Permanent GNSS Networks and Official Geoid Undulations Model as a Substitute for Orthometric Control

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Key words: vertical orthometric control, vertical ellipsoidal control, geoid-undulations model.

SUMMARY

For many years Vertical Geodetic Control was the nickname of a framework of control points (benchmarks) having Orthometric Heights achieved by precise leveling. Precise leveling is indeed a highly accurate measuring method, but it is notoriously time-consuming, very expensive in terms of manpower and extremely cumbersome in having to cover literally step-by-step the space between every pair of end-points. Motorized leveling has solved part of the slow–rate problem, but the price remains high, and still a lengthy meandering is needed in order to cross mountains, wide rivers or lakes. There are areas where precise leveling is practically impossible. The objective of any primary leveling system is to provide a framework on which topographers and engineers can base and adjust their heights with expectation that, except quite locally, its errors will be less than theirs. Another important objective of the primary leveling system was to monitor vertical tectonic changes over a wide area. This objective is achieved already much better by GNSS measurements.

We suggest that the first objective of a primary leveling system can be also achieved much easier with reasonable accuracy on nationwide basis, by a combination of Ellipsoidal Vertical Control (through GNSS measurements) and Official Geoid Undulations Model. Elaboration of this idea is the heart of the paper.

In order to verify our suggestion we conducted a research in Israel. We tested two kinds of tentative Official Models: one is the World Wide Geopotential Model GPM98B. The other is a local Israeli model computed by the SOI based on about 750 benchmarks of the precise leveling network, whose Ellipsoidal heights were deducted from GPS measurements. We compared the "synthetic" orthometric height differences (GPS measurements + computed undulation) with the known orthometric differences. The ellipsoidal height differences were measured directly by GPS and also by using post-processing VRS (Virtual Reference Station) service of the permanent GPS stations of Israel. The paper presents the results of those experiments. It verifies the capability of the suggested technique to define Seamless Orthometric Vertical Control, adequate for most purposes, by a low-cost and fast procedure. This technique is especially important in difficult terrain, where precise leveling is practically impossible, and therefore it can be of great help anywhere around the world.

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1. INTRODUCTION

Bomford (1980) states: "The object of any primary leveling system is to provide a framework on which topographers and engineers can base and adjust their heights with the expectation that, except quite locally, its errors will be less than theirs". Another important objective of primary leveling system was (according to Bomford) to monitor vertical tectonic changes over a wide area. The use of the expression "Leveling System" as a nickname for Vertical Control was accepted naturally - since prior to the GPS era there was no alternative to precise leveling as a tool to achieve the mentioned objectives. Now, we already know that GNSS measurements are quite more effective for monitoring vertical tectonic changes over a wide area. We are exposed more and more to the ideas of Vertical Ellipsoidal Control, actually 3D Geodetic Control, based on Permanent GNSS Networks (called also CORS - Continuous Operating Reference Stations), see e.g. Steinberg and Papo (1996, 1998, 1999), Meyer et al., 2004, Wonnacott 2005, etc. The advantage of GNSS Networks over precise leveling is quite obvious already. A major question still exists however whether Ellipsoidal Height Control Networks can replace the Orthometric ones. The authors of this paper are convinced that there is no more room for new country-wide Vertical Geodetic Control based on precise leveling. However we are acquainted to the needs for orthometric heights and for Orthometric Control Networks.

The well-known connection between ellipsoidal (h) and orthometric (H) heights is given by: $h = H + N$, where N is the geoid undulation at that point. Enormous efforts are undertaken around the world in order to achieve cm-level-geoid-models with which one can get orthometric heights by GPS measurements. The usual attitude is that you can't use GPS measurements in order to have cm-level-orthometric-heights, unless you have a higher-accuracy geoid model, even on local basis. We suggest that we do not have to wait for the 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 Official Geoid Undulations Model - OGUM.

2. VERTICAL ORTHOMETRIC CONTROL

The classic Vertical control is composed of several hierarchical networks which follows the principle "from the whole to the part". The primary Vertical Orthometric Control Network contains loops of first order precise leveling of some hundreds of kilometers in length. The accuracy of precise leveling (high precision leveling) should be at the millimeter- level per kilometer (Bomford, 1980). The other subnets in the network are densifications of the primary one, according to the needs - with decreasing accuracy. The Survey of Israel has managed to supply a first/second-order network (with loops misclosure of less than $3\,\mathrm{mm}/\sqrt{\mathrm{km}}$) all over the country, and a third-order one (line misclosure less than $15\,\mathrm{mm}/\sqrt{\mathrm{km}}$) in the northern (densely populated) part of the country. It is worth to note, that it is reasonable to establish a third-order network, only in the densely populated area. We shall not describe here the well-known difficulties encountered in precise leveling. It is enough to note, for example, that even with the most advanced technology of motorized leveling it took some 25 years to accomplish the first-order network in Sweden (Eriksson et al., 2002). Due to these difficulties, and sometimes the lack of patience to wait for the official results- it is actually impossible to get heights for lower-order networks with absolute accuracy (relative to the higher-order) better than 5-10 cm. It is not surprising to find discrepancies of this order and bigger, between neighboring municipalities. Inconsistencies in the measured heights for lower-order control points is quite built into the system of leveling networks, as long as those points are separate, and not a part of a dense, well-maintained network of, say, less than $2 \times 2\,\mathrm{km}$.

3. VERTICAL ELLIPSOIDAL CONTROL

Ellipsoidal Control is the imminent replacement for the orthometric control. The Survey of Israel already decided to move towards 3D Geodetic Control, based on the Israeli Permanent GPS Network (Steinberg and Even-Tzur, 2005). It will be within the framework of New Survey Regulations that are being prepared now (Steinberg, 2006). Generally speaking, Vertical Ellipsoidal (Geometric) Control should be based on Permanent GNSS Network as one part of the 3D Geodetic Control. The Permanent GNSS Network is the first order of the 3D Control. By its nature (operating cost), Permanent Stations are quite far from each other. Due to the dependency of GPS accuracy on the length of the baselines (which can be compensated by longer measuring times), especially in the vertical direction, it is recommended to densify the first-order control by more orders, according to actual needs. This densification should be accomplished, of course, by GPS measurements. In Israel, we decided that the accuracy of the Second-Order network will be 1cm (2σ), and that of the third-order, 2cm, relative to the nominal heights of the Permanent GPS stations.

4. GEOID UNDULATIONS MODEL OVER ISRAEL

A Geoid-Undulations model constitutes an important part of modern geodetic infrastructure. Undulations model enables the conversion of ellipsoidal heights to orthometric heights. Intensive utilization of GPS for geodetic and engineering applications necessitates a quick development of an undulations model. An accurate geoid of the State of Israel does not exist, except for a small area (about 600 square kilometers) on and around the Carmel Mountains in the north part of Israel (Sharni and Papo, 2000).

In the last few years, the Survey of Israel made relative GPS measurements between points of the primary vertical orthometric control network in Israel. These provided WGS84-ellipsoidal heights at about 750 points that cover most of Israel. Subtracting orthometric heights from

WGS84 ellipsoidal heights at those points yields discrete estimates of the separation between the local Israel vertical datum and the WGS84 ellipsoid, which can be interpolated to form a geometrically-derived geoid model. Kriging interpolation was used by SOI to compute a local Israeli geoid-undulations model, where over most of the country the accuracy of the model is better than 10cm (Tuchin, 2006).

GPM98B is a global geopotential model, which approximates the Earth's gravity field and computes geoid heights in terms of spherical harmonics to degree 1800 (Wenzel, 1998). GPM98B contains few gravity data from Israel; therefore it should fit Israel better than any other global geopotential model. Earlier experiments of using the GPM98B in Israel showed local accuracy of about 10-20cm, and differences of up to about +2 meters in the north to -2 meters in the south (between the known orthometric heights and those obtained from the model).

5. THE IDEA OF OFFICIAL GEOID UNDULATIONS MODEL (OGUM) AS A SUBTITUTE FOR ORTHOMETRIC CONTROL

The efforts to improve the geoid-undulations model to accuracy of one centimeter-level in any place over a whole country, seems to be endless - just like the efforts to achieve leveling network of that kind. In addition to "Bomford's" objective of obtaining a leveling network, another very important objective of the network, is to bring about consistent and identical heights to all points (within the desired accuracy) obtained by every surveyor. As was mentioned in chapter 2, this goal is practically impossible, using the classic leveling networks. It is also impossible, if we have to wait for completing a geoid-model that will be accurate everywhere. In order to overcome this problem, we suggest declaring the best available Geoid Undulations Model as an Official Model for a certain time. This Official Model can be replaced from time to time by an improved model. We should, of course, maintain the documentation for each version, as a change of datum. The combination of OGUM with vertical Ellipsoidal Control based on CORS, produces a practical countrywide network of Orthometric Height Control, appropriate for most of the geodetic/surveying needs. Our idea is not a "magic panacea" for everything everywhere. Utilizing this idea depends of course, on the specific needs for the accuracy of the orthometric heights, the accuracy of the Vertical Ellipsoidal Control Network, and last but not least, the accuracy of the best-available undulations model. There are certainly projects, for which we need higher accuracy of the Orthometric Control. Those projects do not need a nationwide accurate orthometric control system. Wherever the proposed idea is not sufficient, one can use local "orthometric islands" as proposed in Steinberg and Papo 1999. However, any Orthometric Island System should be always regarded as a secondary control, which "draws" its datum from the national ellipsoidal control (there may be an overlap between some orthometirc islands). Within the scope of the New Survey Regulations for Israel (Steinberg 2006), it was decided to adopt the proposed idea. The OGUM will be a local Israeli model, as described in chapter 4. An effort will be made to improve this model by gravity measurements and computations, prior to the publication of the New Regulations.

In order to verify our suggestion, and to estimate the accuracy of the obtained orthometric height differences, we conducted a research in Israel. The world-wide geopotential model GPM98B was tested, in addition to the "Israeli" one. The research is described in the next chapter.

6. THE OFFICIAL UNDULATIONS MODEL EXPERIMENTS

The goal of the experiment was to examine the accuracy of orthometric height differences, based on GPS measurements and OGUM in different locations in Israel. Four adjacent orthometric control points (benchmarks), with known orthometric heights, were measured simultaneously by GPS. The duration of the measurement-session was 40 minutes. The orthometric height differences between the benchmarks (six differences) are presented, and the ellipsoidal height differences were processed from the GPS measurements. By using OGUM, we can calculate the undulation differences between the points. Those differences, together with the measured ellipsoidal height differences, yield computed orthometric height differences. Comparison between the known orthometric height differences and those obtained by GPS measurements, allow evaluation of the accuracy of orthometric height differences based on GPS measurements and OGUM. Two alternative options for OGUM were tested: a local Israeli model produced by SOI, and the aforementioned global model GPM98B. The estimated relative accuracy of the known orthometric height differences between the benchmarks, as well as the measured ellipsoidal height differences, is about 1-2cm.

In addition, the GPS data from each point was processed relative to VRS (Virtual Reference Station) data. The ellipsoidal height differences between points were computed based on the processed ellipsoidal height of each point. Those differences from the calculated undulation differences between the points were also used to obtain computed orthometric height differences.

The experiment was held in eight locations in Israel, from Eilat in the south to Kiryat-Shmona in the north (see fig. 1). In table 1 we present the results, by showing the root mean square (rms) and the mean ppm value of differences between the known orthometric height differences and the orthometric height differences obtained based on GPS measurements and the two alternatives for the OGUM in each area.

Figure 1 – Eight locations (red square) where the OGUM experiment was held in Israel. The numbers denote the place's name as appears in table 1.

Table 1 – The rms and the mean ppm value of the differences between the known orthometric height differences and the orthometric height differences obtained by GPS measurements, and the two alternatives for the OGUM in each area. In brackets is the maximum difference (absolute value).

			SOI Undulations Model		**GPM98B**	
Place	Min. distance [km]	Max. distance [km]	RMS (max. difference) [cm]	Mean (max. difference) [ppm]	RMS (max. difference) [cm]	Mean (max. difference) [ppm]
1. Eilat	1.4	4.5	5.0 (6.8)	14 (23)	18.5 (35.8)	61 (105)
2. Hazeva	2.9	5.6	5.2 (8.1)	11 (20)	6.7 (13.5)	15 (26)
3. Nitzana	1.8	4.5	3.9 (9.3)	11 (50)	3.2 (5.3)	12 (17)
4. Mizpe-Ramon	0.6	3.3	1.0 (1.6)	8 (24)	3.1 (7.2)	25 (46)
5. Beer-Sheva	1.3	4.8	3.8 (8.7)	10 (27)	1.4 (4.2)	8 (18)
6. Jerusalem	1.0	4.1	2.4 (3.5)	9 (16)	1.2 (2.6)	5 (10)
7. Tel-Aviv	1.8	7.6	1.9 (3.1)	4 (7)	1.7 (2.8)	3 (6)
8. Kiryat-Shmona	0.3	1.8	4.0 (9.0)	27 (57)	2.5 (4.5)	20 (48)

7. DISCUSSION

In most of the surveying works, we actually rarely need accuracy better than 1cm in orthometric height difference between two points 100 meters far from each other. This means a relative accuracy of 100ppm. On the other hand, an accuracy of 10cm between two control points 1km apart is not satisfactory, due to the nature of leveling~~,~~ - in which one might make a gross error of 10cm in his work, but still will not find any abnormal misclosure, once he conducted one-way leveling. That is why, for a reasonable orthometric control of a fourth-order, we actually need a height-differences accuracy of about 25mm for benchmarks 1km apart, or 25ppm, in other words. In all our experiments with the temporary Israeli OGUM, we achieved this goal. As a matter of fact, this goal was achieved also using the GPM98B model, except for one area (Eilat, on the northern edge of the Red Sea), where the topography is extremely rugged.

Similar results were obtained by using ellipsoidal height differences, which were measured directly by GPS, or by using post-processing VRS.

These results demonstrate the capability of our idea, for most of the engineering works. It is especially adequate for orthometric control points for large scale topographic mapping (either by Photogrammetry, EDM or GPS). We do not suggest using this idea wherever a dense and stable leveling network of accurate and consistent control points already exists. In Israel, it will be permitted to use existing local networks (mainly municipal~~s~~) as well as "governmental" (SOI) old benchmarks. But, at the same area, it will be legal to use the OGUM and deduce the orthometric heights from GPS measurements tied to the Ellipsoidal Vertical Control that we shall maintain. It will be essential to note the datum of every work.

We can see a special benefit of using our idea in undeveloped areas and countries, were establishing the classic leveling network is practically "mission impossible". The big advantage of the OGUM is its consistency. One can regard it as "errorless" (even though, absolutely, it obviously has an implied error; see below). The nominal accuracy of the orthometric height at a certain measured point is dependant on the accuracy of the GPS measurements only. This "errorless model" is true obviously as long as we do not establish new control points by leveling based on GPS-borne benchmarks. As professional surveyors it is our duty to understand the applicability of the OGUM to our needs. The main issue is the accuracy of the chosen model. As mentioned in chap. 5, we suggest choosing the best available model. Since we are dealing with a nationwide model, the preferred model is one which fits best the existing benchmarks by direct GPS measurements at certain benchmarks. A global model like GPM98B can be used in case that nothing better is available, but in this case we strongly suggest fitting it best to as many benchmarks as possible. We found differences of up to plus (in the north) and minus (in the south) 1.9 meters, between the Israeli model and the GPM98B, over a distance of about 400 km. As the general rules of geodesy mandate, it is important to know the accuracy of the chosen model, and to use it accordingly.

8. CONCLUSION

Following the idea of Vertical Ellipsoidal Control, as a part of 3D Geodetic Control based on CORS, and understanding that some kind of National Orthometric Control is still necessary, we believe that the suggested idea of OGUM is a proper substitute to the National Leveling Network. The users of this idea can gain a lot, as described in the paper; but they must be aware to its limitations. To those who wish to learn more about our entire concept of Ellipsoidal Control and Orthometric Islands, we refer to Steinberg and Papo 1999. The heights which will be attained by using GPS measurements and OGUM will create such nationwide Orthometric Island. The idea is especially recommended for undeveloped areas, far from existing benchmarks. A certain benchmark that its orthometric height was deduced using this technique, can obviously determine a datum for a local Orthometric Island, where higher accuracy is needed.

Within the scope of measuring orthometric heights based on GNSS measurements, we would like to propose another idea that might be helpful: In order to improve the accuracy of measuring the height above a benchmark, we urge instrument developers to enable GNSS antennas to be mounted on levels. It can be built-in in new levels, and can be adapted to existing levels by special adaptors (like it was done in the first years of EDM systems). This arrangement will also help prevent gross errors in measuring the antenna's height, and will enable direct measurements to wall-benchmarks (see figure 2) and others which are not suitable for occupation or for GPS measurements. The convenient adaptation of GPS antenna to the level, can also contribute to improving the Geoid Model along leveling lines.

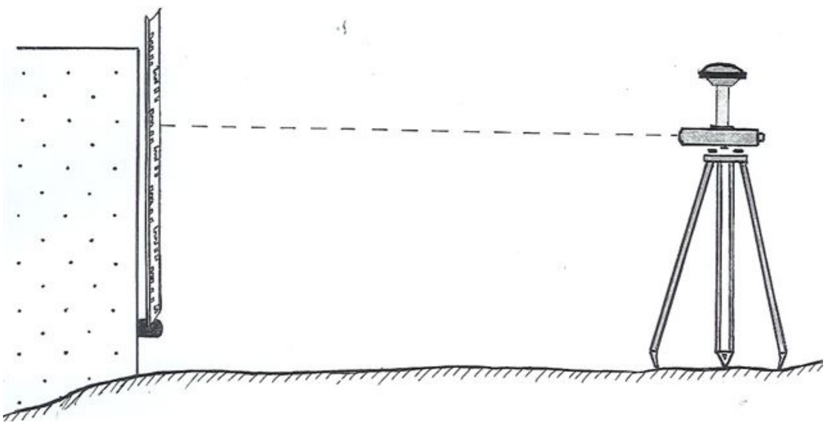

Figure 2 - GNSS antenna mounted on a level observing staff on a wall-benchmark

The described experiments that we conducted in Israel in order to verify the potential of the proposed idea for using OGUM, proved its efficiency for most of the surveyors' needs. We hope that the described ideas will contribute mainly to those countries which can not afford the luxury of establishing and maintaining dense leveling networks. We are actually convinced that this is the case even in the most developed countries.

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I would also like to give thanks, with great appreciation, to Professor Jean-Marie Becker from Sweden, the former chair of commission 5, who encouraged me to present our ideas about the Future of Vertical Geodetic Control, at the symposium that he conducted in Gavle, Sweden on March 1999 ("Geodesy and Surveying in the Future, The Importance of Heights") that was organized on the occasion of the 25 anniversary to the motorized leveling.

REFERENCES

Bomford G., 1980. Geodesy. 4th edition, Clarendon Press, Oxford.
Eriksson P.O., Lilje M., Olsson P.A. and Svensson R., 2002 Validation and Preparation of Data for the Computation of a New Height System in Sweden. FIG Congress 2002, 19-26 April, Washington, DC, USA.
Meyer T.H., Roman D.R., Zilkoski D.B., 2004. What does height really mean? Part 1: Introduction. Surveying and Land Information Science, 64(4):223-233.
Sharni D. and Papo H., 2000. The Carmel Mountains Precise Geoid. “Quo Vadis - International Conference”, FIG Working Week 2000, 21-26 May, Prague.
Steinberg G., 2006. New Survey Regulations for Israel. XXIII International FIG Congress, 8-13 October 2006, Munich, Germany.
Steinberg G. and Even-Tzur G., 2005. Establishment of National Grid Based on Permanent GPS Stations in Israel. Surveying and Land Information Science, 65(1):47-52.
Steinberg G. and Papo H., 1999. The Future of Vertical Geodetic Control. Geodesy and Surveying in the Future, The Importance of Heights, March 15-17 1999, Gavle, Sweden.
Steinberg G. and Papo H., 1998. Ellipsoidal heights: The future of Vertical Geodetic Control. GPS world, 9(2):41-43.
Steinberg G. and Papo H., 1996. Vertical Geodetic Control of the Future. Geoinformatics ’96, Wuhan International Symposium, Wuhan, China.
Tuchin Y., 2006. Development of the Geoid-Ellipsoid Separations Model in Israel. XXIII International FIG Congress, 8-13 October 2006, Munich, Germany.
Wenzel, H.G., 1998. Ultra-high degree geopotential models GPM98A, B, and C to degree 1800. Proceedings of the joint meeting of the International Gravity Commission and International Geoid Commission, September 7-12, Trieste, Italy.
Wonnacott R., 2005. AFREF - Background and Progress towards a Unified Reference System for Africa. FIG Working Week 2005, April 16-21, Cairo, Egypt.

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Steinberg G. and Even-Tzur G., 2005, Establishment of National Grid Based on Permanent GPS Stations in Israel. Surveying and Land Information Science, 65(1):47-52

Steinberg G, 2001, Implementation of Legal Digital Cadastre in Israel. FIG WW Seoul 2001.

Steinberg G, and Papo H, 1999, The Future of Vertical Geodetic Control. In Proceedings of geodesy and surveying in the future, The Importance of Heights", pp.313-320, Gavle, Sweden, March 1999.

Steinberg G, and Papo H, 1998, Ellipsoidal Heights: The Future of Vertical Geodetic Control. GPS World, February 1998.

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