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Evaluation of EGM2008 and latest GOCE-based satellite only global gravity field models using densified gravity network: a case study in south-western Turkey

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ABSTRACT Gravity standardisation network of Turkey is being renewed and densified within the "Turkish Height System Modernisation" project. 2190 new relative gravity sites at about 10-km spatial resolution and 16 new absolute gravity sites are established and measured with A10 absolute and Scintrex CG-5 relative gravimeters in the south-western Turkey. The densified network is adjusted based on the weighted constrained least squares method using the gravity observations reduced for environmental and instrumental effects, resulting with a mean formal error of 17 μGal. The gravity disturbances from this highly precise network are used as a reference data set to evaluate the four latest GOCE-based satellite-only models in the same region by spectral enhancement method minimising the omission errors in GOCE models using EGM2008 and ERTM2160 gravity models. Results show improvements in the spectral bands ~120 to ~190 in terms of spherical harmonic degrees for all GOCE-based models compared to EGM2008. Of all the GOCE models assessed, GOCE-DIR5 is found to be best extending the improvement to degree ~220. Furthermore, it is found that GOCE models detect significant bias in EGM2008 reaching up to 5 mGal which is verified by regional comparisons of GOCE-based models and EGM2008 with TR-GravNet ground truth data.

Key words: TR-GravNet, absolute gravimetry, relative gravimetry, gravity reduction, GOCE model assessment.

1. Introduction

The knowledge about the spatially and temporally varying gravity is an essential tool for geosciences and engineering. In geodesy, gravity is fundamental input for the determination of Earth's physical surface, notably the geoid, which serves as a reference for the heights (Heiskanen and Moritz, 1967; Moritz, 1980; Vaníček and Krakiwsky, 1986). Gravity data may enable geoscientists to map out the subsurface geology and distinguish density variations which then enable oil, gas and mineral exploration (Hinze *et al.*, 2013). Analysis of gravity field data can contribute substantially to the development of crust-mantle models (Reguzzoni and Sampietro, 2015; van der Meijde *et al.*, 2015), detection of large tectonic structures, continental grabens, deep sea trenches, oceanic ridges and swells (Hinderer *et al.*, 1991; Groten and Becker, 1995; Mazzotti *et al.*, 2011; Tenzer *et al.*, 2012; Hwang *et al.*, 2014; Sandwell *et al.*, 2014). Long term monitoring of gravity at specific locations provides a means of measuring mass transport and redistribution in the atmosphere, ocean, terrestrial water and cryosphere (Crossley *et al.*, 2005).

Measuring the magnitude of gravity acceleration by relative gravimeters is very common due to their simplicity, mobility and relatively cheaper prices. However, the relative surveys should be tied to a gravity reference frame, e.g. a high precision gravity standardisation network to define the scale and datum of the measurements (Morelli *et al.*, 1974). The existing gravity network of Turkey, established between the periods 1993 to 1999 by General Command of Mapping, is a very sparse network with only 68 sites (Wilmes *et al.*, 1997; Demir *et al.*, 2006) unevenly distributed throughout the country. Moreover, the network is now outdated owing to the human-induced damages at the site locations and the restless geodynamical processes.

With the widespread use of GNSS technology in the mapping society, the need for a high-resolution and high-precision national geoid model has grown to determine the orthometric heights in a faster and cheaper way than traditional spirit levelling. A five-year-long collaborative project entitled "Turkish Height System Modernisation and Gravity Recovery" has been initiated in 2015. The project has four major objectives: i) to densify Turkish gravity standardisation network (TR-GravNet) as a homogeneously distributed and highly qualified reference data set; ii) to find out the best fitting GOCE-based satellite-only global gravity field model (GGM) which describes the middle-to-low degree components of the Earth's gravity field; iii) to improve the Turkish gravity database not only for geodesy but also for geophysics, removing the discrepancies in historical gravity data using TR-GravNet reference data set along with the best fitting GOCE GGM; and iv) to compute a Turkish gravimetric geoid model with a precision of few centimetres at 1-3 km spatial resolution using all the available terrestrial and satellite gravity data.

This study focuses on the first and second objectives of the project, describes the TR-GravNet densification in south-western Turkey, and investigates the contribution of this densified network to reveal the best fitting GOCE GGM in south-western Turkey to be used in the subsequent geoid computations. Four different GOCE satellite-only solutions are evaluated namely GOCE-DIR5, GOCE-TIM5, GOCE-SPW5 and GOCO05S as they are free from possible errors such as datum inconsistencies in the historical gravity data sets (Bomfim *et al.*, 2013). Second part of the manuscript is devoted to gravity network densification in south-western Turkey including network design, site selection, positioning, and instrument calibrations. The processing of new absolute and relative gravity data is then presented in the third part with some remarks on the data reduction and network adjustment. The fourth part is devoted to the demonstration of the contribution of the densified gravity network data to the assessment of latest GOCE GGMs in south-western Turkey to determine the best fitting one.

2. Densification of TR-GravNet in south-western Turkey

2.1. Network design and site selection

The densification of TR-GravNet in south-western Turkey has been carried out between April and November 2016 by the collaborative work of five national institutions using their state-of-the-art absolute and relative gravimeters and GNSS receivers. A grid structure of 5-arc minute spatial resolution for the new points including the existing network points is chosen for the densification of TR-GravNet. To define the scale and datum of the network, at least one absolute gravity site per 10,000 km^2 is selected. Approximate locations of the new sites are carefully selected from the recent topographic maps and high resolution orthophoto imageries trying not to locate any of them near large water reservoirs, major roads, railways, excavations, and marshy ground to avoid micro-seismicity. 2190 new sites including 16 new absolute gravity are marked to the actual locations on the ground by a 10-cm solid round iron bar and positioned by GNSS. In general, new sites are located in monumental buildings such as mosques, public schools and places in the urban areas, in order to ensure the permanence of the stations. In non-residential areas most of the sites are attached to stabile rocky places that can easily be accessed by car. Except the secure sites of the existing network points, all the new sites are outdoors. Relative gravimeters are used to identify the position of the absolute sites by selecting the quietest places among the candidates based on stability indicators such as instrument tilts, standard deviations of the gravity readings, spikes, and rejections.

2.2. Positioning of the network sites

The 3D positions of the outdoor stations are determined using the network-based real time kinematic GNSS service in Turkey called TUSAGA-Active operated by General Directorate of Mapping and General Directorate of Land Registration and Cadastre (www.tkgm.gov.tr/tr/icerik/tusaga-aktif-0). In order to standardise the positioning, all survey teams utilise Topcon GR-5 Advanced RTK receivers and FC-250 controller units (www.topconpositioning.com) configured in the same way in the office before the field works. 10 epoch readings are collected and averaged when the receivers are fixed and get the corrections properly. Otherwise, at least 45-minute static data is collected and post-processed using the Topcon Tools processing and analysis software (www.topconcare.com) when faced with the fixing problems. The coordinates of the indoor stations are measured via traverse surveys using high precision electronic total stations due to the signal attenuation inside the closed area. The overall precision of the site positions given in the ITRF96 coordinate reference frame at epoch 2005.0 is a few centimetres in the horizontal component and better than 1 dm in vertical component.

2.3. Periodic checking of gravimeters

The relative and the absolute gravimeters used in the project delivered in November 2015. Since then, the instruments have been subjected to series of checks recommended by the manufacturers and some tests to assess the behaviour and capabilities of the gravimeters (Bonvalot *et al.*, 1998). Gravity sensor, long term drift rate, temperature compensation, tilt sensor zero adjustment, tilt sensor sensitivity adjustment, tilt sensor cross coupling, battery and clock checks for the relative gravimeters (Scintrex, 2009) are performed at the laboratory. Internal real-time clocks are synchronised with the GPS UTC time. In order to estimate linear drift rates, long term data have been collected almost every weekend from Friday afternoon to Monday morning, when the man-made noise is very low. During the first months of the operation, the drift rates for all the gravimeters are quite large, some reaching up to 2.5 mGal/day but progressively decreased in time. Repeated measurements in lab and field conditions give standard deviation of 5 to 10 μGal, consistent with the specifications of Scintrex CG-5. A10 (#044) is installed at national metrology institute laboratory and number of measurements are conducted. The standard deviation of a single station occupation in the laboratory and field conditions is found to be 4-9 μGal, which is also consistent with the values given by the manufacturer (Micro-g LaCoste, 2008).

2.4. Calibration of relative gravimeters

Calibration of relative gravimeters is of utmost importance for the accuracy of subsequent gravity surveys (Torge, 1989; Hugill, 1990; Becker *et al.*, 1995; Seigel *et al.*, 1995). The calibration or scale factor should be determined with a relative accuracy of at least 0.01% (1 μGal measurement error in 10-mGal gravity range) to acquire high precision measurements (Gabalda *et al.*, 2003). The main calibration constant, namely GCAL1 of the Scintrex CG-5 gravimeter determined by the manufacturer in Toronto, may change after the initial period of a few months due to the stress relaxation effects in the fused quartz spring sensor (Scintrex, 2009). It is recommended that the scale factor should be estimated to recalibrate the instrument. As shown in Eqs. 1 and 2, the accuracy of the linear scale factor k depends on the absolute gravity range Δg_{ij} between two successive stations i and j, reading differences corrected for all known instrumental and environmental effects ΔR_{ij} (see section 3), and the precision of these values $\sigma_{\Delta g}$ and $\sigma_{\Delta R}$, respectively:

$$\Delta g_{ij} = k \,.\, \Delta R_{ij} \tag{1}$$

$$\sigma_k = \frac{1}{\Delta R_{ij}} \cdot \sqrt{\sigma_{\Delta g}^2 + \sigma_{\Delta R}^2 \frac{\Delta {g_{ij}}^2}{\Delta {R_{ij}}^2}} \tag{2}$$

A new calibration baseline consisting of three absolute gravity sites is constructed in central Turkey, at the approximate location 40° N and 33° E. The key advantages of the new baseline are large gravity range up to 210 mGal and close geographical proximity between stations with an average distance of 10 km apart which enables short transportation time (e.g. 10-20 minutes). Hence, it can allow us to increase the observation redundancy by carrying out a number of relative measurements within a day. The absolute sites are observed with A10 (#044) free-fall absolute gravimeter with precision better than 10 μGal, thus allowing a best achievable relative calibration accuracy of 0.007% if $\sigma_{\Delta g}$ and $\sigma_{\Delta R}$ is assumed 10 μGal. More information about the absolute and relative gravity measurements and processing is given in the following sections. The scale factors and associated uncertainties of the six Scintrex CG-5 relative gravimeters used in the project are estimated by the linear regression of Eq. 1.

2.5. Relative gravity measurements

The profile method with the measurement sequence of "A-B-C-D-E-C-B-A" is adopted as a general observation scheme to control and determine the gravimeters daily drifts. The gravimeters are transported by car between stations in their standard padded cases. Bottomless wind shelter tent and umbrella are used to minimise influence from the wind or to protect the gravimeters from direct sun light, where necessary. The gravimeters are oriented to the north using a compass to secure the possible magnetic field influences, waited at rest minimum 10 minutes being levelled on its tripod before starting the first reading to provide the internal temperature and sensor stability. In order to increase the precision, read time options of the gravimeters are set to 60 seconds. Data acquisition is terminated as soon as the variation in the latest five readings is less than 5 μGal and no apparent downward or upward trend exists in the data set. Readings having absolute tilt values above 5 arcseconds and the standard deviation greater than 0.300 mGal are discarded.

Atmospheric pressure, temperature and instrument height is also observed and registered during each reading. The optional internal corrections and filters, e.g. tide and continuous tilt correction, auto rejection filter and seismic filter, are activated.

2.6. Absolute gravity measurements

A routine gravity measurement scheme at the new calibration baseline and densified TR-GravNet absolute sites is based on two setups in opposite direction with 12 sets each with the A10 (#044) absolute gravimeter. A set is composed of 150 drops with 1 second drop interval. The time interval between the sets is 6 minutes yielding a duration of 72 minutes for the whole series in a single setup. The gravimeter is oriented to the north during the first 12 sets and, then, dismantled and re-mounted in the opposite direction for the remaining 12 sets, to detect any possible gross errors in the setup and measurement process (Mäkinen *et al*., 2010). Third or consecutive setups are also performed where the difference between the first two setups is larger than 10 μGal (Dykowski *et al*., 2012). The gravimeter and its electronic unit are transported between sites with a dedicated van which is specially configured for the transport boxes of the dropper and interferometer, electronics and battery-based continuous power supplies. Vertical gravity gradient measurements are performed with Scintrex CG-5 gravimeters to reduce the absolute gravity measurements from the effective height of the instrument to the benchmark level. A special tripod is designed for this purpose, which has three different height levels ranging from 25 to 140 cm, that also covers the measurement height of A10. Three different height levels enable the detection of a non-linear term in the gradient estimation. L-M-U-M-L-M-U-L-U (L: lower, M: middle, U: upper) setup sequence is followed to increase the precision and redundancy.

3. Data processing and network adjustment

3.1. Relative gravimetry

Relative gravity measurements are subject to several environmental and instrumental effects caused by solid Earth and ocean tides, atmospheric mass movements, polar motion, groundwater and soil moisture variations and instrumental drift which can be regarded as systematic effects that must be corrected as much as possible when a specific gravity signal is sought (Torge, 1989; Timmen, 2010). Scintrex CG-5 relative gravimeters can compute and apply real-time Earth tide, long-term instrumental drift, tilt and temperature corrections to the gravity readings (Scintrex, 2009).

However, the online corrections computed by the gravimeter processor provide approximate results since they are based on simple first-order models and some corrections such as pressure, pole, and ocean tide not applied by Scintrex CG-5 instrument may limit the overall measurement precision to 10-20 μGal (Cattin *et al*., 2015). The real-time CG-5 Earth tide correction based on Longman (1959) algorithm and long-term linear drift correction are removed from 21,750 readings taken during the network densification campaign in south-western Turkey and more accurate and complete corrections are recomputed in the pre-processing stage to acquire higher accuracy from the Scintrex data in agreement with the previous studies (Jousset *et al*., 1995; Bonvalot *et al*., 1998; Gabalda *et al*., 2003; Lederer, 2009; Cattin *et al*., 2015; Hector and Hinderer, 2016). The corrected gravity reading R^c at time t is determined as:

$$R^c(t) = \left(R^R(t) + \Delta g^T(t) + \Delta g^A(t) + \Delta g^P(t) + \Delta g^O(t) + \Delta g^H(t) + \Delta g^D(t)\right) \times k \quad (3)$$

where R^R is raw reading, Δg^T, Δg^A, Δg^P, Δg^O, Δg^H, Δg^D are the corrections for solid Earth tide, atmospheric pressure, polar motion, ocean tide loading, gravimeter height variation and instrumental drift, respectively, and finally the scale factor of the gravimeter is used. Corrections for the groundwater and soil moisture variations are not applied to the raw readings because the transfer function between changes in the groundwater table and the related gravity effect at the measurement site is not well known. All the computations to obtain the corrected gravity reading are performed by our own software developed in MATLAB (www.mathworks.com). Each correction term in Eq. 3 is explained in detail in the following sections.

3.1.1. Solid Earth tide and ocean loading correction

Harmonic development of the tidal potential is used for the accurate determination of solid Earth tide correction. In the harmonic method the compound tidal signal can be described as a sum of periodic terms called tidal constituents each having a unique name, frequency and phase:

$$\Delta g^T = \sum_{i=1}^{n} \delta_i A_i \cos\left(\omega_i t + \varphi_i + \Delta \varphi_i\right) \quad (4)$$

where n is the number of tidal constituents, δ_i is amplitude or gravimetric factors, A_i and φ_i are the amplitudes and phases of theoretical tides, ω_i is the frequency of the tidal constituents and $\Delta\varphi_i$ is the phase lead. The ETGTAB version 3.0 written by prof. H.-G. Wenzel (www.bfo.geophys.uni-stuttgart.de/etgtab.html) is modified and integrated into our software. Although there are several options for the tidal potential catalogues including Doodson (1921), Cartwright and Edden (1973), Tamura (1987) with varying waves, we find out that they are generally in agreement within a few μGal and give almost similar results for our data set. To be consistent with the absolute gravimetry processing, Tamura (1987) with 1200 waves is selected as a standard tidal catalogue for the relative gravimetry. The local amplitude factors δ_i and phase leads $\Delta\varphi_i$ for the wave groups are interpolated from the global grid of Timmen and Wenzel (1995). However, using the global factor δ=1.16 and zero phase shifts for the main wave groups does not have significant numeric effects on the computed tide because the differences are never greater than 3 μGal in our case with the use of local or global tidal parameters. The permanent Earth tides are treated according to zero-tidal gravity concept (Ekman, 1989) i.e. δ_i=1.0 and $\Delta\varphi_i$=0 for the M_0S_0 tides (Rapp, 1983). The magnitude of the solid Earth tide corrections applied to the raw gravity readings collected during the TR-GravNet densification in south-western Turkey varies from -109 μGal to 175 μGal depending on the site location and measurement time.

The direct method proposed by Munk and Cartwright (1966) is also compared with the above results obtained from harmonic method. For the direct computation of the solid Earth tide, the FORTRAN codes originally written in 1969 by Jonathan Berger at the Scripps Institution of Oceanography and later improved by Agnew (2007, 2012) are used. This method is also implemented as “Berger Correction” in the g9 absolute gravity processing software (Micro-g LaCoste, 2012). In this method, the tidal potential is directly computed in the time domain taking the recent ephemeris into account as well as the Honkasalo (1964) correction. The solid Earth tide corrections computed from the direct method differ less than 1 μGal from the values obtained from harmonic method using Tamura potential.

The gravity reduction due to ocean loading can be computed following the below equation (McCarthy and Petit, 2004):

$$\Delta g^T = \sum_{i=1}^{11} f_i A_{oi} \cos\left(\omega_i t + \chi_i + u_i - \varphi_{oi}\right) \tag{5}$$

where A_{oi}, φ_{oi}, ω_i, χ_i is amplitude, phase shift, angular velocity, and astronomical argument at $t = 0$ of tidal wave i, f_i and u_i nodal factor and phase which depends on the longitude of the lunar node used for correcting the modulating effect of the 18.6 year lunar node (Doodson, 1928). Ocean loading coefficients (A_{oi} and φ_{oi}) for the semidiurnal (M_2, S_2, N_2, K_2), diurnal (O_1, P_1, Q_1, K_1) and long-period (M_F, M_m, S_{sa}) tides are provided from 'Free Ocean Tide Loading Provider' of the Onsala Space Observatory in BLQ format. In order to compute the astronomical argument, astronomical longitudes are computed first following the algorithms given in TASK-2000 tidal package (Bell *et al*., 2000). Nodal factor and nodal phase values for the 11 tidal constituents are calculated using the formulae given in Luick (2004). Several ocean tide models, such as FES2004 (Lyard *et al*., 2006), FES2014 (Carrère *et al*., 2016), and EOT11a (Savcenko and Bosch, 2012), are tested and the magnitude of the ocean tide loading on the gravimetric measurement is found below 2 μGal for all these models due to the small ocean tides in the eastern Mediterranean (holt.oso.chalmers.se/loading/tidemodels.html).

3.1.2. Pressure correction

Analytical formulation given by Torge (1989) is applied for the computation of gravity effect induced by the air pressure variations:

$$\Delta g^A = 0.3 \times \left(P_H - 1013.25 \times \left(1 - \frac{0.0065 \times H}{288.15}\right)^{5.2559}\right) \tag{6}$$

where P_H in hPa is the atmospheric pressure at station elevation expressed in metres. The first term 0.3 μGal·hPa^{-1} is regarded as linear coefficient for pressure correction and the last term after P_H is regarded as normal pressure at sea level expressed in hPa. The vast majority of pressure corrections computed for the measurements of TR-GravNet densification in south-western Turkey are distributed within ±10 μGal levels depending on the station elevation and atmospheric pressure measured.

3.1.3. Polar motion correction

The polar motion correction, which compensates the long-periodic effects due to the deviations of the instantaneous pole from the reference pole, can be computed by (Wahr, 1985):

$$\Delta g^P = \delta_P \,.\, \omega^2 \,.\, R \,.\, \sin 2\varphi\left(x_P \cos\lambda - y_P \sin\lambda\right) \tag{7}$$

where δ_P=1.16 is the amplitude factor that considers the elastic response of the solid Earth as compared to a rigid Earth's body, ω is the angular velocity of the Earth, R is the Earth's radius, φ and λ are the geographical latitude and longitude of the site, and finally x_P and y_P denote the pole coordinates provided by IERS Bulletin B at (www.iers.org). Maximum gravity reduction due to the pole motion is found 4 μGal for the 21,750 individual gravity readings collected at different times and locations during the network densification campaign in south-western Turkey.

3.1.4. Instrument height correction

The sensor of the Scintrex CG-5 gravimeter is placed a few tens of centimetres above the station markers during the measurements. Therefore, gravity readings registered at the sensor height must be reduced to the top of the benchmark using the well-known formula:

$$\Delta g^H = W_{zz} \times \Delta h \tag{8}$$

where W_{zz} is the vertical gravity gradient and Δh denotes the vertical distance between the marker and the gravimeter sensor. In most of the densified TR-GravNet sites the normal vertical gradient value $W_{zz} = -0.3086$ mGal·m^{-1} is used to transfer the measured gravity to the top of the benchmark, except for the absolute sites where the observed values are available (see section 3.2). The average of the instrument height corrections computed during the densified TR-GravNet processing in south-western Turkey is around 80 μGal with maximum values reaching up to 150 μGal depending on the sensor height.

3.1.5. Instrumental drift correction

Instrument dependent drift reduction is the most important correction term of the relative gravimetry data processing as it can potentially reach up to a few mGal/day especially for the new instruments, as it is the case in TR-GravNet densification in south-western Turkey. Stationary and transportation drifts inherent in the gravity readings are removed prior to the network adjustment to avoid an over-parameterisation in the processing. Drift rate of each gravimeter, used in the project, is estimated on daily basis from the repeated readings at the same sites in different times. The correction term at any time $\Delta g^D(t)$ is, then, computed from the estimated drift rate following the below equations:

$$\Delta R^{d,gr} = \sum_{i=0}^{n} a_i^{d,gr} \cdot \left(\Delta t^{d,gr} \right)^i \tag{9}$$

$$\Delta g^D\left(t^{d,gr}\right) = \sum_{i=0}^{n} \hat{a}_i^{d,gr} \cdot \left(t^{d,gr} - t_1^{d,gr}\right)^i \tag{10}$$

where $\Delta R^{d,gr}$and $\Delta t^{d,gr}$ are the vectors consisting of repeated reading and time differences, respectively, at the same site occupations for the day d and the gravimeter $gr \cdot a_i^{d,gr}$ is the n-th order drift polynomial coefficients to be estimated and $\hat{a}_i^{d,gr}$ denotes the estimated quantities. $t_1^{d,gr}$ is the time at which the first reading in the beginning of the day is registered and $t^{d,gr}$ corresponds to the subsequent reading times. Although first or second-order polynomial function usually produces similar results due to the short daily measurement schema lasting less than 10 hours, second-order polynomial is used to remove any possible non-linear changes. As shown in Fig. 1a, the linear drift rates of the gravimeters have positive upward trends during the first four months of the operation but starts decreasing for the last three months. The instruments #41359 and #41358 have slightly larger drift rates reaching up to 1.6 mGal per day. The maximum drift correction applied to the readings is about 950 μGal based on the data obtained with Scintrex CG-5 #41359 on 30 September.

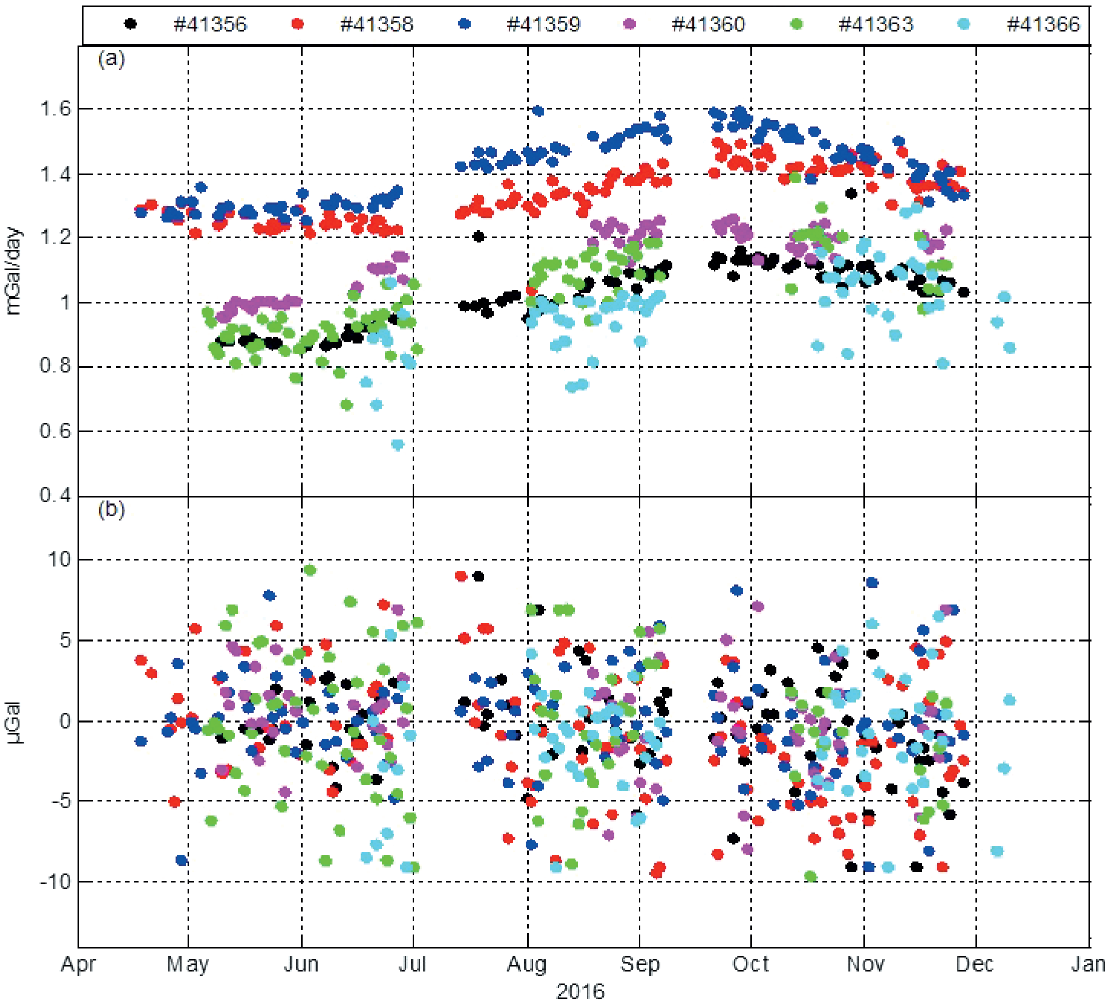

Fig. 1 - Daily linear drift rates of the Scintrex CG-5 gravimeters in mGal/day (a) and daily gravity closures in µGal (b).

3.1.6. Daily gravity closures

Profile method adopted in the network realisation can allow us to compute the daily gravity closures since the daily loops are always closed on the same site. The expected value of the daily closures is zero which can be determined via:

$$C^{d,gr} = \sum \Delta R_{ij}^{d,gr} + \varepsilon_C \tag{11}$$

where the gravity closure $C^{d,gr}$ for the day d and the gravimeter gr is equal to sum of the corrected reading differences $\Delta R_{ij}^{d,gr}$ registered at the successive sites and with corresponding closure error ε_C. It can easily be seen in Fig. 1b that the closures for each gravimeter are almost ±5 µGal: this implies that there are in general no accidental errors in the reading process and the systematic effects are corrected properly.

3.2. Absolute gravimetry

Absolute gravity observations are processed with the g9 software provided by Micro-g LaCoste (Micro-g LaCoste, 2012). Gravity reductions due to environmental effects mentioned above can be computed and applied to the measurements by the software. ETGTAB option is selected for the solid Earth tide correction. Ocean tide loading effects are modelled from FES2004 ocean tide model (Lyard *et al.*, 2006) even if the effect is very small in south-western Turkey. Daily pole coordinates published in IERS Bulletin B and amplitude factor of 1.16 are used for the polar motion correction. Empirical admittance factor of 0.3 μGal·hPa^{-1} is utilised for the gravity reduction due to atmospheric mass variations. The gravity values are estimated at the empirically determined effective height of the instrument which is the point on the drop trajectory, where the result is independent of the value of the gradient used (Timmen, 2003). The effective height of A10 (#044) is found 3.74 cm below the factory height. The total uncertainties, including both the system and set scatter (Micro-g LaCoste, 2012) uncertainties, are about 10 μGal level at all 16 absolute gravity sites measured in south-western Turkey.

Vertical gradient of gravity required for the gravity transferring from the effective height of the instrument to user specified height is determined fitting a quadratic function to gravity readings at different height levels:

$$R^c(h) = a \,.\, h^2 + b \,.\, h + c \tag{12}$$

$$W_{zz}(h_i) = a \,.\, h_i + b \tag{13}$$

where $R^c(h)$ is gravity readings on the measurement height h with respect to the top of the benchmark corrected for instrumental and environmental effects, a, b, c denote the coefficients of the second-order polynomial, and finally $W_{zz}(h_i)$ is the vertical gravity gradient at user specified height h_i which is 68.26 cm effective height in our case. The gravity gradient at the 16 absolute gravity sites estimated at the effective height of the gravimeter ranges from -2.22 to -4.13 μGal/cm with a maximum estimation uncertainty of 0.085 μGal/cm.

3.3. Network adjustment

There are mainly two conceptual approaches for the adjustment of gravity networks. While the first method uses corrected gravity readings as observations (Andersen and Forsberg, 1996; Oja, 2008), the second one introduces reading differences into the adjustment to take the advantages of differencing (Torge, 1989; Hwang *et al.*, 2002; Martin *et al.*, 2011). Densified TR-GravNet is adjusted based on the second method where the observation equation can be expressed as:

$$\Delta l_{ij} + \Delta v_{ij} = g_j - g_i + \sum_{n=1}^{N} d_n \left(t_j - t_i\right) \tag{14}$$

where Δv_{ij} is the residual of the relative gravity observation Δl_{ij} between sites i and j measured at times t_i and t_j; g_i and g_j are the gravity values at site i and j; d_n is the residual linear drift rate coefficient for each gravimeter. Scale factor parameters are not included in the observation equation because they are estimated at the calibration baseline prior to the adjustment. Final gravity reading R_i^{wm} and its standard deviation σ_i^{wm} for a single site occupation consisting of a number of gravity readings and corresponding standard errors *SE* (Scintrex, 2009) are computed by weighted mean of *NR* corrected gravity readings R_n^c as follows:

$$R_i^{wm} = \frac{\sum_{n=1}^{NR} \frac{R_n^c}{SE_n^2}}{\sum_{n=1}^{NR} \frac{1}{SE_n^2}} \tag{15}$$

$$\sigma_i^{wm} = \sqrt{\frac{1}{\sum_{n=1}^{NR} \frac{1}{SE_n^2}}} \tag{16}$$

Relative gravity observation Δl_{ij} is formed by simple differences of R_i^{wm} and R_j^{wm} and its associated standard deviation σ_{ij} is determined by error propagation:

$$\Delta\, l_{ij} = R_j^{wm} - R_i^{wm} \tag{17}$$

$$\sigma_{ij} = \sqrt{\left(\sigma_i^{wm}\right)^2 + \left(\sigma_j^{wm}\right)^2} \tag{18}$$

The least squares solution of Eq. 14 is obtained by weighted constrained adjustment introducing at least one fixed gravity value as a gravity datum or a constraint (Hwang *et al.*, 2002). The estimate of the unknown parameters $\boldsymbol{X}$ in Eq. 14, residual vector $\boldsymbol{V}$, the *a posteriori* variance of unit weight $\hat{\sigma}_0^2$ and the *a posteriori* covariance matrix $\boldsymbol{C}_{\hat{X}}$ can be computed by:

$$\hat{\boldsymbol{X}} = \left(\boldsymbol{A}^T\boldsymbol{P}\boldsymbol{A} + \boldsymbol{A}_g^T\boldsymbol{P}_g\boldsymbol{A}_g\right)^{-1}\left(\boldsymbol{A}^T\boldsymbol{P}\boldsymbol{L} + \boldsymbol{A}_g^T\boldsymbol{P}_g\boldsymbol{L}_g\right) \tag{19}$$

$$\boldsymbol{V} = \begin{bmatrix}\boldsymbol{V}\\ \boldsymbol{V}_g\end{bmatrix} = \begin{bmatrix}\boldsymbol{A}\\ \boldsymbol{A}_g\end{bmatrix}\hat{\boldsymbol{X}} - \begin{bmatrix}\boldsymbol{L}\\ \boldsymbol{L}_g\end{bmatrix} \tag{20}$$

$$\hat{\sigma}_0^2 = \frac{\boldsymbol{V}^T\boldsymbol{P}\boldsymbol{V} + \boldsymbol{V}_g^T\boldsymbol{P}_g\boldsymbol{V}_g}{n + r - u} \tag{21}$$

$$\boldsymbol{C}_{\hat{X}} = \hat{\sigma}_0^2\left(\boldsymbol{A}^T\boldsymbol{P}\boldsymbol{A} + \boldsymbol{A}_g^T\boldsymbol{P}_g\boldsymbol{A}_g\right)^{-1} \tag{22}$$

where $\boldsymbol{L}$ is the $n\times1$ vector of relative gravity observation $\Delta\, l_{ij}$ with $n\times n$ weight matrix $\boldsymbol{P}$ formed by the inverse of the variance of the observation σ_{ij}^2 along the diagonal, $\boldsymbol{A}$ is the $n\times u$ design matrix of the observation equation given in Eq. 14, $\boldsymbol{L}_g$ is the $n\times1$ vector containing a priori gravity values determined at absolute gravity sites with $n\times n$ weight matrix $\boldsymbol{P}_g$ composed of the inverse variance of the a priori gravity values, and finally $\boldsymbol{A}_g$ is the $n\times u$ design matrix of the additional observation equation for constraint adjustment. The number of observation equation is indicated by n given also in the denominator of Eq. 21, r number of additional observation equation or fixed gravity values for constraint, and u number of unknown parameters to be estimated.

Global test or Chi-squared χ^2 test for variance (Koch, 1987) and outlier detection based on Pope (1976) τ-test is applied for post-adjustment data screening. Global test is an evaluation procedure to assess the quality of the survey as a whole based on the compatibility of the *a posteriori* variance factor with the *a priori* one, which is assumed unity in this study. Acceptance of this test implies that the functional and stochastic models are correct and complete. According to Pope's τ-test, the normalised residuals should be less than the critical τ value computed with a certain confidence level and degrees of freedoms. If the test is failed for any residual, then this is regarded as a gross error which should be removed from the observations and the adjustment should be re-iterated.

Fig. 2 shows the distribution of 3403 relative gravity ties between 2190 sites during the densification of TR-GravNet in south-western Turkey. Minimally constrained adjustment is executed first by introducing only one fixed absolute gravity value out of 16 to test the internal consistency of the network and check for any blunder and systematic errors. Final results are obtained from fully constrained solution where the 16 absolute gravity values held fixed in the adjustment.

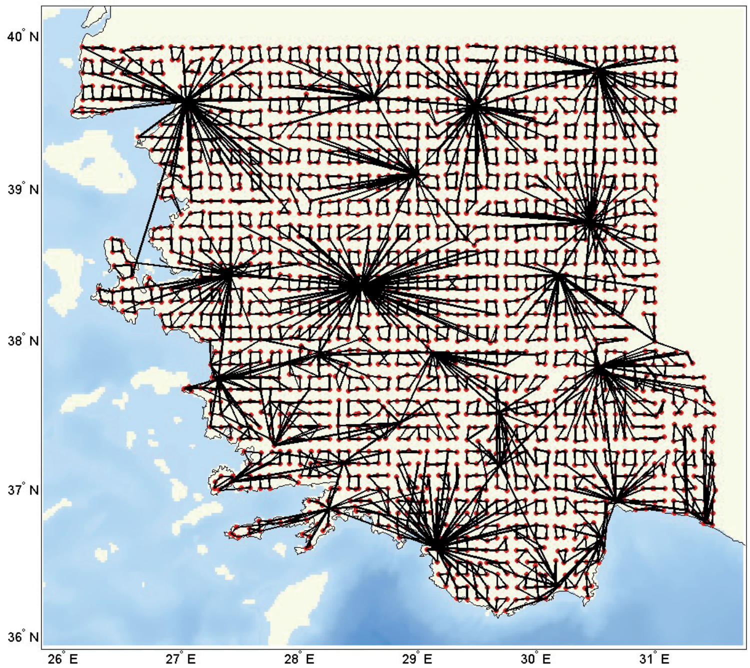

Fig. 2 - Daily relative gravity ties of the TR-GravNet densification in south-western Turkey.

The first iteration of the minimum constraint adjustment at the 95% confidence level yields a few outlying observations whose test statistics are close to critical τ values. The outliers are down-weighted instead of removing them from the observations list. The second iteration results in better solution with *a posteriori* variance factor of 1.002 which passes the global test perfectly. Moreover, the agreement between the gravity values measured with A10 (#044) at the 15 absolute gravity sites not included in the adjustment and the corresponding gravity estimations at these sites are quite well within ±25 μGal (Fig. 3).

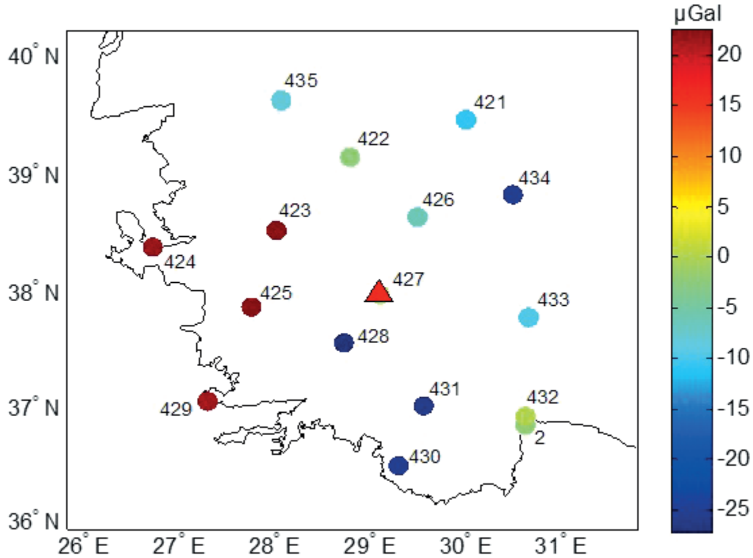

Fig. 3 - Comparison of gravity values at the absolute gravity sites (Site #427 depicted with red triangle is held fixed during the minimum constraint adjustment).

The results obtained from the final adjustment of the network using all the available absolute sites as constraints are given in Table 1. The distribution of the standard errors and the histogram of the residuals are shown in Fig. 4.

Table 1 - Final adjustment statistics in μGal (σ_g is standard error of estimated gravity value, v is residual of the observations).

σ_g^{max}	σ_g^{min}	σ_g^{mean}	σ_g^{RMS}	v^{max}	v^{min}	v^{mean}	v^{RMS}
26.3	6.2	17.2	17.3	38.1	-36.2	-0.3	26.3

Final adjustment yields a mean gravity standard deviation of about 17 μGal which can be considered as the precision of the densified network. The maximum standard deviations of 26 μGal are observed generally in north-western and south-eastern part of the study area. One-sample Kolmogorov Smirnow test applied to the residuals reveals that the residuals follow a normal distribution at 5% significance level with a mean of almost zero and standard deviation of 8 μGal.

4. Assessment of latest GOCE-based satellite only global models in south-western Turkey

The densified TR-GravNet in south-western Turkey, as a homogenously distributed and highly qualified reference data set, is considered as "ground truth data" to find out the best fitting GOCE-based satellite-only GGM in this region. The latest versions (release 5) of GOCE GGMs computed by four different strategies namely DIR5, SPW5, TIM5, and GOCO05 are evaluated along with EGM2008 gravity field model (Table 2).

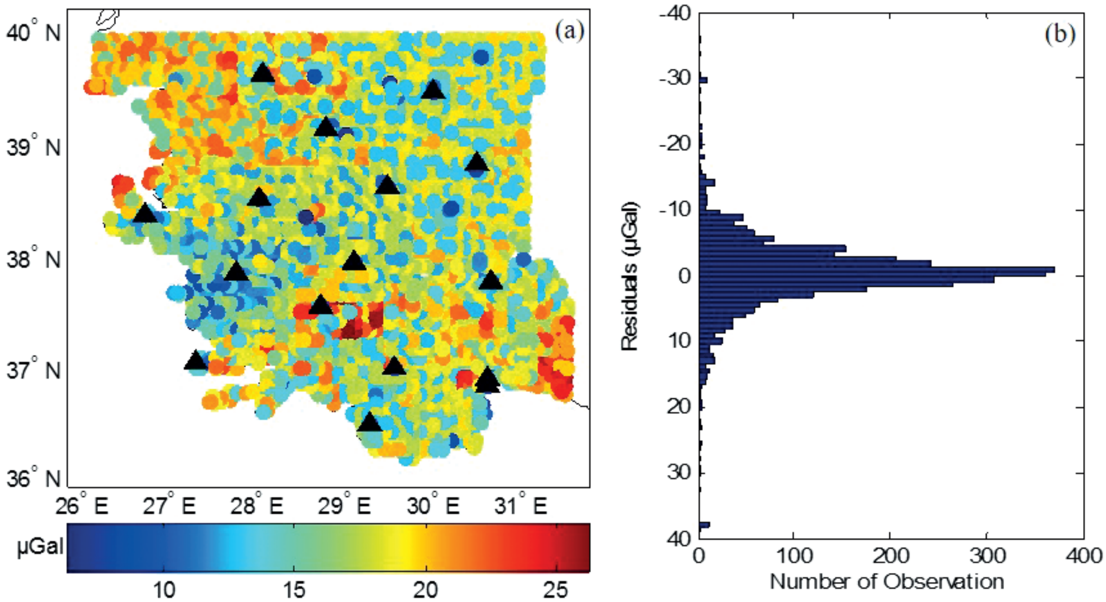

Fig. 4 - Estimated standard errors in μGal (a) and the residuals in μGal (b). (Black triangles show the 16 absolute gravity sites held fixed in the final adjustment).

Table 2 - Descriptions of the GGMs included into the assessment.

Model	N_{max}	Data Period	Reference
SPW5	330	GOCE (42 months)	Gatti *et al.* (2016)
TIM5	280	GOCE (42 months)	Brockmann *et al.* (2014)
DIR5	300	GOCE (42 months), GRACE (10 years), LAGEOS (25 years)	Bruinsma *et al.* (2014)
GOCO05S	280	GOCE (42 months), GRACE (10.5 years), CHAMP (8 years), SLR (5 years)	Mayer-Gürr *et al.* (2015)
EGM2008	2160	GRACE, terrestrial gravity and altimetry derived marine gravity data	Pavlis *et al.* (2012)

The omission error due to the limited spatial resolution of GOCE-based satellite-only GGMs is minimised using spectral enhancement method (Hirt *et al.*, 2011) to compare with terrestrial gravity disturbances of densified TR-GravNet which contain the full spectral signal. This method is widely used to estimate the accuracy of the satellite-only GGMs, accounting for the medium-to-short wavelength gravity field signal beyond the maximum degree and order of satellite-only GGMs. To compensate the medium-to-short wavelength gravity field signal, EGM2008 and ERTM2160 short-scale gravity model (Hirt *et al.*, 2014) are utilised.

Firstly, the gravity disturbances are calculated by subtracting the normal gravity at the ellipsoidal height of the densified TR-GravNet points ($\boldsymbol{\delta g}^{TR-GravNet}$). Secondly, the gravity disturbances at the same TR-GravNet points from the combination of GOCE GGMs and EGM2008 are computed, in which the spherical harmonic models of the GOCE GGMs start from degree 2 to N_{max}, where N_{max} varies from 10 to 250 with a 10-degree interval, and EGM2008 starts from N_{max}+1 up to degree 2160

($\boldsymbol{\delta g}^{GOCE\ GGMs,\ 2:N_{max}}_{EGM08,\ N_{max}+1:2160}$). Subsequently, the gravity disturbances from ERTM2160 gravity model ($\boldsymbol{\delta g}^{ERTM\ 2160}$) are added to the gravity disturbances from GOCE GGMs combined with EGM2008. Finally, RMS (root mean square) values of the gravity disturbance differences between TR-GravNet and GOCE GGMs combined with EGM2008/ERTM2160 as a function of the combination degree are obtained as given in Eq. 23.

$$\mathrm{RMS}\left(\boldsymbol{\delta g}^{TR-GravNet} - \boldsymbol{\delta g}^{GOCE\ GGMs,\ 2:N_{max}}_{EGM08,\ N_{max}+1:2160} - \boldsymbol{\delta g}^{ERTM2160}\right),\ \ N_{max} = 10, 20, \cdots,\ 250 \qquad (23)$$

The black dots in Fig. 5 show the RMS values of the gravity disturbance differences between TR-GravNet ground truth data and EGM2008/ERTM2160 combination only. The coloured lines in Fig. 5 represent the RMS values computed using Eq. 23 from four different GOCE GGMs as a function of the combination degree.

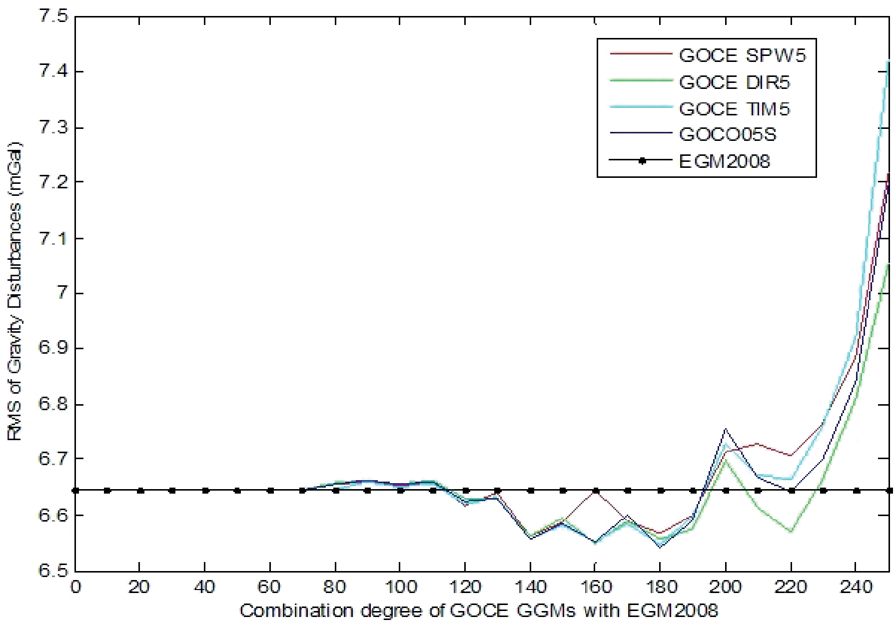

Fig. 5 - RMS of the gravity disturbance differences at TR-GravNet sites computed by various GGMs and combination approaches.

Fig. 5 implies that TR-GravNet ground truth gravity disturbances can successfully detect the improvements of GOCE-based satellite-only models over EGM2008 in the spectral band from ~120 to 190. Among the four different GOCE GGMs evaluated in this study, GOCE-DIR5 is found to be the best as it extends the improvement to ~220 spherical harmonic degree. It can easily be seen that, after the spherical harmonic degrees ~230 for GOCE-DIR5 and ~190 for the other GOCE GGMs, EGM2008 performs better in the study region.

We also compare the differences between GOCE-DIR5 and EGM2008 between the spherical harmonic degrees 2-220. There seem significant biases in EGM2008 reaching up to several mGals in terms of gravity disturbances in sub-regions A, B, and C, shown in Fig. 6. The numerical statistics are given in Table 3 for these three extreme sub-regions.

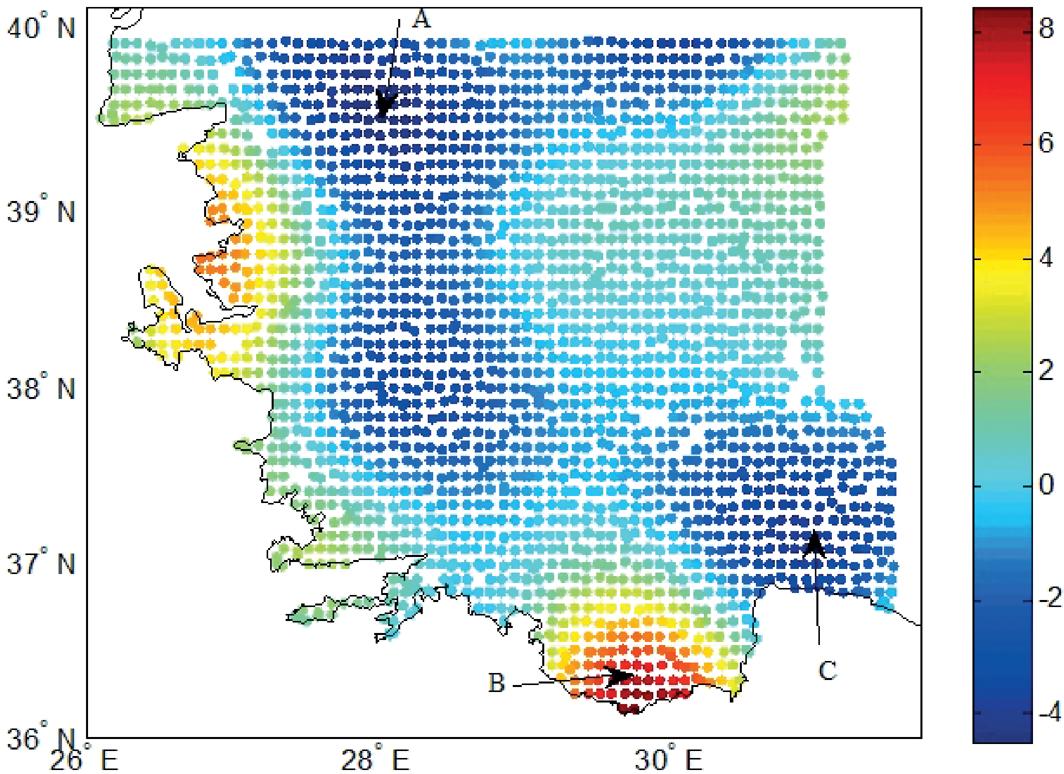

Fig. 6 - Gravity disturbance differences (mGal) between EGM2008 and GOCE-DIR5 model in spherical harmonic degree band from 2 to 220. Letters A, B, C show the sub-regions where the extreme differences exist.

Table 3 - Statistics of the differences between EGM2008 and GOCE-DIR5 model in the spectral degree band from 2 to 220 in sub-regions A, B, and C. Unit is in mGal.

Sub-Region	Number of Points	Max	Min	Mean	RMS
A	121	-2.60	-4.48	-3.51	3.55
B	105	8.43	2.66	5.03	5.28
C	134	-2.01	-3.86	-2.89	2.93

In order to check and verify these findings, EGM2008 and GOCE-DIR5 models are individually compared with gravity disturbances of TR-GravNET ground truth data in each sub-regions. The statistics of the gravity disturbance difference between EGM2008/ERTM2160 and TR-GravNet given in Table 4 suggest almost similar biases in EGM2008 in the order of -1.9 mGal, 4.8 mGal, and -2.6 mGal in sub-regions A, B, and C, respectively. However, the comparison of TR-GravNET with GOCE-DIR5 combined with EGM2008/ERTM2160 at degrees 220 shows relatively small bias values with respect to the biases detected in EGM2008. These biases in EGM2008, estimated by comparison of EGM2008 with GOCE-DIR5 model in spectral band 2-220 degrees and verified by TR-GravNet ground truth data, are possibly caused by datum inconsistencies present in the medium-to-low frequency band between degrees 2 and 220, and/or low accurate and scarce input gravity data used in EGM2008 development (Pavlis *et al.*, 2012).

Table 4 - Statistics of the gravity disturbance differences between TR-GravNet and GGM combinations in sub-regions A, B, and C. Unit is in mGal.

Sub-Region	EGM2008/ERTM2160				GOCE-DIR5 combined with EGM2008/ ERTM2160			
	Max	Min	Mean	RMS	Max	Min	Mean	RMS
A	14.66	-21.22	-1.94	5.87	19.14	-16.94	1.56	5.82
B	6.39	-15.26	4.80	9.93	23.53	-22.08	-0.23	8.68
C	12.52	-13.83	-2.64	5.37	6.02	-11.21	0.24	4.75

5. Conclusion

Gravity standardisation network for Turkey (TR-GravNet) is renewed and densified in south-western Turkey by measurements using A10 (#044) free-fall absolute and six Scintrex CG-5 quartz spring relative gravimeters between April and November 2016.

Spatially and temporally varying corrections for the relative gravity readings due to the solid Earth and ocean tides, atmospheric mass movements and polar motion, as well as the instrumental effects such as drift and sensor height reductions, are computed using our own software developed in MATLAB and applied to the raw gravity readings. The correction for the solid Earth tide can reach up to 175 μGal, but the methods adopted for computing the tide, e.g. direct method or harmonic method with and without local tidal parameters, differ less than a few μGal. Owing to the small ocean tides in the eastern Mediterranean, the magnitude of the ocean tide loading on the gravimetric measurement is found less than 2 μGal from the recent global ocean tide models. Local pressure data registered during the readings with the empirical admittance factor of 0.3 $\mu Gal \cdot hPa^{-1}$ leads to a few tens of μGal correction depending on the station elevation and atmospheric pressure measured. Maximum correction due to the variations in the pole coordinates during the first measurement campaign is about 4 μGal. Considering the average instrument height of about 25-30 cm and mean vertical gradient value of 0.3086 $mGal \times m^{-1}$, the gravity reduction due to the sensor height is around 80 μGal. Scintrex CG-5 gravimeters used in the TR-GravNet densification in south-western Turkey exhibit relatively high linear drift rates up to 1.6 mGal per day during the first few months of operation but the rates start reducing due to the sensor aging. After all the known systematic effects are corrected properly, the daily gravity closures for each gravimeter are found around ±5 μGal, which implies that the reading processes are avoided by accidental errors.

The total uncertainties at all the absolute gravity sites measured in south-western Turkey are found about 10 μGal level. The vertical gravity gradient required for transferring the gravity value from the effective height of the instrument to the user specified height is estimated with a maximum uncertainty of 0.085 μGal/cm at the 16 absolute gravity sites.

The comparison between the absolute gravity values at the 15 absolute gravity sites not included in the adjustment and the corresponding gravity estimations at these sites agrees within ±25 μGal which is in agreement with the mean precision of network of about 17 μGal obtained from fully constrained solution.

Eventually, four latest GOCE-based satellite-only GGMs namely GOCE-DIR5, GOCE-TIM5, GOCE-SPW5 and GOCO05S, whose omission errors are minimised by spectral enhancement method with the use of EGM2008 and ERTM2160, are evaluated with TR-GravNet points as ground truth data in south-western Turkey. Results indicate improvements in the spectral band ~120 to ~190 in terms of spherical harmonic degrees for all GOCE-based GGMs compared to EGM2008. GOCE-DIR5 is found to be best among them extending the GOCE improvement over EGM2008 to spherical harmonic degree ~220. Furthermore, it is found that GOCE GGMs detect significant bias in EGM2008 reaching up to 5 mGal which is verified by regional comparisons of GOCE-based models and EGM2008 with TR-GravNet gravity disturbances. The bias in EGM2008 may be caused by datum inconsistencies present in the medium-to-low frequency, and/or historical terrestrial gravity data used in EGM2008 development.

This study shows the usefulness of the highly precision and densified TR-GravNet for the assessment of GOCE GGMs in south-western Turkey and suggests that GOCE-based GGMs have the capability to improve existing geoid models in Turkey, which are based on EGM2008.

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