ABSTRACT

The International GNSS Service (IGS) had used the relative phase center model for the calibration of the GPS antenna receivers from 30 of June 1996 till 6 of November 2006. However in this period the absolute calibration model has been developed by the company “Geo++” for almost all antenna types. This model involved significant differences on the scale of GPS networks compared to the networks measured by VLBI and SLR techniques. That was the main reason why IGS did not chose this absolute antenna phase center model. The differences were due to the lack of the GPS satellite antenna calibration model. This problem was faced sufficiently and therefore IGS decided to switch from relative to absolute model for both satellites and receivers. The decision caused significant variations to the results of the GPS network solutions.

The aim of this paper is to study the differences on local and regional scale networks and to propose a suitable processing scheme. For that reason two appropriate GPS networks were adjusted using several combinations of the official calibration models. Comparisons on coordinate differences and useful remarks are presented.

1. Introduction

During the last few years most of the geodetic and surveying applications are implemented through GNSS systems. The evolution of the receivers and antennae as well as the sophisticated algorithms provide us the opportunity to determine points with accuracy of few mm. Taking into account the Antenna Phase Center Corrections (APCC) for the receivers and the satellites is of great importance to achieve high accuracy. In this paper a review of the receiver and the satellite antenna calibration methods is presented followed by the effects through tests in local and regional scale networks.

Antenna Phase Center Corrections are given by (Rothacher et. al., 1995, Dach et. al., 2007)
\[ \Delta \Phi(a, z) = \Delta \phi(a, z) + Dr \cdot e \]  

Where,
\( \Delta \Phi(a, z) \): Total phase center corrections in direction \( \{a \text{ (azimuth)}, z \text{ (zenith angle)}\} \).
\( Dr \): Phase center offset vector of the antenna.
\( e \): The unit vector in the direction receiver to satellite.
\( \Delta \phi(a, z) \): The spherical harmonic function of the phase center variation.

APC Corrections are divided in two categories:

a. *Antenna Phase Center Offset (APCO)*: This is the distance between the electrical phase centre and the mechanical/reference point (Figure 1). APCO’s are different for each antenna type and for each frequency.

b. *Antenna Phase Center Variation (APCV)*: A GNSS receiver tracks the satellite signals from different directions (azimuth and elevation angles). The position of the APC depends on this direction and the result is the APCV.

![Fig. 1: Representation of antenna phase center corrections (APCC)](image)

In a GPS network solution measured by different antenna types, the APC corrections should be taken into account, otherwise errors up to 10 cm would be resulted at the relative heights (Rotacher et. al., 1995) regardless of the baseline length. In case that the same antenna types are used a scale error up to 0.015 ppm could be arise (Dach et. al., 2007). The scale error is caused by the earth’s curvature and as a consequence it is possible that two receivers could track the same satellites from totally different elevation angles, mainly in very long baselines. In order to avoid the mentioned errors the antennae of the receivers should be calibrated and the APC corrections should be estimated.

### 2. Receiver antenna calibration methods

In the beginning of 1990’s two main antenna calibration methods had been developed, the relative and the absolute method. On the 30\textsuperscript{th} of June 1996, IGS chose the relative antenna calibration method as the official one because it was easier to be
implemented and on the other hand the absolute antenna calibration method did not produce satisfactory results.

2.1 The relative calibration method

The relative antenna calibration method was based on the assumption that the Alan Osborn antenna (AOAD/M_T) had zero PCV and (L1, L2) offsets were defined as L1=11cm and L2=12.8cm (Mader 1999). Therefore AOAD/M_T was used as the reference antenna in order to estimate antenna phase center corrections for any other antenna types. The realization of the relative antenna calibration method was implemented using two well established pillars. The height of each pillar was 1.8 m and the distance between them 5 m, both of them measured with high accuracy. The field test setup is shown in Figure 2 where the reference antenna is put on the one pillar and the antenna under calibration on the other. In brief the APC offsets for each frequency is firstly estimated using double differences and the antenna PCV follow from the process of single differences and accounting only for the zenith angle of the signal reception. In order to avoid multipath errors a 10° cut of angle was being selected.

![Fig. 2: Implementation of the relative antenna calibration method](image)

However the relative antenna calibration method had some drawbacks:

a. The antenna PCV's were estimated with a 10° cut of angle.
b. The PCO's and PCV's of the reference antenna were known with low accuracy.
c. The lack of azimuth angles in the antenna PCV’s estimation.

These deficiencies were the reason that at the same time the absolute antenna calibration method was being developed, as the suitable method, especially for regional and global networks.

2.2 The absolute calibration method

There are two methods for the absolute antenna calibration. The field calibration and the anechoic chamber test.

The field calibration method was developed by the company ‘GEO ++’ in collaboration with researchers of the Hannover University (Wübbena et. al., 2000). This technique is based on the existence of a perfectly calibrated robot on which the test antenna is located. The accuracy of this method is increased because the robot
rotates the antenna fast in different axes and as a result the calculation of the PCO's and PCV's depended on the zenith and azimuth angles are estimated. Multipath error is eliminated since PCV's calculation is derived for 0° to 90° zenith angles and 0° to 360° azimuth angles. It is obvious that the absolute antenna calibration method is more accurate than the relative one.

Despite the advantages of the absolute method the IGS did not decide to accept this method as the official antenna calibration method until 2006. The first reason was that the absolute PCV values of the reference AOAD/M_T were totally different from the used official IGS values. The second reason was that the use of absolute APC corrections caused an unreasonable scale error (15 ppb) between the global IGS GPS network and the IERS ITRF network (Rothacher 2001) and as a result a height change of 5 to 10 cm! In addition the comparison with the VLBI and SLR networks showed significant differences.

A lot of experiments were held in order to understand the source that introduces the previous mentioned scale error. Rotacher and others researchers (Rothacher 2001, Mader and Czopek 2002, Schmid and Rothacher 2003, Zhu et. al., 2003) found out that the source of this error was not the new absolute APC values but the lack of the satellite antenna calibration.

3. Satellite antenna calibration methods

The satellite antennae consist of two homocentric circles. The inner circle is comprised of four elements transmitting 90% of the signal and the outer circle is comprised of eight elements transmitting the other 10% of the signal. At the moment there are five satellite blocks {II, IIA, IIR (IIR-A, IIR-B, IIR-M), IIR-M, IIF}.

It should be pointed out that during the period of the relative antenna calibration method usage, a few was known about the satellite antenna calibration. Only for the blocks II and IIA PCO’s (dx = 0.279 m, dy = 0 m, dz =1.023 m) were known and used but with doubtful accuracy. Some researchers (Schmid and Rothacher 2003, Mader and Czopek 2002, Zhu et. al., 2003) proved that the variation of the satellite antenna PCO affects the GPS network solution.

The precise ephemeris provides the satellite coordinates of the mass centre of the satellite vehicle while the geometrical distance between satellite and receiver is referred to their electrical phase centers. It is clear that the distance dz (Fig. 3) between the satellite antenna electrical phase centre and its centre of mass should be known, otherwise an error dr of the geometrical distance may occur, given by

\[ dr = dz \cdot \cos(b) \]  

where \( b \) is the angle formed between the directions (satellite, earth center) – (satellite, receiver). This error is mainly caused by the z – offset of the satellite antenna. In most cases the z – offset affects mainly the heights of the ground points. The angle that a satellite can ‘see’ two receivers varies from 0° to almost 15° in very long baselines. Using single differences in the process of observations the greatest part of the error dr is absorbed by the clock estimated parameters as angle \( b \) is small. However a big variation of dz affects mainly the height difference of the ground points of a baseline according to the relation,

\[ \Delta dr = dz \cdot [\cos(b_1) - \cos(b_2)] \]
In 2004 the IGS International Workshop discussed the scale error source between the global GPS and ITRF networks in Bern (Switzerland) and as a result the IGS decided to make the absolute field calibration method as the official one as long as the satellite antennas were calibrated.

The estimation of the satellite antenna PCO's and PCV's was finally made by GeoForschungsZentrum (GFZ) and Technical University of Munich (TUM). Each one of these Institutes used different GPS processing software (GFZ: EPOS.P-v2, TUM: BERNESE v5). GPS data of ten years time span and of more than 100 permanent stations were collected. The stations choice and the processing parameters were different for each Institute. The only common aspects were the satellite antennae PCC parameters and the receiver antennae absolute values that “GEO++” provided to them. It should be pointed out that as “GEO++” had not calibrated all antenna types, that used to the test networks, a new methodology was developed to convert the relative PCV and PCO values to the corresponding absolute values, given by the following expressions,

\[
\text{PCO}_{\text{abs}} = \text{PCO}_{\text{rel}} + \text{PCO}_{\text{abs}} \left( \text{AOAD/M}_T \right) - \text{PCO}_{\text{rel}} \left( \text{AOAD/M}_T \right) \tag{4}
\]

\[
\text{PCV}_{\text{abs}} = \text{PCV}_{\text{rel}} + \text{PCV}_{\text{abs}} \left( \text{AOAD/M}_T \right) \tag{5}
\]

It was decided that only the z-offsets and the PCV with respect to the elevation angle would be estimated (Schmid et. al., 2007). Because the PCV's between satellites of the same block was almost zero, the PCV's were estimated for each satellite block. On the contrary the PCO's were estimated for each satellite antenna. The final antenna phase center corrections for each satellite antenna were the average of the two Institute’s solutions.

The results of the satellite antennae PCC were presented in the IGS International Workshop held in 2006 at Dresden (Germany). Indeed the scale error was eliminated due to the absolute satellite APCC. Finally IGS announced at 6th of November 2006 the use of the absolute PCO and PCV values from now on.
4. Experimental results in local and regional networks

The main goal of this paper is to study the effects caused by switching between the two calibration methods, i.e. from relative to absolute. For that reason two GPS networks were selected and adjusted. A local network at the broader area of Thessaloniki (Greece) and a regional network at the area of South-East part of Europe. Three different processing scenarios, called here models, were applied to both networks:

- **Model 1**: The relative APC model for the antennae of the receivers and the standard IGS antenna offsets for the GPS satellites. This is the old model used by sophisticated software like Bernese.
- **Model 2**: The absolute APC model for the antennae of the receivers and the standard IGS antenna offsets for the GPS satellites. This is partly the new model used probably by commercial software.
- **Model 3**: The absolute APC model for the antennae of the receivers and absolute APC model for the antennae of the satellites. This is the new model used by software like Bernese in a correct way.

The results of the three processes are compared between them by means of computed differences derived from the adjusted coordinates. Differences between pairs of processing models are given with respect to the baseline length formed between the fixed point (AUT1 in local and MATE in regional network) and the rest network points, the longitude, the latitude and the height. Processing models are compared according to the difference scheme,

a. \([\text{model 3} - \text{model 2}]\)  
b. \([\text{model 3} - \text{model 1}]\)  
c. \([\text{model 2} - \text{model 1}]\)

4.1. The local network

The local GPS network at the area of Thessaloniki consists of baseline lengths 4 to 90 km and 21 points, including the permanent EPN - AUT1 station. This network was measured in eight 4-hour sessions in four subsequent days. In each session four different pairs of receiver - antenna were used: a) LEICA GRX1230GG - LEIAX1202 b) LEICA SR9500 - LEIAT302-GP c) LEICA SR520 - LEIAT502 and d) LEICA GRX1200PRO - LEIAT504-LEIS.

For the data processing and the network adjustment the BERNESE GPS software v.5 was used with the following appropriate processing parameters:

- IGS orbits and pole information
- 10° elevation mask
- Niell mapping function
- One tropospheric parameter every three hours
- AUT1 kept fixed
- Strategy baseline selection: Defined
- Ambiguities resolution method: Sigma (wide – narrow lane)

After the session solutions the network multisession solution followed. As mentioned above the three different processing scenarios - models were applied.

The first comparison (models 3 – model 2) shows the effect of the satellite antenna PCC, as illustrated in Figure 4. As it was expected the impact of the satellite antenna PCC on the local network solution is almost zero (± 0.5 mm).
The effect of the satellite antenna calibration lack on the local network solution

The second comparison (model 3 – model 1) gave almost the same results as the third comparison (model 2 – model 1). This was also expected as the satellite antenna PCC’s do not have an impact on local networks as resulted from the first comparison.

The comparison (model 3 - model 1) was chosen to be shown separately in Figure 5 because it describes the total change from relative to absolute calibration models. In Figure 5 the 2-d horizontal differences are shown in blue color (or slightly bold in grey scale) while the vertical differences between models 3 and 1 are shown in red color.

Fig. 4: The effect of the satellite antenna calibration lack on a local network (model 3 – model 2).

Fig. 5: (model 3-model 1) comparison: Horizontal and vertical differences
According to Figure 5, 9 out of 21 points differ from 0.5 mm to 2 mm in the horizontal and in the vertical component. The rest 11 points show a remarkable systematic difference at the level of 9 mm in latitude, 4 mm in longitude and 5.5 mm in height, which could be significant in engineering networks of high accuracy. However, furthermore, study is needed in order to come up with a reliable conclusion.

4.2. The regional network

The regional network, with 400 to 1100 km baseline lengths, consists of 9 GPS permanent stations at the area of South-East Europe. Five of the selected stations are located in Greece (AUT1 in Thessaloniki, NOA1 in Athens, TUC2 in Chania, RLS in Achaia, VLS in Cephalonia), two in Italy (MATE in Matera, NOT1 in NOTO), one in Bulgaria (SOFI in Sofia) and one in Turkey (TUBI in Istanbul). Seven of these stations (AUT1, NOA1, TUC2, MATE, NOT1, SOFI and TUBI) belong to the EPN Network (Bruyninx 2004) and the other two to the National Observatory of Athens Permanent Network. It should be noted that the antenna types of the test network were LEIAT504 (AUT1, NOA1, TUC2) and LEIAX1202 (RLS, VLS) of Leica Geosystems, TRM29659.00 (MATE, NOT1, TUBI) of Trimble and AOAD/M_T (SOFI).

The Bernese software v5.0 (Dach et. al., 2007) was used to process the GPS data. The processing strategy was based on the script file RNX2SNX with a slight modification (Chatzinikos et. al., 2007) and the following processing parameters were used:

- Precise IGS orbits and pole information
- 10° elevation mask
- Niell mapping function
- One tropospheric parameter every one hour
- MATE kept fixed
- Strategy for baseline selection: Star
- Fix ambiguities: QIF strategy

The time period of GPS observation covers seven days, from 323 to 329 GPS day of 2006. Daily solutions of the GPS network were processed first and the multi-session solution for the whole period followed.

The same processing scenarios were also applied to this regional network. The effect of the satellite antenna PCC in a regional network is described by the first comparison (model 3 - model 2). Baseline differences from the fixed point MATE are shown in Figure 6. In the same figure, the latitude, longitude and height point differences between the two models are also illustrated.
It is evident that in Figure 6 the baseline length differences are increasing as the distance increases from the fixed point and the lack of the absolute PCO and PCV satellite antenna values has a certain effect in the network solution. The height differences show a systematic error of 5 mm for all points apart from TUBI station where the difference is 9 mm. In addition the longitude is more influenced than the latitude.

The results of the second comparison (models 3 – model 1) are shown in Figure 7.
In this comparison vertical differences variate from -6.4 mm to 19.4 mm while horizontal differences are obviously smaller, from -6 mm to 1 mm. Let us remind that the absolute method calibrates the receiver antenna with the radome type while the relative method ignored radome and thus the relative PCO and PCV values for an antenna were the same no matter if there was a radome type or not.

The third comparison (model 2 – model 1) is depicted in Figure 8 where the differences in the vertical component are larger (1 to 28 mm) than in the horizontal (1 to 7 mm) as previously.

![Fig. 8: (model 2 – model 1) comparison: Horizontal and vertical differences.](image)

In all comparisons it is shown that moving away from the fixed point (MATE) the differences, mainly in the vertical component, increase. These differences are basically due to different observing angles between receivers and satellites as a consequence of the larger baseline length.

### 5. Conclusions

Care should be taken when mixing results derived by GPS data processed with different receiver and satellite antenna calibration models. Note that from 6 November 2006 (1400 GPS week) precise ephemerides are referred to satellite coordinates estimated by absolute calibration models.

Switching from relative to absolute models has insignificant effect in a local scale GPS network solution except sometimes in high accuracy applications.

In regional networks with baseline lengths of some hundreds of km the effect of the new absolute calibration models cannot be ignored.

In general differences between the results derived by relative and absolute calibration models are larger in the vertical than in the horizontal component.
In case precise ephemerides are used (high accuracy applications) then the absolute calibration values should be apply. Otherwise errors of the order of 1 cm could be present.

References

Fotiou A, Pikridas C (2006): GPS and Geodetic Applications. Aristotle University of Thessaloniki, Editions Ziti, Greece
Rothacher M (2001): Comparison of absolute and relative antenna phase center variations. GPS Solutions, Vol.4, No.4, pp. 55–60
AUTHORS:

**Msc. Eng. Miltiadis Chatzinikos**, PhD student at the Department of Geodesy & Surveying, Faculty of Rural and Surveying Engineering, Aristotle University of Thessaloniki, Greece. Tel. +30 - 2310994224, fax +30 – 2310 996408, e-mail mchatzin@topo.auth.gr.

**Prof. Aristeidis Fotiou**, Department of Geodesy & Surveying, Faculty of Rural and Surveying Engineering, Aristotle University of Thessaloniki, Greece. Tel. +30 - 2310996135, fax +30 – 2310 996408, e-mail afotiou@topo.auth.gr.

**Assistant Prof. Christos Pikridas**, Department of Geodesy and Surveying, Faculty of Rural & Surveying Engineering, Aristotle University of Thessaloniki, Greece. Tel. +30 – 2310 996110, fax +30 – 2310 996408, e-mail cpik@topo.auth.gr.