Estimation and validation of the IGS absolute antenna phase center variations

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Abstract

To validate the IGS proposed absolute antenna phase center variations (APCVs) and offsets for the GPS satellites, an independent APCV model is derived with the EPOS software using data of 90 IGS stations for the days 292 to 326 in 2003. The estimated block-type-specific models agree with the IGS ones within 1 mm rms for the APCVs and about 10 cm in the offsets. However, we found significant differences up to 0.8 m in the offsets among satellites belonging to the same block type. The APCVs for the individual satellite could be divided into 5 groups. Therefore, we suggest group-specific APCVs plus satellite-specific offset for IGS application. Furthermore, the same data set is also analyzed fixing the IGS proposed APCVs and offsets. Their impact is investigated by comparing the new results with those using the relative PCVs and offsets.

1. Introduction

It is well known that antenna phase center variations (PCVs) must be taken into account for precise applications. Until now, only relative PCVs, referred to the Dorne Magolin T antenna, are used in the IGS data analysis. This is not sufficient for global GPS networks, where over longer baselines the satellites are observed with different parts of the antenna in addition to varying cut-off angles and distributions of satellites in view. The recent developments in the absolute antenna calibrations provide more reliable absolute phase center variations (APCVs) to be used for precise modeling. Therefore, the IGS is speeding up the planned transition from the relative to absolute PCV models. For clarification, in this paper 'PCV model' means PCVs and the related offsets.

Several tests have shown that using the APCV models for receivers results in a terrestrial frame scale change of about 15 ppb. Rothacher [2001] concluded that the scale change is most likely caused by a wrong position of the satellite antenna phase center, which is very little known. Under the assumption that all satellites of the same block type have the same PCV and offset, block-type-specific APCV models are estimated by Schmid and Rothacher [2003] using the BERNESE software and data of more than 100 stations for the days 195 to 200 in 2002. The solution was made available as the IGS proposed model, which includes receiver and satellite antenna APCV models and should be checked by the IGS Analysis Centers.

To validate the IGS APCV and offsets for the satellites, we first estimated the combined effect of phase center variation and offset as raw PCV parameters for each satellite as described by Schmid and Rothacher [2003]. Then the estimates were converted to offsets and PCVs. We obtained a block-type-specific APCV model for the satellites, which is in good agreement with the IGS values. However, we noticed a significant difference in raw PCVs even among satellites belonging to the same block types. The differences are mainly caused by the fact that the offsets within one block type are not homogeneous. According to the converted PCVs, satellites should also be divided into groups with clear but small difference in PCVs. Therefore, we suggest group-specific PCVs and satellite-specific offsets as the APCV models for the IGS. To assess the impact of the APCV models on the IGS products, the same data set is analyzed using exactly the same strategy as it is used for the IGS final data processing at GFZ. The products including orbits, clocks, station coordinates and zenith total delay, derived with the relative and absolute PCV models are investigated.

2. Strategy for estimation

In practice, the position of the actual antenna phase center is described by a mean phase center with a constant offset to a physical point on the antenna and the variation to the mean phase center with respect to the signal transmitting direction, i.e. offset and PCV. A change of the phase offset can be balanced by a corresponding change of the PCV. That indicates that offset and PCV are fully correlated and cannot be estimated simultaneously from GPS observations. We only estimate their combined effect, which is called the "raw PCV" in the following. For an observation to a satellite i with offset Δr_i and PCV correction of $pcv_i(\phi)$ at nadir angel ϕ, its correction due to PCV and offset is

$$\begin{aligned}\delta obs_i(\phi) &= pcv_i(\phi) - \Delta r_i \cos\phi \\ &= pcv_i(\phi) + \Delta r_i (1-\cos\phi) - \Delta r_i = p_i(\phi) - \Delta r_i\end{aligned} \tag{1}$$

where, $p_i(\phi)$ is the raw PCV and the constant part Δr_i will be absorbed by the satellite clock parameter.

The raw PCV of each satellite is modeled by a piece-wise constant function of the nadir angle of the signal transmitting direction, so we have

$$p_{i,j} = p_i(\phi_j) = pcv_i(\phi_j) + \Delta r_i (1-\cos\phi_j) \quad \text{, j – index for nadir interval.} \tag{2}$$

It is easy to understand that the raw PCV of a satellite is correlated with the satellite clock. A satellite clock bias can be interpreted as a constant shift in the PCV or vice versa. To prevent the singularity of the normal equation, the following constraint over all the parameters for an individual satellite is imposed,

$$\sum_{j=1}^{n} p_{i,j} = 0 \ . \tag{3}$$

Additionally, antenna offsets correlated with the terrestrial frame scale. Zhu et al. [2003] pointed out that an offset of 1 m for all satellites leads to about 7.8 ppb scale change. Therefore, we have to fix the scale, by constraining a sufficient number of well-determined stations, while estimating raw PCVs, i.e. the result depends on the defined reference frame.

The receiver antenna APCV models must also be fixed. They are correlated with the raw PCVs for the satellites through the one by one relationship between nadir angle and elevation of the signal receiving direction, i.e. the estimated raw PCVs for the satellites depend on the PCV models of receiver antennas.

An optional constraint on PCV parameters of any two satellites can be applied to get the common PCVs for them. This can be used to compute for example block-type-specific or group-specific PCVs. For satellite i and k, the constraint reads as

$$p_{i,j} - p_{k,j} = 0 \quad , \quad j = 1,2,...n \ . \tag{4}$$

To separate offset and PCV, we can assume that e.g. the PCV value on the geometrical top of the antenna is zero, or the PCV should have the smallest deviations (the most flat PCV). From the estimates, the most flat PCV and related offset can be separated by the following least squares fit,

$$\sum_j \left[p_{i,i} - a_i - \Delta r_i \left(1-\cos\phi_j\right)\right]^2 = \min \, , \tag{5}$$

where a_i is the constant part in raw PCV and the residuals of the fit are the most flat PCVs.

In summary, PCV and offset of a GPS satellite are estimated together as raw PCV by fixing APCV models for receivers as well as the scale of the terrestrial network. The sum of the raw PCV values for each satellite is constrained to zero for separating raw PCV and satellite clock parameters. The raw PCV is separated into the most flat PCV and the related offset by means of least squares fit.

3. Data processing

The GFZ EPOS software was modified for both using APCV models (for satellites and receivers) and estimating raw PCVs for satellites. Five weeks of data from 90 IGS stations for days 292 to 326 in 2003 were analyzed to estimate satellite APCV models and to validate the IGS proposed APCV models for both satellites and receivers.

The data processing procedure was kept the same as that for our IGS routine data processing. We used 24-hour arc length, 5 minute sampling rate, 7° cutoff elevation angle and an elevation dependent weighting. Receiver PCVs and offsets were fixed to the IGS proposed models. For all satellites, raw PCVs were estimated as piece-wise constant functions with the IGS offsets of 2.3384 m and 1.3326 m for II/IIA and IIR as initial values, respectively. Together with the raw PCV parameters, station coordinates, satellite orbits, earth rotation parameters, satellite and receiver clocks and zenith total delays every 4 hours and ZTD gradients in east and north directions every 12 hours at each station were estimated as well. Then for each day, 3-day normal equations, by adding one day before and one after, were combined to obtain the daily raw PCVs by fixing station coordinates to IGS00 and imposing constraint (3). For block-type-specific or group-specific raw PCVs proper constraints of type (4) were additionally implemented. The daily raw PCVs were then averaged and converted to PCVs and offsets for further analyses and comparisons.

For validation of the given IGS APCV models, daily solutions were derived in the same way except that the satellite PCVs were fixed to the given IGS values.

4. Results of the estimation

4.1. Estimated PCVs

Figure 1 shows the daily estimated raw PCVs of PRN 01. The scattered smaller symbols indicate the daily estimates and the large squares and triangles are for the mean and repeatability, respectively. The repeatability with an average of 0.6 mm, gets worse at the boundary areas to 1 mm, where observations are few or deweighted.

Figure 2 summarizes the mean of the raw PCVs for all the satellites observed in the data interval. The difference between satellites belonging to II/IIA and IIR is very clear. All block IIR satellites have a curve with a peak in the middle while the others are rather flat. The differences among satellites belonging to the same block types are significant, up to 10 mm at the boundary areas. Simply assuming as usual that satellites belonging to the same block type have the same antenna offset and PCV is not correct.

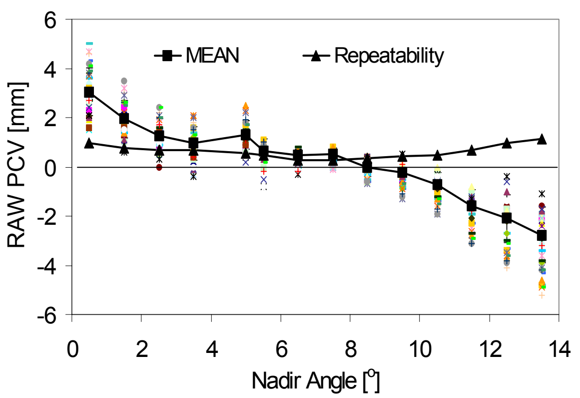

Figure 1. Estimated daily raw PCVs for PRN01.

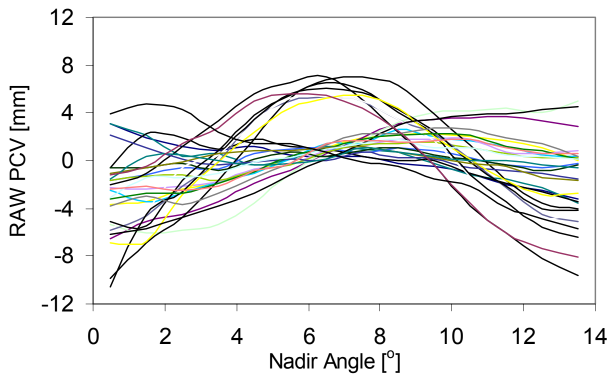

Figure 2. Mean raw PCVs for all satellites.

4.2. Comparison with IGS results

For a direct comparison with the IGS proposed models, we imposed a tight constraint on raw PCVs for satellites belonging to the same block type and convert the resulting estimates to offsets and PCVs. Figure 3 shows the PCVs results from IGS and GFZ, and Table 1 lists the statistics of the comparison.

The PCVs agree with ±1.1 and ±3.0 mm standard deviation for Block II/IIA and IIR, respectively. The major difference is from the last point. Ignoring the last point, the agreement is ±0.3 and ±1.1 mm.

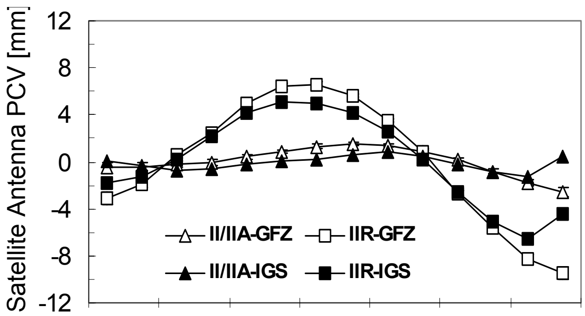

Figure 3 Comparison of PCVs of GFZ and IGS

	OFFSET	PCV Dif		PCV Dif(*)	
		Mean	STD.	Mean	STD
II/IIA	119.8	-0.1	1.1	-0.4	0.3
IIR	220.8	0.2	3.0	-0.2	1.1

Table 1 Comparison of offsets and PCVs from GFZ and IGS. Unit in mm. (*) without the last point in Fig. 3

However, the differences in the offsets are 12 and 22 cm for Block II/IIA and IIR, respectively. It is mainly caused by the scale difference of the two software packages used, as it is known, GFZ's and CODE's results have 1 ppb scale difference in the IGS combination. An additional difference may come from the different satellite constellation used for deriving the IGS values (in 195 to 200 in 2002) and the GFZ results. The two new Block IIR satellites PRN16 and 21 with very small offset corrections (see Fig. 5) increase the mean Block IIR offset also by about 6 cm. As both results were obtained with data sets over a short period not modeling all seasonal station motions, like atmosphere loading effects, a scale difference up to several tenth in ppb may also be possible.

4.3 Offsets and PCVs for groups

We already realized that the raw PCVs differ among satellites belonging to the same block type. By closer inspection, they can be divided into 5 groups, 3 for Block II/IIA and 2 for Block IIR. The satellites for each group are:

II/IIA(1) 02 05 08 09 10 15 24 25 26 27 29 30,

II/IIA(2) 01 04 07 31 17,

II/IIA(3) 03 06 23,

IIR(1) 13 14 16 18 20 21

IIR(2) 11 28.

We converted the daily raw PCVs to the most flat PCVs and offsets. From the daily PCVs and offsets we got the mean PCV and offset for each satellite. Figure 4 shows the PCVs of the five groups. The scattered symbols are for the mean PCV of each satellite and the black squares are for the mean PCV of the group. From the plots, the rms at the boundary areas is better than 1 mm. Moreover, the differences among groups from the same block type are not very large, 4 mm maximum. Therefore, there should be no big difference using block-type-specific or group-specific patterns. This also reveals that the major difference in the raw PCVs is due to the inhomogeneous offsets. The last panel is the PCVs of the newly launched satellite PRN22, which has a quite different pattern, compared to all the others.

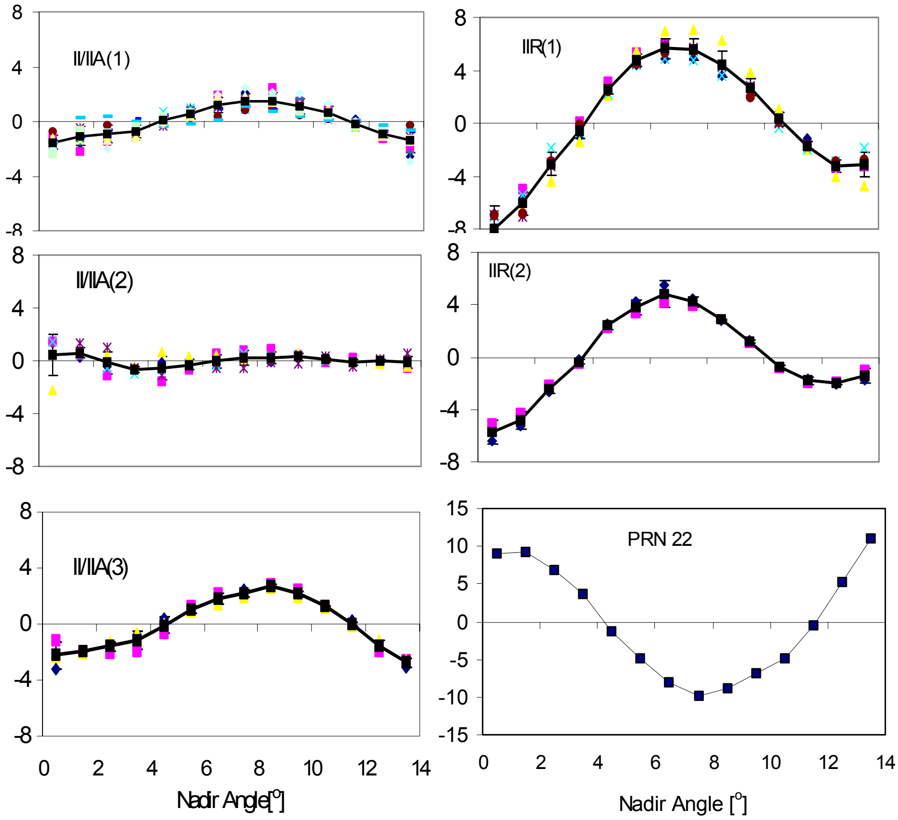

Figure 4. PCVs for the five groups. The scattered symbols are for PCVs of each satellite in the group and the black squares indicate the mean of the group. The last panel is for PCVs of the newly launched satellite PRN22.

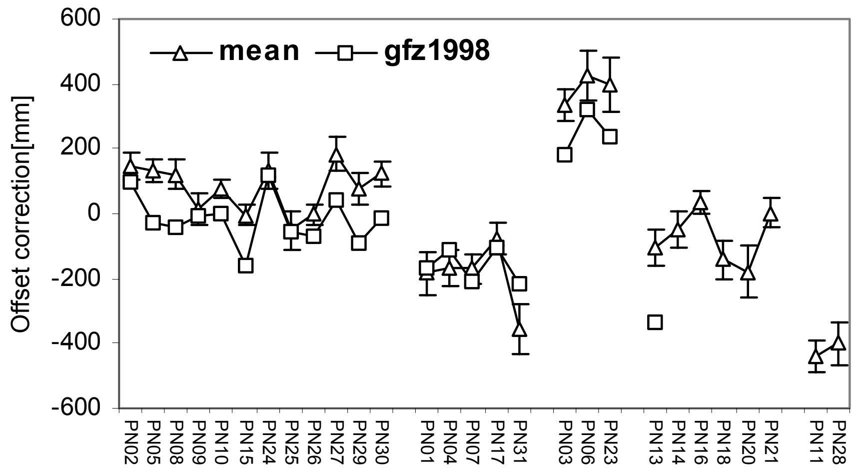

Figure 5. Offsets for each individual satellite. Triangles are for the estimated mean offsets, error bars for their repeatability. Squares are for the values estimated in 1998 at GFZ. Satellites are arranged in groups in the order of II/IIA(1), (2), (3) and IIR(1) and (2).

Figure 5 shows the mean offset of each satellite related to the most flat PCVs. The black triangles indicate the mean offsets with error bar for its repeatability. The repeatability is about 5 cm. The offsets are clearly grouped. The new offsets are in general consistent with the result estimated at GFZ in 1998, indicated by squares in the plot. This is clear evidence that GPS satellite antenna offsets are not homogenous. They differ from the nominal values given in IGS standards by several dm. The biased nominal values may lead to a non-negligible scale error in the network. Therefore group-specific PCVs plus offsets for individual satellites should be more suitable.

5. Impact of APCV model on IGS products

To assess the impact of IGS proposed APCV models on the IGS products, they were applied in the analysis of the same data using the GFZ's final analysis procedures. The results are compared with that from our routine data processing where relative PCVs are used.

The orbit difference is very small, about 1 cm in rms. On the other hand, the satellite clocks are shifted by 1.31 m in average because of the additional offset changes.

The repeatability of the station coordinates is exactly the same, 1.4, 1.4 and 4.2 mm in north, east and vertical component, respectively. Table 2 shows the transformation parameters of different solutions to the IGS00. With relative PCV models, the scale is 1 ppb smaller than the IGS00. With the APCV models, it is expected to get the same scale as IGS00, hence they are estimated fixing the scale. However, with the IGS APCV models, the scale is 1.1 ppb larger than the IGS00. This is mainly caused by the scale difference of the two software packages. To confirm the fact, we processed one week data in 2004 with our estimated APCV models and got a scale change of 0.1 ppb.

	Dx(mm)	Dy(mm)	Dz(mm)	Scale(ppb)
A PCV	2.0	0.2	1.5	-1.1
R PCV	0.5	1.1	-2.0	1.0
GFZ_A	1.2	-0.2	-0.4	0.1

Table 2. Transformation parameters from the solutions with IGS absolute and relative PCVs as well as GFZ absolute PCVs to IGS00.

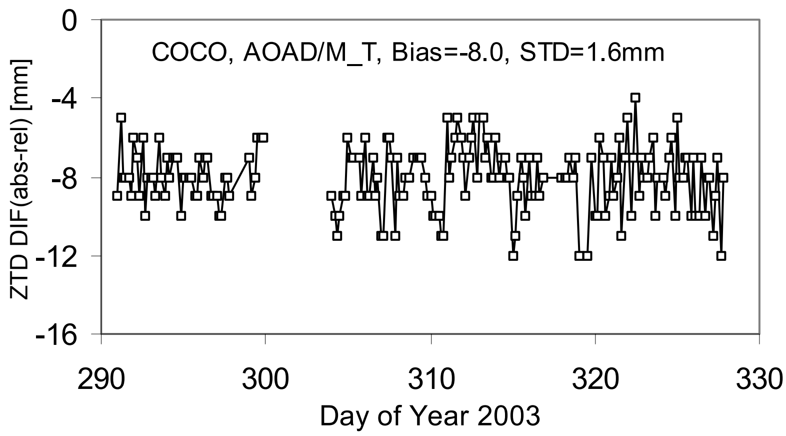

Figure 7. ZTD difference at station COCO between solutions with absolute and relative PCVs.

With the APCV models, the zenith total delay is shifted by -7.0 mm in average with a standard deviation of ±1.9 mm over the whole network. Figure 7 shows an example of the ZTD difference between results using relative and absolute PCV models for the station COCO. The comparison of GPS derived ZTD and that from radiosondes has shown that GPS ZTD is overestimated. The 6 mm mean bias between GPS and radiosondes presented by Haase et al. [2003] may be reduced with the APCV models.

6. Summary

Raw PCVs are estimated satellite by satellite with a daily repeatability of better than ±1 mm. Block-type-specific APCV models are derived under the assumption that satellites belonging to the same block type have the same offset and PCV. The results agree with the IGS proposed models within ±1 mm rms for PCVs and ±10-20 cm for offsets. The offset difference is mainly due to the scale difference of the two software packages and different satellite constellations.

We found significant differences in raw PCVs of satellites belonging to the same block type. According to the estimates of the raw PCVs, satellite antennas are divided into 5 groups. The PCVs of groups for the same block type differ slightly, whereas the offset differs from satellite to satellite up to 0.8 m. When the satellite constellation changes, using the constant offset for each block type might bring a non-negligible scale bias to the network. Therefore, we suggest using group-specific or block-type-specific PCVs together with satellite-specific offsets.

Using the IGS APCV models as correction leads to 1 cm rms in satellite orbits compared to that with the relative ones. Satellite clocks are shifted by 1.31 m due to the additional offsets. Zenith total delay at stations will be reduced by 7 mm in average. That makes the ZTD from GPS and radiosondes almost consistent with each other.

It must be mentioned that the estimated result depends on the APCV models of receiver antennas fixed in the estimation as well as on the fixed reference frame. Thus the current scale difference caused by software packages used by ACs must be taken into account while providing APCV models to define the IGS standard. A longer data set should be used to reduce the seasonal effects in the station coordinates for getting more reliable APCV models.

Reference

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