

Advances in volcano gravimetry: Handling topographic effects

PETER VAJDA¹, PAVOL ZAHOREC¹, JURAJ PAPČO², DUŠAN BILČÍK¹,
FILIPPO GRECO³ and MASSIMO CANTARERO³

¹Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia; Peter.Vajda@savba.sk

²Dept. of Theoretical Geodesy, Slovak University of Technology, Bratislava, Slovakia

³Istituto Nazionale di Geofisica e Vulcanologia (INGV Catania) — Osservatorio Etneo, Catania, Italy

Abstract: In volcano gravimetry, spatiotemporal gravity changes are observed, processed and interpreted. This requires the application of proper correction for the sensor height of a gravimeter to reduce the gravity reading from the sensor position to the benchmark on the ground or to a common reference level when executing the repeat surveys using various types of gravimeters or various plates or tripods. Such correction/reduction, called the Free-Air Correction requires the use of true in situ vertical gradient of gravity (VGG). In the absence of in-situ measured VGG values, the constant value of the theoretical (normal) free air gradient (FAG) is commonly used. We propose an alternative to this practice which may significantly reduce systematic errors associated with the use of theoretical FAG. The true VGG appears to be better approximated, in areas with prominent or rugged topographic relief, such as alpine or many volcanic regions, by a value based on the modelled contribution of the topographic masses to the gradient. Such prediction can be carried out with a digital elevation/terrain model (DEM/DTM) of sufficient quality: resolution of 5 m or better and vertical accuracy at the order of 10 cm, depending on the roughness of the relief. We quantify also the need of improving the VGG prediction at gravimetric monitoring networks for benchmarks adjacent to man-made structures (walls, buildings, etc.). We also present the possibility to improve the VGG prediction by locally refining the DEM by drone-flown photogrammetry. The predictability of VGGs in regions of rugged relief was verified by in-situ observations in the Central Volcanic Complex (CVC) of Tenerife (Canary islands) and at Mt. Etna (Italy). We illustrate how strongly and sharply the VGG field deviates spatially from the constant value of FAG. We also analyze the sensitivity of the VGG prediction to the resolution and accuracy of the used DEM. Finally we discuss the role and treatment of the Deformation-Induced Topographic Effect (DITE) in compiling and interpreting residual time-lapse gravity changes in 4D micro-gravimetry.

Prediction of VGG

The value of VGG at a benchmark consists basically of 3 components: that generated by the normal reference (level) ellipsoid, that generated by the topographic masses (of constant reference density), and that generated by the subsurface density anomalies (geological heterogeneities).

The component due to level ellipsoid (normal reference ellipsoid) can be globally (up to altitude of 9 km) approximated by the constant theoretical free-air gradient ($FAG = -308.6 \mu\text{Gal/m}$) with accuracy better than $0.5 \mu\text{Gal/m}$ (e.g., Zhao et al. 2015). In regions with prominent and rough topographic relief the contribution of topo-masses to the gradient can be expected to be significantly higher than the contribution of geological heterogeneities. Upon neglecting the geological component we can predict the actual VGG by adding to the constant value of FAG the accurately modelled VGG component due to the topographic masses. It can be modelled with sufficient accuracy suppose a digital elevation (terrain) model (DEM/DTM) of sufficient quality is available. The topo-component is computed by a numerical volumetric Newtonian integration, such as

that facilitated by the Toposk software (Zahorec et al. 2017). Its accurate realization in micro-gravimetric applications in areas of prominent and rough topographic relief requires a DEM with a resolution at the level of several meters and vertical accuracy at the order of 10 cm. In regions with rugged topography the predicted VGG severely deviates from the constant FAG. This deviation is high in amplitude and exhibits sharp spatial variability (Figs. 1 and 2). In absolute sense the high values of VGG are associated with sharp convex terrain features (peaks, ridges), while the small values with the concave ones (canyons, gullies, craters). In alpine regions like the High Tatras of the northern Slovakia the predicted VGGs depart from constant FAG by as much as 88 %. A departure of 77 % was observed in the CVC of Tenerife (Fig. 1). The situation is similar at the Phlegrean fields (Fig. 2).

In situ verification

The accuracy of predicting the VGGs by adding the computed (modelled) topo-component to the constant FAG was verified in selected volcanic regions by in-situ

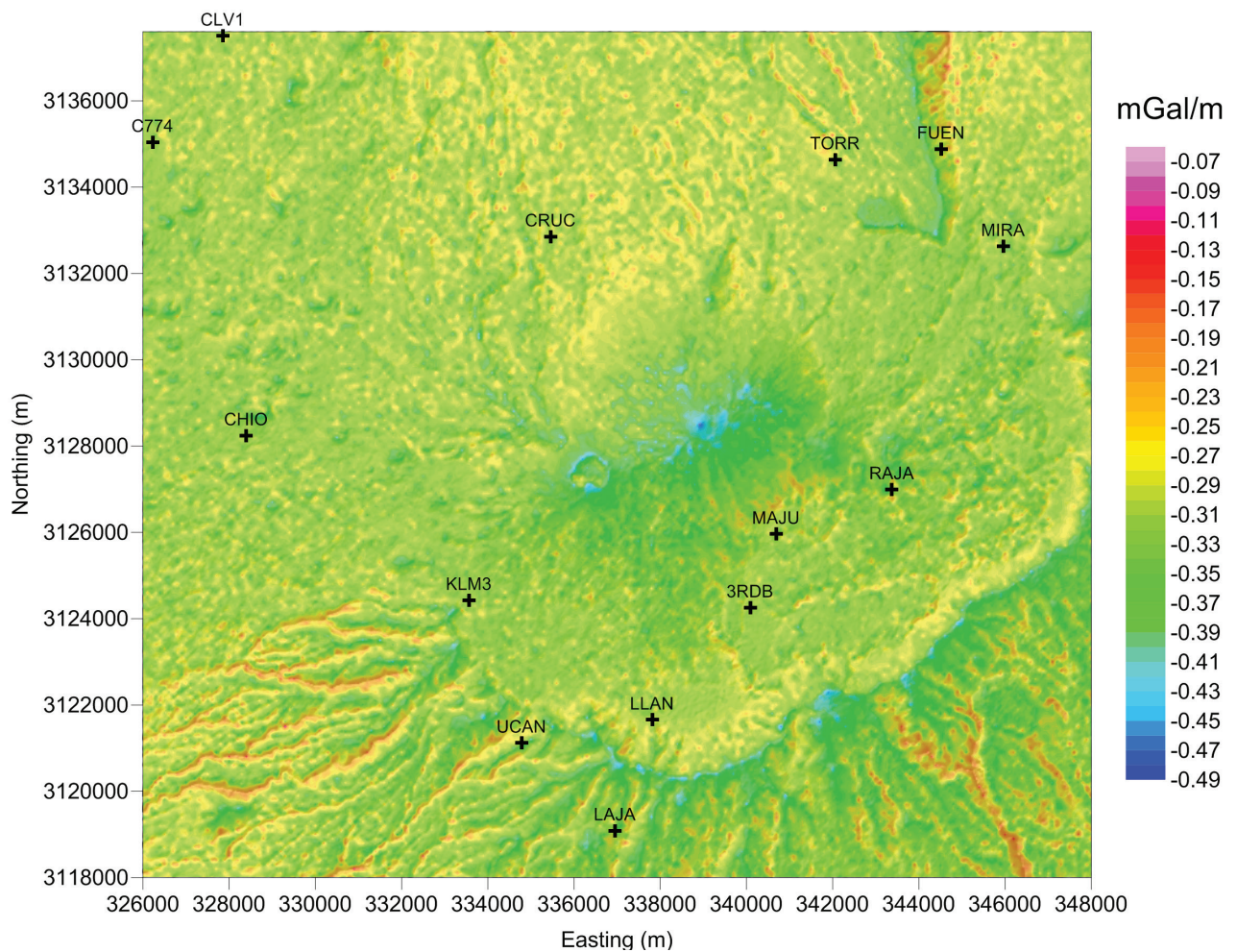


Fig. 1. The predicted VGG field (mGal/m) at the CVC of Tenerife based on a 2 m LiDAR DTM.

observations of VGGs (Fig. 3). Results of the verification campaign in the CVC of Tenerife (Canary islands) and on Mt. Etna (Italy) are presented. When a DEM of adequate quality is used for modelling the topo-contribution to the gradient, the match between predicted and in-situ VGGs is generally very good. Accurate modelling requires LiDAR-derived DEM with resolution at the level of 5 m and accuracy at the order of 10 cm. However, discrepancies may occur at some benchmarks due to geological signal/component (heterogeneities) such as subsurface (near-surface) hydrothermal alteration.

Refinement of VGG prediction

If benchmarks of a gravimetric network are at or inside (or in close proximity to) man-made structures like walls or buildings, the gravitational effect (on VGG) of these

structures must be accurately modelled in addition to the effect of topographic masses, as it is significant, too. In addition, the nearest-terrain DTM, and its modelled effect on VGG, may be refined by constructing a local drone-borne photogrammetry-derived local DTM within the nearest zone of the modelled topo-contribution (Zahorec et al. 2018).

Applicability — 3D microgravimetry

Various gravimeters, in combination with various tripods, have various vertical positions of their sensors above the ground. Therefore micro-gravimetric observations require an accurate reduction of the measurement from the meter sensor to the benchmark on the ground or to a common adopted level. This reduction is accomplished based on the true in-situ VGG. If the true VGGs are not available, they can be topo-predicted. The use of

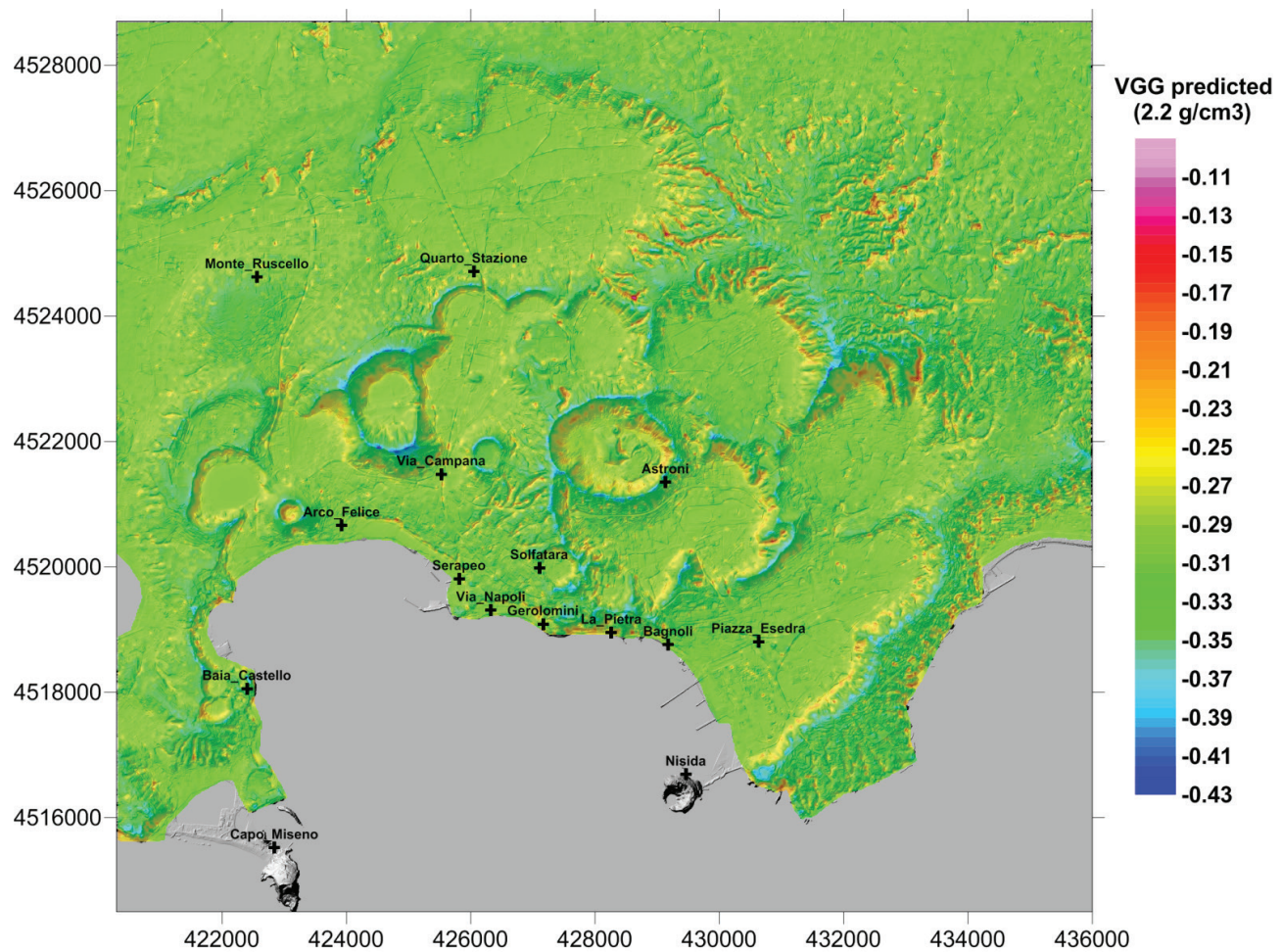


Fig. 2. The predicted VGG field (mGal/m) at Campi Flegrei (Italy) using a 5 m LiDAR DTM.



Fig. 3. In situ VGG observations on Etna (NE crater) using a relative gravimeter in tower mode.

the predicted VGGs in free-air correction is in regions of prominent topography a better choice than the use of the constant FAG.

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Applicability — 4D microgravimetry

In volcano-gravimetric studies often residual spatio-temporal gravity changes are compiled and interpreted. Some studies apply the free-air effect (FAE) as a correction, which is based on the true in situ VGG, while other studies use the constant FAG instead. The rigorous treatment of deformation-induced topographic effect (DITE) and its numerical realization is outlined here and dealt by in due detail in (Vajda et al. 2019).

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