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

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Background

Consistent absolute phase center corrections for Global Navigation Satellite System (GNSS) receiver and satellite antennas are of greatest importance in high precision GNSS positioning. The continuously updated antenna model of the International GNSS Service (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 on-board the GNSS satellites, however, were derived from long-time GNSS series, as the results from ground calibration have proven to be unusable. Estimating the satellite antenna parameters exclusively from ground-based GNSS measurements, however, has two conceptual disadvantages:

1) Due to the four-to-one ratio between orbital altitude r and Earth radius R, the range of the observation ("nadir") angle z' under which a ground station is seen from a GNSS satellite is rather small (between 0º and 14º). This fundamental weakness of the GNSS technique manifests itself in high mathematical correlations between station heights, tropospheric zenith path delay (ZPD) parameters and orbit radius. To still be able to solve for the satellites' antenna z-offsets, the scale of the terrestrial network (mean station height) has to be fixed by adopting a global set of fiducial station coordinates and velocities. In this way, however, uncertainties inherent in the TRF solution propagate into the z-offset estimates. A common error in the station heights of only +5 mm may lead to a common error of -10 cm in the satellite antenna z-offsets 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 transmitter antennas were derived exclusively from ground-based measurements their applicability is naturally limited to observations made under nadir angles between 0° and 14°. GNSS receivers on-board LEO satellites, however, track signals beyond a nadir angle of 14° .

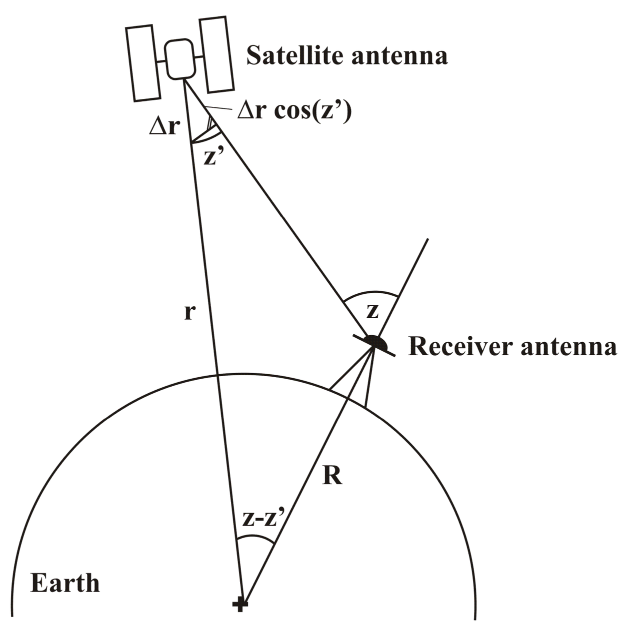

Fig. 1: Geometric relationship between transmitting and receiving antenna (Schmid and Rothacher 2003)

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

Using observables 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 POD constraints imposed by the physical trajectory model of the LEO (Haines 2004).
2) Troposphere-free: GNSS measurements collected by a LEO GNSS receiver are not affected by propagation delays through the troposphere thanks to orbital altitudes of several hundred kilometers (400 - 1300 km). The benefits under troposphere-free conditions are twofold: 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. 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 down to almost zero-degree, which additionally strengthens the solution.
3) Geometry: The rapidly changing geometry of the LEO satellite provides strong dynamics for the orbit determination of the GNSS satellites which, in turn, should 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 on-board 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° 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 LEO receiving antenna PCVs propagating directly into the GNSS transmitting antenna PCVs. Unmodeled PCVs may arise due to the presence of reflecting surfaces located in the closest vicinity of the antenna, its "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 cm due to the presence of the wing (Dilssner et al. 2006). 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 years of GPS dual-frequency code and phase data acquired by the advanced-codeless BlackJack receivers on-board Jason-1 and Jason-2. The distribution of the observables clearly underlines the need for extended GPS satellite antenna corrections as about half of the amount of observations is made beyond a nadir angle of 14° (Fig. 2). Rather than introducing the GPS ephemeris and clocks 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 jointly estimated along with the GPS and LEO satellite antenna parameters. For this purpose, the LEO GPS measurements are processed simultaneously along with ground-based GPS data from a globally well-distributed set of IGS tracking stations. All observations are decimated to 60-second intervals and processed in 24-hour batches using ESOC's Navigation Package for Earth Observation Satellites (NAPEOS), Version 3.6. SLR data are only used for quality control of the LEO satellites' ephemeris. Integer cycle ambiguities in the ground stations' carrier phase observables are resolved where possible.

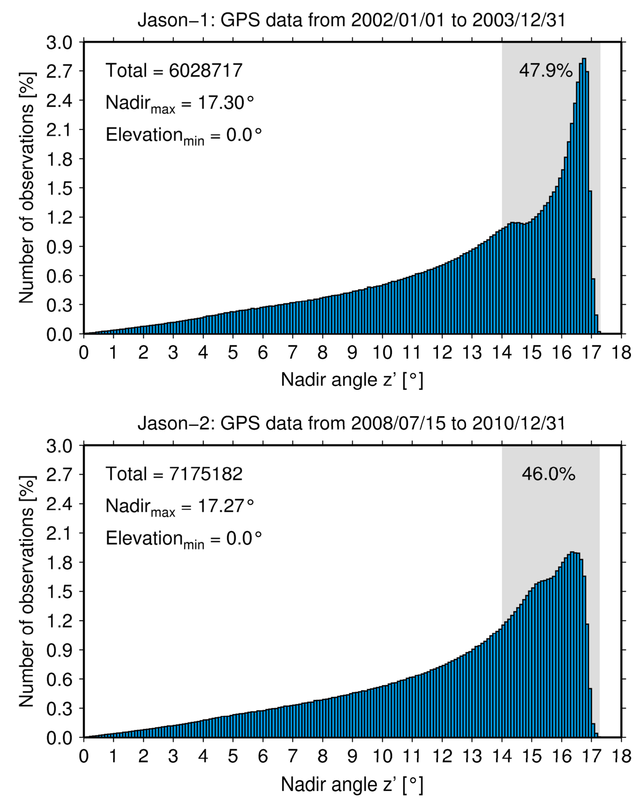

Fig. 2: Distribution of Jason-1/2 GPS data

Antennas: For the tracking antennas attached to the GPS ground receivers, we adopted the absolute PCO and PCV values of the latest igs05.atx model. The GPS and LEO satellite antenna PCVs 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 with the igs08.atx patterns, we transform the "raw" GPS satellite antenna PCVs into "minimum" PCVs and z-PCOs forcing the PCV curves to be as flat as possible over the nadir interval between 0° and 14°.

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 to absorb dynamical modeling deficiencies. For the LEO spacecraft, 19 orbit parameters are estimated: six state vector elements, four periodic along-track and across-track parameters every 12 hours and five atmospheric drag parameters every 24 hours. Details on the underlying Jason-1/2 POD standards and models can be found in Flohrer et al. (2011).

Coordinates: Ground-station coordinates are "stacked" on a weekly basis, minimally constrained ("no-net-rotation") to the a-priori TRF and then eliminated from the normal equation (NEQ) system. The network scale is implicitly left free to adjust. The multi-year solution is finally generated by stacking together all GPS and LEO antenna parameters contained in weekly NEQs.

Estimated GPS satellite antenna parameters

- reasonable agreement between "scale-free" z-PCO estimates and "scale-fixed" IGS values
- z-offsets closer to igs05.atx than to igs08.atx; bias of +2.5 ± 6.4 cm wrt igs05.atx and -13.6 ± 5.2 cm wrt igs08.atx (Fig. 3)
- excellent agreement with igs08.atx PCVs for z' ≤ 14º (Fig. 4)
- largest PCVs found for Block IIR-B/M series (up to 34.5 mm), followed by those of the new Block IIF spacecraft (20.3 mm)
- PCV estimates for z' ≤ 14º could easily be fixed to igs08.atx values in order to derive extended PCV patterns for LEO POD that are fully consistent with current IGS standards

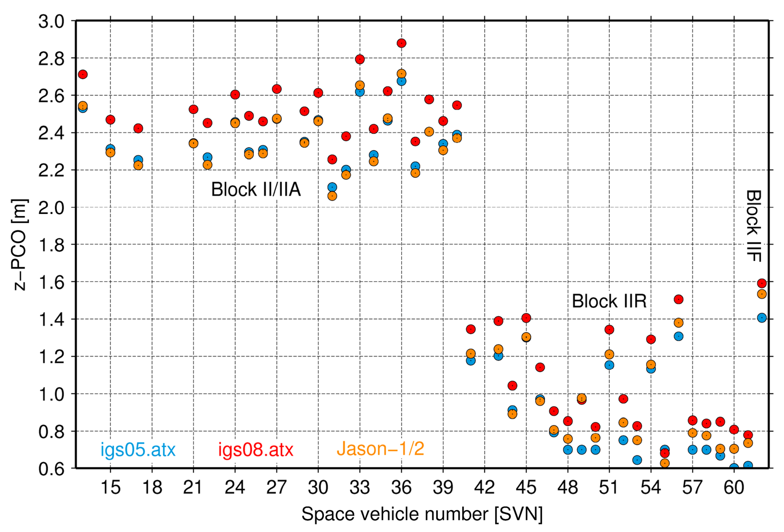

Fig. 3: Estimated z-PCOs vs. IGS standards

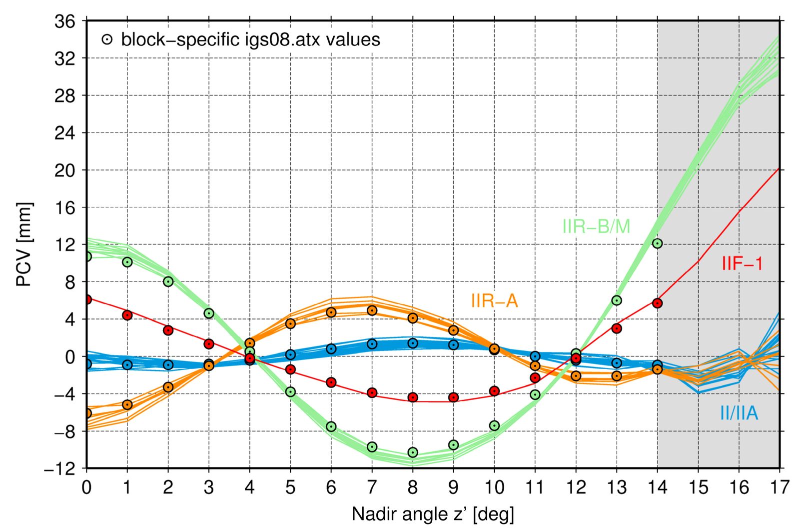

Fig. 4: Estimated PCVs vs. IGS standards

Validation of the estimated antenna corrections

Extended, block-specific satellite antenna PCV corrections for the GPS constellation plus the PCOs/PCVs that we obtained for the Jason-2 receiving antenna have been introduced into a "traditional" LEO POD GPS-only analysis covering 180 days from July 2008 to January 2009. The results have been compared to those of a second run using igs05.atx PCOs/PCVs and Jason-2 PCO corrections originating from an on-ground antenna calibration. It turned out that the phase residuals (RMS) drop down in average from ±7.2 to ±6.5 mm (Fig. 6). The effect on the orbit quality is still under investigation.

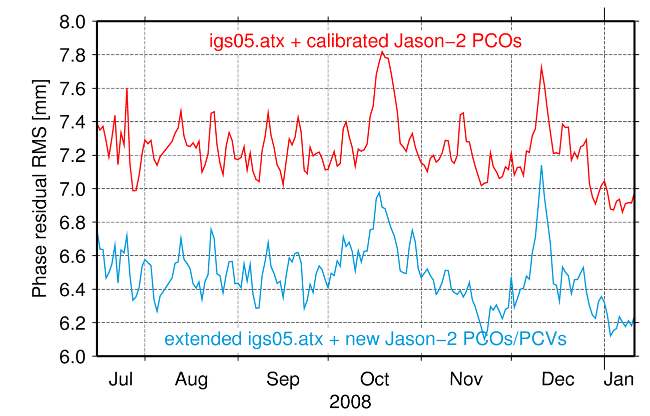

Fig. 6: Impact on Jason-2 GPS phase residuals

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 per day and station), we restricted our combined IGS/LEO processing scheme to 100 ground sites. 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 (Fig. 7). The same conclusion can be drawn from the comparison with IGS Final orbits (Fig. 8). A significant improvement due to the inclusion of Jason-2 may only be noticed in case of a very sparse ground network with less than 20 sites (see Fig. 7-8). Likewise worth mentioning is that, in a integrated IGS/LEO adjustment, a well-distributed GPS tracking network of only 20 sites is obviously enough to get a proper orbit for the LEO satellite (see Fig. 9), that is, a IGS-Final-like station scenario (≥100 sites) seems to be unnecessary.

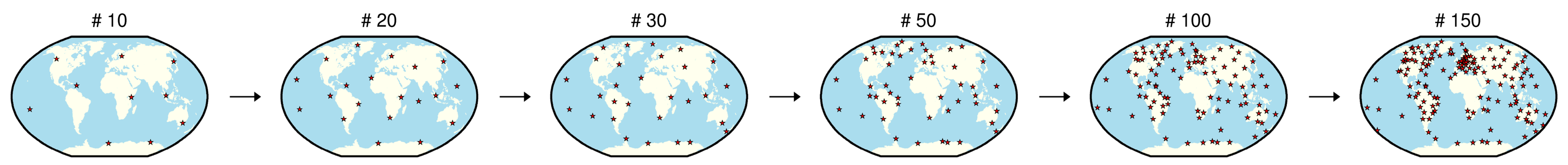

Fig. 6: Ground network scenarios used to assess the impact of additional tracking stations on the orbit quality

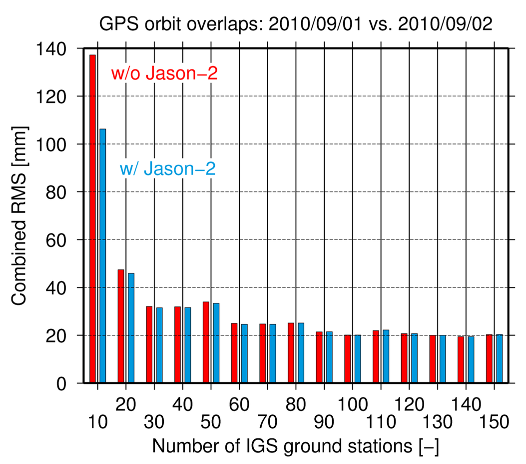

Fig. 7: GPS orbit consistency as a function of number of ground stations

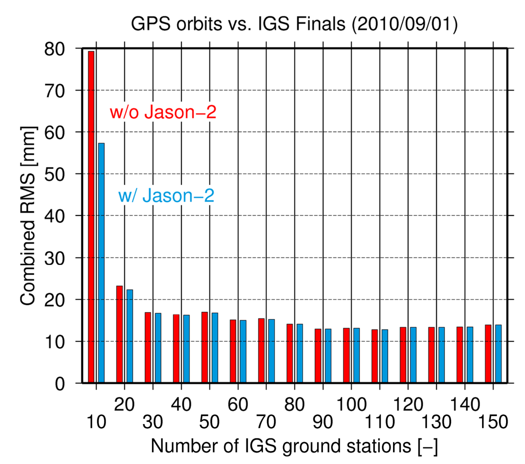

Fig. 8: GPS external orbit validation as a function of number of ground stations

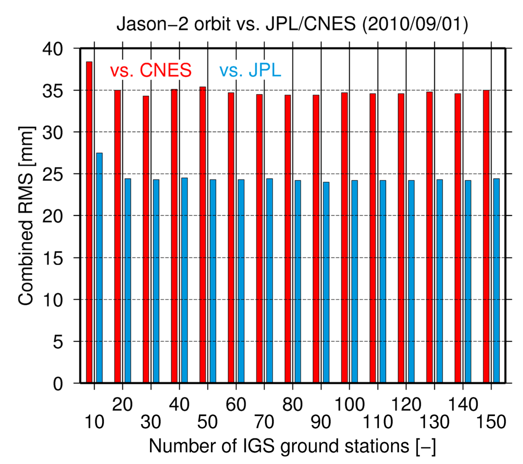

Fig. 9: Jason-2 orbit validation as a function of number of ground stations

Future work

- reprocessing of the entire Jason-1/2 data series from 2002 until present, using data of all three tracking techniques (GPS, DORIS, SLR) in one integrated IGS/LEO adjustment
- modeling of azimuth-dependent PCV patterns using spherical harmonics
- switch from 1-day to multi-day arc lengths
- resolving of the LEO carrier phase ambiguities
- comparison of the TRF realization with IGS08

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