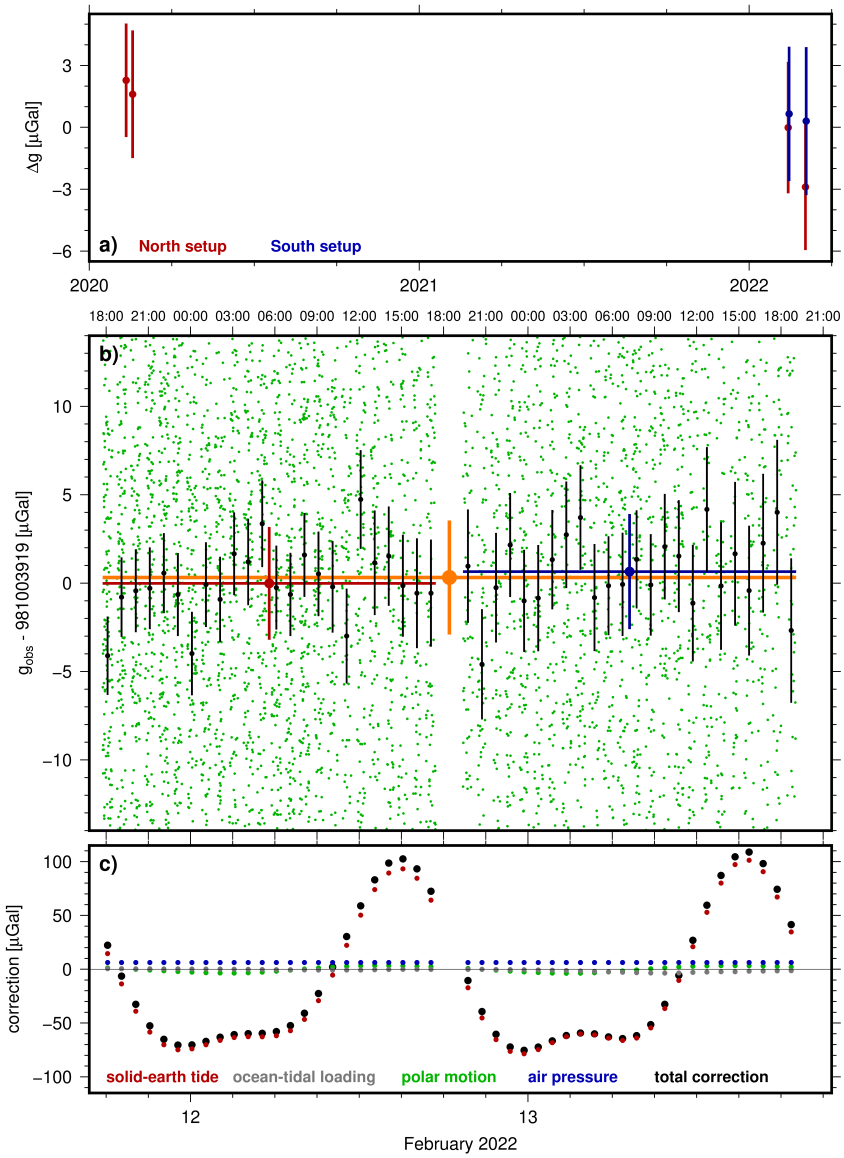

Figure 4. *Example for the analysis of the absolute gravimetric measurements for site FTE.* ***a)*** *Comparison of the individual absolute gravity values and their confidence intervals derived for each FG5-227 gravimeter setup at FTE during the 2020 and 2022 GravPatagonia campaigns.* ***b)*** *Variation of gravity values, measured during the first observation at FTE in 2022, over time. Tiny green dots: individual drops (11,865 of 12,000 accepted); black: mean and standard deviation of individual measurement sets comprising nominally 120 drops each; red (blue): mean and standard deviation of all accepted sets in the North (South) orientation gravimeter setup; orange: final mean and standard deviation of the entire observation dataset shown.* ***c)*** *Corrections applied to the gravity measurements shown in* ***b)*** *as a function of time. Solid-earth tide (red), ocean-tidal loading (grey), polar motion (green), air-pressure (blue) corrections are shown during the 53 h observation interval. The total gravity correction (black) is obtained as the sum of these individual geophysical corrections.*

using the GNSSrefl software (Larson, 2024), yielding mean reflector heights for each GNSS satellite arc visible within a defined elevation angle range. The comparison of simultaneous observations in 2022 suggests accuracies of below 1 cm and 2 cm for buoy and reflectometric observations, respectively, of the water height averaged over a typical arc duration of 1 h (Maciel & Richter, 2025). These results demonstrate the success of the reflectometric observations and their applicability for the purpose of water-level monitoring in our project. GNSS reflectometry allows for continuous water-level monitoring over several days, without the restriction imposed by the buoy's battery autonomy or dependence on the sea state. By combining the reflector height determination with the antenna phase center positioning using PPP-AR, the water levels are referred to a geocentric reference, providing for a stable reference in the comparison between campaigns. The reflectometry is slightly less precise

Table 3. *Comparison of absolute gravity determinations on collocated sites of the Argentine RAGA network (Instituto Geográfico Nacional, n.d.). g_R: absolute gravity value of RAGA site (measured with A10 gravimeter); g_G: absolute gravity value of GravPatagonia site in 1.25 m height above marker (measured with FG5-227 gravimeter); Δg_{GR}: gravity difference between RAGA site and GravPatagonia site in 1.25 m height above the marker (measured with CG5 relative gravimeter); $\delta g = g_R - g_G - \Delta g_{GR}$: resulting gravity mismatch between RAGA and GravPatagonia measurements.*

			2020			**2022**		
RAGA site	g_R [μGal]	GravPatagonia site	g_G [μGal]	Δg_{GR} [μGal]	δg [μGal]	g_G [μGal]	Δg_{GR} [μGal]	δg [μGal]
CHAL	980858984	CHT	980858996	+40.5	-52.5	980858978	+40.9	-34.9
RIGA	980993919	PSJ	980993366	+546.1	+6.9	980993364	+543.5	+11.5
TLAG	980959907	TLG	980960372	-446.1	-18.9	980960368	-446.1	-14.9
		TLGc				980959549	+372.7	-14.7

than buoy observations, although the stated uncertainty refers to a single arc while multiple arcs are usually observed simultaneously using receivers capable of multi-system recording (GPS, GLONASS, GALILEO, BeiDou). Nevertheless, the accuracies of both buoy and reflectometric observations are sufficient to derive water-mass change corrections for the gravimetric measurements in the scope of the project, as a 2 cm thick lake-water layer changes gravity by less than 1 μGal.

At the present stage, with the project still in progress, the achieved results allow to conclude on the feasibility of high-accuracy absolute gravity determinations for geodynamic research in southern Patagonia. The accuracy and consistency of the gravity values determined in two campaigns so far demonstrate the adequacy of our choice of the instruments and measurement procedures (Figure 4, Table 2). The repeatedly determined vertical gravity gradients remain constant within the estimated observational uncertainty, as expected. In particular, the preliminary results show that the FG5-227 achieves an accuracy of the absolute gravity under Patagonia's rough conditions only slightly inferior to that obtained under laboratory conditions at AGGO. However, this demands extraordinary skills of the observers, long and exhausting campaigns, and a careful monitoring of ambient processes in the vicinity of the gravimetric sites. AGGO's gravimetric infrastructure plays a fundamental role in our project, as the reference measurements before and after each campaign are crucial for ensuring the performance and stability of the FG5-227.

Another outcome, of interest especially for the Argentine geodetic community, is the validation of the absolute gravity values of three RAGA network sites in southern Patagonia. The sites TLAG and RIGA were observed in 2014, and site CHAL in 2016, in a cooperation of IGN with the University of São Paulo (Brazil, USP), using the Micro-g LaCoste A10 field absolute gravimeter of USP. Table 3 shows the comparison of the gravity values determined by our nearby FG5-227 measurements including the relative gravimetric connection (accounting for differences in both location and reference height between GravPatagonia and RAGA sites) with the values published by IGN at the RAGA sites RIGA (PSJ), TLAG (TLG) and CHAL (CHT). It shows a good agreement between both determinations, well within the expected confidence intervals. Differences between the determinations are to be expected due to the measurement uncertainties of the two absolute gravimeters (typically A10: 10 μGal, FG5: 2.5 μGal), but also from the relative gravimetric connection measurements and further factors such as non-measured gravity gradients). Thus, the results of our project allow to attest the RAGA network a high accuracy in this remote part of the country.

Finally, several lessons learned in the course of the project constitute also a valuable outcome of the project. These experimental insights include, for example, the realization of the importance of the thermal isolation of components of the FG5 measuring system during the absolute gravimetric observations, or the need for *in situ* tidal observations in the Bahía San Julián.

CONCLUSIONS & OUTLOOK

The FG5-227 absolute gravimeter is contributing to the geodetic investigation of one of the most enigmatic places on Earth regarding the solid-Earth response to ice-mass change. This instrument, destined by BKG primarily to the calibration of the superconducting gravimeter SG038 and the provision of a gravimetric reference at AGGO, forms the centerpiece of a DFG-funded, geodetic-geodynamic research project since 2019. The results of the project will allow a significant improvement of the GIA correction applied to GRACE and GRACE Follow-On satellite gravimetry data in the regional ice-mass monitoring (The GlaMBIE Team, 2025), as well as improved projections of relative sea-level change along the Patagonian coasts.

At the present stage, it is too early to conclude on the scientific success of the project. At least one more campaign is needed to derive interpretable gravity-change rates. Yet beyond the scientific challenges and technical innovations, the project has already achieved success in terms of extending a precise absolute gravity infrastructure in Patagonia and the cooperation between Argentine and German scientists. It builds on a long-standing cooperation between German and Argentine researchers dedicated to the geodetic observation of geodynamic processes in Tierra del Fuego and the Patagonian Icefields (Mendoza et al., 2011; Richter et al., 2009; Del Cogliano et al., 2007). However, the expertise of the gravimetrists from BKG and AGGO is indispensable for the GravPatagonia project. A broad research consortium has been formed that unites experts from AGGO, BKG, TUD, UNLP, EARG and IGN. Problems and challenges that have arisen in the course of the project have inspired new research projects and thesis topics, both in Argentina and Germany, for example a BSc thesis at TUD on water-level determinations based on GNSS (Burkhardt, 2023) or the application of ICESat-2 satellite laser altimetry for monitoring water levels in Bahía San Julián (Suad Corbetta et al., 2023) and the great Patagonian lakes (Suad Corbetta et al., 2026). The project boosted also cooperations between project partners within Germany or Argentina, for example between geodesists from AGGO and UNLP.

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REFERENCES

Altamimi, Z., Rebischung, P., Collilieux, X., Métivier, L., & Chanard, K. (2023). ITRF2020: An augmented reference frame refining the modeling of nonlinear station motions. *Journal of Geodesy*, *97*, 47. https://doi.org/10.1007/s00190-023-01738-w

Amante, C., & Eakins, B. W. (2009). *ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis.* [Dataset]. Boulder, CO, NOAA National Geophysical Data Center. https://doi.org/10.7289/V5C8276M

Aniya, M., Sato, H., Naruse, R., Skvarca, P., & Casassa, G. (1996). The use of satellite and airborne imagery to inventory outlet glaciers of the Southern Patagonia Icefield, South America. *Photogrammetric Engineering and Remote Sensing*, *62*(12), 1361–1369.

Antokoletz, E. D., Wziontek, H., Tocho, C. N., & Falk, R. (2020). Gravity reference at the Argentinean–German Geodetic Observatory (AGGO) by co-location of superconducting and absolute gravity measurements. *Journal of Geodesy*, *94*, 81. https://doi.org/10.1007/s00190-020-01434-z

Ben-Mansour, W., Wiens, D. A., Mark, H. F., Russo, R. M., Richter, A., Marderwald, E., & Barrientos, S. (2022). Mantle flow pattern associated with the Patagonian slab window determined from azimuthal anisotropy. *Geophysical Research Letters*, *49*, e2022GL099871. https://doi.org/10.1029/2022GL099871

Bilker-Koivula, M., Mäkinen, J., Ruotsalainen, H., Näränen, J., & Saari, T. (2021). Forty-three years of absolute gravity observations of the Fennoscandian postglacial rebound in Finland. *Journal of Geodesy*, *95*, 24. https://doi.org/10.1007/s00190-020-01470-9

Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems*, *4*(3), 1027. https://doi.org/10.1029/2001GC000252

Bos, M. S., Fernandes, R. M. S., Williams, S. D. P., & Bastos, L. (2012). Fast error analysis of continuous GNSS observations with missing data. *Journal of Geodynamics*, *87*(4), 351–360. https://doi.org/10.1007/s00190-012-0605-0

Boy, J.-P., & Hinderer, J. (2006). Study of the seasonal gravity signal in superconducting gravimeter data. *Journal of Geodynamics*, *41*(1–3), 227–233. https://doi.org/10.1016/j.jog.2005.08.035

Braun, M. H., Malz, P., Sommer, C., Farías-Barahona, D., Sauter, T., Casassa, G., Soruco, A., Skvarca, P., & Seehaus, T. C. (2019). Constraining glacier elevation and mass changes in South America. *Nature Climate Change*, *9*, 130–136. https://doi.org/10.1038/s41558-018-0375-7

Breitsprecher, K., & Thorkelson, D. J. (2009). Neogene kinematic history of Nazca–Antarctic–Phoenix slab windows beneath Patagonia and the Antarctic Peninsula. *Tectonophysics*, *464*, 10–20. https://doi.org/10.1016/j.tecto.2008.02.013

Burkhardt, D. (2023). *Bestimmung von Wasserständen in Südpatagonien basierend auf GNSS-Messungen* [Unpublished undergraduate thesis]. Technische Universität Dresden.

De Linage, C., Hinderer, J., & Rogister, Y. (2007). A search for the ratio between gravity variation and vertical displacement due to a surface load. *Geophysical Journal International*, *171*(3), 986–994. https://doi.org/10.1111/j.1365-246X.2007.03613.x

Del Cogliano, D. H., Dietrich, R., Richter, A., Perdomo, R. A., Hormaechea, J. L., Liebsch, G., & Fritsche, M. (2007). Regional geoid determination in Tierra del Fuego including GPS levelling. *Geologica Acta*, *5*(4), 315–322. https://doi.org/10.1344/105.000000292

Dietrich, R., Ivins, E. R., Casassa, G., Lange, H., Wendt, J., & Fritsche, M. (2010). Rapid crustal uplift in Patagonia due to enhanced ice loss. *Earth and Planetary Science Letters*, *289*(1–2), 22–29. https://doi.org/10.1016/j.epsl.2009.10.021

Instituto Geográfico Nacional. (n.d.). Tipos de redes. *INA*. Retrieved December 12, 2025, from https://www.ign.gob.ar/NuestrasActividades/Geodesia/Gravimetria/TiposRedes

Ivins, E., & James, T. (1999). Simple models for late Holocene and present-day Patagonian glacier fluctuations and predictions of a geodetically detectable isostatic response. *Geophysical Journal International*, *138*, 601–624. https://doi.org/10.1046/j.1365-246x.1999.00899.x

Ivins, E. R., & James, T. S. (2004). Bedrock response to Llanquihue Holocene and present-day glaciation in southernmost South America. *Geophysical Research Letters*, *31*, L24613. https://doi.org/10.1029/2004GL0215

Ivins, E. R., Caron, L., Adhikari, S., Larour, E., & Scheinert, M. (2020). A linear viscoelasticity for decadal to centennial time scale mantle deformation. *Reports on Progress in Physics*, *83*(10), 106801. https://doi.org/10.1088/1361-6633/aba346

Křen, P., Pálinkáš, V., & Mašika, P. (2018). On the determination of verticality and Eötvös effects in absolute gravimetry. *Metrologia*, *55*(4), 451. https://doi.org/10.1088/1681-7575/aac522

Křen, P., Pálinkáš, V., Vaľko, M., & Mašika, P. (2020). Improved measurement model for FG5/X gravimeters. *Measurement*, *71*, 108739. https://doi.org/10.1016/j.measurement.2020.108739

Lange, H., Casassa, G., Ivins, E. R., Schröder, L., Fritsche, M., Richter, A., & Dietrich, R. (2014). Observed crustal uplift near the Southern Patagonian Icefield constrains improved viscoelastic Earth models. *Geophysical Research Letters*, *41*(3). https://doi.org/10.1002/2013gl058419

Larson, K. M. (2024). Gnssrefl: An open source Python software package for environmental GNSS interferometric reflectometry applications. *GPS Solutions*, *28*, 165. https://doi.org/10.1007/s10291-024-01694-8

Lenzano, M. G., Rivera, A., Durand, M., Vacaflor, P., Carbonetti, M., Lannutti, E., Gende, M., & Lenzano, L. (2023). Detection of crustal uplift deformation in response to glacier wastage in southern Patagonia. *Remote Sensing*, *15*(3), 584. https://doi.org/10.3390/rs15030584

Maciel, M. G., & Richter, A. (2025, October 15–17). *Monitoring water levels using GNSS interferometric reflectometry* [Conference presentation]. 6th SEG Latin America Virtual Student Conference.

Malz, P., Meier, W., Casassa, G., Jaña, R., Skvarca, P., & Braun, M. H. (2018). Elevation and mass changes of the Southern Patagonia Icefield derived from TanDEM-X and SRTM data. *Remote Sensing*, *10*(2), 188. https://doi.org/10.3390/rs10020188

Mark, H. F., Wiens, D. A., Ivins, E. R., Richter, A., Ben Mansour, W., Magnani, M. B., Marderwald, E., Adaros, R., & Barrientos, S. (2022). Lithospheric erosion in the Patagonian slab window, and implications for glacial isostasy. *Geophysical Research Letters*, *49*, e2021GL096863. https://doi.org/10.1029/2021GL096863

Mazzotti, S., Lambert, A., Henton, J., James, T. S., & Courtier, N. (2011). Absolute gravity calibration of GPS velocities and glacial isostatic adjustment in mid-continent North America. *Geophysical Research Letters*, *38*, L24311. https://doi.org/10.1029/2011GL049846

Mendoza, L., Perdomo, R., Hormaechea, J. L., Del Cogliano, D., Fritsche, M., Richter, A., & Dietrich, R. (2011). Present-day crustal deformation along the Magallanes–Fagnano Fault System in Tierra del Fuego from repeated GPS observations. *Geophysical Journal International*, *184*(3), 1009–1022. https://doi.org/10.1111/j.1365-246X.2010.04912.x

Mendoza, L. P. O., Richter, A., Marderwald, E. R., Hormaechea, J. L., Connon, G., Scheinert, M., Dietrich, R., & Perdomo, R. A. (2021). Horizontal and vertical deformation rates linked to the Magallanes-Fagnano Fault, Tierra del Fuego: Reconciling geological and geodetic observations by modeling the current seismic cycle. *Tectonics*, *41*, e2021TC006801. https://doi.org/10.1029/2021TC006801

Micro-g LaCoste. (2012). *G9 User's Manual* [User manual]. https://microglacoste.com/download/g9-users-manual/

Naganawa, K., Kazama, T., Fukuda, Y., Miura, S., Hayakawa, H., Ohta, Y., & Freymueller, J. T. (2022). Updated absolute gravity rate of change associated with glacial isostatic adjustment in Southeast Alaska and its utilization for rheological parameter estimation. *Earth, Planets and Space*, *74*, 116. https://doi.org/10.1186/s40623-022-01666-7

Naujoks, M. (2008). *Hydrological information in gravity: Observation and modelling* [Unpublished PhD Thesis]. Friedrich-Schiller-Universität Jena.

Niebauer, T. M., Sasagawa, G. S., Faller, J. E., Hilt, R., & Klopping, F. (1995). A new generation of absolute gravimeters. *Metrologia*, *32*, 159–180. https://doi.org/10.1088/0026-1394/32/3/004

Niebauer, T. M., Billson, R., Ellis, B., Mason, B., van Westrum, D., & Klopping, F. (2011). Simultaneous gravity and gradient measurements from a recoil-compensated absolute gravimeter. *Metrologia*, *48*, 154–163. https://doi.org/10.1088/0026-1394/48/3/009

Olsson, P.-A., Breili, K., Ophaug, V., Steffen, H., Bilker-Koivula, M., Nielsen, E., Oja, T., & Timmen, L. (2019). Postglacial gravity change in Fennoscandia: Three decades of repeated absolute gravity observations. *Geophysical Journal International*, *217*(3), 1141–1156. https://doi.org/10.1093/gji/ggz054

Richter, A., Hormaechea, J. L., Dietrich, R., Perdomo, R., Fritsche, M., Del Cogliano, D., Liebsch, G., & Mendoza, L. (2009). Anomalous ocean load tide signal observed in lake-level variations in Tierra del Fuego. *Geophysical Research Letters*, *36*, L05305. https://doi.org/10.1029/2008GL036970

Richter, A., Ivins, E., Lange, H., Mendoza, L., Schröder, L., Hormaechea, J. L., Casassa, G., Marderwald, E., Fritsche, M., Perdomo, R., Horwath, M., & Dietrich, R. (2016a). Crustal deformation across the Southern Patagonian Icefield observed by GNSS. *Earth and Planetary Science Letters*, *452*, 206–215. https://doi.org/10.1016/j.epsl.2016.07.042

Richter, A., Marderwald, E., Hormaechea, J. L., Mendoza, L., Perdomo, R., Connon, G., Scheinert, M., Horwath, M., & Dietrich, R. (2016b). Lake-level variations and tides in Lago Argentino, Patagonia: Insights from pressure tide gauge records. *Journal of Limnology*, *75*(1), 62–77. https://doi.org/10.4081/jlimnol.2015.1189

Richter, A., Groh, A., Horwath, M., Ivins, E., Marderwald, E., Hormaechea, J. L., Perdomo, R., & Dietrich, R. (2019). The rapid and steady mass loss of the Patagonian Icefields throughout the GRACE Era: 2002–2017. *Remote Sensing*, *11*(8), 909. https://doi.org/10.3390/rs11080909

Russo, R. M., Luo, H., Wang, K., Ambrosius, B., Mocanu, V., He, J., James, T., Bevis, M., & Fernandes, R. (2022). Lateral variation in slab window viscosity inferred from global navigation satellite system (GNSS)–observed uplift due to recent mass loss at Patagonia ice fields. *Geology*, *50*(1), 111–115. https://doi.org/10.1130/G49388.1

Suad Corbetta, F., Richter, A., Marderwald, E., & Mendoza, L. (2023). Aplicación de la altimetría satelital láser a la determinación de variaciones locales del nivel del mar. In M. A. Arecco, P. A. Larocca, & F. A. Oreiro (Eds.), *IV Jornadas de Geociencias para la Ingeniería* (Vol. 2, pp. 73–77). Facultad de Ingeniería, Universidad de Buenos Aires.

Suad Corbetta, F., Gómez, M. E., & Richter, A. (2026). Modelling spatio-temporal surface elevation changes in Argentino and Viedma lakes, Patagonia, employing ICESat-2. *Remote Sensing*, *18*(7), 993. https://doi.org/10.3390/rs18070993

The GlaMBIE Team. (2025). Community estimate of global glacier mass changes from 2000 to 2023. *Nature*, *639*, 382–388. https://doi.org/10.1038/s41586-024-08545-z

Wahr, J., Dahong, H., & Trupin, A. (1995). Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic Earth. *Geophysical Research Letters*, *22*(8), 977–980. https://doi.org/10.1029/94GL02840

Wahr, J., van Dam, T., Larson, K., & Francis, O. (2001). Geodetic measurements in Greenland and their implications. *Journal of Geophysical Research*, *106*(B8), 16567–16581. https://doi.org/10.1029/2001JB000211

Wziontek, H., Bonvalot, S., Falk, R., Gabalda, G., Mäkinen, J., Pálinkáš, V., Rülke, A., & Vitushkin, L. (2021). Status of the International Gravity Reference System and Frame. *Journal of Geodesy*, *95*, 7. https://doi.org/10.1007/s00190-020-01438-9