GPS IIF-1 Satellite

Antenna Phase Center and Attitude Modeling

FLORIAN DILSSNER
LOGICA/EUROPEAN SPACE AGENCY

Calculating the distances between satellites and user equipment is a basic operation for GNSS positioning. More precisely, these ranges are measured from the antenna phase centers of the satellites' transmitting antenna. However, phase centers vary among types and generations of spacecraft and, further, the calculation requires knowledge of a satellite's orientation or attitude. A researcher at the European Space Operations Center has analyzed the initial performance of the first GPS Block IIF space vehicle and found some expected — and unexpected — results.

On May 27, 2010, the U.S. Air Force successfully launched the first satellite of the Block II "follow-on" (Block IIF) series, the fourth generation of GPS spacecraft that features more precise and powerful signals, an extended design life, and several other technical advances.

Space vehicle IIF-1, also referred to as SVN62/PRN25, has been injected into the orbital plane B, slot 2 position of the GPS constellation and is expected to be

set healthy for navigation uses by the end of August.

Since the activation of the L-band transmitter on June 6, a set of around 170 globally distributed ground stations of the International GNSS Service (IGS) equipped with "all-in-view" receivers (which are capable of tracking both healthy and unhealthy satellites) have been collecting dual-frequency L1/L2 pseudorange and carrier phase measurement data from SVN62/PRN25 (**Figure 1**).

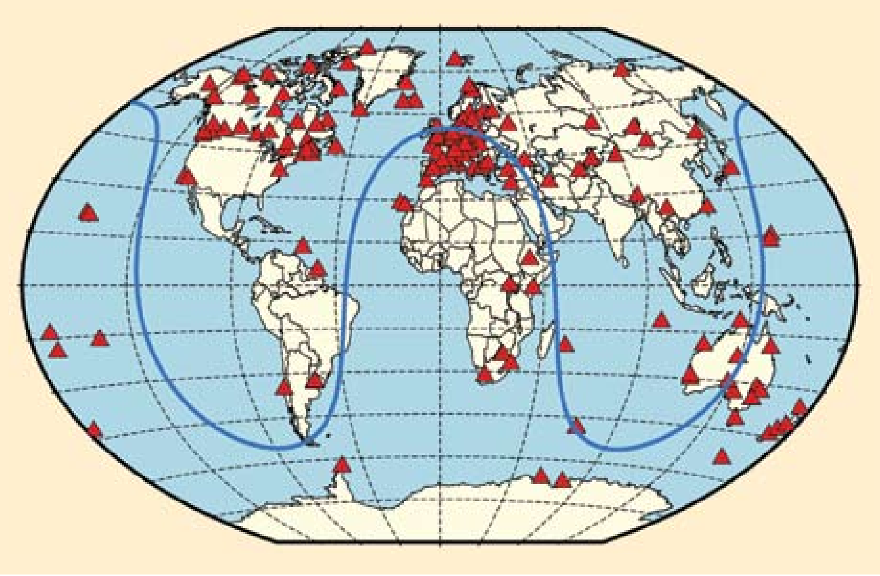


FIGURE 1 Geographical overview of the 170 IGS stations tracking SVN62/PRN25 during its current 90-day checkout period. The blue curve illustrates the ground track of the spacecraft on August 9, 2010.

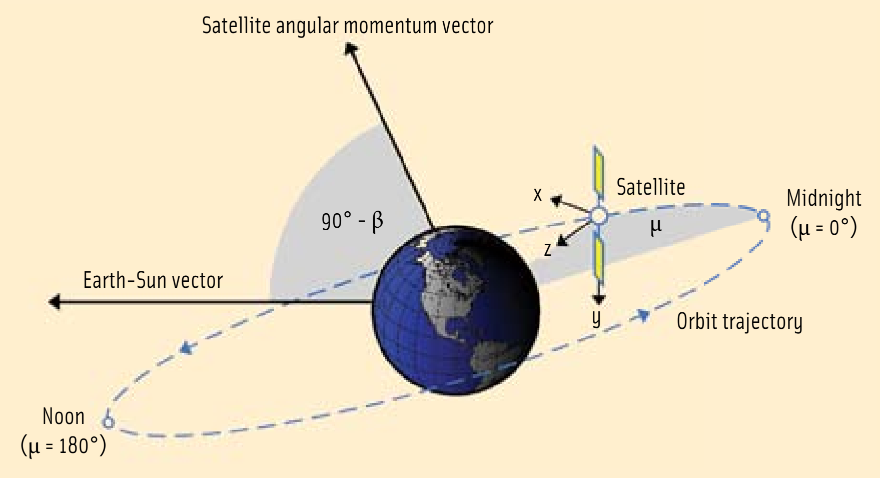


FIGURE 2 Orientation of the spacecraft-fixed reference system with respect to the Sun and the Earth. The spacecraft's position within the orbital plane is commonly expressed as the geocentric angle μ between satellite and orbit midnight, measured in the direction of the spacecraft's motion. "Midnight" denotes the farthest point of the orbit from the Sun whereas "noon" denotes the closest point. The "ß-angle" indicates the elevation of the Sun above the satellite's orbital plane.

To relate the measurements consistently to the satellite's center of mass, the phase center characteristics of the transmitting antenna on board the spacecraft must be precisely known. Because GPS satellites usually exhibit different (block- as well as satellite-specific) antenna phase center characteristics, the IGS community is now faced with the question of how to deal with the relevant antenna phase center parameters for the new Block IIF spacecraft.

Whereas "official" values for the phase center offsets (PCOs) have recently been published by the satellite's manufacturer, hardly anything is known about possible direction-dependent variations (PCVs) of the antenna phase center location. This prompted us to make a first attempt to estimate the satellite's antenna PCOs and PCVs based on the first weeks of IGS data (available at <http://igs.org>). In the course of the PCO determination, we also studied the yaw-attitude behavior of the new Block IIF-1 spacecraft during the recent eclipse season of orbital plane B.

This article relates the initial analyses and results of those studies.

Spacecraft-Fixed Reference System

To gain a clear understanding of the satellite antenna phase center and attitude issue, let us first introduce a spacecraft-fixed reference system. The origin of this system coincides with the satellite's center of mass.

The y-axis points along the nominal rotation axis of the solar panels, the z-axis points along the navigation antenna boresight toward the center of the Earth, and the x-axis pointing toward the hemisphere containing the Sun completes the right-hand system (**Figure 2**). The azimuth under which a tracking station is seen from the satellite is chosen to count clockwise from the y-axis toward the x-axis when looking in the direction of the negative z-axis.

To meet the above-mentioned Sun-Earth-pointing requirement, GPS satellites have to constantly rotate their solar panels while at the same time "yawing" along their z-axis by means of momentum wheels. The position of the two celestial bodies is permanently monitored by Sun and Earth sensors.

Under a certain orbital regime, however, the spacecraft are pushed to the edge of their physical limits. Whenever the elevation β of the Sun with respect to the satellite's orbital plane (see Figure 2) is below a certain limit and a satellite approaches the point on the orbit trajectory closest to the Sun ("orbit noon") or farthest away from it ("orbit midnight"), it cannot keep up with the required yaw rate anymore.

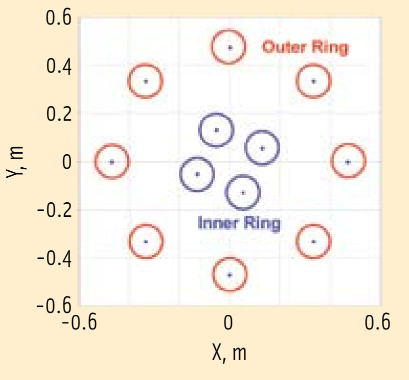


FIGURE 3 L-band antenna element locations (courtesy GPS Wing).

Maneuvers that deal with this situation are called "noon-turn maneuvers" and "midnight-turn maneuvers," respectively. We will come back to this point later on.

Satellite Antenna Phase Center Characteristics

The L-band navigation antenna array on board a GPS spacecraft is designed to illuminate the Earth hemisphere with nearly constant signal strength. It consists of 12 single helical elements arranged in two concentric rings on the Earth-facing satellite panel (**Figure 3**). Where the inner-ring is composed of four equally spaced elements that produce a broader beam with high signal power, the outer-ring contains eight elements that produce a narrow beam with a weaker signal.

The signals transmitted through the two rings are phased 180 degrees apart in order to achieve a composite (shaped) antenna pattern. Due to the particular array design, however, the antenna may have gain and phase- and group-delay variations across the beam.

	x-offset [cm]	y-offset [cm]	z-offset [cm]
Estimated	39.3 ± 1.9	-1.7 ± 1.3	127.4 ± 6.1
Manufacturer	39.4	0.0	109.3

TABLE 1. Estimated PCOs versus manufacturer's PCOs.

To get a first impression of the Block IIF-1 satellite antenna phase center characteristics, we analyzed the ionosphere-free linearly combined L1/L2 tracking data collected by 170 IGS sites from June 8 to August 9, 2010. The observations were processed in 24-hour batches using a five-minute sampling interval. The final multi-day solution is generated by combining ("stacking") the daily normal equations.

Scale and orientation of the ground network were fixed to the scale and orientation of an IGS-specific realization of the International Terrestrial Reference Frame (ITRF2005). The overall phase pattern is described by a fully normalized spherical harmonic expansion of maximum degree and order (8, 4).

In order to obtain the desired PCOs and PCVs, we did a separate least-square adjustment forcing the GPS IIF-1 PCVs to be as flat as possible over the whole nadir angle range up to 14.0 degrees. For the PCOs and PCVs of the other (transmitting and receiving) antennas involved in the analysis, we adopted the values of the latest IGS antenna phase center model ("igs05.atx"). The full details on the processing strategy can be found in the article by F. Dilssner et alia listed in the Additional Resources section.

The estimated PCOs are quite close to the official manufacturer's values (**Table 1**). The agreement between the two x-offsets and the two y-offsets is excellent (≤ 1.7 centimeters). The repeatability of the daily horizontal PCO estimates (**Figure 4**) is better than ±1.9 centimeters (standard deviation 1-sigma).

The estimated z-offset deviates from the manufacturer's value by +18.1 centimeters, which is still an acceptable result considering the relatively short observation period in the context of the high correlations existing between z-offset, terrestrial scale, and troposphere parameters. Moreover, one should always keep in mind that the z-offset parameter strongly depends on the underlying nadir angle range. Because we do not have any specific details regarding the manufacturer's calibration setup, the question arises whether the two z-offset solutions are comparable at all.

The estimated PCVs are between –7 and +11 millimeters (**Figure 5**). We can clearly see the well-known fourfold pattern reflecting the geometry of the inner quad of antenna elements (cf. Figure 3). The pure nadir-dependent PCVs are between -4 and +5 millimeters, whereas the pure azimuth-dependent variations range from -6 to +5 millimeters.

The comparison with the block-specific correction values given in the igs05.atx antenna phase center model indicates that the Block IIF-1 PCVs differ significantly from those of the other GPS satellite blocks. If we the estimate the Block IIF-1 PCVs as a piece-wise linear function of the nadir angle along with PCVs of the other GPS satellites, rather than fixing those to their block-specific igs05.atx model

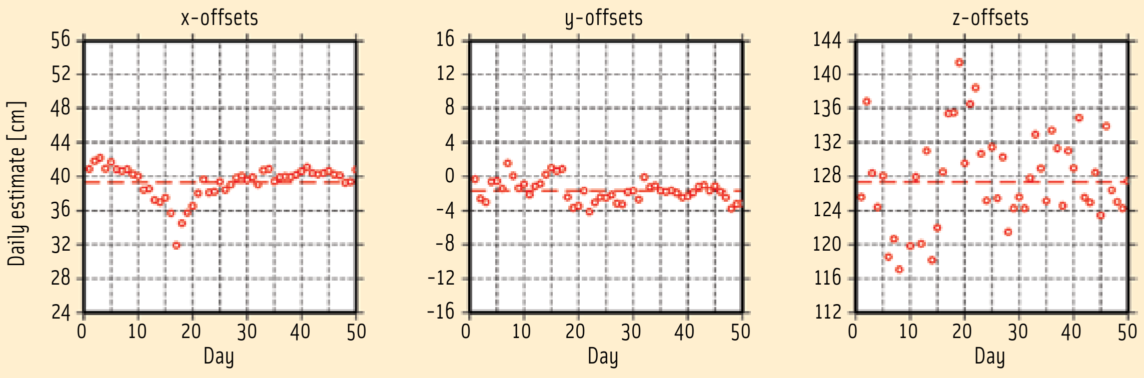


FIGURE 4 Daily PCO estimates giving an indication of the quality of the final (multi-day) PCO solution.

values, we come to the same conclusion (**Figure 6**). We therefore suggest including a new PCV group into the igs05.atx model.

GPS IIF-1: A Bad Attitude?

The best knowledge about the satellite antenna phase center characteristics is useless in the end, if the spacecraft's orientation, also referred to as its attitude, with respect to the inertial reference system is wrong.

Satellite antenna phase center correction models accounting for "horizontal" PCOs and PCVs strongly depend on the azimuth of the particular tracking station on the ground. The precise calculation of the azimuth, however, requires an exact knowledge of the satellite's yaw angle at each point in time. The yaw angle is the angle between the spacecraft-fixed x-axis and the direction of the spacecraft velocity ("along-track") vector.

To get an insight into the yaw-attitude laws of the GPS Block IIF-1 spacecraft during eclipse season, we studied the evolution of the horizontal satellite antenna PCO estimates in the vicinity of orbit noon and orbit midnight using a technique that we refer to as "reverse kinematic point positioning." In this approach, we keep all relevant global geodetic parameters fixed and estimate the satellite clock and antenna phase center positions epoch-by-epoch using the 30-second observation and clock data from the IGS ground station network. The estimated horizontal antenna PCOs implicitly provide the instantaneous state of the spacecraft's yaw-attitude.

We found that the Block IIF-1 satellite, when passing through the Earth's shadow, behaves to a certain extent like a Block IIR vehicle. That means that the satellite is basically able to keep its nominal yaw-attitude even in the absence of sunlight.

Initial comparisons between estimated and nominal yaw angle values have shown that the accuracy the spacecraft maintains its nominal yaw-attitude with during shadow crossings is better than ±3 degrees (RMS). However, this only holds as long as the elevation β of the Sun is greater than 8 degrees. If the craft enters the Earth's umbra at a β-angle smaller than 8 degrees, we clearly notice a linear drift in the estimated yaw angle (**Figure 7**).

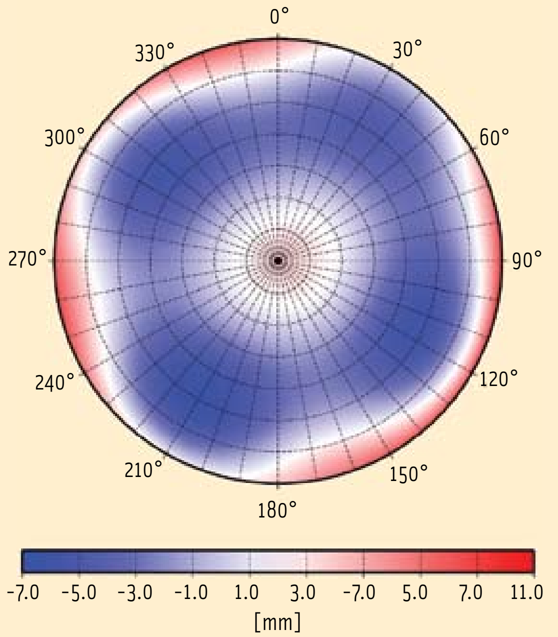


FIGURE 5 Estimated PCVs of the GPS Block IIF-1 satellite antenna as a function of azimuth and nadir angle. The center of the plot represents the nadir direction, the outer circle a nadir angle of 14.0°.

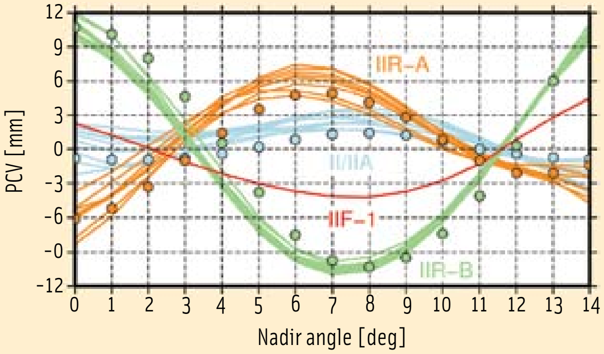


FIGURE 6 Estimated PCVs for different GPS satellite blocks as a function of the nadir angle. The circle symbols indicate the block-specific igs05.atx model values.

The slope of a straight line fit tells us that the satellite is now rotating around its z-axis ("yaw-axis") with a nearly constant rotation rate of 0.06 degree/second. The yaw angle catches up with the nominal yaw angle towards the end

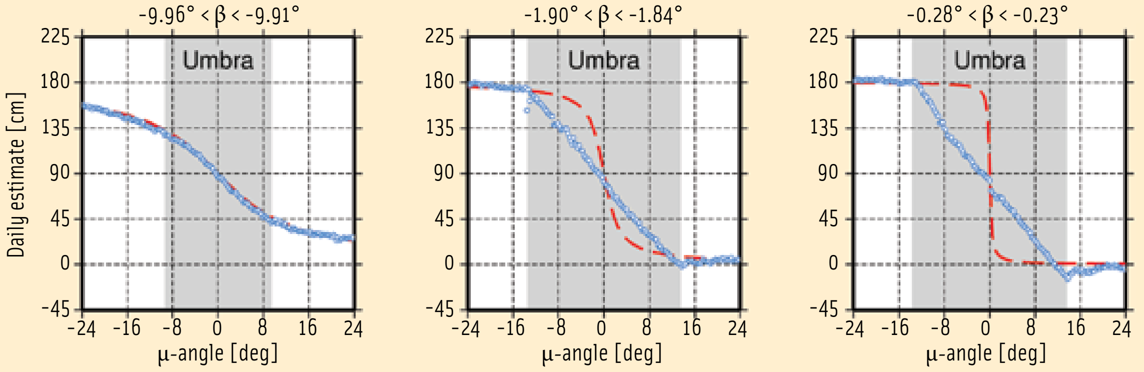
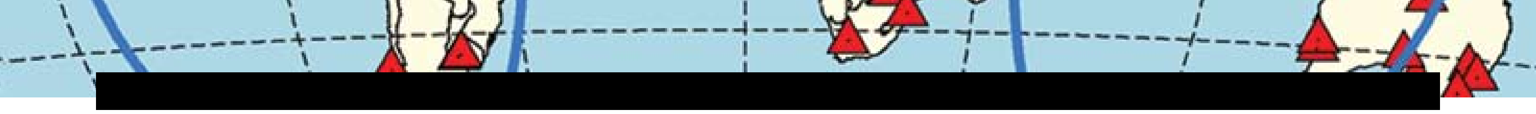


FIGURE 7 Estimated and nominal yaw angles of the GPS Block IIF-1 space vehicle crossing the Earth's shadow under different β-angles. The red dashed curves show the yaw angle assuming the midnight-turn maneuver is performed "nominally". The estimated yaw angle values are displayed as blue circles. They expose the actual yaw-attitude behavior of the satellite during its midnight-turn.



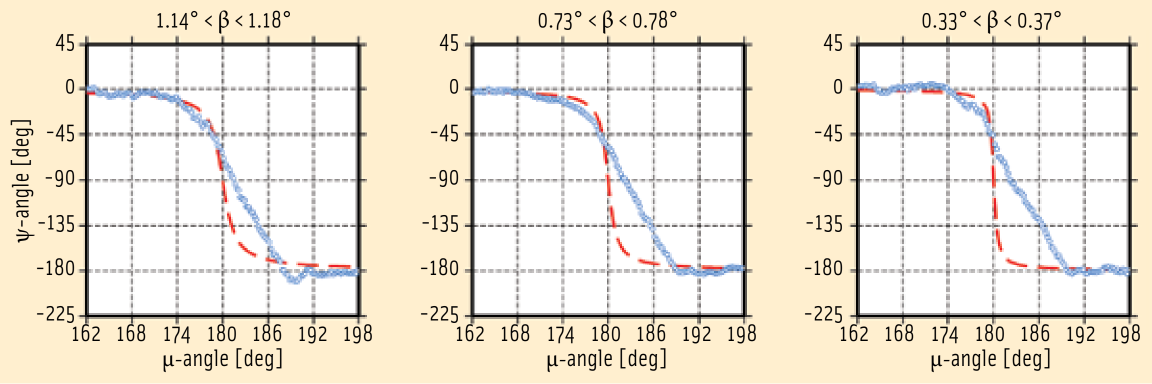


FIGURE 8 Estimated and nominal yaw angles of the GPS Block IIF-1 space vehicle when passing the orbit's noon point (μ = 180°) under different β-angles. The red dashed curves show the yaw angle assuming the noon-turn maneuver is performed "nominally." The estimated yaw angle values are displayed as blue circles. They expose the actual yaw-attitude behavior of the satellite during its noon-turn.

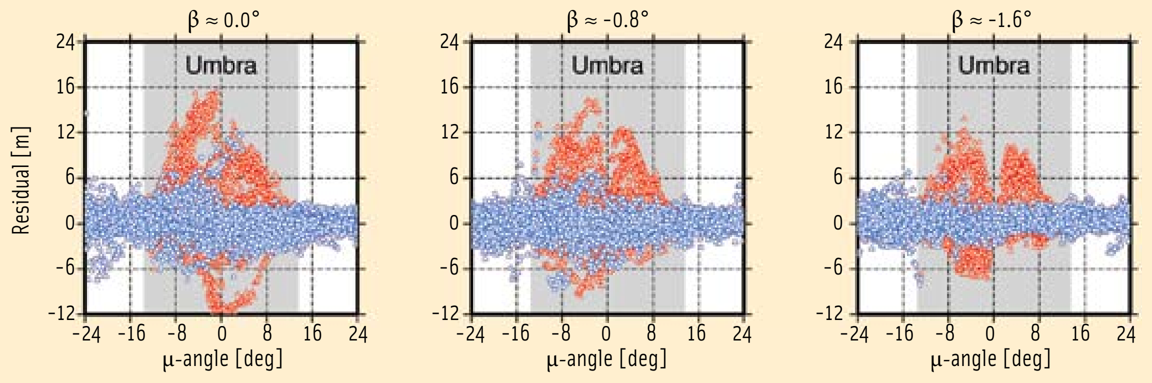


FIGURE 9 Ionosphere-free observation residuals for the carrier phase measurements between the IGS ground stations and the Block IIF-1 satellite inside and outside the Earth's shadow. The residuals associated with the nominal yaw-attitude model are displayed as red triangles. The blue circle symbols show the residuals obtained with an attitude model taking the linear yaw rate of 0.06 degree/second into account.

of the Earth's shadow. As evident from Figure 7 (right), a short post-shadow maneuver might be needed in case the actual yaw attitude upon shadow exit differs from the required nominal yaw attitude.

Compared to the Block II/IIA and Block IIR satellites that feature maximum hardware yaw rates of 0.10-0.13 degree/second and 0.20 degree/second, respectively, the yaw-motion of the Block IIF-1 spacecraft during its Earth's shadow passage is surprisingly slow and consequently results in a relatively long-lasting maneuver. The duration of the maneuver increases as the β-angle decreases. A complete half turn, required under the condition that the Sun lies exactly in the satellite's orbital plane (β = 0°), lasts about 55 minutes.

However, the rotation rate we found for the midnight-turn maneuver is apparently not the maximum hardware rate of the Block IIF-1 spacecraft, as the evolution of the yaw angle at the other side of the orbit reveals (**Figure 8**). We found that for a β-angle below 4 degrees, the satellite is rotating with a nearly constant rate of R = 0.11 degree/second in order to accomplish its required yaw-flip at orbit noon. In consequence, the noon-turn maneuver goes twice as fast as the midnight-turn maneuver, that is, it "only" lasts about 27 minutes at most.

During the noon-turn and the midnight-turn maneuvers, the actual yaw angle may deviate from the nominal one by up to ±180 degrees and ±90 degrees, respectively. Neglecting yaw errors in this order of magnitude may have a serious effect on the satellite antenna phase center modeling.

Depending on the azimuth and the nadir-angle under which a particular ground station is seen from the satellite, the resulting error in the (ionosphere-free) range correction in the vicinity of orbit midnight may amount to ±13 centimeters as a close inspection of the carrier phase residuals during the eclipse clearly confirms (**Figure 9**). Employing a simple attitude model that takes the actual, linear yaw rate into account, however, reduces the residuals down to the normal level outside the eclipse phase (cf. Figure 9).

Conclusions

This article reports on the phase center characteristics of the transmitting antenna on board the first GPS Block IIF satellite. The L1/L2 pseudorange and carrier phase observables of about 170 IGS sites have been analyzed in order to derive the satellite's antenna PCOs and PCVs.

We found that the estimated horizontal PCOs are in excellent agreement with those provided by the satellite's manufacturer. The estimated PCVs differ significantly from those of the other GPS satellite blocks and show the typical fourfold pattern with variations in an order of magnitude that cannot be ignored in high-precision GPS applications.

PCO/PCV analyses involving the L5 carrier phase are still pending. They will become possible as soon as an adequate set of globally distributed stations exists that are equipped with L5-capable receivers and L5-calibrated geodetic antennas.

In its second part, the article gives a first insight into the yaw-attitude behavior of the new spacecraft during the recent eclipse season. We have demonstrated that the presence of the horizontal antenna phase center eccentricity in combination with the significant azimuth-dependent PCVs requires a proper model for the satellite's noon-turn and the midnight-turn maneuvers.

Future studies are needed to assess whether the results actually represent the final operational attitude control or just reflect initial in-orbit tests done by the U.S. Air Force operators.

Acknowledgments

The author gratefully acknowledges IGS for providing global GPS data and ephemerides.

Additional Resources

[1] Dilssner, F. , and T. Springer, C. Flohrer, and J. Dow, "Estimation of phase center corrections for GLONASS-M satellite antennas", *Journal of Geodesy,* Volume 84, Issue 8, Page 467-480, 2010

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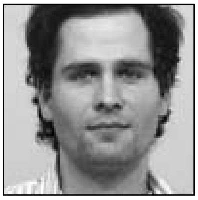

Florian Dilssner received his Dipl.-Ing. and Dr.-Ing. degrees in geodesy from the University of Hannover, Germany. He worked in the field of GNSS as a research assistant at the University of Hannover from 2003 focusing on absolute GNSS antenna field calibration and GNSS station calibration. In 2007 Dilssner joined Logica to work as a technical consultant at the Navigation Support Office of the European Space Agency's European Space Operations Center in Darmstadt, Germany. His current activities include GNSS analysis software development, EGNOS performance monitoring, and satellite antenna phase center and attitude modeling for GPS/GLONASS/GIOVE. IG