GPS Antenna Calibration at the National Geodetic Survey

GERALD L. MADER National Geodetic Survey N/NG56, 1315 East-West Highway, Silver Spring, MD 20810

The precise point whose position is being measured when a GPS baseline is determined is generally assumed to be the phase center of the GPS 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. Azimuthal effects are only introduced by the local environment around each individual antenna site. These phase center variations affect the antenna offsets that are needed to connect GPS measurements to physical monuments. Ignoring these phase center variations can lead to serious (up to 10 cm) vertical errors. This article will describe the procedure by which the National Geodetic Survey is calibrating GPS antennas and how this information may be obtained and used to avoid problems from these antenna variations. © 1999 John Wiley & Sons, Inc.

INTRODUCTION

Differential GPS solutions are used routinely to provide geodetic positions with precisions that are often as good as a few millimeters. These positions are typically obtained from a baseline vector that extends from a station whose position is known and constrained to a station whose position is being determined. With increasing frequency, the constrained station may be part of a continuously operating reference network operated as a service to users by a variety of agencies around the world. Consequently, Global Positioning System (GPS) users will often find they are using different antenna types within a single baseline as well as within a given network. The use of different antenna types demands that the contribution of the antennas themselves to the geodetic solution be examined.

A GPS geodetic solution for a baseline provides the vector between the phase centers of the antennas at either end of the baseline. However, a real antenna does not have a single well-defined phase center. Instead, the location of the phase center is a function of the direction from which the antenna receives a signal. If this variation is ignored, the measured baseline will be between the average phase centers of the two antennas. These average phase center locations are a weighted average of all the individual phase centers for each of the measurements included in the solution. When the antennas at opposite ends of relatively short baselines are identical, these variations should cancel out and no effect is seen. However, different antenna types exhibit different phase variations, and baselines with different antenna types will show increasing sensitivity to such things as elevation cutoff angle and the distribution of observations within a solution.

In addition, the phase center is not a physical point that can be accessed with a tape measure by a user who needs to know the connection between a GPS solution and a monument embedded in the ground. However, this kind of connection must be known if a site is ever to be occupied by different antenna types and continuity of positioning is expected. This requires that the vector between the phase center and an external antenna reference point (ARP) on the antenna be known.

To illustrate these problems, consider some test data taken between two different antenna types in fairly

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common usage. The reference antenna for these examples is a Dorne/Margolin antenna element mounted on a choke ring designed by the Jet Propulsion Laboratory (JPL) and designated as type T (hereafter referred to as JPL D/M+crT). The test antenna is a Trimble compact L1/L2 with groundplane (hereafter referred to as TRM 22020.00). Table 1 shows the vector components (North, East, and Up) for three different solutions over this baseline, L1 only, L2 only, and the ionosphere-free L1/L2 combination, hereafter called L3.

The vector components shown in Table 1 are between the average L1 phase centers of the two antennas, the average L2 phase centers, and the average L3 phase centers. No phase center antenna offsets or phase center variations have been applied. The solutions used the same 24-hour data set, and no tropospheric unknowns were solved for.

Table 1 shows that the vector components are not the same for each solution frequency. The differences in the North component are about 1 mm and are essentially negligible. The East component differences from the average are about 5 mm and probably do reflect real systematic differences in this component of the phase centers of the two antennas. The largest differences, several cm, are in the Up component. These differences are due to the different L1 and L2 average phase centers in these two antennas. Clearly, a lack of knowledge of these phase center locations can lead to significant vertical errors.

The National Geodetic Survey (NGS) has measured the average L1 and L2 phase center offsets from these ARPs by a technique that will be described shortly. Table 2 shows the results when these offsets are used to reference the baseline determinations to a physical point on the antenna rather than to the previously ill-defined phase centers.

TABLE 1

TRM 22020.00—JPL D/M+crT vector components (no phase center offsets or variations applied)

Frequency	*North (cm)*	*East (cm)*	*Up (cm)*
L1	497.12	7.36	3.71
L2	497.24	6.94	5.62
L3	496.93	8.02	0.74

TABLE 2

TRM 22020.00—JPL D/M+crT vector components (phase center offsets applied)

Frequency	*North (cm)*	*East (cm)*	*Up (cm)*
L1	497.27	7.24	.22
L2	497.14	7.10	.26
L3	497.48	7.45	.95

Table 2 shows that the discrepancies between the solutions have significantly improved in the Up component and the East component. The offsets for these solutions used values for the TRM 22020.00 antenna that averaged calibrations for four different antennas of this particular model. The deviation of individual antennas from the average calibration values can sometimes be several millimeters. Using standard calibrations to find an L1 and L2 average phase center is essential not only for reconciling the differences between solutions made with different frequencies or frequency combinations, but also for baselines using different antennas over the same monuments.

While this example shows the utility of calibrating the average L1 and L2 phase centers with respect to the ARP, it does not illustrate the problems encountered by ignoring the variation of the phase center location with direction to the signal. Fortunately, almost all GPS antennas currently in use are azimuthally symmetric, and the dominant phase variation occurs with elevation. However, the local environment around the antenna can introduce both azimuth and elevation variations from the ideally measured phase patterns. These local variations will be ignored for the sake of these calibrations. One effect of these phase center variations (PCV) can be illustrated by varying the elevation cutoff angle. This dependence is shown in Table 3 for the same data used previously. Only the L3 solutions are shown.

Table 3 shows that the Up component of the baseline varies by about 1 cm as the elevation cutoff changes from 10 to 25 degrees for these L3 solutions. The horizontal components of this baseline change by only 1 to 2mm. If the information that describes the change in phase center location as a function of elevation is included, the results shown in Table 4 are obtained. The horizontal components have systematically shifted by about 1 mm, and the excursion of the Up component

TABLE 3

TRM 22020.00—JPL D/M+crT vector components (L3 solutions as function of elevation cutoff with phase center offsets only)

Cutoff (deg)	*North (cm)*	*East (cm)*	*Up (cm)*
10	497.41	7.41	1.22
15	497.48	7.45	0.95
20	497.53	7.35	0.64
25	497.63	7.31	0.25

with elevation cutoff angle is now reduced to only about 3 mm.

Elevation-dependent PCV can also affect a baseline solution in which a tropospheric scale factor is being adjusted. GPS solutions usually include an estimate of the phase delay to the signals as they travel through the troposphere to each antenna. Different propagation path delays may seriously affect the baseline components, particularly the vertical, if left uncorrected. Because the estimates of these propagation delays computed by the model in the software may be inaccurate, the GPS data themselves can be used to estimate the remaining differential path delays by including in the GPS solution an adjustment for a tropospheric scale factor. Simply expressed, this scale factor adjustment is a constant multiplicative factor for each tropospheric delay computed by the model used in the solution software. For this technique to work properly, the phase delay contained in the GPS data, as a function of elevation must be due solely to the troposphere. An additional phase change, introduced by the antennas and superimposed on the GPS data, will still be interpreted by the software as being due to the troposphere alone. The result will be incorrect tropospheric scale factor adjustments and incorrect baseline height components. Table 5 illustrates the magnitude of the problems that can result. This table repeats the L3 result from Table 2, where only the phase center offsets were applied to the solution (+OFF). The next line shows the baseline components when the tropospheric scale factor is adjusted (+OFF, +T). The Up components change by over 3 cm. Table 5 also shows the result when the offsets and PCV are applied (+PCV) and when the tropospheric scale factor adjustment is included along with these calibrations (+PCV, +T). The last two lines of Table 5 show only a 1 mm height change when the tropospheric scale factor is included. The correct Up component for this baseline, based on leveling data, is − 0.3 cm. The solutions using the full calibration data (offsets and PCV) give results closest to this value.

Having demonstrated the importance of using antenna calibrations for GPS baseline solutions, the techniques by which NGS determines these calibrations will now be examined.

NGS ANTENNA CALIBRATION PROCEDURE

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 and absolute antenna calibrations have not yet been satisfactorily demonstrated. There is no practical difference to using relative or absolute antenna calibrations until the base-

TABLE 4

TRM 22020.00—JPL D/M+crT vector components (L3 solutions as function of elevation cutoff with phase center offsets and variations)

Cutoff (deg)	*North (cm)*	*East (cm)*	*Up (cm)*
10	497.36	7.54	−0.01
15	497.43	7.59	−0.14
20	497.45	7.48	0.03
25	497.54	7.45	0.15

TABLE 5

TRM 22020.00—JPL D/M+crT vector components (effect of PCV on L3 solutions with and without troposphere)

	North (cm)	*East (cm)*	*Up (cm)*
+OFF	497.48	7.45	0.95
+OFF,+T	497.49	7.45	−2.74
+PCV	497.43	7.59	−0.14
+PCV,+T	497.42	7.54	−0.04

line lengths approach several thousand km in length. As the baseline length increases, the curvature of the Earth's surface causes the same satellites to appear at increasingly different elevations at the ends of the baseline. These situations would require an absolute calibration in order to remove the direct contribution of possible errors in the defined calibrations for the reference antenna to the scale of the baselines. For almost all other situations short of a global network, relative antenna calibrations should be satisfactory.

To perform these antenna calibrations, a test range has been established at NGS's Instrumentation and Methodologies Branch in Corbin, Virginia. This test range, pictured in Figure 1, consists of two stable 6-in-diameter concrete piers rising about 1.8 m above ground. On the tops of these piers, antenna-mounting plates are permanently attached. The piers, separated by 5 m, are located in a flat grassy field and lie along a north-south line. Leveling data show that the south (test antenna) pier is 3.4 mm taller than the north (reference antenna) pier. The reference and test antennas are connected to Ashtech Z12 receivers that are set to track to an elevation mask of 10°. A Rubidium oscillator is used as an external frequency standard for both of these receivers.

The reference antenna used for these calibration measurements is a Dorne/Margolin choke ring antenna, type T originally designed by JPL and designated as JPL D/M+crT. These tests do not provide the absolute phase calibration for each antenna tested, but rather the relative calibrations with respect to this reference 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 PCV.

Beginning several years ago, and at intervals since then, additional JPL D/M+crT antennas have been placed on the test pier in order to determine the location of this antenna's L1 and L2 phase centers on this pier. As illustrated in Figure 2, 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. Since the average L1 and L2 phase center offsets of the JPL D/M+crT are defined to be 11.0 cm and 12.8 cm, respectively, the average L1 and L2 phase center offsets of the test antennas can be easily found.

As shown earlier, the average phase center position is a function of the elevation cutoff angle. For the NGS antenna calibrations, a standard elevation cutoff angle of 15° has been defined 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 software. This software uses

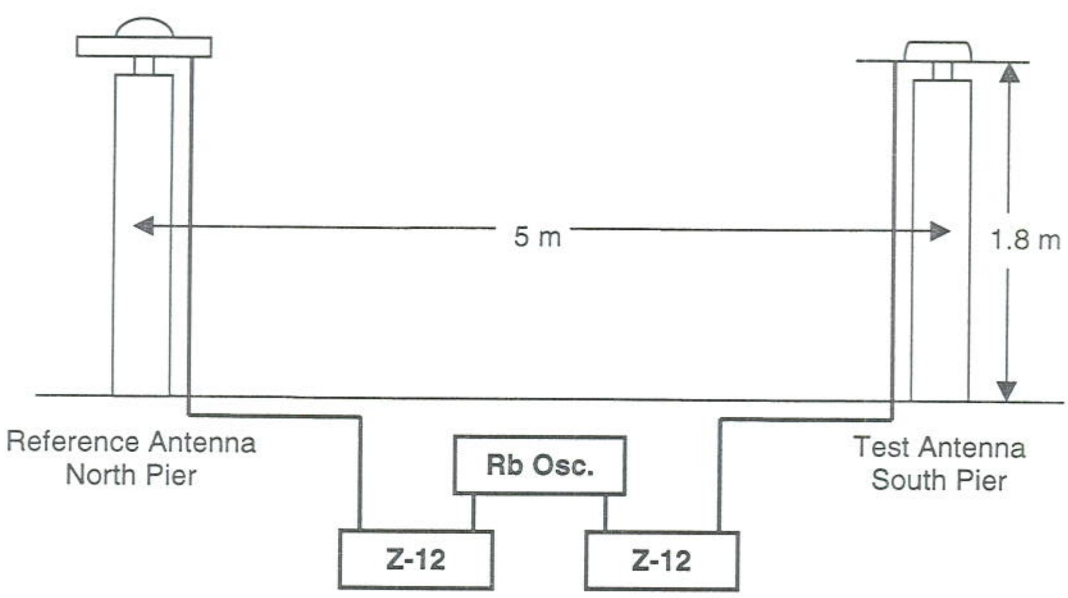

FIGURE 1. The NGS antenna calibration test facility at Corbin, VA uses a JPL D/M+crT as a reference antenna. The test antennas are located 5 m away at approximately the same height. Both antennas are connected to Ashtech Z-12 receivers that use a Rubidium oscillator as an external frequency standard.

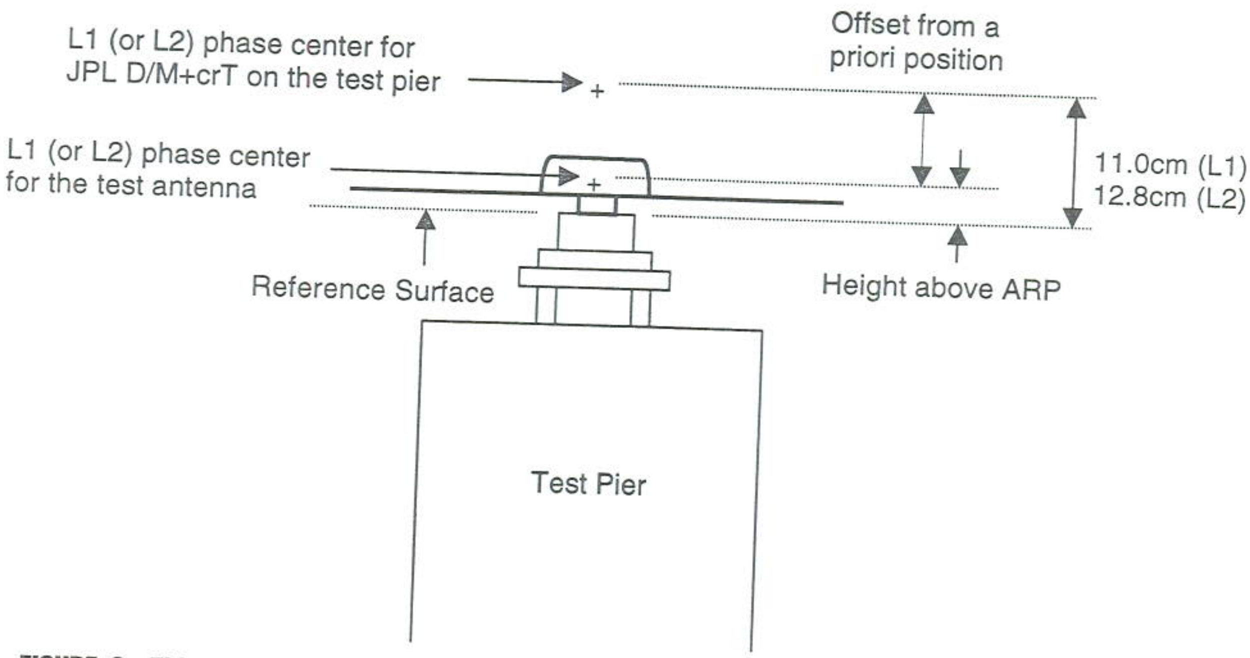

FIGURE 2. This figure shows how the average phase center offsets are found. Multiple measurements of several JPL D/M+crT reference antennas were made on the test pier to establish a priori L1 and L2 positions for all antennas tested on this pier. The offsets from these a priori positions are combined with the defined offsets for the reference antenna to find the L1 and L2 phase center offsets from the test antennas' ARP.

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 these L1 and L2 offsets have been found, the test antennas PCV can be determined.

The variation of the phase center as a function of elevation is determined separately for L1 and L2. No azimuth dependence is estimated 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 elevations. 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.

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. A least squares solution is used to solve for a clock offset for each measurement epoch and for a fourth-order polynomial in elevation. The observation equation is expressed as

$$\Delta(\Phi_{obs} - \Phi_{calc})_i = \tau_i + \alpha_1\theta_i + \alpha_2\theta_i^2 + \alpha_3\theta_i^3 + \alpha_4\theta_i^4 \qquad (1)$$

where $\Delta(\Phi_{obs} - \Phi_{calc})_i$ is the single-difference phase residuals, θ is the elevation angle in degrees, α_i is the polynomial coefficient, and τ_i is the remaining relative time delay. This procedure has been coded into a FORTRAN program call ANTCAL.

Separate polynomials are estimated for L1 and L2. A constant term for the polynomial is not estimated since it is not readily separable from the clock values and would be lost in any case during double difference data processing. An elevation cutoff of 10° is now used to extend the coverage of these corrections to lower elevations. These coefficients define the PCV for this antenna.

In order to accommodate other calibration techniques using different methods, the PCV is expressed in a tabular format rather than as the coefficients defined earlier, which are unique to NGS. This allows GPS solution software to adapt to a standard format without regard to the source of these data. An example of this format is shown in Figure 3. All the NGS antenna calibrations are contained in a file designated as ant_info.002. The first line of this file contains the file name and a version designation. The version gives the initials of the person to last modify the file, the date of this modification, and the current number of antennas in the file. This allows users to easily monitor changes to the file, which most commonly are due to the addition of new antenna models. More significant changes to the format or to previously published information will cause a change to the extension of the ant_info file name.

The first few lines of the ant_info.002 file are a header that explains the format for the data. The antenna calibration for any antenna begins with the antenna identification code. This is a standard name for each model antenna and consists of a 3-character designation for the manufacturer followed by the antenna model number, which is found stamped on each antenna. This model number may be followed by a suffix that indicates if certain options are included with this antenna model (e.g., if an optional groundplane is attached or not, +gp or −gp or a radome is included or not, +rd or −rd). The remainder of this line may include a description of the antenna or an alias by which the antenna is also known. The agency providing this data, the number of measurements, and the date entered into this file are also included on this line.

The North, East, and Up L1 antenna, offset from the ARP, are given in millimeters on the next line. This is followed by the L1 PCV on the next 2 lines. The PCV is expressed in millimeters also and is given in 5° elevation increments beginning with 90 and going down to 0°. Since the NGS PCV measurements extend to only 10° elevation, the last 2 PCV entries (5 and 0°) are left at 0.0.

```
<ant_info.002>                                                      <GLM-98/11/20-48>

ANTENNA ID           DESCRIPTION                       DATA SOURCE (# OF TESTS) YR/MO/DY
 [north]  [ east]  [  up ]                                           | L1 Offset (mm)
 [90]  [85]  [80]  [75]  [70]  [65]  [60]  [55]  [50]  [45]          | L1 Phase at
 [40]  [35]  [30]  [25]  [20]  [15]  [10]  [ 5]  [ 0]                | Elevation (mm)
 [north]  [ east]  [  up ]                                           | L2 Offset (mm)
 [90]  [85]  [80]  [75]  [70]  [65]  [60]  [55]  [50]  [45]          | L2 Phase at
 [40]  [35]  [30]  [25]  [20]  [15]  [10]  [ 5]  [ 0]                | Elevation (mm)

JPL D/M+crT          DORNE MARGOLIN T                                NGS (  0) 97/10/27
       0.0        0.0        110.0
   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
       0.0        0.0        128.0
   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

. . .

TRM 22020.00         GEOD L1/L2 (COMPACT)                            NGS (  4) 97/10/27
       -.1        -.6         74.2
    .0   4.6   8.9  12.6  15.8  18.3  20.0  20.9  21.1  20.6
  19.5  18.1  16.3  14.5  13.0  12.0  11.8    .0    .0
       -.5        2.8         70.5
    .0    .3   1.0   1.9   2.8   3.6   4.3   4.8   5.1   5.0
   4.7   4.1   3.3   2.4   1.4    .5   -.1    .0    .0
TRM 22020.00-gp      GEOD L1/L2 - NO GP  (COMPACT)                   NGS (  3) 97/10/27
       2.4       -1.0         83.4
    .0    .0    .6   1.5   2.7   3.8   4.9   5.7   6.1   6.2
   5.9   5.3   4.2   2.8   1.2   -.6  -2.3    .0    .0
        .4        2.7         82.5
    .0  -1.2  -1.6  -1.3   -.8    .0    .7   1.3   1.8   1.9
   1.7   1.2    .3   -.8  -2.1  -3.4  -4.7    .0    .0
```

FIGURE 3. This figure shows a sample from the antenna calibration file ant_info.002. The file contains a format explanation followed by the results for each antenna tested. The antennas are identified by an unambiguous and machine-readable standard name.

The lines containing the same data for L2 immediately follow the L1 data. If a particular antenna is an L1-only antenna, the L2 data fields will contain all 0.0's.

As mentioned previously, the solution for the PCV coefficients does not include a constant term. Consequently, the initial computation of the PCV tabular values includes an arbitrary constant value with no particular physical meaning. Since the essential information from the PCV is its curvature, a constant is subtracted from each tabular entry so that the PCV value at 90° is always 0.0. This is done by convention to keep all the PCV values for the various antennas within a similar range and to facilitate comparisons. It has no effect on the results obtained with these PCVs.

The PCV for the JPL D/M+crT is defined to be 0.0 over the entire elevation range. In reality this is certainly not the case. The phase center meanders with elevation for these antennas just as it does for any other antenna. These adopted PCV values only reflect the fact that an absolute PCV for this antenna has not been satisfactorily measured and that this is the adopted reference antenna.

The PCV data are used to correct the observed GPS phase data as it is obtained from a RINEX file. Each L1 and L2 phase observation is corrected. This is done by using the elevation of a satellite at the time of each measurement to interpolate linearly the L1 and L2 PCV value from the PCV table. This interpolated value is converted to the appropriate units (meters or L1 or L2 cycles) and added to the observed phase. This procedure effectively removes each change in phase introduced by the antenna as the satellites move across the sky.

The PCV of an antenna is inseparable from the offset for that antenna. Using a different average phase center offset will cause ANTCAL to produce a different set of PCV values. However, when the PCV are applied to observed phase data (and provided the appropriate set of PCV values are used), different average phase center offsets will give the same position for the ARP. The fact that GPS measures the location of the phase center and that different phase center heights above the ARP can yield the same position for the ARP may seem strange. However, this fact emphasizes the arbitrary location of the phase center and the importance of always using the PCV and the offsets that were determined together.

Figure 4 shows the data used to determine the PCV for one particular test antenna. The points shown in Figure 4 are essentially the a priori single-difference phase residuals with the epoch-by-epoch time delays removed. The phase variation with elevation is clearly evident. Figure 4 also shows the polynomial fit to these data and the location of the tabular PCV values (before the normalizing constant has been subtracted). Careful examination of Figure 4 also shows the effect of multipath due to reflections from the ground. These multipath signals are at a much higher frequency than the overall PCV and hence do not influence the low order polynomial used to estimate the PCV. Plots like that shown in Figure 4 are maintained by NGS as a quality control for each individual antenna calibration.

NGS ordinarily tries to calibrate at least three different members of each antenna species in order to get even a rough idea of the repeatability of the calibrations. The numbers reported in the ant_info.002 file are an average of each of these individual calibrations. An example of this root mean square (RMS) repeatability is shown in Figure 5 for the four separate calibrations that went into the averages for the TRM 22020.00 that was shown earlier. The RMS repeatabilities of several millimeters in the Up offset and the PCV are typical of most of the antennas that have been calibrated. NGS has also calibrated five separate JPL D/M+crT antennas for comparison to the single member of this model that is used as a reference for all calibrations. These results are shown in Figure 6. Except for the north offset, the average offsets and PCV for this group is within a fraction of a millimeter of the reference antenna. The north offset is larger than the other offsets but is on the order of the RMS. While this offset and RMS is comparable to what is seen for most other antennas, it does seem large for what is otherwise a very repeatable set of measurements for this class of antenna.

SUMMARY

GPS antennas are calibrated under somewhat ideal conditions. These NGS in situ calibrations are performed at the same site, at a consistent height, and on flat terrain with no reflectors, other than the ground, that may cause unwanted multipath reflections leading to azimuthal asymmetries. Users should always remember that the conditions under which these calibrations were determined are, hopefully, a reasonable approximation to the unique circumstances for the antennas to which they are applied. Under ideal circumstances, every antenna would be individually calibrated at its own site.

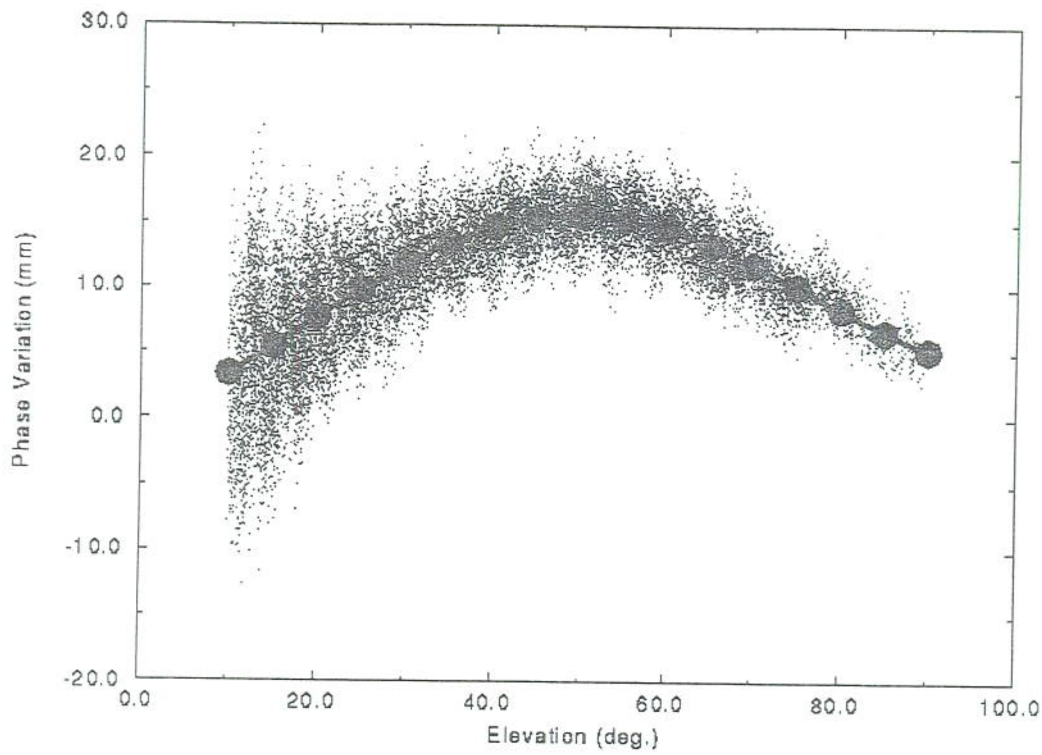

FIGURE 4. This figure shows the phase residuals for an antenna calibration as a function of elevation. The phase variation is clearly evident. The solid curve is the polynomial fit to these data, and the dots indicate the elevation increments used in the summary file.

While this is possible and might be accomplished for permanent GPS tracking sites, it is impractical for sites that are only infrequently and briefly occupied.

An antenna calibration is an essential part of doing the most precise GPS surveying possible. However, an antenna calibration by itself is not a statement about the relative merits of any particular model of antenna. All antennas have an average phase center offset and a PCV with respect to an antenna reference point. It is essential to know what these are, but knowing them says nothing about whether an antenna is "good" or "bad" for any particular application. This sort of evaluation would be the subject of a different series of measurements. The most significant contribution of antenna calibrations is ensuring interoperability within the growing community of GPS antenna types.

```
TRM22020.00
         -.1          -.6          74.2
    .0    4.6    8.9   12.6    15.8   18.3   20.0   20.9   21.1   20.6
  19.5   18.1   16.3   14.5    13.0   12.0   11.8     .0     .0
         -.5           2.8         70.5
    .0     .3    1.0    1.9     2.8    3.6    4.3    4.8    5.1    5.0
   4.7    4.1    3.3    2.4     1.4     .5    -.1     .0     .0

rms -   4  measurements
         1.3           1.3          3.3
    .0     .3     .5     .6      .6     .7     .6     .8     .9    1.1
   1.3    1.6    1.9    2.1     2.3    2.5    2.6     .0     .0
          .6            .5      1.5
    .0     .4     .6     .7      .7     .7     .8     .8     .8     .9
   1.1    1.2    1.3    1.4     1.5    1.4    1.4     .0     .0
```

FIGURE 5. The average calibration results for the TRM 22020.00 are shown along with the RMS repeatability for the four measurements of this antenna that went into the average.

JPL D/M+crT

	1.3	.0		110.6					
.0	.2	.3	.4	.4	.4	.4	.4	.4	.4
.4	.4	.4	.4	.3	.2	.0	.0	.0	
	1.1	1.2		128.3					
.0	-.1	-.1	-.1	-.1	.0	.0	.0	.0	.0
.0	-.1	-.1	-.1	-.1	.0	.1	.0	.0	

rms - 5 measurements

	1.2	.6		.5					
.0	.2	.4	.4	.4	.4	.4	.4	.4	.4
.5	.5	.5	.5	.5	.4	.3	.0	.0	
	.6	.4		.4					
.0	.3	.4	.5	.4	.4	.4	.3	.3	.3
.4	.4	.5	.5	.4	.3	.3	.0	.0	

FIGURE 6. The average calibrations for five separate JPL D/M+crT antennas relative to the JPL D/M+crT antenna chosen as the reference antenna are shown.

All NGS antenna calibrations are performed relative to a specific antenna and have been done under identical conditions. These calibrations are a consistent set of measurements, and it would not be advisable to use the results from another source of calibrations with these NGS or yet another source of calibrations. While calibrations may be internally consistent within any given measurements scheme, different calibration techniques have different sources of systematic error that may not cancel out when using results from different schemes.

NGS, along with numerous other groups, has been using these calibrations in its software and GPS processing for several years already. These calibrations are available to other GPS users via the World Wide Web at www.ngs.noaa.gov. The Web site contains the complete summary of all calibration results as well as additional information about the antennas, including photographs and engineering drawings to aid in identifying the correct antenna offsets and the antenna reference points to which they refer. NGS will continue its antenna calibration program to provide a consistent set of reliable calibrations for all geodetic-quality GPS antennas. ■

BIOGRAPHY

Gerald Mader received his Ph.D. in astronomy from the University of Maryland in 1975. He serves as chief of the Geosciences Research Division at the National Geodetic Survey in Silver Spring, Maryland. Besides his research interest in improving GPS results through better understanding of GPS antennas, Dr. Mader is also continuing his research on techniques and applications of kinematic GPS.