REAL-TIME SATELLITE LEVELLING OF LINEAR STRUCTURES

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SUMMARY

Providing the users in Poland with the ASG-EUPOS system in the mid-2008 has significantly influenced the popularization of satellite survey techniques, especially real-time surveys. Real-time satellite levelling has become a very effective way of determining normal heights of points. The paper discusses the problem of satellite levelling carried out for linear structures using, the most popular among the users, Real Time Network surveys referring to the ASG-EUPOS system, as well as RTK GPS surveys carried out in relation to a physical reference station. The conclusions regarding the possibility of applying satellite levelling in real time on railway areas were based on the surveys of several sections of a railway line, for which geodetic precise leveling was also conducted.

1. INTRODUCTION

An increased interest in satellite levelling is mainly due to making the ASG-EUPOS system available to users in June 2008, which theoretically functions on the territory of the entire country, and practically in the area covered by the range of the GPRS service of GSM network operators in Poland. Thanks to the ASG-EUPOS network system, the user needs a single GPS receiver to carry out a survey, and the NAWGEO data stream enables to determine the position of points in real time, which is a strong competition for direct levelling due to the greater effectiveness of such a survey. Although the surveyors' enthusiasm associated with the use of the NAWGEO real-time service of the ASG-EUPOS network system was cooled by frequent problems with its availability, still the surveys in relation to reference station of the ASG-EUPOS network are becoming more and more common.

In addition, a model of a quasi-geoid "Levelling Geoid 2001" was developed and distributed as an Appendix to the Technical Instruction G-2, so that each user has a free access to an easy-to-use model. Also in a GPS receiver, a model of the quasi-geoid can be installed.

The draft revision of the Council of Ministers Regulation of 10th January 2008 [GUGiK, 2008], which was supposed to replace the Council of Ministers Regulation of 8th August 2000 on the national spatial reference system [GUGiK, 2000], there are records legally sanctioning satellite levelling.

The subject of this study is real-time satellite levelling. The aspect of real-time of satellite levelling may be looked into for the following two cases:

- the normal height of a point is determined directly in the field by a GPS receiver, which requires the availability of the quasi-geoid and interpolating algorithm in the satellite receiver,
- the ellipsoidal height is determined in the field by a GPS receiver and the calculation of the normal height of a point on its basis is carried out with the use of a computer.

The essence of the concept is therefore the calculation of the normal height of a point on the basis of the ellipsoidal height of a point in real time. The difference in accuracy between determining the height from a static measurement and in real time is important, especially in the case of using the NAWGEO service of the ASG-EUPOS system.

The accuracy of real-time satellite levelling, which determines the possibility of its practical use, is affected by the accuracy of determining the ellipsoidal height from the real-time kinematic surveys by a satellite receiver, as well as the accuracy of the quasi-geoid model. In the case of creating a local model of the quasi-geoid (LMQ) the selection of an appropriate algorithm for calculating normal heights may be of some importance.

The study presents the question of real-time satellite levelling in terms of surveys carried out in railway areas, whose important characteristic features are their linear shape and high incidence of obstructing the horizon for satellite signals. The conclusions were formulated on the grounds of the results of test surveys carried out on three sections of the railway line Kraków-Medyka, of a total length of about 8.3 km. The subject of the analysis was the accuracy of determining the normal height of the points from the RTK GPS surveys, as well as RTN (Real Time Networks) surveys.

2. DETERMINING THE NORMAL HEIGHTS FROM REAL-TIME SATELLITE LEVELLING

The normal heights system is legally binding in Poland under the Council of Ministers Regulation of 8th August 2000 on the national spatial reference system [GUGiK, 2000]. The draft revision of the Council of Ministers Regulation of 10th January 2008 [GUGiK, 2008] in Appendix 2 sets out the possibility of determining the normal heights through the use of satellite surveys taking into account the height of the quasi-geoid above the reference ellipsoid. Appendix 3 indicates the validity of the quasi-geoid model marked with the symbol Quasigeoid 2001. The Appendix to the Technical Instruction G-2 of 2001 [GUGiK, 2001] uses the term "Levelling Geoid 2001". The model "Levelling Geoid 2001" was created as the result of fitting of the model of a gravimetric quasi-geoid quasi97b into the satellite/levelling quasi-geoid QGEOID'PL01 [Pażus et al, 2002].

The draft revision of the Council of Ministers Regulation allows for redefining the quasi-geoid model on the territory of Poland in the case of developing a new model of a gravimetric quasi-geoid of an improved quality, or in the case of a redefinition of the height system in the country. Within the scope of the project [Kryński, 2007], the models of the quasi-geoid quasi05c_corr and "2005" have been developed, based on gravimetric, satellite/levelling and topographic data. According to the evaluation included in the aforementioned study, both models qualitatively surpass the model "Levelling Geoid 2001", whose accuracy in that study was estimated at 1.8 cm.

Determination of the normal height of the points (H) on the basis of the quasi-geoid undulation and satellite survey is one of the easiest ways, which is implemented according to the following formula:

$$H = h - \zeta \tag{1}$$

The ETRF89 (European Terrestrial Reference Frame) is the terrestrial reference system on the territory of Poland, together with the geocentric reference ellipsoid GRS80, allowing it to be expressed in surveying coordinates. However, in terms of geometry, the ellipsoid GRS-80 is virtually identical with the ellipsoid WGS84 (a difference of 0.1mm in the semi-axis of both ellipsoids). The transfer of the terrestrial reference system ETRF89 onto the territory of Poland is conducted through a network of reference stations of the ASG-EUPOS system and the points of national geodetic control network EUREF-POL and POLREF through GNSS satellite observations (Global Navigation Satellite Systems). However, in the case of the "Levelling Geoid 2001" we are dealing with the ITRF96 system. In the case of satellite levelling, a correction must therefore be introduced due to different reference systems. The normal height in the Kronsztadt 86 system, including appropriate corrections which can be computed from the formulas contained in [Boucher, Altamimi, 2008], as well as with the parameters given in [Pażus et al, 2002], is defined by the following formula [Banasik, Uznański]:

$$H^{Kronsztadt\,86} = h^{ETRF\,89} - (\zeta^{2001} + \Delta\zeta^{ETRF\,89-ITRF\,96}) \qquad (2)$$

where: h^{ETRF89} – ellipsoidal height from the GPS survey,

ζ^{2001} – undulation from the model "Levelling Geoid 2001",

$\Delta\zeta^{ITRF96\text{-}ETRF89}$ – ITRF96-ETRF89 - correction to the undulation resulting from the differences between the ETRF89 and ITRF96 systems.

The model of the quasi-geoid "Levelling Geoid 2001" is a discrete model represented by a grid of points with the resolution: …B = 1 ', .. L = 1'. Therefore, an interpolation of undulations of the quasi-geoid from the ellipsoid is needed (). Bilinear interpolation was used, implemented by a program set out in the Appendix to the Technical Instruction G-2 [GUGiK, 2001] according to the formula:

$$\zeta = (\delta B,\delta L) = a + b\delta B + c\delta L + d\delta B\delta L \qquad (3)$$

where: $a = \zeta_1$

$b = -\ (\zeta_1 - \zeta_2)/\Delta B$

$c = -\ (\zeta_1 - \zeta_4)/\Delta L$

$d = (\zeta_1 - \zeta_2 + \zeta_3 - \zeta_4)/\Delta B\Delta L$

Distances between the points at which the undulations of the quasi-geoid from the ellipsoid for the model "Levelling Geoid 2001" were known, amounted to tens of kilometers. In the local quasi-geoid model, the distances between the points of adjustment will typically amount to a few kilometers. Additionally, in the LMQ in the algorithm of determining normal heights, the specificity of an object can be taken into account and be matched to its character. For this purpose, straight sections should be rationed out in the structure, for which a simplified linear interpolation and curvilinear parts requiring the use of surface interpolation can be applied. Linear interpolation can be used for a narrow belt of the structure, whose width (s) can be calculated assuming the local slope of the quasi-geoid to the ellipsoid, and a permissible error in determining the undulation of the quasi-geoid () according to the following formula [Banasik, Uznański, 2010]:

$$s = \frac{\Delta\zeta}{\Theta} = \frac{\Delta H - \Delta h}{\Theta} \tag{4}$$

For areas with a radius of several kilometers, which for linear structures is quite a sufficient range, the interpolation of undulations of the quasi-geoid from the ellipsoid, a polynomial of the 1st degree can be used:

$$\zeta(X,Y) = a_0 + a_1X + a_2Y \tag{5}$$

3. TEST SECTIONS AND SURVEYS

Verification of the possibility to use real-time satellite surveys to determine the normal heights of the points of linear structures were carried out on three sections, a few kilometers in length each, of the railway Kraków - Tarnów (Fig. 1). This line was selected because in 2008 new benchmarks of the 1st class were installed there, together with surveying and determining new heights for all vertical control network points.

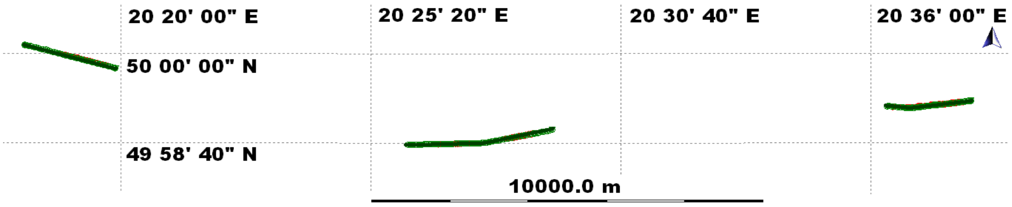

Fig. 1. Sketch of the location of the test sections.

The location of the test sections of a total length of approximately 8.3 km was selected, *inter alia,* due to the presence of diversified field obstructions to satellite signals in their immediate vicinity (Figures 2, 3, 4), as well as due to the starting and ending of the levelling sequence on the vertical control network point. In addition to these benchmarks, on each of these sections there were still another three or four benchmarks.

Fig. 2. The section in Brzesko.

Fig. 3. The section in Bochnia.

Fig. 4. The section in Kłaj.

The section in Brzesko was characterized by the presence of trees and station buildings, control station and a footbridge in its middle part, as well as trees on its eastern end. At the beginning of the four-kilometer section in Bochnia there were buildings, and near the middle part, there were short rows of trees. As far as satellite surveys are concerned, the most difficult section was in Kłaj. From the northern side the test section was surrounded by a forest, and from the southern side by a row of trees.

Reference heights for the accuracy analysis of determining heights and their differences from real-time satellite surveys were computed from the precise geometric levelling conducted with digital level DNA03 with an accuracy of 0.3 mm/km using levelling rods. The least accurate sequence was marked with an error of 1.2 mm/km. With regard to real-time satellite surveys, the heights computed from the geometric precision levelling may be regarded as virtually faultless, as they are characterized by an accuracy of at least one level higher. Real-time RTN kinematic network surveys in relation to the ASG-EUPOS system were performed with the receiver GX1230GG with the antenna AX1202GG, using the real-time data stream VRS_3_1 of the NAWGEO service. For each point two surveys were carried out, each lasting 6-7 one-second epochs, and the final coordinates were the mean value of the two determinations. In Brzesko, additional surveys were conducted according to the following sequence:

- **two surveys lasting six one-second epochs, the final coordinates were averaged,**
- **a survey lasting 2 minutes,**
- **additional surveys (from one to several) at selected points lasting 6 one-second epochs.**

In the carried out RTK GPS real-time kinematic surveys, reference stations for the sections were located so as to cover the entire measured section with the range of a radio modem. RTK GPS surveys were carried out twice at each point, with the automatic averaging of the coordinates.

The precision of satellite surveys was evaluated in the field after each point had been measured, and it was quite often at the level of 1 mm both for the RTN and for the RTK surveys.

For the longest section in Bochnia, the RTK GPS and RTN surveys were repeated after about nine months. At the section covering 16 points there were problems with the position determination. The reason for the problems in positioning of the points was a thunder storm in the area located southwest of the measured section. This also resulted in problems with maintaining communication with the ASG-EUPOS network system via the GPRS packet data transmission of the GSM network operator.

4. ANALYSIS OF TEST RESULTS

The applicability of real-time satellite levelling to determine the normal heights of points will be determined by an accuracy achievable in such surveys, which will mainly depend on the accuracy of the quasi-geoid model as well as on the accuracy of determining the ellipsoidal height from satellite surveys. According to [Pażus et al, 2002] and [Kryński, 2007] a national model for the quasi-geoid in the form of a discrete geographical grid, is characterized by a standard deviation of ± 20 mm. Local quasi-geoid models will be characterized by greater accuracy in the case of the exact heights of benchmarks used to build the model. Their greater accuracy will be more distinct in areas which are more diverse topographically. In other areas, the difference between a national and local models will often be insignificant. A comparative analysis of using a national and local models of the quasi-geoid have been presented in [Banasik, Uznański, 2010].

According to the information [www.asgeupos.pl] the ellipsoidal height will be determined in the RTN surveys with an accuracy not worse than 5 cm, which would significantly limit the usefulness of such surveys. For this reason, investigating the use of satellite levelling in practice is possible in the case of analyzing differences in heights between the points, because then the errors of a systematic nature will be eliminated. Since the test sections have a length of several kilometers and were not located in a mountainous area, it can be assumed that the error of determining the national quasi-geoid model will be removed from the differences in heights between the points [Łyszkowicz, 1991]. The difference in the accuracy of determining the ellipsoidal heights from the real-time kinematic RTK GPS and RTN surveys will largely remain in the analysis.

Table 1 depicts the difference values expressed in percentages between the differences in normal heights (H) of the successive points of levelling sequence computed from the precision geometric levelling, and the differences in normal heights of the same points computed from the RTK GPS and RTN surveys, as well as from the national model of the quasi-geoid (h), according to the following formula:

$$H^n = H_{i,\,i+1} - h_{i,\,i+1} \qquad (6)$$

Table 1. Values expressed in percentages of the differences in heights computed according to (6) in ranges

Range in [cm]	Survey RTK [%]	Survey RTN [%]
[-0.5,0.5]	35.4	20.9
[-1.0, -0.5) (0.5, 1.0]	26.0	16.4
[-2.0, -1.0) (1.0, 2.0]	25.7	25.8
[-3.0, -2.0) (2.0, 3.0]	9.7	23.6
[-5.0, -3.0) (3.0, 5.0]	2.8	9.3
[-8.0, -5.0) (5.0, 8.3]	0.3	4.0

In the case of the GPS RTK surveys, the values of differences ... Hn accounting for almost 2/3 of all the differences (61.4%) did not exceed ± 1 cm. This range comprises a little more than a third of the differences (37.3%) computed from the RTN surveys. Every tenth difference of the differences in heights in the RTN surveys was placed in the range from 3 cm to approximately 8 cm. In the case of the RTK GPS surveys it occurred

three times less frequently. In the analysis of the RTN surveys, the 16 points located on the section in Bochnia, where the GPS receiver had had problems with determining the positions due to a thunder storm, were not taken into account. For these points, the differences in heights were at the level of several centimeters, and reached a maximum value of 18 cm.

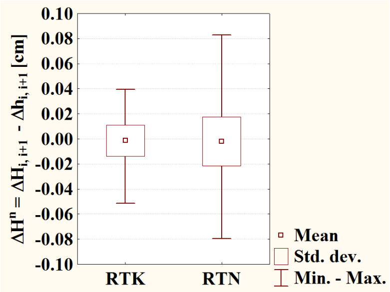

Fig. 5. Selected statistics of the RTK GPS and RTN surveys.

Dispersion of the results around the mean value of 1.1 cm in the RTK GPS survey was twice smaller than in the RTN surveys, for which the standard deviation was 2.0 cm. Variance of the difference values of the differences in heights for the RTK GPS surveys was 8.6 cm, and for the RTN surveys it was twice larger and reached the value of 16.3 cm.

5. CONCLUSIONS

The most popular satellite surveys are currently RTN surveys using the ASG-EUPOS network system, as well as the RTK GPS and RTK GNSS surveys, which give them way in terms of popularity. On the basis of the carried out surveys and their analysis it was concluded, that the primary criterion for the possibility of using satellite surveys to determine the normal heights is the accuracy of determining the ellipsoidal height using the GPS receiver. Other factors are of secondary importance. However, using the quasi-geoid model "Levelling Geoid 2001", it should be noted that due to different spatial reference systems it is necessary to make correction to undulation of the geoid.

The heights determined from satellite surveys regardless the surveying method, are clearly less accurate than the horizontal coordinates. It is assumed that this accuracy is approximately two times lower, and in the case of the RTN surveys, it can be even up to three times lower. For this reason, the accuracy of the height differences between successive measured points was analyzed. The basis for the analysis and conclusions was the implementation of the formula (6) for all the measured points at the three test sections. From the conducted analyses it follows that about twice as accurate results of determining the normal heights of the points can be obtained on the basis of the RTK GPS surveys than from the RTN surveys, which are currently most popular. For the vast majority of the surveying tasks to be carried out, the RTN surveys should not be used to determine the heights of the points or the height differences between the points due to the high probability of making errors of even several centimeters. The RTK GPS surveys ensure a higher probability of determining the height differences between points at ± 1 cm, but do not guarantee such accuracy, thus their use is associated with high risk.

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