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Prediction of vertical gradient of gravity and its significance for volcano monitoring – example from Teide volcano

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Abstract: We present a detailed calculation of the topographic contribution to the vertical gradient of gravity (VGG) based on high-resolution digital elevation model (DEM) and new developed software (Toposk) for the purpose of predicting the actual VGGs in the field. The calculations presented here were performed for the Central Volcanic Complex (CVC) of Tenerife. We aimed at identifying the most extreme VGGs within the CVC, as well as predicting the VGGs at benchmarks of the former microgravity/deformation network set up to monitor the 2004/5 unrest. We have carried out an observational campaign in June 2016 to verify the predicted VGG values, both the extreme ones and those at the benchmarks. The comparison between the predicted and the in-situ verified VGGs is presented here. We demonstrate the sensitivity of the VGG prediction to the choice of the topo-rock density, which is inherent to the volcanic areas with high variability of rock densities. We illustrate the significance of the use of actual VGG in volcano monitoring microgravimetric surveys on a couple of benchmarks of the CVC network.

Key words: microgravimetry, tower VGG measurements, topographic effect, DEM, gravimetric networks

1. Introduction

Repeated gravity measurements acquired at different height levels need proper consideration of the vertical gradient of gravity (VGG). There are

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several reasons why the gravity acceleration at a given point happens to be measured at different height levels. One of them is the use of various types of gravity meters, relative and/or absolute ones, with different sensor heights. One has to use the actual VGG value to "reduce" the data readings to the ground or a common level in order to compare such measurements. Using the theoretical VGG, called also the normal or free-air gradient, which approximately equals to -0.3086 mGal/m ($10^{-5}\mathrm{s}^{-2}$), instead of the actual VGG value, can lead to significant errors. The deviation of the real VGG from the normal value depends strongly on the nearby topography (so far we have observed deviations up to 88%, *Zahorec et al., 2014*). However, most of this deviation can be modelled. We are able to predict the approximative value of the actual VGG by adding the calculated topographic effect, assuming that a detailed elevation model (DEM) and rock-density information are available. In this way the predicted VGG values are useful in the case when in-situ measured VGGs are not at disposal. On the other hand, one has to be aware that there are also other effects (geological, hydrological, etc.) contributing to the actual VGG that usually remain unmodelled.

Other situations when we need to carefully treat the measurements performed at different heights are the repeated (time-lapse) gravity measurements (monitoring of spatio-temporal gravity changes) in volcanic areas affected typically also by vertical deformation. In such cases we have to separate the desired time-dependent geological signal (associated with magmatic processes) from the undesired height-dependent effects.

We have analyzed the effect of the topography on VGG in the case of the Teide volcano on Tenerife, Canary Islands. The first part of our paper focuses on the VGG prediction and its subsequent verification by field measurements on several points situated in the extreme terrain conditions on the volcano. In the second part we discuss the significance of the VGG for the gravity monitoring of volcanic areas.

2. VGG prediction for Teide volcano area

Our first numerical study of the expected VGGs within the central part of Teide volcano (*Vajda et al., 2015*) showed interesting results. Predicted VGG values vary from -0.070 to -0.481 mGal/m ($10^{-5}\mathrm{s}^{-2}$), which represents deviations up to 77% of the normal (theoretical) gradient. Both extremes, low and high in absolute sense, are associated with extreme terrain conditions: narrow valleys (gorges, canyons) and sharp convex features (peaks, ridges, caldera rims), respectively. Therefore we focused in detail on the selected areas of rugged topography for the purpose of finding places with extreme VGGs that could be subsequently verified by in-situ measurements. We focused on canyons and gorges situated in the Corona Forestal (CF) Park area, as well as the rim of the Las Cañadas caldera and the Teide summit itself in the Teide National Park (TNP), see Fig. 1.

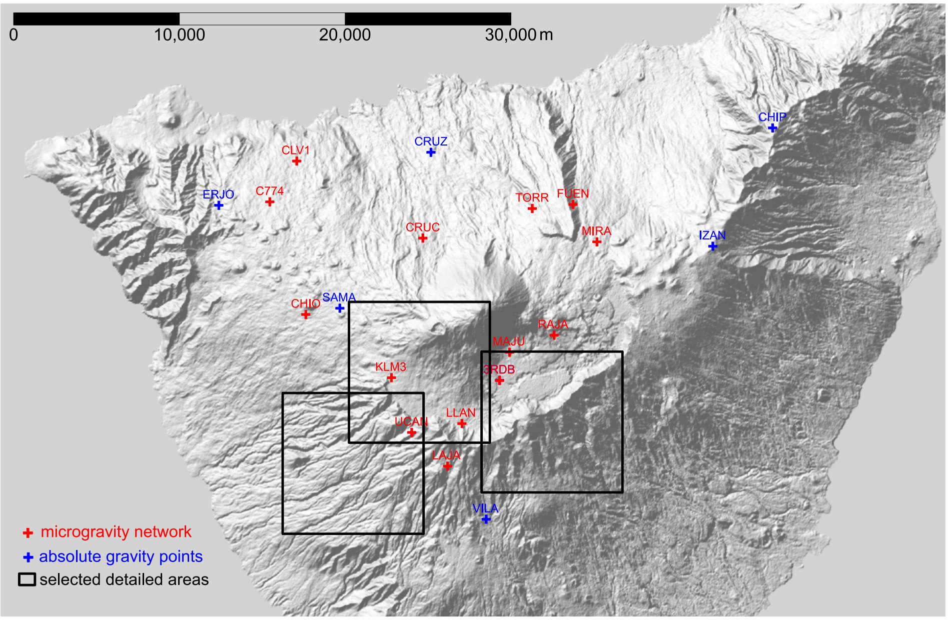

Fig. 1. Central part of the Tenerife Island showing the areas of detailed studies (black rectangles). Red crosses represent benchmarks of the microgravity network (*Gottsmann et al., 2006*), blue ones are absolute gravity points (IGN, Madrid).

The topographic contribution to the VGG was calculated using the proprietary software Toposk (*Marušiak et al., 2013*). This program enables to calculate the topographic effect (i.e. the gravitational effect of the masses between the topo-surface and the zero level) at arbitrary point, e.g. above the topographic masses, which is desirable in the case of VGG prediction. The topographic contribution to the VGG is simply computed as the difference between the topographic effects (in terms of the vertical component of the attraction vector of the topographic masses) calculated at the heights of 1.25 and 0.25 m, respectively, above the surface. These heights equal approximately to the CG-5 gravity meter sensor positions during the tower VGG measurements in the field. Such computed topo-contribution (and consequently predicted VGG) does not represent a point value of the VGG, rather it represents an average value within the given vertical interval. However, since the in-situ VGGs are observed with a relative gravimeter in a tower mode, we tailored also the prediction of the VGG to match the observed VGGs.

The topographic (and also bathymetric) effect is considered up to the standard distance of 166.7 km, while the calculated area is divided into the following zones: inner zone up to 250 m around the calculation point, intermediate zone 250–5240 m and outer zones from 28.8 up to 166.7 km. The inner and intermediate zones play dominant roles in the contribution to the VGG. A high-precision DEM, such one derived from LIDAR data, is required especially within the inner zone. In the presented study we used a DEM derived from PNOA[1] with the 2 m resolution. Original unfiltered data were obtained from PNOA project (*Plan Nacional de Ortofotografía Aérea*) of the Spain National Geographic Institute and National Geographic Information Centre (*Instituto Geográfico Nacional, Centro Nacional de Información Geográfica*[2]). Lidar data were acquired in 2009 with a density of 0.5 points/m and vertical accuracy better than 20 cm RMS. Original data were processed and filtered using open-source efficient LiDAR processing software LAStools (*LAStools, 2016*). Bare-earth extraction was performed by *lasground* function with custom settings. Final grids were prepared in the Surfer software using Kriging interpolation procedure from previous classified LAZ (compressed exchange file format) 2 × 2 km tiles.

The topography as well as bathymetry contributions from the outer zones were calculated using SRTM data (*Jarvis et al., 2008; Becker et al., 2009*). Their contribution to the VGG represents only several μGal/m (10^{-8}s^{-2}).

Volcanic areas are characterized by high rock-density variability. We have used the density of 2200 kg/m^3 reported by *Gottsmann et al. (2008)* within their Boguer anomaly study on Tenerife. But we have to be aware

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[1] http://pnoa.ign.es/

[2] http://www.ign.es/

that possible large deviations from this mean density can lead to an error in the predicted VGG. We briefly analyze the problem of real densities and their influence to the VGG in the next section.

The total estimated topographic contribution to the VGG is added to the theoretical value −0.3086 mGal/m to predict the VGG at a given point. Figure 2 shows one detailed area (covered by calculation points in the net 100 × 100 m) with predicted extreme values of about −0.460 mGal/m at points situated on the caldera rim, and of about −0.120 mGal/m at points situated inside the adjacent canyons. The selected small areas were afterwards recalculated in a very dense calculation point networks of 5 × 5 m.

As the result of our study, we chose several extreme terrain locations (including the Teide summit with predicted value of −0.565 mGal/m!) for subsequent in-situ verification by means of tower VGG measurements.

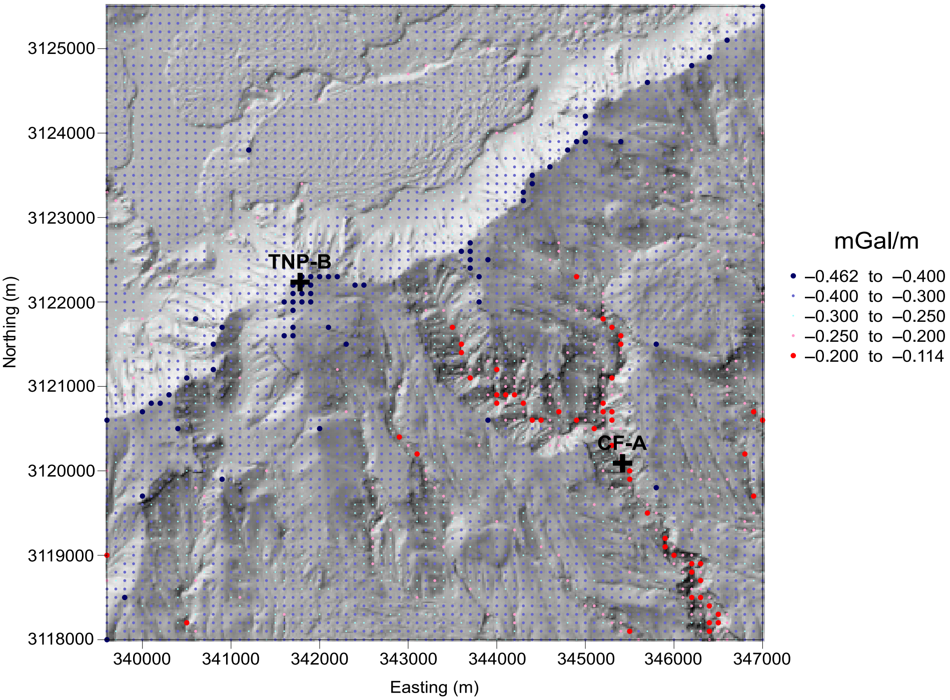

Fig. 2. Example of the VGG prediction in detailed area of the Las Cañadas caldera rim with adjacent canyons. Two places with extreme predictions (TNP-B and CF-A) were later verified by field measurements (measured values are displayed in Fig. 7).

In addition to the above mentioned selected areas, we focused closely on several benchmarks situated on the island. The deformation/microgravity network consisting of 14 benchmarks was established in 2004 within the CVC, after the signs of volcano reawakening (*Gottsmann et al., 2006*). Besides these benchmarks, several absolute gravity points established by *Instituto Geográfico Nacional, Madrid* are situated on the island (Fig. 1). All these points are of special interest for us seeing that we can demonstrate the importance of the VGG on actual gravity points. In Fig. 3 are shown predicted VGGs on these benchmarks, some of them are compared with measured values. The predicted VGGs vary from −0.261 to −0.460 mGal/m. As one can see, there is a general correlation between predicted and measured VGG at points shown in the right hand part of the graph. However, many points show only small deviations from the normal value, which is obvious, as they are not situated in extreme terrain conditions. On the contrary, some of them caught our attention. The microgravity network points LLAN and UCAN are of special interest, since they are fairly close to each other (see Fig. 1), yet they exhibit very different VGGs. We decided to confirm these predictions, together with absolute gravity points CHIP and SAMA, which also showed interesting predicted VGG values, while the VGG has not been measured yet on these points.

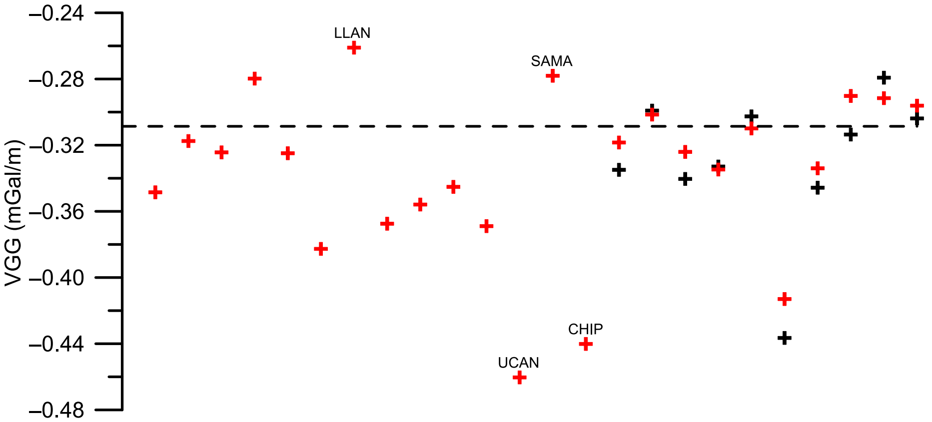

Fig. 3. Predicted VGGs (red crosses) on microgravity network benchmarks and on selected absolute gravity points. Black crosses represent measured VGGs (IGN Madrid). Dashed line represents theoretical (normal) VGG of −0.3086 mGal/m. The labelled extreme points were later verified by field measurements.

3. Verification by in-situ tower VGG observations

During a week in June 2016 we realized a gravimetric expedition on the Tenerife island in order to verify the calculated (predicted) VGGs at selected sites. Our goal was to confirm the predicted VGG values on several existing benchmarks together with "hunting" for extreme VGG values in special rugged terrain conditions (Fig. 4). We focused on sharp "convex" terrain forms (summit of Pico del Teide and the caldera rim) in order to measure high extreme VGGs (in their absolute value) and, on the contrary, deep narrow canyons for low extreme VGG values. We performed the VGG measurements in a tower mode using relative gravity meter CG-5 and geodetic tripod (Fig. 5).

Spatial coordinates of the measurement points were determined using GNSS measurements in Real Time Kinematic (RTK) or Fast Static Post-processing (FS) mode. RTK measurements were realized using the Spain

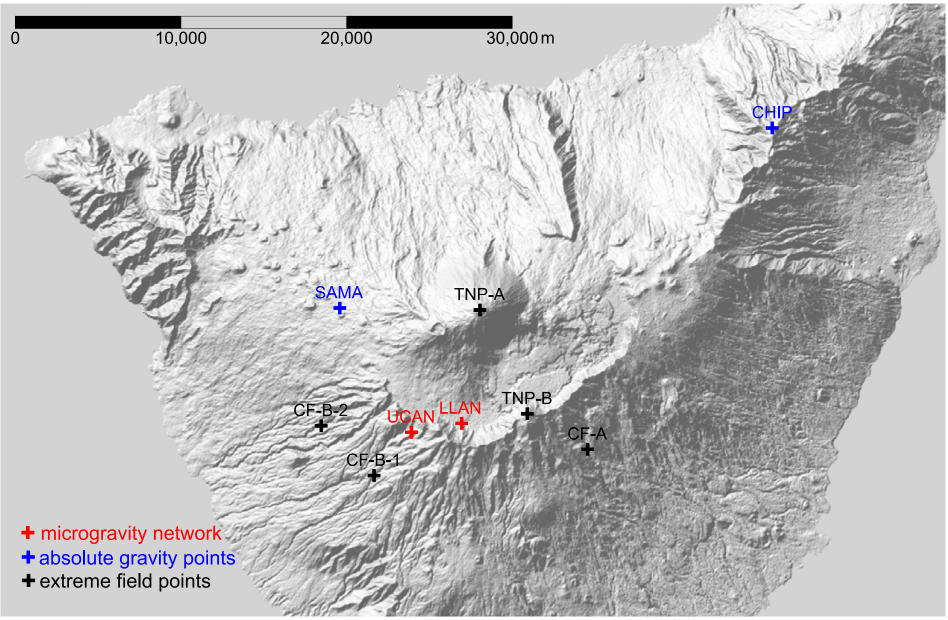

Fig. 4. Set of points where the in-situ verification tower VGG measurements were performed in June 2016.

official positioning service ERGNSS (*IGN GNSS, 2016*) in nearest Single Reference Station concept (CERCANA[3]). Fast static method with precise postprocessing was used on sites with no internet-connection or with bad observation conditions (canyons, gorges). Nearest permanent GNSS stations from the ERGNSS network (IZAN, TN01, TN02, TN03) were used as reference stations in both methods. Measurements were realized with the Trimble R10 GNSS receiver. Average observation period was about 10 minutes in the case of the RTK measurements, about 20 minutes in the case of the fast static measurements in good conditions, and about 50–80 minutes in bad conditions (canyons). Final processing was performed in Trimble Business Centre (v. 3.6) software. Spatial positions of the points were determined primarily in the ETRS89 coordinates system and then transformed to UTM28 projection. Physical heights of the points were transformed from ellipsoidal ones using global geopotential model EGM2008 (*Pavlis et al., 2012*). Horizontal and vertical accuracy of the VGG points are better than 5 cm, except for the points situated in canyons. Here, due to the large obstacles and very bad observation conditions, the horizontal accuracy is about 40–70 cm and the vertical accuracy is at the level of 1–1.5 m.

The benchmark points were easily accessible as they are situated along main roads. Some of them had been destroyed, though we performed measurements on their exact position determined by GNSS. The points with high-extreme predicted VGG values (TNP-A and TNP-B, Fig. 4) are situated on the Pico del Teide (3713 m a.s.l.) and Mt. Guajara (2713 m a.s.l., Fig. 5), so they required some hours of hiking along the tourist path in the TNP, which posed no difficulty. On the contrary, points with low-extreme VGGs were really difficult to access because of their position inside the poorly accessible gorges. We were unable to access the two of the three planned points because of the steep rocky thresholds on the riverbeds (we were not equipped for climbing). In these cases we had to find alternative sites for measurements. Naturally, the points in canyons were also characterized by bad GNSS observational conditions. At two points it was impossible to perform GNSS measurement exactly on the measurement point. Therefore we took the GNSS measurement in their proximity and then we used laser rangefinder (Fig. 6) to transfer the position from GNSS point to the VGG measurement point. As we realized later during the data processing,

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[3] http://ergnss-tr.ign.es:2101/sourcetable.htm

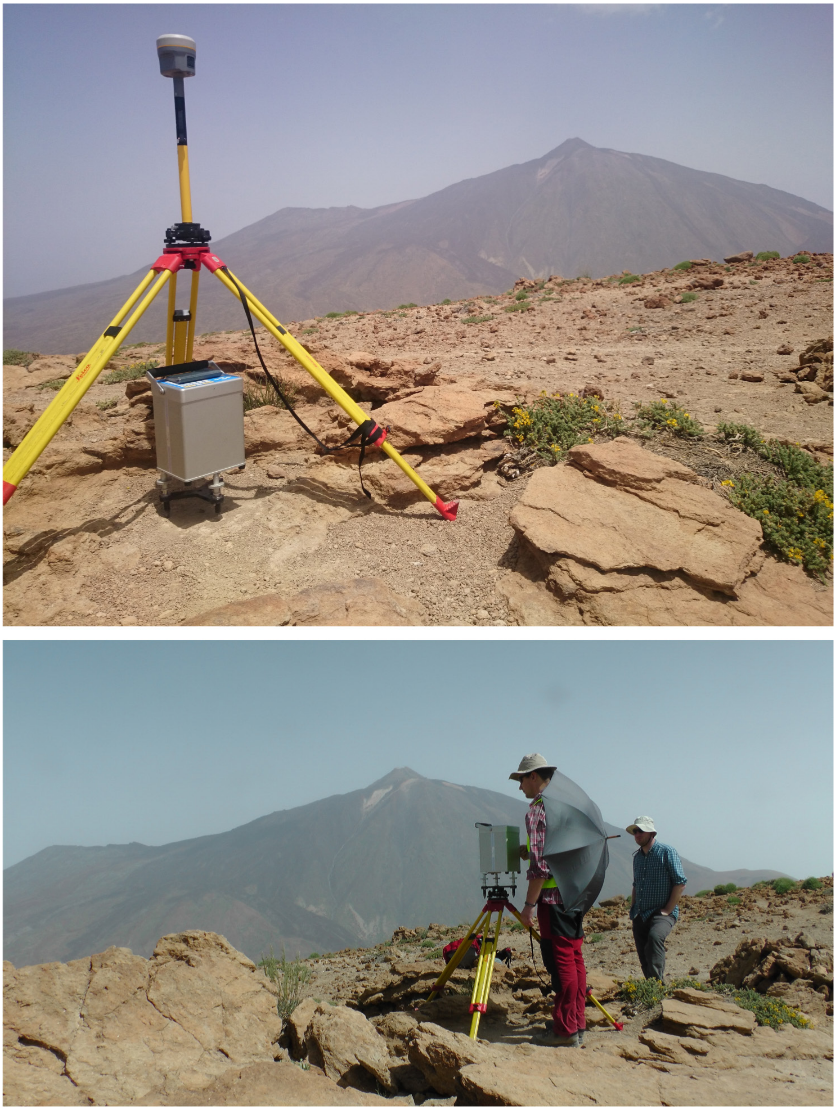

Fig. 5. Tower VGG measurement equipment on point TNP-B with a view of Pico del Teide on the right and Pico Viejo on the left in the background. The setup with gravity meter in the bottom position (upper picture) and in the top position (bottom picture). Umbrella is used to shield the meter from wind.

the use of laser rangefinder, which has the built-in magnetic compass, can be problematic in such background (basaltic rocks), because of the discrepancy between actual declination and that taken from the global models. Declination differences of several degrees can occur and produce errors of several meters within the horizontal position measured over distance of approximately one hundred meters.

The laser rangefinder (Fig. 6), connected with the GNSS receiver via Bluetooth, recording distance, as well as horizontal and vertical angles, can be used also to map the terrain of a very close area around the measurement points to improve the innermost topographic effect calculation. Inside the narrow gorges it was possible to map the surroundings of the points only to the distance of several meters in the direction of the steep slopes. Therefore these data improved the calculation only slightly (Fig. 7, blue crosses).

Gravity acceleration on each point was measured by A-B-A-B-A repeating method at two height levels (Figures 5 and 8). At the bottom level (A) the gravity meter sensor was approximately 0.25 m above the ground, at the top level (B) it was about 1.3 m, depending on the geodetic tri-

Fig. 6. Laser rangefinder (TruPulse 360B) was used either for mapping the closest terrain to improve the computation of the topographic effect or to transfer the position of the GNSS point positioning to the VGG point in the absence of GNSS signal on the VGG point.

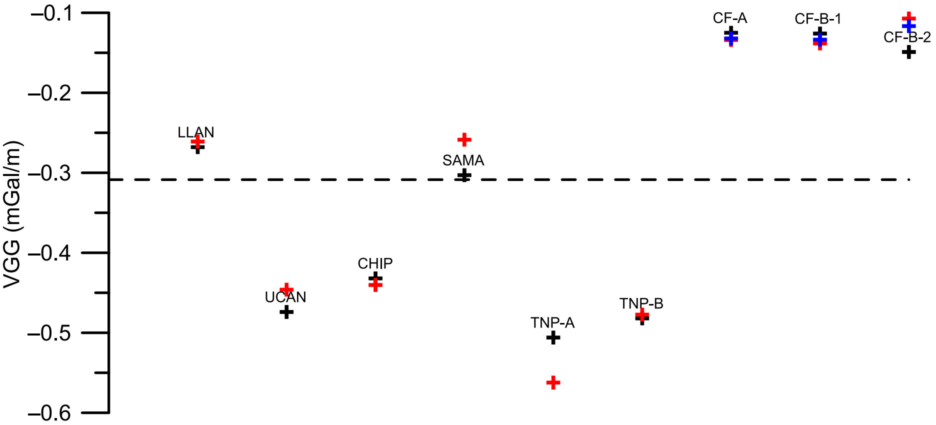

Fig. 7. Comparison of the in-situ observed (black crosses) and the calculated (red ones) VGGs. Positions of the observation points are shown in Fig. 4. Blue crosses represent slightly improved calculations using near-station detailed terrain models derived from laser rangefinder data. Dashed line represents theoretical (normal) VGG of −0.3086 mGal/m.

pod setup. The exact height of the gravity meter sensor above the ground (point/benchmark) was measured using the smart high-precision laser distance meter Disto D8. The striking wind represents a serious problem for the tower VGG measurement accuracy, especially in the top setup. Practical functioning shielding should be applied on windy days. We used a common umbrella (Fig. 5) to shield the gravity meter from the wind, but it was very problematic to get reasonable results in several cases and we had to repeat the measurement many times. Beside these conditions, we have been able to achieve the final measurement error on the level of approx. ±2 μGal.

We acquired the VGG values in the range from −0.125 up to −0.506 mGal/m, which represents deviations of more than 60% from the normal gradient (for a comparison, *Rymer (1994)* reported previously measured gradients at some volcanos from −0.201 up to −0.420 mGal/m). The in-situ determined exact horizontal positions and elevations of the measured points, as well as exact gravity meter sensor heights above the ground, were used for backward calculation ("prediction") of the VGG values (based on the topo-contribution) for testing purposes. In Fig. 7 and Table 1 we summarize the measured and the calculated values (for the density of 2200 kg/m^3).

A good agreement between measured and calculated VGG values was achieved at most observation points. On the other hand, those with larger discrepances (e.g. TNP-A, SAMA) raise questions about the calculation accuracy, particularly about the used density. The area of the CVC of Tenerife is characterized by high variability of volcanic rocks. During the field measurements we observed compact rocks as well as very porous young lavas, which obviously leads to a high density variability. For example, the absolute gravity point SAMA is situated in the area of youngest slag "Aa" lavas with high porosity and, consequently, very low density. As a result, the real topographic contribution to the VGG is weak (nearly negligible) and the measured VGG is almost equal to the theoretical gradient (see Fig. 7), whereas the predicted topographic contribution (assuming an overestimated density of 2200 kg/m^3) is considerable.

Very interesting is the point TNP-A situated on the Teide summit, at which we expected a much more extreme VGG value than was acquired by in-situ measurements. As we realized, the summit is built by the highly altered lavas. Therefore we suppose that the real density of the surrounding topographic masses in this case should be less than the adopted mean value of 2200 kg/m^3. As a matter of interest, we could roughly estimate the real density (assuming its constant value and perfect accuracy of the used DEM) by the recalculation and fine-tuning of the topographic contribution

Table 1. Numerical values of the measured and the calculated (predicted) VGGs that are shown in Fig. 7.

Point	**VGG measured**	**VGG calculated**	**VGGcalc-laser**	**Remark**
LLAN	−0.268	−0.261	–	Grav. network
UCAN	−0.474	−0.446	–	Grav. network
CHIP	−0.432	−0.440	–	Abs. point
SAMA	−0.303	−0.257	–	Abs. point
TNP-A	−0.506	−0.562	–	Field point
TNP-B	−0.482	−0.477	–	Field point
CF-A	−0.125	−0.134	−0.132	Field point
CF-B-1	−0.126	−0.138	−0.134	Field point
CF-B-2	−0.149	−0.107	−0.117	Field point

Fig. 8. Measurement of the VGG in a tower mode in bottom (upper picture) and top (bottom picture) positions of the gravity meter taken in a canyon.

to the VGG to fit the measured VGG value. In this way, we estimated the near topographic masses density for the point TNP-A equal to 1720 kg/m^3, which seems to be quite a low value. This estimate is very coarse, we have to bear in mind also the measurement error, as well as geological and other contributions to the VGG. However, both the mentioned examples indicate that, especially in volcanic areas, the density plays a very important role regarding the VGG.

4. Remark on significance of the VGG in volcano-monitoring gravimetric networks

We can clearly demonstrate the significance of the VGG on two mentioned neighboring points within the deformation/microgravity network (*Gottsmann et al., 2006*), namely the points LLAN and UCAN (see Figs. 1 and 3). These points are relatively close to each other, the distance between them is about 4 km. However, they show very different real VGGs, namely -0.268 and -0.474 mGal/m, respectively (Table 1). The point UCAN lies on the approximately 1 m tall concrete pillar (Fig. 9), so we used this pillar instead of the tripod (we are aware, that this fact changes the measured VGG a little). It is easy to estimate the error resulting from, say for example, a height difference of 20 cm between the repeated gravity measurements on

Fig. 9. Measurement of the VGG at benchmark UCAN on a concrete pillar.

these points. The adopted 20 cm could roughly correspond to the sensor height difference between commonly used gravity meters, such as the Scintrex CG-5/3 and the LaCoste & Romberg. When one uses the normal gradient of -0.3086 mGal/m instead of the real VGG values to compare the repeated gravity measurements between these two points, the resulting error in the gravity difference between them is of the order of 40 μGal. Such error greatly exceeds the required accuracy within the microgravity networks. We do not need to emphasize that this error can be even multiplied in the case of larger height differences between gravity meters sensors, which is valid e.g. for absolute gravity meters. One way to reduce this error, when the measured VGGs are not available, is the use of the predicted VGG values (those that account for the topographic contribution to the VGG) instead of the normal gradient. Specifically in our case, the error in gravity difference between the points will decrease from those 40 to only about 4 μGal. Of course, we are aware of many related problems such as DEM accuracy and resolution, the above mentioned density variability, or the contribution of geology to the VGG.

5. Remark on using measured vs. normal VGG in deformed volcanic areas

Many authors recommend using the in-situ measured VGG rather than the normal gradient to account for the deep geology contribution on the VGG in the areas affected by vertical deformation. As an approximation, *Berrino et al. (1992)*, *Rymer (1994)*, *Gottsmann and Battaglia (2008)* and others propose to calculate the "static Bouguer contribution" based on the amplitude of Bouguer anomaly in the area and the estimated depth of a point source. *Berrino et al. (1992)* estimated this effect at about of 20 μGal/m in the case of Campi Flegrei area. Although these authors in their consideration underestimated the magnitude of the topographic contribution to the real VGG, they correctly pointed out that VGG measurements should not be made in regions of extreme topography. As we have shown, the topography contribution to the VGG could be much greater than the expected "static Bouguer contribution" (which is of the order of only the first tens of μGal/m), even at the points of microgravity networks, which are not situated in extreme conditions. However, we are in agreement with the statement by *Rymer (1994)*, that the local (near-station) terrain moves during the deformation together with the gravity station and therefore its contribution to the actual VGG, although large, becomes irrelevant. We indicated this statement in our previous paper *Vajda et al. (2015)*, where we showed that DITE (Deformation Induced Topographic Effect) is a smooth function of the deformation (the vertical displacement field) even though the predicted VGG shows very high spatial variability. This issue is however outside of the scope of this paper and will be treated in a separate work by additional numerical simulations as well as analytical derivations.

6. Conclusions

We have obtained a good agreement between the predicted (based on the computed topographic contribution to the VGG) and the subsequently in-situ verified VGGs. The measured VGG values are in the range from -0.506 to -0.125 mGal/m. We have proved that extremely high VGGs (in their absolute values) are inherent to the convex topography shapes, especially cone-like peaks (*Zahorec et al., 2015*), as the Pico del Teide is. By contrast, extremely low VGG values are inherent to narrow deep canyons.

Although the mean adopted density of 2200 kg/m^3 (which, of course, greatly differs from the commonly used 2670 kg/m^3) brings in this volcanic region in general successful results, we have shown on two examples that the real density can be even considerably smaller in some cases such as the areas of young slag lavas or thermally altered layers (we got an estimate of 1720 kg/m^3). Consequently, the calculated topography contribution to the VGG, using unrealistic density, will be off-set.

We have discussed two examples when using the actual (or predicted) VGG vs. normal gradient. At the first one, considering the height difference of 20 cm between the gravity measurements at selected two network points shows the error of 40 μGal, when using the normal gradient instead of the actual VGG values. Using the predicted VGG values decreases this error to only about 4 μGal. In contrast to that, we have considered a different example, when the observation station moves vertically together with the topographic surface, which is the case of the areas affected by vertical deformation. We emphasize that the use of in-situ measured VGG, when interpreting time-lapse gravity changes, is valid only in the really flat areas seeing that the example with two mentioned real benchmark points, although not situated in extreme terrain, shows that the topography contribution to VGG can be much higher than the expected static geology (Bouguer) contribution.

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