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Abstract:	A detailed comparison of the performances of two absolute gravimeters at three different sites in Italy between 2009 and 2011 is presented. The measurements of the gravity acceleration g were performed using the absolute gravimeters Micro-g LaCoste FG5#238 and the INRiM prototype IMGC-02, which represent the state of the art in ballistic gravimeter technology (relative uncertainty of a few parts in 109). For the comparison, the measured g values were reported at the same height by means of the vertical gravity gradient estimated at each site with relative gravimeters. The consistency and reliability of the gravity observations, as well as the performance and efficiency of the instruments, were assessed by measurements made inside dedicated and non-dedicated infrastructures characterized by different logistics and environmental conditions. Furthermore, the various factors affecting the measurements and their uncertainty were thoroughly investigated. The measurements showed good agreement, with the minimum and maximum differences being -4.0 and 8.3 μGal. The normalized errors are very much lower than 1, ranging between 0.06 and 0.45, confirming the compatibility between the results. This is an excellent agreement and can be attributed to several factors, including the good working order of gravimeters and the correct setup and use of the instruments in different conditions. These results can contribute to the standardization of absolute gravity surveys largely for applications in geophysics, volcanology and other branches of geosciences, allowing achieving a good trade-off between uncertainty and efficiency of gravity measurements.

Absolute gravity measurements at three sites characterized by different environmental conditions using two portable ballistic gravimeters

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Abstract

A detailed comparison of the performances of two absolute gravimeters at three different sites in Italy between 2009 and 2011 is presented. The measurements of the gravity acceleration *g* were performed using the absolute gravimeters Micro-g LaCoste FG5#238 and the INRiM prototype IMGC-02, which represent the state of the art in ballistic gravimeter technology (relative uncertainty of a few parts in 10^9). For the comparison, the measured *g* values were reported at the same height by means of the vertical gravity gradient estimated at each site with relative gravimeters. The consistency and reliability of the gravity observations, as well as the performance and efficiency of the instruments, were assessed by measurements made inside dedicated and non-dedicated infrastructures characterized by different logistics and environmental conditions. Furthermore, the various factors affecting the measurements and their uncertainty were thoroughly investigated. The measurements showed good agreement, with the minimum and maximum differences being -4.0 and 8.3 μGal. The normalized errors are very much lower than 1, ranging between 0.06 and 0.45, confirming the compatibility between the results. This is an excellent agreement and can be attributed to several factors, including the good working order of gravimeters and the correct setup and use of the instruments in different conditions. These results can contribute to the standardization of absolute gravity surveys largely for applications in geophysics, volcanology and other branches of geosciences, allowing achieving a good trade-off between uncertainty and efficiency of gravity measurements.

Keywords: absolute gravimeter, gravity acceleration, comparison of absolute gravimeters.

1. Introduction

Portable absolute gravimeters are essential to carry out accurate gravity measurements. The robustness and transportability of modern absolute gravimeters also enable them to be used in the field, allowing combinations with conventional relative gravimeters in a hybrid approach [1,2,3]. In volcanic areas, the use of field-usable absolute gravimeters allows optimizing traditional techniques of relative gravity measurements, ensuring improvement in data quality [4,5].

Since 2007, the Istituto Nazionale di Geofisica e Vulcanologia has been carrying out absolute gravity measurements to monitor the Mt. Etna volcano, one of the most active and hazardous volcanoes in the world. To this end, we introduced two transportable absolute gravimeters, both state of the art in ballistic gravimeter technology: the FG5#238, a commercial instrument made by Micro-g LaCoste Inc. and the IMGC-02, a prototype developed in Italy by the Istituto Nazionale di Ricerca Metrologica (INRiM). The IMGC-02 is recognized as a national primary standard in Italy [6] and the FG5 is more commonly employed for absolute gravity studies while, specifically, the FG5#238 gravimeter is normally used for different applications ranging from volcano monitoring [5] to the study of gas storage areas [7].

Absolute gravimeters are often compared for the purpose of assuring their good working order, but also to test the capability of the operators to provide values with the associated uncertainty that are consistent with other operators. Comparisons are also essential for long-term absolute measurements in geophysics to insure the consistency of the observations over a time period of decades [8].

The main goal of this work is to investigate the behaviour of the FG5#238 and IMGC-02 gravimeters, never before used together on field. Then, in keeping with previous works [9,10], the innovative aspect is the measurement and the possibility of achieving a standardization of absolute gravity surveys in areas where logistics are unfavourable, optimizing quality of the measurements and minimizing resources. To address this issue, we take advantage of several test measurements conducted both indoors and in the field to analyze the behaviors of both gravimeters under different conditions. At the same time, in order to achieve a trade-off between uncertainty and efficiency of gravity measurements, we tested different measurement procedures and different setups.

The comparison between the two absolute gravimeters was conducted at three different sites in Italy (Table 1; Fig. 1): two of them are dedicated laboratories and the third is a geophysical point of interest with harsh environmental conditions (low temperature, high humidity, high vibration, etc.). The selected sites are:

1. *Gravity Laboratory of Istituto Nazionale di Geofisica e Vulcanologia (INGV) at Catania (CTA).* This site is normally used as the reference for the Etna gravity monitoring network. The gravity field here may be considered unaffected by volcano-induced gravity anomalies. Furthermore the FG5#238 is maintained and tested here.

2. *Serra la Nave gravity station at Mt. Etna volcano (SLN).* This site is one of the absolute monitoring stations at Etna and is characterized by the typically difficulties encountered in a very hard environment such as on an active volcano.
3. *Gravity Laboratory of INRiM at Turin (TRN).* At this site the IMGC-02 is regularly maintained, tested and improved.

The two instruments used, FG5#238 and IMGC-02 gravimeters, were included in the International and European Comparisons of Absolute Gravimeters (ICAG 2005 – 2009 and ECAG 2011; Fig. 1) [11,12,13]. The good results achieved during these events ensure the traceability of measurements to the SI units, as requested by the new strategy document developed by CCM and IAG [14].

2. Instruments, field experiment measurements, uncertainties and vertical gravity gradient

2.1. Two transportable absolute gravimeters

The two instruments used in this study measure the absolute *g* value through the reconstructed trajectory of a corner-cube prism, subjected to the gravity field, which moves vertically in a vacuum chamber. The IMGC-02 measures both the rise and fall motions of the flying object, while the FG5 instrument measures the acceleration during free-fall motion only. A laser interferometer measures the distance between the free falling corner cube test mass and a second retroreflector mounted on the quasi-inertial mass of a vibration isolation system, namely a seismometer for IMGC-02 and a super-spring system for the FG5 [6,15].

For the FG5, a total of 700 time-position points are recorded over the 20 cm length of each drop. Drops can be produced up to every two seconds but during routine operation, the drops are repeated every 10 s. Typically, the average of 50 or 100 drops is a "set". The FG5 measurements consist of one set per hour with the average of several sets (usually 12 to 48) providing a resultant "gravity value". The instrumental accuracy of the FG5 is about 1–2 μGal as reported by the manufacturer [15]; the precision is time-dependent and it is given by the drop-drop scatter (single drop scatter) divided by the square-root of the number of drops. A precision of 1 μGal (usually much better; largely depends on the site) can be achieved within an hour at most sites if the FG5 is running continuously.

Regarding the IMGC-02, in laboratory conditions, one observation session typically lasts 12 hours and consists of about 1500 launches. It corresponds to an experimental standard deviation of the population of measurement results equal to 35 μGal and an associated standard deviation of the mean value lower than 1 μGal. Instead, when the instrument is operating in noisy environmental conditions, an observation session with an experimental standard deviation of the population of measurement results equal to

50 μGal, about 2500 launches are needed to reach a standard deviation of the mean value equal to 1 μGal. But, to reach standard deviation twofold smaller than the above reported experimental value, the number of launches should be quadrupled.

For both instruments, the final gravity value is obtained after applying correction for Earth tides, ocean loading, local atmospheric effects (using single admittance of -0.3 μGal/hPa due to loading and mass attraction and local air pressure record) and polar-motion effects. Since the measurements with both instruments were carried out in a short time interval and roughly in the same meteorological conditions, the hydrological effects have been disregarded.

2.2. Field experiment Measurements

Due to the logistical difficulties on Mt Etna, the arrangement of the absolute stations mainly depends on the availability of suitable structures to protect the instrumentation. The quality of gravity measurements gathered with transportable absolute gravimeters is further influenced by numerous factors, such as performance of the instruments themselves, quality of the site, ability of the operator to set up the instrument correctly, weather conditions, etc. In general, with the absolute gravimeters, after a sufficient amount of averaging, a limit is reached where precision will still increase though the uncertainty will not improve because of the intrinsic accuracy of the instruments. By averaging long enough data in any one spot all of the instruments should have a similar uncertainty. Taking account of this latter aspect, we tested different measurement procedures to reduce the acquisition time to a few hours, allowing balancing the accuracy and precision of gravity measurements. Specifically, we tried to: (a) increase the frequency of measurements by reducing the interval between sets; (b) reduce both the number of drops for each set and the drop interval; (c) reduce the number of sets; (d) collect measurements during both day and night. The tests carried out using the FG5 have shown that the set scatter and the *g* values are still comparable with those obtained through standard procedure and the results may be considered reliable. For the IMGC-02, low uncertainty levels like those achieved with the FG5 are reached after an observation session lasting about 12 hours. Comparable results in terms of reproducibility and uncertainty are also obtained using the instruments during daylight hours.

Measurement reproducibility is defined by the International Vocabulary of Metrology (VIM) [16] as precision under reproducibility conditions; where reproducibility condition means out of a set of conditions that includes different locations, operators, measuring systems and repeated measurements on the same or similar objects.

As a rule, at Mt Etna, to prevent negative effects in field measurements performed in harsh and noisy environments, it was necessary to use additional equipment in some measurement sessions, such as: i) a tent to protect the instruments against the humidity, low temperature etc.; ii) a heater to heat the room where the instruments were installed; iii) an electric generator in sites not supplied with electricity and iv) a continuous and precise realignment of the laser beam, equipped the FG5, in the higher altitude sites to achieve reliable measurements [17].

Finally, operating these gravimeters in different conditions has proved a useful test to improve the operators ability to manage the instruments, to find optimal strategies in different environments and lastly to ensure high quality in the data collection.

2.3. Uncertainty evaluation

The evaluation of measurement uncertainty was carried out in accordance with the GUM [18] and the terminology is used in agreement with the VIM [19]. The uncertainty associated with the g measurement, u_{comb}, takes into account the contributions of (i) the instrumental uncertainties, u_{inst}, whose most important influence factors are: vacuum level, non-uniform magnetic field, temperature gradient, electrostatic attraction, self-attraction effect, laser beam verticality and divergence, overall drift due to misalignment of the instrument, air gap modulation, length and time standards, retro-reflector balancing and reference height; (ii) the contribution of uncertainty depending on the observation site, u_{site}, whose main influence factors are: Coriolis force, floor recoil, and geophysical effects, such as local barometric pressure, gravity tides, ocean loading, and polar motion, and (iii) the scattering of measurements, u_{mean}, estimated with the experimental standard deviation of the mean g value; this value is heavily dependent on the ground vibrations and the floor recoil.

Combining the standard deviation of the free-fall acceleration value, due to the scattering, with the instrumental uncertainty and site-dependent influence factors, we calculated the combined standard uncertainty and the expanded uncertainty (at the 95% confidence level) related to the measurements acquired with both gravimeters. The same approach was used for the uncertainty evaluation in the International Gravity Comparisons [11,12].

Considering all the contributions to the uncertainty, the minimum achievable combined uncertainties, as used in the International Comparisons, are 2.6 μGal and 4.3 μGal, respectively for FG5 and IMGC-02 [12]. However, the uncertainty of both instruments increases up to 10-15 μGal at sites affected by almost continuous ground vibrations such as those existing a few hundred meters away from the constantly active summit craters of Etna volcano [5,17].

2.4. Vertical gravity gradient determination

Due to different instrument design of the FG5#238 and the IMGC-02, their measured g-values refer to about 1.3 m and about 0.5 m from the ground, respectively. The FG5#238 specific factory height is equal to 1.1637 m plus the upper and lower set up heights sum; the IMGC-02 specific height is evaluated combining all measurement heights of each single trajectory. Therefore, to compare the values reported by the two different instruments (actual height) we referred all the measurement values to a common height of 0.5 m (transfer height) using vertical gravity gradients. We determined the gradients at each absolute station using two Scintrex relative gravimeters (CG-3M#9310234 and CG-5#08064041). Finally, the vertical gradient values are used to reduce the gravity values from the "actual height" to the "transfer height".

The vertical gravity gradient γ was estimated by measuring the gravity change at four different levels from the ground, which roughly correspond to the following heights: h_0 = 30 cm, h_1 = 60 cm, h_2 = 90 cm and h_3 = 120 cm (Fig. 3). Since those values are less than the reference height of the FG5#238, the effect of the extrapolation was estimated using Montecarlo simulations [20].

The measurements were executed using the step method, in which adjacent elevations were connected at least three times. After the correction for the Earth tide, γ was obtained by fitting the following equation model to the experimental data, i.e. the collected g value and the acquisition time t:

$$g = \gamma \cdot h + \alpha \cdot t + k$$

where the parameters γ, h, α, k are the vertical gravity gradient, the level from the floor, the instrumental drift, and the gravity offset, respectively. For each site, the residuals between fit function and data do not show any parabolic shape, indicating that a second degree polynomial fit is not preferable (Fig. 3).

The vertical gravity gradients range from station to station from -273.6 to -335.0 μGal/m. Standard uncertainties of 6.1 μGal/m, 5.2 μGal/m, and 4.2 μGal/m were evaluated for the vertical gravity gradient at CTA, SLN, and TRN stations, respectively, measured in 2009 and 2011. Such values were increased to 9.2 μGal/m, 7.6 μGal/m and 6.2 μGal/m, respectively, to consider the contribution of the extrapolation error (Table 1). We are aware that any measurement errors in the vertical gravity gradients will have a negligible effect on the IMGC-02 final results (because the top of the drop is within few centimetres of the chosen transfer height of 0.5 m); conversely the effect will be higher on the FG5#238 final results owing to the transfer from the top of the drop height of about 1.3 m to the transfer height of 0.5 m.

We used the following equation to refer a measurement result $g(h_m)$ collected at a level h_m from the floor to a level h:

$$g(h) = g(h_m) + \gamma \cdot (h - h_m)$$

The final combined uncertainty $u_g(h)$ (Table 2) at the level h is calculated by combining the uncertainty of the measurement u_{comb} and the uncertainty of the vertical gravity gradient u_γ to transfer properly measured gravity from the measurement level h_m to an arbitrary reference level h:

$$u_g(h) = \sqrt{(u_{comb})^2 + (h - h_m)^2 \cdot u_\gamma^2}$$

Therefore, the uncertainty due to the height of measurements h_m (normally 0.5 – 1 mm) can be considered negligible.

3. Measurements

Absolute gravity measurements were carried out in July 2009 at the Gravity Laboratory of INGV (CTA) in Catania and at the absolute gravity station of Serra La Nave (SLN) on Etna volcano, and in November 2011 at the Metrology Laboratory of INRiM (TRN) in Turin (Tab. 1; Fig 1).

Concerning the FG5#238 gravimeter, typically, each data set was acquired with 50 or 100 drops. On every single data set the standard deviation σ has been calculated, rejecting any drop outside the 3σ range.

For the IMGC-02 gravimeter, the gravity values are filtered by applying rejecting criteria. The most critical factor is the visibility variation of the interference signal recorded along the rise-and-fall trajectory. It highlights a horizontal motion of the test-body due to parasitic forces in the launch phase [21]. The effect due to the Coriolis force and the beam share are minimized by rejecting the launches that exhibit a decrease of visibility bigger than 10%. Outliers are found by applying the Chauvenet criterion [22,23] to the collected g values and other estimating parameters such as the vertical gradient and the friction of residual air.

Considering the state-of-the-art of gravimetry measurements [11,12,13], data have been corrected for diffraction effect, caused by the inherent curvature of the laser wave front and for the self-attraction-effect, due to the masses of the single parts that make up the different gravimeters [24].

Lastly, to confirm the compatibility between the measurement results, we calculated for each site the normalized error [25,26] variable as follows:

$$E_n = \frac{g_{FG5\#238} - g_{IMGC-02}}{\sqrt{(U_{FG5\#238}^2 + U_{IMGC-02}^2)}}$$

where U represents the expanded uncertainty at the 95% confidence level.

When uncertainties are estimated in a way consistent with the Guide to the expression of uncertainty in measurement (GUM), E_n number expresses the validity of the expanded uncertainty estimate associated with each result. A value of $|E_n| < 1$ provides objective evidence that the estimate of uncertainty is consistent with the definition of expanded uncertainty given in the GUM and that the two different measurements are compatible and justified from their uncertainties.

3.1. Gravity Laboratory in Catania (CTA)

The absolute gravity station of Catania (CTA; Table 1) is located at the underground Gravity Laboratory of the INGV. The instruments can be placed on a suitable concrete pillar, insulated from the building. During the day the vibrations induced by noise from human activity are significant but still acceptable. An observation session lasting 12 hours is sufficient to reach a satisfactory uncertainty. The measurements with the FG5#238 were carried out from 3 to 5 July 2009, during the week-end when the noise is minimal. The environmental parameters during the measurement sessions were sufficiently stable. The ambient temperature varied from 33.5 °C to 34.5 °C and the local pressure changed from 1008.0 mbar to 1006.0 mbar. A total of 40 sets, each including 100 drops, were acquired, in about 39 hours. The dispersion between the drops acquired was about ± 20 μGal, while the dispersion between the data sets was less than ± 10 μGal. All data passed the selection criteria (see Section 3), hence there was no need to eliminate any set of measurements (see Table 2 for the results). It is important to also note that, among all data collected, the same result is achieved by considering only a limited number of sets (3-5).

With the IMGC-02 gravimeter, the measurements were carried on from 8 to 9 July 2009 [27]. The measurements were taken at night. During the measurements session the environmental parameters were stable, the maximum variations of the temperature were between 30.0 °C and 32.0 °C. The pressure varied between 1008.0 mbar and 1010.4 mbar. A total of 1337 drops were processed and stored. The apparatus experienced a scatter of about ± 15 μGal and averaged trajectory residuals within $\pm 1 \times 10^{-9}$ m. The final g value and associated standard deviation were obtained by averaging 477 drops (see Table 2 for the results).

3.2. Gravity station at Mt. Etna (SLN)

The observation station of Mt. Etna (SLN; Table 1) is located at Serra La Nave site, about 6 km from the summit craters, in a bunker in the grounds of the Astrophysical Observatory and is part of the Etna gravity monitoring network [5,28,29,30,31]. There is a large stable concrete pillar inside the bunker where the instruments can be installed (Fig. 2). Human noise is practically absent and ground vibrations, such as those accompanying the explosive activity of the volcano [32], were not present. To do the measurements in this site we have made the most of the experience gained in other hostile sites for absolute gravity measurements at Etna [5,17]. The high ambient humidity and low temperature were mitigated using an electric heater kept on during the measurements; a tent was needed to reduce the space to be heated.

With the FG5#238 gravimeter, from 10 to 11 July 2009, in about 19 hours (most during the night), we acquired in all 33 sets, 100 drops each. The mean value of the ambient temperature was 25.0 °C with variations within 0.5 °C, the mean value of the local pressure was 830 mbar with variations of 0.15 mbar, while the humidity was about 60%. The dispersion between the drops acquired was about ± 20 μGal (only a few sets showed a higher dispersion), while the dispersion between the set was less than ± 10 μGal. The first three sets of measurements were rejected (see Table 2 for the results). Measurements acquired during daylight hours, when the time interval between sets was also reduced, exhibited the same characteristic as those acquired during the night. This confirms that with proper and careful setup, the FG5 could provide accurate and reliable results at different conditions and even in short acquisition times.

Gravity data with the IMGC-02 gravimeter were collected on 9-10 July 2009, during the night. The environmental parameters were fairly stable: temperature changes between 38.0 °C and 40.3 °C were recorded; air pressure values, from 829.5 mbar to 831.4 mbar, were observed. A total of 1462 drops were processed and stored. A scatter of about ± 10 μGal was found in the collected data and averaged trajectory residuals within ± 1 x 10^{-9} m were estimated. The final *g* value and the associated standard deviation were achieved by averaging 372 drops (see Table 2 for the results).

3.3. GRAVITY LABORATORY IN TURIN (TRN)

The absolute gravity station in Turin (TRN; Table 1) is located at the Metrology Laboratory of the INRiM [33]. In the laboratory there is a stable concrete basement where the instruments can be installed. Human noise is practically absent. We installed the gravimeter FG5#238 from 29 to 30 October 2011, during the week-end. The environmental parameters during the measurement sessions were fairly stable. The mean value of the ambient temperature was 28.1 °C with variations within 0.2 °C; the mean value of the local pressure was 996.0 mbar with variations of 0.1 mbar. In total, 46 sets of 50 drops each one were recorded in about 36 hours. The dispersion between the drops acquired was about ± 20 μGal while the dispersion between the data sets was less than ± 10 μGal. There was no need to eliminate any set of measurements (see Table 2 for the results). Likewise in this case, the gravity value obtained considering also a restricted number of sets can be considered reliable compared to the final value evaluated on 46 sets.

The IMGC-02 gravimeter collected gravity data at night on 25 and 26 October 2011. During the measurement session the temperature varied between 26.0 °C and 26.4 °C, while the pressure changed between 984.0 mbar and 990.1 mbar. A total of 1867 drops were processed and stored. The apparatus experienced a scatter of about ± 15 μGal and averaged trajectory residuals within ± 2.5 x 10^{-9} m. The final *g* value and the associated standard deviation were obtained by averaging 473 drops (see Table 2 for the results).

3.4. Validation and traceability via the International and European Comparisons of Absolute Gravimeters

To ensure the traceability of the absolute gravity measurements collected with the two different instruments to the SI units, we include a link to the 7th and 8th International and European Comparisons of Absolute Gravimeters (ICAGs 2005 and 2009) managed by the Bureau International des Poids et Mesures (BIPM) of Sèvres (France) and ECAG 2011 run by METAS and the University of Luxembourg at Walferdange (Luxemburg).

Specifically, data were selected from the 7th ICAGs for the IMGC-02 and from the 8th ICAGs for the FG5#238. Data from the ECAG 2011 are also taken for the IMGC-02 (Fig. 1). Unfortunately, it was not possible to make a comparison during ICAGs and ECAG between both instruments, because during ICAG 2005 the FG5#238 was not yet available, during ICAG 2009 the IMGC-02 did not work properly, and during the ECAG-2011 the FG5#238 did not take part in the comparison.

Absolute gravity measurements at the BIPM were performed in a laboratory of the Pavillon du Mail building (B-BIPM; Table 1), where the instruments can be installed in 7 stations [12].

During the 7th ICAG (2005), the IMGC-02 was installed at different sites. The obtained results show that with respect to the reference gravity values calculated for all absolute gravimeters participating in the ICAG 2005, the IMGC-02 obtained a difference of less than 1 μGal, with an expanded uncertainty at 95% confidence level of 8.6 μGal [12].

During ECAG 2011 the IMGC-02 was installed at three measurement sites in the Underground Laboratory for Geodynamics in Walferdange in Luxembourg (WFG; Table 1). The g values obtained by the IMGC-02 were consistent with the Key Comparison Value: a difference of 2.2 μGal with a declared uncertainty of 5.4 μGal was obtained [13].

During the 8th ICAG (2009), the FG5#238 was installed at three different sites. The final measurement values (expanded uncertainty ranging between 5.4 μGal and 6.5 μGal) are consistent within 5 μGal with respect to the key comparison reference values of g at the three different sites [11].

4. Summary and concluding remarks

We compared two different absolute portable gravimeters at three sites characterized by diverse logistics and environmental conditions to understand the performances of both instruments and improve the balance between uncertainty and efficiency of gravity measurements.

The results of the performances of the two gravimeters at the three sites, referred to 0.5 m from the ground using the experimental values of the vertical gravity gradient measured at each station, are presented in Table 2.

The measurements showed a good agreement within a few microgals. The differences are (1.5 ± 18.9) μGal at CTA, (8.3 ± 15.3) μGal at TRN, and (-4.0 ± 16.6) μGal at SLN (the errors represent the expanded uncertainties at 95% confidence level; Fig. 4). Furthermore, the normalized errors calculated for each site, as stated in Section 3, are very much lower than 1, specifically 0.06 for CTA, 0.45 for TRN and 0.21 for SLN, and confirm the compatibility between the results.

This excellent agreement can be attributed to multiple factors, including gravimeters that were in good working order and ability of the operators to set up the instruments correctly. We demonstrated that, with proper and careful setup, the performances of both gravimeters when used in laboratories that are not specially prepared for gravity measurements or even in the field, where the environmental conditions are very harsh such as at Mt. Etna (the highest and most active volcano in Europe), are always reliable They are comparable to those achieved when used in specially equipped laboratories, like those during ICAGs and ECAG where the best performances can be obtained.

The results also show that both gravimeters are suitable for monitoring long term gravity variations with a precision of a few microgals. Furthermore, this implies that both instruments can be used interchangeably at different times at the same station, ensuring the reliability of the recorded gravity data.

In conclusion, even if the use of absolute gravity measurements for field applications have many difficulties with regard to transportation, site arrangements, environmental conditions etc., the results of this study indicate that, using some additional precautions, both gravimeters are suitable not only for laboratory conditions but also in noisy sites like Mt. Etna. These results can be used to standardize gravity surveys, where absolute gravity measurements may successfully replace or supplement the less accurate and time-consuming relative gravity surveys applied so far for such objective. This has an immediate positive feedback especially when extensive gravity surveys are scheduled for applications in geophysics and volcanology in areas where the logistics are unfavourable.

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Figures

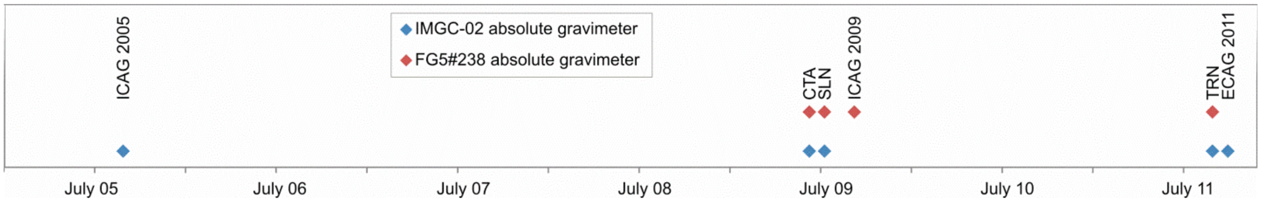

Fig. 1 - Timeline showing the sequence of absolute measurements for the IMGC-02 and FG5#238 gravimeters at the gravity stations CTR, SLN and TRN and in the frame of the ICAGs 2005 and 2009 and ECAG 2011.

Fig. 2 – Gravity station at Serra La Nave (SLN, Mt. Etna): on the left the FG5#238, on the right the IMGC-02 during the measurements.

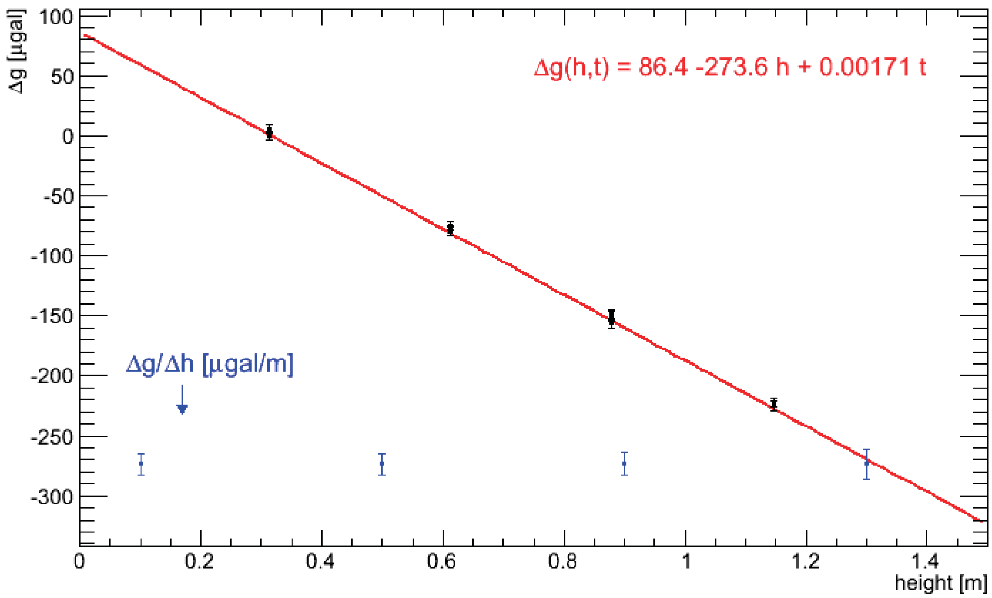

Fig. 3 – Example of vertical gravity gradient determination at TRN. The measured gravity difference with respect to the first value at 30 cm are shown versus the height. The fit function is superimposed (red). The extracted values of the vertical gravity gradient relative to different heights are represented with the estimated uncertainty (blue).

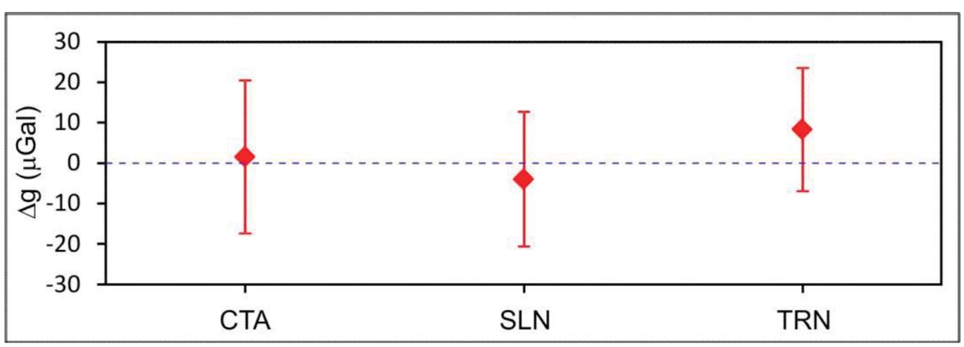

Fig. 4 – Gravity differences (Δg) between the two absolute gravimeters at three different stations CTA (1.5 ± 18.9) μGal, SLN (-4.0 ± 16.6) μGal and TRN (8.3 ± 15.3) μGal. The error bars represent the expanded uncertainties at 95% of confidence level.

Tables

Station	Acronym	Latitude/ deg	Longitude/ deg	Elevation/ m a.s.l.	VGG/(µGal/m)	u_{VGG} (fit)/ (µGal/m)	u_{VGG} (final)/ (µGal/m)
Catania (Italy)	CTA	37.514	15.083	50	276.7	6.1	9.2
Serra La Nave (Mt. Etna)	SLN	37.694	14.973	1730	335.0	5.2	7.6
Turin (Italy)	TRN	45.017	7.642	236	273.6	4.2	6.2

Table 1 – Coordinates of the absolute gravity stations and vertical gravity gradient values (VGGs) at CTA, SLN and TRN stations. The standard uncertainties uvgg (fit), evaluated for the vertical gravity gradients and the final standard uncertainties uvgg (final), calculated considering also the contribution of the extrapolation error, are also shown.

Meter	Site	Date	sets/drops per set	H m	u_{inst} /µGal	u_{site} /µGal	u_{mean} /µGal	u_{comb} /µGal	Corrected g(0.5 m)/ µGal	$u_g(h)$/µGal
FG5#238	CTA	3-5 July 2009	40/100	1.2867	2.3	1.1	1.87	3.2	980031508.2	7.9
IMGC-02	CTA	8-9 July 2009	1/477	0.5009	3.8	1.8	3.0	5.2	980031506.7	5.2
FG5#238	SLN	11 July 2009	33/100	1.2937	2.3	1.1	1.85	3.2	979641626.8	6.8
IMGC-02	SLN	9-10 July 2009	1/372	0.4982	3.8	1.8	2.2	4.8	979641630.8	4.8
FG5#238	TRN	29-30 October 2011	46/50	1.2922	2.3	1.1	1.86	3.2	980534206.2	5.8
IMGC-02	TRN	25-26 October 2011	1/473	0.4772	3.8	1.8	2.6	4.9	980534198.0	5.0

Table 2 – Absolute values of the gravity acceleration g acquired with the FG5#238 and the IMGC-02 gravimeters in Catania, Serra La Nave and Turin stations. The number of sets and drops per set are also shown. The table also reports the height H above the ground to which g is measured, the instrumental uncertainty u_{inst}, the site-dependent uncertainty u_{site}, the experimental standard deviation of the mean due to the scattering u_{mean}, and the combined standard uncertainty u_{comb} which takes into account the previous three contributions of uncertainty. The table includes the g values reported at 0.5 m from the ground and

the combined uncertainties ug(h) of the final g values, evaluated by combining ucomb and the uncertainty of the vertical gravity gradient at each site.

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Absolute gravity measurements at three sites characterized by different environmental conditions using two portable ballistic gravimeters

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Abstract

A detailed comparison ~~analysis~~ of the performances of two absolute gravimeters at three different sites in Italy between 2009 and 2011 is presented. The measurements of the gravity acceleration *g* were performed~~conducted~~ using the absolute gravimeters Micro-g LaCoste FG5#238 and the INRiM prototype IMGC-02, which represent the state of the art in ~~recent advances in~~ ballistic gravimeter technology (relative uncertainty of a few parts in 10^9). For the comparison, the measured *g* values were reported at the same height by means of the vertical gravity gradient estimated at each site with relative gravimeters. The consistency and reliability of the gravity observations, as well as the performance and efficiency of the instruments, were~~are~~ assessed by measurements made~~conducted~~ inside dedicated and non-dedicated infrastructures characterized by different logistics and environmental conditions.~~dedicated laboratories and under different infrastructures and environmental conditions encountered in a site belongs to the absolute gravity monitoring network of the Etna volcano.~~ Furthermore, the various factors affecting the measurements and their uncertainty were~~are~~ thoroughly investigated. The measurements showed ~~a~~ good agreement, with the minimum and maximum differences being ~~are~~ -4.0 and 8.3 µGal. The normalized errors are very much lower than 1, ranging between 0.06 and 0.45, confirming the compatibility between the results. This is an excellent agreement and can be attributed to several factors, including ~~gravimeters that were in~~the good working order of gravimeters and the correct~~proper~~ setup and use of the instruments in different conditions. These results can contribute to the standardization of absolute gravity surveys largely for~~mainly oriented to~~ applications in geophysics, volcanology and other branches of geosciences, allowing ~~to~~ achieving~~e~~ a good trade-off between uncertainty and efficiency of gravity measurements.

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Keywords: absolute gravimeter, gravity acceleration, comparison of absolute gravimeters.

1. Introduction

Portable absolute gravimeters are essential to carry out accurate gravity measurements. The robustness and transportability of modern absolute gravimeters also enable them to be used~~run~~ in the field, allowing combinations with conventional relative gravimeters in a hybrid approach [1,2,3]. In volcanic areas, the use of field-usable absolute gravimeters allows ~~to~~ optimizinge traditional techniques of relative gravity measurements, ensuring ~~an~~ improvement in data ~~the~~ quality ~~of the data~~ [4,5].

Since 2007, the Istituto Nazionale di Geofisica e Vulcanologia has been carrying out absolute gravity measurements to monitor the Mt. Etna volcano, one of the most active and hazardous volcanoes in the world. To~~For~~ this ~~purpose~~end, we introduced two transportable absolute gravimeters, both~~which represent the on-going improvements~~ state of the art in ballistic gravimeter technology: the FG5#238, a commercial instrument ~~produced~~ made by ~~the~~ Micro-g LaCoste Inc. and the IMGC-02, a prototype developed in Italy by the Istituto Nazionale di Ricerca Metrologica (INRiM). The IMGC-02 is recognized as a national primary standard in Italy [6] and the FG5 is more commonly employed for absolute gravity studies while, specifically, the FG5#238 gravimeter is normally used for different applications ranging from volcano monitoring [5] to the study of gas storage areas [7].

Absolute gravimeters are often compared ~~to one another~~ for the purpose of assuring their good working order, but also to test the capability of the operators to provide ~~a~~ values with the associated uncertainty that are consistent with ~~the~~ other operators. Comparisons are also essential for long-term absolute measurements in geophysics to insure the consistency of the observations over a time period of decades [8].

The main goal of this work is to investigate the behaviour of the FG5#238 and IMGC-02 gravimeters, never before used together on field. Then, in keeping ~~agreement~~ with previous ~~recently published~~ works [9,10], the innovative aspect is the measurement and the possibility of ~~to~~ achievinge a standardization of absolute gravity surveys in areas where ~~the~~ logistics are unfavourable, optimizing quality of the measurements and minimizing resources. To address this issue, ~~For this purpose,~~ we take advantage of several test measurements conducted both indoors and in the field to analyze the behaviors of both gravimeters under different conditions. At the same time, in order to achieve a trade-off between uncertainty and efficiency of gravity measurements, we tested different measurement procedures and different setups~~arrangements~~.

The comparison between the two absolute gravimeters was conducted at three different sites in Italy (Table 1; Fig. 1): two of them are dedicated laboratories and the third is a geophysical point of interest with harsh environmental conditions (low temperature, high humidity, high vibration, etc.). The selected sites are:

1. *Gravity Laboratory of Istituto Nazionale di Geofisica e Vulcanologia (INGV) at Catania (CTA).* This site is normally used as the reference for the Etna ~~volcano~~ gravity monitoring network. ~~Indeed, t~~The gravity field here may~~can~~ be considered unaffected by volcano-induced gravity anomalies. Furthermore the FG5#238 is maintained and tested here.
2. *Serra la Nave gravity station at Mt. Etna volcano (SLN).* This site is one of the absolute monitoring stations ~~located~~ at ~~Mt.~~ Etna and is characterized by ~~presents~~ the typically difficulties ~~normally~~ encountered in a very hard environment such as on an active volcano.
~~2.~~ *Gravity Laboratory of INRiM at Turin (TRN)*. At this site the IMGC-02 is regularly maintained, tested and improved.

~~3.~~

~~To validate the absolute measurements performed with the two instruments, we refer to the International and European Comparisons of Absolute Gravimeters (ICAG 2005 – 2009 and ECAG 2011), which included the two FG5#238 and IMGC-02 gravimeters.~~

The two instruments used, FG5#238 and IMGC-02 gravimeters, were included in the International and European Comparisons of Absolute Gravimeters (ICAG 2005 – 2009 and ECAG 2011; Fig. 1) [11,12,13]. The good results achieved in these international comparisons ensures the traceability of measurements to the SI units, as requested by the new strategy document developed by CCM and IAG [14].

2. Instruments, field experiment measurements, uncertainties and vertical gravity gradient

2.1. TWO TRANSPORTABLE ABSOLUTE GRAVIMETERS

The two instruments used~~employed~~ in this study measure the absolute *g* value through the reconstructed trajectory of a corner-cube prism, subjected to the gravity field, which moves vertically in a vacuum chamber. The IMGC-02 measures both the rise and fall motions of the flying object, while the FG5 instrument measures the acceleration during free-fall motion only. A laser interferometer measures the distance between the free falling corner cube test mass and a second retroreflector mounted on the quasi-inertial mass of a vibration isolation system, namely a seismometer for IMGC-02 and a super-spring system for the FG5 [6,~~11~~15].

For the FG5, a total of 700 time-position points are recorded over the 20 cm length of each drop. Drops can be produced up to every two seconds but during~~in~~ routine operation, the drops are repeated every 10 s. Typically, the average of 50 or 100 drops is a "set". The FG5 measurements consist of one set per hour

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with the average of several sets (usually 12 to 48) providing a resultant "gravity value". The instrumental accuracy of the FG5 is about 1–2 μGal as reported by the manufacturer [~~11~~15]; the precision is time-dependent and it is given by the drop-drop scatter (single drop scatter) divided by the square-root of the number of drops. A precision of 1 μGal (usually much better; largely~~mostly~~ depends ~~up~~on the site) can be achieved within an hour at most sites if the FG5 is running continuously.

Regarding the IMGC-02, in laboratory conditions, one observation session typically lasts 12 hours and consists of about 1500 launches. It corresponds to an experimental standard deviation of the population of measurement results equal to 35 μGal and an associated standard deviation of the mean value lower than 1 μGal. Instead, when the instrument is operating in noisy environmental conditions, an observation session with an experimental standard deviation of the population of measurement results equal to 50 μGal, about 2500 launches are needed to reach a standard deviation of the mean value equal to 1 μGal. But, to reach standard deviation twofold smaller than the above reported experimental value, the number of launches should be quadrupled.

For both instruments, the final gravity value is obtained after applying correction for Earth tides, ocean loading, local atmospheric effects (using single admittance of -0.3 μGal/hPa due to loading and mass attraction and local air pressure record) and polar-motion effects. Since the measurements with both instruments were carried out in a short time interval and roughly in the same meteorological conditions, the hydrological effects have been disregarded.

2.2. Field experiment Measurements

Due to the logistical difficulties ~~existing~~ on Mt Etna, the arrangement of the absolute stations mainly depends on the availability~~presence~~ of suitable structures~~buildings~~ to ~~that can provide~~ protect~~ion for~~ the instrumentation. The quality of gravity measurements gathered with transportable absolute gravimeters is further influenced by numerous factors, such as performance of the instruments themselves, quality of the site, ability of the operator to set up the instrument correctly, weather conditions, etc. In general~~Basically~~, with the absolute gravimeters, after a sufficient amount of averaging, a limit is reached where ~~the~~ precision will still increase though~~but~~ the uncertainty will not improve because of the intrinsic accuracy of the instruments. By averaging long enough data in any one spot all of the instruments should have a similar uncertainty. Taking ~~into~~ account of this latter aspect, we tested different measurement procedures to reduce the acquisition time to a few hours, allowing ~~to~~ balancing~~e~~ the accuracy and precision of gravity measurements. Specifically, we tried to: (a) increase the frequency of measurements by reducing the interval between sets; (b) reduce both the number of drops for each set and the drop interval; (c) reduce the number of sets; (d) collect measurements during both ~~the~~ day and ~~the~~ night. The tests carried out using the FG5 have shown that the set scatter and the *g* values are still comparable with those obtained through standard procedure and the results may~~can~~ be considered reliable. For the IMGC-02, low uncertainty levels like those achieved with the FG5 are reached after an observation session lasting about 12 hours. Comparable results in terms of reproducibility and uncertainty are also obtained using the instruments during daylight hours.

Measurement reproducibility is defined by the International Vocabulary of Metrology (VIM) [16] as precision under reproducibility conditions; where reproducibility condition means out of a set of conditions that includes different locations, operators, measuring systems and repeated measurements on the same or similar objects.

As a rule~~Generally~~, at Mt Etna, to prevent negative effects in ~~the~~ field measurements performed in harsh and noisy ~~-~~environments, ~~in some measurement sessions~~ it was necessary to use additional equipment in some measurement sessions, such as: i) a tent to protect the instruments against the humidity, low temperature etc.; ii) a heater to heat the room where the instruments were installed; iii) an electric generator in sites not supplied with electricity and iv) a continuous and precise~~ly~~ realignment of the laser beam, equipped the FG5, in the higher altitude~~elevation~~ sites to achieve reliable measurements [~~12~~17]. Finally, operating these gravimeters in different conditions has proved ~~to be~~ a useful test ~~for~~to improv~~e~~ing the operators ability to manage the instruments, to find ~~the~~ optimal strategies in different environments and lastly to ensure ~~the~~ high quality in the data collection.

2.3. Uncertainty evaluation

The evaluation of measurement uncertainty was carried out in accordance with the GUM [~~13~~18] and the terminology is used in agreement with the VIM [~~14~~19]. The uncertainty associated with the g measurement, u_{comb}, takes into account the contributions of (i) the instrumental uncertainties, u_{inst}, whose most important influence factors are: vacuum level, non-uniform magnetic field, temperature gradient, electrostatic attraction, self-attraction effect, laser beam verticality and divergence, overall drift due to misalignment of the instrument, air gap modulation, length and time standards, retro-reflector balancing and reference height; (ii) the contribution of uncertainty depending on the observation site, u_{site}, whose main influence factors are: Coriolis force, floor recoil, and geophysical effects, such as local barometric pressure, gravity tides, ocean loading, and polar motion, and (iii) the scattering of measurements, u_{mean}, estimated with the experimental standard deviation of the mean g value; this value ~~it~~ is heavily dependent on the ground vibrations and the floor recoil.

Combining the standard deviation of the free-fall acceleration value, due to the scattering, with the instrumental uncertainty and ~~the~~ site-dependent influence factors, we calculated the combined standard uncertainty and the expanded uncertainty (at the 95% confidence level) related to the measurements acquired with both gravimeters. The same approach was used for the uncertainty evaluation in the International Gravity Comparisons [11~~5~~,12~~6~~].

Considering all the contributions to the uncertainty, the minimum achievable combined uncertainties, as ~~they are~~ used in the International Comparisons, are 2.6 μGal and 4.3 μGal, respectively for FG5 and IMGC-02 [~~16~~12]. However, the uncertainty of both instruments increases up to 10-15 μGal at sites affected by almost continuous ground vibrations such as those existing a few hundred meters away from the constantly active summit craters of Etna volcano [5,~~12~~17].

2.4. VERTICAL GRAVITY GRADIENT DETERMINATION

Due to different instrument design of the FG5#238 and the IMGC-02, their measured g-values refer to about 1.3 m and about 0.5 m from the ground, respectively. The FG5#238 specific factory height is equal to 1.1637 m plus the upper and lower set up heights sum; the IMGC-02 specific height is evaluated combining all measurement heights of each single trajectory. ~~Due to different instrument designs, of the FG5#238 and the IMGC-02, their measured g-values refer to about 1.3 m (this includes the FG5#238 specific factory height equal to 1.1637 m plus the upper and lower set up heights sum) and about 0.5 m from the ground, respectively.~~ Therefore, to compare the values reported by the two different instruments (actual height) we referred all the measurement values to a common height of 0.5 m (transfer height) using vertical gravity gradients. We determined the gradients at each absolute station using two Scintrex relative gravimeters (CG-3M#9310234 and CG-5#08064041). Finally, the vertical gradient values are used to reduce the gravity values from the "actual height" to the "transfer height".

The vertical gravity gradient γ was estimated by measuring the gravity change at four different levels from the ground~~floor~~, which roughly correspond to the following heights: h_0 = 30 cm, h_1 = 60 cm, h_2 = 90 cm and h_3 = 120 cm (Fig. 3~~2~~). Since those values are less than the reference height of the FG5#238, the effect of the extrapolation was estimated using Montecarlo simulations [~~17~~20].

The measurements were executed using the step method, in which adjacent elevations were connected at least three times. After the correction for the Earth tide, γ was obtained by fitting the following equation model to the experimental data, i.e. the collected g value and the acquisition time t:

$$g = \gamma \cdot h + \alpha \cdot t + k$$

where the parameters γ, h, α, k are the vertical gravity gradient, the level from the floor, the instrumental drift, and the gravity offset, respectively. For each site, the residuals between fit function and data do not show any parabolic shape, indicating that a second degree polynomial fit is not preferable (Fig. 3~~2~~).

The vertical gravity gradients range from station to station from -273.6 to -335.0 μGal/m. Standard uncertainties of 6.1 μGal/m, 5.2 μGal/m, and 4.2 μGal/m were evaluated for the vertical gravity gradient at CTA, SLN, and TRN stations, respectively, measured in 2009 and 2011. Such values were increased to

9.2 µGal/m, 7.6 µGal/m and 6.2 µGal/m, respectively, to consider the contribution of the extrapolation error (Table 1). We are aware that any measurement errors in the vertical gravity gradients will have a negligible effect on the IMGC-02 final results (because the top of the drop is within few centimet~~er~~res of the chosen transfer height of 0.5 m); conversely the effect will be higher on the FG5#238 final results owing to ~~because of~~ the transfer from the top of the drop height of about 1.3 m to the transfer height of 0.5 m.

We used the following equation to refer a measurement result $g(h_m)$ collected at a level h_m from the floor to a level h:

$$g(h) = g(h_m) + \gamma \cdot (h - h_m)$$

The final combined uncertainty $u_g(h)$ (Table 2) at the level h is calculated by combining the uncertainty of the measurement u_{comb} and the uncertainty of the vertical gravity gradient u_γ to transfer properly measured gravity from the measurement level h_m to an arbitrary reference level h:

$$u_g(h) = \sqrt{(u_{comb})^2 + (h - h_m)^2 \cdot u_\gamma^2}$$

Therefore, the uncertainty due to the height of measurements h_m (normally 0.5 – 1 mm) can be considered negligible.

3. Measurements

Absolute gravity measurements were carried out in July 2009 at the Gravity Laboratory of INGV (CTA) in Catania and at the absolute gravity station of Serra La Nave (SLN) on Etna volcano, and in November 2011 at the Metrology Laboratory of INRiM (TRN) in Turin (Tab. 1).

Concerning the FG5#238 gravimeter, ~~normally~~typically, each data set was acquired with 50 or 100 drops. On every single data set the standard deviation σ has been calculated, rejecting any drop outside~~resulting beyond~~ the 3σ range.

For the IMGC-02 gravimeter, the gravity values are filtered by applying rejecting criteria. The most critical factor is the visibility variation of the interference signal recorded along the rise-and-fall trajectory. It highlights a horizontal motion of the test-body due to parasitic forces in the launch phase [~~18~~21]. The effect due to the Coriolis force and the beam share are minimized by rejecting the launches that exhibit a decrease of visibility bigger than 10%. Outliers are found by applying the Chauvenet criterion [~~19~~22,23~~0~~] to the collected g values and other estimating parameters such as the vertical gradient and the friction of residual air.

Considering the state-of-the-art of gravimetry measurements [~~15~~11,12~~6~~,~~2~~13], data have been corrected for diffraction effect, caused by the inherent curvature of the laser wave front and for the self-attraction-effect, due to the masses of the single parts that make up the different gravimeters [~~22~~24].

Lastly, to confirm the compatibility between the measurement results, we calculated for each site the normalized error [25,26] variable as follows:

$$eE_n = \frac{g_{FG5\#238} - g_{IMGC-02}}{\sqrt{(U_{FG5\#238}^2 + U_{IMGC-02}^2)}}$$

where U represents the expanded uncertainty at the 95% confidence level.

When uncertainties are estimated in a way consistent with the Guide to the expression of uncertainty in measurement (GUM), E_n number expresses the validity of the expanded uncertainty estimate associated with each result. A value of $|E_n| < 1$ provides objective evidence that the estimate of uncertainty is consistent with the definition of expanded uncertainty given in the GUM and that the two different measurements are compatible and justified from their uncertainties.

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3.1. Gravity Laboratory in Catania (CTA)

The absolute gravity station of Catania (CTA; Table 1) is located at the underground Gravity Laboratory of the INGV. The instruments can be placed on a suitable concrete pillar, insulated from the building. During the day the vibrations induced by noise ~~due to~~from human activity are significant but still acceptable. An observation session lasting 12 hours is sufficient to reach a satisfactory uncertainty. The measurements with the FG5#238 were carried out from 3 to 5 July 2009, during the week-end when the noise is minimal. The environmental parameters during the measurement sessions were sufficiently stable. The ambient temperature varied from 33.5 °C to 34.5 °C and the local pressure changed from 1008.0 mbar to 1006.0 mbar. A total of 40 sets, each including 100 drops, were acquired, in about 39 hours. The dispersion between the drops acquired was about ± 20 µGal, while the dispersion between the data sets was less than ± 10 µGal. All data passed~~ing~~ the selection criteria (see Section 3), hence~~then~~ there was no need to eliminate any set of measurements (see Table 2 for the results). It is important to also note ~~also~~ that, among all data collected, the same result is achieved by considering only a limited number of sets (3-5).

With the IMGC-02 gravimeter, the measurements were carried on from 8 to 9 July 2009 [~~23~~27]. The measurements were taken at night. During the measurements session the environmental parameters were stable, the maximum variations of the temperature were between 30.0 °C and 32.0 °C. The pressure varied between 1008.0 mbar and 1010.4 mbar. A total of 1337 drops were processed and stored. The apparatus experienced a scatter of about ± 15 µGal and averaged trajectory residuals within ± 1 x 10^{-9} m. The final *g* value and associated standard deviation were obtained by averaging 477 drops (see Table 2 for the results).

~~3.2. Gravity laboratory in Turin (TRN)~~

~~The absolute gravity station in Turin (TRN; Table 1) is located at the Metrology Laboratory of the INRiM [24]. In the laboratory there is a stable concrete basement where the instruments can be installed. Human noise is practically absent. We installed the gravimeter FG5#238 from 29 to 30 October 2011, during the week-end. The environmental parameters during the measurement sessions were fairly stable. The mean value of the ambient temperature was 28.1 °C with variations within 0.2 °C; the mean value of the local pressure was 996.0 mbar with variations of 0.1 mbar. In total, 46 sets of 50 drops each one were recorded in about 36 hours. The dispersion between the drops acquired was about ± 20 µGal while the dispersion between the data sets was less than ± 10 µGal. There was no need to eliminate any set of measurements (see Table 2 for the results). Also in this case the gravity value obtained considering also a restricted number of sets can be considered reliable compared to the final value evaluated on 46 sets.~~

~~The IMGC-02 gravimeter collected gravity data at night on 25 and 26 October 2011. During the measurement session the temperature varied between 26.0 °C and 26.4 °C, while the pressure changed between 984.0 mbar and 990.1 mbar. A total of 1867 drops were processed and stored. The apparatus experienced a scatter of about ± 15 µGal and averaged trajectory residuals within ± 2.5 x 10^{-9} m. The final *g* value and the associated standard deviation were obtained by averaging 473 drops (see Table 2 for the results).~~

3.2~~3~~. Gravity station at Mt. Etna (SLN)

The observation station of Mt. Etna (SLN; Table 1) is located at Serra La Nave site, about 6 km from the summit craters, in a bunker in the grounds~~within the area~~ of the Astrophysical Observatory and is part of the Etna gravity monitoring network [5,29~~5~~,30~~26~~,31~~27~~,32~~8~~]. ~~Inside the bunker~~T~~-t~~here is a large stable concrete pillar inside the bunker where the instruments can be installed (Fig. ~~1~~2). Human noise is practically absent and ~~the~~ ground vibrations, such as those ~~that~~ accompanying the explosive activity of the volcano [33~~29~~], were not present. To do the ~~make~~ measurements in this site we have made the most ~~put in place all~~ of the experience gained in other hostile sites for absolute gravity measurements at Etna [5,17~~2~~]. The high ambient humidity and low temperature were mitigated~~controlled~~ using an electric heater kept on ~~maintained in operation~~ during the measurements; a tent was needed ~~necessary~~ to reduce the space to be heated.

With the FG5#238 gravimeter, f~~F~~rom 10 to 11 July 2009, in about 19 hours (most during the night), we acquired in all 33 sets, 100 drops each, ~~with the FG5#238 gravimeter in about 19 hours (most during the night)~~. The mean value of the ambient temperature was 25.0 °C with variations within 0.5 °C, the mean value of the local pressure was 830 mbar with variations of 0.15 mbar, while the humidity was about 60%. The dispersion between the drops acquired was about ± 20 μGal (only a few sets showed a higher dispersion), while the dispersion between the set was less than ± 10 μGal. The first three sets of measurements were rejected (see Table 2 for the results). Measurements acquired during daylight hours, when the time interval between sets was also reduced, exhibited the same characteristic as those acquired during the night. This confirms that with proper and careful setup, the FG5 could provide accurate and reliable results at different conditions and even in short acquisition times.

Gravity data with the IMGC-02 gravimeter were collected on 9-10 July 2009, during the night. The environmental parameters were fairly stable: temperature changes between 38.0 °C and 40.3 °C were recorded; air pressure values, from 829.5 mbar to 831.4 mbar, were observed. A total of 1462 drops were processed and stored. A scatter of about ± 10 μGal was found in the collected data and averaged trajectory residuals within ± 1 x 10^{-9} m were estimated. The final *g* value and the associated standard deviation were achieved by averaging 372 drops (see Table 2 for the results).

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3.3. Gravity laboratory in Turin (TRN)

The absolute gravity station in Turin (TRN; Table 1) is located at the Metrology Laboratory of the INRiM [28]. In the laboratory there is a stable concrete basement where the instruments can be installed. Human noise is practically absent. We installed the gravimeter FG5#238 from 29 to 30 October 2011, during the week-end. The environmental parameters during the measurement sessions were fairly stable. The mean value of the ambient temperature was 28.1 °C with variations within 0.2 °C; the mean value of the local pressure was 996.0 mbar with variations of 0.1 mbar. In total, 46 sets of 50 drops each one were recorded in about 36 hours. The dispersion between the drops acquired was about ± 20 μGal while the dispersion between the data sets was less than ± 10 μGal. There was no need to eliminate any set of measurements (see Table 2 for the results). Likewise in this case, the gravity value obtained considering also a restricted number of sets can be considered reliable compared to the final value evaluated on 46 sets.

The IMGC-02 gravimeter collected gravity data at night on 25 and 26 October 2011. During the measurement session the temperature varied between 26.0 °C and 26.4 °C, while the pressure changed between 984.0 mbar and 990.1 mbar. A total of 1867 drops were processed and stored. The apparatus experienced a scatter of about ± 15 μGal and averaged trajectory residuals within ± 2.5 x 10^{-9} m. The final *g* value and the associated standard deviation were obtained by averaging 473 drops (see Table 2 for the results).

3.4. Validation and traceability via the International and European Comparisons of Absolute Gravimeters

To ensure the traceability of validate the absolute gravity measurements collected with the two different instruments, to the SI units, we include a link to the 7th and 8th International and European Comparisons of Absolute Gravimeters (ICAGs 2005 and 2009) managed by the Bureau International des Poids et Mesures (BIPM) of Sèvres (France) and ECAG 2011 run by METAS and the University of Luxembourg at Walferdange (Luxemburg).

Specifically, data were selected from the 7th ICAGs for the IMGC-02 and from the 8th ICAGs for the FG5#238. Data from the ECAG 2011 are also taken for the IMGC-02 (Fig. 1). Unfortunately, it was not possible to make a comparison during ICAGs and ECAG between both instruments, because during ICAG 2005 the FG5#238 was not yet available, during ICAG 2009 the IMGC-02 did not work properly, and during the ECAG-2011 the FG5#238 did not take part in the comparison.

Absolute gravity measurements at the BIPM were performed in a laboratory of the Pavillon du Mail building (B-BIPM; Table 1), where the instruments can be installed in 7 stations [1612].

During the 7th ICAG (2005), the IMGC-02 was installed at different sites. The obtained results show that with respect to the reference gravity values calculated for all absolute gravimeters participating in the ICAG 2005, the IMGC-02 obtained a difference of less than 1 µGal, with an expanded uncertainty at 95% confidence level of 8.6 µGal [1612].

During ECAG 2011 the IMGC-02 was installed at three measurement sites in the Underground Laboratory for Geodynamics in Walferdange in Luxembourg (WFG; Table 1). The *g* values obtained by the IMGC-02 were consistent with the Key Comparison Value: a difference of 2.2 µGal with a declared uncertainty of 5.4 µGal was obtained [2113].

During the 8th ICAG (2009), the FG5#238 was installed at three different sites. The final measurement values (expanded uncertainty ranging between 5.4 µGal and 6.5 µGal) are consistent within 5 µGal with respect to the key comparison reference values of *g* at the three different sites [1511].

4. Summary and concluding remarks

We compared two different absolute portable gravimeters at three sites characterized by diverse logistics and environmental conditions to understand the performances of both instruments and improve the balance between uncertainty and efficiency of gravity measurements.

The results of the performances of the two gravimeters at the three sites, referred to 0.5 m from the ground using the experimental values of the vertical gravity gradient measured at each station, are presented in Table 2.

The measurements showed a good agreement within a few microgals. The differences are (1.5 ± 18.9) μGal at CTA, (8.3 ± 15.3) μGal at TRN, and (-4.0 ± 16.6) μGal at SLN (the errors represent the expanded uncertainties at 95% confidence level; Fig. 4~~3~~). Furthermore, the normalized errors calculated for each site, as stated in Section 3, are very much lower than 1, specifically ~~are~~ 0.06 for CTA, 0.45 for TRN and 0.21 for SLN, and confirm the compatibility between the results.

This excellent agreement can be attributed to multiple factors, including gravimeters that were in good working order and ability of the operators to set up the instruments correctly. We demonstrated that, with proper and careful setup, the performances of both gravimeters when used in laboratories that are not specially prepared for gravity measurements or even in the field, where the environmental conditions are very harsh such as at Mt. Etna (the highest and most active volcano in Europe), are always reliable They are ~~and~~ comparable to those achieved when used in specially equipped laboratories, like those during ICAGs and ECAG where the best performances can be obtained.

The results also show ~~also~~ that both gravimeters are suitable for monitoring long term gravity variations with a precision of a few microgals. Furthermore, this implies that both instruments can be used interchangeably ~~one or the other~~ at different times at the same station, ensuring the reliability of the recorded gravity data.

In conclusion, even if the use of absolute gravity measurements for field applications have many difficulties ~~dealing~~ with regard to transportation, site arrangements, environmental conditions etc., the results of this study indicate that, using some additional precautions, both gravimeters are suitable not only for laboratory conditions but also in noisy sites like Mt. Etna. These results can be used to standardize gravity surveys, where absolute gravity measurements may successfully replace or supplement the less accurate and time-consuming relative gravity surveys applied so far for such objective~~goal~~. This has an immediate positive feedback especially when extensive gravity surveys are scheduled for applications in geophysics and volcanology in areas where the logistics are unfavourable.

Acknowledgments

The final form of this manuscript benefited from the constructive comments ~~of~~ by the editor Erricos C. Pavlis and by anonymous reviewers. The authors wish to thank Eni S.p.a., Exploration & Production Division for providing the FG5#238 absolute gravimeter and the Scintrex CG5#08064041 relative gravimeter and the financial support (Contract n. 5200004173/SG3).

Figures

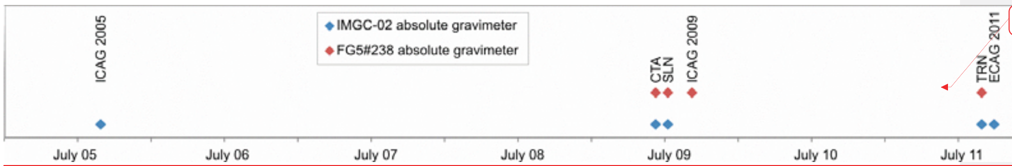

Fig. 1 - Timeline showing the sequence of absolute measurements for the IMGC-02 and FG5#238 gravimeters at the gravity stations CTR, SLN and TRN and in the frame of the ICAGs 2005 and 2009 and ECAG 2011.

Fig. ~~1~~ 2 – Gravity station at Serra La Nave (SLN, Mt. Etna): on the left the FG5#238, on the right the IMGC-02 during the measurements.

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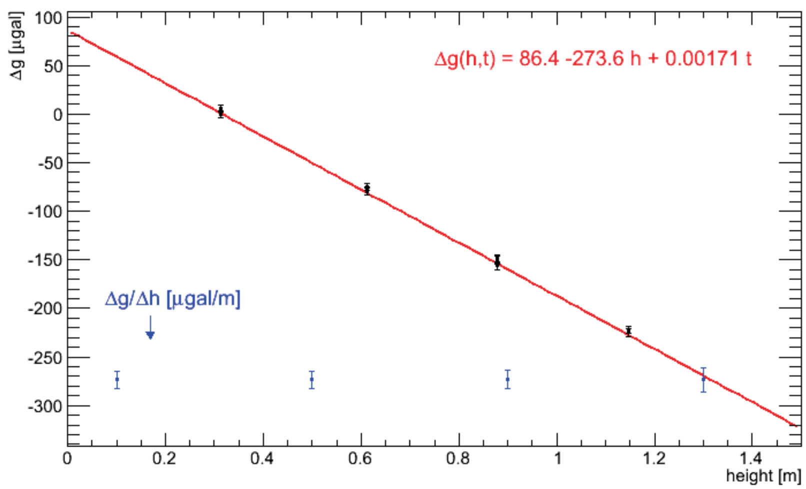

Fig. 3~~2~~ – Example of vertical gravity gradient determination at TRN. The measured gravity difference with respect to the first value at 30 cm are shown versus the height. The fit function is superimposed (red). The extracted values of the vertical gravity gradient relative to different heights are represented with the estimated uncertainty (blue).

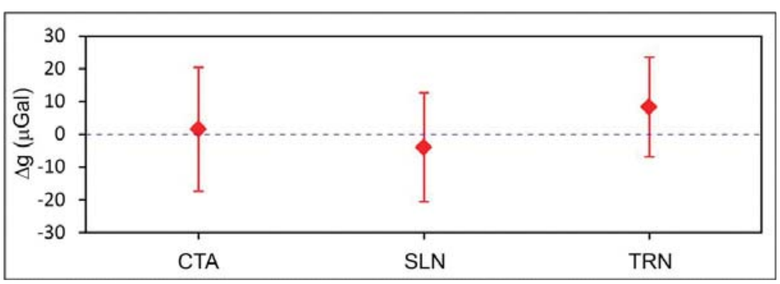

Fig. 4~~3~~ – Gravity differences (Δg) between the two absolute gravimeters at three different stations CTA (1.5 ± 18.9) μGal, SLN (-4.0 ± 16.6) μGal and TRN (8.3 ± 15.3) μGal. The error bars represent the expanded uncertainties at 95% of confidence level.

Tables

Station	Acronym	Latitude/ deg	Longitude/ deg	Elevation/ m a.s.l.	VGG/(µGal/m)	u_{VGG} (fit)/ (µGal/m)	u_{VGG} (final)/ (µGal/m)
Catania (Italy)	CTA	37.514	15.083	50	276.7	6.1	9.2
Serra La Nave (Mt. Etna)	SLN	37.694	14.973	1730	335.0	5.2	7.6
Turin (Italy)	TRN	45.017	7.642	236	273.6	4.2	6.2

Table 1 – Coordinates of the absolute gravity stations and vertical gravity gradient values (VGGs) at CTA, SLN and TRN stations. The standard uncertainties uvgg (fit), evaluated for the vertical gravity gradients and the final standard uncertainties uvgg (final), calculated considering also the contribution of the extrapolation error, are also shown.

Meter	Site	Date	sets/drops per set	H m	u_{inst} /µGal	u_{site} /µGal	u_{mean} /µGal	u_{comb} /µGal	Corrected g(0.5 m)/ µGal	$u_g(h)$/µGal
FG5#238	CTA	3-5 July 2009	40/100	1.2867	2.3	1.1	1.87	3.2	980031508.2	7.9
IMGC-02	CTA	8-9 July 2009	1/477	0.5009	3.8	1.8	3.0	5.2	980031506.7	5.2
FG5#238	SLN	11 July 2009	33/100	1.2937	2.3	1.1	1.85	3.2	979641626.8	6.8
IMGC-02	SLN	9-10 July 2009	1/372	0.4982	3.8	1.8	2.2	4.8	979641630.8	4.8
FG5#238	TRN	29-30 October 2011	46/50	1.2922	2.3	1.1	1.86	3.2	980534206.2	5.8
IMGC-02	TRN	25-26 October 2011	1/473	0.4772	3.8	1.8	2.6	4.9	980534198.0	5.0

Table 2 – Absolute values of the gravity acceleration g acquired with the FG5#238 and the IMGC-02 gravimeters in Catania, Serra La Nave and Turin stations. The number of sets and drops per set are also shown. The table also reports the height H above the ground to which g is measured, the instrumental uncertainty u_{inst}, the site-dependent uncertainty u_{site}, the experimental standard deviation of the mean due to the scattering u_{mean}, and the combined standard uncertainty u_{comb} which takes into account the previous three contributions of uncertainty. The table includes the g values reported at 0.5 m from the ground and

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the combined uncertainties ug(h) of the final g values, evaluated by combining ucomb and the uncertainty of the vertical gravity gradient at each site.

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