ABSOLUTE AND RELATIVE GRAVITY MEASUREMENTS AT ETNA VOLCANO (ITALY)

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Abstract

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Employing both absolute and relative gravimeters, we carried out three hybrid microgravity surveys at Etna volcano between 2007 and 2009. The repeated measurements highlighted the spatio-time evolution of the gravity field associated with the volcanic unrest. We detected a gravity increase attained an amplitude of about 80 µGal on the summit area of the volcano between July 2008 and July 2009. The observed gravity increase could reflect mass accumulations into shallow magma storage system of the volcano located at 1÷2 km below sea level. We present here data and the advantages in using the combined approach of relative and absolute measurements performed at Etna volcano.

Introduction

Detection of clear gravity signals associated with the renewal of the volcanic activity and the emerging need of characterizing the dynamic changes of subsurface systems have led to increased application of microgravity method in time-lapsed monitoring, also known as 4D gravity. Since the 1980s, we have been intensively monitoring the gravity field on Mt Etna to detect underground mass movements due to the volcanic activity, which could trigger a pre-eruptive state. Through relative gravity measurements, we were able to reveal significant correlations between eruptive activity of Etna volcano and temporal changes in the gravity field, occurring with different patterns (Budetta et al., 1999; Carbone et al., 2003; Branca et al., 2003; Bonforte et al., 2007; Carbone and Greco, 2007; Greco et al., 2010).

Conventionally, Etna's gravity network has been traditionally based on discrete relative measurements referred to fixed reference site. Recently, with the aim of compare relative microgravity measurements routinely acquired on Etna with absolute gravity observations, we performed repeated surveys using transportable absolute gravimeters. Since 2007, measurements of the free-fall acceleration (g) have been carried out in five sites on Etna using the new version of the IMGC-02 absolute gravimeter. In 2009, others 8 new absolute stations were added and measured using the absolute gravimeter Microg LaCoste FG5#238 (owned by ENI s.p.a.).

Gravity networks at Etna volcano

Relative stations and measurements

The relative gravity network of Mt Etna is currently made up of 71 benchmarks (Fig. 1) located 0.5 to 4 km apart and covering an area of about 400 km^2. Four array subsets have been distinguished in different sectors of the volcano. The sub-arrays differ from one another in station density, access (determined by snow coverage), and the time required to collect gravity measurements. Each sub-array can be occupied independently, optimizing the flexibility in data collection to accommodate variations in activity and accessibility of the volcano. Measurements over the entire Etna microgravity network are generally conducted once a year when also absolute measures are performed. More frequent surveys are carried out in the southern and in the summit area of the volcano (almost 1 survey/month; in the latter only during the summer time). Almost all gravity benchmarks are close or coincident with GPS stations. Since 1994, discrete gravity measurements at Mt Etna have performed using a Scintrex CG-3M gravimeter. This instrument, even when used under the unfavorable conditions encountered on Mt Etna (rough unsurfaced roads, large elevation differences, etc.), yields a high precision thanks to its low sensitivity to both shocks and external temperature changes. The uncertainties in measurements collected by the Scintrex CG-3M gravimeter on Etna ranges between 10 and 15 μGal at the 95% confidence interval.

Absolute stations and measurements

Due to the logistical difficulties existing on Mt Etna, the arrangement of the absolute station network mainly depends on the buildings present which provide protection for the instrumentations. The first 4 Etna stations for absolute measurements were installed in 2007 on the volcanic edifice, allowing measurements along a North–South profile crossing the summit craters at elevations ranging between 1250 (North flank) and 1700 m a.s.l. (South flank). Another station was installed outside the volcanic edifice, inside the gravity laboratory of INGV (Istituto Nazionale di Geofisica e Vulcanologia) – Catania (CTA) used as reference. In order to improve its geometry, the absolute gravity network was renewed and integrated in 2009 with stations arranged as a ring around the volcano at elevations of between 1500 and 2000 m a.s.l. Besides the CTA station, the Etna gravity network for absolute measurements is now composed of 13 stations that cover quasi-regularly the volcano edifice between 1500 and 2800 m a.s.l. (see Fig. 1 for location).

Since 2007, absolute gravity measurements were carried out using the IMGC-02 gravimeter. In 2009, the Microg LaCoste FG5#238 was also employed. The CTA and Serra La Nave (SLN) stations were used to compare both instruments (Fig. 2). The free-air vertical gradients obtained from relative gravity measurements at each observation site were used to refer the absolute gravity values at the same elevation (Fig. 3).

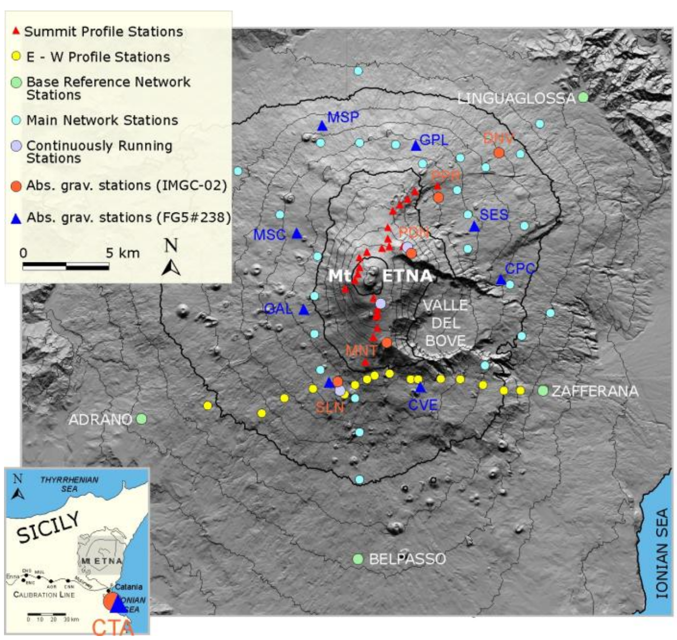

Fig. 1 - Sketch map of Etna showing the microgravity networks for relative and absolute measurements. The inset at the bottom left shows the location of Etna volcano with respect to Sicily. The different symbols used for relative stations are to distinguish the four arrays in different sectors of the volcano that compose the entire network. The orange circles indicate the absolute station arranged along a North-South profile and measured by the IMGC-02 gravimeter. The blue triangles indicate the absolute stations arranged as a ring around the volcano edifice and measured by the FG5#238 gravimeter.

Fig. 2 – Absolute gravity measurements carried out at CTA and SLN stations using the the IMGC-02 and Microg LaCoste FG5#238 gravimeters.

Hybrid gravity

We applied the combined use of absolute and relative gravimeters as hybrid method (Furuya et al., 2003) to extend the potential of gravity measurements for investigating the Etna volcanic area (Fig. 3). The hybrid approach allow of optimizing techniques and strategies of the microgravity surveys on the Etna's network, ensuring an improvement in the quality of the data. On large volcanoes such as Mt Etna, operators using an absolute gravimeter are not obligated to reach "stable" reference stations that are generally far from the active areas (Etna reference stations, unaffected by volcano-related gravity changes, are about 20 km away from the summit zone), at the cost of propagating-measurement errors and greatly increasing measurement time. Thus, the time required to accomplish discrete surveys drastically decreases and the reliability of discrete data improves.

The 13 absolute stations located on Etna volcano were used as references for relative measurements acquired in different benchmarks of the relative gravity networks (Fig. 1). Basically, we connect three or four relative gravity benchmarks at each absolute site, so that the height precision absolute values for all relative benchmarks were obtained by adding the differences (Δg) between each absolute station with the relative ones to the absolute value measured at each reference point. The uncertainly affecting absolute gravity data in different stations ranges between 4 and 30 µGal, while the error affecting the single Δg between an absolute and relative station generally ranging between 3 and 7 µGal. This strategy, allows also to minimize the error due to the instrumental drift that significantly increases when spring relative instruments are subjected to mechanical and thermal shocks during long vehicle transportation. On the other hand, the availability of absolute points very close to areas experiencing volcanic unrest episodes, where significant gravity anomalies are expected, represents a crucial step in volcanic monitoring, reducing the typical interpretation ambiguities for single-component methods.

Fig. 3 – On the top: relative spring gravimeters Scintrex CG-3M (on left) and CG-5 (on the right) used for relative measurements. On the bottom: schema of the hybrid gravity method (on the left); example of vertical gravity gradient measurements (in the middle) with schedule procedure (on the right).

Gravity changes during 2008-2009 period

The absolute gravity variations and the gravity data from the whole Etna network were combined and contoured over July 2008 – July 2009 time interval (Fig. 4). Combined gravity contour map is mainly characterized by a positive variation involving the summit area of the volcano. The annual gravity variation shows a wavelength of about 10 km elongated in the North-South direction and with a maximum amplitude of about 80 μGal. The map also shows an absence of important gravity variations elsewhere at the scale of the volcano. No significant vertical ground movements are evidenced by GPS measurements in this sector of the volcano in the same time interval.

Since gravity measurements alone cannot unambiguously identify the shape of the source at depth, the similarity in wavelength and position of the 2008-2009 positive gravity variation with respect to previous gravity changes observed in the same zone suggests that a mass increase likely to take place within the same area of the previous gravity variations. We inverted the recorded gravity changes searching for the source parameters that minimize the misfit between the observed and computed gravity changes. As forward model, we used the analytical solutions for all the source geometries (Singh, 1977; Clark et al., 1986; Blakely, 1995) and included the topography, taking into account the altitude difference between the gravity stations and the source. The results show that, despite the different geometries, all the sources can reproduce the observed anomaly with a misfit lower than 20 μGal. Finally, we applied an oblate ellipsoidal source and the best fit to the recorded data (misfit less than 20 μGal) is given for a source located at a depth of 2000 m bsl, with the major semi-axes of 1100 m in the direction North-South and the other two semi-axes b=c= 350 m. A density contrast of 400 kg/m^3 is necessary to justify the measured gravity change. The calculations performed show a mass increase of about 200 x 10^9 kg, which yields at least a source volume of about 500 x 10^6 m^3 considering a density contrast of 400 kg/m^3.

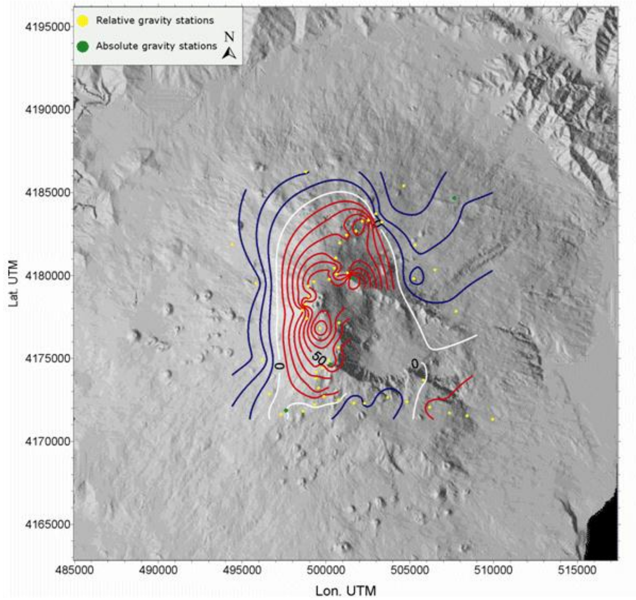

Fig. 4 – The annual absolute gravity variations observed and the gravity data from the entire Etna network (relative measurements) were combined and contoured over July 2008 – July 2009 time interval (at 10 µGal intervals). Errors affecting relative gravity changes are typically 10 µGal; larger errors affect gravity changes along the Summit Profile (within 15 µGal).

Conclusive remarks

For the first time at Etna volcano we employed the combined use of absolute and relative gravimeters as hybrid method to extend the potential of gravity measurements for surveying the Etna volcanic area. The hybrid approach allowed of optimizing techniques and strategies of the repeated microgravity surveys on the Etna's network, ensuring an improvement in the quality of the data.

The combined absolute and relative gravity data have permitted the detection of mass redistribution, to define its temporal and spatial evolution and to recognize processes involving volcanic activities minimizing the ambiguity typical for single component methods.

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