Two Years Experience with the Israeli Official Geoid Undulations Model

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Key words: OGUM (Official Geoid Undulations Model)

SUMMARY

In 2005 the new datum of geodetic coordinates, IGD05, was introduced in Israel. It was suggested then that the national geodetic control network will be defined as 3D control, i.e. every control point shall have horizontal coordinates (longitude, latitude and plane coordinates) and ellipsoidal height. The network is based on the Permanent GNSS stations of Israel which constitute the higher order of the 3D control. As from May 2007 the Israeli surveyors can define orthometric heights of 4th and 5th order vertical control points using GNSS measurements and an Official (statutory) Geoid Undulations Model (OGUM). The first version of the Israeli OGUM, named ILUM 1.0 - IsraeLi Undulations Model, was released by the Survey of Israel accompanied by special "Director General Instructions" for measuring control points for photogrametry and for topographic mapping as well. The ILUM is updated on regular basis according to additional and improved data. Using the official model, the orthometric heights are derived from GNSS measurements based on the Israeli CORS instead of on four (at least) bench-marks of higher order.

Following a description of ILUM and its updating process, the paper analyzes the accuracy of the derived orthometric height differences. The paper deals with the dilemma of handling heights based on different versions of the geoid model (the third version ILUM 1.2 was released in March 2008, and it is permitted to use each of the three versions). The advantages of deriving orthometric heights by OGUM rather than by other means, mainly due to the consistency of its results are demonstrated and discussed. Comparing derived orthometric height differences from new accurate GNSS measurements with the known 1st and 2nd order heights result in differences of few PPM, which are very good for 4th order bench-marks.

In order to learn more about the effectiveness of using permanent GNSS networks and OGUM as a substitute for orthometric control (as was suggested by Steinberg and Even-Tzur in Munich, 2006) in other countries, we made use also with the EGM08. The results are very good, demonstrating a great potential for developing countries and areas in which it is difficult to achieve an accurate geoid model.

From the Israeli surveyors' point of view, the new possibility to define orthometric heights is a great success. They can install the ILUM in the controller of the GNSS receiver, and they can measure orthometric heights in real time. In conclusion, the two years experience with the official geoid undulations model in Israel, fulfilled our expectations, and the idea is recommended to be used in other countries.

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1. INTRODUCTION

In 2005 the new datum of geodetic coordinates, IGD05, was introduced in Israel. It was suggested then that the national geodetic control network will be defined as 3D control, i.e. every control point shall have horizontal coordinates (longitude, latitude and plane coordinates) and ellipsoidal height (Steinberg, 2006). The network is based on the Permanent GNSS stations of Israel which constitute the higher order of the 3D control. As from May 2007 the Israeli surveyors can define orthometric heights of 4th and 5th order vertical control points and control points for photogrametric mapping, using GNSS measurements and an Official (statutory) Geoid Undulations Model (OGUM). The first version of the Israeli OGUM, named ILUM 1.0 - IsraeLi Undulations Model, was released by the Survey of Israel accompanied by special "Director General Instructions" for measuring those control points, and for topographic mapping as well. The ILUM is updated on regular basis according to additional and improved data. Using the official model, the orthometric heights are derived from GNSS measurements based on the Israeli CORS instead of on four (at least) bench-marks of higher order.

2. WHAT DO WE MEAN BY "OFFICIAL GEOID MODEL"?

2.1 What are the surveyors' needs for geoid model?

To be simple: surveyors need a geoid model in order to convert ellipsoidal heights, measured by GNSS, to orthometric heights. It is well understood that the higher the accuracy of the geoid undulation model is, the more accurate is the conversion of the ellipsoidal heights to orthometric heights. The surveyors are used to base their orthometric leveling on vertical control points (bench-marks) of higher order. When we replace the measuring method for achieving orthometric heights, from geometric or trigonometric leveling to GNSS methods, the surveyors still expect the heights to be consistent with the existing bench-marks system. In order to fulfill that expectation, the combined accuracy of the geoid model and the GNSS measurements should be at the same level of the bench-marks accuracy. The local accuracy of existing bench-marks for regular surveying works is in the centimeter level. Countrywide accuracy of those bench-marks is much lower (sub-decimeter to decimeter level) due to error propagation and systematic effects in long lines leveling. Today, the efforts to develop a geoid undulations model with an accuracy level of one centimeter over the entire country demand multiple resources, much like the efforts needed to achieve a dense leveling network with this accuracy. So, while the surveyors enjoy the GNSS technology for horizontal measurements, they still face a problem using it for vertical measurements. The question is whether we really need to stick with what we are used to, or we have another alternative.

2.2 The concept of an official geoid undulations model

An official geoid undulations model, as was first suggested by Steinberg and Even Tzur (2006), is the undulations model that was adopted by the national geodetic authority and was declared to be official. It is preferable to use the best available model and to fit it best to the existing bench-marks of the vertical orthometric control network. But, as was shown in the above mentioned paper and in paragraph 6 here, even a global geoid model is sufficient for most of the surveyors every day needs. The combination of official geoid undulations 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. It should be noticed that those 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 with its known (registered) height. However those derived official (or statutory, as we call it in Israel) orthometric heights are consistent with each other, and they produce a new system of vertical orthometric control network based on the ellipsoidal one. Of course, the utilization of this concept depends on the specific accuracy needs of the orthometric height-differences, the accuracy of the vertical ellipsoidal control network, and last but not least, the accuracy of the best available undulation model. There are certainly projects, for which a higher accuracy level of the orthometric control will be required. These projects do not require a nationwide accurate orthometric control system. Wherever the proposed idea is insufficient, one could use a local "Orthometric Island" as proposed by Steinberg and Papo (1996, 1999).

2.3 The advantages of using OGUM for deriving orthometric heights

2.3.1. Efficiency

These days, there is no need any more to describe the efficiency of GNSS leveling over geometric or trigonometric leveling of long lines and/or difficult topography. The Israeli survey regulations of 1998 enables measuring 4th and 5th order vertical control by means of GPS and local geoid based on (at least) four bench-marks of higher order. The OGUM enables using just one GNSS receiver (and the Israeli CORS service) and occupying just one known bench-mark, 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 any more for establishing and maintenance of 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.

2.3.2. 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). It cannot be achieved by GNSS measurements as well, unless we use a very accurate geoid model. When the measurements are based on GNSS and on the orthometric heights of bench-marks, as described in 2.3.1 above, the results depend on the bench-marks we choose and their location. If one surveyor bases his measurements on one set of bench-marks, and another surveyor who works nearby, bases his measurements on a different set of bench-marks (even one of them), they might get inconsistent heights even if their GNSS measurements are perfect. 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. When used relatively, the OGUM can be regarded as errorless. The nominal accuracy of the orthometric height differences depends solely on the accuracy of the GNSS measurements.

3. ILUM - THE ISRAELI OFFICIAL GEOID MODEL

3.1 ILUM 1.0

ILUM 1.0 is the name of the first version of the Israeli official geoid model, which was published on January 2007. The model is a mathematical surface formed by the points of the State leveling network. The details of its development are described in Tuchin (2006). The undulation surface was constructed on the basis of 684 bench-marks which were measured by GNSS. To interpolate geoid-ellipsoid separations, Kriging interpolation (optimal prediction) method is applied. The model is realized as a grid with the resolution 0.5x0.5 km. Any arbitrary value is inside any cell of the grid, it is calculated as a weighed average by 4 points of the cell.

Orthometric heights in the model are assumed to be free of error. To prove the validity of the model, a series of measurements of ellipsoidal heights was conducted in 2004/5 in different parts of the country. The measurements were taken on 96 bench-marks which were not included in the model. Orthometric heights estimated by means of the model demonstrated good agreement of the model with the orthometric heights datum. The obtained residuals almost always agree with the estimations computed by means of the model. The discrepancy did not exceed 14 cm and the average relative deviation value (deviation/ model expected accuracy) was 0.34.

Between the years 2004 – 2008 the Survey of Israel carried out a GNSS measurements campaign of the G2 geodetic network (Tuchin et al, 2009). Within the framework of this campaign the measurements were performed on the bench-marks of the State orthometric Vertical Control network (precise leveling) where it was possible. For these stations the values of orthometric heights were calculated using the ILUM 1.0. Up to now (Feb 2009) 706 points have been tested. 513 points out of this number were not included previously in the model and were measured for the first time. 193 points were part of the model and were re-measured. The orthometric heights predicted by the model were compared to the ones obtained through leveling which enabled upgrading and updating of the model.

3.2 Upgrading and Updating of the ILUM

Shortly after publishing ILUM 1.0 it had to be updated because the southern area close to Eilat was not covered by the model. Therefore, 45 points had to be added to the initial interpolation table in order to extend the model. During the short time when the model was in use it became obvious that it contained a number of errors that needed immediate correction. Thus, 21 values of undulation were replaced by the new ones obtained during the 2004-2008 campaign. 26 points were completely removed; 33 points were added where the data were missing. Among these 33 points 14 belong to stations of Active Permanent Network (APN), the Israeli CORS, whose orthometric heights were measured soon after the ILUM 1.0 was published. This modification of the model, named ILUM 1.1, was published in August 2007.
Model ILUM 1.2, published in February 2008, appeared when more stations were added in the Negev area and the Beit-Shean valley, where the measurements were not conducted previously. The differences of undulations values between the model versions exceeding 5 cm are given in orange color in Fig.1 and Fig.2.

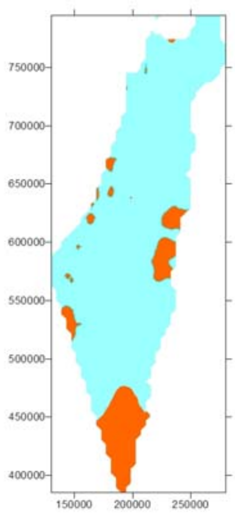


Fig.1. The regions (in orange) where the undulation values of the ILUM 1.1 and ILUM 1.0 differ more than 5cm.

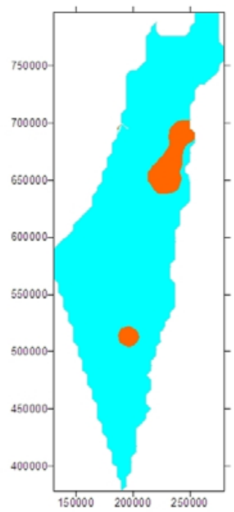


Fig.2 The regions (in orange) where the undulation values of the ILUM 1.2 and ILUM 1.1 differ more than 5cm.

ILUM 1.1 and ILUM 1.2 are the intermediate versions of the model which were constructed in such a way as not to differ significantly from the initial model ILUM 1.0. The next version of the model, ILUM 2.0 will be based on the new datum and measurements of the ellipsoidal heights, with the minimal inclusion of the old measurements. The previous measurements will be used in the areas where new ones were not conducted for various reasons.

4. ACCURACY OF THE DERIVED ORTHOMETRIC HEIGHTS

The model accuracy is determined by the underlying mathematical method, by the quality of the GNSS measurements and leveling, and by the density of the points on the territory of the country.

The statutory (official) model is free of errors by definition. However, for the effective use of the orthometric heights derived from the model it is desirable that the reference surface was as close to the physical surface as possible. The calculated heights should be as close to the leveled heights as possible. It is also essential to estimate the actual accuracy of calculation of the orthometric heights according to the model.

Kriging standard deviation is taken as the error value of the model and is realized in the model on the same grid of 0.5x 0.5 km as the undulation values. A number of numerical experiments were conducted to determine the variogram parameters in order to obtain close to real values of the interpolated function and interpolation errors. The ultimate accuracy evaluation becomes possible only if the residuals are available.

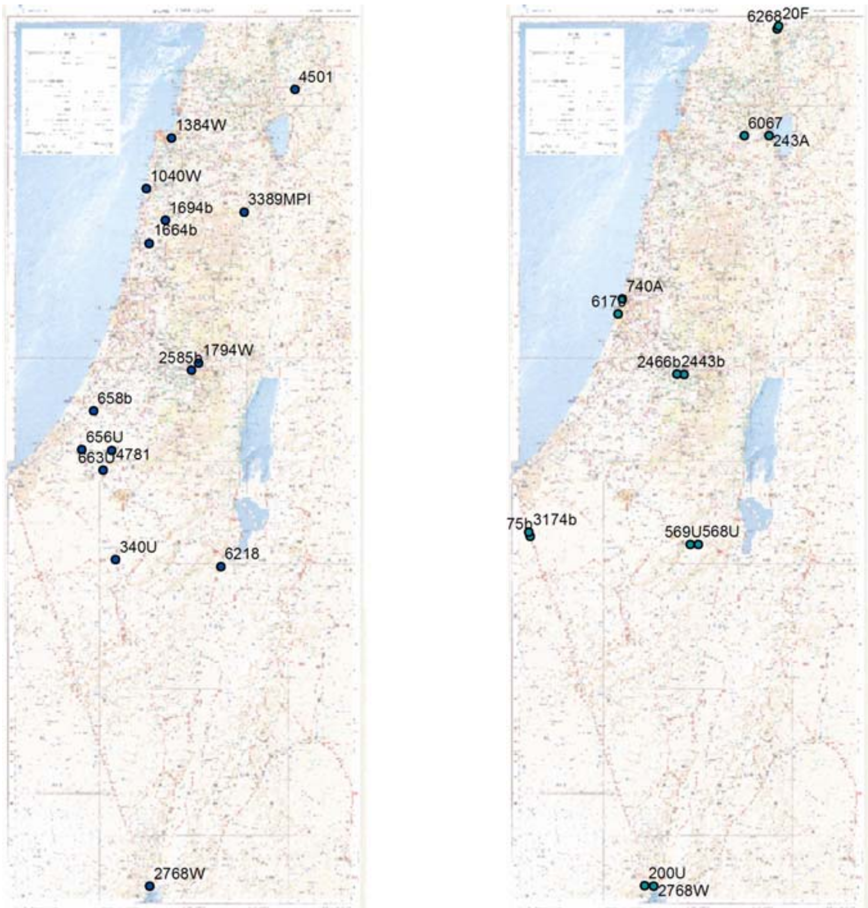
The measurement campaign of 2004-2008 provided abundant material for the model testing. Experience demonstrates that Kriging approximation has been a productive mathematical tool for the construction of the model. Predicted accuracy gives the correct results in most of the cases. It means that residuals are on the one hand less or equal to the predicted values, and on the other hand residuals and predicted accuracy are almost identical. In other words, the estimated error is moderately pessimistic. Table1 demonstrates residuals and predicted values of errors for several random points from different areas of the country. See the distribution of points in the Fig3a.

Station		ILUM 1.0		ILUM 1.1		ILUM 1.2	
NAME	Leveled height	Predicted Accuracy	ILUM 1.0 minus leveled	Predicted Accuracy	ILUM 1.1 minus leveled	Predicted Accuracy	ILUM 1.2 minus leveled
4501	339.362	0.074	-0.035	0.050	-0.019	0.050	-0.019
4781	235.497	0.051	-0.005	0.022	-0.010	0.022	-0.010
6218	-242.886	0.102	-0.125	0.022	-0.007	0.022	-0.007
1040W	12.490	0.054	-0.164	0.051	-0.115	0.051	-0.115
1384W	4.460	0.043	-0.113	0.024	-0.018	0.024	-0.018
1664b	19.793	0.064	-0.064	0.064	-0.067	0.028	-0.007
1794W	788.084	0.081	0.024	0.009	0.000	0.009	0.000
2585b	715.970	0.042	-0.022	0.017	0.000	0.017	0.000
3389MPI	429.445	0.078	-0.074	0.038	0.010	0.038	0.007
340U	405.502	0.030	-0.040	0.031	0.003	0.031	0.003
656U	125.138	0.064	-0.093	0.024	-0.002	0.024	-0.002
658b	112.677	0.071	0.046	0.027	0.007	0.027	0.007
663U	189.928	0.034	-0.010	0.029	-0.004	0.029	-0.004
MAML	683.533	0.036	-0.007	0.080	0.079	0.032	-0.007
2768W	63.051	0.043	0.105	0.039	0.025	0.039	0.025

Table1. The predicted accuracies and calculated residuals for some of the stations measured/re-measured during the 2004-2008 campaign. The names of the stations where predicted values are less than residuals are given in bold.

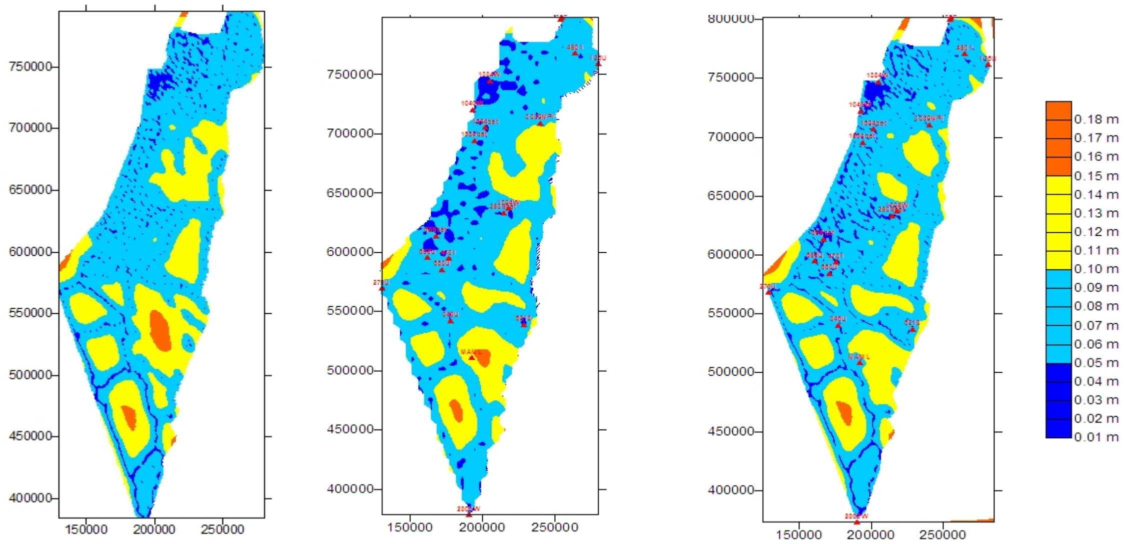
The station MAML (given in italic in the Table1) was the part of the ILUM 1.0 version. Later it was excluded from the ILUM 1.1 version. After re-measuring, it became evident that the exclusion was done by mistake and the point was returned into the ILUM 1.2 version.
Inclusion of stations 6218 and 656U into the version ILUM 1.1 increased the efficiency of the model.

In the areas of the high density of the points some of them can be eliminated and used for the accuracy estimation. Wherever the density is low, prediction remains the only means of the accuracy estimation.



a b

Fig3. Distribution of the bench-marks (a) and pairs of bench-marks (b).



a b c

Fig4. The accuracy of ILUM 1.0 (a), ILUM 1.1(b) and ILUM 1.2(c)

The validity of the model in calculations of the height differences is illustrated in Table 2 (b) by 7 pairs of bench-marks, from the North of the country to the South. See the distribution of the pairs of benchmarks in the Fig3b. In the third pair (Tel Aviv), for example, version ILUM 1.0 was less accurate than the two others; however, here, the height differences for all three versions coincide with those obtained by leveling. For the fourth pair (Jerusalem), all three versions of the model give the same values of orthometric heights, which almost coincide with the results of the leveling. It is obvious that the calculated height differences also coincide.

The error of 4 cm is considered reasonable for the distance of 7.6 km (ILUM 1.0 in Tel Aviv case).

Region	Name	orthometric height (m)			
		leveling	ILUM 1.0	ILUM 1.1	ILUM 1.2
Kiryat Shmona	20F	511.334	* * *	511.219	511.220
	6268	552.769	* * *	552.641	552.641
Tiberias	243A	-196.516	-196.482	-196.490	-196.490
	6067	287.590	287.660	287.670	287.670
Tel Aviv	740A	4.233	4.136	4.228	4.228
	6170	19.249	19.193	19.249	19.249
Jerusalem	2443b	638.821	638.830	638.825	638.825
	2466b	727.487	727.488	727.482	727.482
Nitzana	3175b	142.240	142.169	142.198	142.198
	3174b	128.812	128.730	128.767	128.767
Dimona	569U	391.575	391.662	391.579	391.579
	568U	403.041	403.105	403.011	403.011
Eilat	2768W	63.051	63.156	63.076	63.076
	200U	346.262	346.359	346.267	346.267

a

Region	from	to	distance	height difference (m)			
			(km)	leveling	ILUM1.0	ILUM1.1	ILUM1.2
Kiryat Shmona	20F	6268	1.4	41.435	* * *	41.422	41.421
Tiberias	243A	6067	11.8	484.106	484.142	484.160	484.160
Tel Aviv	740A	6170	7.6	15.016	15.057	15.021	15.021
Jerusalem	2443b	2466b	3.3	88.666	88.658	88.657	88.657
Nitzana	3174b	3175b	2.1	13.428	13.439	13.431	13.431
Dimona	569U	568U	4.0	11.466	11.443	11.432	11.432
Eilat	2768W	200U	4.4	283.211	283.203	283.191	283.191

b

Table 2. The orthometric heights values (a) and height differences (b) obtained using the first three versions of ILUM, in different parts of the country.

5. LIVING WITH HEIGHT SYSTEMS BASED ON DIFFERENT ILUM VERSIONS

5.1 Living with the "old" system

Before introducing the possibility to work with the OGUM, we had two kinds of bench-marks in the 4th and 5th order: those which were measured by geometric or trigonometric leveling, and those which were measured by GNSS based on four (at least) other bench-marks. Most of those bench-marks were measured in order to use as a base for large scale topographic mapping or for other engineering works in small areas. Inconsistency between those points could often reach 5 to 10 centimeters due to the basic accuracy of the stations height, the errors of the measurements, and some times due to datum inconsistency. In any case, for every work, the surveyor had to note the nominal height of the basic bench-marks he used.

5.2 What has been changed?

As was explained in 2.3.2 above, using the OGUM improves dramatically the consistency of the derived orthometric heights. However we face inconsistency when using a different version of OGUM. The solution for this dilemma is simply to note always the OGUM version that we use, just like the need to note the nominal height of the basic bench-marks as was needed before. The Survey of Israel keeps all the OGUM versions, and they are available for the surveyors.

6. COMPARISON WITH THE GLOBAL MODEL EGM08

In order to learn more about the effectiveness of using permanent GNSS networks and OGUM as a substitute for orthometric control (as was suggested by Steinberg and Even-Tzur in Munich, 2006) in other countries, we made use also with the EGM2008. In Steinberg and Even-Tzur (2006) the experiments in order to test the feasibility of using ILUM and the worldwide geopotential model GPM98B were described. The comparison of orthometric height differences obtained by GNSS measurements with the known orthometric differences was conducted. Here we give an example of calculation of the height differences using the

Global Model EGM08 WGS84 version. We took the 7 pairs of benchmarks: from ultimate North (Kiryat Shmona) to ultimate South (Eilat).They are the same benchmarks as in Table 2 in paragraph 4 above. The results of the calculation are represented in the Table 3.

Region	name	latitude	longitude	undulation	h	H		leveled minus EGM08
						EGM08	leveled	
Kiryat Shmona	20F	33.28250	35.57806	23.950	534.655	510.705	511.334	0.629
	6268	33.27111	35.57083	23.833	576.001	552.168	552.769	0.601
Tiberias	243A	32.80722	35.52722	21.625	-175.437	-197.062	-196.516	0.546
	6067	32.80861	35.40056	21.690	308.979	287.289	287.590	0.301
Tel Aviv	740A	32.10278	34.78333	18.816	22.787	3.971	4.233	0.262
	6170	32.03667	34.76111	18.672	37.703	19.031	19.249	0.218
Jerusalem	2443b	31.77778	35.05833	19.973	658.778	638.805	638.821	0.016
	2466b	31.77611	35.09444	20.030	747.558	727.528	727.487	-0.041
Nitzana	3175b	31.07030	34.32330	17.175	159.241	142.066	142.240	0.174
	3174b	31.08778	34.29250	17.116	145.807	128.691	128.812	0.121
Dimona	569U	31.03750	35.12528	17.706	409.250	391.544	391.575	0.031
	568U	31.03917	35.02861	17.477	420.542	403.065	403.041	-0.024
Eilat	2768W	29.55861	34.94806	17.146	79.793	62.647	63.051	0.404
	200U	29.56028	34.90306	17.275	363.225	345.950	346.262	0.312

a

Region	benchmarks		distance (km)	height difference		leveled minus EGM08	
	from	to		EGM08	leveled	delta (mm)	ppm
Kiryat Shmona	20F	6268	1.4	41.463	41.435	-28	20.0
Tiberias	243A	6067	11.8	484.351	484.106	-245	20.8
Tel Aviv	740A	6170	7.6	15.060	15.016	-44	5.8
Jerusalem	2443b	2466b	3.3	88.723	88.666	-57	17.3
Nitzana	3174b	3175b	2.1	13.375	13.428	-53	25.2
Dimona	569U	568U	4.0	11.521	11.466	-55	13.8
Eilat	2768W	200U	4.4	283.303	283.211	-92	20.9

b

Table 3. The orthometric heights values (a) and height differences (b) obtained using the Global Model EGM08 WGS84 version for 7 pairs of benchmarks in the different parts of the country.

When comparing with Steinberg and Even-Tzur (2006) we can see that the new EGM08 global model is more accurate (at least in Israel) than GPM98B. It gives almost as good results as the ILUM if used for heights differences calculation. Although the "absolute" heights differ up to 63 cm, the relative differences between the leveled and the deduced height differences are few parts per million. It means that those height differences are proper for most of the surveyor's purposes. Those results are very good, demonstrating a great potential for developing countries and areas in which it is difficult to achieve an accurate geoid model.

Better results, mainly for the "absolute heights", can be achieved by fitting the global model to the national precise leveling network.

7. CONCLUSION

There is nothing new with getting orthometric heights by means of GNSS measurements and geoid undulations model. Intensive utilization of GNSS for geodetic and engineering applications necessitates a quick development of geoid undulations models. Today, the efforts to develop a geoid undulations model with an accuracy level of one centimeter over the entire country demand multiple resources, much like the efforts needed to achieve a dense leveling network with this accuracy. Few developed countries have succeeded to develop an accurate geoid model, based on gravimetric geoid combined with GPS/leveling measurements. Many other countries, including Israel, continue with the efforts to achieve this goal. The Survey of Israel decided not to wait for the "perfect" geoid undulations model. Instead of waiting, we adopted the best available model and declared it as the official (statutory) one. Updating and upgrading of ILUM, the Israeli official undulations model is continued, producing a new version with every change. Our two years experience with the three versions already released is good and it fulfilled our expectations. From the Israeli surveyors' point of view, the new possibility to define orthometric heights is a great success. They can install the ILUM in the controller of the GNSS receiver, and they can easily measure orthometric heights even in real time. As is shown in this paper, although the absolute accuracy of our geoid model is not high, the derived orthometric height differences are very good. It is also shown in the paper that similar good accuracy of height differences can be achieved by using the new EGM08 global model, although it's absolute accuracy in Israel is worse than 20 cm (r.m.s). The advantages of using the concept of OGUM (efficiency and consistency) are discussed in the paper. We recommend using that concept in other countries, especially in undeveloped or rough areas where establishing a classic vertical orthometric control network is difficult or even impossible.

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BIOGRAPHICAL NOTES

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Israel’s delegate to commission 5 of FIG.
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