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PROBLEM OF ANTENNA PHASE CENTR VARIATIONS IN SATELLITE LEVELLING

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Abstract. Satellite leveling is the procedure used to determination orthometric (normal) heights, on the base of ellipsoidal heights derived with GNSS techniques and additional information which make possible geoid (quasi-geoid) undulation determination. Geoid to ellipsoid separations can be get from geoid models, which accuracy in last years has significantly grown. However, for accurate determination of orthometric (normal) heights it is also important exact determination of ellipsoidal heights from GNSS measurements, which accuracy degrades a number of factors. One of the most important in heights determining, is antenna phase center variations problem. It is well known that magnitude of antenna phase center variations (PCV) can reach several centimeters. Unfortunately part of so-called commercial GNSS post-processing software does not include corrections to the antenna PCV. The paper presents results of solutions this problem with help of a subroutine which introduces PCV corrections to code and phase observations. This approach has been tested using GPS data at four measurement points. Three different types of antenna were used in observations. Processing GPS observations ware done with Ashtech Solutions and Topcon Tools software. The heights derived with satellite leveling were compared to heights got from geometrical precise leveling. The results of studies on one hand confirmed significant influence of antenna PCV onto exactitude of heights determination as well as usefulness of proposed procedure to introducing correction to GNSS observations.

Key words: phase center variations, GNSS data processing, satellite leveling, geoid models, normal heights

INTRODUCTION

Relative GNSS positioning encourage users to compute orthometric height diferences, $\Delta H = H_2 - H_1$, by use of the well-known realation (Fig. 1):

$$(H_2 - H_1) = (h_2 - h_1) - (N_2 - N_1) \qquad (1)$$

where: $\Delta h = h_2 - h_1$ – the difference in elipsoidal heights,
$\Delta N = N_2 - N_1$ – the difference in geoid heights.

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The accuracy of thus calculated ΔH is dependent on the accuracy of Δh and ΔN. Whereas Δh can be derived by GNSS on distances of the order of 100 and more km with centimeter, or even, seubcentimeter accuracy, ΔN has to be determined using other data sources that do not guarante the same level of accuracy.

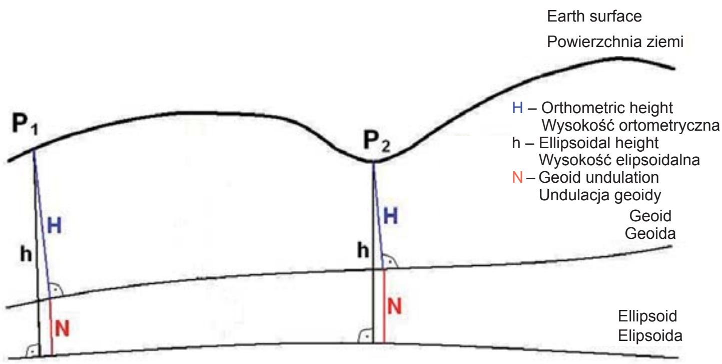

Fig. 1. The idea of GNSS satellite levelling
Rys. 1. Idea niwelacji satelitarnej GNSS

There is a number of categories of techniques for the computation of geoid undulation [Banasik 1999, Łyszkowicz 1993]. Currently genaral strategy for computation of geoid undulation is composed of combination of three effects: global, regional and local, that are represented by geopotential model, mean free-air gravity anomalies and topography respectively [Czarnecki 1994].

Precise modelling of global and regional geoid become one of the major tasks of numerous research groups and surveying and mapping agencies. The first gravimetric quasigeoid model for Poland of accuracy of about 10 cm was calculated at the Space Research Center of the Polish Academy of Science in 1993 [Łyszkowicz 1993]. It was then replaced by the quasi97b quasigeoid model of 5 cm accuracy [Łyszkowicz 1998].

In oredr to provide determination of normal heights using satellite measurements techniques, The Main Office of Geodesy and Cartography in Poland began, from 1999 year, intensive works to create a suitable model of quasigeoid. The result of this work were two published quasigeoid models. The model called "Geoida niwelacyjna 2000" is a purely geometric satellite-levelling quasigeoid model based on hights of the EUREF-POL, POLREF, EUVN, WSSG and Tatry network points. This model was included to TRANSPOL software, which is enclosure to the Technical Guidelines G1-10.

Another published version of quasigeoid is approved in 2001 by General Surveyor of Poland for use in geodetic practice model called "Geoida niwelacyjna 2001". This model is the result of fitting the gravimetric quasigeoidy model quasi97b in the satellite-levelling quasigeoid model *QGEOID'PL01 based on 752 points, of which 62 belong to the EUVN network, 11 to the EUREF-POL network, 330 to the POLREF network, 23 to the Tatry network and 326 to the WSSG network. Discrete model in the form of quasigeoid heights in grid nodes* 1' × 1' was determined using spline function of third's degree. Together with bilinear interpolation formula of quasigeoid heights it was used in the software GEOIDA attached to the Technical Instruction G-2.

Access to raw gravity data, development of high-resolution digital terrain models and densification of precice GPS-levelling heights simulated an extensive research on modeling precise quasigeoid in Poland. The team of reserches, under the leadership of the Institute of Geodesy and Cartography in Warsaw, conducts from 2002 year an advanced research on modeling a centimetre quasigeoid in Poland with the use of geodetic, gravimetric, astronomical, geological and satellite data [Kryński and Łyszkowicz 2006 a,b]

Accuracy of GPS measurements is degraded by many factors. Below are presented a complete classification of the GPS error sources [Figurski 2001]:

1) imprecise knowledge of the satellite orbit parameters;
2) the measurement technique used (Static, Fast-static) and geometry parameters of the network;
3) instrumental errors:
   a) associated with the satellites:
      – the on-board clock error,
      – the variation of antenna phase centre,
      – accuracy of the satellite ephemeris,
   b) related to the receiver:
      – the clock error,
      – orientation and location of the antenna phase centre,
      – the antenna height;
4) propagation disturbances:
   a) the tropospheric refraction,
   b) the ionospheric refraction,
   c) the indeterminacy of the initial number of phase cycles,
   d) the asymmetry of the constellation of satellites in the horizon,
   e) the multipath,
   f) the relativistic effects;
   5) the adopted values of physical constants:
   a) models of the physical phenomena,
   b) the system parameters,
   c) the transformation parameters between the reference systems,
   d) the earth's polar motion parameters;
6) the numerical accuracy and random errors.

One of the most important errors relating to the heights appointment with the use of GPS measurements is the antenna phase centre variation problem.

The electrical antenna phase center is the point in space where GPS signal is received. Although the actual location where the signal is received varies depending on the direction of the incoming signal. To solve antenna phase center variations problem some additional antenna points must be defined (fig. 2).

First of them is a mean position of the electrical antenna phase center (MPC).

Second – the antenna reference point (ARP). ARP is the point marked on the antenna to which the height above the physical network point, at which the antenna is situated, are measured. The IGS has defined the ARP as the intersection of antenna's vertical axis of symmetry with the bottom of the antenna.

Following value – the antenna phase center offset (PCO) is defined as the distance between the ARP and the MPC.

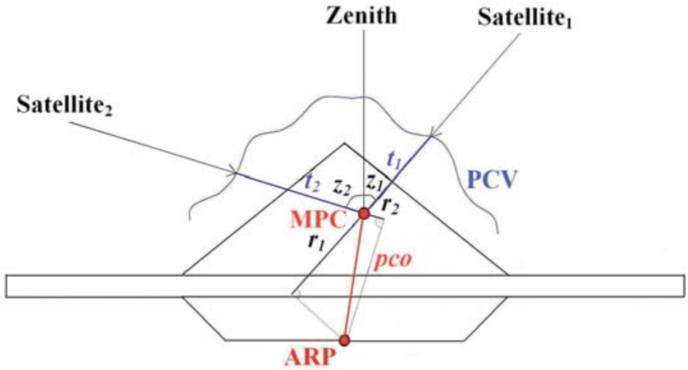

Fig. 2. Diagram of the antenna phase center variations problem
Rys. 2. Schemat zagadnienia zmienności położenia centrum fazowego anteny

And finally antenna phase center variations (PCV) – deviation between positions of the electrical antenna phase center of an individual measurement and the mean electrical antenna phase center.

A review of the antenna phase center variations problem can be found e.g. in Braun et al. 1993, Geiger 1998, Hofmann-Wellenhof et al. 2008, Rocken 1992, Schmid et al. 2005, Schmitz et al. 2002, Schupler and Clark 1991.

Spatial relations between ARP, MPC and PCV points are determined by the calibration process and then the antenna models are created.

Antenna phase center variations can have an amplitude of several centimeters. The effect is more crucial in the elevation dependent component although azimuth dependent effects can become important over very long baselines. Ignoring these phase center variations can lead to serious (up to 10 cm) vertical errors [Rothacher and Mader 1996, Mader 1999].

In some commercial post-processing software, the solution to the antenna phase center variations problem is simplified. For example the Ashtech Solutions 1.0 software does not include the antenna PCV corrections [Magellan... 1998]. Only the newest versions of so-called commercial software are equipped with models of antenna phase center variations corrections. An example is Topcon Tools in which from version 6.11 by default absolute antenna calibration models are applied. Unfortunately even this software is not equipped with models of satellite antenna phase centers variations, which is very important when precise orbits in observation processing are used [Topcon… 2006].

The paper presents a proposal of a subroutine which introduces PCV corrections to code and phase observations. Observations prepared in such way can be then processed with use of any commercial software. GPS measurements were carried out on points with normal heights determine by precise geometric leveling. This allowed to determine the effect of PCV, on the accuracy of the heights determining with satellite leveling procedure.

METHODOLOGY OF STUDIES

Description of subroutine

The subroutine allows correction of observation by using information about the real position of antenna phase center. This information, obtained as a result of antenna calibration is available, for example, on International GNSS Service website in ANTEX format text file.

The proposed subroutine, written in MATLAB programming language, introduces (fig. 3) corrections to code and phase observations basing on the antenna phase center positions and RINEX observation and navigation files. The satellites coordinates on observational epoch are calculated in the first stage. Then, elevation and azimuth of each satellite are calculated using satellites positions data and approximate coordinates of the receiver. The next stage is reading the proper data from the antenna phase center position file. These values are then used to calculate the corrections to code and phase observations. The subroutine can make calculations using antenna calibration results from all centers where they are created. The observations can be reduced to MPC and to ARP.

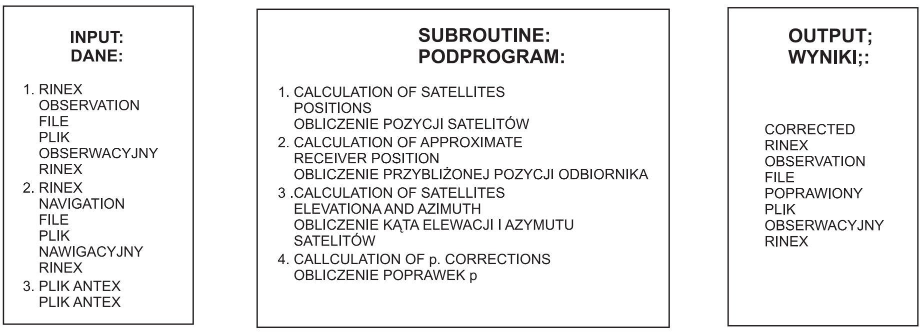

Fig. 3. Diagram of the proposed subroutine
Rys. 3. Schemat zaproponowanego programu

Corrections to ARP are computed using the below formula (Fig. 2):

$$p = r + t = (pco)\cos z + t \tag{2}$$

where:
p – correction to the observation,
r – correction of the phase center position as function of *pco* and elevation of the satellite,
t – correction of the phase center position as function of the satellite's elevation or elevation and azimuth,
pco – position of phase center in relation to ARP ("up" offset),
z – elevation of the satellite.

In the present version of the subroutine, the estimation of r value is simplified because only the "up" offset is used in calculations. Such approximation does not affect the results significantly, because comparing to "up" offset, the other two offsets are very small and their values are mostly less than 1mm and do not exceed several millimeters for any antenna. Because the value of t is expressed in five degrees interval in ANTEX file, its proper value (for current elevation or elevation and azimuth) is calculated by a well known linear interpolation formula. For phase observations, the corrections calculated using equation 2 are additionally converted to phase cycles. In case of reduction of observations to the MPC, correction *p* simply equals *t* value interpolated for current satellite's elevation or elevation and azimuth.

Similar research was performed by Góral and Kudrys [2007]. ASHANT subroutine, described by them, worked with Ashtech binary files (b-files), and made possible to correct observations only in function of elevation of incoming GPS signal. L2 observations were reduced to MPC of L1 frequency, differently than in the subroutine proposed by the author (L1 and L2 observations can be reduced to their MPC or both observations can be reduced to ARP). In the paper author concentrated also on the PCV calculation and its reduction when medium baselines are measured and this causes the necessity to use linear combination of observations in processing. Additionally in the paper it was defined influence of PCV on normal heights determination.

Measurement points

four points situated between 53º34' and 54º00' north latitude and 20º04' and 20º27' east longitude were selected for test measurements. The longest measured baseline has about 49 km, the shortest – 25 km. The location of proposed points causes the necessity to use linear combination in observations processing, which causes antenna phase center variations of both frequencies to appear in final results.

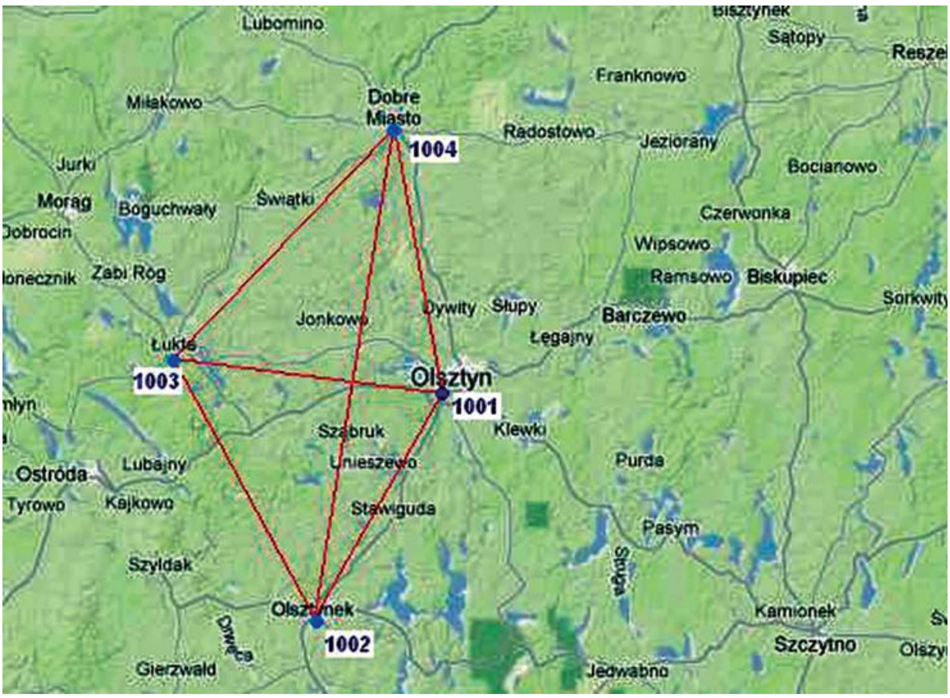

Fig. 4. Diagram of measurement points
Fig. 4. Schemat położenia mierzonych punktów

For the all network points there ware normal heights appointed by precise leveling (Tab. 1). Precise leveling was done with use Ni007 Zeiss level. The distance between the points of network and the benchmarks was on average about 100 m. Table 1 contains also the separations between geoid and ellipsoid on measured points calculated with "Geoida niwelacyjna 2000" and "Geoida niwelacyjna 2001" models.

Table 1 Normal height and geoid to ellipsoid separation on measured points
Tabela 1. Wysokości normalne oraz odstępy geoidy od elipsoidy mierzonych punktów

Numer mierzonego punktu Measurement point number	Wysokość normalna [m] Normal height	Odstępy geoidy od elipsoidy z modelu Geoida niwelacyjna 2000 Geoid to ellipsoid separation from Geoida niwelacyjna 2000 model	Odstępy geoidy od elipsoidy z modelu Geoida niwelacyjna 2000 Geoid to ellipsoid separation from Geoida niwelacyjna 2000 model
1001	119.491	29.853	29.850
1002	172.564	30.258	30.249
1003	94.583	29.725	29.706
1004	101.836	29.190	29.221

Geoid undulation for network points calculated with use "Geoida niwelacyjna 2000" and "Geoida niwelacyjna 2001" models change in the range from 0.003 m (1001 point) to 0.021 m (1004 point).

Testing hardware and software

Two measurement sessions were performed on the test points. The following GPS parameters were assumed for all measurement sessions: sampling interval 10s, minimum satellite's elevation 15°, time of measurement 4 hours. Following types of antenna, presented on Figure 5, were used in the measurements: ASH700228A (session 1), ASH700718A (session 1 and 2) and AOAD_M_T (session 2).

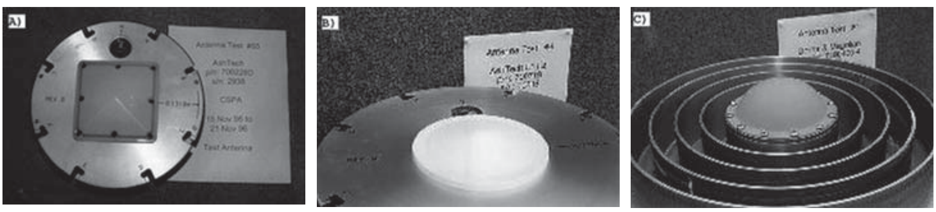

Fig. 5. Antenna used in measurements: A) ASH700228A; B) ASH700718A; C) AOAD_M_T (source: http://www.ngs.noaa.gov/ANTCAL/)

Rys. 5. Anteny wykorzystane w trakcie pomiarów: A) ASH700228A; B) ASH700718A; C) AOAD_M_T (źródło: http://www.ngs.noaa.gov/ANTCAL/)

The locations of MPC over ARP ("up" offset) for L1 and L2 frequencies for these antennas are respectively (in millimeters): ASH700228A (61.14; 71.26); ASH700718A (68.54; 55.46); AOAD_M_T (91.24; 120.06).

Figure 6 presents comparison of the elevation dependent phase center variations for antennas used in two measurement sessions – it is visible that they have completely different profiles.

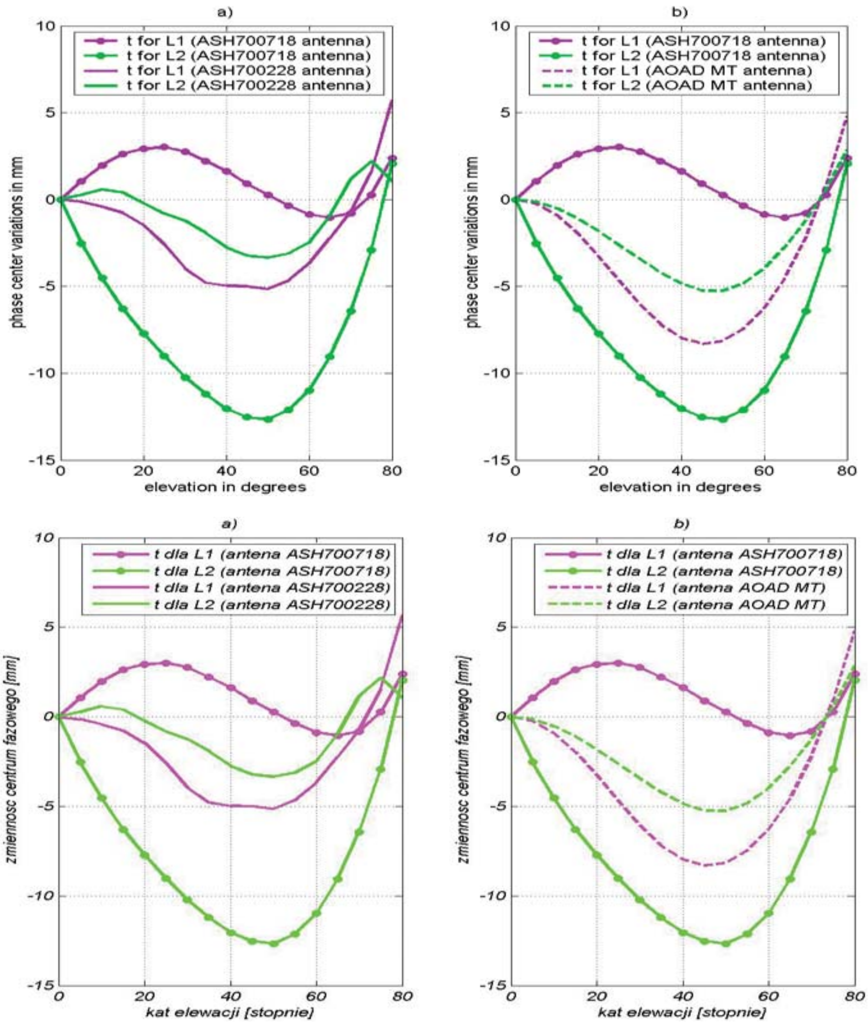

Fig. 6. Elevation dependent phase center variations: a) for antenna pair ASH700228A and ASH700718A; b) for antenna pair AOAD_M_T and ASH700718A

Rys. 6. Wartości zmian położenia centrum fazowego anteny w zależności od kąta elewacji: a) dla anten ASH700228A i ASH700718A; b) dla anten AOAD_M_T i ASH700718A

One of the purpose of this study was testing a subroutine which, using the results of antenna phase center variation calibrations, can prepare GPS observations for processing with software which is not equipped with proper correction algorithms. An example of such software is Ashtech Solutions 1.0, which does not give any possibility of antenna type selection [Magellan... 1998]. To control the subroutine calculation results was choesn Topcon Tools 6.11 software, which uses the US National Geodetic Survey's absolute antenna calibration models.

Both chosen software types are examples of so-called commercial software and selection of processing frequency is automatic and looks as follows:
- 0–10 km baselines processing is L1 and L2,
- 10–30 km baselines processing is ionosphere-free combination,
- 30–400 km baselines processing is wide-lane combination.

Because using linear combination of observations causes antenna phase center variations for both frequencies to appear in final results, suitable distant points locations were proposed for test measurements.

GPS observations processing results

The GPS observations for all sessions were corrected by proposed subroutine with use of igs_05.atx file, which contains values of absolute elevation and azimuth dependent antenna phase center variations. The corrected and the uncorrected observations were processed with Ashtech Solutions 1.0 software. To control the results of a calculation Topcon Tools 6.11 software was used.

Point 1001 situated in Olsztyn (ASH700718A antenna), with coordinates appointed in reference to IGS LAMA station, was chosen as the reference station. Post-processing was done in the following variants:
- processing uncorrected observations using Ashtech Solutions 1.0 software (AS without corrections),
- processing corrected by proposed subroutine observations using Ashtech Solutions 1.0 software (**AS subroutine corrections**),
- processing corrected observations using Topcon Tools 6.11 software (TT software corrections).

Cost-effectiveness is a requirement for most geodetic projects. Some investigations were address how the accuracy of an relative positions vector, between the GPS antenna at a control point and a new point, depends on the baseline length and on the duration of the observing session [Eckle at al. 2001, Psimoulis at al. 2004]. Because of the length of baselines in our test, processing was done with use dual frequency (linear combination of observations). The commercial software tutorials recommend that dual frequency session would be observe for 2 or more hours for reasonable baseline resolutions [ASHTECH… 1990]. For additional, aimed to the economy, analysis 4 hour sessions were divided into two 2 hour sessions.

Analyzing the results (Fig. 7) obtained from four hour session processing is visible that, when the same type of antenna as on the reference station was on the new point (1004 point), heights from all processing variants were consistent with 10 mm range. Processing medium baseline, with the same type of antenna on both ends, without using PCV corrections, does not influence the results because systematic error is reduced in differential elaboration. When there was a different type of antenna on the new point than on the reference station (1002 and 1003 points) it was clear that processing without the PCV corrections caused systematic error of about 3–4 cm. The error magnitudes are similar for antennas ASH700228A and AOAD_M_T surely because the both antennas have very similar phase center variation characteristics (Fig. 6). The heights, obtained from observations processing with use of the PCV corrections method proposed by author and with use of antenna phase center variation corrections available in Topcon Tools software, are consistent with 8 mm range. For 4 hour session, heights differences between resolutions got for session 1 and session 2, do not exceed 10 mm.

Analyzing the results obtained from two hour session processing is observe a similar trend as in the four hour session solution. Visible is however smaller stability of the solution. The difference between heights, obtained from observations processing using the PCV corrections method proposed by author and using antenna phase center variation corrections available in Topcon Tools software increases in the extreme case to 30 mm (1002 point, session 1, 2 hour session (1)). In two hour session is also visible increase heights differences between resolutions got for session 1 and session 2, which in many cases reaches 20 mm or even more.

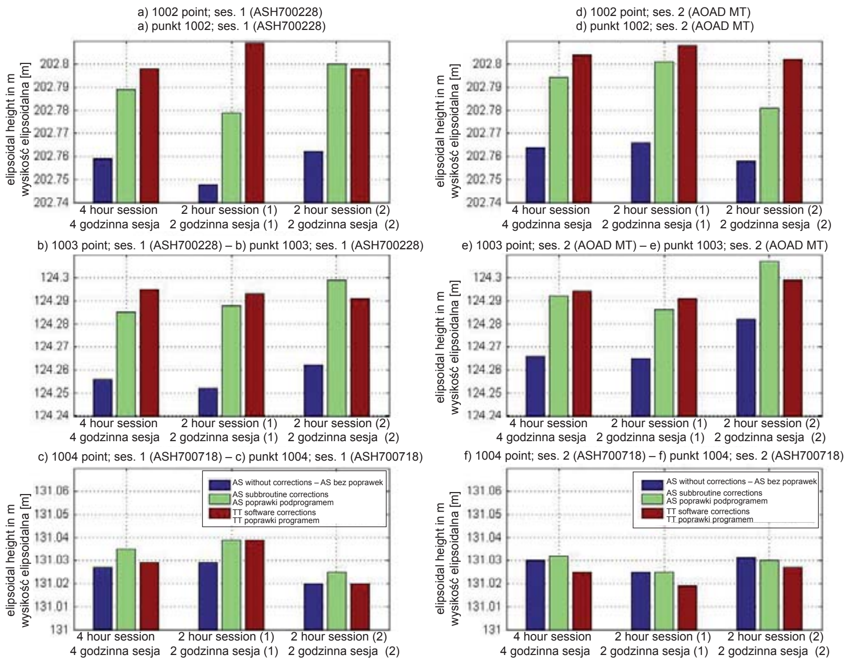

Fig. 7. Ellipsoidal height obtained for points depending on the used software and used or no the antenna calibration file: a) 1002 point session 1; b) 1003 point session 1; c) 1004 point session 1; d) 1002 point session 2; e) 1003 point session 2; f) 1004 point session 2 (in brackets type of antenna used in respective sessions)

Rys. 7. Wysokości elipsoidalne uzyskane dla punktów w zależności od użytego oprogramowania oraz wprowadzenia bądź nie korekt do PCV: a) punkt 1002 sesja 1; b) punkt 1003 sesja 1; c) punkt 1004 sesja 1; d) punkt 1002 sesja 2; e) punkt 1003 sesja 2; f) punkt 1004 sesja 2 (w nawiasach typ anteny użytej w danej sesji).

Satellite leveling results

For all processing variants obtained with use 4 hour sessions, normal heights were calculated. The calculation was done with use a well-known satellite leveling formula (1).

The "Geoida niwelacyjna 2000" and "Geoida niwelacyjna 2001" models was used to calculate the distances between geoid and ellipsoid. Fitting of the geoid models to precise leveling network was done by calculating the ellipsoidal height of reference station as sum of the normal height and the distance between geoid and ellipsoid. Comparison of the ellipsoidal height calculated in such way, with the ellipsoidal height used in GPS observations processing, allowed to define the shift between that two surfaces in measured area. This shift was then used to calculate of normal heights of measured points. The normal heights calculated in such way were then compared with the heights received from precise leveling, which were considered true. Influence of GPS observations processing without PCV modeling on normal heights calculation was made on the basis of that comparison. Normal heights differences between the heights obtained from precise leveling and the heights obtained from satellite leveling are presented on figure 8. If we will assume the value of difference between normal heights obtained from precise leveling and heights obtained from satellite leveling as an average error of heights appointment then the red lines on Figure 8 determine value of the admissible error for four class vertical network points height determining (Instrukcja Techniczna G-2. 2001).

When results from the GPS observations processing without the PCV correction were used for normal heights calculation, the differences between heights obtained from precise leveling and heights obtained from satellite leveling (for points where there were different types of antenna than on the reference station) reached values from 2.2 cm to 5.4 cm ("Geoida niwelacyjna 2001" model) and from 4.2 cm to 6.3 cm ("Geoida niwelacyjna 2000" model).

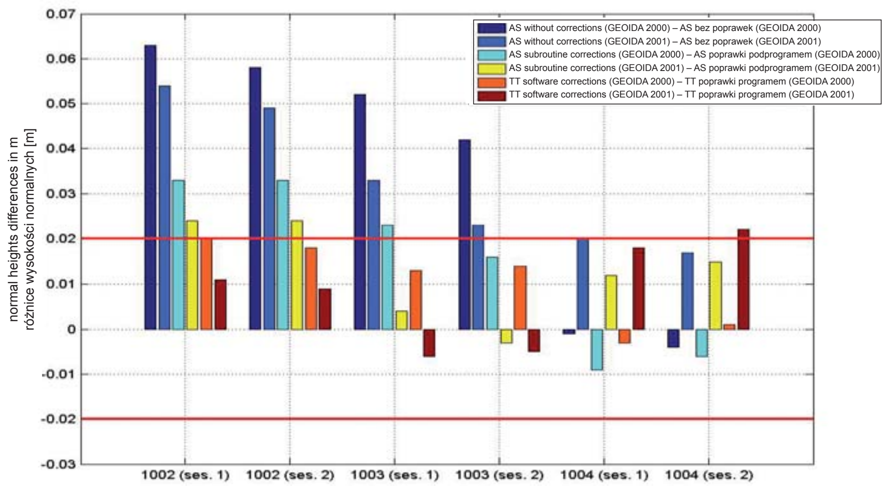

Fig. 8. Normal heights differences between heights obtained from precise leveling and heights obtained from satellite leveling

Rys. 8. Różnice wysokości normalnych pomiędzy wynikami uzyskanymi z niwelacji precyzyjnej i wynikami z niwelacji satelitarnej

When results from processing corrected observations by the proposed by author subroutine were used for normal heights calculation, the differences between heights obtained from precise leveling and heights obtained from satellite leveling (for points where there were different types of antenna then on the reference station) got smaller respectively from -0.3 cm to 2.3 cm ("Geoida niwelacyjna 2001" model) and from 1.7 cm to 3.3 cm ("Geoida niwelacyjna 2000" model). Similar differences were obtained when results from processing corrected observations by Topcon Tools software were used for normal heights calculation.

For 1004 point, where there was the same type of antenna than on the reference station, the differences between heights obtained from precise leveling and heights obtained from satellite leveling do not exceed 2.2 cm irrespective of the geoid model used and variant of the GPS observations processing.

It is visible, that all differences, obtained from results got from GPS observations processing without antenna phase center variations corrections, significantly exceed value of admissible error for four class vertical network points height determining.

CONCLUSIONS

Analyses were done using GPS data collected at four measurement points distant from 25 to 49 km. Such long baselines cause the necessity of conducting suitably long observational sessions. Shortening duration of the sessions from four to two hours decreased solution stability expressed e.g. in enlargement of the differences between resolutions got for session 1 and session 2.

Moved analyses confirmed that the PCV problem cannot be disregarded in surveying measurement – apparently very similar surveying antennas (ASH700228A and ASH700718A) have significantly different PCV characteristics. Using those antennas in measurements and then processing observations without PCV corrections causes a systematic vertical error of several centimeters.

In effect it cause increase of the error of normal heights calculation. All differences, obtained from results got from GPS observations processing without antenna phase center variations corrections, significantly exceed value of admissible error for four class vertical network points height determining.

The results presented in this paper also show, that the subroutine proposed by the author can be successfully used in processing with commercial software which is not equipped with PCV correction algorithms.

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PROBLEM ZMIENNOŚCI CENTRUM FAZOWEGO ANTENY W NIWELACJI SATELITARNEJ

Streszczenie. Niwelacja satelitarna jest procedurą wykorzystywaną do wyznaczania wysokości ortometrycznych (normalnych), na podstawie wysokości elipsoidalnych uzyskanych z pomiarów GNSS oraz dodatkowych informacji, które umożliwiają wyznaczenie przebiegu geoidy (quasi-geoidy). Odstęp między geoidą a elipsoidą może być określony z modeli geoidy, których dokładność w ostatnich latach znacząco wzrosła. Jednak dla dokładnego wyznaczenia wysokości ortometrycznych (normalnych) istotne jest również właściwe wyznaczenie wysokości elipsoidalnych z pomiarów GNSS, których dokładność degraduje szereg czynników. Jednym z istotniejszych przy wyznaczaniu wysokości jest problem zmienności położenia centrum fazowego anteny. Powszechnie wiadomo, że wartość zmian położenia centrum fazowego anteny (Phase Center Variations – PCV) może osiągać kilka centymetrów. Niestety, część tzw. programów firmowych nie zawiera modeli służących do korekty PCV anten. W pracy zaprezentowano wyniki rozwiązania tego problemu z pomocą autorskiego programu, który wprowadza poprawki PCV do obserwacji kodowych i fazowych. Podejście to zostało sprawdzone przy wykorzystaniu obserwacji GPS wykonanych na czterech punktach. Trzy różne typy anten zostały użyte w trakcie pomiarów. Opracowania obserwacji dokonano z użyciem programów: Ashtech Solutions i Topcon Tools. Wysokości uzyskane z niwelacji satelitarnej zostały porównane z wysokościami uzyskanymi z niwelacji precyzyjnej. Wyniki analiz z jednej strony potwierdzają istotny wpływ PCV anteny na dokładność wyznaczenia wysokości oraz z drugiej – przydatność zaproponowanej procedury do wprowadzania poprawek ze względu na PCV do obserwacji GNSS.

Słowa kluczowe: zmienność położenia centrum fazowego, opracowanie danych GNSS, niwelacja satelitarna, modele geoidy, wysokości normalne

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