Free-Air and Deformation-Induced Topographic Effects (FAE and DITE) in volcano geodesy

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Repiská, Demänová

Vajda, P., Zahorec, P., Papčo, J., Bilčík, D., Carbone, D., Greco, F., Cantarero, M.

Earth Sci Inst SAS, Bratislava
Dept Geod SUT in Bratislava
INGV Catania, Osservatorio Etneo

VERTICAL GRADIENT OF GRAVITY (VGG)

DECOMPOSITION OF VGG

$$\Gamma(h,\Omega)=\Gamma_N(h,\Omega)+\delta\Gamma_T(h,\Omega)+\delta\Gamma_G(h,\Omega)\,,$$

normal ellipsoid | topo-masses const ref density | subsurface density anomalies

$$\Gamma_N(h,\Omega)\approx\Gamma_0,\ where\ \Gamma_0 = \text{-}308.6\ \mu\text{Gal/m}$$

globally better than 0.5 μGal/m

PREDICTION OF VGG FIELD (VGG VALUES)

$$\Gamma(h,\Omega)\approx\Gamma_P(h,\Omega)\,,\ where\ \Gamma_P(h,\Omega)=\Gamma_0+\delta\Gamma_T(h,\Omega)\,.$$

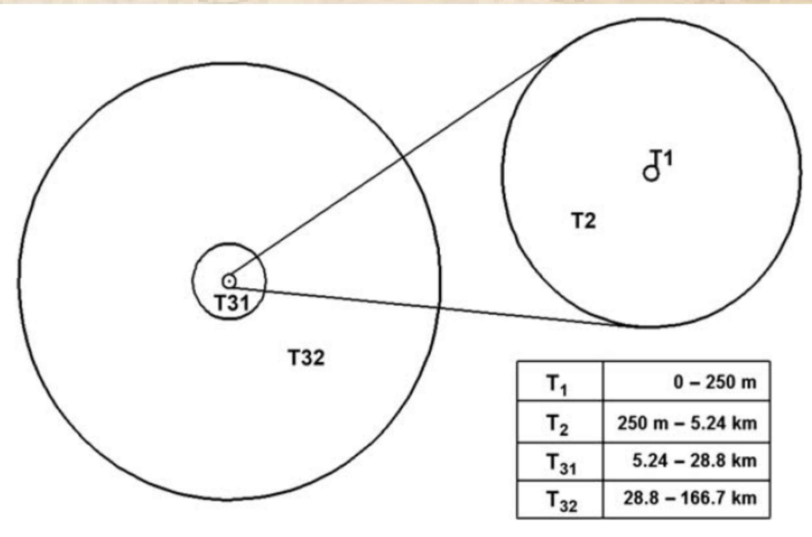
Neglecting the effect of geology (contribution of subsurface density anomalies)

MODELLING THE CONTRIBUTION OF TOPO-MASSES TO VGG

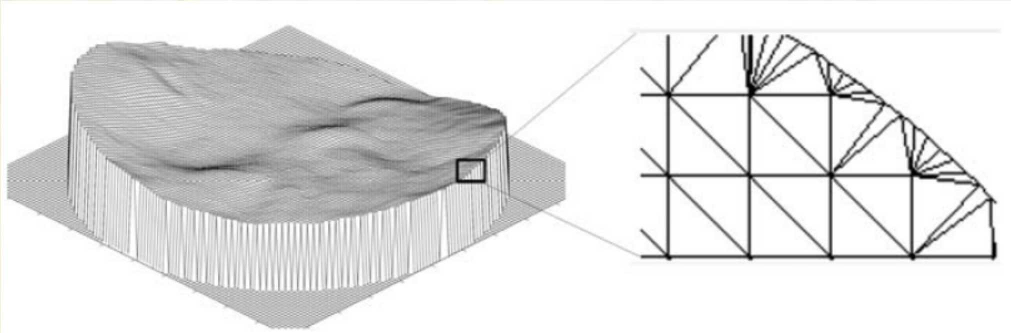
- High resolution (a few meters) high accuracy (10 cm) DEM (DTM, DMR)
- Correct choice of representative constant reference topo-density
- Accurate numerical volumetric Newtonian integration (e.g., Toposk software)

TOPOSK Computing topo-attraction

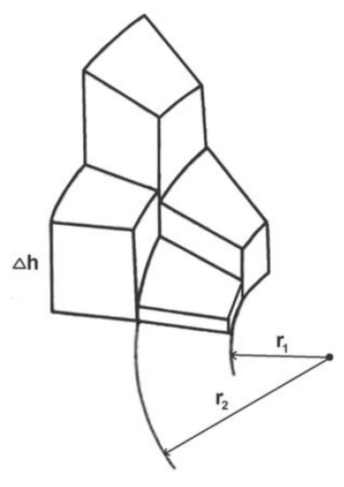
topo-contribution to VGG =
difference of topo-attractions at (1.25—0.25 m) / 1m



Inner zone (0-250 m)
planar, polyhedra, boundary treatment



Intermediate zone (250-5240 m) planar,
triangular prisms/cylinder segments 30x30 m

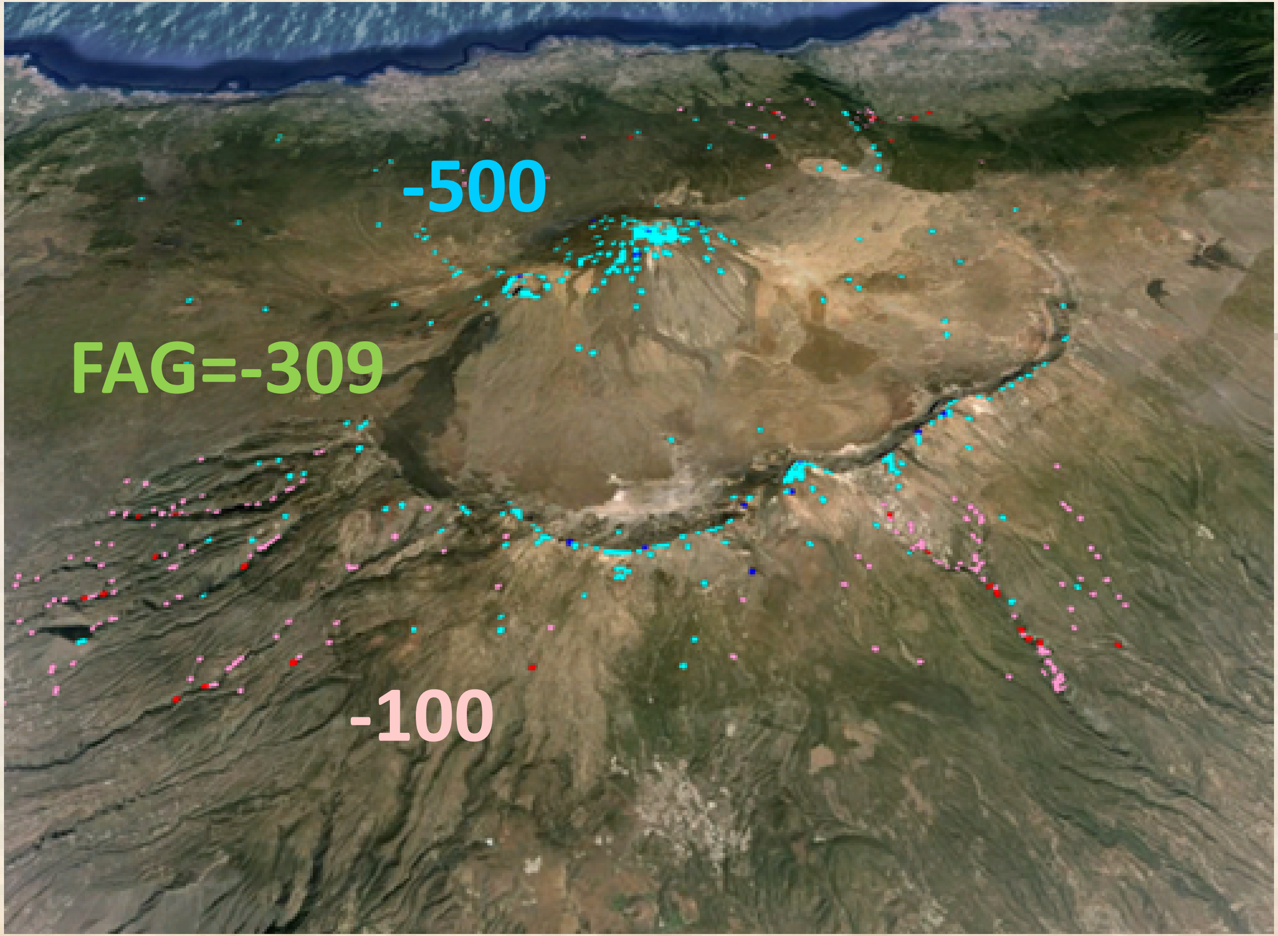


Outer zones (5.24-28.8 km) and (28.8-166.73 km) spherical,
spherical layer segments, SRTM grids 3x3 and 30x30 arcsec

PREDICTED VGG FIELD SIGNIFICANTLY DEVIATES FROM FAG

Predicted VGG field CVC of Tenerife Canary islands

Based on LiDAR-derived DEM (5m)

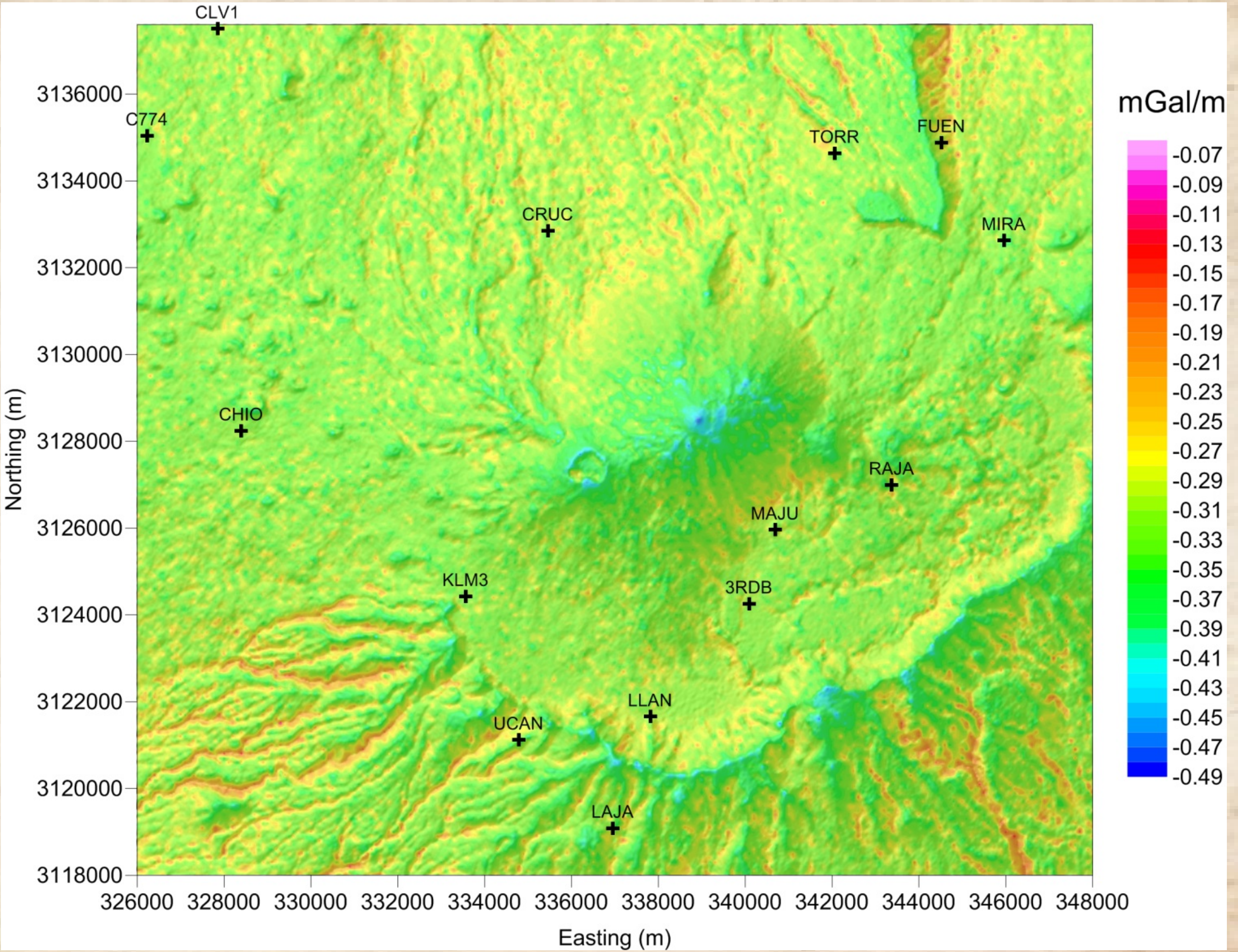


up to 90 %

in regions of rugged topo relief

High values (in abs sense) **at convex low values at concave relief features**

VGG field deviation from FAG is not only high in amplitude, it is spatially very sharp



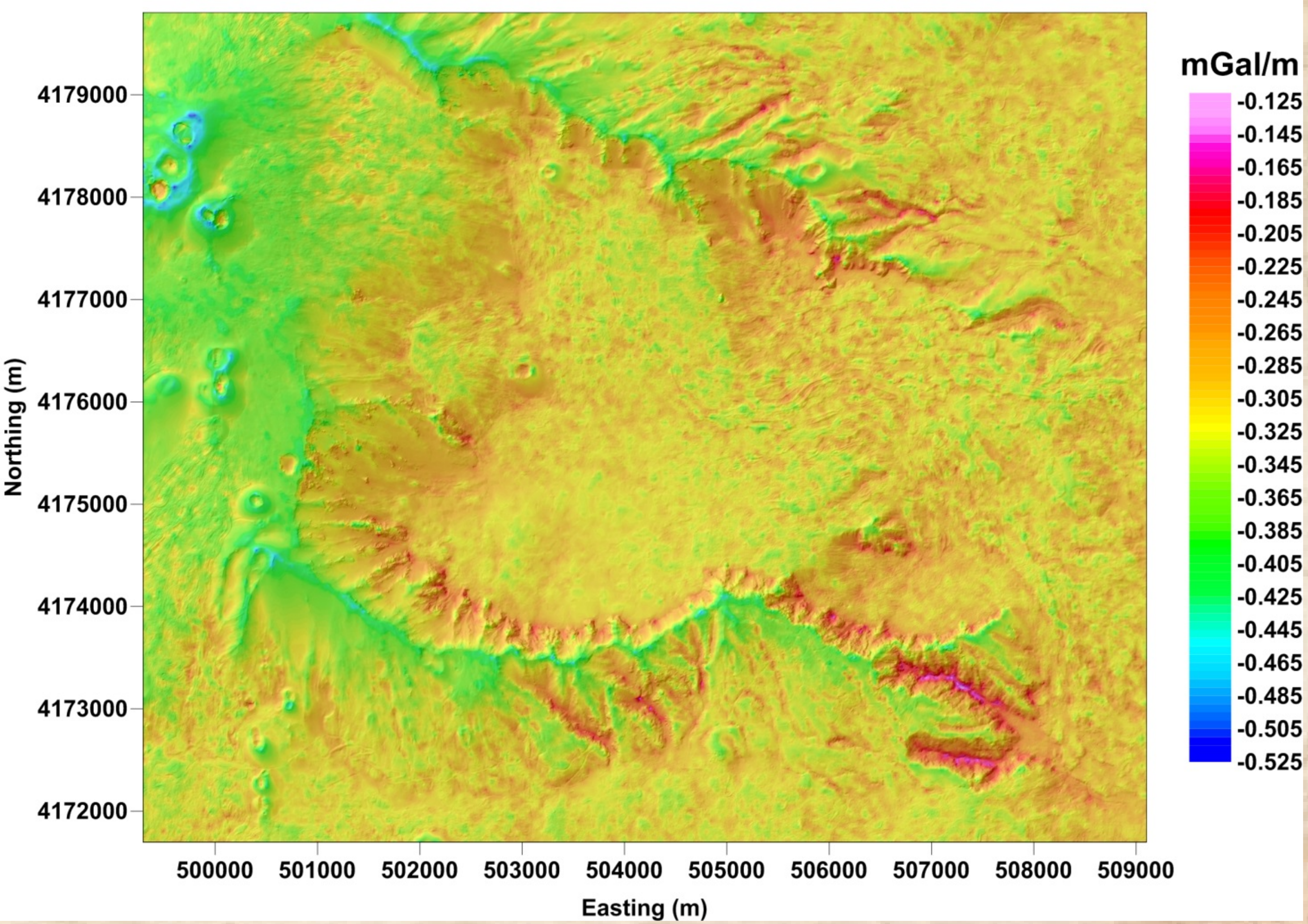
Predicted VGG field
CVC of Tenerife
Canary islands

PREDICTED VGG FIELD

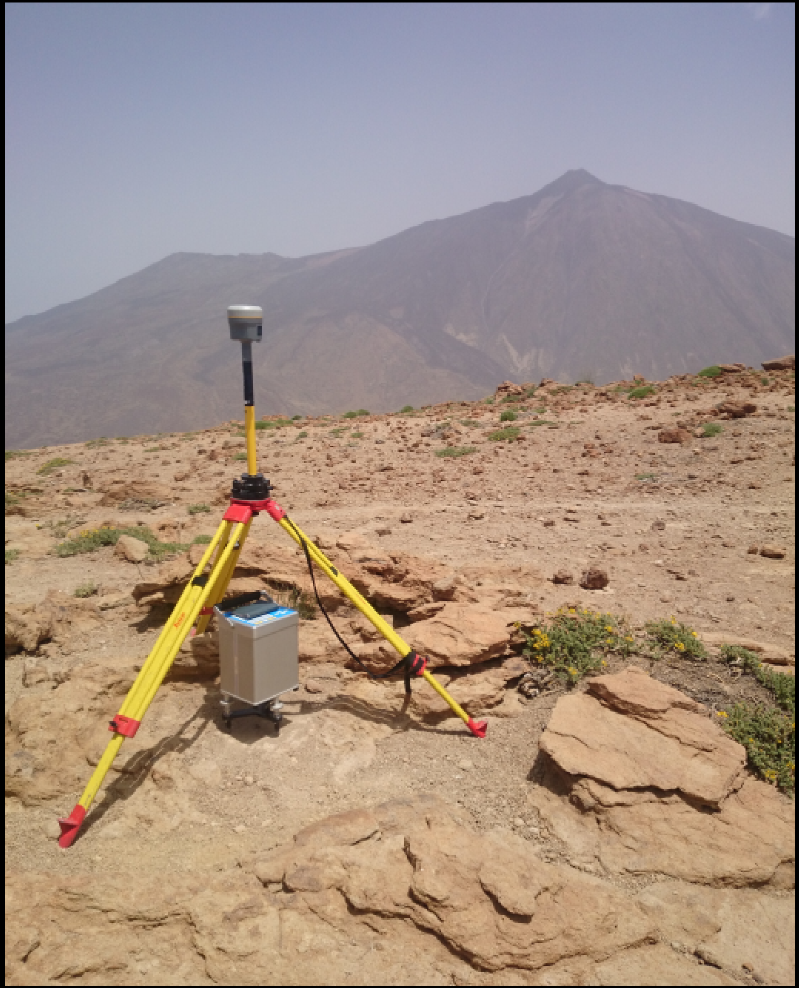
ETNA

Valle del Bove and summit craters

125 to 525 μGal/m

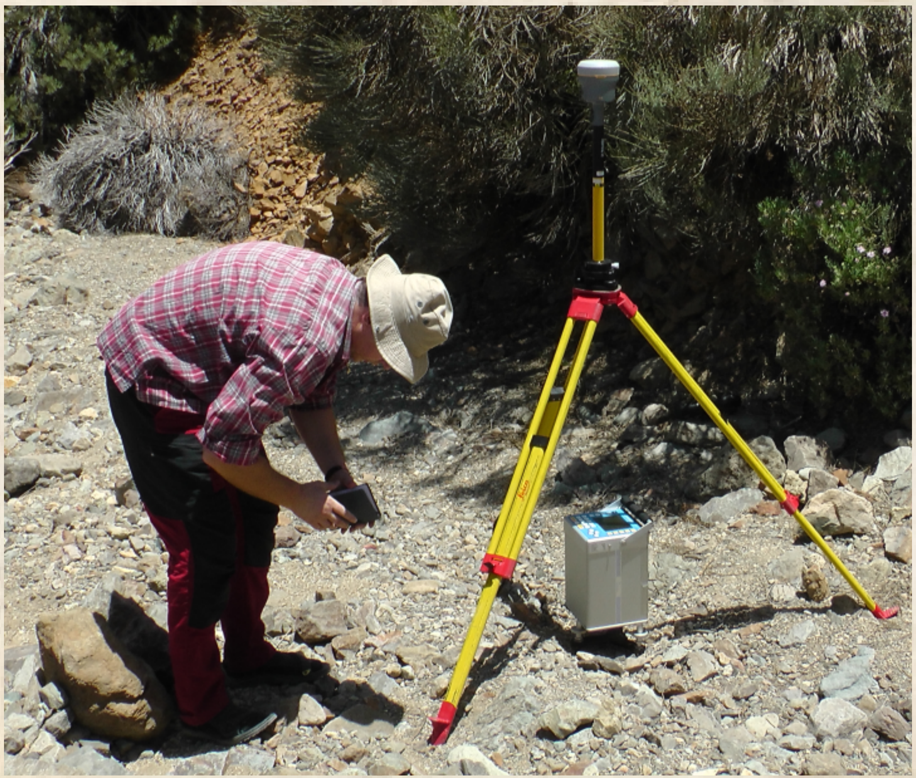


IN SITU VERIFICATION OF PREDICTED VGG

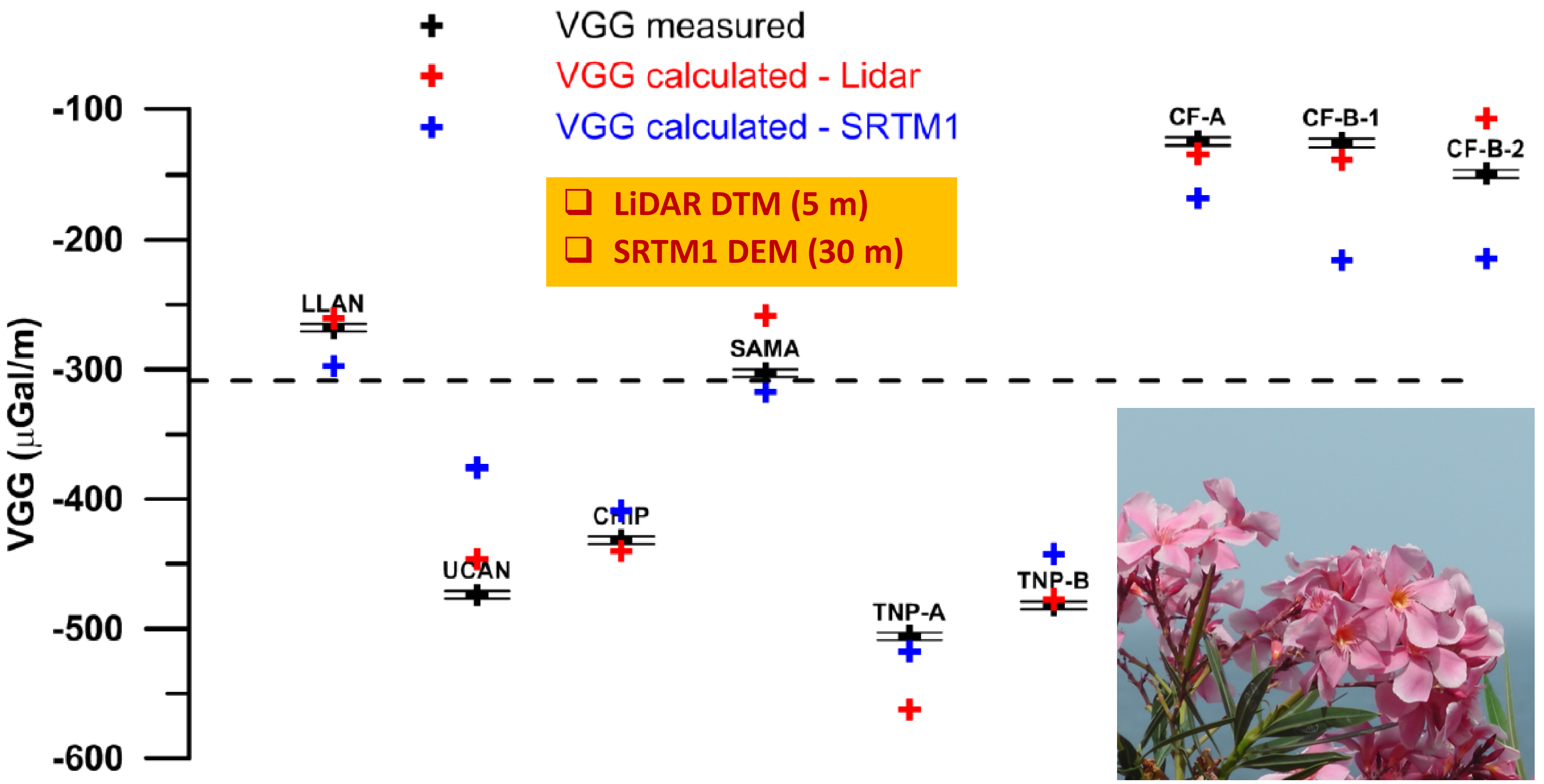


VGG OBSERVATION

with relative gravimeter in tower mode



TEIDE
TENERIFE
CANARY
ISLANDS
JUNE 2016


VGG measured
VGG calculated - Lidar
VGG calculated - SRTM1
LiDAR DTM (5 m)
SRTM1 DEM (30 m)
VGG (μGal/m)
-100
-200
-300
-400
-500
-600
LLAN
UCAN
CHIP
SAMA
TNP-A
TNP-B
CF-A
CF-B-1
CF-B-2

ETNA
SICILI
ITALY
JULY
2018


seco
seco

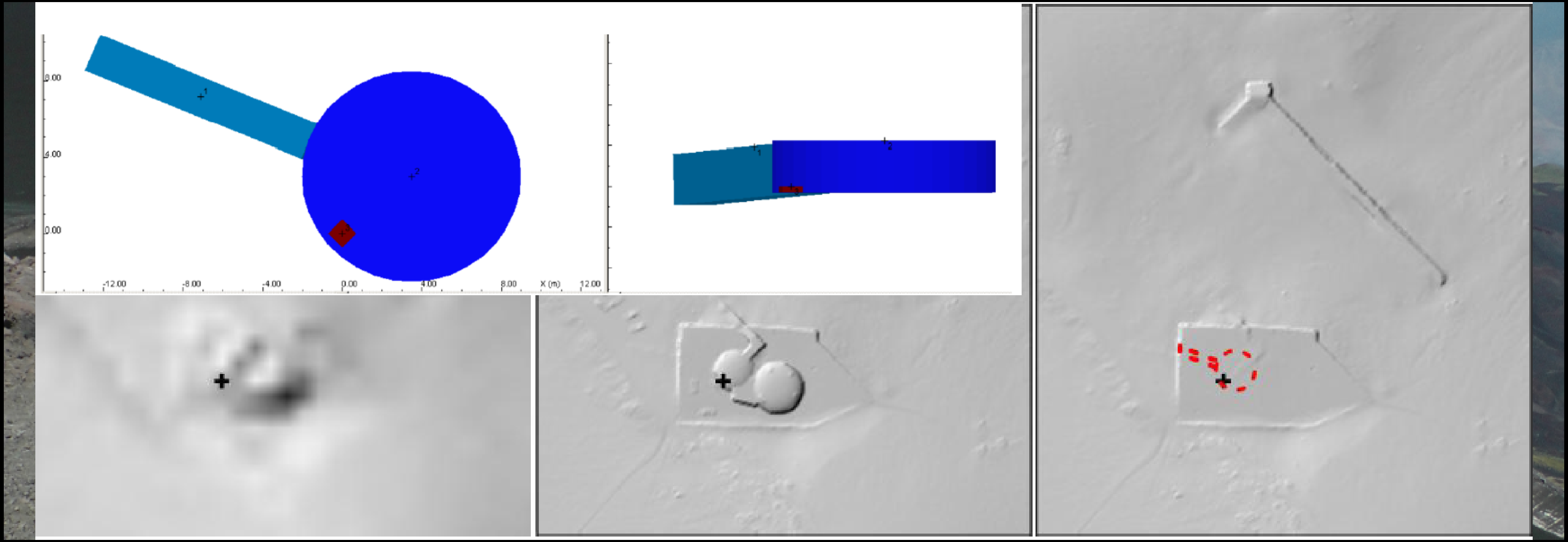
Improvements to VGG prediction

- ❑ correction for anthropic structures (at monitoring networks)
- ❑ local in-situ DEM improvement (drone-borne photogrammetry)

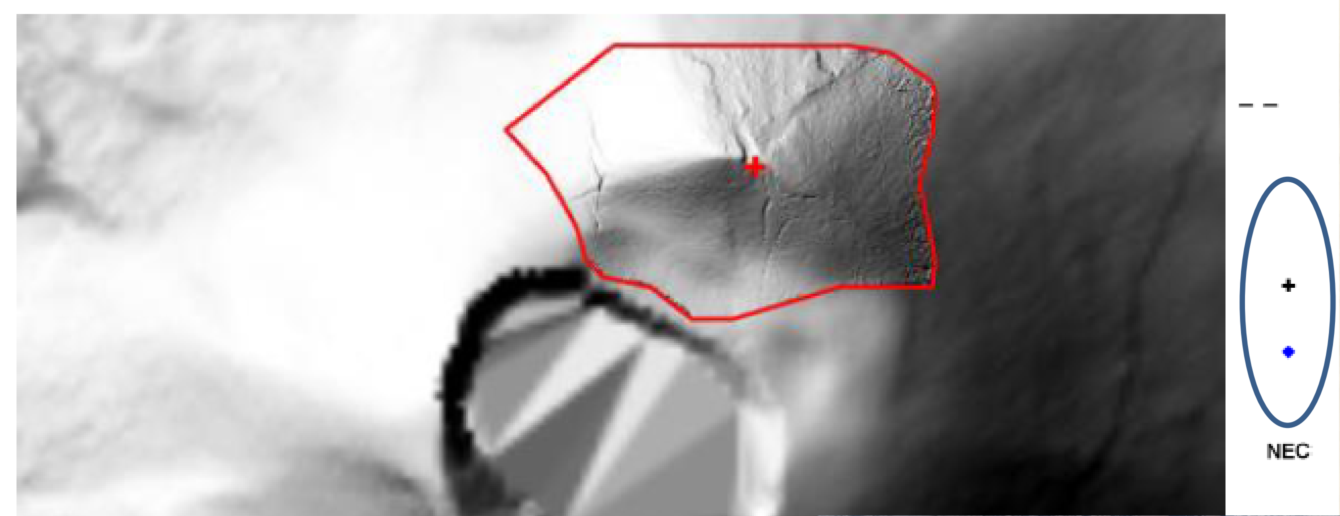
ETNA VOLCANO MONITORING NETWORK: PIZZI DENERI OBSERVATORY

REFINED VGG PREDICTION AND IN SITU VERIFICATION (PDN 2847M)

- ❑ drone-flown photogrammetry (res **50 cm**, vert.acc. **10 cm**) to improve the inner-most zone DEM for topographic contribution to VGG computation



IN SITU VERIFICATION OF PREDICTED VGG FIELD



ETNA (SICILY)

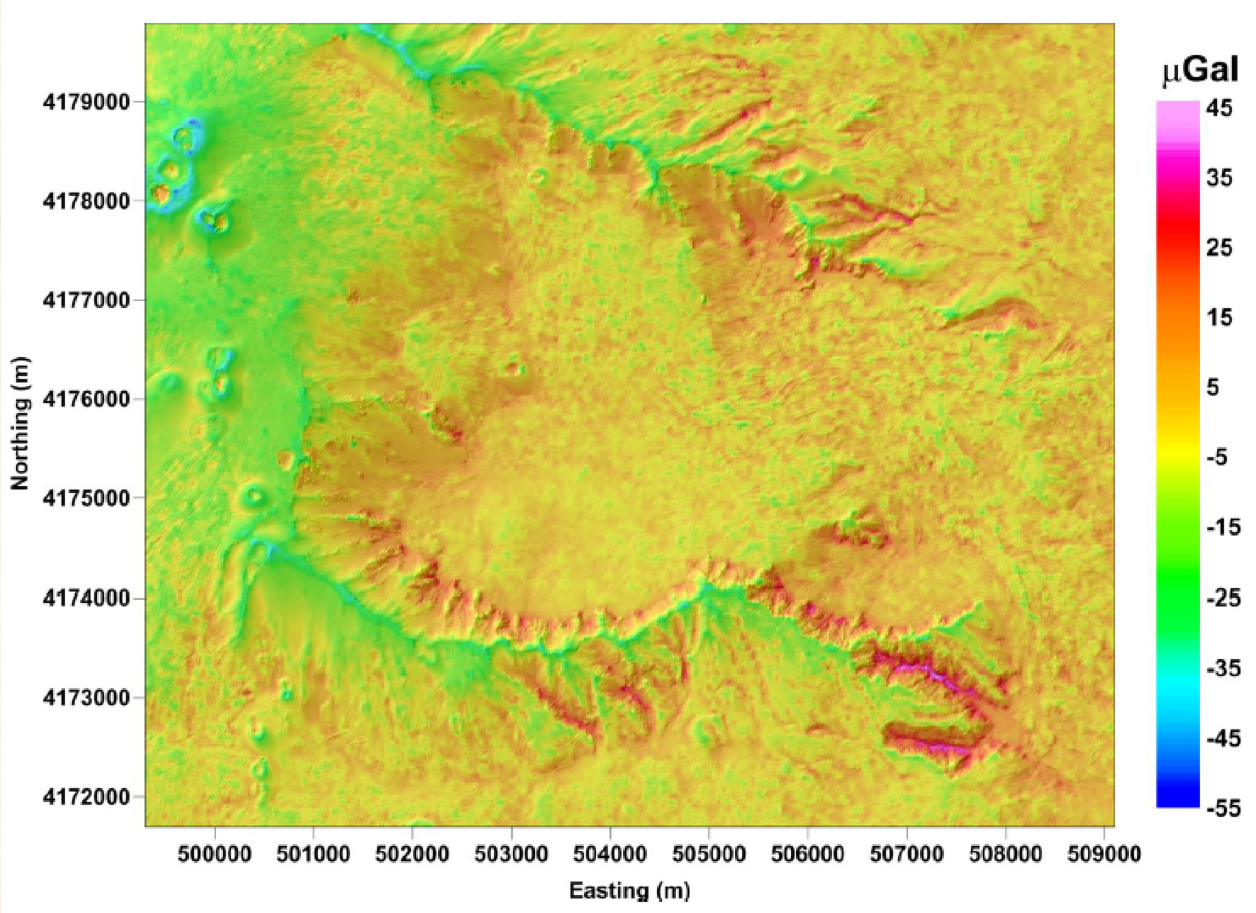
- ❑ relative points
- ❑ absolute points
- ❑ field points

FREE AIR EFFECT (FAE)
FREE AIR CORRECTION

constant theoretical (normal)
FREE AIR GRADIENT (FAG)

versus VGG

Microgravimetric surveys: Diff btw FAE and nFAE



FAE

- ❑ FAE is based on VGG
- ❑ nFAE is based on constant normal FAG
- ❑ FAE can be approximated by using topographically predicted VGG
- ❑ Correction for gravimeter sensor height above ground
- ❑ Illustrated is difference between FAE and nFAE for sensor height 25 cm on Etna
- ❑ Systematic error of +45 to -55 mjuGal

FREE AIR CORRECTION

4D MICROGRAVIMETRY

FAG, VGG,
FAE, DIE and DITE

VOLCANO GEODESY

surface deformation and spatiotemporal gravity changes

Residual SpatioTemporal Gravity Change

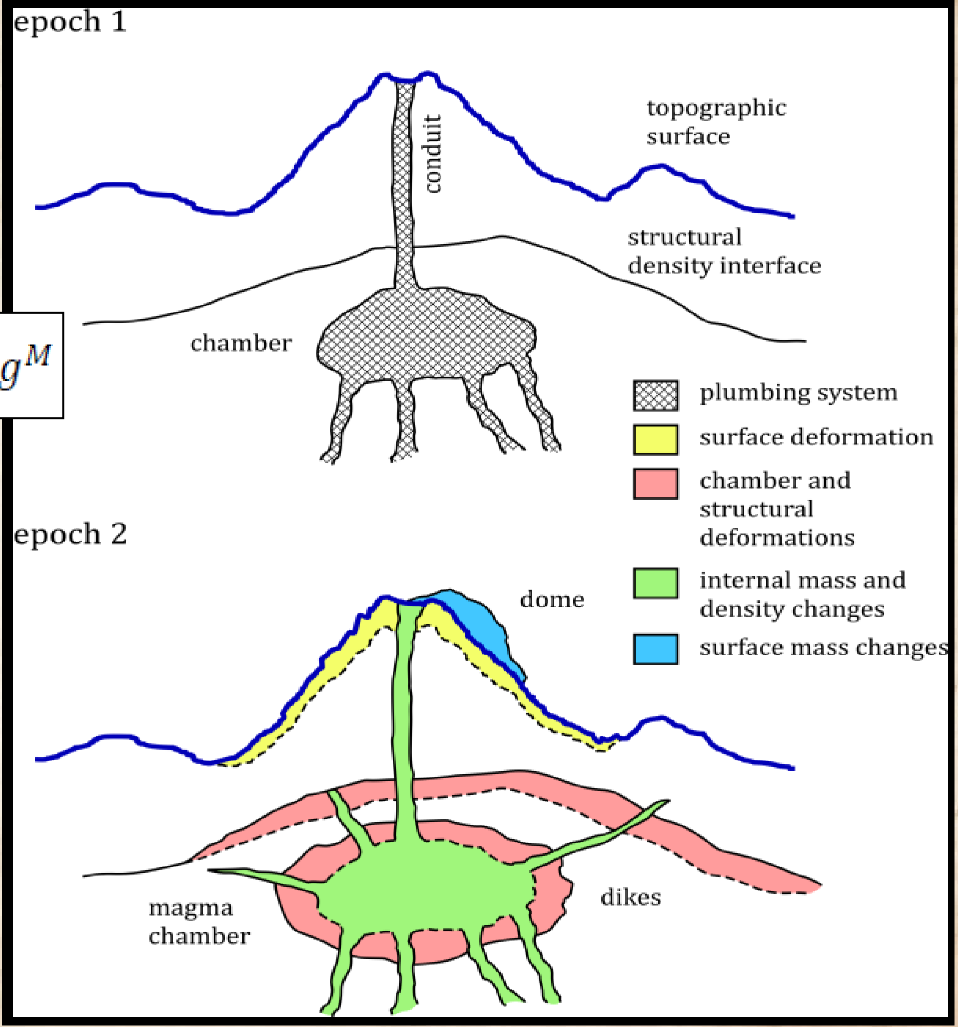
complex composite signal

deformation-induced topo effect (DITE)

$$\Delta g = \boxed{\Delta g^{FAE} + \Delta g^{TDE}} + \Delta g^{idef} + \Delta g^{surf} + \Delta g^{M}$$

component	description (gravitational effect)
Δg^{FAE}	free air effect (gradient effect) FAE
Δg^{TDE}	topographic deformation effect (TDE) (attraction of masses trapped between pre– and post–deformation topographic surfaces)
Δg^{idef}	attraction of temporal density changes due to internal deformations
Δg^{surf}	attraction of temporal surface mass changes
Δg^{M}	attraction of subsurface mobile mass changes (redistribution and density changes of mobile magma and/or its volatiles)

coupling between Δg and Δh



Deformation induced effects (DIE) in volcano gravimetry

DIE = FAE + surface and internal deformatons Bouguer effect (Battaglia et al. 2008)

$$\Delta g_{\mathrm{def}}(P) = \Gamma(P)\Delta h(P) + \Delta g_{\mathrm{D}}(P) \, .$$

FAE approximation of DIE

$$\Delta g_{\mathrm{def}}(P) \approx \Gamma(P)\Delta h(P) \, .$$

Acceptable under specific conditions when surface and internal deformations effects cancel out

DITE: most accurate numerical realization (Vajda et al. 2019, Surveys in Geophysics)

$$\Delta g^{\mathrm{DITE}}(P) \approx \Gamma_0 \Delta h(P) + [a^{\mathrm{T}*}(P^*) - a^{\mathrm{T}}(P)] \, ,$$

Requires vertical displacement field known in areal form – otherwise:

nFAE approximation of DITE

$$\Delta \mathrm{g}^{\mathrm{DITE}}(P) \approx \Gamma_0 \, \Delta h(P) \, ,$$

Bouguer approximation of DITE

$$\Delta g^{\mathrm{DITE}}(P) \approx BCFAG * \Delta h(P) \, , \text{ where } BCFAG = \Gamma_0 + 2\pi G \varrho_0$$

DITE CONCLUSIONS

- The nature of DITE varies between normal–free–air–like and Bouguer-like depending on the shape and horizontal extent of the deformation field and on the shape of the relief over which it is exposed (in most cases it is closer to Bouguer-like)
- the most accurate numerical realization of DITE is:

$$\Delta g^{\mathrm{DITE}}(P) \approx \Gamma_0 \Delta h(P) + [a^{\mathrm{T}*}(P^*) - a^{\mathrm{T}}(P)] ,$$

  However, it requires the deformation field to be known in areal form
- if vertical displacements are known only on benchmarks, two approximations of DITE are available: BCFAG-DITE and nFAE-DITE
- nFAE-DITE approximates DITE well only in special cases of very narrow spiky deformation fields over cone-shaped steeper relief
- in all other cases BCFAG-DITE approximates DITE better


IN GV
GENETIC CODE
seco