Brazilian Journal of Geophysics, 40 (2022), Suppl. 1, 35-46
Brazilian Geophysical Society
ISSN 2764-8044
DOI: 10.22564/brjg.v40i5.2141

REFERENCE GRAVITY FRAME IN LATIN AMERICA

Denizar Blitzkow [1,2*], Iuri M. Björkström [3], Ana Cristina O. Cancoro de Matos [1,2], Valéria Cristina Silva [1], Gabriel N. Guimarães [4], and Edvaldo Simões da Fonseca Junior [3]

[1]Escola Politécnica da Universidade de São Paulo - POLI-USP, São Paulo, SP, Brazil
[2]Centro de Estudo de Geodesia - CENEGEO, São Paulo, SP, Brazil
[3]Geovertentes Engenharia Geográfica, São Paulo, SP, Brazil
[4]Universidade Federal de Uberlândia - UFU, Uberlândia, MG, Brazil

*Corresponding author e-mail: dblitzko@usp.br

ABSTRACT. With the development of the ballistic gravimeter in the late 80s, the efforts to establish reliable absolute gravity reference around the world became a reality. The need for the so-called International Terrestrial Gravity Reference Frame (ITGRF[1]) to substitute the IGSN 71 (International Gravity Standardization Net 1971) is one of the demands of modern Geodesy. In that context, the *Laboratório de Topografia e Geodesia, Escola Politécnica da Universidade de São Paulo* (LTG/EPUSP), Brazil, started in 2013, with the acquisition of the A10 nº 32 (A10-032) absolute gravimeter, a large number of campaigns to measure gravity acceleration in the states of São Paulo, Minas Gerais, Paraná and abroad. The gravimeter was purchased by *Instituto Geográfico e Cartográfico* (IGC), state of São Paulo. After eight years of operation under the coordination of the *Centro de Estudos de Geodesia* (CENEGEO) and with the support of different institutions, a total of five national Gravity Reference (GR) was established: Argentina, Brazil, Costa Rica, Ecuador and Venezuela. The present efforts are the selection of a set of local GR in the different countries of Latin America and a possible contribution to the ITGRF.

Keywords: absolute gravity, Gravity Reference, Latin America

INTRODUCTION

In the 1980s, the International Association of Geodesy (IAG) established two important geodetic references: The International Terrestrial Reference System (ITRS) materialized by the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference System (ICRS), materialized by the International Celestial Reference Frame (ICRF), established in both cases for a specific epoch. Since then, the geodetic community has defined, materialized, and maintained consistent geocentric systems that meet the needs of Geodesy. On the other hand, the materialization and realization of unified vertical and gravimetric systems are still a great challenge for the geodesy.

Physical and geometrical characteristics of those systems are fundamental for monitoring and studying the dynamic process of the Earth. They integrate the Global Geodetic Reference System (GGRS), whose framework, the Global Geodetic Reference Frame (GGRF), was recognized by the United Nations (UN) on February 26, 2015. It understands the need of GGRS for the sustainable development of the world. During the UN General Assembly, Sixth-ninth session, Agenda item 9, the UN reinforces the economic and scientific importance of an accurate and stable global geodetic reference frame for the Earth, combining geometric positioning and gravity field-related observations, as the basis and reference in location and height for geospatial information (Resolution No. A/RES/69/266; see https://ggim.un.org/documents/A_RES_69_266_E.pdf).

[1] The ITGRS/F acronyms were approved by IAG JWG 2.1.1 in April 2022, replacing the former IGRS/F acronyms.

Therefore, the IAG Resolutions at the XXVI IUGG General Assembly 2015 were established and published (see https://www.iag-aig.org/doc/5d10c798b5280.pdf).

The first resolution described the definition and implementation of an International Height Reference System (IHRS). Its materialization is under development by the International Height Reference Frame (IHRF). The computation will be based on the mean value of the Earth's gravity potential, W_0=62,636,853.4 m^2s^{-2}, and specific parameters to standardize the framework. In addition, this system, strictly based on the gravity field, will be related to the ITRF coordinates with its variation in time. The parameters, observations, and data must be related to the mean tidal or mean crust concept, and the unit of length is the meter and the unit of time is the second in the International System of Units (SI). The vertical coordinates are differences -ΔW_p determined between the gravity potential at a given point P (W_P) and W_0; such differences in gravity potential are also referred to as geopotential numbers (C_P). The spatial reference of P position for the potential W_P= W(X) is related to the X coordinates of the ITRS (Drewes et al., 2016; Ihde et al., 2017; Tóth, 2017).

The second resolution described the establishment of a global absolute gravity reference system, denominated International Terrestrial Gravity Reference System (ITGRS). The objective behind this implementation is to make the gravity reference system accessible to any user and to initiate the replacement of the IGSN 71 and the latest International Absolute Gravity Base Station Network by the new Global Absolute Gravity Reference System. The ITGRF is the realization of the ITGRS; it addressed the attention for reliable absolute measurements all over the world. These gravimetric reference stations need to be linked to the ITRS through spatial geodetic techniques. The ITGRF is under the definition and recommendations of the IAG Joint Working Group 2.1.1 "Establishment of a global absolute gravity reference system" (JWG 2.1.1; Wilmes et al., 2016; Wziontek et al., 2021). The document "Strategy for Metrology in Absolute Gravimetry" (Marti et al., 2014), developed jointly by the IAG and the Consultative Committee for Mass and Related Quantities (CCM), contributed to standardize gravity measurements and procedures at the highest level for Metrology and Geodesy and should be mentioned in this paper.

The ITGRS is defined by the instantaneous acceleration of free fall expressed in the SI, a set of conventions and temporal gravity corrections for the time-dependent effects: the zero-tide concept for the tidal correction, the standard atmosphere ISO 2533:1975 (DIN 5450) for the correction for atmospheric gravity effects and the reference pole of the International Earth Rotation and Reference Systems Service (IERS) for the correction for polar motion (Wziontek et al., 2021). See Table 1 for details.

Table 1: Scheme of the gravity reference system and frame (Wziontek et al., 2021).

REFERENCE SYSTEM	REFERENCE FRAME
- The fundamental principles: the definition of gravity must be stable over time.	- The realization of the system: the numbers obtained.
- Instantaneous acceleration of free fall is expressed in the International System of Units (SI).	- Observations with absolute gravimeters: epoch, position, gravity, vertical gravity gradient, reference height.
- Set of conventional corrections: - Zero-tide concept; - Standard atmosphere ISO 2533:1975; - Earth rotation axis IERS reference pole, which defines the conventional quantity "acceleration of gravity".	- Comparisons of absolute gravimeters: traceability and compatibility of the observations and the processing, assessment of systematic effects. - Set of conventional models for correction of temporal changes (tides, ocean tide loading, atmosphere, polar motion). - Compatible infrastructure (markers, points) and documentation (database).

A large collaborative network between Latin American countries was created and it is presented in this paper. A series of international campaigns was carried out. At the moment a careful analysis is underway to select the most suitable stations to participate in the ITGRF, which is in the implementation phase.

GRAVITY DETERMINATION

A resting object over the Earth's surface or close by is subjected to two forces: attraction (gravitational) and centrifugal. According to Newton's law, the resulting force is called gravity. The gravitational field is the space where the points are submitted to the gravitational force. The gravity field is the space subjected to the gravity force. The module of the gravity vector is gravity acceleration. The latter is measured by gravimeters. They can be either relative or absolute. In the first case, the relative observations provide the difference in gravity acceleration between stations. These measurements are taken generally with a spring gravimeter; the readings need to be corrected by lunisolar attraction, drift and converted into acceleration to become the referred difference. In the case of absolute gravimeters, the measurements are related to International Standards of time and distance and are usually done by tracking a test mass in free fall inside a vacuum chamber to determine its acceleration instantly, after every fall (Niebauer, 2015). WG 2.1.1 established that the measurements with absolute gravimeters have to follow some recommendations. The traceability of the gravimeters has to be ensured by comparisons and monitoring of reference stations (Wziontek et al., 2021).

The free fall method is based on the expression of motion of a body in free fall:

$$m\ddot{z} = mg(z) \tag{1}$$

where m is the mass, z is the distance along the vertical axis, and $\ddot{z} = d^2z/dt^2$, the derivative of distance concerning time.

Assuming a homogeneous gravity field along the fall distance, a double integration of Equation 1 leads to free fall Equation 2 (Torge, 1991; Sneeuw, 2006; Torge and Müller, 2012):

$$(t) \; = \frac{1}{2}gt^2 + z_0 + \dot{z}_0 t \tag{2}$$

The constants of integration z_0 and $\dot{z}_0$ represent the position and velocity of the body at t = 0. In practice, it is not possible to start the measurement exactly when $z_0 = \dot{z}_0 = 0$. What happens is to start the measurement at a certain point in the fall trajectory. Thus, z_0 and $\dot{z}_0$ are unknown. Consequently, three pairs of measurements (t_i, z_i) must be known. In the case of having exactly three measurements (Figure 1a), the initial parameters are eliminated resulting in:

$$g = 2\,\frac{(z_3 - z_1)(t_2 - t_1) - (z_2 - z_1)(t_3 - t_1)}{(t_3 - t_1)(t_2 - t_1)(t_3 - t_2)}. \tag{3}$$

For a symmetric ascent and descent, the test mass is thrown upwards and returns after reaching the apex (Figure 1b). Therefore, it is possible to measure the time in the same position during the ascent and descent of the mass.

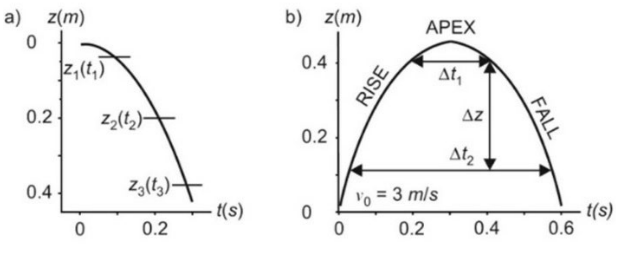


Figure 1: Distance-time diagram. 1a) free fall method. 1b) symmetrical rise and fall method (Torge and Müller, 2012).

In practice, more measurements are performed during the drop experiment to provide a given problem, that is, more equations than unknown observations. Instead of just considering the fall of the mass, it is possible to launch it vertically and measure the time it takes to fall again. With the technological advancement of the devices resulting in increasingly accurate measurements, the change in gravity acceleration along the vertical axis must be considered (non-homogeneous gravity field). Therefore, by introducing $\partial g/\partial z = g_z$, Equation 1 becomes:

$$m\ddot{z} = m(g_0 + g_z z) \tag{4}$$

with $g_0 = g$ in the rest position and $z = 0$. Double integration of Equation 4 leads to the following equation:

$$z = \frac{g_0}{g_z}(cosh\,\sqrt{g_z}\,t - 1) \tag{5}$$

for $z_0 = \dot{z}_0 = 0$. A series development of z (up to order t^4) including z_0 results in the observation Equation 6 (Cook, 1965):

$$z = z_0\left(1 + \frac{1}{2}g_z t^2\right) + \dot{z}_0\left(1 + \frac{1}{6}g_z t^3\right) + \frac{1}{2}g_0\left(t^2 + \frac{1}{12}g_z t^4\right) + \cdots \tag{6}$$

where the vertical gradient is often determined using a relative gravimeter.

Currently, the accuracy of absolute gravity observations is on the order of 10^{-9} Gal or 10^{-8} ms^{-2}. Hence, according to Equation 2 for a drop distance of 0.2 m (fall time of 0.2 s), an accuracy of 0.2 nm and 0.1 ns is required for position and time, respectively. This is achieved through interferometric distance measurements and electronic timing. For absolute gravimeters, a polarized laser is used as the length standard, while a rubidium clock is used as the time standard. Figure 2 illustrates the working principle of a free fall gravimeter that uses laser interferometry.

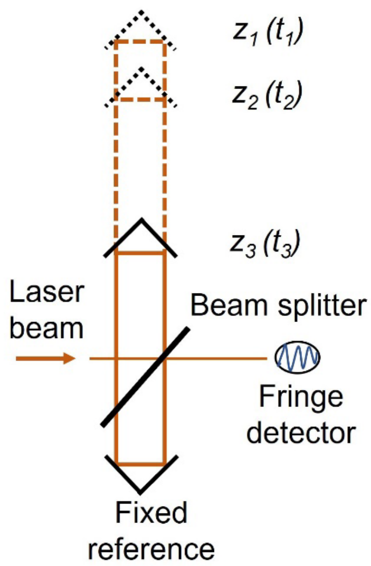
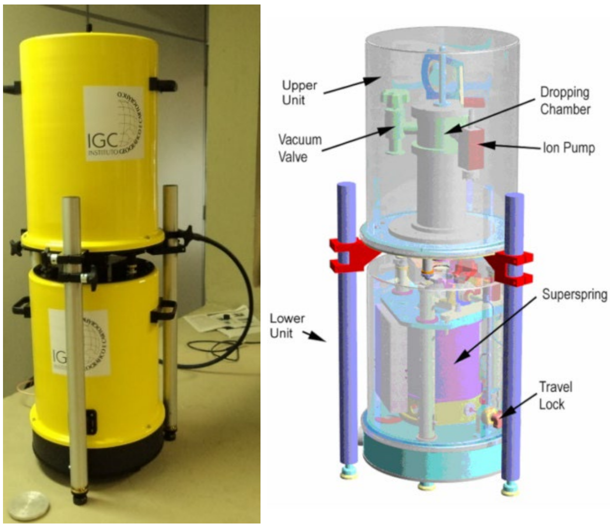


Figure 2: Working principle of a gravimeter that uses laser interferometry (adapted from Niebauer et al., 1995).

METHODS

Measuring with the A10 by Micro-g LaCoste

The A10 is a robust field gravimeter manufactured by the North American company Micro-g LaCoste Inc (Figure 3). Since the decade of 2000, the A10 has become a reference for field operations with respect to absolute measurements. Relatively easy to handle and transport, the measuring procedure takes about one hour including setup and unmounting (Micro-g LaCoste, 2008).



(a) **(b)**

Figure 3: a) A10-032 at Astronomical Observatory, Valinhos, Brazil; b) A10 Schematic.

The A10 has 3 modules connected by coaxial cables powered by 12V source. The interferometric base is a thermos-stabilized cylinder that emits a dual-frequency laser beam. The dropping chamber is the unit that contains a vacuum-sealed cylinder with a test mass inside and a small engine to lift it up after every fall. The third module is a central station with a computer that controls a combination of corrections and parameters. The nominal accuracy of A10 is 10 μGal.

The operation is relatively easy to carry out. The working principle of the A10 is simple. An object keeps dropping inside a vacuum chamber and laser interferometry is used to accurately track its free fall. The precise timing of the optical fringes (which provides distance information) is given by an atomic clock, allowing the acceleration of gravity to be determined.

The assisted software g9 for observations allows users to set data acquisition parameters and apply a series of corrections to determine the best estimate of the final value (Figure 4), such as lunisolar attraction, ocean load, barometric pressure, and polar motion (Micro-g LaCoste, 2012).

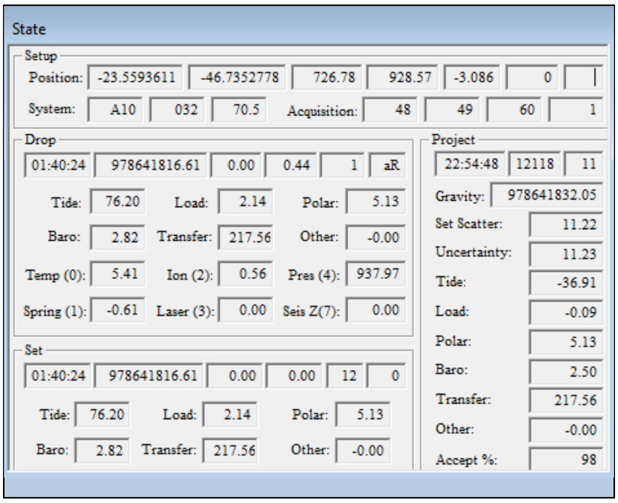


Figure 4: Screen view of a state window generated by the g9 software.

For barometric correction, it is necessary to insert the height of the benchmark. The software uses a normalized gradient to infer ambient pressure. The polar motion effect is corrected by inserting its daily coordinates, published by the International Earth Rotation and Reference Systems Service (IERS) in the EOP (Earth Orientation Parameters) bulletin. The g9 software allows selecting between two Tide Correction methods, Berger and ETGTAB. The first one uses a non-harmonic computation with global tidal parameters to determine the tidal potential for a point on Earth's surface. While the ETGTAB correction consists of a finite sum of sine and cosine terms of the tidal frequencies of the harmonic method (Van Camp, 2003).

The gravimeter has a sophisticated seismic isolation device called super spring. It absorbs high-frequency vertical ground motions and minimizes the effects of unmodeled noise sources that could affect gravity value along the measurement. The final value of absolute gravity is the least squares fit of all observations, with the proper corrections applied. Normally 10 sets of measurements are made, each with 120 falls of 1 second.

An adapted vehicle is used for transportation and for carrying out the campaigns (Figure 5a). To maintain the vacuum inside the dropping chamber, two high voltage ion pumps have to be always on, as well as the heaters for the Interferometric Base. Thus, temperature control and power supply are among the necessary items in the vehicle. Appropriate boxes are also used to avoid damage during transportation/operation (Figure 5b).

a)

(b)

Figure 5: (a) Van used to transport the A10-032; (b) set up of the equipment inside the vehicle.

A10-032 status

The gravimeter A10-032 has been visiting Micro-g LaCoste three different times since 2013. A maintenance schedule was achieved in the opportunities with a complete checking list of the parts and calibrations. The last time was in May/June 2022. The report of Micro-g LaCoste included the following items and results. The Service summary was as follows:

1. Dropper service;
2. New Ion Pumps x2;
3. Super spring alignment, repair, and retune;
4. Laser calibration;
5. Clock calibration;
6. Electronics diagnostics;
7. Pre- and post-repair of the Quick Check (QC) data observations;
8. Factory Height: 71.9 cm;
9. Rubidium frequency: 9,999,999.981Hz;
10. Red Lock: 632.9919469 nm;
11. Blue Lock: 632.9909129 nm.

In the sequel, the following comparisons were accomplished with FG5 equipment. The result is shown in Table 2.

In the opportunity, A10-032 gravimeter visited also the very important NOAA's Table Mountain Gravity Observatory (TMGO). It is located in a seismically quiet federal preserve near Boulder, Colorado (see https://www.ngs.noaa.gov/GRD/GRAVITY/TMGO.html). TMGO's mission is to conduct gravimetric surveys and perform high-precision gravity measurements in the USA and abroad. It has FG-5, cryogenic gravimeters and a GPS receiver. The tested meter report shows the agreement of A10-032 with the gravity facilities at TMGO as follows: "The A10-032 value is 979 622 739.5 ±10.7 µGal on 18 May 2022; FGX-102 measured 979 622 741.2 ±1.8 µGal on Pier AG on 2 March 2022; and FG5X-111 measured 979 622 739.6 ±1.8 µGal on adjacent Pier AH on 13 April 2022". The expected difference between Piers AG and AH is less than 0.2 µGal, and the expected change in gravity between March and May of this year is less than 1 µGal.

In short, according to Derek Van Westrum of the NOAA's National Geodetic Survey (National Oceanic and Atmospheric Administration), the tested meter is basically in perfect agreement with the expected gravity value at TMGO (van Westrum, 2019).

RESULTS

The establishment of the ITGRS has mobilized the geodetic community over the last few years. The efforts made by the LTG, CENEGEO, and other Latin American institutions are an important contribution to the materialization of a gravity frame (ITGRF) in the continent.

Table 3 shows the mean values of standard deviation, measurement precision and total uncertainty for each of the 5 countries where the surveys were carried out. A10-032 is compatible, as much as possible, with the recommendations of the JWG 2.1.1 for the observations at ITGRF stations.

In the next sub-sections, the reference gravities of countries such as Argentina, Brazil, Costa Rica, Ecuador, and Venezuela are presented.

Table 2: Comparison among processing results provided by absolute gravity equipment.

INSTRUMENT	“g” VALUE (µGal)	DATE	UNCERTAINTY (µGal)	PIER SETS
FG5-218	979 631 876.6	23 FEB 2022	2.1	MGL3 8
FG5X-265	979 631 879.2	26 APR 2022	2.1	MGL6 20
A10-032	**979 631 883.3**	**27 APR 2022**	**10.5**	**MGL7 28**
FG5X-301	979 631 876.4	22 MAR 2022	2.2	MGL4 26
FG5-217	979 631 878.0	21 APR 2022	2.0	MGL4 24
FG5-202	979 631 877.8	07 FEB 2022	2.0	MGL4 24

Table 3: Mean statistics results of the RGN.

COUNTRY	GR	STATIONS	SCATTER (µGal)	PRECISION (µGal)	UNCERTAINTY (µGal)
ARGENTINA	RAGA	38	6.16	2.15	11.01
BRAZIL	REGRAB	72	12.46	4.12	12.06
COSTA RICA	AGNCR	18	8.94	2.91	11.39
ECUADOR	REGA-EC	25	10.27	3.29	11.34
VENEZUELA	-	13	10.09	3.57	12.10

Gravity References in Argentina (GRA)

The GRA was established under three different campaigns between 2014 to 2016 with the support of *Instituto Geográfico Nacional* (IGN), *Universidad Nacional de Rosario* (UNR) and *Universidad Nacional de San Juan* (UNSJ). A total of 38 GRA were measured from Ushuaia in Patagonia to San Lorenzo in the north (Figure 6). A GR was also established in Paysandú, Uruguay (acronym PAYS in red in Figure 6).

Gravity References in Brazil (GRB)

For the period between October 2013 to June 2016, 18 GRB were established in four different campaigns. The first efforts to implement a set of GRB across the country began with surveys carried out in São Paulo State. Other campaigns were performed to establish GRB along a profile that extends from Manaus (in Amazon) to Santana do Livramento (near the border with Uruguay), which also included observation in Rivera, Uruguayan territory (Figure 7). Among the observed sites, three GRB had previous absolute gravity values established in the year 2007 by the Observatório Nacional (ON) with A10-011.

A second effort was in the state of Minas Gerais with a total of 22 GRB established in the years 2016 to 2021. In 2021 and 2022, six and fourteen new GRB were observed in Paraná state, respectively. In the Brazilian territory, so far, 72 GRB have been established; see Figure 7.

It is important to point out that in Brazil there are 17 GRB close to Brazilian Network for Continuous Monitoring of the GNSS Systems (RBMC, in Portuguese: Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS), which accomplish at least one exigence of the WG 2.1.1. They are: Manaus, Porto Velho, Presidente Prudente, Cananéia, Ubatuba, Botucatu, Cuiabá, Cachoeira Paulista (bearing also a DORIS station), Uberlândia, Monte Carmelo, Montes Claros, Inconfidentes (<1 km), Juiz de Fora, Itaipu (Foz do Iguaçu), Curitiba, Guarapuava and Santa Maria. Valinhos Observatory is a particular important point due to a very high stability of the special pilar constructed on the rock (Figure 3). Unfortunately, however, there is no RBMC station close to this GR.

The implementation of GRB in Brazil had the support of the Centro Gestor e Operacional do Sistema de Proteção da Amazônia (CENSIPAM), Instituto Água e Terra (IAT), Universidade Estadual de Maringá (UEM), Universidade Federal de Uberlândia (UFU), Universidade de Brasília (UnB), Universidade Federal de Rondônia (UNIR), Universidade Federal de Mato Grosso (UFMT) and ITAIPU Binacional.

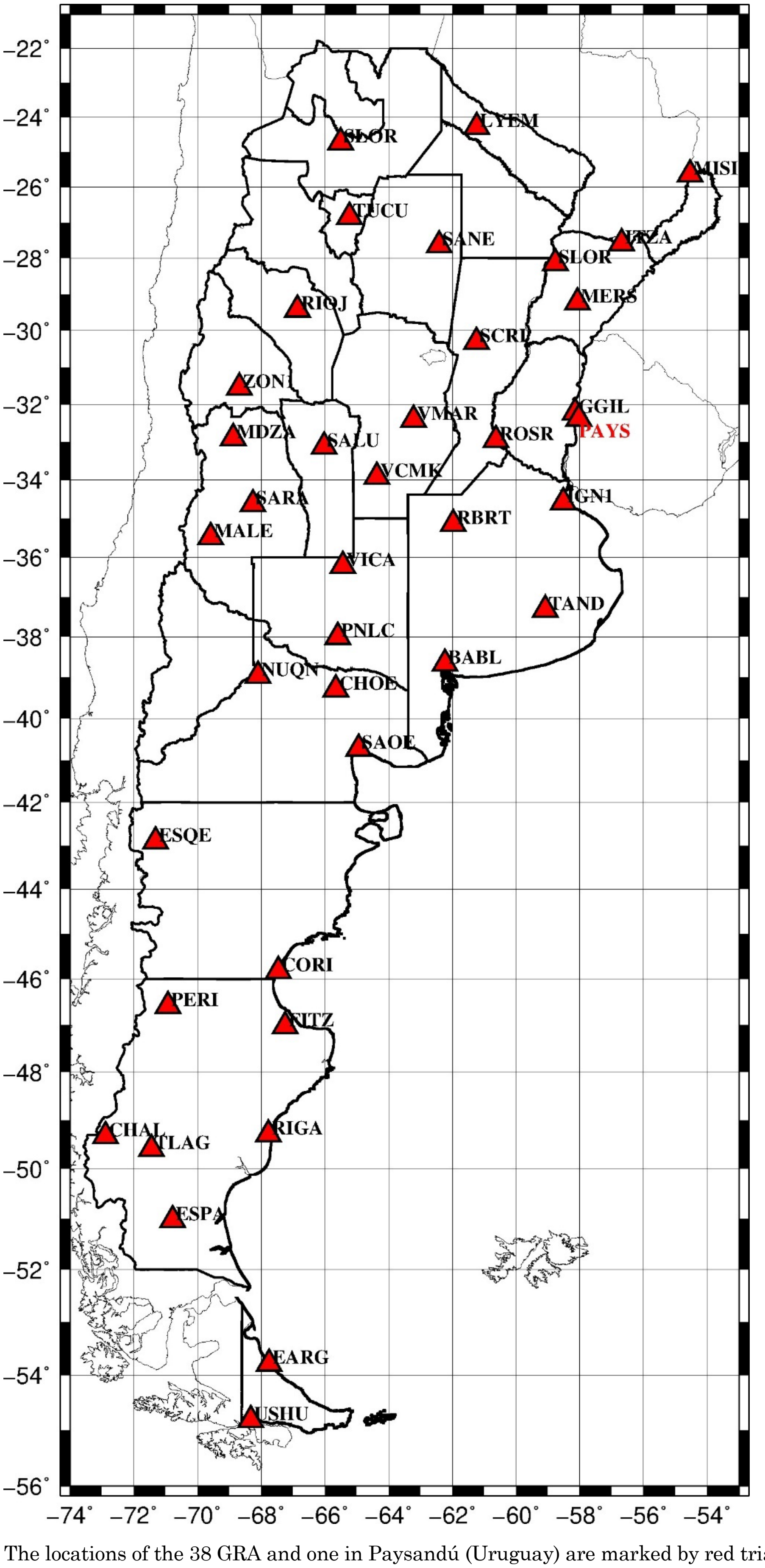


Figure 6: The locations of the 38 GRA and one in Paysandú (Uruguay) are marked by red triangles.

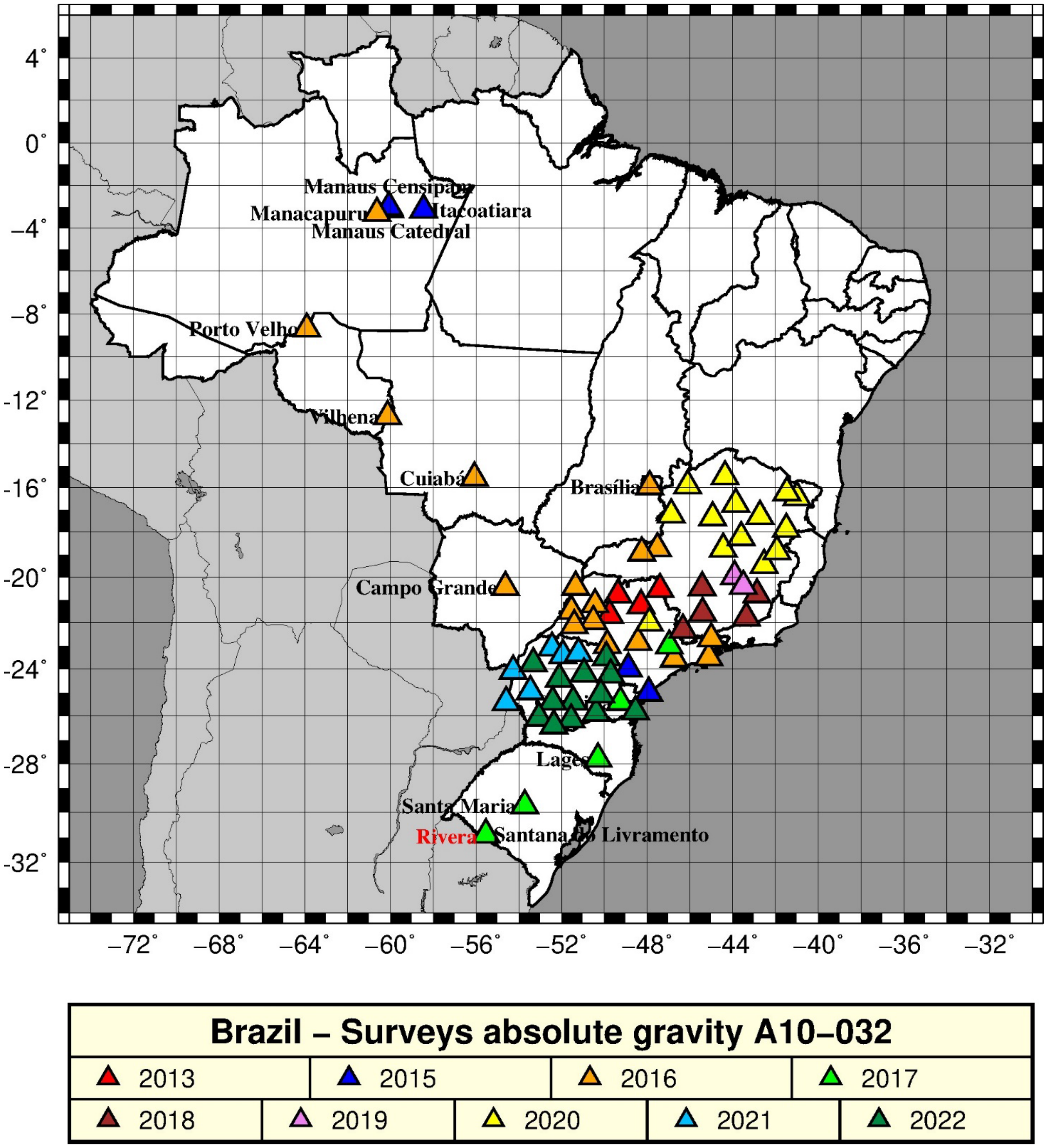


Figure 7: The locations of the 72 GRB and one in Rivera (Uruguay) are marked by the triangles.

Gravity References in Costa Rica (GRCR)

With the support of *Universidad de Costa Rica* (UCR) and the *Instituto Geográfico Nacional* (IGN/CR), a total of 18 GRCR were observed along the country (Figure 8).

Despite the high geophysical activity, improved locations for the benchmarks provided good results and very stable measurements. Great altitude differences were possible to be achieved in a few hours in the mountain region, serving as a good calibration line for relative measurements (Crossley et al., 2013). Quepos GR is designed to be the IHRF station and has a continuous operating GNSS station.

Gravity References in Ecuador (GRE)

With the support of the *Instituto Geográfico Militar* (IGM), the campaign was held in 2017 lasting for two months. A total of 26 GRE were measured abroad in the country with restrictions to the Amazon forest area, northeast part of the country, as shown in Figure 9. In Ecuador, there are five GRE close by GNSS continuous monitoring: San Lorenzo, Quito3, Tena, Rio Bamba and Libertad. Rio Bamba GR is designed to be the IHRF station.

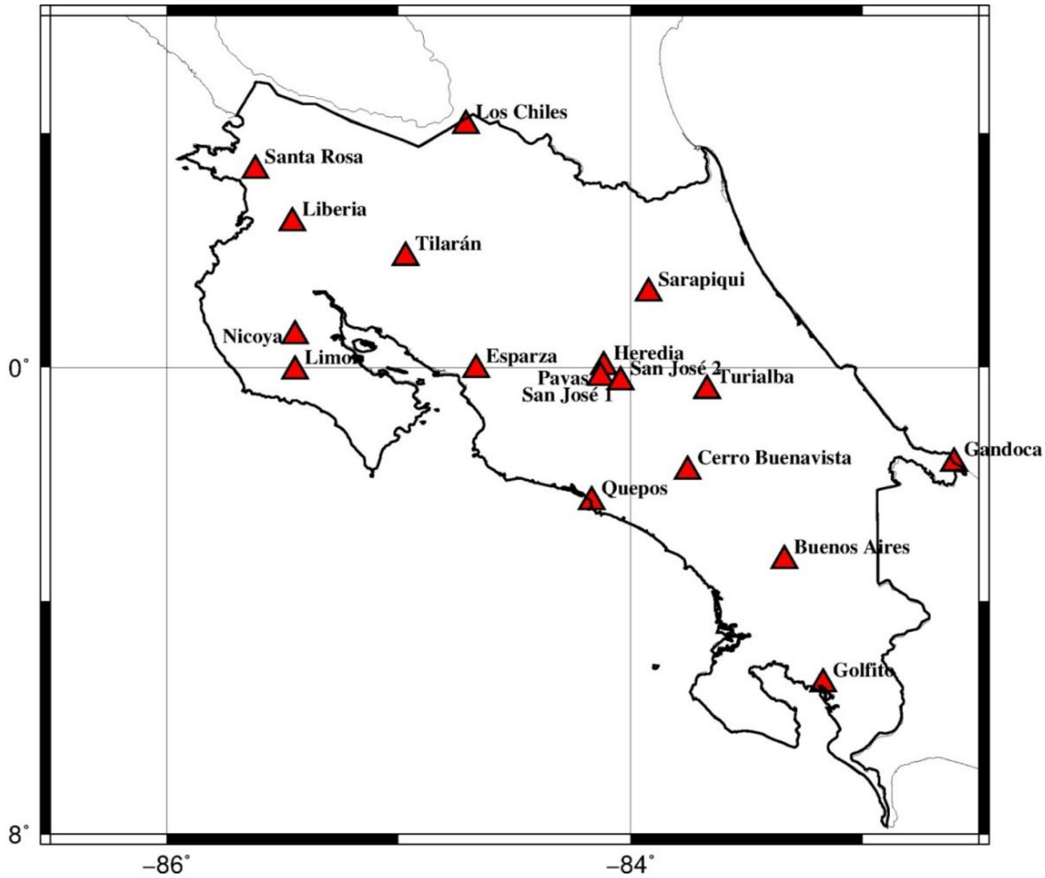


Figure 8: The locations of the 18 GRCR are marked by the red triangles.

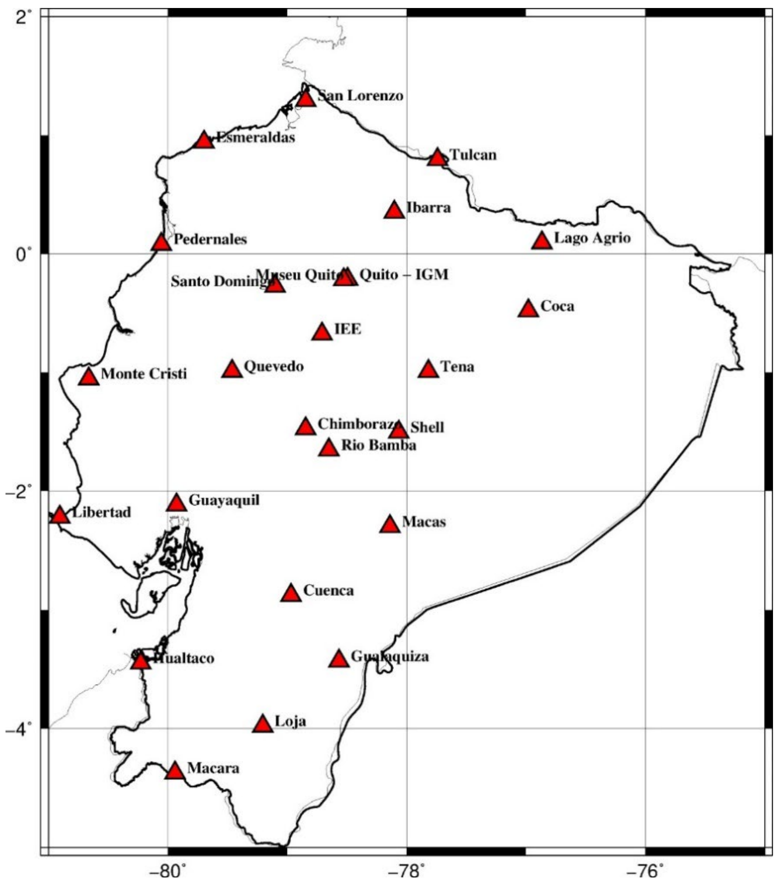


Figure 9: The locations of the 25 GRE are marked by the red triangles.

Gravity References in Venezuela (GRV)

The GRV was established during the years 2015 to 2016 with the support of *Instituto Geográfico de Venezuela Simón Bolívar* (IGVSB). The possibility of traveling to the border by car allowed measuring in several places along the way, but also represented a real logistic challenge when crossing the Amazon River basin. The stretch between Porto Velho and Manaus was performed on a ferry for one week in 2015 and 2016 (Figure 10). A total of 13 GRV were established in Venezuela with restrictions to the south part of the country with difficult access (Figure 11).

Figure 10: A10-032 at the ferry in Madeira River.

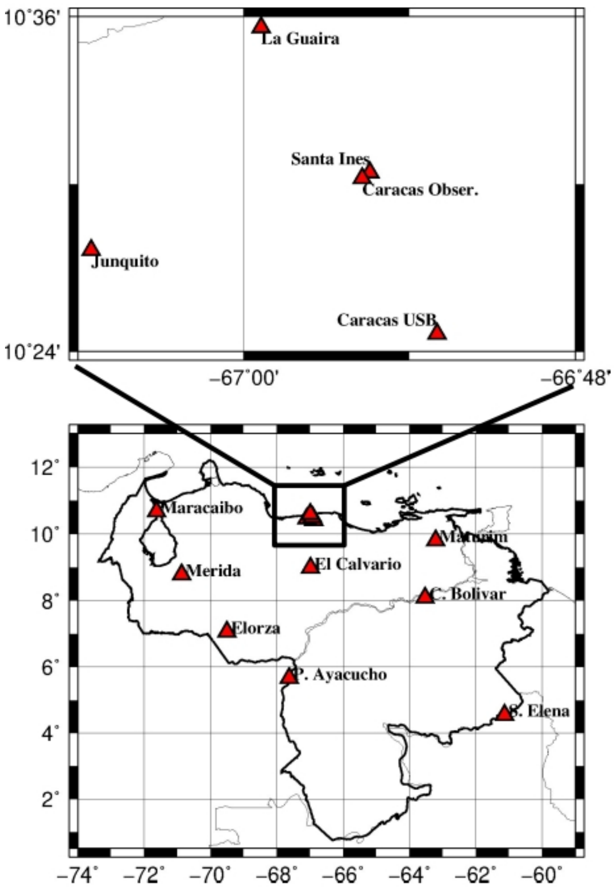


Figure 11: The locations of the 13 GRV are marked by the red triangles.

CONCLUSIONS

The establishment of absolute gravity observations is the basis for the realization of the ITGRF to support the IHRF, in addition to replace the IGSN-71. The agreement of the gravity value with other stations (for example, the successful measurement in TMGO) and the comparison of different absolute gravimeters certify the reliability of the A10-032, while the ITGRF did not define the standard for measurements to establish the metrological traceability of gravity measurement.

Additional efforts will be made to ensure the highest accuracy of the A10-032 through cross-equipment measurement. In this way, it is intended to take this equipment to the Argentinean–German Geodetic Observatory (AGGO) to make comparisons with the two high precision gravimeters (absolute FG-5 and superconductor) located in La Plata, Province of Buenos Aires, Argentina. AGGO is a Fundamental Geodesic Observatory located in South America that emerged from a joint initiative of the *Consejo Nacional de Investigaciones Científicas y Técnicas* (CONICET), Argentina, and the Federal Agency for Cartography and Geodesy (*Bundesamt für Kartographie und Geodäsie* - BKG), Germany. It brings together, in addition to the gravimeters mentioned above, other techniques of modern geodesy, such as a radio telescope for Very-Long-Baseline Interferometry (VLBI); a laser telescope for telemetry to artificial satellites, receivers of global navigation satellites systems (GNSS), atomic clocks (Cesium, Rubidium, and Hydronium MASER), seismographs, meteorological and hydrological sensors, etc. AGGO contributes to six international scientific services: International Earth Rotation and Reference Systems Service (IERS), the International VLBI Service (IVS) for Geodesy and Astrometry, Satellite Laser Ranging (SKR), the GNSS, the International Gravity Field Service (IGFS), and the International Bureau of Weights and Measures (BIPM); see https://www.aggo-conicet.gob.ar/observ.php.

In addition, continuing the efforts to establish gravimetric references in Latin America, an agreement was signed with the *Facultad de Ingeniería de la Universidad Nacional de Asunción* (FIUNA). It is intended to establish twenty gravimetric references in Paraguay. A preliminary campaign is already accomplished. A second effort will be undertaken in 2023. Other countries were contacted to establish the referred reference, such as the Dominican Republic and Uruguay.

Finally, it is intended to reobserve some of the established references to verify the temporal variation of the absolute gravity value, mainly in regions with large seismic events. In this way, it is intended to reobserve 10 gravimetric references in Chile in 2023.

Since 2013, CENEGEO has been working together with several institutions and established 169 gravimetric references in Latin America. It is worthy to emphasize that these activities require hard work. So, it had the participation of several technicians and researchers. In this context, part of the presented results is from three master's theses developed at the *Universidade de São Paulo* (Guerra Neto, 2020; Silva, 2020; Bjorkstrom, 2021) and a Ph.D. thesis of the UNR in Argentina (Lauría, 2017).

The Brazilian, Argentinian and Ecuadorian gravity references database is available on the CENEGEO website (https://www.cenegeo.com.br/rede-grav-absoluta), IGN (https://www.ign.gob.ar/NuestrasActividades/Geodesia/Gravimetria/RAGA) and IGM (https://www.geoportaligm.gob.ec/gravimetria/public), respectively. Another important gravity reference database site is AGRAV, maintained by BKG and *Bureau Gravimétrique International* (BGI). It is currently in the process of being updated (Wziontek et al., 2012).

ACKNOWLEDGMENTS

The authors would like to acknowledge Instituto Geográfico e Cartográfico do Estado de São Paulo/Brazil (IGC), Universidade Federal de Uberlândia/Brazil (UFU), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Instituto Água e Terra (IAT), Itaipu Binacional, Instituto Geográfico Nacional/Argentina (IGN), Universidad Nacional de Rosario/Argentina (UNR), Universidad Nacional de San Juan/Argentina (UNSJ), Universidad de Costa Rica/Costa Rica (UCR), Instituto Geográfico Nacional/Costa Rica (IGN), Instituto Geográfico Militar/Ecuador (IGM), Instituto Geográfico de Venezuela Simón Bolívar/Venezuela (IGVSB), and other organizations, universities and geographic institutes that allowed establishing an absolute station in their institutions. Absolute gravity measurements have an important role in the modernization and internationalization of a height reference frame.

REFERENCES

Bjorkstrom, I. M., 2021, Fundamentos da medição absoluta da aceleração de gravidade: contribuição ao estabelecimento de referências na América Latina (in English, Foundations of the absolute gravity measurements: a contribution for the establishment of references in Latin America): M.S. dissertation, Escola Politécnica, Universidade de São Paulo, SP, Brazil, doi: 10.11606/D.3.2021.tde-28072021-094331.

Cook, A. H., 1965, The Absolute Determination of the Acceleration Due to Gravity: Metrologia, **1**, 3, 84, doi: 10.1088/0026-1394/1/3/003.

Crossley, D., J. Hinderer, and U. Riccardi, 2013, The measurement of surface gravity: Rep. Prog. Phys., **76**, 4, 046101, doi: 10.1088/0034-4885/76/4/046101.

Drewes, H., F. Kuglitsch, J. Adám, and S. Rózsa, 2016, The Geodesist's Handbook 2016: J. Geod., **90**, 907–1205, doi: 10.1007/s00190-016-0948-z.

Guerra Neto, H. L., 2020, Implementação de referencial altimétrico: estudo de caso na usina hidrelétrica de Funil (in English, Implementation of altimetric reference: case study at the Funil hydroelectric power plant): M.Sc. dissertation, Escola Politécnica, Universidade de São Paulo, Brazil, doi: 10.11606/D.3.2020.tde-27032021-121124.

Ihde, J., L. Sánchez, R. Barzaghi, H. Drewes, C. Foerste, T. Gruber, G. Liebsch, U. Marti, R. Pail, and M. Sideris, 2017, Definition and Proposed Realization of the International Height Reference System (IHRS): Surv. Geophys., **38**, 3, 22 pp, doi: 10.1007/s10712-017-9409-3.

ISO - International Organization for Standardization, 1975, Standard Atmosphere, ISO 2533:1975: Available on: https://www.iso.org/obp/ui/#iso:std:iso:2533:en.

Lauría, E. A., 2017, Medición y cálculo de la Red Gravimétrica Nacional RED ARGENTINA DE GRAVEDAD ABSOLUTA (RAGA) (in English: Measurement and calculation of the National Gravimetric Network – ARGENTINE ABSOLUTE GRAVITY NETWORK (RAGA)): Ph.D. thesis, Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Available online: http://hdl.handle.net/2133/24536.

Marti, U., P. Richard, A. Germak, L. Vitushkin, and V. Pálinkáš, 2014, CCM-IAG Strategy for Metrology in Absolute Gravimetry: p. 1–8. Available online: https://www.bipm.org/documents/20126/41442296/CCM++IAG+Strategy+for+Metrology+in+Absolute+Gravimetry/7f9bc651-a2b6-08cc-7bba-f63b0a7e9765.

Micro-g LaCoste, 2008, A-10 Portable Gravimeter User's Manual: Available online: https://www.microglacoste.com/pdf/A-10Manual.pdf. 59 pp.

Micro-g LaCoste, 2012, g9 User's Manual: Available online: https://microglacoste.com/download/g9-users-manual. 53 pp.

Niebauer, T., 2015, Gravimetric Methods – Absolute and Relative Gravity Meter: Instruments Concepts and Implementation: Treatise on Geophysics, **3**, 37–57, doi: 10.1016/B978-0-444-53802-4.00057-9.

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

Silva, V. C., 2020, Sistema Gravimétrico de Referência do estado de São Paulo: contribuição ao referencial geodésico (in English, Gravity reference system of São Paulo: contribution to the geodetic reference.): M.S. dissertation, Escola Politécnica, Universidade de São Paulo, SP, Brazil, doi: 10.11606/D.3.2020.tde-05042021-153203.

Sneeuw, N., 2006, Physical Geodesy: Lecture Notes. Institute of Geodesy, Universität Stuttgart, 137 pp.

Torge, W., 1991, Geodesy. Berlin, Boston: De Gruyter. compl. rev. and ext. ed. 264 pp.

Torge, W., and J. Müller, 2012, Geodesy: Berlin, Boston, De Gruyter, 4th ed., 434 pp.

Tóth, G., 2017, IAG Newsletter: J. Geod., **91**, 1, 113–116, doi: 10.1007/s00190-016-0994-6.

Van Camp, M., 2003, Efficiency of tidal corrections on absolute gravity measurements at the Membach station, Proceedings of the Workshop IMG2002, **10**, 99–103. Available online: https://publi2-as.oma.be/record/1683/files/ECGS_22_Efficiency_Tides.pdf.

van Westrum, D., 2019, North American Regional Comparison of Absolute Gravimeters (NACAG18): NOAA Technical Memorandum NOS NGS 80), National Geodetic Survey, Available on: https://geodesy.noaa.gov/library/pdfs/NOAA_TM_NOS_NGS_0080.pdf

Wilmes, H., L. Vitushkin, V. Pálinkáš, R. Falk, H. Wziontek, and S. Bonvalot, 2016, Towards the Definition and Realization of a Global Absolute Gravity Reference System, *in* Freymueller, J.T., and Sánchez, L., eds, International Symposium on Earth and Environmental Sciences for Future Generations: International Association of Geodesy Symposia, **147**, 25–29. Springer, Cham.

Wziontek, H., H. Wilmes, and S. Bonvalot, 2012, AGrav: An International Database for Absolute Gravity Measurements, *in* Kenyon, S., M. Pacino, and U. Marti, eds., Geodesy for Planet Earth: International Association of Geodesy Symposia, **136**, Springer, Berlin, Heidelberg, doi: 10.1007/978-3-642-20338-1_130.10.1007/1345_2016_245.

Wziontek, H., S. Bonvalot, R. Falk, G. Gabalda, J. Mäkinen, V. Pálinkás, A. Rülke, and L. Vitushkin, 2021, Status of the International Gravity Reference System and Frame: J. Geod., **95**, 7, 9 pp, doi: 10.1007/s00190-020-01438-9.

Blitzkow, D.: responsible for the absolute gravimeter and all campaigns; performed the absolute gravity measurements; supervised all the surveys; aided in writing and editing the article; **Björkström, I. M. M.:** performed the absolute gravity measurements in Brazil, Costa Rica, Ecuador and Venezuela; processed the data in the g9 software; aided in writing the article; **Matos, A. C. O. C.:** responsible for analyzing the data collected and maintaining the database; aided in writing and editing the article; **Silva, V. C.:** processed the data in the g9 software; aided in writing the article; **Guimarães, G. N.:** performed the absolute gravity measurements in Argentina and Brazil; supervised and aided in writing and editing the article; **Fonseca Junior, E. S.:** managed the absolute gravimeter within the university.

Received on June 24, 2022 / Accepted on October 10, 2022