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The new IMGC-02 transportable absolute gravimeter: measurement apparatus and applications in geophysics and volcanology

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Abstract

The research carried out at the Istituto Nazionale di Ricerca Metrologica (formerly Istituto di Metrologia «G. Colonnetti») aiming to develop a transportable ballistic absolute gravimeter ended with a new version of the instrument, called the IMGC-02. It uses laser interferometry to measure the symmetrical free rising and falling motion of a test mass in the gravity field. Providing the same accuracy achieved with previous versions, the instrumental improvements mainly concern size, weight, data processing algorithms and operational simplicity. An uncertainty of 9 μGal (1 μGal$=1\times10^{-8}$ m·s^{-2}) can be achieved within a single observation session, lasting about 12 h, while the time series of several observation sessions show a reproducibility of 4 μGal. At this level, gravity measurements provide useful information in Geophysics and Volcanology. A wide set of dynamic phenomena, *i.e.* seismicity and volcanic activity, can produce temporal gravity changes, often quite small, with an amplitude ranging from a few to hundreds of microgals. Therefore the IMGC absolute gravimeter has been employed since 1986 in surveying the Italian active volcanoes. A brief history of the gravimeter and the description of the new apparatus, together with the main results of ongoing applications in Geophysics and Volcanology are presented.

Key words *gravity – absolute gravimeter – measurements – geophysics – volcanology*

1. Introduction

The best accuracy achievable in measuring the acceleration due to gravity g is estimated to be few microgals (1 μGal$=1\times10^{-8}$ m·s^{-2}) and concerns modern absolute ballistic gravimeters. The local g value is extracted from the trajectory of a free falling test body by fitting a suitable motion model to the time-space coordinates. Such accuracy is reached by using optical interferometric methods to track the test mass flight. The wavelength of an iodine-stabilized laser beam (helium-neon) used to illuminate the interferometer is the standard of length while the frequency of an atomic resonator (rubidium) used to synchronize the acquisition system, is the standard of time.

Since 1968, starting with the technical assistance of the Bureau International des Poids et Mesures – BIPM, the construction and maintenance of transportable absolute gravimeters has been continued at the Istituto di Metrologia «G. Colonnetti» (now Istituto Nazionale di Ricerca Metrologica – INRIM) (Cerutti, 1967, 1971; Cerutti *et al.*, 1974). Figure 1 shows the first ver-

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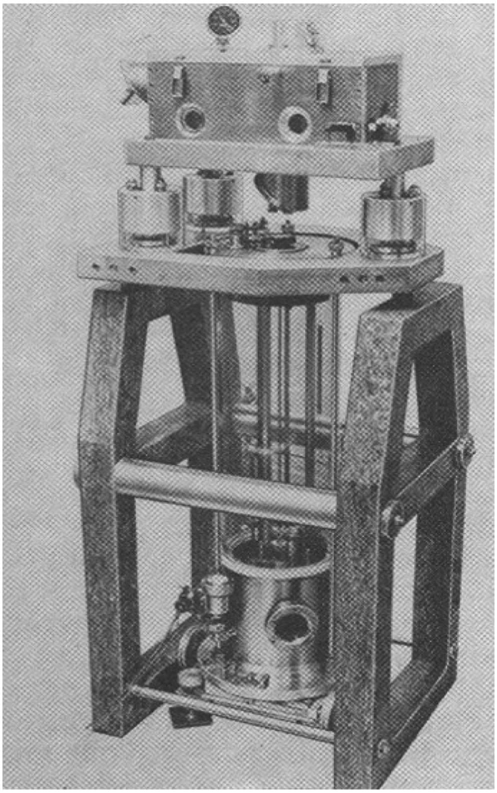

Fig. 1. First version of the IMGC absolute gravimeter.

sion of the apparatus while the picture in fig. 2 shows the present one, called IMGC-02, which benefits from nearly forty years of research activity in this field (D’Agostino, 2005; Germak *et al.*, 2006). Although the mechanical action of projecting vertically upwards is far more difficult than dropping an object, all prototypes adopted the symmetrical method, where both the rising and falling trajectories are used to fit the motion model. In the case of transportable apparatus this is particularly advantageous because the technical solutions used to cancel out the effect of the residual air resistance on the falling body are not so demanding and the vacuum system of the apparatus can be simplified. Furthermore this method is the most promising due to its inherent high precision and its relative freedom from systematic errors such as timing errors. Nevertheless, there are in practice very few working instruments adopting the symmetric method. The majority of other gravimeters adopt the simple free falling method, where only the falling trajectory is used (Niebauer *et al.*, 1995). This is a matter of concern for the metrological community because the experimental way to highlight any inherent systematic error is to compare instruments adopting different measuring methods and techniques. As an example, only two rise and fall systems participated in the last International Comparison of Absolute Gravimeters – ICAG, organized by BIPM and held in 2005: the IMGC-02 and the TBG absolute gravimeter, Ukraine.

Several new features characterize the present instrument, which is smaller and lighter than the previous versions. Among them there is the au-

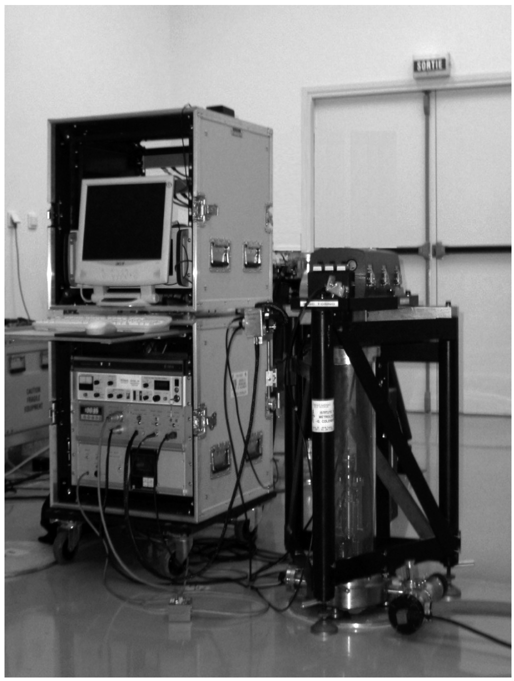

Fig. 2. Picture of the new absolute gravimeter (IMGC-02).

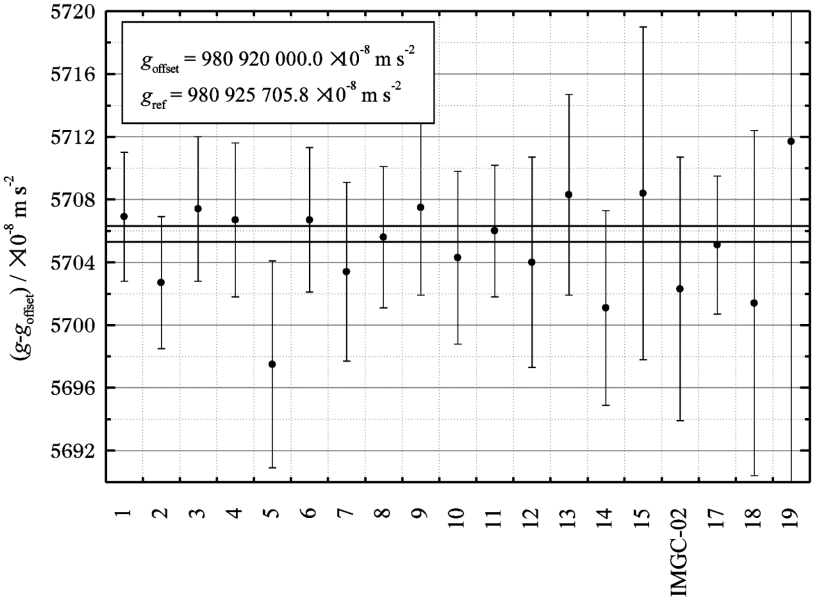

Fig. 3. Results of the last International Comparison of Absolute Gravimeters (ICAG05). Errors bars represent the measurement expanded uncertainties.

tomatic running, which allows a higher measurement rate and shorter time to measure the gravity value. The IMGC-02, like every prototype developed before, participates regularly in the ICAGs, assuring the long-term reliability of the recorded gravity data. Confidential results of the last ICAG-05, reported in fig. 3, confirm that the IMGC-02 has reached a point in its development where the measurement results agree within the expanded uncertainty, estimated to be about 9 μGal. Such an uncertainty level is achieved with one observation session that lasts about 12 h, even if the apparatus showed a measurement reproducibility of about 4 μGal at the INRIM gravity laboratory. At this level, the information extracted from gravity measurements can be useful in many applications of Geophysics and Volcanology. In fact, geodynamics, seismicity, and volcanic activity can produce temporal variation in the gravity field, often quite small, within the amplitude range from a few to hundreds of microgals. For this reason, since 1986, the IMGC absolute gravimeter has been employed in surveying the Italian active volcanoes in co-operation with the Osservatorio Vesuviano (presently Istituto Nazionale di Geofisica e Vulcanologia - INGV) and the University «Federico II», both in Napoli (Italy) (Berrino *et al.*, 1988; 1999; Berrino, 1995). In particular, the IMGC-02 has already been employed to collect absolute gravity data in three new absolute stations placed by the INGV in the Colli Albani volcanic area (Berrino *et al.*, 2007).

New features and technical solutions of the IMGC-02 are described later on together with an overview of the ongoing applications in Geophysics and Volcanology.

2. Description of the apparatus

The schematic drawing in fig. 4 describes the present instrument, 1 m high, 0.5 m wide and 0.6 m long, respectively, which consists of

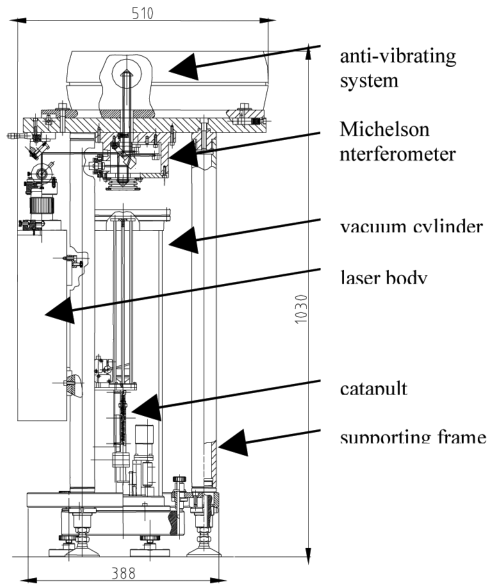

Fig. 4. Schematic drawing of the IMGC-02 absolute gravimeter.

five easily separable parts: i) a catapult in a vacuum cylinder, ii) a Michelson interferometer in a case connected to an anti-vibrating system, iii) a laser body, iv) a photodetector and v) a supporting frame. The whole apparatus, 180 kg weight including the rack housing the electronic systems, a vacuum pump and mounting tools, can be transported in a small van and reassembled by an operator within one hour. The complete automation of the instrument allows a measurement rate of about 120 launches every hour. Thus one absolute station, consisting of a record of about 1500 gravity data, can be created in one night. It is recommended, before the optical alignment, to let the mechanical parts reach thermal stability and start the measurement after a warm up of the electronic systems. The IMGC-02 is designed to run at room temperature with a stability of about ±2°C.

The test mass, 40 g in weight and 6.5 cm high, consists of a solid cube corner reflector rigidly fixed on an aluminium support. To avoid the systematic error introduced in case of rotation of the free falling object, the center of gravity of the test mass is adjusted to coincide within 0.1 mm with the optical center of the cube corner (Germak *et al.*, 2002).

A purpose-built catapult throws the reflector upwards about 20 cm in vacuum while giving it a spurious rotation and a horizontal velocity. Although intensity and direction are both random, it is estimated an average rotation of 25×10^{-3} rad·s^{-1} and an average velocity of 0.25×10^{-3} m·s^{-1}. These motions are the major source of error for the IMGC-02. They add to the measurement result two non-gravitational components: an apparent centrifugal acceleration and the Coriolis acceleration. The contribution of these effects to the combined measurement uncertainty is about 4 μGal.

The reference corner reflector is fixed to the inertial mass of a long-period (≅20 s) seismometer. This technical solution is employed to attenuate the perturbation of the gravity measurement due to the ground motion and the mechanical shocks caused by the launching of the test mass. By means of this device the effect is estimated to be reduced by more than 10 times. As an example, at the INRIM gravity laboratory, the experimental standard deviation of the recorded data decreases from hundreds to a few tens of microgals (Germak *et al.*, 2006). In normal working conditions this corresponds to an experimental standard deviation of the mean value of about 1 μGal for one observation session, which contributes to the combined measurement uncertainty.

The measurement uncertainty is a combination of effects due to influence factors characteristic of the instrument, reported in table I, together with the effects characteristic of the observation site, reported in table II. The overall expanded uncertainty is about 9 μGal. It is evaluated as the combined standard uncertainty times the coverage factor at the 95% confidence level.

The present prototype adopts a unique data-processing technique to time the interference signal, called the local-fit method (D'Agostino *et al.*, 2005b) where a digital oscilloscope, synchronized to a reference rubidium oscillator, is

Influence parameters, x_i	Value	Unit	u_i or a_i	Type A, s_i	Type B, a_i	Correction Δg	Type of distribution	Equivalent variance	Sensitivity coefficients $c_i = \frac{\Delta g}{\Delta x_i}$	Contribution to the variance $u_i^2(g) = c_i^2 u^2(x_i)$	Degrees of freedom, ν_i	Equivalent standard uncertainty
Drag effect			negligible									
Outgassing effect			negligible									
Non-uniform magnetic field effect			negligible									
Temperature gradient effect		$m \cdot s^{-2}$	±2.7E-09		2.7E-09		U	3.6E-18	1.0E+00	3.6E-18	10	1.9E-09
Effect for Electrostatic			negligible									
Mass distribution effect		$m \cdot s^{-2}$	±5.0E-09		5.0E-09		rectangular	8.3E-18	1.0E+00	8.3E-18	10	2.9E-09
Laser beam verticality correction	6.6E-09	$m \cdot s^{-2}$	±2.1E-09		2.1E-09	6.6E-09	rectangular	1.5E-18	1.0E+00	1.5E-18	15	1.2E-09
Air gap modulation effect			negligible									
Laser effect		$m \cdot s^{-2}$	1.0E-09	1.0E-09				1.0E-18	1.0E+00	1.0E-18	30	1.0E-09
Index of refraction effect			negligible									
Beam divergence correction	1.14E-07	$m \cdot s^{-2}$	1.1E-08	1.1E-08		1.14E-07		1.2E-16	1.0E+00	1.2E-16	10	1.1E-08
Beam share effect	unknown		unknown									
Clock effect		$m \cdot s^{-2}$	6.0E-09	6.0E-09			rectangular	3.6E-17	1.0E+00	3.6E-17	30	6.0E-09
Finges timing effect			negligible									
Finite value of speed of light effect			negligible									
Retroreflector balancing	0.0E+00	m	±1.0E-04		1.0E-04		rectangular	3.3E-09	6.3E-04	1.3E-15	15	3.6E-08
Radiation Pressure effect			negligible									
Reference height	5.2E-01	m	±5.0E-04		5.0E-04		rectangular	8.3E-08	3.0E-06	7.5E-19	30	8.7E-10

Corr. 1.21E-07 $\mathbf{m \cdot s^{-2}}$ — **Variance** $u^2(g) \cong \sum_{i=1}^{N} u_i^2(g)$	**1.5E-15**	$\mathbf{m^2 \cdot s^{-4}}$
Combined standard uncertainty, *u* $\frac{u^4(y)}{\nu_{eff}} = \sum \frac{u_i^4(y)}{\nu_i}$	**3.8E-08**	$\mathbf{m \cdot s^{-2}}$
Degrees of freedom, ν_{eff} **(Welch-Satterthwaite formula)**	**19**	
Confidence level, *p*	**95%**	
Coverage factor, *k* (calculated with t-Student)	**2.10**	
Expanded uncertainty, *U* = *ku*	**8.1E-08**	$\mathbf{m \cdot s^{-2}}$
Relative expanded uncertainty, $U_{rel} = U/g$	**8.2E-09**	

Table I. Influence factors characteristic of the instrument.

Influence parameters, x_i	Value	Unit	u_i or a_i	Type A, s_i	Type B, a_i	Correction Δg	Type of distribution	Equivalent variance	Sensitivity coefficients $c_i = \frac{\Delta g}{\Delta x_i}$	Contribution to the variance $u_i^2(g) = c_i^2 u^2(x_i)$	Degrees of freedom, ν_i	Equivalent standard uncertainty
Instrument uncertainty		$m \cdot s^{-2}$	3.8E-08	3.8E-08				1.5E-15	1.00E+00	1.5E-15	19	3.8E-08
Coriolis effect		$m \cdot s^{-2}$	±2,6E-08		2.6E-08		rectangular	2.3E-16	1.00E+00	2.3E-16	10	1.5E-08
Floor recoil effect			negligible									
Barometric pressure correction	3E-08	$m \cdot s^{-2}$	±1,0E-08		1.0E-08	3.0E-08	rectangular	3.3E-17	1.00E+00	3.3E-17	15	5.8E-09
Tide correction	6E-07	$m \cdot s^{-2}$	3.0E-09	3.0E-09		6.0E-07		9.0E-18	1.00E+00	9.0E-18	15	3.0E-09
Ocean loading correction	1E-07	$m \cdot s^{-2}$	2.0E-09	2.0E-09		1.0E-07		4.0E-18	1.00E+00	4.0E-18	15	2.0E-09
Polar motion correction	3E-09	$m \cdot s^{-3}$	negligible			3.0E-09						
Standard deviation of the mean value		$m \cdot s^{-2}$	1.8E-08	1.8E-08				3.2E-16	1.00E+00	3.2E-16	3277	1.8E-08

Corr. **7.3E-07** $\mathbf{m \cdot s^{-2}}$	**Variance** $u^2(g) \approx \sum_{i=1}^{N} u_i^2(g$	**2.1E-15**	$\mathbf{m^2 \cdot s^{-4}}$
Combined standard uncertainty, u	$\frac{u^4(y)}{\nu_{eff}} = \sum \frac{u_i^4(y)}{\nu_i}$	**4.5E-08**	$\mathbf{m \cdot s^{-2}}$
Degrees of freedom, ν_{eff} (Welch-Satterthwaite formula)		**36**	
Confidence level, p		**95%**	
Coverage factor, k (calculated with t-Student)		**2.03**	
Expanded uncertainty, $U = ku$		**9.2E-08**	$\mathbf{m \cdot s^{-2}}$
Relative expanded uncertainty, $U_{rel} = U/g$		**9.4E-09**	

Table II. Influence factors characteristic of the observation site (INRIM gravity laboratory).

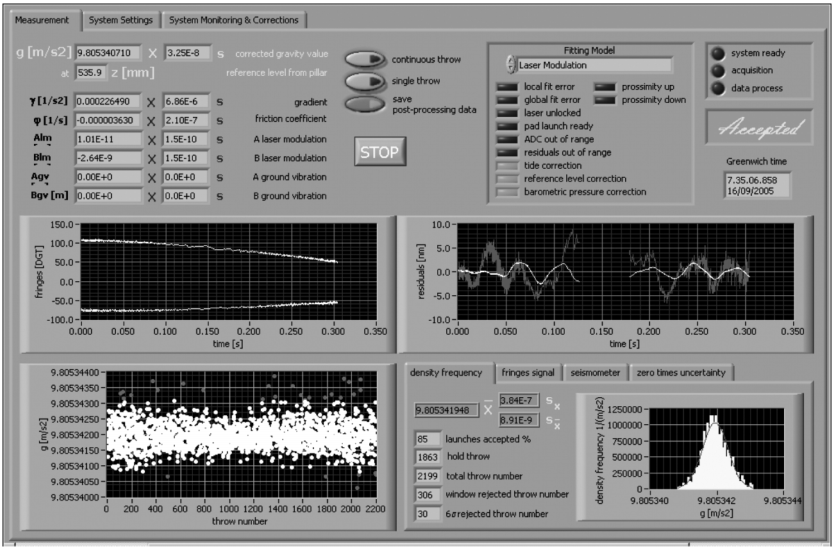

Fig. 5. User interface panel of the Gravisoft *M*.

used to sample and buffer the output voltage of the photo detector during the test body trajectory. The time-space coordinates are extracted from the acquired signal by fitting a suitable equation model to the interference fringes. This method offers new powerful tools for post-processing the stored data because the full acquisition of the interference signal opens a direct way to assess the quality of the trajectory. It shows less sensitivity to large fringe variation and makes the IMGC-02 smaller, lighter and cheaper than before since previous expensive and bulky electronic components are avoided. Experimental comparisons show that the local-fit method is at least as accurate as traditional methods. From a theoretical point of view, its application removes, as an additional advantage, the frequency-dependent time delays in timing the interference signal, even if, as already mentioned, the relevant effect is cancelled out in a rise and fall system like the IMGC-02.

A new software code was developed and tested to manage the instrument during the automatic working. The code runs in a personal computer directly plugged into the rack housing all the electronic devices. The software package was developed with Labview platform and consists of two different programs: one for controlling the instrument and storing the experimental data during the measurement session (Gravisoft M), the other for processing and filtering the recorded data during the post-processing session (Gravisoft PP).

The user interface panel of the Gravisoft M is showed in fig. 5. Graphic screens supply the operator with immediate information on the residual noise of the least-squares fit, gravity time series, histograms and statistical data. After the measurement session, the Gravisoft PP analyses and displays all stored trajectories. Data are filtered according to rejecting criteria relevant to the measurement conditions. The most critical factor is the visibility variation of the interference fringes, which indicates a horizontal motion of the test mass. Outliers are found by applying the Chauvenet criterion to the parameters estimated with the least-squares regression. Moreover there is the possibility to elaborate the data by applying geophysical corrections relevant to the tide and ocean loading, the polar motion and the local barometric pressure.

The present instrument is the first fully automated prototype developed by INRIM. Its optical alignment is easier than before and the apparatus can work automatically without the operator. This makes the IMGC-02 a modern absolute gravimeter suitable for future applications in Geophysics and Volcanology requiring the above-declared level of uncertainty.

3. Applications in geophysics and volcanology: comparison with relative measurements on some Italian active volcanoes

Many gravimetric surveys have been carried out since 1981 on the Neapolitan (Vesuvio, Campi Flegrei and Ischia) and on some Sicilian (Vulcano and the whole Aeolian Islands and Pantelleria) volcanoes to investigate their dynamics (Berrino and Corrado, 1991; 2007). The results show that combining absolute and relative measurements is definitely the most complete and reliable way to define and distinguish between long-term and short-term variations (Berrino *et al.*, 1999; Berrino, 2000). Sometimes both repeating absolute measurements and establishing a greater number of absolute stations in the dynamic area are necessary. In fact, absolute measurements define the reference station (or «base station») and, if they are repeated, detect its variation or confirm its stability (within 10 μGal) on long time. Being absolute measurements directly linked to standards of time and length, they are fairly independent from instrumental reference. As a consequence they allow performing measurement schedules lasting long time and to calibrate and compare relative gravimeters.

Since 1986, absolute gravity measurements have been carried out to survey the dynamics of Italian active volcanoes (Berrino *et al.*, 1988, 1999, 2006; Berrino, 1995, 2000). The observation points have been chosen in correspondence of reference stations and on selected ones of the relative gravity networks on volcanoes.

The following absolute stations have been settled (see fig. 6 for their location): in 1986, Napoli (reference station of the gravity networks of Neapolitan volcanoes) and Vesuvio; in 1990, Milazzo (reference station of the gravity networks of Vulcano and Aeolian Islands) and Vulcano; in 1993, the island of Pantelleria; in 1995, Stromboli; in 1998, Campi Flegrei and Ischia; and recently, in 2005, Sant'Angelo Romano and Palestrina (both reference stations of the gravity networks of the Colli Albani area) and Castel Gandolfo (D'Agostino *et al.*, 2005; Berrino *et al.*, 2007).

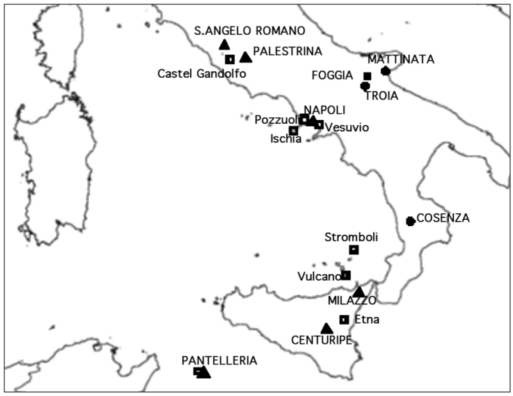

Fig. 6. Location of absolute stations in Southern Italy. Squares represent the reference stations for the relative gravity network, triangles represent the absolute stations located on the dynamic areas. Circles are the stations constituting the fundamental ties of the «Calibration line» for relative gravimeters and a station (Cosenza) settled in a seismic area.

Regarding the island of Pantelleria, the distance from Sicily did not allow the link of the local relative gravity network to an external reference station, therefore two absolute stations were established, one of which was selected as a local reference, according to the dynamics singled out since 1980 (Berrino, 1997; Behncke *et al.*, 2006).

Moreover, in the framework of a European Project, in 1991 two stations were established on Mt. Etna and Centuripe (reference station for this area) (Berrino *et al.*, 1999). The reference stations of Napoli, Milazzo and Centuripe, established in 1986, 1990 and 1991 respectively, are also ties of the «Italian Gravity Network of Zero Order» (Berrino *et al.*, 1995). Finally, in the framework of a project for the establishment of new absolute stations to survey seismic areas, one station in Cosenza and three stations in Troia, Foggia and Mattinata were set up, the latter constituting the fundamental ties of a calibration line of relative gravimeters (Berrino *et al.*, 1988; Berrino, 1995). The vertical gradient of gravity was measured in every station to transfer the absolute *g* value to the measurement height of a relative spring gravimeter. Furthermore, each absolute station is supplied with one or more «satellite» external stations on which the absolute value is transferred by means of several relative gravity links.

It has to be noted that absolute stations on active volcanoes are well located in the monitoring networks taking into account logistic requirements. They are chosen to be in correspondence with selected relative stations according to the dynamics of the surveying area.

Most of the stations have been surveyed more than once. The periodical surveying checks long-term variations of the selected stations, as well as periodic calibration and comparisons for relative gravimeters. In order to make comparable the absolute and the relative measurements, gravity readings are also corrected for polar motion effect, in addition to the usual reduction such as earth tide, atmospheric load and drift in the case of relative measurements. Moreover, the absolute measurements are also referred to the same height then the relative one taking into account the value of the measured vertical gravity gradient.

The absolute gravity measurement at the Vesuvio station was repeated four times, in particular in 1994, 1996, 1998 and 2003. Always in 2003, absolute measurements at the stations of Pozzuoli and Ischia were repeated. During the 2003 the base station of Napoli was moved to a new point of the same building, because the room containing the old point underwent some structural modifications that could have changed the gravity value. In fact a decrease of 58 μGal was recorded at the old point whereas the links among the two absolute reference stations and the external satellite station confirmed that the satellite point was stable. For this reason the decrease was believed only due to its structural modifications. This was confirmed by the comparison between the gravity changes from absolute measurements in all and that from relative ones obtained taking into account as reference station the external satellite relative station.

Also, the absolute gravity measurements were repeated in 1995 at Vulcano (Berrino *et al.*, 1999) and from 1991 to 1994 twice at Etna (1992 and 1994) and once at Centuripe (1994) (Berrino, 1994; Berrino *et al.*, 1999).

There is in general a good agreement between the gravity changes revealed by relative measurements and the absolute gravity data collected in repeated observations at the same observation site. No significant gravity changes were measured at Vulcano, Pozzuoli and Ischia, and also on Mt Etna in spite of the large eruption which occurred from 1991 to 1993. As an example the record of absolute and gravity data collected at Vulcano is reported in fig. 7.

On the contrary, a considerable variation was observed at the absolute station of Vesuvio from 1986 to 1994 (fig. 8): the gravity value decreased by about 60 μGal. This huge variation is in agreement with the gravity changes measured with relative gravimeters. Moreover, the long-term stability of the reference relative gravity station (satellite station) of Napoli was already confirmed taking into account data referred to it. The gravity decrease also occurred when also: i) the seismic activity increased (1989-1991); ii) the continuous gravity measurements showed a significant change in the tidal parameteres from 1991 to 1994; iii) the relative gravity measurements spanning the whole network indicated a progressive enlargement in two distinct areas respectively characterized by a decrease (in the north-western sector of the network) and an increase (in the south-eastern part of the network and at the base of the cone). The absence of ground deformation implied a mass redistribution without significant volume changes, probably fluid migration at the depth of the seismic foci, *i.e.* at a few kilometers (Berrino *et al.*, 1993).

4. Conclusions

The latest development of the transportable apparatus for absolute gravity measurements,

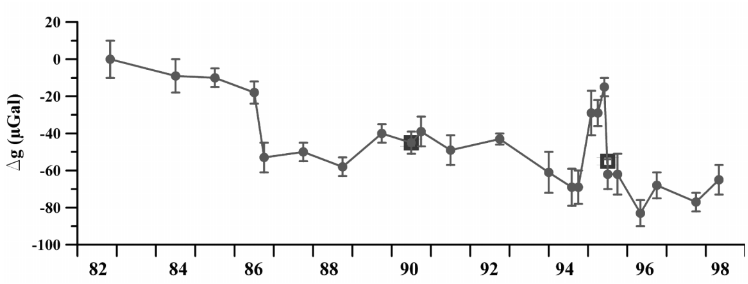

Fig. 7. Record of repeated relative (circle) and absolute (square) gravity measurements at Vulcano.

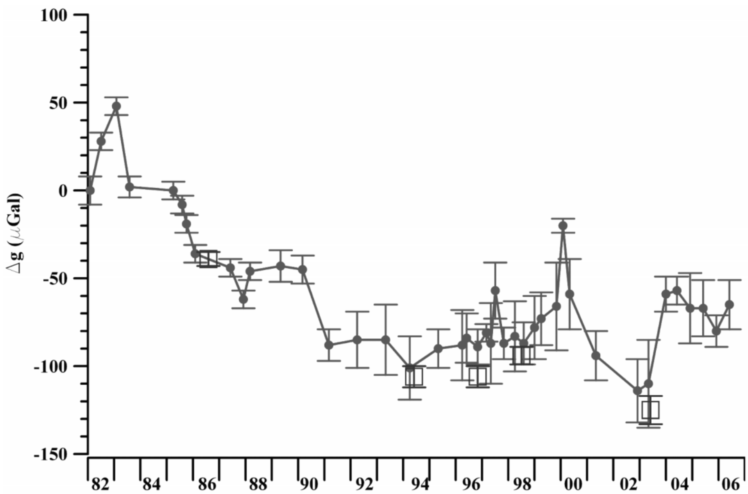

Fig. 8. Record of repeated relative (circle) and absolute (square) gravity measurements at Vesuvio.

called IMGC-02, fully designed at the laboratories of INRIM, was here discussed together with achievements coming from absolute gravity data collected in active volcanic areas of Southern Italy. Like its previous versions the IMGC-02 particularly proves to be a useful tool for applications in Geophysics and Volcanology. The instrument has reached a quite good level of user friendliness in acquiring absolute gravity data, at the microgal level of accuracy, for the surveying of dynamical processes. This was experimentally demonstrated by the repetition of absolute gravity measurements in some selected gravity stations on volcanoes, specifically at Vesuvio and the isle of Vulcano. The recent measurement results, obtained at the absolute stations in the Colli Albani area, are therefore added to the data set collected in the past.

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