AZIMUTH- AND ELEVATION-DEPENDENT PHASE CENTER CORRECTIONS FOR GEODETIC GPS ANTENNAS ESTIMATED FROM GPS CALIBRATION CAMPAIGNS

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ABSTRACT

Using the GPS data of a special antenna calibration campaign involving most of the current high-precision geodetic receivers, mean antenna offsets and elevation- and azimuth-dependent phase center variations were estimated. The phase center variations were modeled using spherical harmonics. Due to the fact that the antennas were rotated by 180° and also interchanged between sessions, it was possible to estimate site coordinates *and* horizontal antenna phase center offsets at the same time. Rotating the antennas also made it possible to distinguish between multipath and real antenna phase patterns in the azimuth and to solve the problem posed by the "northern hole" in the satellite distribution.

INTRODUCTION

It is well-known that biases caused by phase center variations are one of the accuracy-limiting factors in high-precision GPS processing, in particular when combining different antenna types. Corrections obtained from anechoic chamber measurements (one of the possibilities to get information on phase center variations) did not find a wide user group so far. When applying these corrections to the processing of short baselines, some inconsistencies still remain. The estimation of antenna phase center variations from GPS phase data — discussed in this paper — represents an alternative method to obtain phase center corrections that is (apart from the absolute calibration) independent of anechoic chamber results and allows to check and complement those. Only the differences between antenna phase center variations are, however, accessible to GPS.

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THE WETTZELL ANTENNA CALIBRATION CAMPAIGN

In spring 1995, March 20–24, an antenna calibration campaign was organized by the *Institut für Angewandte Geodäsie (IfAG)* in Wettzell. IfAG was supported by the *Deutsches Geodätisches Forschungsinstitut München* supplying two Wild GPS Systems 200 and the *Institut für Erdvermessung, Universität Hannover*, contributing two Ashtech Z-12 receivers. Observations were taken during 4 sessions of 24 hours each. Between day 079 and 080 (first and second session) all antennas — with the exception of the permanent Rogue and Turborogue antennas (points L and M) — were rotated by 180°. For days 081 and 082 the antennas were switched between the pillars. The details of the observation scenario are summarized in Table 1. Table 1 also lists the various antenna types involved.

	Day 079		**Day 080**		**Day 081**		**Day 082**	
	Antenna	**N/S**	**Antenna**	**N/S**	**Antenna**	**N/S**	**Antenna**	**N/S**
A	Trimble Comp. 1	N	Trimble Comp. 1	S	Trimble Geod. 2	N	Trimble Geod. 2	S
B	Turborogue 1	N	Turborogue 1	S	Trimble Comp. 2	N	Trimble Comp. 2	S
C	Ashtech 1	N	Ashtech 1	S	Leica Inter. 2	N	Leica Inter. 2	S
D	Leica Inter. 1	N	Leica Inter. 1	S	Turborogue 2	N	Turborogue 2	S
E	Trimble Geod. 1	N	Trimble Geod. 1	S	Ashtech 2	N	Ashtech 2	S
F	Leica Inter. 2	N	Leica Inter. 2	S	Turborogue 1	N	Turborogue 1	N
G	Ashtech 2	N	Ashtech 2	S	Leica Inter. 1	N	Leica Inter. 1	N
H	Turborogue 2	N	Turborogue 2	S	Trimble Comp. 1	N	Trimble Comp. 1	N
I	Trimble Comp. 2	N	Trimble Comp. 2	S	Trimble Geod. 1	N	Trimble Geod. 1	N
K	Trimble Geod. 2	N	Trimble Geod. 2	S	Ashtech 1	N	Ashtech 1	N
L	Rogue IGS	N	Rogue IGS	N	Rogue IGS	N	Rogue IGS	N
M	Turborogue IGS	N	Turborogue IGS	N	Turborogue IGS	N	Turborogue IGS	N

Table 1: Observation Scenario of the Wettzell Antenna Calibration Campaign, March 20–24, 1995. The column "N/S" gives the orientation of the antenna.

ESTIMATION STRATEGIES

The processing of the GPS data was performed in two steps: (1) the estimation of mean antenna phase center offsets and (2) the estimation of elevation- and azimuth-dependent phase center variations.

In the first step the antenna phase center *offsets* were estimated *together* with site coordinates. This was possible because most of the antennas were rotated by 180° between the sessions. The *Bernese GPS Software* was modified to enable the estimation of horizontal and vertical antenna offsets allowing different antenna orientations and grouping of antennas. To prevent the normal equation system from becoming singular all site coordinates were constrained in all components within 3 mm to the terrestrial ground truth values. *Horizontal* antenna offsets were freely estimated except those of the two IGS sites where the antennas were not rotated (see Table 1) and where therefore 3-mm constraints were applied. All *vertical* offsets were constrained with 5 cm. To avoid a deterioration of the results due to multipath an elevation cut-off angle of 20° was used in this step.

The second step consisted in estimating the coefficients of a *spherical harmonics expansion* of the elevation- and azimuth-dependent phase center variations (see also (Rothacher et al., 1995) for details on this modeling technique). When only elevation-dependent coefficients were determined, the *station heights* had to be fixed to their ground truth values. Coefficients up to degree 10 and order 0 (11 parameters) were estimated. To compute both the elevation- and azimuth-dependence *all three components* of the site coordinates had to be fixed. Here coefficients up to degree 10 and order 5 (91 parameters) were set up. For all computations of the second step the *Trimble Geod. 1 antenna* was used as a reference antenna — only differences between antenna phase variations may be determined by GPS — and the antenna offsets determined in the first step were introduced. As we will see later, the multipath environment is certainly not optimal around the Wettzell facilities (radio telescopes and buildings). Therefore phase center variations were estimated down to 15° elevation only.

RESULTS

Antenna Phase Center Offsets

The *vertical* antenna phase center offsets computed from a combined solution of all the sessions are given in Figure 1.

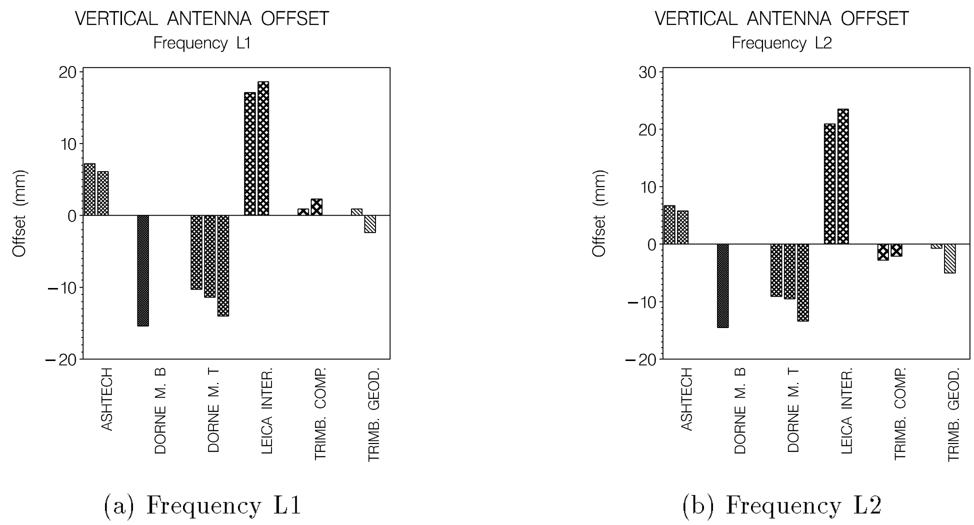


Figure 1: Vertical Antenna Offsets Determined from GPS Data with Respect to the Official IGS Values for Both Frequencies

The zero line is referring to a "mean" offset of all antennas and the values are corrections with respect to the official IGS antenna offsets (see files `ANTENNA.GRA` and `RCVR_ANT.TAB` at the *IGS Central Bureau Information System* described in (Gurtner et al., 1995)). We see that the differences between antenna types may be up to about 3 cm (e.g. Dorne Margolin – Leica Inter.). These offsets are in good agreement with values obtained from the calibration campaign published in (Rothacher et al., 1995). The site coordinates estimated in separate L1 and L2 solutions were compared to each other and to the "ground truth" available allowing for a translation between the individual coordinate sets. The L1 and L2 solutions agreed with each other on the 1 mm level (rms) in all components, whereas an rms of about 2 mm resulted when comparing the L1-solution with the terrestrial solution.

Elevation- and Azimuth-Dependent Phase Center Corrections

The results of the estimation of elevation-dependent variations using all four sessions are given in Figure 2 for the first frequency — corrections obtained with respect to the vertical antenna offsets shown in Figure 1.

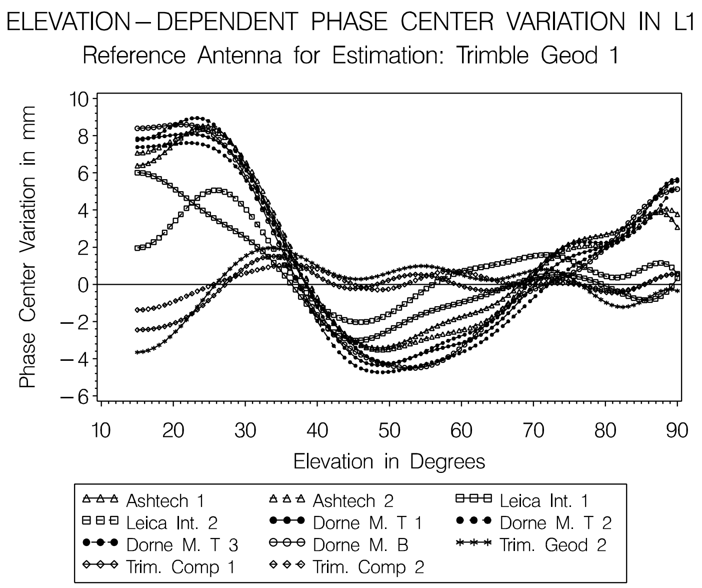
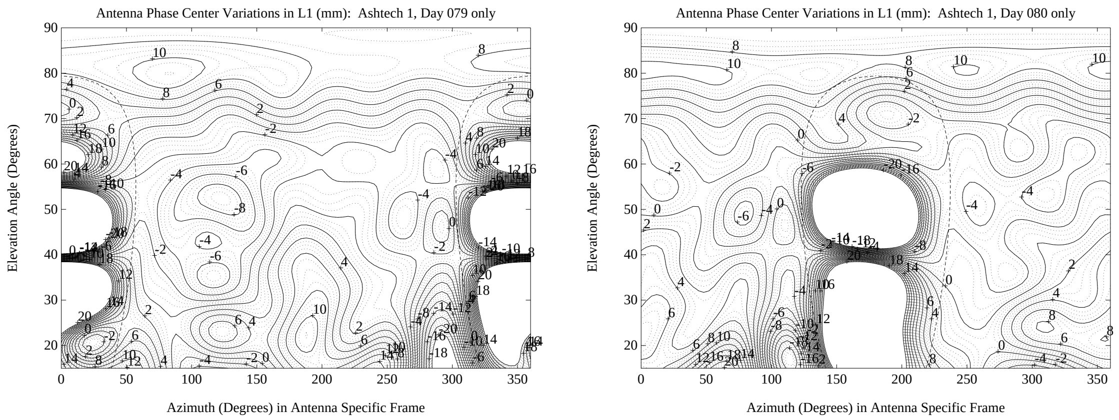


Figure 2: Elevation-Dependent Phase Center Variations in L1 for all Antennas Taking Part in the Wettzell Calibration Campaign

The phase center variations of antennas of the same type are in general consistently determined within about 1 mm. It is also evident that the Ashtech and Dorne Margolin antennas exhibit quite a different elevation-dependence compared to the Trimble Geod. antennas (used as reference here). This differences are responsible for the problems reported by several groups when combining Trimble with Ashtech or Dorne Margolin antennas (see e.g. (Rocken et al., 1992), (Mader et al., 1994), or (Breuer et al., 1995)).

The advantages gained by rotating the antennas during the campaign are becoming very evident when looking at the azimuth-dependence. Figure 3a shows the phase center variations in L1 in elevation and azimuth for the Ashtech 1 antenna as determined using the data of day 079. The antennas were oriented towards the north for this day. The region in the north, where no satellites can ever be tracked, is surrounded by dashed lines. Figure 3b shows the results for the same antenna pair on day 080, the antennas now being oriented towards the south.



(a) Day 079

(b) Day 080

Figure 3: Elevation/Azimuth-Dependent Phase Center Variations in L1 as determined from GPS Data with respect to the Trimble Geod. 1 antenna

The "azimuth" in Figures 3a and 3b is referring to the azimuth of the antenna alignment (measured relative to the north direction indicated on the antenna itself). Therefore the "northern hole" is at an azimuth angle of 180° in Figure 3b. It is obvious then, that when combining the GPS data of all days into one solution the "northern hole" is no problem any more, so that the azimuth-dependent corrections of the combined solution may also be used for data taken at different geographical latitudes. We would like to point out two different features visible in Figure 3. The values obtained for day 079 (Figure 3a) indicate a large "anomaly" at an elevation of 20° and an azimuth of 290°. The same feature can be detected on the Figure 3b at the same elevation angle but at an azimuth of about 110° (in both cases to the west of the "northern hole"). Therefore this anomaly cannot be part of the antenna phase center behaviour but is probably a multipath effect. We see that this anomaly is extended up to more than 30° elevation, indicating that much care has to be taken not to interpret multipath effects as antenna phase center variations. The combined solution (not shown here) reduces the impact of multipath considerably. The feature at an elevation of about 50° and an azimuth of 120° for day 079, however, reappears at the same location for day 080, as it should happen in the case of a *real* antenna pattern. These examples show the clear advantage of rotating the antennas, when trying to obtain azimuth-dependent corrections.

CONCLUSIONS

Using the GPS data of the antenna calibration campaign organized in Wettzell, by the *Institute for Applied Geodesy*, it could be shown that phase center offsets and elevation-dependent phase center variations may be derived from GPS data. The interchange of antennas between sessions allowed us to estimate not only the antenna offsets but also the horizontal positions of the points.

Because the antennas were pointing towards the north for some sessions and to the south for other sessions azimuth-dependent corrections could be estimated that are not affected by the "depopulated" region of the satellite coverage. In addition it is an interesting method to identify and detect multipath effects. As already pointed out in (Rothacher et al., 1995) phase center variations from chamber tests are necessary to (a) check the results obtained using GPS data only and (b) to get the absolute calibration of the variations not accessible to GPS as an interferometric technique. The combination of both types of results should finally lead to a consistent, reliable set of antenna corrections for all the major geodetic antenna types. There is still some way to go before reaching this goal.

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