Comparison of Absolute and Relative Antenna Phase Center Variations

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Three major GPS antenna calibration methods are available today: the relative field calibrations using the GPS data collected on short baselines, the absolute field calibrations, where the GPS antenna is rotated and tilted by a robot, and calibration measurements in an anechoic chamber. Mean antenna offsets and the elevation-dependent phase center variations of GPS antennas determined by all three techniques are compared to assess their accuracy. The analysis of global GPS data with these sets of calibration values reveals that the offsets and variations of the satellite antenna phase centers have to be considered, too, to obtain a consistent picture. © 2001 John Wiley & Sons, Inc.

INTRODUCTION

From antenna calibration studies it is well known that not only receiver antenna offsets but also elevation-dependent and even azimuth-dependent variations of the antenna phase center have to be taken into account for high-precision GPS applications. So far, however, only antenna calibration values relative to a reference antenna (typically obtained from relative field calibrations) have been used to correct for differences in the phase center behavior between different antenna types. Absolute antenna phase available from anechoic chamber measurements have not been applied because they produce an unreasonably large terrestrial scale change in global GPS solutions.

Recently, the group of Prof. G. Seeber at the University of Hannover together with the company Geo++ established a new method for the determination of absolute antenna phase center variations (PCVs) from GPS data collected by two receivers on a short baseline. To obtain the absolute antenna patterns the antenna to be calibrated is constantly rotated and tilted by a robot. The absolute PCVs derived with this new approach allow new comparisons and quality checks between the different methods and shed new light on the problem of absolute antenna PCVs.

After a short overview of the antenna calibration methods available today the results of the various techniques are compared on a relative and absolute level, the influence of these calibration values on global GPS solutions is studied, and the role played by the satellite antenna is discussed.

CALIBRATION METHODS

Three major methods are presently available to determine mean antenna phase center offsets as well as variations of the phase center with elevation and azimuth for GPS receiver antennas:

- Anechoic chamber measurements
- Relative field calibrations
- Absolute field calibrations

If the GPS antenna of interest is put into an anechoic chamber, the absolute antenna phase center variations may be obtained by measuring how the phase of an artificial GPS signal is changed when the antenna is rotated and tilted. The point of rotation of the antenna has to be carefully measured relative to a physical reference point of the antenna, usually called the antenna reference point (ARP).

In relative field calibrations the mean phase center offsets and the phase center variations of one antenna may be determined with respect to another antenna, the reference antenna. Both antennas are set up (together with the GPS receivers) on a very short baseline with accurately known coordinates, and the GPS measure-

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ments are used to estimate the position of the phase center depending on the elevation (and azimuth) of the measured satellites. Because the GPS phase measurements are evaluated in an interferometric mode, only the differences in the phase center behavior between the two antennas may be computed. This method has been widely used by different groups to calibrate all major geodetic GPS antenna types (Rothacher et al., 1996; Mader, 1999).

Absolute field calibrations may be performed using a high-precision robot that rotates and tilts the antenna to be calibrated while the reference antenna is kept fixed. This calibration method was jointly developed by the Institut für Erdmessung, University of Hannover (Prof. G. Seeber) and the company Geo++ and is described in detail by Menge et al. (1998) and Wübbena et al. (2000).

This third method combines most of the advantages of the other two techniques: It gives absolute calibration values; the entire hemisphere of the antenna can be homogeneously covered with observations; multipath can be eliminated in the analysis procedure; phase center patterns may be obtained down to zero degrees elevation; the determination of azimuthal variations does not suffer from the northern and southern "hole" in the satellite constellation; and the antenna is set up in a usual environment with normal geodetic receivers tracking real GPS signals (as opposed to the setup in an anechoic chamber). The robot needed to do this type of calibration has to be extremely precise in positioning the antenna and is therefore very expensive.

COMPARISON OF ANTENNA PHASE CENTER OFFSETS AND VARIATIONS

In order to assess the quality and consistency of the different calibration methods four sets of antenna calibration values have been compared:

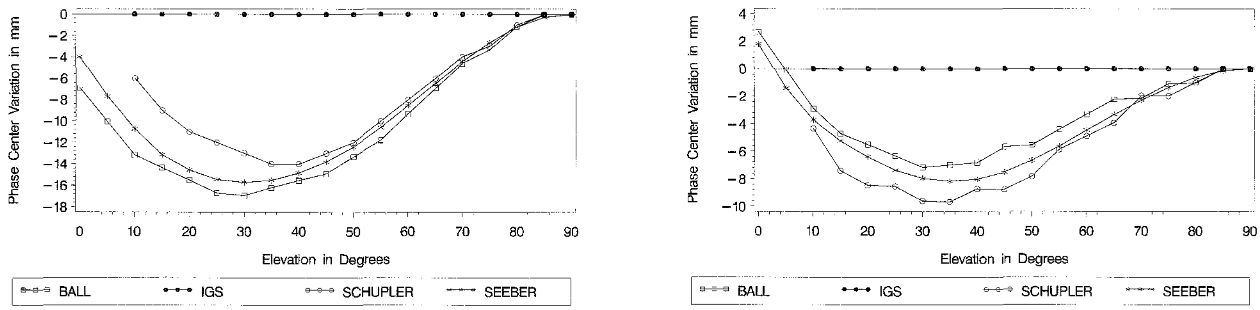
- Anechoic chamber measurements were determined by Schupler et al. in 1994 and 1995 (Schupler et al., 1996). These absolute phase center calibrations will be called "Schupler" in the following.
- With a considerable effort UNAVCO performed measurements in an anechoic chamber operated by Ball Aerospace in 1995 (Rocken et al., 1996). Much care was taken to establish the exact point of rotation of the antenna in the chamber setup. We will refer to these calibration sets as "Ball."
- The absolute field calibrations obtained by Prof. Seeber in 1999/2000 using a robot were already described above and will be named "Seeber."
- The antenna calibration values used as a standard by the International GPS Service (IGS) (see ftp://igscb.jpl.nasa.gov/igscb/station/general, file igs_01.pcv) were computed in July 1996, combining the relative field calibration results of several groups to obtain the best possible set of calibration values. The IGS values are given relative to the AOAD/M_T choke ring antenna (Dorne Margolin T). For this reference antenna, mean offsets of 11.0 cm and 12.8 cm were adopted for the L1 and L2 phase center, respectively, and the elevation-dependent corrections were defined to be zero for all elevation angles. The relative IGS values will be denoted by "IGS."

Three antenna types took part in all the four calibration activities, namely the AOAD/M_T and the two Trimble antennas TRM22020.00+GP and TRM14532.00.

When comparing the horizontal mean offsets of the four sets, the agreement is in general well below 1 mm for each of the three antennas. The maximum difference found actually amounts to 1.1 mm. The mean offsets in height show a much larger variation of up to 10 mm between the four sets. We have to keep in mind, however, that the height offsets are mean values and depend on the elevation range and distribution of the measurements considered in the averaging process. The four sets differ in how these mean offsets were defined. This explains the relatively large differences between the sets. Only a mean offset together with the corresponding elevation-dependent variations of the antenna phase center will give a unique description of the elevation dependence of the antenna. Let us therefore compare the elevation-dependent variations of the phase center given by the three sets with absolute calibration values ("Schupler," "Ball," and "Seeber"). In order to do this the elevation-dependent variations of each set have to be referred to the same mean antenna offset. The results of the comparisons after this transformation are shown in Figure 1 for all three antenna types and both frequencies.

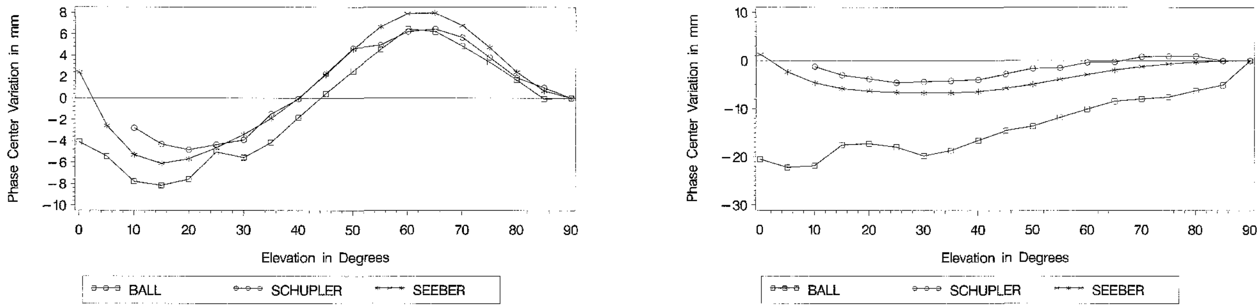
Figures 1(a) and 1(b) show that there is a very good agreement between the three sets of absolute calibrations for the AOAD/M_T antenna. The discrepancies are of the order of 1–4 mm. This is very encouraging, because the patterns "Ball" and "Seeber," which are very close, were derived with two fully independent techniques.

We also added the values used by the IGS in Figures 1(a) and 1(b) to show that the adoption of zero elevation dependence for the IGS values is not compatible at all with the absolute calibration results. This will be discussed in more detail in the next section.



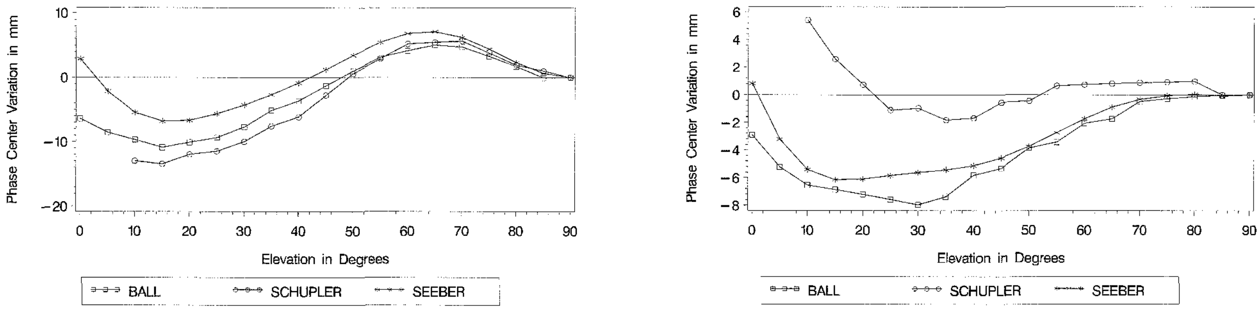
(a) AOAD/M_T, L1 Frequency

(b) AOAD/M_T, L2 Frequency



(c) TRM14532.00, L1 Frequency

(d) TRM14532.00, L2 Frequency



(e) TRM22020.00+GP, L1 Frequency

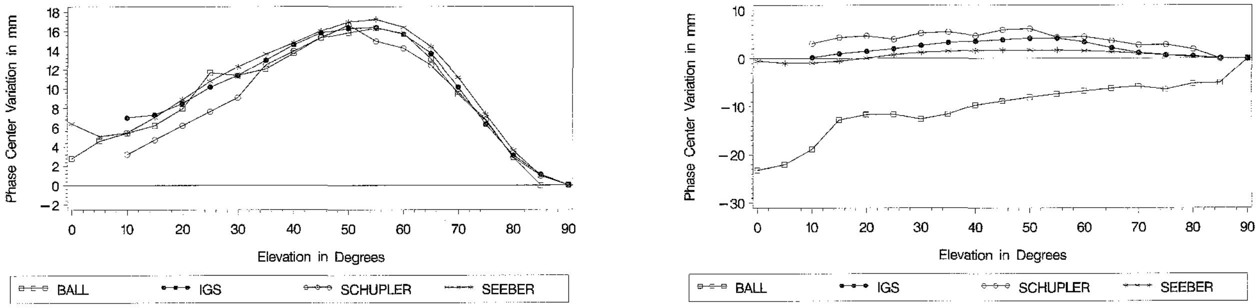
(f) TRM22020.00+GP, L2 Frequency

FIGURE 1. Comparison of absolute elevation-dependent antenna phase center variations from different calibration methods for three different antenna types and both GPS frequencies.

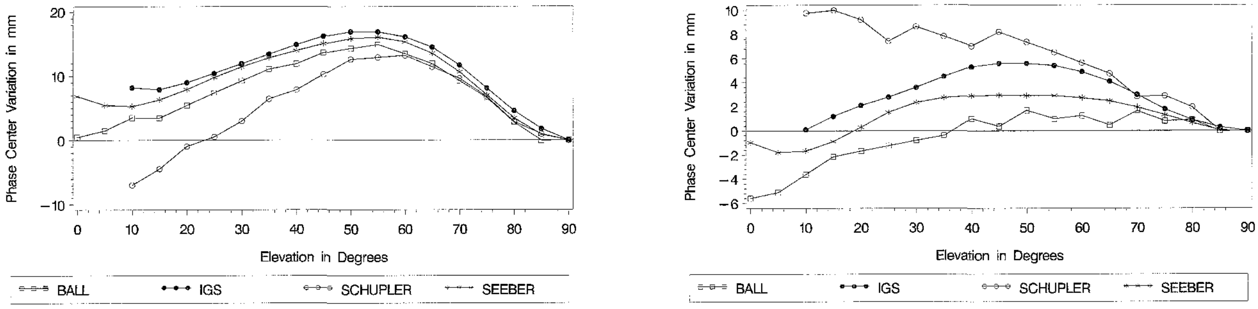
The comparison results for the TRM14532.00 antenna are given in Figures 1(c) and 1(d). Whereas the results are pretty consistent for the L1 frequency, we see that the "Ball" values in L2 differ from the other sets by up to 2 cm. Such a deviation might be caused by using a height for the antenna rotation point, that is in error by 2 cm. Finally, the patterns of the TRM22020.00+GP antenna depicted in Figures 1(e) and 1(f) show differences of maximum 10 mm in L1. In L2, the "Ball" and "Seeber" patterns agree very well, but the values by "Schupler" are offset by several millimeters. Part of the discrepancies might be due to differences between antennas of the same type, but some unexplained variations remain between the various techniques that are not yet understood and need further investigations.

In order to assess how well these absolute patterns agree with the relative IGS values, we formed differences between pairs of antenna patterns. The AOAD/M_T antenna was thereby used as reference antenna. The comparisons of the relative patterns are shown in Figure 2.

The elevation dependence of the TRM14532.00 relative to the AOAD/M_T antenna of all four calibration sets are in very good agreement for the L1 frequency. In L2, only the "Ball" chamber measurements show a large deviation, which we already detected in Figure 1(d). In particular the IGS and the "Seeber" values, both computed from GPS field calibrations, show a remarkable consistency at a level of 1–2 mm. This is also true for the relative pattern between the second pair of antennas (TRM22020.00+GP and AOAD/M_T), whereas the other



(a) TRM14532.00–AOAD/M_T, L1 (b) TRM14532.00–AOAD/M_T, L2



(c) TRM22020.00+GP–AOAD/M_T, L1 (d) TRM22020.00+GP–AOAD/M_T, L2

FIGURE 2. Comparison of relative elevation-dependent antenna phase center variations from different calibration methods; reference antenna AOAD/M_T.

sets ("Ball" and "Schupler") sometimes deviate by several millimeters. We therefore conclude that the absolute field calibrations from the robot are very promising and might form the basis for the introduction of absolute antenna phase center variations within the IGS in the near future.

EFFECT ON GLOBAL GPS SOLUTIONS

Absolute antenna phase patterns have been available from chamber measurements for several years. We may ask, therefore, why the IGS did not make any use of absolute PCVs and stayed with the relative patterns, which are based on the unfounded assumption that the elevation dependence of the AOAD/M_T antenna should be zero. The reason is that the absolute patterns differ very much from the IGS values (see Figure 1(a) and (b)) and give very different solutions for global station coordinates. The absolute patterns ("Ball," "Schupler," or "Seeber"), when used in global GPS solutions, lead to a terrestrial frame scale change of about 15 ppb in the global network. This scale factor of 15 ppb corresponds to a height change of about 10 cm in all global sites, a change that is 5–10 times greater than the quality of present IGS results and is in obvious conflict with results from Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) (Springer, 1999). When introducing the IGS values into a global solution, however, the resulting scale is consistent with the VLBI- and SLR results on the level of 1–2 ppb. For this reason, most GPS analysis experts did not really trust the chamber calibration values. In the previous section, we have seen that the "Ball" chamber measurements and the absolute calibration values of "Seeber," two sets produced using fully independent calibration methods, are very consistent for the AOAD/M_T antenna, the antenna most commonly used in the IGS network. Furthermore, the relative patterns computed from the "Seeber" values (by forming differences between antennas) are in very good agreement with the IGS values.

We are forced to draw the conclusion, therefore, that the absolute PCV for the AOAD/M_T are most probably correct and that another unmodeled effect has to be the cause of the unacceptable scale factor of 15 ppb: the position of the satellite antenna phase center.

THE SATELLITE ANTENNA PHASE CENTER

It is interesting to note that, in contrast to receiver antennas, very little is known about the mean offsets and phase center variations of the satellite antennas. In view of the fact that the "satellite antenna" actually consists of an array of individual helical antennas, it is quite evident that the satellite antenna phase center may vary with the direction of the emitted signal. Only one offset value, however, is known for each of the satellite blocks (Block I, Block II, Block IIA, Block IIR) and it is not even clear whether these offsets denote the phase center of the L1 or L2 frequency or perhaps the phase center of the ionosphere-free linear combination of L1 and L2, which is of more importance for global solutions.

When looking at Figure 3 we can easily determine that a one-to-one relationship can be established between elevation-dependent PCVs of the satellite antenna and those of the receiver antenna. The nadir angle z' at the satellite is related to the zenith angle z for the receiver at the ground by

$$\sin(z') = \frac{R}{r}\sin(z)$$

where R is the Earth radius and r the geocentric distance of the satellite. Whereas the zenith angle z at the receiver ranges from 0° to 90°, the corresponding nadir angle z' as seen from the satellite only varies between 0° and 15°. An elevation-dependent phase center pattern $\Delta\phi(z)$ of the receiver antenna may then be interpreted as a phase center pattern $\Delta\phi'(z')$ of the satellite antenna and vice versa with

$$\Delta\phi'(z') = \Delta\phi(z)$$

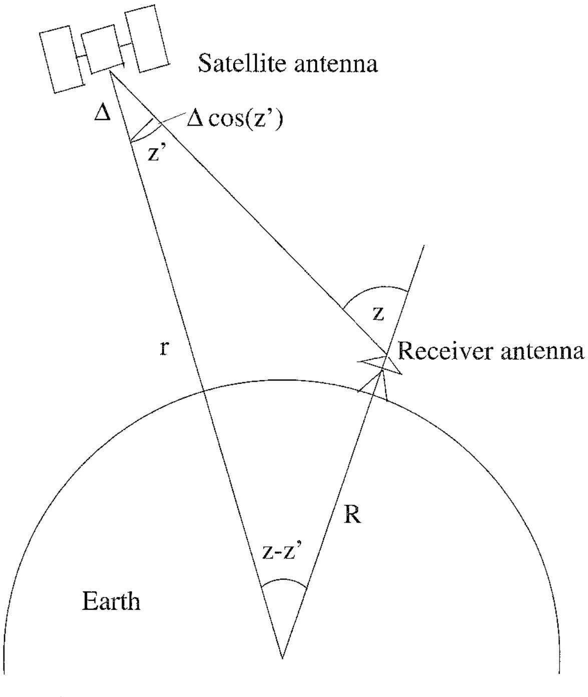


FIGURE 3. Relationship between satellite and receiver antenna phase center variations.

An elevation-dependent pattern of the satellite antenna may be obtained simply by changing the satellite antenna offset by the amount Δ (see Figure 3). The corresponding change in the satellite antenna pattern is then given by

$$\Delta\phi'(z') = \Delta \cdot (1 - \cos(z')) = \Delta \cdot \left(1 - \sqrt{1 - \frac{R^2}{r^2}\sin^2(z)}\right)$$

In order to approximately compensate for the difference between the IGS values and the absolute calibrations values (see Figures 1(a) and (b)), the satellite antenna offsets would have to be changed by about 2 m (in the direction towards the Earth). This is illustrated by Figure 4, where estimates of the satellite antenna offsets from the GPS data (corrections to the a priori values used by the IGS) are given for 5 global 1-day solutions in 1999 with the "Ball" PCV values applied. Although this seems to be a large change, we should keep in mind that, first, the phase center of the ionosphere-free linear combination (which is of most importance here) is a linear combination of the L1 and L2 phase center positions and may be much larger than the offsets of the individual frequencies and, second, that the same effect may also be produced by a real dependence of the satellite antenna phase center from the emission direction. A change of the satellite antenna phase pattern of about 2 cm over the 15-degree range—i.e., the difference between the IGS and the absolute calibration values in Figures 1(a) and (b)—would be sufficient to explain the scale problem apparently created by the absolute receiver antenna pattern.

Thus, before we can adopt any absolute antenna PCVs for the receiver antennas, we have to determine satellite antenna offsets (and possibly antenna patterns) that are consistent with the absolute antenna PCVs on the receiver side, i.e., that will not result in a wrong scale of the global network.

A joint working group of the IGS, the IVS (International VLBI Service) and the ILRS (International Laser Ranging Service) is presently studying whether VLBI could be used to obtain information about the satellite antenna phase center. Another possibility to establish the position of the satellite antenna phase center would be calibration measurements of a GPS satellite antenna on the ground before the launch.

CONCLUSIONS

With results available from the new antenna calibration method developed at the Institut für Erdmessung, University of Hannover, and the company Geo++ using a robot to rotate and tilt the GPS antenna, the absolute

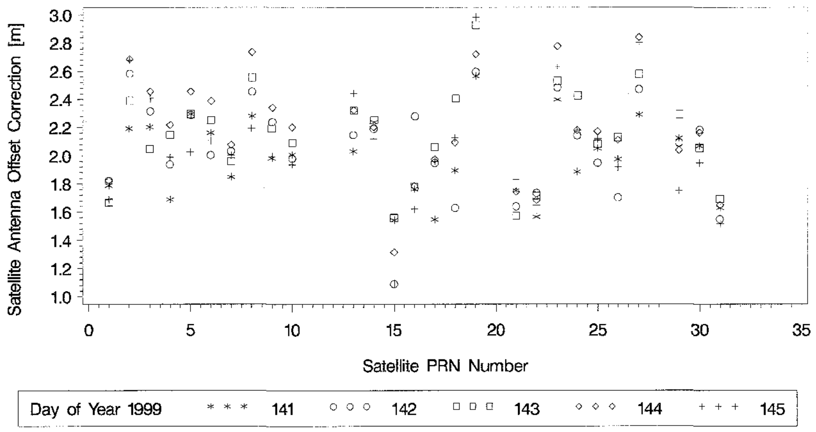


FIGURE 4. Estimation of satellite antenna offset corrections from five global 1-day solutions in 1999 using the "Ball" PCV values for the receiver antenna patterns.

antenna PCVs from two independent approaches (field calibrations and chamber measurements) can now be compared. In general, the two methods are in good agreement, especially for the AOAD/M_T antenna, the reference antenna of the IGS calibration values. The values derived by the Hannover group are also very consistent with the relative IGS values on the level of 1–2 mm.

Through these comparisons it became clear that the absolute patterns are most probably correct and that the scaling of the global GPS solutions by 15 ppb has to be due to poorly known offsets and variations of the satellite antenna phase center.

It will be the goal for the next release of IGS antenna calibration values to supply an accurate set of absolute PCVs for all major geodetic antenna types down to 0° degrees elevation together with a consistent set of satellite antenna offsets (and, if necessary, elevation-dependent variations) to avoid the wrong scaling of global (and regional) GPS solutions when using the absolute PCVs for the receiver antennas.

The establishment of precise satellite antenna PCVs using VLBI or by calibrating a satellite antenna on the ground will be a challenging task for the future. ■

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BIOGRAPHY

Markus Rothacher got his Ph.D. in astronomy from the Astronomical Institute, University of Berne, Switzerland. From 1992 to 1999 he was technical director of the CODE Analysis Center of the International GPS Service (IGS), head of the GPS group in Berne, and responsible for the development of the Bernese GPS Software. Since 1999 he has been Professor for Space Geodesy at the Institute of Astronomical and Physical Geodesy, Technical University of Munich, and head of the Research Facility on Satellite Geodesy (FESG).