Innovation

The Block IIA Satellite

Calibrating Antenna Phase Centers

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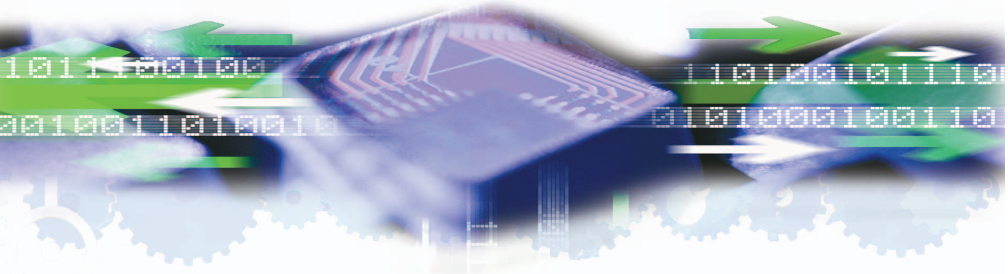
A GPS receiver determines the biased distance between the electrical phase center of its antenna and the phase center of a GPS satellite's transmitting antenna as a pseudorange or carrier-phase measurement. This distance measure is biased due to the lack of synchronization between satellite and receiver clocks, atmospheric propagation delays, ambiguities, and other factors. To determine the position of the receiving antenna, the receiver's operating software (or a user's post-processing software) combines a number of simultaneous measurements on different satellites with information on the positions of the satellites, the offsets of the satellite clocks, and other parameter values in an accurate theoretical model of the measurements. The position of a satellite inferred from the ephemeris data in the broadcast navigation message is actually the position of the phase center of its antenna as determined by the GPS control segment. However, the antenna phase center is not the most natural point of reference for accurately describing the motion of an Earth-orbiting satellite and its response to the various forces that perturb its motion. The satellite's center of mass is more appropriate. Accordingly, the precise GPS ephemerides produced by the International GPS Service (IGS) and others refer to the satellite center of mass. To both generate and use these ephemerides to process GPS data, the offset between the center of mass and the satellite's antenna phase center must be accurately known. In this month's column, Gerald Mader and Frank Czopek discuss their recent calibration of the phase center of a GPS Block IIA satellite antenna and the implications of the new results.

Gerald Mader received his B.A. in physics from Rutgers University and his Ph.D. in astronomy from the University of Maryland. He currently serves as the chief of the Geosciences Research Division of the National Geodetic Survey in Silver Spring, Maryland. His special research interests include kinematic GPS techniques and applications, automated GPS processing and antenna calibrations. **Frank Czopek** is currently the program manager of the On Orbit Support contract for the GPS Block II/IIA satellites at The Boeing Company in Seal Beach, California. He has worked for Boeing for the past 17 years, mainly on the GPS Block II/IIA program, supporting satellite and subsystem testing. He has authored papers on GPS and other satellite technologies and has received the GPS Super Star award and three commendations from upper management for outstanding achievement and performance for his work on GPS. He earned his B.S.M.E degree from Michigan Technological University.



The precise point whose position is measured by a GPS receiver is generally assumed to be the electrical phase center of the GPS receiver's antenna. However, the phase center of a GPS antenna is neither a physical point nor a stable point. For any given GPS antenna, the phase center will change with the changing direction of the signal from a satellite. Ideally, most of this phase center variation depends on satellite elevation angle. Inherent azimuthal effects should be small and generally are only introduced by the local environment around each individual antenna site. GPS antenna calibrations consist of two parts: 1) an average phase center offset with respect to a physical feature of the antenna, and 2) the phase center variation (PCV) with elevation angle (and possibly azimuth). The offset and PCV must be used together to correctly apply the antenna calibration.

The receiver antenna is not the only phase center that is of interest to a user. Each GPS satellite has an L-band transmitting antenna which also has a phase center which changes with elevation angle, or more appropriately for this case, the off-axis angle, and is influenced by the local environment around each satellite. The correct location of this phase center with respect to the satellite's center of mass is critical for accurate orbit determination.

Absolute Calibrations. The National Geodetic Survey (NGS) has used field measurements and a standard reference antenna to determine the relative phase center locations and phase center variations for a wide variety of GPS receiving antennas commonly used for precise geodetic work. These calibrations are widely used to remove differences between receiver antennas that may contribute to position errors. Recently, a team at Geo++ and the University of Hannover in Germany have performed an absolute phase calibration for this standard reference antenna which has allowed us to transform the NGS relative measurements into absolute calibrations for all the tested antennas. However, when these absolute calibrations are used in global GPS solutions, a large scale difference is seen between these GPS solutions and the International Terrestrial Reference Frame (ITRF). The lead suspect for this discrepancy is an erroneous value for the satellite L1 and L2 phase center offsets from the satellite center of mass. This article presents results of field measurements on an actual Block IIA antenna here on the ground showing that these offsets are significantly different from the currently assumed values.

NGS Calibration Method

The NGS antenna calibration procedure uses field measurements to determine the relative phase center position and phase center variations of a series of test antennas with respect to a reference antenna. Relative antenna calibrations are used because these calibrations are easy to perform in a consistent manner. Our German colleagues have presented results (see Further Reading sidebar) of a technique for measuring absolute phase calibrations which utilize a device for rapidly reorienting the pointing of the test antenna. These results are in good agreement with the relative calibrations and provide a means for using the large database of relative calibrations to yield absolute calibrations. There is no practical difference to using relative or absolute antenna calibrations until the baseline lengths exceed about a thousand kilometers. As the baseline length increases, the curvature of Earth's surface causes the same satellites to appear at increasingly different elevation angles at the ends of the baseline. These situations require that the absolute phase center variation be known in order to remove these effects. Ideally, relative calibrations may be made to a reference antenna whose absolute calibrations are known. That is the procedure we have used to calibrate the Block IIA antenna.

Test Range. Ordinarily, NGS's antenna calibrations are carried out at a test range established at NGS's Instrumentation and Methodologies Branch in Corbin, Virginia. This test range consists of two stable concrete piers with a diameter of 6 inches (15.24 centimeters) rising about 1.8 meters above ground. On the tops of these piers, antenna-mounting plates are permanently attached. The piers, separated by 5 meters, are located in a flat grassy field and lie along a north-south line. The reference and test antennas are connected to 12-channel, dual-frequency geodetic-grade receivers, which are set to track to an elevation cutoff or mask angle of 10 degrees. A single rubidium oscillator is used as an external frequency standard for both of the receivers.

The reference antenna used for these calibration measurements is a dual-frequency choke ring antenna. Since the reference antenna is the same for all tests, the antenna calibrations for all test antennas may be used in any combination to find the antenna phase centers and the phase center variation.

Identical antennas to the reference antenna have been placed on the test pier in order to determine the location of the reference antenna's L1 and L2 phase centers on this pier. These positions are then used as the a priori positions for the L1 and L2 phase centers of the test antennas. The displacements that are found from the test antenna solutions then give these test antenna phase center locations relative to the reference antenna. When the L1 and L2 phase center offsets from the bottom of the reference antenna are known, the L1 and L2 phase center offsets of the test antennas can be easily found.

Average Phase Center. The average L1 and L2 phase center position is a function of the elevation cutoff angle used in the solutions to determine these positions. For its antenna calibrations, NGS has defined a standard elevation cutoff angle of 15 degrees for the determination of the test antenna's L1 and L2 average phase center locations. These single frequency solutions use no PCV corrections or tropospheric scale factor estimation and are done using the NGS PAGES GPS data processing software. This software uses double-difference phase observations, which are free of any differential tropospheric or ionospheric effects for this extremely short baseline. The solutions use 24 hours of data to determine these L1 and L2 offsets. Once they have been found, we can determine the test antenna's PCV.

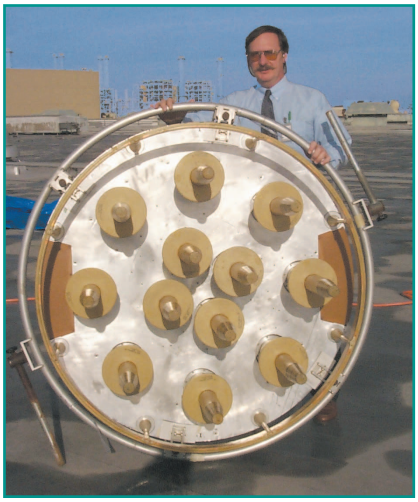


FIGURE 1 The first author holds the Block IIA antenna used for these tests, showing the location of the transmitting elements.

The variation of the phase center as a function of elevation angle is determined separately for L1 and L2. At NGS, we do not estimate an azimuth dependence in these PCV solutions. The PCV is determined using L1 or L2 single differences rather than double differences in order to determine the relative PCV directly rather than from different satellites at different elevation angles. The PCV is essentially a curve and this curve is better determined from direct measurements of points on this curve rather than differences along this curve.

Time Delays. Since single differences are being used as the observable, the clock differences between the two GPS receivers do not cancel out as they do with double differences. Therefore, a rubidium oscillator is used as an external frequency standard to remove most of the variation due to clock differences and time delays from the a priori single difference phase residuals. With these a priori phase residuals now relatively flat as a function of time, editing cycle slips and outlying data points is easily accomplished. The L1 and L2 single difference phase residuals are formed by constraining the test antenna to its L1 or L2 position using the previously determined average phase center offsets. These residuals now contain only variation due to residual time delay differences and to the PCV. The software performs a least-squares solution to solve for a clock offset for each measurement epoch and for a fourth order polynomial in elevation angle which describes the PCV.

Antenna Description

The antennas used on both the Block II and the Block IIA satellites have the same configuration. The Block II/IIA array consists of two concentric rings of elements as shown in Figure 1. The inner quad consists of four equally spaced helical elements centered on a ring with radius of 15.24 centimeters. The outer ring, with a radius of 43.82 centimeters, is an eight element octagonal array. The elements are 62.10 centimeters in height and are tapered over the final 13.21 centimeters.

The antenna pattern is achieved by having the outer ring radiate the L-band signal 180 degrees out of phase with respect to the inner ring. To achieve the composite (shaped) pattern, not only does the phasing between the two rings need to be controlled, but also the ratio of power supplied to the two rings. On the Block II/IIA array, ninety per cent of the L-band signal is supplied to the inner four elements with the rest going to the outer ring.

Theoretical Offsets. As part of the Block II development effort, the phase center of the L-band helix was estimated by assuming the helix element to be a linear, end-fire array of *n* identical elements (*n* in this case is the number of turns in the helix). This model assumed a freestanding constant diameter helix; however, the GPS helix is constant for only the first 8-1/2 turns and tapered for the remaining 2-1/2 turns. In addition each helix is partially surrounded by a truncated metallic cone, called a launcher. Because the pitch distance across the length of the helix is constant, the use of this model with tapered helix was deemed

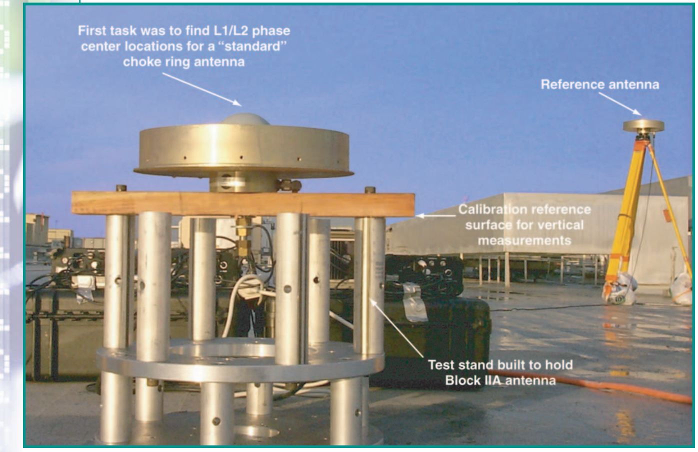


FIGURE 2 The reference station is shown on a tripod in the background and the standard reference choke ring is shown on the test stand.

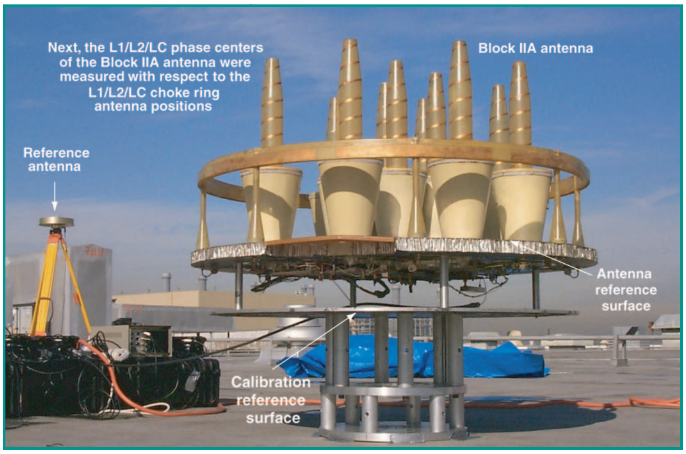


FIGURE 3 The Block IIA antenna is shown mounted on the test stand.

acceptable. Furthermore, since the antenna supports a traveling wave forming an axial beam of 28 degrees, the launcher was assumed to have little influence on the phase. These calculations then estimated the L1 and L2 phase centers to be located 9 inches (22.9 centimeters) above the ground plane and along the center of the antenna array. Accordingly, these calculations placed the L1 and L2 phase centers 95.2 centimeters in front of the center of mass. The antenna's axis of symmetry is offset from the z-axis of the Block IIA satellite, lying 27.9 centimeters along the x axis of the spacecraft.

Antenna Calibration Results

Since the Block IIA antenna could not be shipped to the NGS test site in Virginia, we duplicated the basic calibration procedure on the roof of a building at the Boeing complex in Seal Beach, California.

We mounted a reference antenna identical to that used at Corbin on a tripod and stabilized it for the duration of the tests. We determined its position with respect to Continuously Operating Reference Stations (CORS) already operating in the greater Los Angeles area. We mounted a test fixture on the roof approximately 5 meters from the reference antenna. This fixture was designed to hold the reference–type antenna or the Block IIA antenna so that their vertical axes would be colinear.

Tests. Following the usual procedure, we placed a standard choke ring antenna on the test fixture (see Figure 2) and collected 24 hours of data to determine the positions of the L1 and L2 phase centers for this choke ring with respect to the nearby reference choke ring. Next, we placed the Block IIA antenna on the test fixture (see Figure 3) and determined its L1 and L2 phase center positions as if it were a receiving antenna. The most significant departure from the usual calibration procedure was that we limited the elevation cutoff angle for the phase center positions to satellites above 60 degrees. This was required because the beam of the Block IIA antenna is designed to efficiently illuminate Earth as seen from orbit, which extends 14.5 degress off axis. We had to extend these measurements to 30 degrees off axis in order to find enough satellites in view to carry out the solutions. Even though this angular distance goes past the first null in the beam pattern, the antenna was still able to track without much difficulty. Greater off-axis distances, however, rapidly began to include noisier data as satellites were viewed from additional sidelobes of the Block IIA antenna. To avoid any bias due to different satellite scenarios, we used the same elevation cutoff angle to find the reference positions.

From these measurements the locations of the Block IIA phase centers with respect to a physical feature, in this case the top surface of the antenna, can be

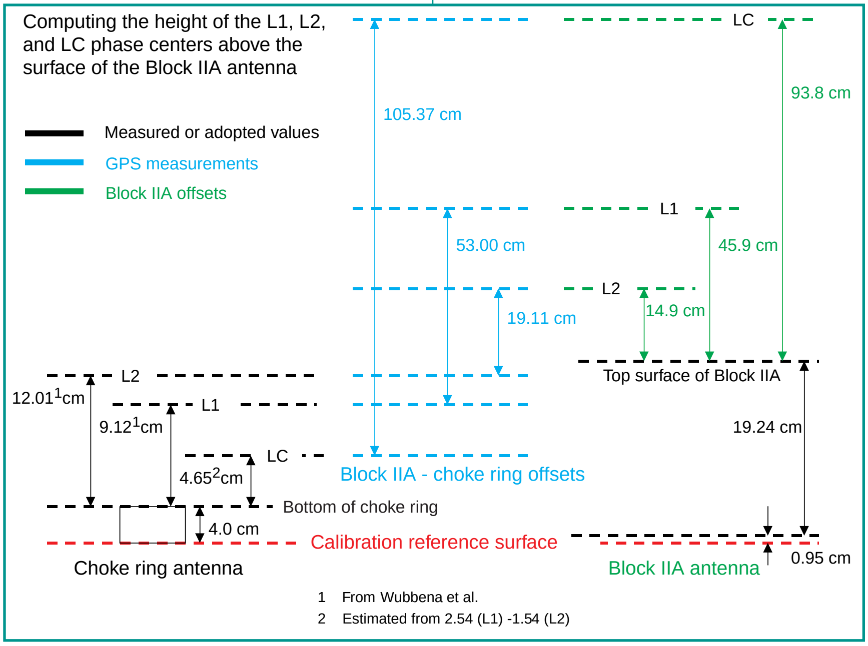


FIGURE 4 The computation of the Block IIA phase centers above the reference surface is illustrated here. The offsets (green) are computed from the measured values (blue) and the known quantities for the choke ring antenna (black).

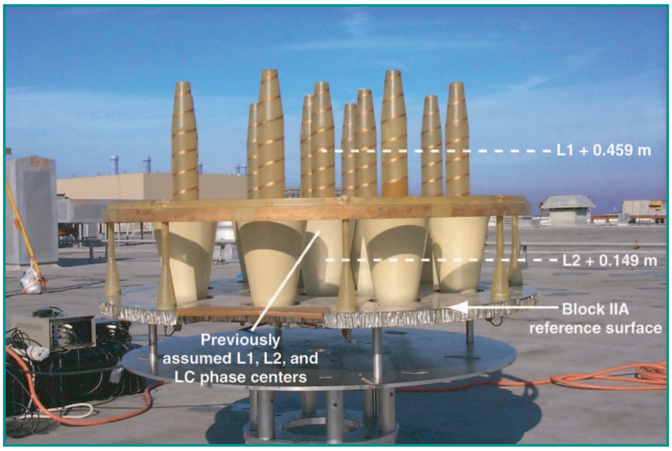


FIGURE 5 The locations of the newly computed phase centers are shown compared to the previously computed locations. The measured LC phase center is off the top of the figure.

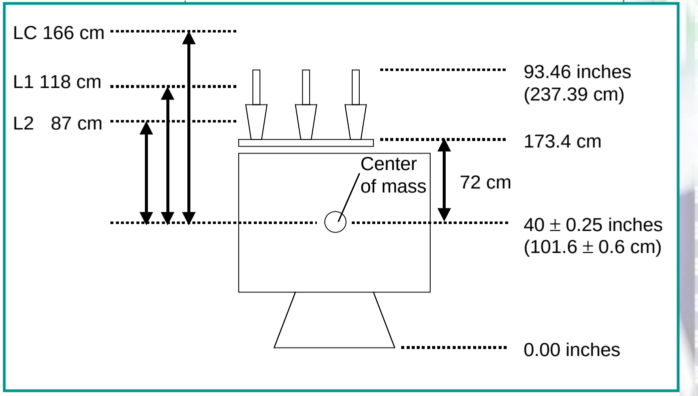


FIGURE 6 From notes provided by Boeing, the reference surface used for these measurements is 72 centimeters from the center of mass (CM). Based on measurements from several satellites, the CM position is known to about 1/4 inch (6.4 millimeters).

determined. Figure 4 summarizes the steps in this determination. The phase center offsets of the choke ring antenna from its reference point are required and we obtained them from our German colleagues. Figure 4 also shows the computation of the LC phase center. LC is the ionosphere-free linear combination of L1 and L2 that is used for precise geodetic work and for orbit computation by the IGS analysis centers.

Center of Mass. Figure 5 shows the actual locations of these phase centers, along with the previously assumed phase center locations. The next step in this calibration is to determine the location of these phase centers with respect to the satellite's center of mass (CM). This requires that the location of the reference surface, from which the L1 and L2 offsets are measured, be known with respect to the CM. Figure 6 summarizes information provided by Boeing regarding the CM and the locations of several features on the Block IIA satellite.

We used these new L1 and L2 phase center offsets in a series of global solutions to yield some preliminary results showing how the scale difference between GPS and the ITRF is affected. We used data from seven consecutive days in January 2000 in minimally constrained solutions to solve for satellite orbit parameters and station coordinates.

Scale Differences. We used approximately 65 tracking stations in these solutions. Figure 7 summarizes the results. The first set of points (green, one point per day) shows the scale differences between these solutions and the ITRF 2000 when using the original phase center offsets for the standard choke ring antenna, relative phase center calibrations for the other receiver antennas, and the original Block IIA offset value. These scale differences are about +3 parts per billion (ppb). The next set (magenta) shows the change when using the same Block IIA offset but now using the absolute phase calibrations for the receiver antennas. The scale discrepancy now goes to about –11 ppb. When we used the new Block IIA offsets along with the absolute calibrations for the receiver antennas, the scale discrepancy decreased to about –5 ppb (red). If the Block IIA offset were to account for all the remaining scale difference, we would have to move the LC offset an additional 60 centimeters closer to Earth (see points for offsets of 200 and 230 centimeters). While we might expect our values to change when we calibrate the antenna again after

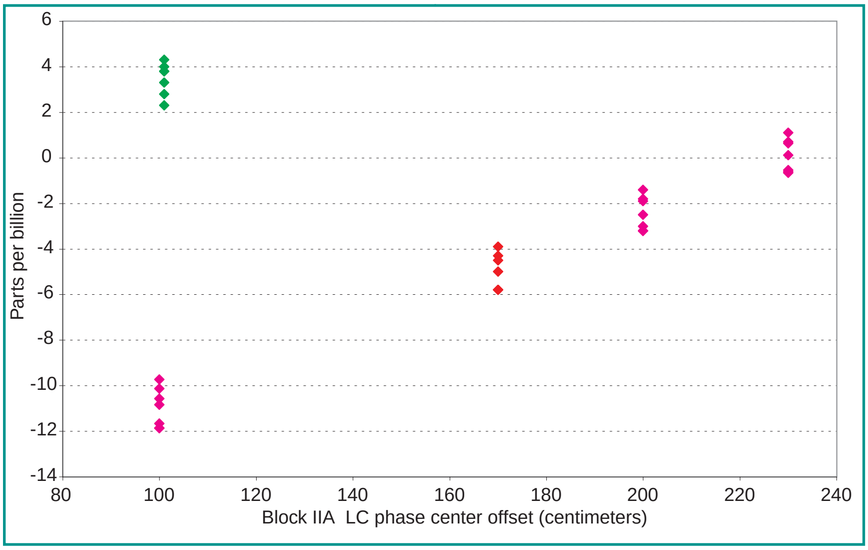


FIGURE 7 The green points show a comparison of a sample solution using original phase calibrations. Using absolute calibrations for the ground antennas only, yields an 11 parts-per-billion (ppb) difference with respect to the International Terrestrial Reference Frame (left-most magenta points). The measured value for the Block IIA antenna offset improves this difference to about 5 ppb (red points).

retuning it, we do not expect a change of this magnitude. There are certainly some other remaining sources of systematic error between GPS and the ITRF but they will be the subject of other investigations.

Conclusions

The precisions that are being achieved today using GPS were not anticipated when the current system was designed and built two decades ago. Antenna calibration specifications required to meet the performance criteria for the current constellation were fully met. However, continued advances in positioning techniques using GPS now demand greater accuracy for the values of certain fundamental parameters of the satellites themselves. The vectors between the satellite center of mass and the phase centers, and the curvature of those phase centers, are among these critical parameters.

We have shown that these phase centers can be accurately measured with a relatively simple technique. However, some questions remain. Only one Block IIA antenna is available for testing and it evidently is “out of spec”. This antenna will be re-tuned to be brought into specification and re-calibrated; however, we do not expect the values presented here to change dramatically. A larger question concerns how representative this one antenna is of the constellation of Block IIA satellites currently in orbit.

Calibration data for the Block IIF antenna has also been collected at Boeing and is being processed. Although no Block IIF satellites have been launched yet, these calibrations will become an important part of the complete measurement chain used for precise positioning. The Air Force has begun launching the Block IIR satellites. In the months ahead we hope to be able to calibrate some of the Block IIR antennas as well.

Precise satellite calibrations, including not just the antenna but the signal characteristics, the shapes affecting radiation pressure, dynamic changes affecting the center of mass, etc., are essential if future generations of GPS are to contribute to the next advance in precise geodetic positioning.

Acknowledgment

This article is based on the paper “Calibrating the L1 and L2 Phase Centers of a Block IIA Antenna” by G.L. Mader and F. Czopek presented at ION GPS 2001, the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation, Salt Lake City, Utah, September 11-14, 2001. ⊕

Manufacturers

The NGS antenna calibrations are carried out using **Thales Navigation**’s Ashtech Precision Products (Santa Clara, California) Z12 GPS receivers and an **Erfatom**, now **Datum, Inc.** (Irvine, California) rubidium oscillator.

The reference antenna used by NGS is an **EDO Corporation** (New York, New York) Dorne & Margolin Type T choke ring antenna.

Further Reading

For an introduction to the characteristics and operation of GPS antennas, see

⊕ “A Primer on GPS Antennas” by R.B. Langley in *GPS World*, Vol. 9, No. 7, July 1998, pp. 50-54.

For a discussion of calibration of GPS antennas in an anechoic chamber, see

⊕ “Characterizing the Behavior of Geodetic GPS Antennas” by B.R. Schupler and T.A. Clark in *GPS World*, Vol. 12, No. 2, February 2001, pp. 48-55.

For further information on the design of the GPS satellite transmitting antennas, see

⊕ “Description and Performance of the GPS Block I and Block II L-Band Antenna and Link Budget” by F.M. Czopek and S. Shollenberger in *Proceedings of ION GPS-93, the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, Utah, September 22-24, 1993, pp. 37-43.

For discussions of absolute and relative GPS antenna calibration, see

⊕ “GPS Antenna Calibration at the National Geodetic Survey” by G. Mader in *GPS Solutions*, Vol. 3, No. 1, 1999, pp. 50-58.

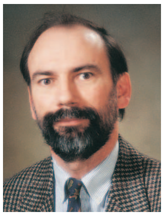
⊕ “Automated Absolute Field Calibration of GPS Antennas in Real-Time” by G. Wübbena, M. Schmitz, F. Menge, V. Böder, and G. Seeber in *Proceedings of ION GPS-2000, the 13th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, Utah, September 19-22, 2000, pp. 2512-2522.

⊕ “A Comparison of Absolute and Relative GPS Antenna Calibrations” by G. Mader in *GPS Solutions*, Vol. 4, No. 4, 2001, pp. 37-40.

⊕ “Comparison of Absolute and Relative Antenna Phase Center Variations” by M. Rothacher in *GPS Solutions*, Vol 4, No. 4, 2001, pp. 55-60.

For access to the archive of NGS antenna calibration results, see

⊕ “GPS Antenna Calibration” <http://www.ngs.noaa.gov/ANTCAL/>.



“Innovation” is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the “Columnists” section on page 2 of this issue.