The development of the Israeli official geoid undulation model

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Key words: Geoid Undulations Model, Hybrid Geoid Model, Orthometric Heights, GNSS

SUMMARY

In the XXIII FIG Congress held in Munich, Germany, October 8-13, 2006 the first two authors proposed the idea of using permanent GNSS networks and Official Geoid Undulations Model (OGUM) as a substitute for Orthometric Control. About half a year later, this idea was adopted by the Survey of Israel (SOI). As of May 2007, surveyors in Israel can define official orthometric heights in real-time using a single GNSS receiver equipped with the Israeli official geoid undulation model (ILUM). Instead of occupying at least 4 benchmarks, they can use just one benchmark for checking and verification purposes only. The ILUM is actually the countrywide orthometric height reference system of Israel. The Israeli OGUM was based on GPS-Leveling. It is flexible to local improvements through changes in its versions, which are well maintained. Over the last years, the SOI continued to sporadically measure GNSS-leveling lines to improve its OGUM. Research introducing a Geoid model that is based on terrestrial gravity measurements in Israel and its surroundings, incorporating shipborne gravity measurements and altimetry data over the Mediterranean Sea, using the EIGEN-6C4 as the reference earth gravity model was recently made. Relying on the conclusions and results of this study, the SOI is working to further improve the consolidation of a hybrid geoid model. Following a short description of the OGUM's concepts and its advantages, the paper elaborates on how the proposed idea was established in Israel 14 years ago. Comparison between precise leveling in different areas of Israel and deduced orthometric height-differences from the Israeli OGUM (ILUM2.0) - as well as the new hybrid model - are presented. The results of this comparison approve the accommodation of using OGUM and a permanent GNSS network as a substitute for the classic orthometric control for most of the engineering works. The Global Geoid model EIGEN-6C4 is also analyzed, demonstrating its potential to contribute to the establishment of an OGUM in other parts of the world.

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1. INTRODUCTION

Understanding and accepting the fact that the vertical geodetic control of the future (Steinberg and Papo 1996, 1998,1999) will be ellipsoidal control based on GNSS measurements, the Survey of Israel (SOI) began to look for ways to its implementation. The SOI is responsible for preparing and updating Survey Regulations for Geodetic Control Networks, Topographic Mapping, Cadastral Surveys and related activities. Licensed Surveyors in Israel are obliged to work according to those regulations. In 2005 a team of experts that prepared a draft for new survey regulations (Steinberg 2006) came to the conclusion that there is neither a practical possibility nor actual need to maintain a countrywide vertical orthometric control network. The decision was that SOI will maintain a vertical ellipsoidal height control network, measured by the GNSS technique as a part of 3D ellipsoidal geodetic control. Although for many kinds of geodetic works ellipsoidal heights are good enough, the team decided to continue with using orthometric heights in most of the works. The team concluded that the transition to ellipsoidal heights only, was premature. It seemed impossible to explain, for example, a difference of 70 cm between the heights of the Sea of Galilee (Lake Kineret) in its northern part relative to its southern one. In addition to the national network of ellipsoidal heights, it was decided to permit maintaining of local networks of orthometric heights, or to measure control points using an official geoid undulation model (OGUM), (Steinberg and Even-Tzur, 2006, 2007, 2008, Even-Tzur and Steinberg 2009). Enormous efforts were, and still are, undertaken around the world in order to achieve a cm-level-geoid-models with which one can get orthometric heights by GNSS measurements. The usual attitude is that this goal cannot be achieved unless you have a higher accuracy geoid model. The main suggestion in those papers was that we do not have to wait for the "perfect" improved geoid model, and that for most of the works in which we need orthometric control, it can be achieved by permanent GNSS networks and OGUM.

2. THE CONCEPT OF AN OFFICIAL GEOID UNDULATION MODEL - OGUM

2.1 Official

There is nothing new in deducing undulations between the geoid and the ellipsoid for converting ellipsoidal heights to orthometric heights. Adding the word "official" to the term "geoid undulation model" means that the model was officially announced by the geodetic national authority although it is not "perfect" and it might be changed from time to time by a new version.

2.2 The advantages of using OGUM over the classic orthometric control.

2.2.1 Efficiency

Today, there is no need to describe the efficiency of GNSS leveling over geometric or trigonometric leveling of long lines and/or difficult topography. The OGUM enables using just one GNSS receiver (and a CORS service) and occupying just one known benchmark, for checking purposes only. It is a significant advantage from the economic point of view. Another important advantage, especially for the national geodetic authority, is that we do not have to take care anymore for establishing and maintaining a traditional vertical geodetic control network by means of precise leveling. Traditional vertical geodetic control networks are notorious for their high price, extensive investment in time and the need for dedicated, reliable and well-trained field crews.

2.2.2 Consistency

The objective of a vertical control network is to bring consistent and identical heights to all points (within the desired accuracy) obtained by every surveyor. In reality, this goal cannot be achieved by means of classic leveling networks, as was explained in Steinberg and Even-Tzur (2006). The biggest advantage of the OGUM is its consistency. Every surveyor who uses the same version of the OGUM will get the same results within the accuracy of the measured ellipsoidal heights. From that point of view, the OGUM can be regarded as errorless. The nominal accuracy of the orthometric height differences depends solely on the accuracy of the GNSS measurements.

2.3 Updating the OGUM

The OGUM can be updated and improved from time to time by adding new information (Steinberg and Tuchin 2009). The managing authority of the OGUM must keep all the published versions of its OGUM for the surveyor's availability. On the other hand, the surveyors must note the OGUM's version they used in every work, just like they needed to note the nominal (published) heights of the benchmarks on which they based their works, before using the OGUM.

3. ILUM, the Israeli OGUM

The first version of the Israeli OGUM, ILUM1.0 was released in 2007. The model was developed based on about 700 points with the given ellipsoidal and orthometric heights. The geostatistical method of Kriging approximation was used for the construction of the undulation surface. The values of differences were calculated on a grid of 0.5×0.5 km (Tuchin, 2006). The model has been updated several times and now the model in use is ILUM2.0 which is based on about 850 points. The model accuracy is determined by the underlying mathematical method, by the quality of the GNSS measurements, the accuracy of the orthometric heights and by the density of the points. The model accuracy in central and northern Israel is better than 5cm and in the south, the accuracy drops to 10cm due to the low density of model points. A precise leveling was carried out in 2017 along about 200km of the Israeli-Egyptian border in the south part of Israel to replace 3rd order leveling. When this information will be part of the new updated version of ILUM we can expect for an improved model in the southern region.

4. DEVELOPING A HYBRID GEOID MODEL

4.1 Goal

Since ILUM, the Israeli OGUM, is based mainly on large loops of precise leveling along roads, its accuracy is decreasing with the distance from those roads to the center of the loops. A new research was done lately in order to improve the geoid model in its weak parts, using a similar way to Felus et al (2008) approach.

4.2 Methodology

The hybrid geoid model calculation process for Israel is based on the 'Remove-Compute-Restore' (RCR) method (Hirt, 2011). This method relies on interpolating a surface with a data amplitude smaller than the original one: 1) 'Remove' the values obtained from the global gravity model from the values of the gravimetric observations; 2) 'Compute' the new surface via the Stokes integral to a point in a regulated grid; and, 3) 'Restore' the calculated undulation value according to the global gravity model. More specifically:

1. Collect all available gravimetric data (ground, aerial, marine and satellite) for the area of Israel and its surroundings (see Figure 1), perform accuracy validation and error filtering, according to:

- Converting the coordinates of all gravimetric observations to the WGS84 reference system and checking that the observations are given in the global datum for gravimetric measurements (IGSN71 system).
- Checking the elevation values of all gravimetric observations against a high-resolution DTM, filtering erroneous data that could cause large errors in the calculation of the free-air anomaly.
- Choosing the global gravity model for the study area in comparison to the gravity anomalies calculated from the ground gravimetric observations, as well as based on the undulation values of the existing control points.

2. Remove:

- Reduction of gravimetric observations and calculation of gravimetric anomalies in the geoid, including reductions to negative altitude points. Checking the anomalies compared to the global gravity model to filter erroneous observations.
- Calculation of ground density values according to the different geological strata that affect the topographic corrections required to the gravimetric anomalies.

- Calculation of the topographic correction (RTM) for each observation – three DTMs are created for this process: 1 arc-second, 30 arc-seconds, and 5 arc-minutes. Since the contribution of the topography is calculated at a radius of 100 km from each observation location, DTMs coverage is generated accordingly.
- Calculate the residual gravimetric anomaly surface after subtracting the anomaly values from a global gravity model and the topographic corrections. Completing missing data at sea from the DTU15 model, and filling holes (areas with missing gravimetric observations) based on the LSC interpolation method.

3. Compute:
   - Integration according to Stokes formula, implementing the Heck and Gruninger (1987) calculation methods, with radius values between 0.5 to 3.0 arc-degrees from each measurement (point) location. The calculation is performed using the FFT function on the residual surface data obtained in the previous step.
4. Restore:
   - Quasi-geoid calculation – adding the contribution of the global gravity model and the topography contribution to the geoid calculation. Comparison of the undulation values obtained using the different models, selecting the model with the lowest standard deviation value.
   - Analyze the results and assess the accuracy with respect to the deflection deviations and existing control points.
5. Hybrid geoid:
   - Finding maxima points in the ILUM model and calculating the hybrid geoid using the LSC interpolation method, where the selected maxima points serve as anchor points for calculating the surface differences. Supplementary points serve as a control for the accuracy of the calculated hybrid model.

4.4 Gravimetric geoid model results

Table 1 depicts the statistical comparison of the undulation values for the ILUM2.0 control points in respect to the Eigen-6C4 gravity model and the gravimetric model produced via the RCR approach. The standard deviation value is decreased when compared to the undulation values calculated from the global Eigen 6C4 model based on the official model control points (ILUM2.0). Moreover, the difference in amplitude between the minimum and maximum points is reduced from 1.220 m to 0.31 m.

Geoid model	Minimum [m]	Maximum [m]	Average [m]	STD [m]
Eigen- 6C4	-0.280	0.940	0.280	±0.190
Gravimetric	-0.790	-0.480	-0.640	±0.057

Table 1. Statistical comparison of the undulation values for the ILUM2.0 control points in respect to the Eigen-6C4 gravity model and the gravimetric model produced via the RCR approach.

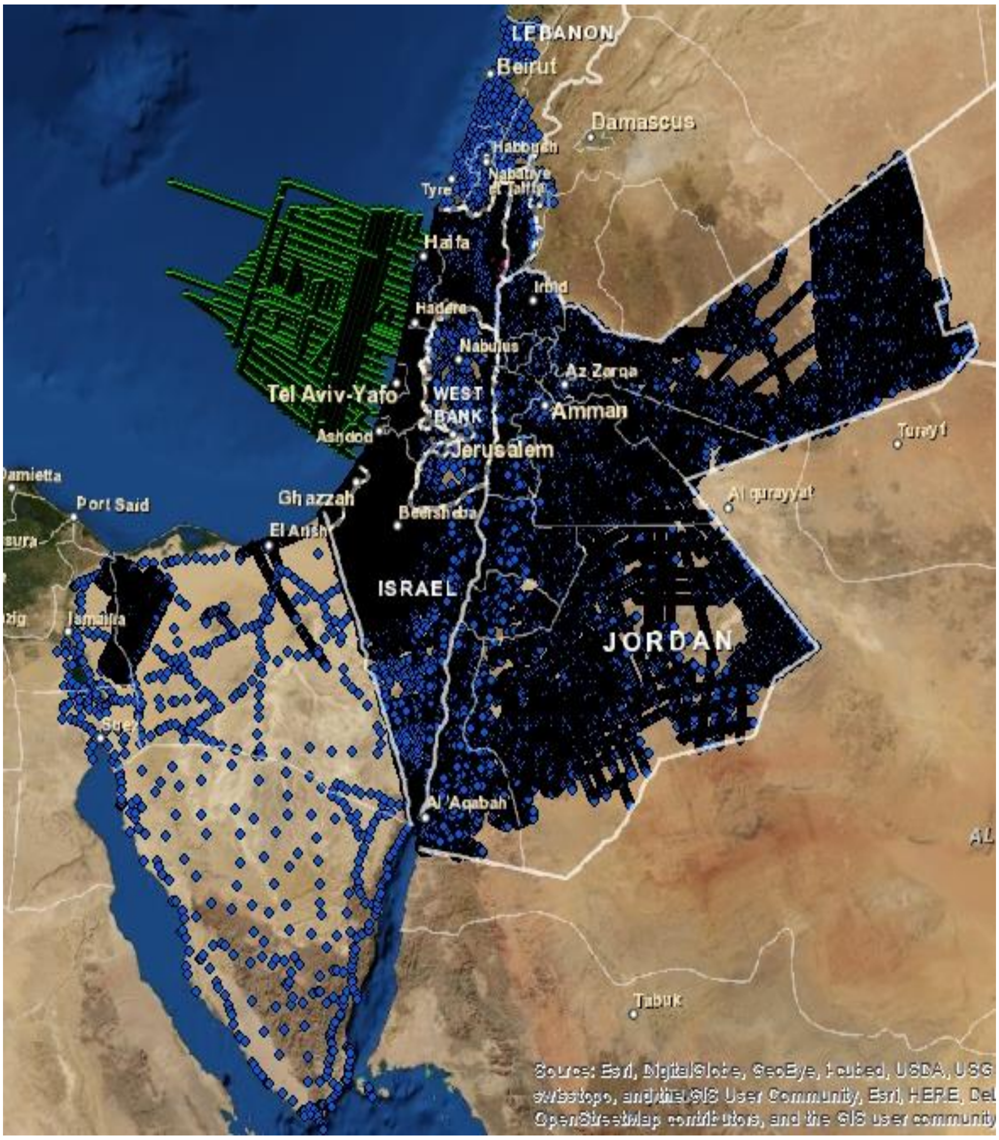

Figure 1. Gravimetric observations in Israel and its surroundings

4.5 Hybrid geoid model

With the help of a morphological detection process, 249 control points are used to calculate the hybrid geoid model. The result validation test was performed for 664 control points that were not part of the calculation process. The hybrid geoid model was calculated with a standard deviation of 2.4 cm with respect to the control points.
Figure 2 depicts the distribution of the undulation value differences for the 664 control points.

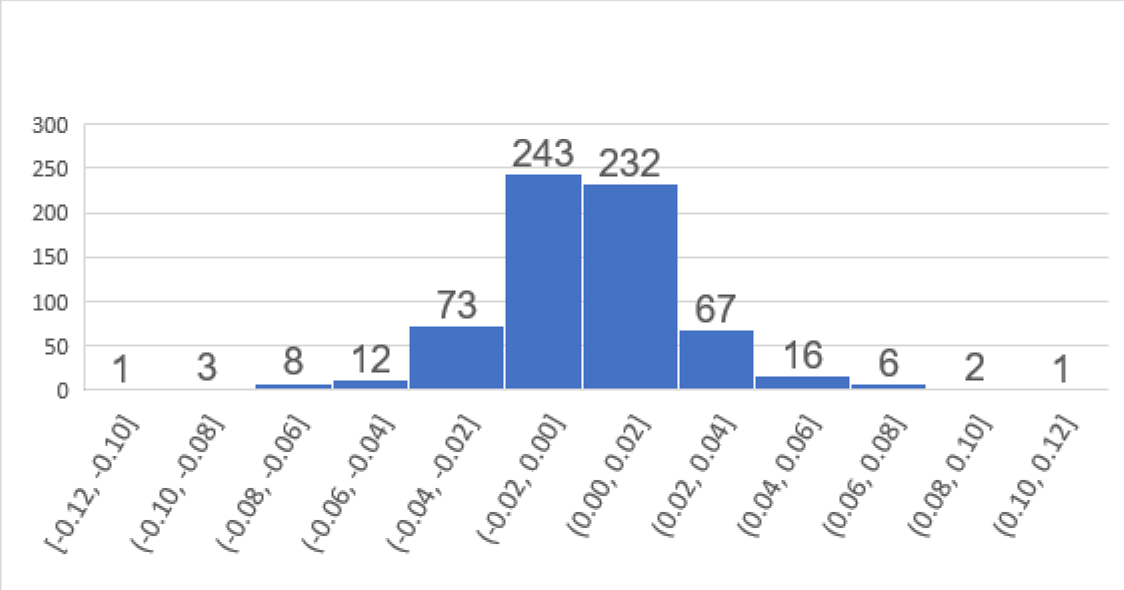

Figure 2. The Undulation height difference distribution for the 664 points (values in X-axis in meters).

5. EXAMPLES OF HIGHT DIFFERENCES BETWEEN DIFFERENT GEOID MODELS

The goal of the experiment is to examine the accuracy of the orthometric height differences, based on GNSS measurements and the OGUM, in different regions throughout Israel. Four alternative options (models) were tested for the OGUM: ILUM2.0, the Hybrid model, the Gravimetric model and the Eigen-6C4 model. In each location, two benchmarks with known orthometric heights were measured using GNSS. It is important to note that the chosen measured benchmarks were not used as part of the abovementioned tested models. The duration of the measurement session was 40 minutes. The ellipsoidal height differences were processed from the GNSS measurements. By using the OGUM, we can calculate the undulation differences between the points, then we compute the orthometric height differences. The existing orthometric height differences between the benchmarks are known. Therefore, a comparison between the known and computed orthometric height differences allows us to evaluate the accuracy of orthometric height differences based on the GNSS measurements and the OGUM. The estimated relative accuracy of the known orthometric height differences between the benchmarks, as well as the measured ellipsoidal height differences, was approximately 1-2 cm.

Table 2 presents typical sample results of ppm values of the differences between the known orthometric height differences and the calculated orthometric height differences for the four OGUM alternatives.

Region	BM		Distance	**ILUM2.0**	**Hybrid**	**Grav.**	**Eigen- 6C4**
	from	to	(km)	[ppm]	[ppm]	[ppm]	[ppm]
1	6262	6263	0.9	11	15	16	81
2	404	413E	4.3	3	6	6	5
3	2443	2454	1	0	1	1	12
4	3888	3893	1.8	3	4	1	8
5	3168	269U	4.8	19	16	6	8
6	7062	7064	1.8	1	3	1	1
7	3361	861	0.6	10	25	24	21
8	1001	1002	0.8	9	3	4	5
9	4406	6221	5.1	4	8	5	14
10	835U	834U	10.8	1	2	0	5
11	3831	3839	3.6	8	9	14	9

Table 2. Typical sample results of ppm value of the differences between the known orthometric height differences and the calculated orthometric height differences for the four OGUM alternatives, ILUM2.0, Hybrid model, Gravimetric model and Eigen-6C4. The locations of the regions can be seen in Fig 3.

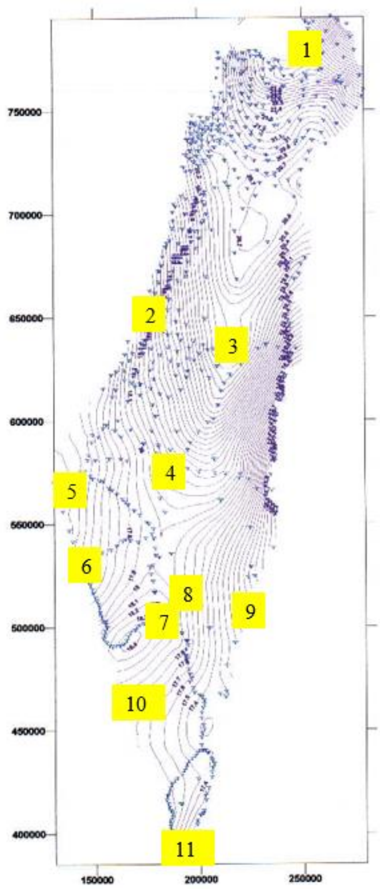

Fig. 3. Eleven locations (numbered squares) where the OGUM experiment was held in Israel, on a background of the SOI undulation map (contour line every 25cm) based on approximately 850 points (dots). The numbers denote the region, as appearing in Table 1.

6. DISCUSSION

A key aspect in geoid modeling and its applications is the accuracy of the slope needed to water flow, which is actually related to the precise leveled height differences. The orthometric heights themselves (classical leveling or GNSS- geoid-model derived) are needed just as a convenient means for computing height differences. We should not forget that "true orthometric heights" do not really exist. There is no direct way to measure orthometric heights because the zero surface (the geoid) is untouchable. On the other hand, ellipsoidal heights measured by GNSS are real, so orthometric heights derived from ellipsoidal heights and OGUM can be considered as official orthometric heights. In General, a vertical control network for most of the surveying and engineering work would be considered reasonable if it consisted of benchmarks 1 km apart, with a local accuracy (including internal stability) of approximately 1-2 cm. That means accuracy of approximately 25 mm in the height difference between those benchmarks, which is a relative accuracy of about 25 ppm (see also Kaula 1987). As is seen in Table 2, all the derived height differences fulfill that goal. It might be seen contradicting the accuracy of ILUM, mentioned in paragraph 3 above (5 -10cm). It is explained by the fact that the quoted accuracy actually relates to the accuracy of the height difference between a base leveled point and a far unleveled point. As a matter of fact, the results are much better even where we used the global geoid model Eigen-6C4. The same results were also achieved using VRS, meaning that this approach provides good results even in areas where the ellipsoidal vertical control is not dense. However, it should be noted that the differences between these geoid-models derived heights are based on the same ellipsoidal heights, while usually, the accuracy of the GNSS measurements should be considered.
However, there are also engineering works where better accuracy is needed. These types of works do not justify a countrywide high accurate orthometric control network. They can be handled as local networks (“orthometric islands”) having their unique datum (Steinberg and Papo 1996, 1999). The combination of official geoid undulation model (OGUM) with a vertical ellipsoidal control based on permanent GNSS stations produces a practical countrywide network of "official" orthometric heights, appropriate for most of the geodetic and surveying needs. However, it should be noted that these heights are not necessarily consistent with the existing bench-marks. It means that a derived official orthometric height of an existing ("old") bench-mark will not necessarily agree exactly with its known (registered) height. See also Marti (2007) for the Swiss OGUM. A further meaning of using OGUM may be that heights obtained from GNSS and the official geoid undulation model prevail over the published elevations of the benchmarks, as was announced by the Natural Resources Canada regarding their geoid model CGG2013a (www.nrcan.gc.ca/height-reference-system-modernization/9054).

7. CONCLUSION

Just like other countries, the SOI, Israel's national geodetic authority, continues to improve its geoid undulation model - although it does not really important and needed to most of the land surveyor's work. However, based on 14 years of the successful experience, we recommend other national geodetic authorities to use the OGUM's concept without waiting to achieve the "perfect" geoid model. We suggest choosing the best fit-for-purpose available geoid model. Countries that still don't have a level-GNSS geoid model can adopt a (free of charge) global geoid model like Eigen-6C4 as their OGUM. In that case, the best fitting of the selected model to the existing vertical orthometric control benchmarks might be preferred, but it should be carefully considered due to available confusions. In our experiments, we found height differences of up to -0.79 and -0.48 (with an average of -0.64) meters between the deduced heights from Eigen-6C4, and the published benchmark's heights. The OGUM's concept is very efficient and very consistent, and it serves well as an important device that enables us to continue the work with orthometric heights in the new era of 3D ellipsoidal geodetic control.

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