



National Research Institute of Astronomy and Geophysics NRIAG Journal of Astronomy and Geophysics

www.elsevier.com/locate/nrjag



Towards a real time leveling using the VRS GPS network in Jeddah

Ahmed El-hattab ^a, Ashraf Mousa ^{b,*}

^a Faculty of Engineering, Port Said University, Port Said, Egypt

^b National Research Institute of Astronomy & Geophysics, Helwan, Cairo, Egypt

Received 29 May 2013; revised 18 July 2013; accepted 29 July 2013

Available online 4 September 2013

KEYWORDS

Jeddah Municipality;
GPS;
Virtual Reference Stations;
Local geoid model

Abstract Jeddah Municipality (JM) established a Virtual Reference Stations (VRS) GPS network for different survey applications. JM provides the users with VRS service to enable them to reach a real time cm-accuracy of horizontal position with single GPS receiver.

To achieve high accuracy for GPS leveling applications a precise geoid model must be defined and applied with the GPS measurements. One of the methods that are used for developing a local geoid model is enhancing a Global Geopotential Model (GGM) with a comprehensive set of gravity, GPS, and leveling measurements.

This paper evaluates six of the recent GGMs with measured GPS and leveling data in Jeddah to select the best model to be used with VRS GPS. That model will be the first candidate to develop a local geoid model for Jeddah. The results indicate that the GO-CONS-GCF-2-TIM-R1 model is the best available model which gives the minimum standard deviation of geoidal height difference.

© 2013 Production and hosting by Elsevier B.V. on behalf of National Research Institute of Astronomy and Geophysics.

1. Introduction

Orthometric heights are normally measured using spirit leveling which is a time consuming hard task. GPS offers a new alternative in orthometric height determination over a comparatively short period. The ellipsoidal height derived from GPS

measurements can be transformed into orthometric height when the geoid model is precisely determined (e.g. Rapp and Rummel, 1975).

Jeddah region is located between Lat. 20.7–22.3 and Long. 39.0–40.5 degrees. It covers a region of about 100 × 50 km. Jeddah Municipality (JM) established a system of GPS Continuously Operating Reference Stations (CORS) to provide the GPS users in Jeddah with VRS services to facilitate and improve the survey applications. The system is composed of nine GPS stations distributed to cover the whole area of Jeddah (Jeddah Survey Directorate web, 2011). Fig. 1 shows the distribution of the stations over Jeddah. Currently the system enables the users to achieve cm-accuracy of horizontal position with single GPS receiver. This high accuracy is not achievable for leveling applications due to the lack of accurate local geoid model.

* Corresponding author. Tel.: +20 01061087313; fax: +20 2 25548020.

E-mail address: ashrafmousa07@yahoo.com (A. Mousa).

Peer review under responsibility of National Research Institute of Astronomy and Geophysics.



Production and hosting by Elsevier

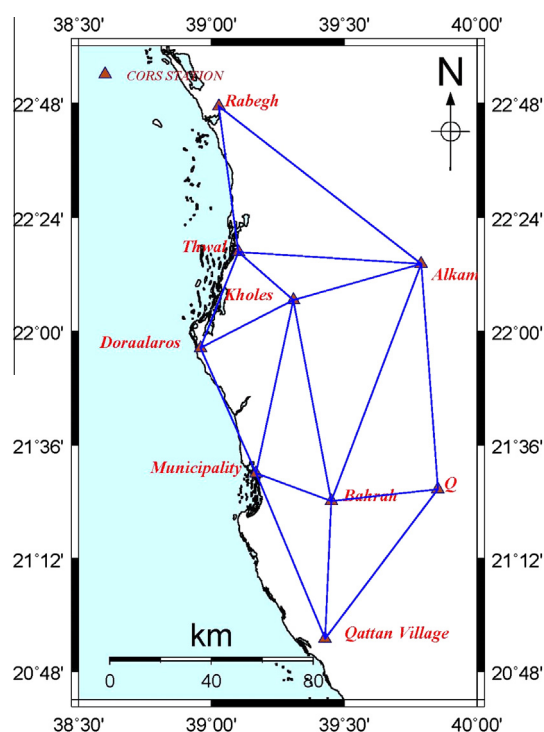


Fig. 1 The VRS network in Jeddah.

In this paper six of the recent Global Geopotential Models (GGMs) (EGM2008, GOCO01S, GGM03 C, EIGEN-51C, GO-CONS-GCF-2-TIM-R1, and GOCO02S) are evaluated using measured GPS and leveling data to select the best GGM to be the first candidate to develop a local geoid model for Jeddah.

2. Heighting with GPS

Geoid is defined as the equipotential surface that coincides with the mean sea level over the oceans and considered as the reference surface that represents the mean sea level in the continent. Geoid can be considered as the true mathematical figure of the Earth. This is definitely because the vertical axis of any surveying instrument is adjusted towards the plumb line, or by other words, perpendicular to its surface at the occupied point. On the other hand, the surveying computa-

tions should be performed relative to a mathematical surface such as the ellipsoid. The relation between the computational (ellipsoid and geoid) and the true surface of the Earth is illustrated in Fig. 2. The high-resolution geoid model is valuable to geodesy, surveying, geophysics and several geosciences, because they represent the datum to height differences and gravity potential. Moreover, they are important for connection between local datum and the global datum, for purposes of positioning, leveling, inertial navigation system and geodynamics (e.g. Vanicek and Christou, 1993).

The fundamental relationship, to first approximation, that binds the ellipsoidal heights obtained from GPS measurements and heights with respect to a vertical datum established from conventional spirit leveling and gravity data is given by numerous authors as: (e.g. Vanicek and Kleusberg, 1987):

$$h = H + N \quad (1)$$

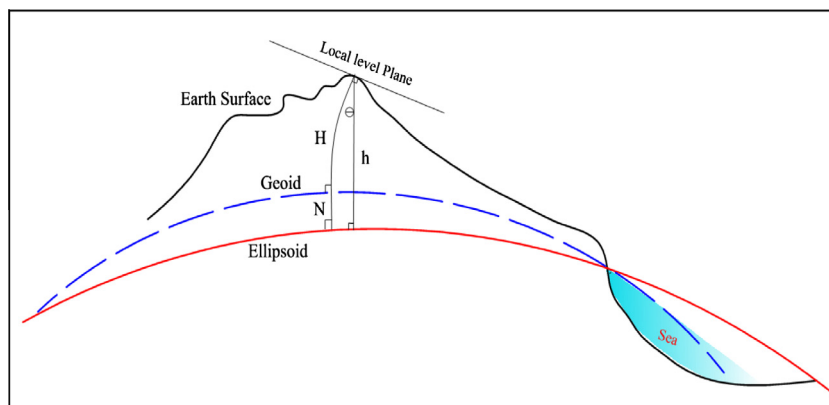


Fig. 2 The relation between ellipsoid height & elevation.

Fig. 2 illustrates h , namely the ellipsoidal height, which is defined as the distance from the point to the ellipsoid surface measured on the ellipsoid normal (the perpendicular line to the ellipsoid at that point). H is the orthometric height, which is defined as the distance from the point to the geoid surface measured on the plumb line (the perpendicular line to the geoid at that point). θ is the angle between the plumb line and the ellipsoid normal. N is the geoid undulation (height), which is the difference between the ellipsoidal height and the orthometric height. The obtained orthometric height must be determined with high accuracy. Therefore, the determination of a high-resolution geoid has become of great importance to cope possibly with accuracy level of height from GPS. An accurate model of geoid undulation is essential in order to convert GPS-derived ellipsoidal heights to orthometric heights.

Geoid height can be separated into three components; long wavelength, medium wavelength, and terrain correction. The long wavelength component can be calculated from the best available GGM, while medium wavelength component can be computed using the Stokes integral of ground gravity anomaly, and terrain correction can be calculated from the topography information (e.g., DTM).

In practice, the application of Eq. (1) is more complicated due to many factors that cause discrepancies when combining the different heights. Some of these factors were discussed in Fotopoulos et al., 2003 as:

- (1) Random noise in the values of the terms h , H and N .
- (2) Datum inconsistencies inherent among the height types, each of which usually refers to a slightly different reference surface.
- (3) Systematic effects and distortions primarily caused by long-wavelength geoid errors, poorly modelled GPS errors, and over constrained leveling network adjustments.
- (4) Assumptions and theoretical approximations made in processing observed data, such as neglecting sea surface topography effects or river discharge corrections for measured tide gauge values in determining sea level. This category of errors is already known to exist at the Lagos tide gauge.
- (5) Various geodynamic effects (post-glacial rebound, land subsidence, plate deformation near subduction zones, mean sea level rise, monument instabilities).

3. Global Geopotential Models

A Global Geopotential Model (GGM) represents Earth's gravity or gravitational potential and/or gravity values for the whole Earth. The GGM is used to determine the long wavelength part of Earth's gravity field and comprises a set of fully-normalized, spherical harmonic coefficients that are obtained from geopotential solutions. These coefficients are determined from the incorporation of satellite observations, land and ship-track gravity data, marine gravity anomalies derived from satellite radar altimetry and airborne gravity data (Yilmaz et al., 2010).

The geoid height is represented at a point, $(\phi_p$ and $\lambda_p)$ from a set of spherical harmonic coefficients in spherical approximation by the following equation (Heiskanen and Moritz, 1967):

$$N(\phi_p, \lambda_p) = \frac{GM}{R\gamma} \sum_{n=2}^{n_{max}} \left(\frac{R}{r}\right)^{n+1} \sum_{m=0}^n \bar{P}_{nm}(\sin(\phi_p))(\bar{C}_{nm} \times \cos m\lambda_p + \bar{S}_{nm} \sin m\lambda_p) \quad (2)$$

where GM is the geocentric gravitational constant, R is the mean radius of the Earth, γ is the mean normal gravity on the surface of the reference ellipsoid, \bar{P}_{nm} are the fully-normalized associated Legendre functions, \bar{C}_{nm} , \bar{S}_{nm} are the fully-normalized harmonic coefficients of the disturbing potential, r is the geocentric radius of the point, $(\phi_p$ and $\lambda_p)$ are the geodetic latitude and longitude of the point. The infinite series is usually truncated at the maximum degree of the expansion $n = L$, where L is the maximum degree used.

Satellite-only GGMs are derived solely from the analysis of the orbits of artificial Earth satellites. Combined GGMs are derived from the combination of satellite data, land and ship track gravity observations, and marine gravity anomalies derived from satellite radar altimetry, and more modern airborne gravity data. Tailored GGMs, derived from a refinement of existing (satellite or combined) GGMs use higher resolution gravity data that may have not necessarily been used previously.

The model data can be obtained from International Centre for Global Earth Models (ICGEM) which is one of six centers of the International Gravity Field Service of the International Association of Geodesy. The center is hosted by GFZ German Research Centre for Geosciences at Potsdam. Website address of ICGEM is <http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html>.

ICGEM collects all existing gravity field models and provides online services to download the models and to calculate different functionals from these models on grids of the users' choice. The calculation service is an interactive Java Applet to calculate different gravity functionals such as geoid heights, gravity anomalies, gravity disturbances, gravity...etc from the models on freely selectable grids, with respect to a reference system of the users' choice.

Six models are selected as recent GGMs to be evaluated. These are EGM2008, GOCE01S, GGM03C, GOCE02S, GO-CONS-GCF-2-TIM-R1 and EIGEN-51C. Description of these models is as follows:

3.1. EGM2008

The Earth Gravitational Model EGM2008 has been developed by the USA National Geospatial-Intelligence Agency (NGA). EGM2008 combines gravitational information from GRACE, with the information contained within a global gravity anomaly database of $5' \times 5'$ resolution. EGM2008 is developed up to degree/order 2160 with some additional terms up to degree/order 2190. The EGM08 offers a spatial sampling resolution (~ 9 km) and incorporates improved 5×5 min gravity anomalies, altimetry-derived gravity (Pavlis et al., 2008).

3.2. GOCO01S

The satellite-only gravity field model GOCO01S is a combination solution based on 61 days of GOCE gravity gradient data, and 7 years of GRACE GPS and K-band range rate data, resolved up to degree/order 224 of a harmonic series expansion. The combination was performed consistently by addition of

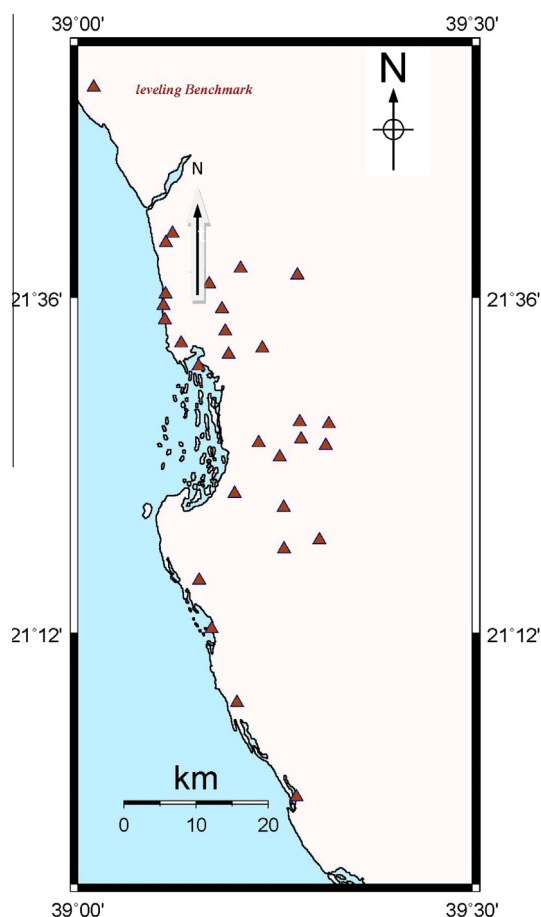


Fig. 3 Distribution of the evaluation benchmarks over Jeddah.

full normal equations and stochastic modelling of GOCE and GRACE observations. In order to improve the signal-to-noise ratio in the high degrees, Kaula regularization starting at harmonic degree 170 was applied (Pail et al., 2010b). It is to be noted here that the main effect of regularization is to reduce the ill-condition of the Least square matrix used for the estimation of the gravity field. The analysis is based on the time-space-wise associated with Kaula regularization.

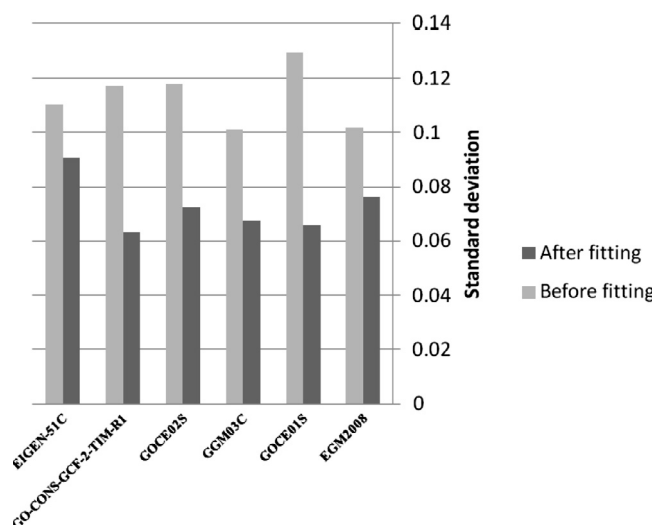


Fig. 4 Comparison between geoidal height difference before and after fitting.

3.3. GGM03 C

GGM03C is a combination of GRACE gravity information from GGM03S model with land and ocean gravity information, complete to degree and order 360. GGM03S was determined from 47 months of GRACE K-band inter-satellite range-rate data, GPS tracking and GRACE accelerometer data spanning the period of about 4 years from January 2003 to December 2006. The terrestrial gravity information was a combination of the NIMA surface gravity anomalies, the CSR mean sea surface (MSS95), and the Arctic Gravity Project (ArcGP) gravity anomalies. GGM03S was used to fill where no terrestrial gravity information was available. The GRACE atmosphere-ocean de-aliasing product (AOD1B) was used, but the mean of the AOD1B for the 47 months has been restored (Tapley et al., 2007).

3.4. GOCO02S

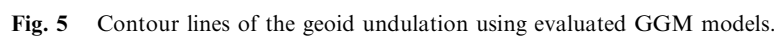
The global gravity field model GOCO02S is complete to degree and order 250. It is composed of six components from GOCE,

Table 1 Statistics of geoidal height difference before fitting. Units in meters.

Model	EGM2008	GOCE01S	GGM03C	GOCE02S	GO-CONS-GCF-2-TIM-R1	EIGEN-51C
Max	-0.015	0.542	0.222	0.470	0.115	0.114
Min	-0.406	0.060	-0.146	-0.091	-0.304	-0.435
Mean	-0.159	0.315	0.055	0.137	-0.075	-0.175
Standard deviation	0.102	0.129	0.101	0.118	0.117	0.110

Table 2 Statistics of the geoidal height difference after fitting. Units in meters.

Model	EGM2008	GOCE01S	GGM03C	GOCE02S	GO-CONS-GCF-2-TIM-R1	EIGEN-51C
Max	0.170	0.142	0.144	0.170	0.148	0.182
Min	-0.196	-0.147	-0.144	-0.184	-0.160	-0.214
Mean	0	0	0	0	0	0
Standard deviation	0.076	0.066	0.068	0.072	0.063	0.091



ITG-GRACE2010s, SLR and Champ. For GOCE, the model is based on 8 month data from the combination of high-low satellite-to-satellite tracking (hl-SST) and 12 months satellite gravity gradiometry (SGG). 7 years of ITG-GRACE2010s have been used for the combination. 8 years of CHAMP data and 5 years of 5 SLR satellite data have also been added to the solution. In order to improve the signal-to-noise ratio in the high degrees, Kaula regularization starting at harmonic degree 189 was applied. The 5 years of SLR and 8 years of CHAMP data are also components of the model (Goiginger et al., 2011).

3.5. GO-CONS-GCF-2-TIM-R1

This GOCE gravity field model is based on two months of GOCE orbit and gradiometry data and has been computed applying the time-wise method. The resulting global gravity field model, resolved complete to degree/order 224 (Pail et al., 2010a).

3.6. EIGEN-51C

The EIGEN-51C model is a global solution consisting of 6 years of CHAMP and GRACE data and the DNSC08 global gravity anomaly data set complete to degree/order 224224 (Bruinsma et al., 2010).

4. Evaluation of the GGMs

The vertical reference network of Saudi Arabia was built in early 1970s as the first order vertical control network. It was built by using spirit leveling based on tidal gauges along the Arabian Gulf and Red Sea. The vertical datum is based on the mean sea level (MSL) at Ras Tanura Tidal BM in the eastern coast of the region. Starting with the first order benchmarks, a second order benchmark network was established and adjusted in 1980.

The evaluation of the GGMs was carried out by performing a comparative analysis between geoid heights as derived from GGMs and from GPS on 30 leveling benchmarks. The leveling benchmarks used here are second order leveling networks which were adjusted in 1980. These data are available from the Jeddah Municipality surveying directorate. Fig. 3 shows the distribution of used benchmarks over Jeddah. The spacing between nearby benchmarks ranges from 500 m. up to 10 km. In 2006, leveling loops have been run to check these points and relative accuracy was found in the range of 1–3 mm.

GPS measurements were taken on these second order benchmarks. The GPS measurements were carried out using Trimble R7 and Lieca system 1200 receivers. The observation is carried out using 4 receivers simultaneously and the observation session was set to 6 h. Trimble total control processing software was used and at least two of the Jeddah CORS stations were used as control points.

The GGMs' geoid undulation was estimated using the interactive calculation services at ICGEM website. This service is a web-interface to calculate gravity functionals from the spherical harmonic models on freely selectable grids. The geoid undulation at the benchmark locations is interpolated from the grid files using the quadratic interpolation technique.

The GGM model selected as the best model is the one which matches best in the statistical sense the observed data. Theoretically, the geoidal height difference, obtained from a GPS/leveling comparison with the different GGMs can be taken as an indication for the model selection but actually that computed geoidal height difference is affected by datum inconsistencies inherent among the height types, systematic effects and distortions, and other factors that are mentioned above. The geoidal height difference can be calculated as:

$$\Delta N_i = N_{\text{GPS}(i)} - N_{\text{GGM}(i)} \quad (3)$$

where ΔN_i is the geoidal height difference at point (i), and N_{GPS} and $N_{\text{GGM}(i)}$ are the geoidal heights at point (i) obtained from GPS/leveling and Global Geopotential Model respectively.

In order to minimize the effects mentioned above, we used a four parameter transformation model. The model is most commonly used in such adjustments and is given by the following equation (Heiskanen and Moritz, 1967):

$$\Delta N_i = a_0 + a_1 \cos \varnothing_i \cos \lambda_i + a_2 \cos \varnothing_i \sin \lambda_i + a_3 \cos \lambda_i + v_i \quad (4)$$

where a_0 to a_3 are four unknown parameters \varnothing_i, λ_i are latitude and longitude of the point i , v_i is the residuals. The parameters a_0 to a_3 are determined minimizing the residuals V_i using a least squares technique.

Tables 1 and 2 show statistics of geoidal height difference before and after fitting by four parameter transformation models.

It is clear from the tables that all results show improvements for all models after fitting the geoidal height difference since the biases are minimized. The maximum improvement is found with the GOCE01S model where the standard deviation reduced from 0.129 m to 0.066 as shown in Fig. 4. The minimum improvement is found with the EIGEN-51C model from 0.110 to 0.091 m.

The minimum standard deviation of the height difference is found when using the GO-CONS-GCF-2-TIM-R1 model and maximum standard deviation of the height difference is found when using the EIGEN-51C model. The GOCE01S model gives the second best standard deviation of 0.066 m.

The standard deviation given by the best model (GO-CONS-GCF-2-TIM-R1) is 0.063 cm which is still big and more work using local measured gravity data is needed to refine that model to account for the short wave length component of the geoid model.

The geoid undulations at a grid with spacing 0.5 min are generated for the six GGM models after applying the transform function as shown in Fig. 5. It is clear that the general shape of the contours is similar with some differences, especially at the edges. The differences are mainly due to the difference in the truncation degree N_{max} for the different models.

5. Concluding remarks

Jeddah Municipality has made a major step to provide valuable surveying services through the establishment of GPS CORS for VRS applications. The next step is to develop a local geoid for Jeddah to enable the users to measure the levels with high accuracy using single GPS receiver. A step towards that goal is the establishment of local geoid for Jeddah.

The aim of the current research is to investigate the possible ways to establish the local geoid.

The current paper evaluates six of the GGM models for use as a first approximation of the local geoid in Jeddah. The process of evaluation is based on comparing the geoid heights as derived from GGMs and from GPS on 30 leveling benchmarks. The results of this study are based on the mean difference between the geoid heights derived from the two methods as well as their standard deviations. As a first approximation, the current paper showed that the model GO-CONS-GCF-2-TIM-R1 is the best GGM in terms of representing the geoid undulations. The GO-CONS-GCF-2-TIM-R1 gives a standard deviation of 0.063 cm which is still big and more work using local measured gravity data is needed to refine that model to account for the short wave length component of the geoid model. For the time being, GO-CONS-GCF-2-TIM-R1 can be used after applying the four parameter transform as a geoid model until establishing a local geoid.

References

- Bruinsma, S.L., Marty, J.C., Balmino, G., Biancale, R., Foerste, C., Abrikosov, O., Neumayer, H., 2010. GOCE Gravity Field Recovery by Means of the Direct Numerical Method, Presented at the ESA Living Planet Symposium 2010, June 27–July 2, Bergen, Norway.
- Fotopoulos, G., Featherstone, W.E., Sideris, M.G., 2003. Fitting a gravimetric geoid model to the Australian Height Datum via GPS data. In: Tziavos, I.N. (Ed.), *Gravity and Geoid 2002*. Department of Surveying and Geodesy, Aristotle University of Thessaloniki, pp. 173–178.
- Goiginger, H., Höck, E., Rieser, D., Mayer-Gürr, T., Maier, A., Krauss, S., Pail, R., Fecher, T., Gruber, T., Brockmann, J.M., Krasbutter, I., Schuh, W.D., Jäggi, A., Prange, L., Hausleitner, W., Baur, O., Kusche, J., 2011. The Combined Satellite-only Global Gravity Field Model GOCO02S, Presented at the 2011 General Assembly of the European Geosciences Union, Vienna, Austria, April 4–8.
- Heiskanen, W.A., Moritz, H., 1967. *Physical Geodesy*. W.H. Freeman, San Francisco.
- Jeddah Surveying Directorate, 2011. Website for Jeddah Municipality Surveying Directorate. Available from: <<http://jeddah.gov.sa/Business/Masaha/index.php>>, visited May 2011.
- Pail, R., Goiginger, H., Mayrhofer, R., Schuh, W., Brockmann, J.M., Krasbutter, I., Höck, E., Fecher, T., 2010a. GOCE Gravity Field Model Derived from Orbit and Gradiometry Data Applying the Time-Wise Method, Presented at the ESA Living Planet Symposium 2010, June 27–July 2, Bergen, Norway. Available from: <www.espace-tum.de/mediadb/910370/910371/Pail10.pdf>.
- Pail, R., Goiginger, H., Schuh, W.D., Höck, E., Brockmann, J.M., Fecher, T., Gruber, T., Mayer-Gürr, T., Kusche, J., Jäggi, A., Rieser, D., 2010b. Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. *Geophys. Res. Lett.* 37, L20314. <http://dx.doi.org/10.1029/2010GL044906>.
- Pavlis, N., Holmes, S., Kenyon, S., Factor, J., 2008. An Earth Gravitational Model to Degree 2160: EGM2008, Presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13–18. Available from: http://www.massen-transporte.de/fileadmin/2kolloquium_muc/2008-10-08/Bosch/EGM2008.pdf.
- Rapp, R.H., Rummel, R., 1975. Methods for the Computation of Detailed Geoids and Their Accuracy, Rep. 233. Dept. of Geodetic Science and Surveying, The Ohio State University, Columbus, 1975.
- Tapley, B., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F., Poole, S., 2007. The GGM03 Mean Earth Gravity Model from GRACE, *Eos Trans. AGU* 88(52), Fall Meet. Suppl., Abstract G42A–03.
- Vanicek, P., Christou, N., 1993. *Geoid and its Geophysical Interpretations*. CRS press, Taylor and Francis group, USA, p. 368.
- Vanicek, P., Kleusberg, A., 1987. The Canadian geoid – Stokesian approach. *Manuscripta Geodetica* 12, 86–98.
- Yilmaz, I., Yilmaz, M., Güllü, Turgut, B., 2010. Evaluation of recent global geopotential models based on GPS/leveling data over Afyonkarahisar (Turkey). *Scientific Research and Essays* 5 (5), 484–493, <http://www.academicjournals.org/sre/PDF/pdf2010/4Mar/Yilmaz%20et%20al.pdf>.