From Relative to Absolute Antenna Phase Center Corrections

Ralf Schmid
Institut für Astronomische und Physikalische Geodäsie, TU München
Gerry Mader
US Department of Commerce, NOAA, Geoscience Research Division
Tom Herring
Massachusetts Institute of Technology

1 Introduction

In order to achieve high-precision GPS results it is necessary to know the exact position of the phase center of the transmitting as well as of the receiving GPS antenna. For many years, relative phase center offsets and variations have been used within the IGS community that can be estimated from the GPS data collected on a short well-known baseline.

These relative phase center corrections, however, are based upon the arbitrary assumption that the phase center variations (PCVs) of the reference antenna `AOAD/M_T` are zero. Moreover, it is impossible to correctly take into account the phase center positions when processing long intercontinental baselines, or simply when the receiver antenna is tilted. Relative antenna calibrations in the field do neither permit a homogeneous distribution of observations with regard to the antenna hemisphere nor the estimation of PCVs below an elevation angle of 10° (at the moment). In addition, relative receiver antenna PCVs contain site-dependent multipath effects. Finally, the systematic PCVs of the different satellite blocks cannot be taken into account using relative receiver phase center corrections only.

Due to this list of disadvantages, relative phase center corrections can no longer satisfy the increasing accuracy requirements. Site positions should be known to the few millimeter level for many geodetic and geophysical applications; people need to use low-elevation observations in order to probe the atmosphere (where relative calibration results are missing!) and the combination of GPS with other space-geodetic techniques is very difficult if any unmodeled systematic technique-specific effects are present.

The only way out would be a transition from relative to absolute phase center corrections. The absolute corrections for the receiver antennas can be obtained from two independent methods: the measurements in an anechoic chamber and the field measurements on a short baseline using a robot capable of tilting and rotating one of the antennas. Recent calibrations by the company Geo++ and the Geodetic Institute of the University of Bonn have shown that both methods agree on the 1 mm-level if one and the same antenna is calibrated. For the absolute satellite antenna corrections presently only one method exists: the estimation from global GPS data. Estimates from two different institutions (TU Munich, GeoForschungsZentrum Potsdam) using two different software packages (Bernese GPS Software, EPOS Software) have shown good agreement ($\approx$ 20 cm for the offsets, $\approx$ 1-3 mm for the patterns). The only problem of introducing the absolute antenna phase center corrections is the fact, that the global terrestrial scale has to be fixed for the estimation of the satellite antenna corrections. But as long as the latter are not known from an independent method the global scale from GPS is doubtful anyway.

In order to prepare the exchange of phase center corrections a test set called *pcv_abs_proposed11.tst* in the new ANTEX format has been compiled by TU Munich that is available at the IGS Central Bureau since March 2003 (*ftp://igscb.jpl.nasa.gov/igscb/station/general/pcv_proposed/*). This consistent set of absolute receiver and satellite antenna phase center offsets and variations contains receiver antenna type means for the most prevalent antennas within the IGS network. The data is made available by the company Geo++ that has a sizeable database at its disposal containing all calibration results of its robot (*http://gnpcvdb.geopp.de*). The phase patterns of these antenna types are both elevation and azimuth dependent. However, the patterns of all the remaining antennas that were converted from the values contained in the official IGS set *igs_01.pcv* by adding the absolute PCVs of the reference antenna `AOAD/M_T` only depend on the elevation. The correction values for the satellite antennas are those estimated by TU Munich from a global data set of six consecutive days in 2002 that should be replaced by estimates over a longer time span.

2 Receiver Antenna Calibration

2.1 Comparison of Antenna Calibrations from Different Methods and Institutions in Germany

[*Rothacher*, 2001] has shown that there is a good agreement (± 1-2 mm) between absolute PCVs from earlier calibrations in anechoic chambers and calibrations by robots in the field as well as between absolute and relative PCVs after adding the absolute PCVs of the reference antenna to the relative patterns. One of the problems of all these comparisons was the fact that they referred to antenna types, but not to identical antennas. Therefore the reason for the discrepancies remained ambiguous: one part was due to the calibration procedure, the other one due to (mostly small) variations of the PCVs within one antenna type.

In order to gain better insight into the performance of the different calibration methods, several institutions in Germany carried out an extensive investigation in 2001 and 2002: a definite set of 5 antennas (3 reference station antennas and 2 rover antennas) was calibrated by 2 institutions using a robot (University of Hannover, Geo++) and by 3 institutions undertaking relative field calibrations (Regional Authorities for Geodesy in Lower Saxony, TU Dresden, University of Bonn). Unfortunately it was not possible to have chamber calibrations involved in these tests. The results were presented at the 4th GPS Antenna Workshop in May 2002 in Hannover (*http://www.sapos.de/4aws.htm*).

Comparing the five individual calibration results, the following could be demonstrated:

- PCVs only depending on the elevation angle differ by up to 2 mm (L1) resp. 4 mm (L2) at the worst.
- PCVs from the two robot calibrations differ only by up to 1 mm (essentially multipath-free).
- Relative field calibrations reveal problems near the zenith (few observations) as well as near the horizon (low-elevation observations affected by multipath, troposphere etc.).
- Absolute PCVs derived from relative field calibrations are a factor of two worse than those from robot calibrations due to systematic multipath effects and due to the errors of the reference antenna calibration.
- Calibration results for reference station antennas show better agreement than those for rover antennas.
- If PCVs depending on the elevation *and* the azimuth are compared, the agreement between individual calibrations is worse.

In August 2002 the University of Bonn and the University FAF Munich had the possibility to calibrate several antennas in an anechoic chamber, among them one that had also been calibrated by the Geo++ robot. The calibration results for this particular antenna agreed on the 1 mm-level. Both the chamber calibrations and the absolute PCVs from robot calibrations are virtually free of multipath (see [*Campbell et al.*, 2004] and [*Böder et al.*, 2001]).

2.2 Problem of Antenna/Radome Combinations

Although it is well known that adding or removing a radome may result in height changes of up to a few centimeters, only one antenna/radome combination (antenna `TPSCR3_GGD` + radome `CONE`) is included in the official IGS phase center correction file *igs_01.pcv* at the moment. For all 75 combinations used in the entire history of the IGS (*ftp://igscb.jpl.nasa.gov/igscb/station/general/uncal_radome.txt*) just antenna-only calibrations are available. Since 27 June 2003 every new combination anyone wants to introduce to the IGS first has to be calibrated. However, this measure does not solve the problem of combinations already in use. Anyhow, for some of these combinations calibration results from Geo++ and/or NGS would exist as can be seen at *ftp://igscb.jpl.nasa.gov/igscb/station/general/radome-calib-table.txt* (relative PCVs could be converted to absolute ones and vice versa). Some of these results might not be freely available, however. Table 1 shows the situation for the IGS00v2 sites.

Table 1: Antenna/radome combinations at IGS00v2 sites.

calibrated?	antenna	radome	sites
not possible	AOAD/M_B	DOME	NYAL
	AOAD/M_B	OSOD	ONSA
	AOAD/M_T	*AUST*	CAS1 CEDU COCO DAV1 KARR MAC1 MAW1 TOW2
not possible	AOAD/M_T	DOME	OHI2 PETP SYOG TSKB
	AOAD/M_T	DUTD	WSRT
	AOAD/M_T	*JPLA*	FAIR GODE GUAM MCM4 MDO1 NLIB SANT TIDB
	AOAD/M_T	SCIS	DUBO FLIN
NGS, Geo++	ASH700936B_M	SNOW	BAHR
NGS, Geo++	ASH700936C_M	SNOW	RIOG
not possible	ASH700936D_M	DOME	ARTU
	ASH700936D_M	JPLA	MAGO
NGS, Geo++	ASH700936D_M	SNOW	TRAB
	ASH700936F_C	SNOW	LAMA
	ASH701073.1	SCIS	THU3 TRO1
not possible	ASH701933B_M	DOME	BILI YSSK
	ASH701933B_M	SCIS	YAKT
	ASH701945C_M	JPLA	EISL
Geo++	TRM29659.00	TCWD	GOUG VES1
NGS	TRM29659.00	UNAV	MANA

It has to be pointed out that `DOME` means any object that cannot be calibrated at all. Perhaps a restriction on such sort of constructions should be considered. The two italicized combinations would be needed most if a calibration of antenna/radome combinations was aimed at. As regards the `JPLA` radome, however, there is no guarantee that it is always mounted in a centered position. For this reason, it is questionable whether a calibration makes sense in that case. If radomes showed strong variations of the phase center in azimuthal direction, a calibration could only be beneficial moreover, if the mount of the radome was reproducible concerning the azimuthal orientation. In any case the best would be to avoid using radomes whenever possible. (See also the new IGS Site Guidelines 2.1.6-2.1.8 and 2.2.5 at *http://igscb.jpl.nasa.gov/network/guidelines/guidelines.html*!)

2.3 Type Mean vs. Calibration of Individual Antennas

The calibration database of Geo++ (*http://gnpcvdb.geopp.de/*) contains the results of about 3000 individual calibrations of about 600 individual antennas. This huge amount of data allows to study the homogeneity of the PCV estimates within one antenna type and the stability of the PCVs for those individual antennas calibrated a second time after a certain time interval (see [*Wübbena et al.*, 2003a]).

As regards the stability, some antennas, particularly rover antennas, exhibit a really bad behavior, so that a change in the characteristics of the antenna phase center due to aging cannot be ruled out. Of course, this conclusion will not change the IGS policy that the worst thing one could do would be to touch the equipment (e.g. to carry out repeated calibrations). But one has to think of the necessity of a local antenna array (with an extension of several meters) that, among other things, would allow the monitoring of the antenna performance and the separation of equipment-induced and geophysical movements (cf. Sect. 6.3).

More important for the practice of IGS reference stations is the conclusion that the PCVs of each individual antenna can easily differ by up to 1 cm from the type mean which is also true for choke ring antennas. Obviously there are antenna types with clear subgroups whose PCVs seem to be rotated by 180°. This could indicate a possible technical failure or modification of the antenna assembly, either of the antenna itself or of the north arrow. In order to detect whether an antenna is an outlier or not, or to find out to which subgroup an antenna belongs, calibrations of each individual antenna would be necessary. As already mentioned above, it does not make sense to touch the equipment in use, but for each new antenna to be introduced into the IGS this procedure should be considered. In Germany, e.g., each individual GPS antenna to be used in the official survey work already has to be calibrated individually. Allowing subgroups would require, of course, new antenna names within the file *rcvr_ant.tab*.

2.4 Site-Dependent Effects: Multipath, Monument Design, ...

Errors due to site-dependent effects are very difficult to reduce and may thus be considered as a major accuracy limiting factor (besides tropospheric refraction) for position determination with GPS in general and for heights in special. Multipath can be divided into two parts: multipath caused by the near field of the antenna (pillar/tripod, tribrach, adapter, marker, ground plane, radome, ...) and multipath caused by the environment. Whereas for the environment-induced multipath one can hope that it averages out over longer time spans, the former part has systematic effects on the position estimate.

In order to demonstrate this effect, [*Wübbena et al.*, 2003b] composed several possible assemblies of reconstructed pillar surfaces, tribrachs and antennas with varying distances between the "pillar surface" and the antenna and calibrated them with their robot. The systematic effects were evident. Increasing the distance between antenna and "pillar surface" (up to a certain value) seems to reduce the multipath effect. Besides, it looks as if symmetric components (round pillars and tribrachs) would be more susceptible to multipath than triangular or quadratic ones. But this will have to be verified by further tests (cf. also [*Elósegui et al.*, 1995]).

The work of the Hannover group (Geo++/IfE) and new developments at Haystack and at NGS (see Sect. 6) might give deeper insight into the possibilities to calibrate site-dependent effects.

3 Satellite Antenna Calibration

3.1 Estimation of Corrections at TU Munich

As already presented at the last IGS Workshop in Ottawa, [*Schmid and Rothacher*, 2003] have estimated block-specific satellite antenna PCVs from global GPS measurements, while absolute PCVs were applied for the receiver antennas. A strong cosine-dependence of the patterns indicating the use of a non-optimal value for the phase center offset, also corrections for the offsets could be found that are of considerable magnitude ($\Delta z_{II/IIA} = +131.5$ cm, $\Delta z_{IIR} = +133.3$ cm). Thus, two different satellite antenna patterns for Block II/IIA and for Block IIR with a range of about 1 cm and an accuracy of better than 1 mm (repeatability from day to day) could be found. Due to the strong dependence of the satellite antenna patterns on the global scale, the ITRF2000 scale stemming from VLBI and SLR had to be adopted. As this dependence also holds vice versa it is clear that GPS is not able to determine the global scale unless the satellite antennas can be calibrated by an independent high-precision method.

3.2 Comparison of Estimates from GFZ Potsdam and TU Munich

In order to validate the results of [*Schmid and Rothacher*, 2003] who used the Bernese GPS Software, M. Ge and G. Gendt from the GeoForschungsZentrum Potsdam made the necessary software modifications to allow for the estimation of satellite antenna patterns by their EPOS Software. In contrast to TU Munich (3°) they used an elevation cut-off angle of 7°, they estimated the patterns as piece-wise constant instead of piece-wise linear functions and they could apply the IGS test set *pcv_abs_proposed11.tst* containing more real absolute receiver antenna calibration results (not only converted from relative PCVs!) than the data set used in Munich. M. Ge and G. Gendt processed the data of the global IGS network from day 291 to day 327 (i.e. 37 days altogether) of the year 2003 (cf. TU Munich: 6 days only!). Besides these differences in the data processing, also the satellite constellation had changed in the meantime due to two Block IIR satellites (PRN16 and 21) launched early in 2003.

Comparing the block-specific offsets derived from the estimated satellite antenna patterns (see Table 2), one can see a difference of 12 cm and 22 cm for Block II/IIA and Block IIR respectively between GFZ and TUM (22 cm of difference in the z-offset correspond to a difference of $\Delta\phi' = -\Delta r \cdot (1 - cos(z')) \approx -6.5$ mm in the pattern for a nadir angle of $z' = 14°$). This discrepancy could be due to the use of different elevation cut-off angles that affect considerably the number of observations for high nadir angles or the different modeling of the patterns (piece-wise constant vs. piece-wise linear functions) that could have an effect if observations were not uniformly distributed. As regards the block-specific patterns, the agreement is much better, as can be seen in Fig. 1. The rms difference is only 1.1 mm and 3.0 mm for Block II/IIA and Block IIR respectively. If the last point of the pattern is ignored, the rms difference is even 0.3 mm and 1.1 mm respectively.

Table 2: Comparison of offset values in z-direction [m].

satellite block	IGS (relative)	TUM (absolute)	GFZ (absolute)	GFZ-TUM
Block II/IIA	1.0230	2.3384	2.4582	0.1198
Block IIR	0.0000	1.3326	1.5534	0.2208

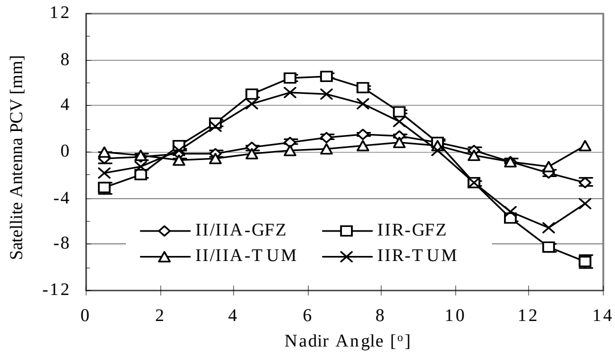

Figure 1: Comparison of satellite antenna patterns (ionosphere-free LC) from GFZ and TUM.

3.3 Grouping of Satellites by GFZ Potsdam

Contrary to TU Munich, GFZ did not only estimate block-specific, but also satellite-specific antenna patterns. This approach allowed to find significant differences in the phase center behavior between certain subgroups of the two analyzed satellite blocks (see Table 3). As the formation of the subgroups as well as the offset differences between the individual subgroups are in good agreement with the results of the former IGS antenna offset campaign (see, e.g., [*Bar-Sever*, 1998]), one can assume that the satellite antenna offsets are not homogeneous within one satellite block. This behavior could also be verified at TU Munich. (Note: The results below differ slightly from those above, as an arbitrary constant was allowed for in the offset estimation instead of fixing the pattern value in nadir direction.)

Table 3: Subgroups of satellite blocks.

satellite block	subgroup	satellites (PRN)	z-offset [m]
Block II/IIA	1	02 05 08 09 10 15 17 24 25 26 27 29 30	2.4056
	2	01 04 07 31	2.1192
	3	03 06 23	2.7251
Block IIR	1	13 14 16 18 20 21	1.2595
	2	11 28	0.9119

On the basis of the GFZ results the question arises how the satellite antenna corrections should be dealt with in the future. As a rule of thumb, [*Zhu et al.*, 2003] stated that changing the offsets of all satellites by Δz [in m] would affect the global scale [in ppb] by $7.8 \cdot \Delta z$. The offsets of the individual subgroups differing by up to 6 dm, a disregard of the subgroups could cause noticeable errors. As the offset estimates of individual satellites within one subgroup differ by up to 2-3 dm (cf. Figs. 2 and 3), one could even think of satellite-specific offsets.

Taking into account the different offsets for the subgroups, one obtains PCVs that only differ by up to 2 mm within one satellite block (see Fig. 4). As there is no reasonable explanation why the patterns should differ in case of identical antennas, one could think of block-specific patterns in contrast to subgroup- or satellite-specific offsets.

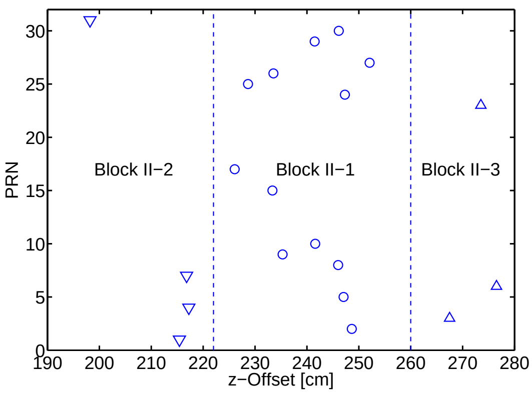

Figure 2: Individual z-offsets for Block II/IIA.

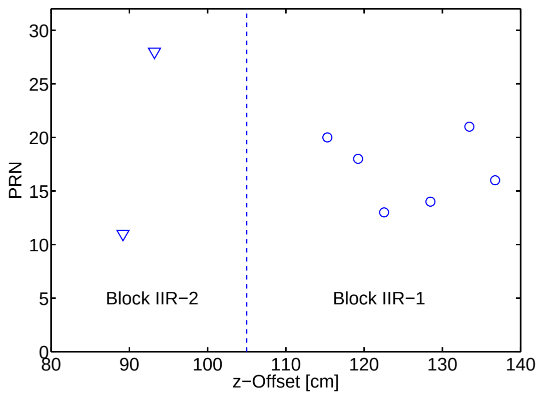

Figure 3: Individual z-offsets for Block IIR.

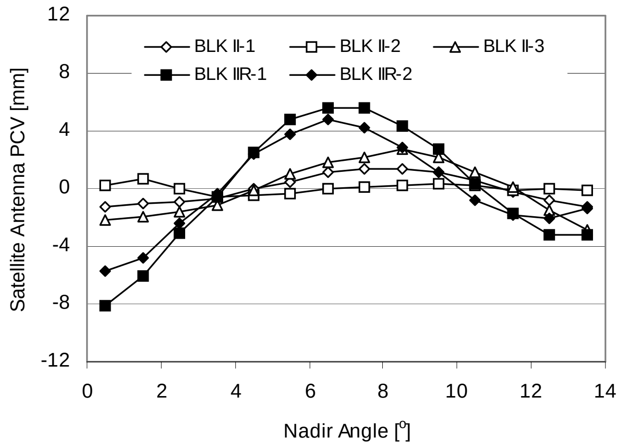

Figure 4: Satellite antenna patterns (ionosphere-free LC) for subgroups of Block II/IIA and Block IIR.

4 Benefit from Absolute Phase Center Corrections

First of all one has to repeat that using absolute phase center corrections allows to eliminate all the disadvantages associated with relative corrections given in Sect. 1: mainly systematic errors due to the convention that the reference antenna is free of PCVs and due to the neglect of satellite antenna PCVs. Besides, in Sect. 2.1 it has been shown that the absolute robot calibration can provide better results than relative field calibrations because it is almost free of multipath, offers a homogeneous distribution of observations and, what is most important, permits the estimation of PCVs also for low elevations.

4.1 Results from TU Munich

In order to demonstrate the effect of the above mentioned improvements on coordinates and troposphere parameters, daily global solutions applying absolute corrections were compared to solutions applying relative ones. As jumps of up to 1 cm have to be expected in all components for the coordinates, the transition from relative to absolute phase center corrections will clearly show up in GPS time series. As expected, the coordinate results, particularly the station heights, depend less on the selected elevation cut-off angle when absolute corrections are applied. Comparing cut-off angles of 15° and 10° the improvement is rather slight. However, the situation changes dramatically when elevation angles below 10° are considered where relative antenna calibration results are completely missing. Normally the PCVs are extrapolated for low elevation angles, some software packages may even put them to zero. As, in addition to station heights, also tropospheric delays are highly correlated with receiver and satellite antenna phase center corrections, the reduction of systematic errors should also benefit the quality of these parameters that are important for meteorological applications. In order to be able to evaluate whether the estimates are better with relative or with absolute corrections one can compare them with results from other observation techniques such as VLBI or water vapor radiometer (WVR) measurements. The existing biases being considerably reduced with regard to both techniques leads to the conclusion that switching to absolute phase center variations is necessary in order to increase the consistency between the different observation techniques (cf. [*Rothacher et al.*, 2003]).

4.2 Results from MIT

First results look promising with regard to the global scale and the overall RMS. More details will be reported in Berne.

5 Status at the IGS Analysis Centers

The status concerning the application and estimation of satellite antenna patterns at the ten current IGS Analysis Centers is given in Table 4. The capability to apply the satellite PCVs is a prerequisite for a transition from relative to absolute antenna phase center corrections. The estimation capability allows the validation of the estimation strategy. In addition, a GPS reprocessing including the estimation of satellite antenna patterns is on its way at TU Munich.

Table 4: Status of satellite antenna patterns at the IGS Analysis Centers.

Analysis Center	application?	estimation?
CODE	x	x
ESOC	?	?
GFZ	x	x
GOPE	?	?
JPL	?	?
MIT	x	–
NGS/NOAA	in preparation	–
NRCan	?	?
SIO	?	?
USNO	?	?

6 New Developments

6.1 Antenna and Multipath Calibration System (AMCS) at Haystack

The procedure for the calibration of site-dependent GPS phase measurement errors (PCVs, multipath, scattering) taking advantage of a steerable multipath-free 3 m-diameter parabolic antenna has already been described in detail by [*Rothacher and Mader*, 2002].

[*Park et al.*, 2004] report on high-frequency multipath errors varying by about 5 mm amplitude over small changes in satellite direction, both in elevation and in azimuth, that are a factor of ten or more greater than the system noise. They also observed day-to-day mm-level changes in the calibration that could be due to changes in multipath caused by changes in the local electromagnetic environment associated with, e.g., weather.

For the time being, [*Park et al.*, 2004] intend to use the AMCS to study the best approach to calibration, to assess the observed variations, and to quantify the effects of environment and weather. Although the construction of "full-sky maps" will remain very time-consuming, as only one satellite in one particular direction can be observed at a time, it is a goal to construct a portable AMCS.

6.2 Phased Array Antenna/Receiver (NAVSYS)

The NAVSYS Corporation, Colorado Springs, Colorado, is testing both 7- and 16-element phased array antenna/receivers. By beam-steering these antennas, multipath from the vicinity of these antennas may hopefully be significantly reduced. If multipath can in fact be suppressed to a sufficiently low level, an antenna that is independent of (or very weakly dependent on) its environment should be the result, yielding uniformly consistent characteristics wherever it is placed. Such an antenna would be essential for the determination of in situ absolute phase patterns - i.e. calibrations that account for the unique effects of the local environment on each individual antenna. At the present time, these antenna/receivers still exhibit some problems, so an evaluation of their multipath suppression capabilities is still waiting. NGS will continue to work with NAVSYS on this approach as well as on some other concepts.

6.3 Local Monitoring of Fundamental GPS Sites

In view of the goal to establish a global terrestrial reference frame with an accuracy of about 1 mm over decades, more and more stringent requirements have to be put on the fundamental stations that are part of the global reference frame definition. As the costs for GPS antennas are manageable compared to the costs of, e.g., VLBI telescopes or manpower, one has to think about the benefit from the installation of further antennas. Besides small networks with an extension of several kilometers that allow the separation of local movements or effects from regional or global plate tectonics, local networks at the station itself (extension of several meters) are of particular interest. They would allow the monitoring of the performance of the GPS antennas and receivers (cf. Sect. 2.3), the influence of the environment on the GPS data (e.g. snow on the antenna, changes in multipath, ...) and the effect of equipment changes on the site coordinates.

7 Recommendations

The sections above have lead to the following recommendations for the "Antenna Effects" session:

1) **Antenna/Radome Combinations**

   - The use of radomes should be avoided at sites to be used for inter-technique comparison unless needed for antenna protection.

- Only radomes that have repeatable calibrations and mountable with reproducible physical relation to the antenna (centered position, azimuthal orientation) should be introduced into the IGS network.
- Combinations of antennas and radomes that are already calibrated by Geo++ and/or NGS should be introduced into *igs_01.pcv* (possibly at the time of the adoption of absolute antenna phase center corrections).
- If new radome calibrations become available, the impact on the RF realization will have to be checked before introduction.
- If existing non-calibrated antenna/radome configurations are removed, they should be calibrated for any future re-analysis.

2) **Subgroups of Receiver Antennas**

If available, subgroups of receiver antennas should be introduced into the files *rcvr_ant.tab* and *igs_01.pcv*.

3) **Local Antenna Arrays**

RF sites should install local antenna arrays in order to guarantee the stability of the global terrestrial reference frame on the (sub-)mm-level.

4) **New Antenna Correction File Format ANTEX**

The ANTEX format (for relative or absolute offsets and patterns) should become the official IGS format.

5) **Absolute Receiver and Satellite Antenna Corrections**

Timescale for the decision on absolute phase center models:

- By June 2004: Reconciliation of the satellite antenna phase center offsets and patterns between the groups generating these results.
- Sep-Dec 2004: IGS AC submission of final products with both relative and absolute phase center models used.
- Jan 2005: Evaluation of the effects of relative and absolute phase center models.
- March 2005: Decision on the adoption of absolute phase center models.

Issues:

- Values for old PRNs and blocks (particularly Block I) are needed.
- Possible time dependence of values as fuel expended on satellites.
- Elevation angle cut-off tests with relative and absolute models (orbits free!).

References

Bar-Sever YE (1998) Estimation of the GPS transmit antenna phase center offset. Presented at the Performance Analysis Working Group (PAWG) meeting 1998 (*http://www.schriever.af.mil/GPS/PAWG/PAWG 1998/Papers/bar-sev.doc*)

Böder V, Menge F, Seeber G, Wübbena G, Schmitz M (2001) How to Deal with Station Dependent Errors - New Developments of the Absolute Calibration of PCV and Phase-Multipath with a Precise Robot. Presented at ION GPS-01, Salt Lake City, Utah (*http://www.geopp.de/download/ion2001-multipath_p.pdf*)

Campbell J, Görres B, Siemes M, Wirsch J, Becker M (2004) Zur Genauigkeit der GPS Antennenkalibrierung auf der Grundlage von Labormessungen und deren Vergleich mit anderen Verfahren. *Allgemeine Vermessungsnachrichten (AVN)*, 1/2004, pp 2-11 (see also *http://www.sapos.de/pdf/5aws/Campbell_AWS03.pdf*)

Elósegui P, Davis JL, Jaldehag RTK, Johansson JM, Niell AE, Shapiro II (1995) Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position. *Journal of Geophysical Research*, Vol. 100, No. B6, pp 9921-9934

Park K-D, Elósegui P, Davis JL, Jarlemark POJ, Corey BE, Niell AE, Normandeau JE, Meertens CE, Andreatta VA (2004) Development of an antenna and multipath calibration system for Global Positioning System sites. Submitted to *Radio Science*

Rothacher M (2001) Comparison of Absolute and Relative Antenna Phase Center Variations. *GPS Solutions*, Vol. 4, No. 4, pp 55-60

Rothacher M, Mader G (2002) Receiver and Satellite Antenna Phase Center Offsets and Variations. Network, Data and Analysis Center Workshop 2002, Position Paper of the "Antenna Session", Ottawa (*http://igscb.jpl.nasa.gov/igscb/resource/pubs/02_ott/session_8.pdf*)

Rothacher M, Thaller D, Schmid R, Krügel M, Tesmer V, Angermann D (2003) Combination of GPS and VLBI Troposphere Parameters of the CONT'02 Campaign and Comparison with WVR. Presented at the AGU Fall Meeting (G42B-02), San Francisco

Schmid R, Rothacher M (2003) Estimation of elevation-dependent satellite antenna phase center variations of GPS satellites. *Journal of Geodesy*, Vol. 77, No. 7-8, pp 440-446

Wübbena G, Schmitz M, Boettcher G (2003a) Analyse umfangreicher Messreihen von GPS Antennen PCV aus absoluten Roboter-Feldkalibrierungen seit Januar 2000. Presented at the 5th GPS Antenna Workshop, Frankfurt/Main (*http://www.sapos.de/pdf/5aws/Boettcher_AWS03.pdf*)

Wübbena G, Schmitz M, Boettcher G (2003b) Zum Einfluss des Antennennahfeldes. Presented at the 5th GPS Antenna Workshop, Frankfurt/Main (*http://www.sapos.de/pdf/5aws/Schmitz_AWS03.pdf*)

Zhu SY, Massmann F-H, Yu Y, Reigber Ch (2003) Satellite Antenna Phase Center Offsets and Scale Errors in GPS Solutions. *Journal of Geodesy*, Vol. 76, No. 11-12, pp 668-672