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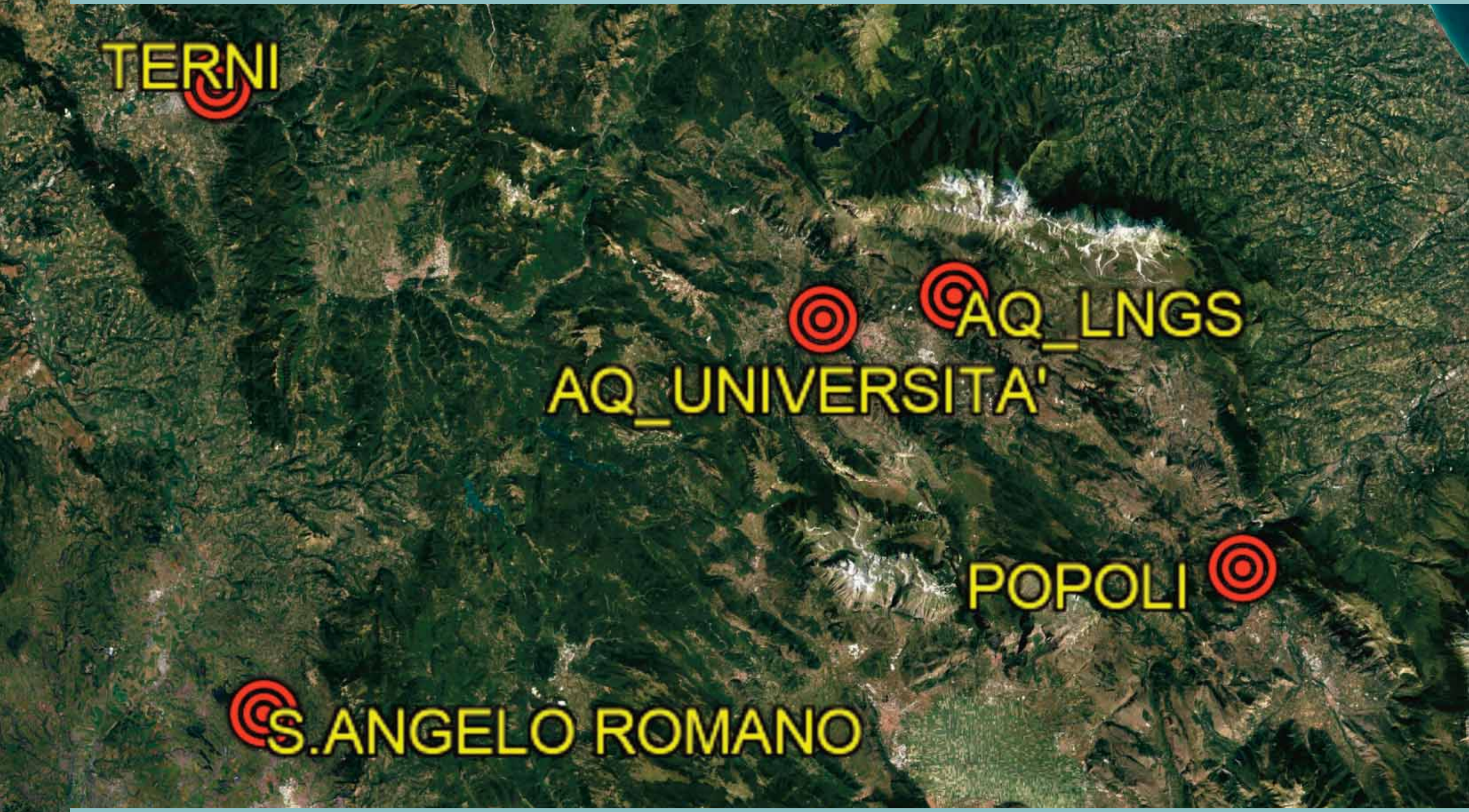

QUADERNI di GEOFISICA

The first combined absolute gravity and GNSS network in Central Italy

167

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The first combined absolute gravity and GNSS network in Central Italy

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Cover Google Earth view of the absolute gravity/GNSS network

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Abstract

A first combined absolute gravity and GNSS network of 5 stations distributed between Lazio, Umbria and Abruzzo regions, was realized in 2018 in order to lay the basics for a multidisciplinary approach to natural risk assessment in the area of Central Italy, affected by the 2009 and 2016 seismic activity. Up to now, two absolute gravity campaigns were carried out using the transportable Micro-g LaCoste FG5#238 and the portable A10#39 absolute gravimeters. The locations of gravimetric sites have been chosen indoor to allow optimal condition of measure; therefore, the heights of the indoor sites have been determined by joining the outdoor GNSS with classical topographic surveys. The good results obtained after the campaigns and data processing lay the foundations for a new multidisciplinary approach to study also seismogenetic areas. In this paper, we present the gravity and GNSS station monographs, together with the absolute gravity values and the coordinates resulting from the first field surveys.

Keywords Sites Monographs; Absolute Gravity Measurements; GNSS Measurements

Introduction

The knowledge of the gravity field has a wide range of applications, among them the study of its varying component. This application is a powerful approach to the detection of space/time variations in underground mass distributions, such as those related to seismic crustal deformations, volcanic dynamics/eruptions and water transfer.

Gravity and physical heights are strictly connected: crustal deformation data, obtained through different geodetic methods, are often used in conjunction with gravity data, allowing to separate different contributes of the same sources and thus providing an overall more complete information of the phenomena [e.g. Berrino, 1994; Bonforte et al., 2017; Greco et al., 2016].

The development of a new generation of transportable absolute gravimeters has increased the accuracy of the gravity measurements to the μGal level, and the development of several permanent GNSS networks has significantly improved the determination of coordinates of points located on the Earth's surface. Consequently, it is possible now to study the related geophysical processes and their time evolution, with finer accuracy.

In Italy, gravimetry is not largely applied in seismic areas in which significant earthquakes generate both coseismic deformations and mass displacements with consequent gravity field changes. The occurrence of the recent seismic events in L'Aquila (2009, Mw 6.3) and then in Amatrice-Norcia (2016, Mw 6.1 and 6.5) suggested the need to implement gravimetric/GNSS networks [Berrino et al., 2018] to start studying such phenomena. Indeed, the study of the medium-long-term gravity and ground deformation variations, related to postseismic effects, observed through highly reliable and accurate data, could provide valuable information for better understanding phenomena related to seismic cycles over this critical area.

The current and recent availability at the INGV of the transportable FG5#238 and the portable A10#39 absolute gravimeters and the wide development of GNSS sites operating continuously, make possible a multidisciplinary approach to study this area. In 2018, the INGV has funded a project entitled "Feasibility of an absolute gravity network in central Italy: toward a multi-disciplinary approach to natural risk assessment", within the call "Progetti di Ricerca Libera", precisely for the purpose of starting this activity.

Therefore, a first wide mesh network of absolute gravity and auxiliary GNSS sites was established, with the idea of expanding it in the next future.

This paper will focus on the monographs in order to properly document the stations of the network; here we give also the first measured absolute gravity values and coordinates determination.

1. State-of-the–art of the gravity/GNSS network in Central Italy

Absolute gravimetric measurements in Italy started in 1970's when a transportable ballistic absolute gravimeter [IMGC; e.g. Alasia et al., 1982] was developed by the Istituto di Metrologia "G. Colonnetti" part of Consiglio Nazionale delle Ricerche based in Turin, and presently Istituto Nazionale per la Ricerca Metrologica (INRiM). Subsequently, several absolute gravity stations were established up to recent times for several purposes, such as:

a. creating a calibration line for relative gravimeters [Berrino, 1995];
b. establishing the Reference Italian Gravity Networks [e.g. Marson and Morelli, 1977; Cannizzo et al., 1978; Berrino et al., 1995; Berrino, 2020];
c. setting up networks for monitoring Italian active volcanoes (Neapolitan and Sicilian volcanoes, Colli Albani) [e.g. Berrino, 1995; 2000; 2020; Berrino et al., 2006; Berrino and Ricciardi, 2020; D'Agostino et al., 2008; Greco et al., 2012; 2015];
d. building up networks to investigate gas storage fields and areas affected by subsidence phenomena [Greco et al., 2011].

The absolute gravity and GNSS basic network established in the framework of the above-mentioned project includes the following five stations [Figure 1; Berrino et al., 2018]:

1. Sant'Angelo Romano (SARO, Province of Rome - Lazio Region);
2. Popoli (POPL, Province of Pescara - Abruzzo Region);
3. L'Aquila (AQUIg, Province of L'Aquila - Abruzzo Region);
4. Terni (TERN, Province of Terni - Umbria Region);
5. INFN Gran Sasso National Laboratory (LNGS, Province of L'Aquila - Abruzzo Region).

The stations were selected taking into account the best geometry of the network in order to optimize the distribution over a large territory, enhancing the interpretation of the phenomena. An important constraint in the choice of the sites was to identify closed and secure structures to house the absolute gravimeters, providing electricity to power the instruments. In addition, particular attention was paid for assessing a possible future re-occupation, ensuring low level of noise to achieve high level of precision and accuracy. A preliminary inspection was also carried out to verify the existence of some sites belonging to the old Italian gravity network in order to possibly carry out new measurements. After this survey, two old gravity stations, Popoli and Terni, measured in 1954 during a gravity survey in Marche and Abruzzo [Morelli, 1955], were found practically not modified. These stations also belonged as main nodes to the 1955 Fundamental Italian Gravity Network, known as the "RFI55" Cunietti and Inghilleri Network [Cunietti and Inghilleri, 1955]. Later, they were also included in the 1977 First Order Gravity Net in Italy [FOGN77; Marson and Morelli, 1978]. This choice could permit to assess the long-term gravity changes, since they have remained unmodified over time.

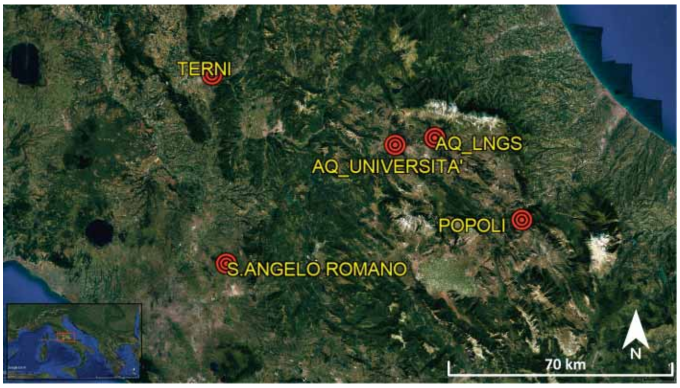


Figure 1 Google Earth view of the absolute gravity/GNSS network, including five stations, measured in 2018 in Central Italy.

The GNSS reference sites of SARO, POPL and TERN were realized outside the buildings hosting the absolute gravimeters. Coordinates and heights of the indoor absolute gravity points were determined connecting the outdoor and indoor points through classical topographic surveys using the optical level station (Leica). At L'Aquila, a permanent GNSS station (AQUI) is continuously working on the roof-top terrace of the Science Faculty and positioned vertically with respect to the gravimetric station (AQUIg), which is located 4 floors below. A total station (Stonex R2-2 plus) has been employed to measure of height difference. The classical survey was carried out on April 5, 2019 in co-operation with the Dipartimento di Ingegneria Civile, Edile e Ambientale (DICEA) of the Sapienza University of Rome [Fortunato et al., 2020].

The GNSS measurements on the 3 non-permanent sites were carried out with a Leica GX1230 receiver and a LEIAX1202 antenna, recording at least 24 h with 30s sampling rate. The compressed raw data were processed in Precise Point Positioning (PPP) modality by the software GAPS (GNSS Analysis and Positioning Service), developed in 2007 at the University of New Brunswick [Canada http://gaps.gge.unb.ca; Leandro et al., 2010], in order to provide users with a free online PPP tool capable of estimating positions and other parameters of interest, using a single GNSS receiver both in static and kinematic mode, through the use of precise orbit and clock products provided by sources such as the International GNSS Service (IGS). The output of the processing provides the geocentric Cartesian coordinates of the sites and their accuracy (Table 1).

Site	2018 doy	X (m)	Y (m)	Z (m)	±X (m)	±Y (m)	±Z (m)
POPL	164	4597005.386	1131816.494	4260115.247	0.004	0.002	0.004
SARO	179	4628413.813	1044129.104	4248794.120	0.003	0.002	0.003
TERN	165	4590524.969	1030790.116	4292232.077	0.002	0.001	0.002

Table 1 Solution after processing with GAPS: sites, measurement epochs, geocentric Cartesian coordinates and accuracies (in meters).

As it is well known, the accuracy obtained after the estimation processing is currently underestimated since some systematic residuals can affect the solutions. Based on our experience, taking into account the temporary feature of the surveys, the accuracy should be within 1 cm in the horizontal and 2 cm in the vertical components.

The coordinates of L'Aquila GNSS permanent site (AQUI) are known with a better accuracy, since obtained after processing long time series of daily observations [Devoti et al., 2017].

The coordinates (latitude, longitude and heights) of the indoor absolute gravity and the outdoor auxiliary gravity and GNSS stations, at the epoch of gravity measurements, are available in Table 2. The table includes both the ellipsoidal and the orthometric heights, thanks to the knowledge of the geoidal undulation model of the Italian area [Barzaghi et al., 2007]. The coordinates and the orthometric heights were useful to post-process the absolute gravity data and to refer all the gravity measurements presented in this work to the equipotential surface of the gravity field (Table 2).

GRAVITY STATIONS	ITRF2014			IGMI-RDN	
	Coordinates		Ellipsoidal height	Orthometric height	Geoidal undulation
	Lat.	Long.	[m]	[m]	[m]
Sant'Angelo Romano (abs. SARO)	42.0351	12.7125	446.928	398.402	48.526
Sant'Angelo Romano (sat.)	42.0351	12.7126	446.904	398.377	48.527
Popoli (abs. POPL)	42.1738	13.8317	291.898	244.370	47.528
Popoli (sat.) - Gate via Marconi 35	42.1737	13.8314	291.800	244.270	47.530
Popoli (sat.) - S. Francesco church (1954 point)	42.1739	13.8385		245.156	
L'Aquila (abs. AQUIg)	42.3682	13.3502	698.004	649.316	48.688
L'Aquila (sat.) from cartography	42.3680	13.3501		650	
Terni (abs. TERN)	42.5658	12.6557	175.123	126.535	48.588
Terni (sat.) - Gate via Brin 30 (1954 point)	42.5652	12.6552	174.823	126.235	48.588
Terni (sat.) - IGMI benchmark (from the school on the left side)	42.5651	12.6557	175.087	126.498	48.589
Terni (sat.) - IGMI benchmark (from the school on the right side)	42.5652	12.6553	175.032	126.444	48.588
INFN Gran Sasso National Laboratory (LNGS) from cartography	42.4204	13.5151		981	

GNSS STATIONS	ITRF2014			IGMI-RDN	
	Coordinates		Ellipsoidal heights	Orthometric heights	Geoidal undulations
	Lat.	Long.	(m)	(m)	(m)
Sant'Angelo Romano	42.0350	12.7126	446.386	397.859	48.527
Popoli	42.1737	13.8315	291.935	244.406	47.529
L'Aquila (AQUI)	42.3682	13.3502	712.974	664.286	48.688
Terni	42.5660	12.6557	175.002	126.414	48.588

Table 2 Coordinates of the absolute (abs.), satellite (sat.) gravity and GNSS stations measured in the frame of the project. The ellipsoidal and orthometric heights, as well as the geoid undulation, are also reported.

For both gravity and GNSS sites (apart from L'Aquila), no dedicated pillars were made for the measurements; the instruments were positioned directly on the floor/ground, avoiding sources of noise and unstable conditions. Each site has been mapped and hence, the exact position, orientation and how the instruments were placed on the ground can be easily recognized (Figures 2-6).

Finally, the determination of the local vertical gradient of gravity at each absolute station was carried out, and in order to "transport" the absolute g values outside and close to the buildings hosting the absolute gravity stations, outdoor satellite gravimetric sites were also established. The presence of the satellite gravimetric sites is important in order to perform rapid links during any gravimetric field survey that need to be linked to the absolute gravity value. Relative measurements were collected using the LaCoste & Romberg model D s.n. 85 (LCR-D#85, owned and managed by INGV–OV) relative gravimeter.

The absolute gravity measurements were performed with two absolute gravimeters available at INGV: the transportable Micro-g LaCoste FG5#238 (owned by ENI and managed by INGV-OE), and the portable Micro-g LaCoste A10#39 (owned and managed by INGV–OV). The FG5 is designed for measurements in laboratory or like-laboratory conditions; it is not well-suited for portable use on the field, since it is large and heavy (about 300 kg in different modules and requires floor space of about 3 m^2), has a limited operating temperature range (10 to 30 °C) and requires facilities to house the instrumentation. Nevertheless, it has been used in adverse field conditions like on active volcanoes [e.g., Kazama and Okubo, 2009; Greco et al., 2012; Kazama et al., 2015; Carbone et al., 2017]. Conversely, the A10 is designed on purpose for field measurements (indoor and outdoor) and fast field operations, while preserving the characteristics of a laboratory instrument. Both instruments work using a ballistic free-fall method: a test mass (retro-reflective corner cube) is dropped vertically by a mechanical device (drug-free cart) inside a vacuum dropping chamber. An ion pump that runs continuously maintains the vacuum. The absolute g value is measured through the reconstructed trajectory of the dropping mass subjected to the gravity field. A laser interferometer generates optical interference fringes as the test mass falls. An atomic clock counts and times the fringes in order to obtain precise time and distance pairs. These data are fitted to a parabolic trajectory to give a measured value of g [Niebauer et al., 1995].

A dedicated software provides the automatic data acquisition, the real time processing and the automatic data storage. It also automatically corrects the measured g value for gravity changes due to solid-earth tides, ocean tide loadings, polar motion and local air pressure changes and if necessary to reduce automatically the g values from the measured heights at any convenient height from the ground, through the measured local value of the vertical gravity gradient. It also permits to reprocess data.

2. Stations monographs and related schemes

In this paragraph and its following sub-sections, we present the monographs of each gravity/GNSS station where also the gravity values and coordinates resulting from the first field surveys are given. During the campaigns, also a photographic survey was carried out.

The absolute gravity station monographic scheme is organized in four sections as shown in the following general scheme:

a. the first section, containing also the INGV's Logo, reports the title of the card with the name of the absolute station;
b. the second section furnishes the name and the acronym of the absolute station, information about the geographic location of the site, the coordinates and the nominal air pressure value depending from the elevation of the station;

c. the third section, shows a Google Earth view of the area where the station is located, a planimetric map of the room with the exact location and orientation of the measurement site and photos of a view of the exterior of the building hosting the absolute station;
d. the fourth section includes photos of both the Micro-g LaCoste FG5#238 and A10#39 during the measurement sessions showing the exact position and orientation of both instruments, and of the supports to measure the vertical gravity gradient at different heights with the relative gravimeter LCR-D#85.

Regarding the outdoor GNSS/topographic benchmarks and the satellite gravity stations, an additional scheme showing photos with the position of the stations is furnished.

Each monographic scheme is introduced by a description of the absolute gravity station including some information about the time of measurements, the measured differences between the two instruments, the measured Δg at the satellite station/s, as well as the value of the vertical gravity gradient. Measured gravity values at different heights and related necessary information are also summarized in a table, which columns show:

1. data, measurement time interval in UTC and the mean value of the measured air pressure during the measurement sessions;
2. the used instrument and the measured height h (elevation above the ground to which g is measured);
3. the number of sets, drops per sets and total number of drops for each session;
4. absolute gravity values at the measured height h;
5. absolute gravity values at the reference height of 0.72 m;
6. absolute gravity values on the ground.

In the table for each absolute gravity value is also indicated the combined standard uncertainty of g. In the lines below the value of the locally measured free-air vertical gradient γ and the measured Δg at the satellite gravity station/s with the uncertainties are also reported.

The coordinates of all the measured stations are given in the above Table 2.

2.1 Sant'Angelo Romano (SARO)

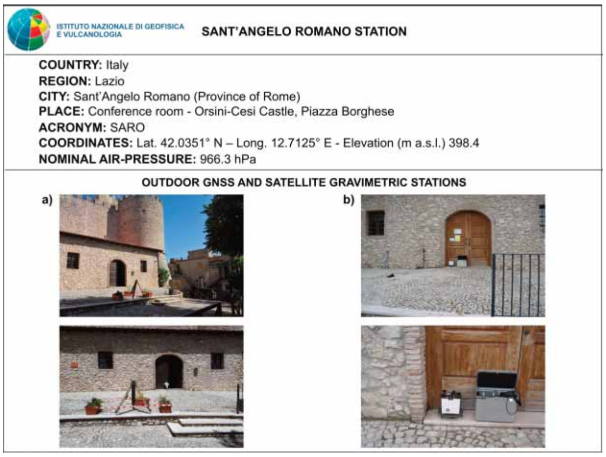
Sant'Angelo Romano (RM) absolute station (SARO) was installed and measured in 2005 and belongs to the gravimetric/deformation network of Colli Albani [Berrino et al., 2006; Riguzzi et al., 2007]. Measurements at this absolute station were repeated in 2007 and 2010 [e.g. Berrino et al., 2010] using the IMGC-02 absolute gravimeter. The station is settled within the conference room of the Orsini-Cesi castle, in Piazza Borghese, located at the top of the village. The GNSS point was placed in front of the entrance of the castle and the satellite station is located on the left side of the entry, on the marble threshold. Figures 2a-b show the monograph of the station. In the frame of the present project, the SARO station was measured twice with the FG5#238, in mid-June and early-October 2018 and in late-September 2018 with the A10#39. With the A10#39, a long-field survey (1 hours) and long-laboratory (14 hours during the night) measurements were carried out on 25 and 25-26 September 2018. By comparing the values obtained with both instruments, referred to the same elevation from the ground and measured during the same period, we found a discrepancy of about −33 µGal between A10#39 and FG5#238 values. The final g values at different heights with the associated combined standard uncertainties are reported in Table 3. A gravity difference (Δg) of + 22 ± 4 µGal was measured by connecting the indoor absolute station (SARO) and the outdoor satellite station, confirming the value measured in 2005.

Absolute gravity measurements at Sant'Angelo Romano station (SARO)					
Date Time UTC (from ÷ to) P (hPa)	Meter and measured height (m)	Number of sets/drops per set/total drops	g at measured height ± Combined Uncertainty (µGal)	g at 0.72 m ± Combined Uncertainty (µGal)	g at ground ± Combined Uncertainty (µGal)
11-12 Jun 2018 17:21 ÷ 06:21 964.6	FG5#238 1.2972	14/100/1400	980285581.2 ± 3.3	980285811.5 ± 4.1	980286098.7 ± 6.3
25 Sept. 2018 14:30 ÷ 15:30 975.0	A10#039 0.72	20/120/2400	980285766.7 ± 3.2	980285766.7 ± 3.2	980286053.9 ± 4.4
25-26 Sept. 2018 16:30 ÷ 05:30 978.1	A10#039 0.72	28/120/3360	980285770.0 ± 2.2	980285770.0 ± 2.2	980286057.2 ± 3.7
01-02 Oct. 2018 14:46 ÷ 06:15 962.5	FG5#238 1.2942	17/100/1700	980285572.2 ± 3.4	980285801.2 ± 4.1	980286088.4 ± 6.3
Vertical gravity gradient (11 June 2018) dg/dh = -398.9 ± 4.1 µGal/m					
Δg at the external relative satellite station respect to the absolute site at ground = + 22 ± 4 µGal					

Table 3 Absolute gravity measurements collected at Sant'Angelo Romano (SARO) station during June-October 2018 period by FG5#238 and A10#39 absolute ballistic gravimeters.

COUNTRY: Italy
REGION: Lazio
CITY: Sant'Angelo Romano (Province of Rome)
PLACE: Conference room - Orsini-Cesi Castle, Piazza Borghese
ACRONYM: SARO
COORDINATES: Lat. 42.0351° N – Long. 12.7125° E - Elevation (m a.s.l.) 398.4
NOMINAL AIR-PRESSURE: 966.3 hPa

Figure 2a Schematic monograph and pictures of Sant'Angelo Romano (SARO) absolute gravity station. a) Google Earth view of Sant'Angelo Romano village where the Orsini-Cesi castle is located; b) map of the conference room with the exact location of the measurement point; c) photos of the exterior of the castle showing the entrance of the conference room; d) and e) the Micro-g LaCoste FG5#238 and A10#39 during the measurement sessions, respectively; f) the supports to measure the vertical gravity gradient at different heights with the relative gravimeter LCR-D#85.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SANT'ANGELO ROMANO STATION

COUNTRY: Italy
REGION: Lazio
CITY: Sant'Angelo Romano (Province of Rome)
PLACE: Conference room - Orsini-Cesi Castle, Piazza Borghese
ACRONYM: SARO
COORDINATES: Lat. 42.0351° N – Long. 12.7125° E - Elevation (m a.s.l.) 398.4
NOMINAL AIR-PRESSURE: 966.3 hPa

OUTDOOR GNSS AND SATELLITE GRAVIMETRIC STATIONS

Figure 2b Photos of Sant'Angelo Romano (SARO) outdoor GNSS (a) installed in front of the main entrance of the Orsini-Cesi castle, and satellite gravity (b) stations on the left side of marble threshold. The exact position and orientation of the relative gravimeter LCR-D#85 is shown.

2.2 Popoli (POPL)

The absolute gravity station at Popoli (POPL) was positioned inside the "Antonio Verna" Day Cultural Center, in Via Guglielmo Marconi 35, in the downtown of Popoli (PE). The instruments were installed on the concrete base of a room, used as a deposit. The GNSS point was placed in the garden of the building; the satellite gravity station has been positioned at the base of the left column of the entrance gate (Figure 3a-b). The absolute station was measured twice with the FG5#238, in June and October 2018 and on 26 September 2018 with the A10#39. With the A10#39, a long-field survey (1 hours) was carried out. We found a difference of -14 µGal between the values collected with the A10#39 with respect that observed in October with the FG5#238.

A gravity difference (Δg) of -324 ± 3 µGal was measured between the indoor absolute station (POPL) and the outdoor satellite station. Moreover, two additional points located at the church of S. Francesco (Piazza della Libertà), one of which corresponding to the 1954 station (see above), were linked to the absolute station and the following Δg were measured (Table 4):

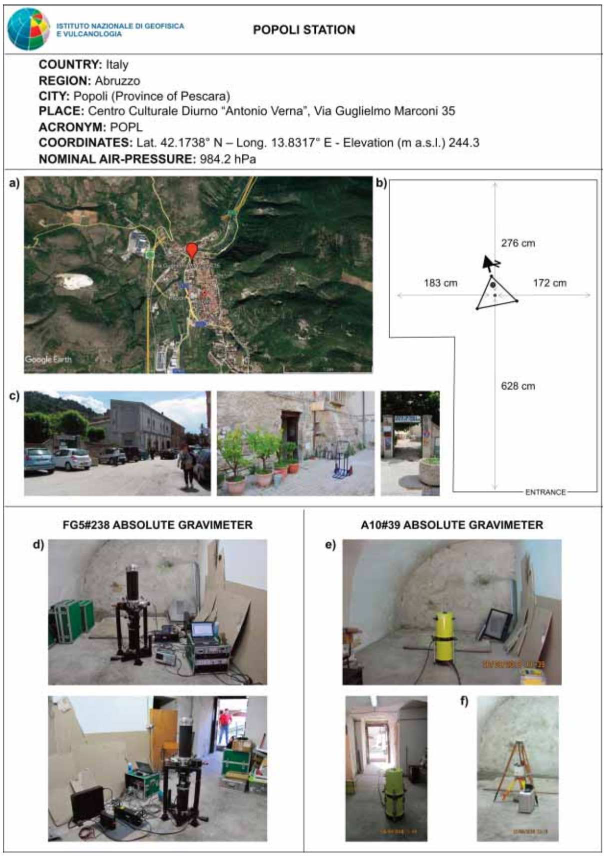
- IGMI monumented horizontal benchmark, on the manhole (at the base of the staircase – left corner of the church) Δg = -269 ± 4 µGal.
- The 1954 relative gravity station (at the base of the staircase, on the road in axis to the entrance door of the church) Δg = -92 ± 4 µGal.

The heights of these gravimetric sites were measured through levelling surveys to the IGMI benchmarks.

Absolute gravity measurements at Popoli station (POPL)					
Date Time UTC (from ÷ to) P (hPa)	Meter and measured height (m)	Number of sets/drops per set/total drops	g at measured height ± Combined Uncertainty (µGal)	g at 0.72 m ± Combined Uncertainty (µGal)	g at ground ± Combined Uncertainty (µGal)
12-13 June 2018 14:25 ÷ 06:25 978.7	FG5#238 1.2957	17/100/1700	980265013.4 ± 3.4	980265150.8 ± 3.5	980265322.7 ± 4.0
26 Sept. 2018 10:00 ÷ 11:00 1003.7	A10#039 0.72	20/120/2400	980265134.4 ± 2.8	980265134.4 ± 2.8	980265306.3 ± 3.1

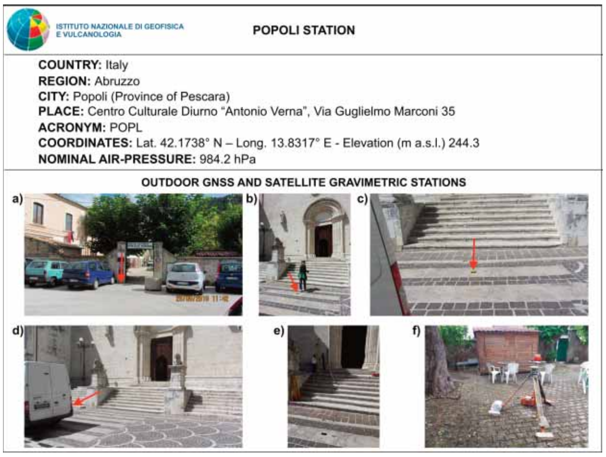
02-03 Oct. 2018 12:01 ÷ 05:33 989.8	FG5#238 1.2957	19/100/1900	980265011.2 ± 3.4	980265148.6 ± 3.5	980265320.4 ± 4.0
Vertical gravity gradient (12 June 2018) dg/dh = -238.7 ± 1.7 μGal/m					
Δg at the external relative satellite station respect to the absolute site at ground = -324 ± 3 μGal					
Δg over the IGMI horizontal benchmark manhole (S. Francesco church, left corner) respect to the absolute site at ground = -269 ± 4 μGal					
Δg at the 1954 relative station (S. Francesco church, on the road) respect to the absolute site at ground = -92 ± 4 μGal					

Table 4 Absolute gravity measurements collected at Popoli (POPL) station during June-October 2018 period by FG5#238 and A10#39 absolute ballistic gravimeters.



COUNTRY: Italy
REGION: Abruzzo
CITY: Popoli (Province of Pescara)
PLACE: Centro Culturale Diurno "Antonio Verna", Via Guglielmo Marconi 35
ACRONYM: POPL
COORDINATES: Lat. 42.1738° N – Long. 13.8317° E - Elevation (m a.s.l.) 244.3
NOMINAL AIR-PRESSURE: 984.2 hPa

Figure 3a Monograph and pictures of Popoli (POPL) absolute gravity station. a) Google Earth view of Popoli village showing the location of the Centro Culturale Diurno "Antonio Verna", selected to make absolute gravity measurements; b) map of the deposit hosting the station with the exact location of the measurement point; c) photos of the exterior of the building; d) and e) the Micro-g LaCoste FG5#238 and A10#39 during the measurement sessions, respectively; f) the supports to measure the vertical gravity gradient with the relative gravimeter LCR-D#85.



COUNTRY: Italy
REGION: Abruzzo
CITY: Popoli (Province of Pescara)
PLACE: Centro Culturale Diurno "Antonio Verna", Via Guglielmo Marconi 35
ACRONYM: POPL
COORDINATES: Lat. 42.1738° N – Long. 13.8317° E - Elevation (m a.s.l.) 244.3
NOMINAL AIR-PRESSURE: 984.2 hPa

Figure 3b Photos of the position of Popoli (POPL) satellite gravity stations: a) located outside the "Antonio Verna" Day Cultural Center, in Via Guglielmo Marconi 35; b) and c) at the Church of S. Francesco, in the Popoli main square (Piazza Matteotti), corresponding to the 1954 station; d) IGMI levelling manhole at the entry of the Church (red arrow); e) IGMI levelling benchmark at the Church of S. Francesco, from which the elevation at the 1954 IGMI station was derived and f) GNSS station positioned inside the center "Antonio Verna" Day Cultural Center.

2.3 L'Aquila (AQUIg)

The absolute gravity station in L'Aquila (AQUIg) was installed at the Science Faculty of the L'Aquila University, located in Coppito village, Via Vetoio n. 42. The station was settled on the floor of the Geomagnetic Laboratory of the Physics Department. No GNSS measurements were carried out because a permanent station is located in the same place; it has been linked to the gravity station by means of a high precise topographic survey [Fortunato et al., 2020]. The satellite station has been placed at the right side of the garage entrance gate, next to the entrance leading to the laboratory. A schematic monograph of the gravimetric station is shown in Figure 4a-b.

The permanent GNSS station named AQUI was installed in 1999 and currently maintained by the Italian Space Agency (ASI) at the Science Faculty of the L'Aquila University. The antenna, a LEIAR20 choke-ring, is settled on the roof-top terrace of the building and screwed on a steel pillar. We adopted the classical topographic survey to estimate the height and coordinates difference between AQUI (on the roof) and the gravimetric benchmark AQUIg, located three floors below the roof of the same building (Table 1; [Fortunato et al., 2020]).

The absolute gravity measurements were carried out twice with the FG5#238, in June and October 2018 and during the second half of September 2018 with the A10#39.

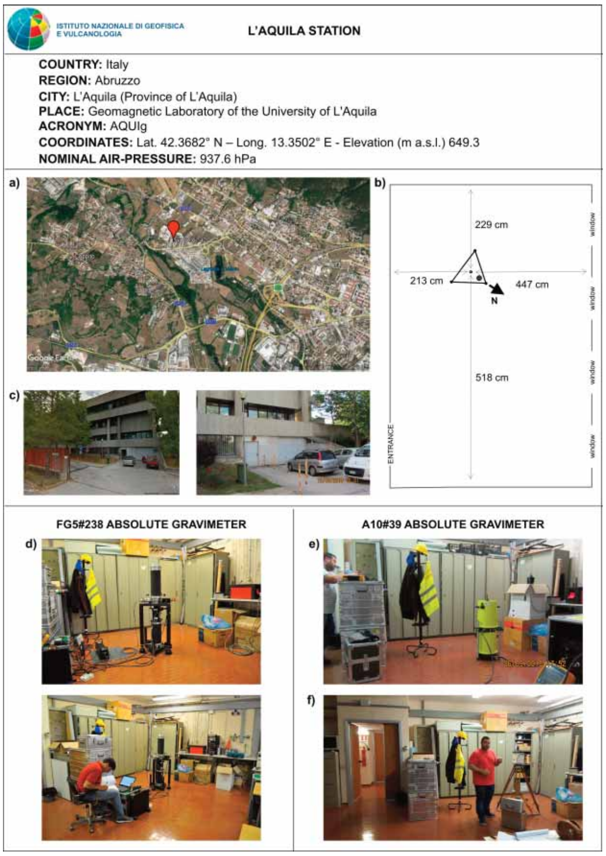
With the A10#39, a long-field survey (1 hours) and long-laboratory (14 hours during the night) measurements were carried out on 26 and 27 September 2018.

By comparing the values obtained with both instruments, referred to the same elevation from the ground, we found a discrepancy of about -19.7 µGal between A10#39 and FG5#238 values. The final g values at the measured heights and at the referred heights with the associated combined standard uncertainties are reported in Table 5.

The AQUIg station was linked to an external satellite station on 26 June 2018 using the LCR-D#85 relative gravimeter and a gravity difference (Δg) of + 88 ± 3 µGal was found.

Absolute gravity measurements at L'Aquila station (AQUIg)					
Date Time UTC (from ÷ to) P (hPa)	Meter and measured height (m)	Number of sets/drops per set/total drops	g at measured height ± Combined Uncertainty (µGal)	g at 0.72 m ± Combined Uncertainty (µGal)	g at ground ± Combined Uncertainty (µGal)
13-14 June 2018 13:54 ÷ 05:54 931.9	FG5#238 1.2932	15/100/1500	980203143.5 ± 3.4	980203298.0 ± 3.5	980203492.1 ± 4.0
26 Sept. 2018 15:40 ÷ 16:40 954.5	A10#039 0.72	20/120/2400	980203279.2 ± 4.1	980203279.4 ± 4.1	980203473.3 ± 4.3
26-27 Sept. 2018 17:00 ÷ 06:03 955.5	A10#039 0.72	18/120/2069	980203271.9 ± 3.9	980203271.9 ± 3.9	980203466.0 ± 4.1
03-04 Oct. 2018 14:46 ÷ 05:46 945.2	FG5#238 1.2952	16/100/1600	980203140.2 ± 3.4	980203295.3 ± 3.5	980203489.4 ± 4.1
Vertical gravity gradient (12 June 2018) dg/dh = -269.6 ± 1.7 µGal/m					
Δg at the external relative satellite station respect to the absolute site at ground = +88 ± 3 µGal					

Table 5 Absolute gravity measurements collected at L'Aquila (AQUIg) station during June-October 2018 period by FG5#238 and A10#39 absolute ballistic gravimeters.



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

L'AQUILA STATION

COUNTRY: Italy
REGION: Abruzzo
CITY: L'Aquila (Province of L'Aquila)
PLACE: Geomagnetic Laboratory of the University of L'Aquila
ACRONYM: AQUIg
COORDINATES: Lat. 42.3682° N – Long. 13.3502° E - Elevation (m a.s.l.) 649.3
NOMINAL AIR-PRESSURE: 937.6 hPa

Figure 4a Schematic monograph and photos of L'Aquila (AQUIg) absolute gravity station. a) Google Earth view showing the L'Aquila University, located in Coppito village, selected to make the absolute gravity measurement; b) map of the Geomagnetism Laboratory of the University of L'Aquila, with the exact location of the measurement point; c) the exterior of the building showing the entrance to the laboratories; d) and e) the Micro-g LaCoste FG5#238 and A10#39 during the measurement sessions, respectively; f) the supports to measure the vertical gravity gradient.

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

L'AQUILA STATION

COUNTRY: Italy
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CITY: L'Aquila (Province of L'Aquila)
PLACE: Geomagnetic Laboratory of the University of L'Aquila
ACRONYM: AQUIg
COORDINATES: Lat. 42.3682° N – Long. 13.3502° E - Elevation (m a.s.l.) 649.3
NOMINAL AIR-PRESSURE: 937.6 hPa

Figure 4b Schematic monograph and photos of L'Aquila (AQUIg) satellite gravity and GNSS (AQUI) stations. a) and b) location of the outdoor satellite gravity station with the exact position of the relative gravimeter LCR-D#85; c) location of the GNSS station (AQUI) settled on the roof-top terrace of the building; d) topographic measurements to connect the outdoor station AQUI with the indoor absolute station (AQUIg; see [Fortunato et al., 2020]).

2.4 Terni (TERN)

Terni station (TERN) was placed within the Officina Motori n. 4 of the Istituto Omnicomprensivo IPSIA "Sandro Pertini", Viale Benedetto Brin, 32 in the city of Terni (Figure 5a). The GNSS point was placed in the area of the school; coordinates and height of the absolute gravity point inside the Officina Motori n. 4 were obtained connecting the outdoor and indoor points.
The new station TERN was measured with the FG5#238 in June and October 2018 and during the second half of September 2018 with the A10#39. The instruments were placed directly on the floor, which guaranteed stability during the measurements. With the A10#39, 1-hour session of measurements was carried out.

By comparing the values obtained with both instruments, referred to the same elevation from the ground, we found a discrepancy of about -25 µGal.

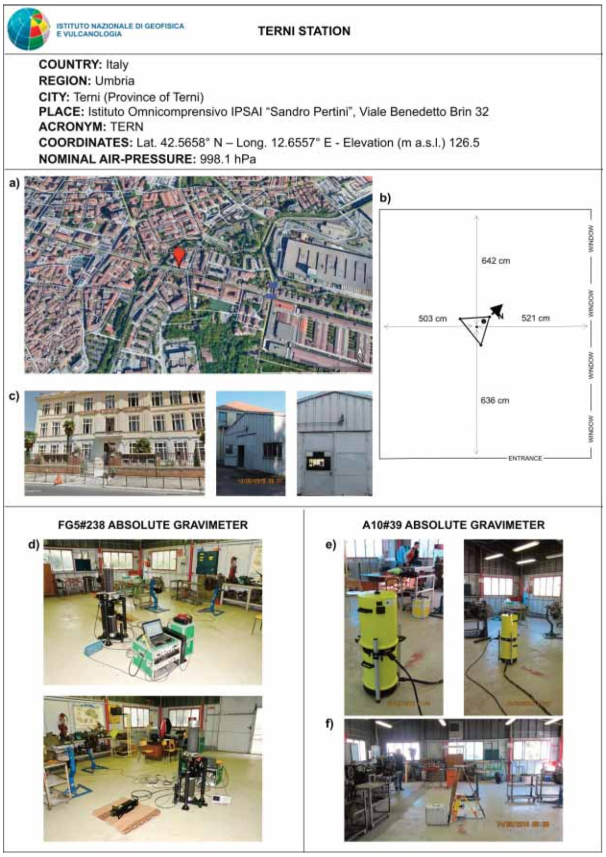
The final g values and the associated combined standard uncertainty are reported in Table 6. It should be emphasized that the site was rather influenced by local environmental disturbance, as can also be seen from the uncertainty values reported for all the measures in the Table 6.

The TERN absolute station, installed within the Officina Motori n. 4, was connected with three satellites stations located in the area of the school. Specifically, the point already measured in 1954 and in 1977, and two IGMI benchmarks monumented laterally at the edges of the garden at the main entry (Figure 5b) and the following Δgs were found:

- Δg from abs station to 1954 satellite station “gate Viale Brin” = -10 ± 2 µGal;
- Δg from abs station to satellite station “IGMI benchmark” (right side looking at the gate) = -48 ± 3 µGal;
- Δg from abs station to satellite station “IGMI benchmark” (left side looking at the gate) = -158 ± 4 µGal.

Absolute gravity measurements at Terni station (TERN)					
Date Time UTC (from ÷ to) P (hPa)	Meter and measured height (m)	Number of sets/drops per set/total drops	g at measured height ± Combined Uncertainty (µGal)	g at 0.72 m ± Combined Uncertainty (µGal)	g at ground ± Combined Uncertainty (µGal)
14-15 June 2018 12:07 ÷ 06:51 991.1	FG5#238 1.2952	9/100/900	980380681.7 ± 3.4	980380859.6 ± 4.9	980381082.3 ± 8.7
27 Sept. 2018 09:39 ÷ 10:39 1011.5	A10#039 0.72	20/120/2400	980380826.5 ± 8.2	980380826.5 ± 8.2	980381049.2 ± 9.3
04-05 Oct. 2018 10:34 ÷ 06:24 1004.9	FG5#238 1.2997	7/100/700	980380671.7 ± 3.4	980380851.0 ± 4.9	980381073.7 ± 8.7
Vertical gravity gradient (14 June 2018) dg/dh = -309.3 ± 6.2 µGal/m					
Δg at the external 1954 relative satellite station respect to the absolute site at ground = -10 ± 2 µGal					
Δg at the IGMI right benchmark respect to the absolute site at ground = -48 ± 3 µGal					
Δg at the IGMI left benchmark respect to the absolute site at ground = -158 ± 4 µGal					

Table 6 Absolute gravity measurements collected at Terni station (TERN) during June-October 2018 period by FG5#238 and A10#39 absolute ballistic gravimeters.

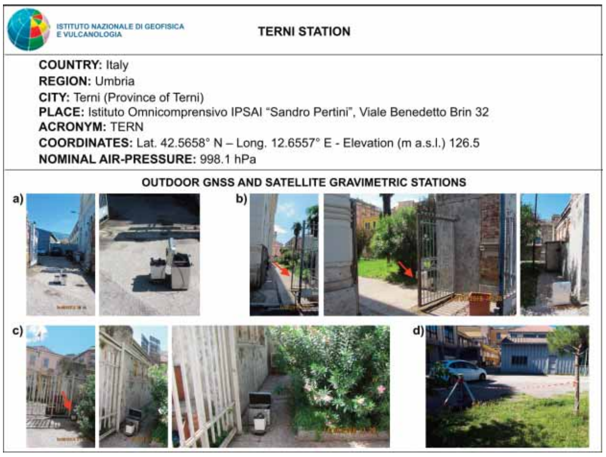


ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

TERNI STATION

COUNTRY: Italy
REGION: Umbria
CITY: Terni (Province of Terni)
PLACE: Istituto Omnicomprensivo IPSAI "Sandro Pertini", Viale Benedetto Brin 32
ACRONYM: TERN
COORDINATES: Lat. 42.5658° N – Long. 12.6557° E - Elevation (m a.s.l.) 126.5
NOMINAL AIR-PRESSURE: 998.1 hPa

Figure 5a Schematic monograph and photos of Terni (TERN) absolute gravity station. a) Google Earth view of the Istituto Ominicomprensivo IPSAI "Sandro Pertini", located in Viale B. Brin 32, in the city of Terni, selected to make the absolute gravity measurement; b) map of the Officina n. 4 with the exact location of the measurement point; c) exterior of the school and the main entrance of the Officina Motori n. 4; d) and e) the Micro-g LaCoste FG5#238 and A10#39 during the measurement sessions, respectively; f) the supports to measure the vertical gravity gradient.



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

TERNI STATION

COUNTRY: Italy
REGION: Umbria
CITY: Terni (Province of Terni)
PLACE: Istituto Omnicomprensivo IPSAI "Sandro Pertini", Viale Benedetto Brin 32
ACRONYM: TERN
COORDINATES: Lat. 42.5658° N – Long. 12.6557° E - Elevation (m a.s.l.) 126.5
NOMINAL AIR-PRESSURE: 998.1 hPa

OUTDOOR GNSS AND SATELLITE GRAVIMETRIC STATIONS

Figure 5b Photos of Terni (TERN) outdoor GNSS and satellite gravity stations installed within the Istituto Omnicomprensivo IPSAI "Sandro Pertini", located in Viale B. Brin 32, in the city of Terni. a) location of the satellite station already measured in 1954 close to the gate of Viale B. Brin; b) location of the satellite gravimetric station on a IGMI monumented benchmark in the courtyard of the main entrance of the school (right side looking at the main entrance gate); c) location of the satellite gravimetric station on a IGMI monumented benchmark in the courtyard of the main entrance of the school (left side looking at the main entrance gate); d) location of the GNSS station in the area of the school.

2.5 INFN Gran Sasso Laboratory (LNGS$_{Ext}$)

The gravity station at the INFN Gran Sasso Laboratory (LNGS$_{Ext}$), External Offices, coincides with a relative gravity point installed in 2010 when, following the 2009 earthquake, also an absolute gravity measurement was carried out for the first time at the Town Hall of L'Aquila city [Berrino et al., 2010]. This last was realized in order to replace a site in the INFN Underground Gran Sasso Laboratory (LNGS$_{Und}$), planned to belong to the Zero Order Gravity Network [Berrino et al., 1995], where in 1995 only the vertical gravity gradient was measured since there was no possibility to perform the absolute measurement. In 2010 the $\mathrm{LNGS_{Ext}}$ station was also linked to the underground station ($\mathrm{LNGS_{Und}}$) and also to the satellites gravity points of the Sant'Angelo Romano, Monte Porzio Catone and Palestrina absolute gravity stations by means of relative measurements [Berrino et al., 2010].

In the framework of the 2018 Project, the link with the original 1995 station inside the $\mathrm{LNGS_{Und}}$ Underground Laboratory, was already attempted, but it was not accomplished because the site was temporarily not employable; therefore, a new $\mathrm{LNGS_{Und}}$ point, just few meters far from the original one and on a very flat concrete floor, was measured.

The new INFN absolute station ($\mathrm{LNGS_{Ext}}$) is located outside the laboratory, where measurements can only be made with field gravimeters (Figure 6). With the A10#39 a 1-hour session measurement was carried out on 26 September 2018; the final g value with the associated combined standard uncertainty is reported in Table 7. The value has not been reported to the ground since we have not measured the vertical gravity gradient.

Absolute gravity measurements at INFN Gran Sasso National Laboratory ($\mathrm{LNSG_{Ext}}$)			
Date Time UTC (from ÷ to) P (hPa)	Meter and measured height (m)	Number of sets/drops per set/total drops	g at 0.72 m ± Combined Uncertainty (µGal)
26 Sept. 2018 13:40 ÷ 14:10 917.7	A10#039 0.72	8/120/960	980135917.1 ± 3.9

Table 7 Absolute gravity value collected at INFN Gran Sasso station ($\mathrm{LNGS_{Ext}}$) on 26 September 2018 using the A10#39 absolute gravimeters designed for field measurements and fast field operations.

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

INFN GRAN SASSO LABORATORY

COUNTRY: Italy
REGION: Abruzzo
CITY: L'Aquila (Province of L'Aquila)
PLACE: INFN Gran Sasso National Laboratory
ACRONYM: LNSG
COORDINATES: Lat. 42.4204° N – Long. 13.5151° E - Elevation (m a.s.l.) 981.0
NOMINAL AIR-PRESSURE: 900.8 hPa

Figure 6 Schematic monograph and photos of INFN Gran Sasso ($\mathrm{LNSG_{Ext}}$) absolute gravity station. a) Google Earth view of the INFN Gran Sasso National Laboratory, selected to make the absolute gravity measurement; b) exterior of the laboratory where the station was settled; c) the Micro-g LaCoste A10#39 during the measurement session; d) location of the satellite station connected with the relative gravimeter LCR-D#85.

3. Conclusions

This paper focused on the monographs of the combined absolute gravity and GNSS stations installed in Central Italy and give information on the main results of the first measurement campaigns carried out in the period June-October 2018. For each absolute gravity station, the direct measure of the local vertical gradient of gravity have been also carried out and at least an auxiliary relative gravity station has been settled.

For all these stations we provide coordinates and both ellipsoidal and orthometric heights referred to the epoch of surveys.

For each absolute station, we furnish a detailed monographic scheme showing, by means of planimetry, maps and photos, the location of the site and the exact position of the instrument, the position of the GNSS and of the satellite gravity stations. All the schemes are preceded by a description of the station also containing information on the dates of the measurements, the instrumentation used, the differences in the gravity values between the two instruments and the Δg measured at the satellite stations. All these data are then summarized in specific tables.

By comparing the g values acquired with both FG5#238 and A10#039 absolute gravimeters at common heights of 0.72 m and at ground, we found differences which cannot be justified by measurements uncertainties. Anyway, these first measurements were fundamental to highlight a possible physiological bias between the two different types of instruments, even if the evaluation of the differences obtained by the two instruments is not the aim of this paper. Here we can only state that some inter-comparisons will be carried out between A10#039 and FG5#238, also together with the IMGC-02 (National Standard Instrument in Italy), to assess any bias between the two instruments. The results of the inter-comparisons will be taken into account in data reprocessing.

Finally, we are confident that this paper could represents a guide for the new researches of the related sciences who wants to study this area of Italy.

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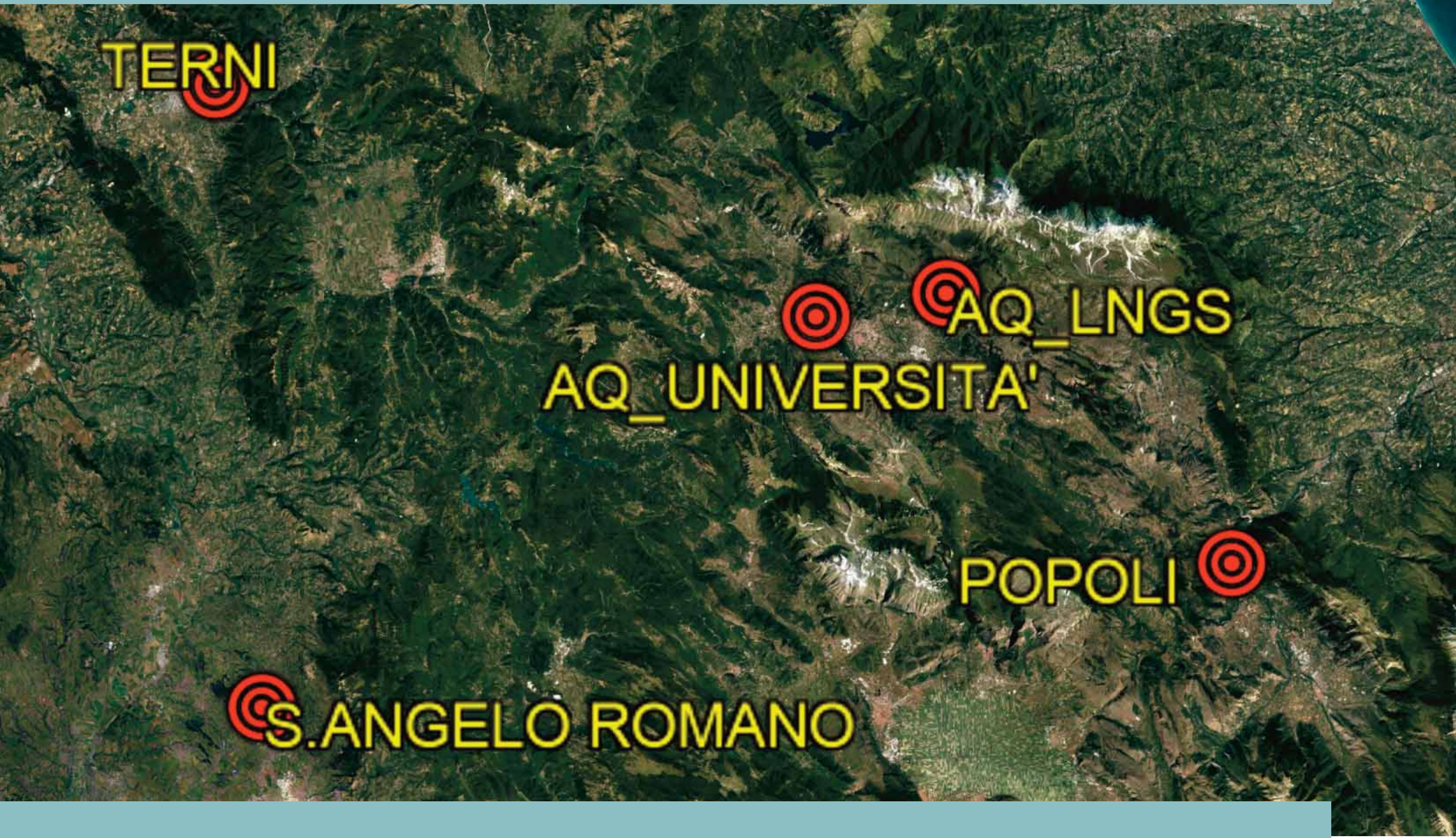

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