Geodetic and Geophysical Approach of the Gravitational field in Santorini Volcanic Group

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ABSTRACT

Santorini is located in the central part of the Hellenic Volcanic Arc (South Aegean Sea) and is well known for the Late-Bronze-Age "Minoan" eruption that might had been responsible for the decline of the great Minoan civilization on Crete island. Dionysos Satellite Observatory (DSO) of the National Technical University of Athens (NTUA) carried out terrestrial gravity measurements in December 2012 and in September 2014 at selected locations on Thira, Nea Kameni, Palea Kameni, Thirasia, Aspronisi and Christiana islands. Absolute gravity values were calculated using raw gravity data at every station to a combined dataset (2012-2014) and, consequently, complete Bouguer gravity anomaly maps were produced following the appropriate data corrections and reductions. The results were compared with gravity measurements that took place in July 1976 by DSO/NTUA and gravity variations at selected common locations were revealed. Marine gravity data that were collected during the *PROTEUS project in November and December 2015* have been graded from University of Oregon and they fill the gravity dataset. An appropriate Digital Elevation Model (DEM) with topographic and bathymetric data was produced for the calculation of new, local scale, quasi-geoid and geoid model in Santorini Volcanic Group using the residual terrain approach and the GRAVSOFT package (Forsberg, 1994; Tscherning et al., 1992). Reliability of the model was assessed with geoid heights from independent measurements such as GPS-leveling in known triangulation points.

I. INTRODUCTION

A. *Scientific Background*

Earth's gravity is a physical field resulting from the purely attraction due to the planet's mass composed of a centrifugal term due to Earth's rotation. Gravity varies from place to place, and in any given place, varies with time. Physical Geodesy associates the morphology of Earth's gravity field to study the shape and dimensions of the planet itself. Geophysics use gravity to better understand deep structures of Earth by modeling their density distributions with depth, while Geodesists care mostly about the shape of the Earth.

Santorini is located in the central part of the Hellenic Volcanic Arc (South Aegean Sea) and is well known for the Late-Bronze-Age "Minoan" eruption that might had been responsible for the decline of the great Minoan civilization on Crete island. There was a quiet rest period of the area from 1950 to 2011. In January 2011, Santorini entered a phase of unrest that lasted until March 2012 (Parks et al., 2012). Thereby, a number of heterogeneous scientific instruments for volcano monitoring have been installed on Santorini volcanic group including GPS continuously operating stations, tide meters, magnetometers, carbon dioxide counters and seismographs. Another geophysical approach that is suitable for volcano monitoring relies on onshore measurements of the gravitational field; particularly, the comparisons between gravity measurements obtained at different time epochs. Dionysos Satellite Observatory of National Technical University of Athens

(DSO/NTUA) obtain a set of measurements for Santorini island from 1976. Furthermore, gravity measurements took place in early December 2012 at selected locations throughout Santorini volcanic group that were also filled out in September 2014.

The aim of this paper is to present and discuss the field gravity measurements obtained at Santorini volcanic group (Thira, Thirasia, Palea and New Kameni and Aspronisi) in two epochs before and after/during the unrest period of 2011-2012 and to present the determination of a geoid model in the area.

B. *Area of interest*

Santorini Volcanic Complex is located in the central of the Aegean sea in Greece (36.3°<λ<36.5°, 25.3°<ϕ<25.5°) and it consists of Thira (Santorini), palea kameni, Nea kameni, Aspronisi, Thirasia and the active submarine volcano of Kolumpo.

II. Materials and method

A. *GRAVITY DATASETS*

In 1976, the NTUA carried out a series of measurements on Santorini island using the gravimeters La Coste & Romberg G51& G63. Besides, in order to obtain altitude information, three Thomson made altimeters and one psychrometer Assman were used. Absolute gravity values of this measurements were used from Paraskevas et. al 2015, Agatza Balodimou et. al 1984.

In 2012 gravity measurements were collected using the gravimeter Scintrex CG5. Observations span 53 stations in total, from which 36 stations are at known orthometric and geometric height. The measurements connected through the "El. Venizelos" airport with the National Gravity Station of HMGS. At each data location, two successive measurements were undertaken to check for repeatability. In addition, as is essential in any precise gravity survey, nearly all stations were revisited for several times, either on the same loop to control drifts or on a different loop to tie loops together. Furthermore, a GPS Promark 100 receiver was used to measure geometric height at the area of each station. The measurements were repeated and filled in during September 2014 using the same instrumentation. Observations span 83 more stations. Finally, the measurements connected through Piraeus port control point to the National Gravity Station of HGMA. Absolute gravity values of these measurements were used after Paraskevas et. al 2015. Measurements from 2012 and 2014 were adjusted together in order to prepare a dense gravity database.

In November and December 2015 Marine gravity data were collected during the PROTEUS project. Those data were graded from University of Oregon and they fill the gravity dataset. 405563 successive absolute gravity values were used in this recherché of almost 1500000 unpublished successive values of the extended area.

B. *Coordinate System*

The selected coordinate system for this research is WGS84 (G1674 edition). In order to be compatible with this system all gravity and GPS points need an appropriate transformation from the epoch of the measurement to the selected coordinate system. Dataset of 1976 was measured at Hayford geographic coordinates while newest datasets were measured at WGS84 geographic system. The exact position of the station measured in 1976 was calculated with local transform between two systems and corrected with descriptions of each station.

Selected gravity datum was WGS 84 which includes atmospheric mass in the calculation of the ellipsoid.

C. *Digital Terrain Model and Seafloor Topography*

Heterogeneous data were used to construct a very detailed Digital Terrain Model and seafloor topography. These data include: (i) geometric altitudes from the NTUA network available at 56 locations, (ii) 5m meter DTM graded from Hellenic Military Geographical Agency (HMGA), originated from combined photogrammetric methods and height measurements, (iii) orthometric and geometric heights at geodetic control points obtained also by the HMGA, (iv) height measurements with GPS receiver, (v) 10 m seafloor contours derived from HMGA, (vi) high resolution swath data that made available from Nomikou et al., 2014, (vii) the high resolution GDEM of ASTER v2 (NASA and METI), (viii) the recent coastline from HMGA and (ix) Lidar data from Nomikou et. al 2014. A dense Digital Elevation Model (DEM) with pixel size of 5m was created in the area of interest and a rather rough DEM with pixel size of 100 m in the surrounding areas.

D. *Global Geopotential Model (ggm)*

Two ggm were tested in the area of interest for this research: EGM2008 (Pavlis et al, 2008), EIGEN6C4 (Forste et al, 2015), until order and class 2190. These models were tested at 128 measured stations at 2012_2014 campaign, to free air gravity anomalies. The whole test was made in matlab code (GRAVSynth (Papanikolaou & Papadopoulos, 2015) where built spherical harmonic synthesis for each ggm at all points and compare calculated values with measured values.

From Table 1 it is obvious that EGM2008 fits better to measured data and is the selected GGM.

Table 1. Comparison of GGMs

Statistics	128 gravity stations	
	EGM2008 mgal	EIGEN6C4 mgal
Min	6.04	26.63
Max	69.08	97.81
Mean	24.86	48.27
Sdv	11.34	13.04

E. *Reduction Scheme*

The reduction scheme for final adjusted Absolute gravity values includes:

1) Geographic latitude corrections: All gravity data were reduced to WGS84 ellipsoid so that consistency is retained with the HMGA gravity measurements, using the closed Somigliana's formula (Somigliana 1930):

$$Gmod = ge * \frac{1+k\sin^2\varphi}{\sqrt{1-e^2\sin^2\varphi}} \quad (1)$$

where ge=978032.67714 mgal
k=0.00193185138639
e^2=0.00669437999013
ϕ latitude of the station in decimal degrees.

2) Free air reduction: The simply free air gradient was used:

$$\delta gFA = -0.3086H \quad (2)$$

where H is the orthometric Height above sea level in meters

3) Bouger Plate: Simply Bouguer reduction was calculated without the effect of the Earth's curvature due to the limited area of interest (William J. Hinze 2005) using the following formula

$$\delta gBC = 2\pi G\rho H \quad (3)$$

where G=6.674x10^{11}Nm^2/kg^2 is the universal gravitational constant
ρ is the mean density of the rock material of the plate (in gr/cm^3)
H is the orthometric height above sea level.

4) Terrain Correction (TC): Terrain correction was calculated using the algorithm proposed by Nagy (1966) and Kane (1962). To calculate corrections, the produced DTM5 was 'sampled' to a grid mesh centered on the station to be calculated. The correction was calculated based on near zone, intermediate zone and far zone contributions. In the near zone (0 to 5m) from the station, the algorithm sums the effects of four sloping triangular sections, measured around the station. (Where there are no measurements the surface between the station and the elevation at each diagonal corner of the pixel of produced dtm was used).

$$g = G\rho\varphi(R - \sqrt{R^2+H^2} + \frac{H^2}{\sqrt{R^2+H^2}} \quad (4)$$

where g is the gravitational attraction; ρ, the terrain density; ϕ, the horizontal angle of the triangular section; G, the gravitational constant; H, the difference between the station elevation and the average elevation of the diagonal corner; and R, the specific distance (here 5m).

In the intermediate zone (5 to 40 m), the terrain effect is calculated for each point using the flat topped square prism approach of Nagy (1966) (eq.5). The terrain height is measured on a regular grid (equal spacing), with a total of N×M points, then the terrain correction can be computed by summing up all these N×M prisms using equation 5:

$$g = G\rho \left|_{z_1}^{z_2} \left|_{y_1}^{y_2} \left|_{x_1}^{x_2} x\ln(y+r) + y\ln(x+r) - z\sin^{-1}\left(\frac{z^2+y^2+yr}{(y+r)\sqrt{y^2+z^2}}\right)\right|\right|\right| \quad (5)$$

where g is the vertical component of the attraction; ρ the density; G, the gravitational constant; and r, the distance between a unit mass and the station.

In the far zone, (40m to 20Km), the terrain effect is derived based on the approximation of an annular ring segment to a square prism, as described by Kane (1962). The gravitational attraction is calculated from equation (6) as follows:

$$g = 2G\rho A^2 \frac{(R_2 - R_1\sqrt{R_1{}^2+H^2} - \sqrt{R_2{}^2+H^2}}{(R_2{}^2 - R_1{}^2)} \quad (6)$$

where g is the gravitational attraction; ρ, the terrain density; A, the length of the horizontal side of the prism; R1, the radius of the inner circle of the annular ring; R2, the radius of the outer circle of the annular ring; and H, the height of the annular ring or prism

The topographic correction derived from the seafloor topography can be calculated by assuming that the water body is replaced by rock material and then subtracting the gravitational attraction caused by the water body. In order to evaluate the topographic effect caused by the seafloor topography the algorithm from Nagy (1966) was used (eq. 5).

In this recherché the densities used were 2.67 gr/cm^3 for land and 1.03 gr/cm^3 for sea water. So the density used in eq. 5 and eq .3 was 1.64 gr/cm^3.

Table 2. Calculated TC

Kind of points	Statistics (mgal)			
	Avg	min	max	sdv
Onshore	4.696	0.9522	22.382	4.064
Offshore	3.89	0.00	35.20	2.99

F. *Gravity Anomalies*

According to the above reduction schema, Gravity anomalies can be calculated by the equations:

Free Air Anomaly (DgFA)= Gads-Gmod-δgFA (7)

Simple Bouguer Gravity Anomaly (SBG)= FAA - δgBC (8)

Complete Bouguer Gravity Anomaly (CBG)=SBG+TC (9)

G. *INTERPOLATION*

In order to present gravity anomaly maps and to use them for geoid determination, gravity anomalies need to be expressed in a regular grid. However, gravity measurements are not homogeneously distributed. According to Eckstein (1989), due to the fact that the effectiveness of a particular interpolation method depends on the distribution of the observations and field gradients, no gridding algorithm should be considered "perfect". However, some interpolation approaches are more suitable than others for a particular case. Therefore, in order to identify the best interpolation algorithm for gravity measurements in this recherché three different gridding techniques were tested to 7 selected gravity anomalies. Results presented at table 3:

Table 3: Statistics of the differences between the gravity anomalies derived from control points and gravity anomaly grids

Gridding method	Max [mgal]	Min [mgal]	Mean [mgal]	STD [mgal]
Minimum-Curvature Spline in Tension	3.743	-0.546	0.546	1.19
Ordinary Kriging	2.545	-0.409	0.369	1.042

Based on the results presented at table 3, ordinary Krigging Method with spherical semivariogram was the interpolation method selected.

H. *Geoid Calculation*

In order to calculate geoid undulation at the selected area a Geoid model was computed, using the remove compute restore (RCR) (Forsberg 1995, Rapp 1992) technique. The long wavelength contribution of the gravity field was modelled by an Earth gravitational model obtained from EGM2008 from degree 0 to 2190. Owing to the roughness of the topography in some areas, terrain effects were computed as mentioned above.

1) Remove

The purpose of the remove step is to make the gravity anomalies smooth and easy to grid by removing as much information as possible according to equation 9:

$$Dgres = DgFA - DgEGM - DgTER \qquad (9)$$

where DgFA is the Free Air Anomaly computed above

DgEGM08 is the free air model obtained by EGM2008 and downloaded from icgem for the selected area.

DgTC is RTM corrections calculated below (Fosberg and Tscherning et al.,1981).

2) Compute

The Stokes integral is applied to the residual gravity anomalies $\Delta gres$ to generate $\zeta\Delta gres$, the residual height anomaly (residual quasi geoid height) according to the Molodenskij approach, if all gravity anomalies used in the calculations refer to the topography (RTM correction), or to generate N$\Delta gres$, the residual geoid undulation, if all gravity anomalies refer to geoid (TC).

Using spherical approximation of Stokes' integral for the reduced observed gravity anomaly $\Delta gRES$ (Heiskanen & Moritz 1967), height anomaly or geoid undulation can be calculated:

$$\zeta(or\ N)res(\varphi,\lambda) = \frac{R}{4\pi\gamma}\int_{\lambda'=0}^{2\pi}\int_{\varphi'=-\frac{\pi}{2}}^{\frac{\pi}{2}} \Delta gRES\ (\varphi',\lambda')\ S(\psi)\ cos\varphi'\ d\varphi' d\lambda' \qquad (10)$$

where S(ψ) can be expressed in terms of Legendre polynomials and it is given by:

$$S(\psi) = \sum_{n=2}^{\infty}\frac{2n+1}{n-1}P_n cos\psi \qquad (11)$$

3) *Restore*

Restore step depends on the Terrain effect used.

- Using RTM corrections the restore equation becomes:

$$\zeta = \zeta res + \zeta EGM + \zeta RTM \qquad (12)$$

where ζEGM is the normal height obtained by egm2008 downloaded from icgem

ζRTM is the quasi geoid restore terrain effects and computed with gravsoft

ζres as computed above

It is necessary to convert quasi geoid to geoid using the following equation :

$$N = \zeta + [\ (\ g' - \gamma'\ ) / \gamma'\ ]\ H \qquad (13)$$

Where: N = the geoid undulations.

ζ = the height anomaly or undulations of quasi-geoid.

g' = the mean gravity along the plumb line between geoid and ground. For an average density = 2.67 g/cm^3, g' can be computed as:

$$g' = g\ (\text{in gal}) + 0.0424\ H\ (\text{in km}) \qquad (14)$$

γ' = the mean normal gravity along the normal plumb line between ellipsoid and telleroid.

H = the orthometric height

III. RESULTS

A. *GRAVITY DATASETS OF 1976*

According to eq. 1,2,3,4,5,6 statistics of calculation are provided at Table 4 and complete bouguer anomaly map at Figure 1.

Table 4. Statistics of the results from 1976 gravity measurements

Kind of points	Statistics (mgal)			
	Avg	min	max	sdv
FAA	127.753	108.007	173.744	14.560
BG	116.846	103.618	133.618	8.620
CBG	121.189	106.567	136.010	8.314

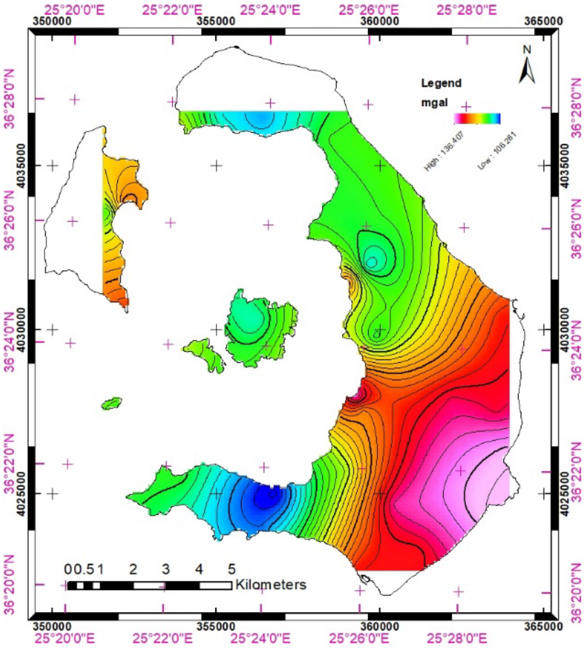

Figure 1: Complete Bouguer Gravity anomaly (1976). For Terrain correction a density value 2.67 gr/cm^3 is adopted. Kriging interpolation assumes a spherical model with pixel size 100 m. The contour interval is 2 mgal.

B. *GRAVITY DATASETS OF 2012_14*

According to eq. 1,2,3,4,5,6 statistics of calculation present at Table 5 and complete bouguer anomaly map at Figure 2.

Table 5. Statistics of the results from 2012_14 gravity measurements

Kind of points	Statistics (mgal)			
	Avg	min	max	sdv
FAA	126.015	107.842	173.896	12.015
BG	114.221	93.553	134.208	8.724
CBG	118.916	106.197	136.478	7.918

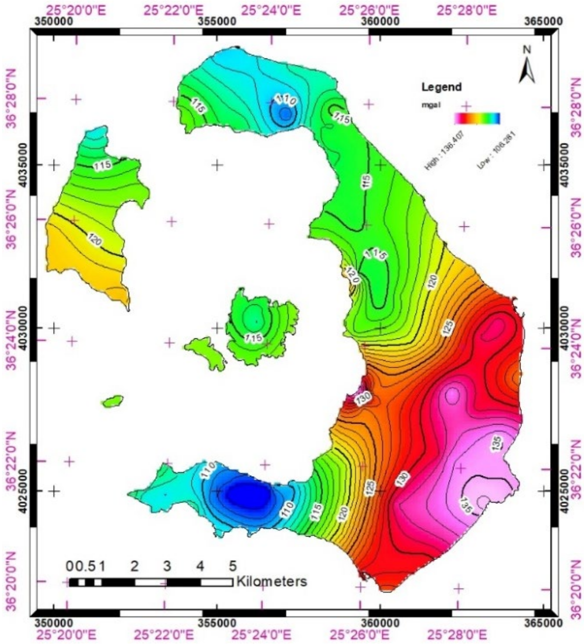

Figure 2: Complete Bouguer Gravity anomaly 2012-2014. For Terrain correction the used density is 2.67 gr/cm^3. Krigging method using spherical model is used for interpolation with pixel size 100m. The contour interval is 2 mgal.

C. *COMPARISON BETWEEN TWO ONSHORE GRAVITY DATASETS*

The qualitive results of the comparison between maps on Figure 1 and Figure 2 are the following:

-Dataset of 2012_14 is more dense than those of 1976, so there can be found more local anomalies.

-The complete Bouguer Gravity anomalies of 1976 indicate four regional maxima at Athinios, Fira, Tripiti and Profitis Ilias, as well as three regional minima located at Southern of Ia, Southern of Imerovigli and at Akrotiri village.

-The complete Bouguer Gravity anomaly for the period 2012-2014 indicate three regional maxima at Athinios, Fira and Pr. Ilias, as well as three regional minima located at southwest of Ia, Riva and Akrotiri village .

-In addition, a significant gravity variation at Nea Kameni between the measurement campaigns of 2012 and 2014 is evident, indicating that the inner process of volcano was active in the past unrest period of 2011-2012.

D. *OFFSHORE GRAVITY DATASET*

According to eq. 1,2,3,4,5,6 statistics of calculation present at table 6 and complete bouguer anomaly map combined with 2012_14 gravity dataset at Figure 3

Table 6. Statistics of the results from 2015 offshore gravity measurements

Kind of points	Statistics (mgal)			
	Avg	min	max	sdv
FAA	93.311	48.806	133.825	16.576
BG	125.832	91.983	164.966	13.396
CBG	126.016	96.022	163.439	13.707

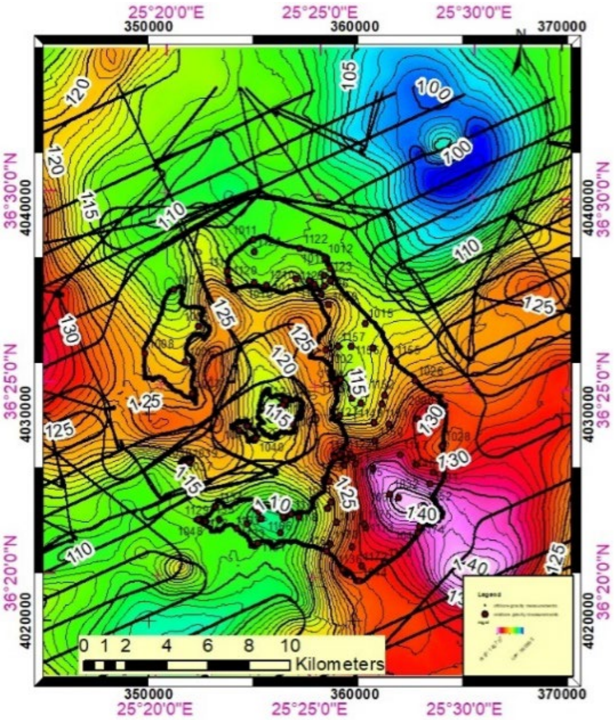

Figure 3: Complete Bouguer Gravity anomaly 2015. For Terrain correction the used density is 1.03 and 2.67 gr/cm^3. Krigging method using spherical model is used for interpolation with pixel size 100m. The contour interval is 2 mgal

E. *GEOID DETERMINATION FROM QUASI GEOID*

Following the methodology described above values with their statistics described at Table 7 were calculated and the final gravimetric geoid is illustrated in Figure 4.

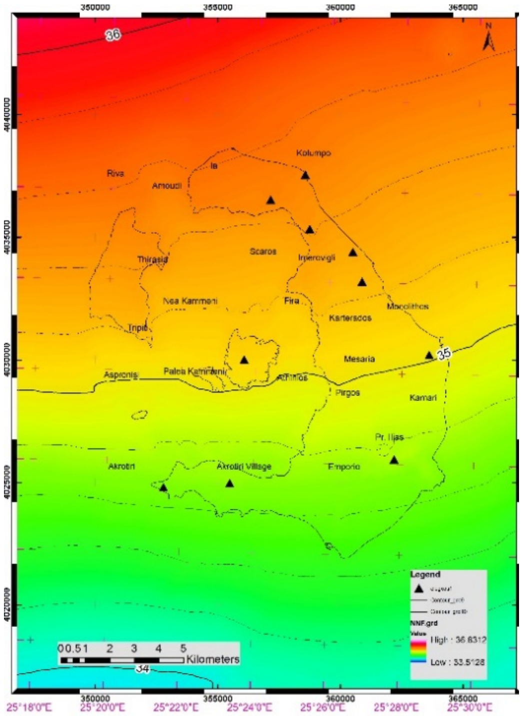

Figure 4: Final Gravimetric geoid of the Santorini Volcanic group.Pixel size is 100m. The contour interval is 0.2 m.

Table 7. Statistics for every step in geoid determination

DATA	TYPE	min	max	mean	sdv
Free Air Anomaly (mgal)	405561 points	69.428	173.896	98.512	12.236
EGM08 Free air Anomaly (mgal)	405561 points	77.158	122.589	99.328	11.700
RTM (mgal)	405561 points	- 18.623	2.834	-0.262	0.486
FAA-FAAEGM (1)-(2) (mgal)	405561 points	- 27.919	54.128	-0.816	8.124
FAA-FAAEGM-RTM (4)-(3)(mgal)	405561 points	- 27.887	63.299	-0.554	8.173
ZRES (m)	53568 GRID	0.094	0.225	0.126	0.0236
zegm08 (m)	159201 GRID	32.825	36.413	34.757	0.932
Ztopo (m)	810000 GRID	-0.016	0.003	-0.006	0.002
Quasi Geoid Z(m)	614460 GRID	33.556	36.846	35.078	0.634
N-Z (m)	1004292 GRID	-0.107	0.686	- 0.0334	0.021
GEOID N(m)	614460 GRID	33.513	36.831	35.051	0.639

The main application of the geoid for surveying is the acquisition of the orthometric height of a point, without measuring height differences and gravity in geodetic (spirit) leveling. Due to datum inconsistencies (tide gauge datum), errors embedded in the Orthometric heights H determined by geodetic leveling, errors in the Global Navigation Satellite System (GNSS) geodetic height h, and undoubtedly errors in the gravimetric geoid height N. There were 10 triangulation points measured with GNSS in 2012 (Dimitrioy et al., 2013), were Orthometric Height was measured since 70s with precise leveling measurements. The differences in accuracy of these model presented in Table 8 are calculated based on eq. 15:

$$\Delta N = Ngeom - Ngrav \qquad (15)$$

Table 8. Accuracy of the model measured at GPS/Levelling triangulation points.

	min	max	mean	sdv
Gravimetric Geoid	0.112	0.567	0.324	0.1355
EGM08	0.251	0.667	0.444	0.128

IV. CONCLUSIONS

From the study of gravitational field of Santorini Complex can be concluded that inner process of the volcano still goes on, as gravity field differs at two datasets.

Regional maxima that were presented at both datasets observed at Athinios, Fira and Pr. Ilias where rock underground seems to be more dense. Regional minima that were presented at both datasets observed at southwest of Ia and at Akrotiri Village where there are located at the kolumpo and Akrotiri fault zone respectively.

The significant differences at the numeric values of complete Bouguer gravity anomalies of two datasets reveal that the inner process of the volcano still goes on.

For this small region geoid calculation using quasi geoid satisfactory results were obtained. The final accuracy of the model measured at GPS/leveling points was better than 33cm and can be further improved if it is fitted to GPS/leveling measurements.

A future challenge consists of the determination of geoid model for this area with other methods (LSC, FFT technics, etc) and the comparison between them in order to choose the gravimetric geoid that fits better to the measurements. And in a next step adding more stations with new GPS/Levelling measurements.

Alongside it seems to be necessary to perform a more thorough comparison of the datasets of 1976 and 2012_14 in order to certify the inner process of the volcano.

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