GPS satellite antenna parameters from combined ground-based and space-borne data processing

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Background

Consistent phase center heights for Global Navigation Satellite System (GNSS) receiver and satellite antennas are of greatest importance in high precision GNSS positioning. The continuously updated antenna models (IGS) has advanced to become the state-of-the-art standard in this field. The forthcoming “igs08.atx” model provides phase center offsets (PCOs) and variations (PCVs) for 217 different receiving antenna types and 122 GNSS satellites. About 70% of all receiving antenna types listed in the igs08.atx file were calibrated by the robot-assisted absolute field calibration technique. Consistent correction values for the transmitter antennas onboard the GNSS satellites have not been available for any GNSS series, as the results from ground-based calibration have proven to be uneven. Estimating the satellite antenna parameters exclusively from ground-based GNSS measurements is thus a very desirable disadvantage.

1) Due to the four-to-one ratio between orbital altitude \( r \) and Earth radius \( R \), the range of the “radial” angle \( \alpha \) is limited to the zenith angle of \( 14^\circ \). This fundamental weakness of the GNSS technique manifests itself in high mathematical correlations between station heights, tropospheric zenith path delay (ZPD) parameters and orbital radius. To still be able to solve for the satellite antenna PCO offsets, the scale of the terrestrial network (mean station height) has to be fixed by adopting a global set of reference station coordinates and velocities. In this way, however, uncertainties inherent in the TRF solution propagate into the ZPD estimates. A common error in the station heights of more than \( 50 \text{ mm} \) may lead to a common error of \( 10^{-13} \text{ km} \) in the satellite antenna values and the other way around. This ultimately means that GNSS, unlike other space techniques like Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), cannot contribute to the scale of a TRF solution.

2) Since the parameters for the GNSS transmitting antennas were derived exclusively from ground-based measurements their applicability is naturally limited to observations made under nadir angles between \( 0^\circ \) and \( 14^\circ \). GNSS receivers onboard LEO satellites, however, track signals beyond a nadir angle of \( 14^\circ \).

Estimating satellite antenna parameters: ground-based vs. space-based approach

Using observations from LEO receivers for recovering the phase center characteristics of the GNSS transmitting antennas provides four substantial advantages as compared to the ground-based approach.

1) Scale: Instead of adopting it from an external TRF solution, the scale can be determined from the dynamical PCO constraints imposed by the physical trajectory model of the LEO (Haines 2004).

2) Troposphere/Atmosphere measurements collected by a LEO GNSS receiver are not affected by propagation delays through the troposphere thanks to orbital altitudes of several hundred kilometers (\( \text{400 - 1300 km} \)). The observation conditions are therefore always fixed. First, there is no need to set up ZPD parameters for the LEO spacecraft, thus preventing high mathematical correlations with station heights, antenna parameters and the radial orbit component. Second, observations made under low elevations are by far less noisy than on ground implying that there is basically no need for an elevation cut-off angle. Thus the observation geometry can be exploited to almost zero-degree PCO antenna estimation.

3) Geometry: The rapidly changing geometry of the LEO satellite provides strong dynamics for the orbit determination. This could improve the estimation of the antenna phase center parameters as well.

4) Coverage: A LEO satellite circles the Earth 10 to 15 times per day, leading to a ground track that covers the whole globe. Unlike an Earth-fixed station on ground, a single GNSS receiver onboard a LEO satellite therefore allows sampling of all parts of a transmitting antenna in a short time. Depending on the LEO satellite’s orbital altitude, sampling at high nadir angles of up to \( 17^\circ \) is feasible.

Relying exclusively on the GNSS observations made by a single LEO satellite, rather than using measurements from a multitude of different ground receiving antennas, however, bears the substantial risk of unmodeled PCO offsets in the GNSS transmitting antennas. Unmodeled PCOs may arise due to the presence of reflecting surfaces located in the closest vicinity of the antenna, the “reactive near-field region”. For the wing-mounted Helix receiving antenna on-board GOCE, for instance, it has been demonstrated that the PCVs may change by up to \( 2 \text{ cm} \) due to the presence of the wing (Dilsner et al. 2004). To alleviate the effect of unmodeled PCVs biasing the GNSS transmitting antenna parameters, it is advisable to include as many LEO satellites as possible into processing and treat their antenna PCO/PCV parameters as deterministic unknowns as well.

Processing strategy

General: We analyzed \( 4.4 \text{ years} \) of GPS dual-frequency (code and phase) data collected by the advanced-codeless black-box receivers onboard Jason-1 and Jason-2. The distribution of the observations clearly underlines the need for extended GPS satellite antenna calibrations as good as half of all receiving antennas was made beyond a nadir angle of \( 14^\circ \) (Fig. 2). Rather than introducing the GPS ephemers and clock as fixed quantities into the least-squares (LS) analysis and post-fitting the observation residuals for recovering the phase center characteristics, as proposed by other authors, the orbit and clock parameters of all spacecraft involved are estimated along with ground-based GPS data from a globally well-distributed set of IGSO tracking stations. All observations are decimated to 60-second intervals and processed in 24-hour batches using ESOC’s Navigation Package for Earth Observation (EPOC). Ground-based GPS data are only used for quality control of the LEO satellites’ elevation-dependent orbit cycle ambiguities in the ground stations’ carrier phase observations are resolved where possible.

Antennas: For the tracking antennas attached to the GPS ground receivers, we adopted the absolute PCO and PCV values of the latest ig05.atx model. The GPS and LEO satellite antenna PCOs are described by satellite-specific, piece-wise linear functions of the nadir and elevation angle, respectively (GPS: 18 parameters, 1° resolution; LEO: 19 parameters, 5° resolution). To make them comparable to the transmitter antenna PCOs forcing the curve values to be as flat as possible over the nadir interval between \( 0^\circ \) and \( 14^\circ \).

Orbits: For the GPS spacecraft, we employed the well-established set of 14 orbit parameters that we use for our routine IGS processing, that is, six state vector elements modeling the satellite’s initial position and velocity, three constant plus two periodic coefficients describing the solar radiation pressure force in the spacecraft-Sun reference frame as well as three tightly constrained along-track parameters with station heights, antenna parameters and the radial orbit component. Secondly, observations made under low elevations are by far less noisy than on ground implying that there is basically no need for an elevation cut-off angle. Thus the observation geometry can be exploited to almost zero-degree PCO antenna estimation. The multi-year solution is finally generated by stacking together all GPS and LEO antenna parameters estimated in weekly IGS solutions.

Reasonable agreement between “scale-free” and “scale-fixed” IGS values

GPS satellite antenna parameters

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Validation of the estimated antenna corrections

Extended, block-specific satellite antenna PCO corrections for the GPS constellation plus the PCO/PCVs that we obtained were introduced into a “traditional” LEO POD GPS-only analysis covering 180 days from July 2008 to January 2009. The results were compared to those of a second run using ig05.atx PCOs/PCVs and Jason-2 PCO corrections originating from in-situ ground antenna calibration. It turned out that the phase residuals (RMS) drop down in average from \( \pm 7.2 \text{ to} \pm 6.5 \text{ mm} \) (Fig. 3).

Impact of additional ground stations and the inclusion of a LEO satellite

In order to prevent the amount of solve-for parameters from becoming unreasonably large, mainly due to the rapidly growing number of receiver clock parameters (\( 1440 \text{ per day and station} \)), we restricted our combined IGS/LEO processing scheme to 100 ground stations. One daily solution involving a total amount of 200,000 parameters takes around 2 hours on our 2.8 GHz Linux machine. This allows us to process one year of data in less than 5 weeks on a single CPU. Using more than 100 stations only slows down the processing speed and barely improves the solution. Comparing the GPS orbit overlaps of consecutive days while successively increasing the number of tracking stations on ground (as illustrated in Fig. 6) shows that the internal GPS orbit consistency hardly improves if more than 100 sites are involved in the analysis (GPS: 1500 parameters plotted against distances drawn from the comparison with IGS orbit solutions). Fig. 7 shows that the effect of introducing a LEO satellite into the solution (GPS only) is negligible.

Fig. 3:
Fig. 4:
Fig. 5:
Fig. 6:
Fig. 7:
Fig. 8:
Fig. 2:
Fig. 1:

References