Metrological traceability for the absolute gravity Italian network

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ABSTRACT

The Absolute Gravity Italian Network project aims to update the Italian gravity network that nowadays is framed to IGSN71, established in 1971. The focal point of the project is to define a new reference for gravity with absolute gravity observations performed according to the international standardised methodology detailed in the document "CCM-IAG Strategy for Metrology in Absolute Gravimetry" (2015). IAG resolution No. 2 and subsequent, moreover establish the need to satisfy the metrological traceability also for Absolute Gravity measurements. This can be exploited by different methods such as reference sites, international comparisons of absolute gravimeters and calibration by comparison.

Measurements have been performed in appropriate sites distributed across the Italian country. The collected and validated data will be stored in an open database, as the absolute gravity database maintained by the Bureau Gravimétrique International/Bundesamt fuer Kartographie und Geodaesie when will be operative, contributing to feed the new International Terrestrial Gravity Reference System.

All the gravimeters used in the measurements participated to the international comparisons organised by CCM and/or EURAMET TC-M obtaining compatible results. However, in order to validate the results and to ensure traceability to the SI, additional comparisons between the absolute gravimeters used in the measurements have been performed just before the measurement campaign. The primary Italian reference instrument is the absolute gravimeter IMGC-02, developed and maintained by INRiM with an expanded measurement uncertainty of 8.5 μGal. The comparison sites are both located at INRiM and are provided with solid basements that guarantee good measurement repeatability and low floor noise which could ensure the final uncertainty. This paper shows the results of these measurements.

1. Introduction

The objective of the Absolute Gravity Italian Network project is to update and modernise the existing Italian gravity network, which is currently based on the outdated IGSN71 established in 1971 [1]. The primary focus of this project is to establish a new reference frame for gravity through the implementation of absolute gravity observations. These observations will be conducted in accordance with the internationally standardised methodology outlined in the document "CCM-IAG Strategy for Metrology in Absolute Gravimetry" (2015) [2]. Additionally, IAG resolution No. 2 in 2015 and subsequent resolutions in next years stipulate the necessity of maintaining metrological traceability for Absolute Gravity measurements. This can be achieved through a variety of means, including the use of reference sites, participation in international comparison of absolute gravimeters, and calibration by comparison.

1.1. State of the art

Gravity and physical heights are closely interconnected within the gravity potential of the Earth's gravity field, known as W(P). Therefore, it is crucial to approach the task of updating them from an integrated perspective [1]. Upon analysing the current state of gravity and physical heights in Italy, certain weaknesses have been identified, necessitating efforts to rationalise and modernise the methods and procedures used for updating the existing networks.

In Italy, absolute gravimetric measurements were first conducted in the 1970s with the development of the transportable ballistic absolute gravimeter by the Istituto di Metrologia "Gustavo Colonnetti" (IMGC) - CNR of Turin become, from 2006, Istituto Nazionale per la Ricerca Metrologica (INRiM). Currently, Italy is equipped with three new absolute ballistic gravimeters, namely 2 Micro-g LaCoste FG5 and 1 Micro-g LaCoste A10, which further support the gravimetric measurements.

The establishment of the first absolute sites in Italy occurred in 1977, with Turin, Rome, Naples, and Catania serving as reference stations for the Italian First Order Gravity Net (FOGN77) within a wider network of absolute gravity measurements in Europe. Subsequently, from 1981 to 2015, IMGC/INRiM collaborated with various Italian research institutions to establish numerous absolute gravity stations throughout the country. Many of these stations have been measured multiple times, utilising the newly available FG5 (ASI and ENI_INGV-OE) and A10 (INGV-OV) absolute gravimeters.

In 1995, most of these stations were selected to form the base network for the Italian Zero Order Gravity Network. However, no absolute value measurements were performed at that time.

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1.2. IAG resolutions

In 2015, the International Association of Geodesy (IAG) took significant steps by adopting two resolutions to address crucial aspects of global geodetic measurements:

a) IAG Resolution (No. 1) focused on defining and implementing an International Height Reference System (IHRS).
b) IAG Resolution (No. 2) aimed to establish a global absolute gravity reference system.

IAG Resolution No. 1 aimed to resolve the lack of coherence in the traditional orthometric height at a global scale. Normally, this vertical coordinate is referenced to the geoid, which is commonly assumed to align with the mean sea level. However, this assumption no longer holds true when considering the precision required in modern times, especially with GNSS technology. The discrepancy between the geoid and mean sea level can reach up to 1–2 m on a global scale, resulting in biased estimates of the geoid obtained from different tide gauges. Consequently, this inconsistency leads to incongruities in orthometric heights on a global scale. IAG Resolution No. 1 aims to tackle this challenge by proposing the establishment of the International Height Reference System (IHRS), a globally unified physical height system. The IHRS seeks to provide a standardised framework for vertical measurements across the globe. This system relies on estimating the gravity potential W(P) at a specific point P on the Earth's surface, utilising gravity data available near that point.

These resolutions mark significant milestones in the pursuit of accurate and standardised geodetic measurements on a global scale. The implementation of the International Height Reference System (IHRS) and the global absolute gravity reference system will undoubtedly contribute to advancing geodetic sciences and promoting consistency in height measurements worldwide.

IAG resolution No. 2 pertains to the establishment of a modern global gravity reference system, conforming to international standards. Currently, the absolute values measured in Italy is based on the outdated International Gravity Standardization Net (IGSN7), which was established in 1971. It is imperative that this obsolete network be replaced with a more up-to-date version. To achieve this, a new reference for gravity will be defined based on absolute gravity observations conducted using an internationally standardised methodology outlined in the document "CCM-IAG Strategy for Metrology in Absolute Gravimetry" (2015). The primary aim of this document is to establish procedures that ensure the traceability of gravity measurements to the International System of Units (SI).

The Absolute Gravity Italian Network project seeks to study and test procedures that will support the establishment of the new absolute gravity network and the IHRS/IHRF in Italy, in accordance with the IAG resolutions, contributing to the advancement of scientific knowledge.

2. Methods and procedures

To ensure traceability to the International System of Units (SI), some additional comparisons [2] have been conducted between absolute gravimeters participating in the project. The Italian primary absolute gravimeter IMGC-02, developed and maintained by INRiM, has an expanded uncertainty of 8.5 μGal. The comparison sites, both situated at INRiM, are equipped with solid basements to ensure excellent measurement repeatability and minimal ambient noise level, thereby enhancing the overall uncertainty of the measurements.

Two measurement sites were defined considering some characteristics such as:

- solid basement availability,
- vibration insulation,
- accessibility,
- previous data availability.

Table 1
Site #1 geodetical coordinates (ETRF2000).

Coordinates	E00-UTM32N	E00-geodetic
E	392 974.58 m	
N	4 985 624.37 m	
H	236.471 m	
Lat		45.0160°
Lon		7.6417°
h		285.57 m

Table 2
Site #2 geodetical coordinates (ETRF2000).

Coordinates	E00-UTM32N	E00-geodetic
E	392 954.95 m	
N	4 985 602.87 m	
H	239.26 m	
Lat		45.0158°
Lon		7.6415°
h		288.36 m

Table 3
Absolute gravimeters summary.

	IMGC-02	FG5-218	FG5-238
Type	Classical (macroscopic object)		
Mode	Rise and fall	Fall-only	
Launch rate	140 per hour	100 per hour	
Laser type	He-Ne iodine stabilised, red		
Standard uncertainty	5.0 μGal	2.0 μGal	2.0 μGal

2.1. Site #1

The first comparison site is located in the Gravity Laboratory of the INRiM facilities. The site has a marble basement 80 cm × 80 cm × 9 cm ($W \times L \times H$) fixed on a concrete pillar of dimensions 100 cm × 100 cm × 210 cm ($W \times L \times H$) and isolated from the rest of the structure to minimise the vibration transmission from external noise sources. The geodetical coordinates of the site are given in Table 1.

2.2. Site #2

The second site, located at the high force laboratory, has a concrete pillar of dimensions 264 cm × 294 cm × 80 cm ($W \times L \times H$) and isolated from the floor to minimise the vibration transmission from external activities. The geodetical coordinates of the site are given in Table 2.

2.3. Absolute gravimeters participating to the independent comparisons

The comparison measurements were performed with the transportable absolute gravimeter IMGC-02 [3] developed and maintained by INRiM and by two FG5 gravimeters [4], namely FG5-218 of ASI and FG5-238 of ENI_INGV-OE. The main data of the instruments are shown in Table 3.

The uncertainty related to the measurement of gravity acceleration (g) with the absolute gravimeters is assessed by combining the uncertainties arising from the instrument itself, defined as instrumental uncertainty, and the uncertainties associated with the observation site [3].

2.4. Traceability

National Metrology Institutes (NMIs) or Designated Institutes (DIs),

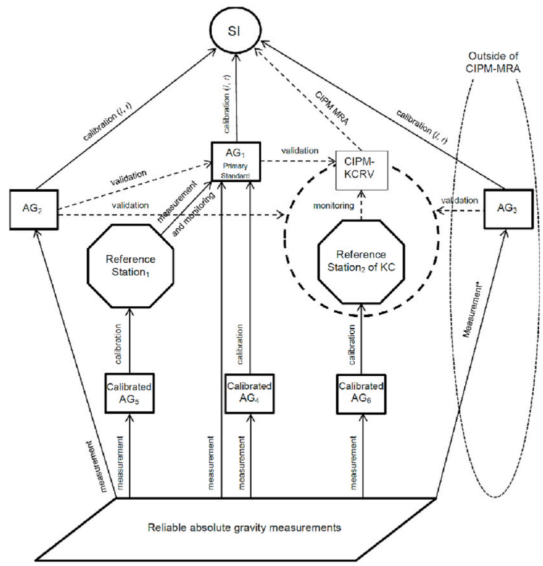

Fig. 1. Traceability chain as established by the "CCM-IAG Strategy for Metrology in Absolute Gravimetry" (2015) document for AG1 (IMGC-02) and AG3 (FG5s of ASI and ENI_INGV-OE).

which are recognised as primary standards, employ absolute gravimeters in Key Comparisons (KCs) such as CIPM KC, Regional KC, and Bilateral/Additional Comparisons. The calibration of absolute gravimeters used in field campaigns is then carried out through comparison, either against a reference gravimeter or against gravity values from reference stations. This measurement chain ensures that instruments with the highest standards of traceability are used. However, in this project, all absolute gravimeters (AGs) can provide measurements traceable to SI having participated to the international KCs or to the Additional Comparisons running simultaneously with KCs, considering that only IMGC-02 AG have contributing to establish the KCRV (Fig. 1).

The last Key Comparison which the IMGC-02 participated was the Regional Key Comparison EURAMET.M.G-K3 [5], organised in 2018 at the Geodetic Observatory in Wettzell (Germany). The last Additional Comparisons which the FG5s of ASI and ENI_INGV-OE participated were those running together to the International Key Comparison EURAMET.M.G-K3 and CCM.G-K2, organised in 2023 at the Table Mountain Geophysical Observatory (TMGO) in Boulder, Colorado, USA (ENI_INGV-OE only). The comparison results, shown in the final report [5], shows that only the FG5-238 has confirmed the declared uncertainty, but this was not true for FG5-218.

The absolute gravity observations will be carefully examined, taking into consideration the outcomes of the inter-comparisons described before. These observations will be adjusted to account for known effects, such as tides, in accordance with internationally recognised standards [6]. Additionally, the observations will be referenced to a specific height by utilising the measured gravity gradients at the observation sites. The topographic surveyed data will undergo a thorough examination to identify any potential outliers, and adjustments will be made to estimate the ITRF coordinates of the gravity stations.

2.5. Measurements sessions

For each site, two contemporary measurement sessions were carried out on the two sites (#1 and #2), then swapping the instruments on the successive night.

The measurements were performed during the night to minimise the anthropological noise effect on the results. Each session took about 12 hours (from late afternoon to the morning). The entire measurement session has been organised in two different periods according to the participant availability. The first session (A) was carried out in November 2023 and the second (B) in January 2024.

Table 4
Measurement session summary.

Absolute gravity values/m/s^2	Site #1	Site #2
Session A - 2023/11		
IMGC-02	9.805 343 391 (87)	9.805 338 166 (88)
FG5-218	9.805 343 317 (50)	9.805 338 096 (50)
E_n	−0.74	−0.69
Session B - 2024/01		
IMGC-02	9.805 343 182 (88)	9.805 337 981 (89)
FG5-238	9.805 343 229 (50)	9.805 338 026 (50)
E_n	0.47	0.44

Table 5
Variations on IMGC-02 acceleration value respect to the previous values.

	Site #1	Site #2
Previous values/m/s^2	9.805 342 010 (85)	9.805 336 636 (85)
Differences/m/s^2		
Session A	-0.35×10^{-8}	$+3.90 \times 10^{-8}$
Session B	-18.80×10^{-8}	-14.57×10^{-8}

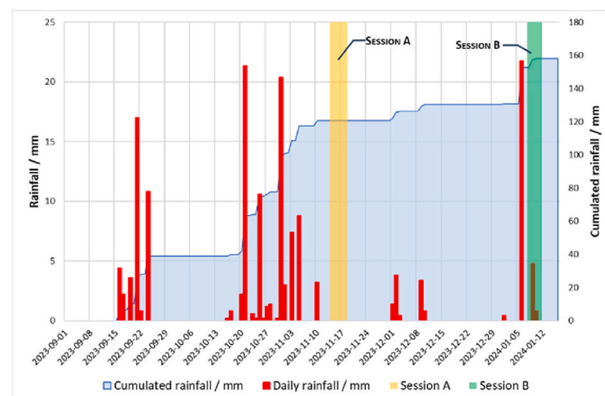

Fig. 2. Daily and cumulated rainfall in Torino Vallere ARPA station [8].

2.6. Data analysis

Raw results of the measurement sessions were independently post-processed from participants considering corrections for Earth tides, polar motion and atmosphere.

For each value were computed the normalised error (E_n), considering IMGC-02 as reference since it was the only lab that participated to both sessions, and the difference with the previous reference value of the site.

3. Results and discussion

The results obtained on both measurement sites, referred to ground, are shown in Table 4, with the associated expanded uncertainties (U) expressed with a confidence level of 95 %.

The differences found for each session between two participants are compatible with the declared uncertainties ($-1 < E_n < 1$). However, it is noted that from results in Table 4 and results at comparison [5] one can assume that FG5-218 is still biased and therefore its measurements should be associated by bigger uncertainty. Another evidence pointed out by the results of the measurements of session B, focused a difference between −15 μGal and −19 μGal respect to the previous values of the site, for both absolute gravimeters and for both comparison sites as shown in Table 5.

This can suggest a hydrological effect [7] due to the change of groundwater level, which in that period was reduced due to a prolonged absence of rainfall as can be deduced from Fig. 2. The total cumulated rainfall between the two sessions was of only 37.6 mm that is about one third of the cumulated rainfall (120.6 mm) referred to the same period of time prior to the session A.

4. Conclusions

The two independent comparison sessions pointed out that the FG5's measurements, on the basis of the $E_n < 1$, are compatible with the results obtained with the IMGC-02. This will ensure that all the measurements provided in the Absolute Gravity Italian Network project will be compatible and traceable, contributing to the advancement of scientific knowledge. Regarding to the absolute gravimeter FG5-218, although the results of the last key comparison in which it participated were not satisfactory at the declared uncertainties levels, the overall traceability is nevertheless confirmed by this independent comparison by the presence of the other absolute gravimeters that performed successfully the Key and Additional Comparisons [5,6].

The results obtained by this independent comparison and the compatibility of the measurements with the IMGC-02 that has higher uncertainties level, suggests further analysis on the causes that introduced higher uncertainties levels for FG5-218.

Further analysis will be focused on the study of the hydrological effects [7,9] on gravity acceleration. However, our preliminary analysis suggest that it is useful to take into account also time-dependent factors when comparing previous measurement of a site [7,10].

Other studies will be conducted to improve the mechanical and optical systems of gravimeter in order to minimise the effects of retroreflector unbalancing and the distance of optical and mass centre [11,12] and other uncertainty factors such as diffraction [13]. The last steps will be concentrated on the development of a new smaller and cheaper transportable gravimeter [14].

Acknowledgments

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References

[1] H. Wziontek, S. Bonvalot, R. Falk, G. Gabalda, J. Mäkinen, Status of the international gravity reference system and frame, J. Geodesy 95 (7) (2021), https://doi.org/10.1007/s00190-020-01438-9.

[2] U. Marti, P. Richard, A. Germak, L. Vitushkin, V. Pálinkáš, H. Wilmes, CCM-IAG Strategy for Metrology in Absolute Gravimetry, BIPM, 2014. https://www.bipm.org/en/committees/cc/ccm/publications.

[3] G. D'Agostino, S. Desogus, A. Germak, C. Origlia, D. Quagliotti, The new IMGC-02 transportable absolute gravimeter: measurement apparatus and applications in geophysics and volcanology, Ann. Geophys. 51 (2008), https://doi.org/10.4401/ag-3038.

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

[5] R. Falk, V. Pálinkáš, H. Wziontek, A. Rülke, M. Vaľko, et al., EURAMET.M.G-K3 Final Report, BIPM, 2020. Online, https://www.bipm.org/documents/20126/48150869/EURAMET.M.G-K3.pdf/2ac2ba0b-5f7b-8c05-b158-193b03b438df. (Accessed 6 February 2024).

[6] H. Wziontek, R. Falk, V. Pálinkáš, A. Engfeldt, J. Glässel, Comparisons of absolute gravimeters as a key component of the international terrestrial gravity reference frame (ITGRF) shown on the example of the WET-CAG2021 at Wettzell, Germany, in: International Association of Geodesy Symposia, Springer, Berlin, Heidelberg, 2023, https://doi.org/10.1007/1345_2023_226.

[7] V. Pálinkáš, M. Lederer, J. Kostelecký, J. Šimek, M. Mojzeš, Analysis of the repeated absolute gravity measurements in the Czech Republic, Slovakia and Hungary from the period 1991–2010 considering instrumental and hydrological effects, J. Geodyn. 87 (2013) 29–42, https://doi.org/10.1007/s00190-012-0576-1.

[8] Dati meteoidrografici giornalieri - Richiesta automatica, Arpa piemonte, Online, https://www.arpa.piemonte.it/dati-ambientali/dati-meteoidrografici-giornalieri-richiesta-automatica, 2024. (Accessed 13 February 2024).

[9] H. Sarkar, S.S. Goriwale, J.K. Ghosh, C.S.P. Ojha, S.K. Ghosh, Potential of machine learning algorithms in groundwater level prediction using temporal gravity data, Ground. For Sust. Dev. 25 (2024), https://doi.org/10.1016/j.gsd.2024.101114.

[10] J.P. Boy, P. Gegout, J. Hinderer, Reduction of surface gravity data from global atmospheric pressure loading, Geophys. J. Int. 149 (2) (2002) 534–545, https://doi.org/10.1046/j.1365-246X.2002.01667.x.

[11] Y. Yu, X. Hu, Q.-Y. Wang, S.-Q. Wu, J.-Y. Feng, Precisely measure the distance between the falling body's mass center and its optical center for absolute gravimeters, Acta Metrol. Sin. 41 (7) (2020) 830–834, https://doi.org/10.3969/j.issn.1000-1158.2020.07.10.

[12] T.M. Niebauer, A. Constantino, R. Billson, A. Hankla, P.G. Nelson, Balancing a retroreflector to minimize rotation errors using a pendulum and quadrature interferometer, Appl. Opt. 54 (18) (2015) 5750–5758, https://doi.org/10.1364/AO.54.005750.

[13] D.V. Westrum, T.M. Niebauer, The diffraction correction for absolute gravimeters, Metrologia 40 (5) (2003), https://doi.org/10.1088/0026-1394/40/5/008.

[14] C. Rothleitner, S. Svitlov, H. Mérimèche, H. Hu, L.J. Wang, Development of new free-fall absolute gravimeters, Metrologia 46 (3) (2009) 283–297, https://doi.org/10.1088/0026-1394/46/3/017.

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