Characterizing the Behavior of Geodetic GPS Antennas

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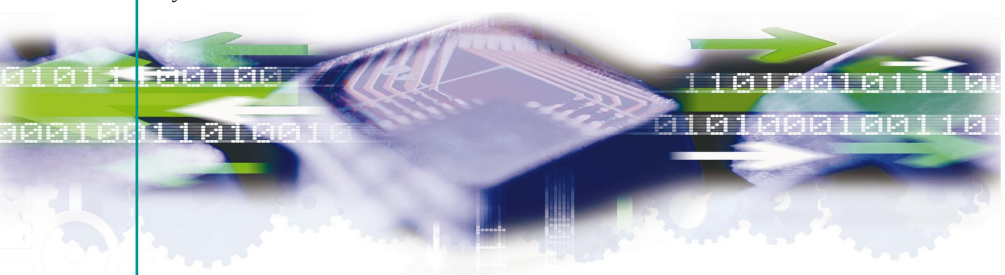
In high-accuracy applications of GPS such as establishing geodetic control networks, monitoring dam deformation, or measuring the Earth's rotation, effects on GPS measurements as small as a few millimeters can be important. To achieve the required positioning accuracies, such effects must be modeled very carefully or preferably avoided in the first place. Although some potential errors originate with the GPS satellites and some with the ionosphere and troposphere through which the signals must travel, some are due to the receiver's antenna and its immediate environment. High-accuracy applications use special antennas designed to reduce antenna-related errors to a minimum. Just how good are these antennas? It is difficult to check the performance of antennas in the field — where the ground, mounting devices, and nearby structures all may have an effect. To isolate an antenna from its environment as much as possible or to change the environment in a controlled fashion, antennas are tested in anechoic chambers — specially designed enclosures that virtually eliminate reflected signals and in which the position and orientation of the antenna can be precisely controlled. In this month's column, Bruce Schupler and Thomas Clark discuss the procedures they have developed to characterize the behavior of GPS antennas using anechoic chamber measurements and discuss some of the results they have obtained.



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Thomas Clark *joined NASA's Goddard Space Flight Center in Greenbelt, Maryland, in 1968. His research interests have centered on developing the techniques of VLBI and GPS for high-accuracy geodesy. His research also has involved the characterization of geodetic GPS antenna performance at millimeter levels and the mitigation of site-specific multipath. Clark has been author or co-author of more than 150 scientific and technical papers in many fields. He has received numerous awards, including NASA's Medal for Exceptional Engineering Achievement.*

The performance of GPS user antennas is influenced by many factors. Some are inherent to the design of the antenna, while others are "outside influences," such as the effect of material close to the antenna (including the antenna radome, if any), the design of any integral antenna amplifier (preamplifier), and the frequency range over which the antenna is operated. The user must be aware of the impact that these factors will have on the performance of the antenna.

For several years we have been characterizing the performance of a variety of geodetic-quality GPS user antennas using the anechoic chamber of the Goddard Space Flight Center (GSFC). We have recently expanded our test program to address some of the outside influences on the performance of the basic antenna. We have tested several antennas both with and without radomes, with and without amplifiers, placing a variety of materials close to the antenna, and performing the antenna characterization at frequencies that range from below the proposed third civil GPS frequency (L5 at 1176.45 MHz) to above the top of the L1 GPS band. (This frequency range includes all of the GLONASS frequencies.) In this article we will describe the results of recent tests on three antennas of interest and available to us or, in one case, that a colleague asked us to test. (Antenna manufacturers answered technical questions and received the test results, but were otherwise not involved in designing the tests.)

Geodetic Antenna Requirements

One of the many benefits of GPS is that it serves a large and varied community of users, from the weekend sailor who is content with positioning accuracies of a few tens of meters to the geodesist to whom even a few millimeters can make a difference.

The level of complexity of the hardware and software needed by these two kinds of GPS users is different. Whereas the weekend sailor may use a simple handheld GPS receiver providing positions based on single-frequency pseudorange measurements, the geodesist uses much more elaborate equipment providing dual-frequency carrier-phase observations in addition to low-noise pseudorange observations. And whereas the weekend sailor's receiver may safely ignore small effects on its measurements, the geodesist's equipment and data processing software must account for effects as small as a few millimeters. Phenomena such as the solid Earth tides and the effect of tropospheric water vapor on the propagation of the GPS signals, for example, must be modeled by the data processing software. The GPS hardware itself also will have an effect on the measurements. In addition to random thermal noise, the measurements will be affected by any instability in the phase center of the antenna and any multipath signals accepted by the antenna.

Two of the more important characteristics of antennas for high-accuracy GPS applications such as geodesy are a high phase-center stability and a low response to multipath signals. Several manufacturers have designed such antennas. However, even these state-of-the-art antennas are not perfect, and it is useful to characterize their performance under different operating conditions. It is difficult to carry out such characterization tests in the field using "live" GPS signals, because

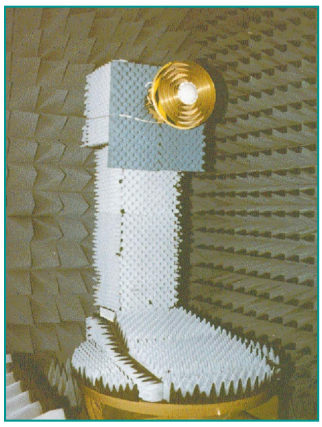


FIGURE 1 The range calibration antenna on the antenna positioner in the anechoic chamber

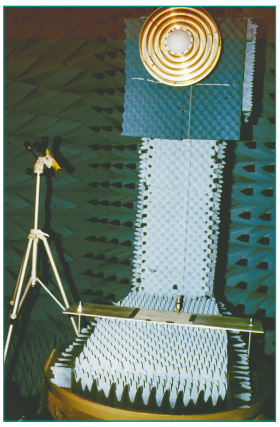


FIGURE 2 The laser, auxiliary table, and plumb bob used to determine the antenna offset

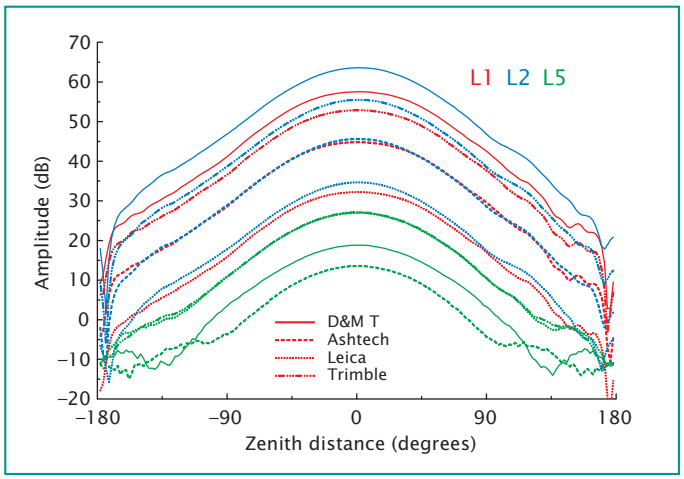


FIGURE 3 The amplitude response of four choke ring antennas at L1, L2, and L5

the various factors affecting the observations cannot be easily isolated. Instead, tests are conducted in a controlled environment — an anechoic chamber — using signals from a generator which mimics real GPS signals.

Measurement Procedures

Previous versions of the measurement and data analysis procedures that we follow have been discussed in some detail (see Further Reading). We will not repeat this detailed discussion here. However, a brief summary of our current measurement process will be useful for those who are unfamiliar with our procedures.

We performed all of our measurements in the anechoic chamber located in GSFC Building 19. This chamber was recently rebuilt and is now fully automated. It consists of a large antenna positioner located at the large end of a room built in the shape of a square horn with a source antenna located 18 meters away at the throat of the horn. All of the interior surfaces of the anechoic chamber are lined with radio-frequency (RF) absorbent material. For our purposes, the source antenna is a dipole that can be rotated under computer control to provide a signal that is horizontally or vertically polarized. The antenna positioner can rotate the antenna under measurement through 360 degrees of motion both in the plane of the antenna (to provide azimuthal coverage) and in a plane perpendicular to the plane of the antenna under measurement (to provide elevation coverage). Figure 1 shows our range calibration standard GPS antenna mounted on the antenna positioner in the anechoic chamber.

As the antenna under test is rotated over the desired angular measurement range, the source signal is stepped through the various frequencies and the amplitude and phase response of the antenna under test is measured. (For our recent tests, we used 129 discrete frequencies.) This measurement process is repeated for horizontally and vertically polarized source signals. From this data, the measurement software can synthesize the antenna response to right and left circularly polarized signals as well as the cross-polarization and axial ratio response functions. The amplitude response is referenced to the response of a well-characterized standard gain horn.

To determine the position of the antenna phase center relative to the base of the antenna, the offset between the projection of the vertical axis of the antenna positioner and the front of the antenna mounting fixture must be determined. This is established through the use of a laser, an auxiliary table, and a plumb bob as shown in Figure 2.

After collecting the magnitude and phase data, sorting them, and extracting them into usable files , we have to process the phase data to extract the antenna phase center and to generate phase patterns that correspond to the computed phase center. This process consists of fitting the data to a model that takes into account the mechanical features of the antenna positioner as well as the effects that the change in range between the RF source and the antenna under test produces as the latter is rotated. As end products of this data processing phase, we obtain files of antenna magnitude patterns, phase patterns, and phase center locations for each frequency that we measured at both right and left circular polarization.

The recovered antenna phase center and, thus, the recovered phase pattern is a function of the elevation angle cutoff that is used to fit the phase center. For all of our work we have used an elevation angle cutoff of 10 degrees when fitting for the phase center.

Our two most recent antenna measurement sessions occurred in October 1998 and November 1999. In Table 1 we list the geodetic antennas and measurement configurations that we measured during these sessions and that we discuss in this article. (In addition to the geodetic antennas, we also measured several L1-only and other experimental antennas. We will not discuss those measurements here.)

Space constraints do not allow us to present all the results we produced from processing the data we obtained from the measurement sessions listed in Table 1. Instead, in what follows, we show selected results that highlight the effects that various parameters can have on the performance of geodetic GPS user antennas.

Changes in Antenna Response with Frequency

The choke ring style GPS antenna exhibits very significant changes in its response as a function of frequency. Figure 3 shows the amplitude response of several choke ring antennas at the L1, L2, and L5 frequencies, and Figure 4 shows the change in phase response.

As may be seen from those two figures, the shapes of the amplitude and phase patterns at the different frequencies for the four different antennas are generally similar. The gain of the antennas varies from unit to unit (most likely due to differences in the integral amplifiers) while all of the units show substantially lower gain at L5 than at L1 or L2.

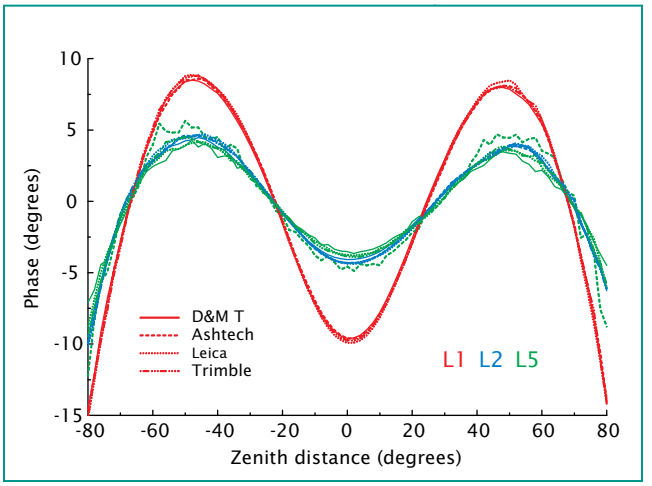


FIGURE 4 The phase response of four choke ring GPS antennas at L1, L2, and L5

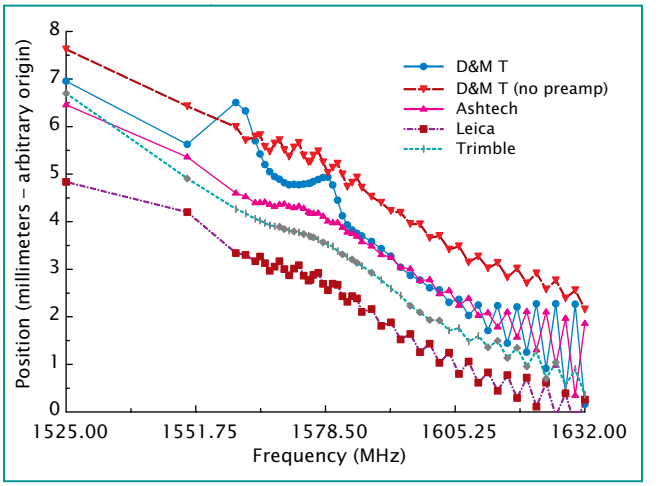


FIGURE 5 Different antennas exhibit different vertical phase center motion as a function of frequency

The phase patterns are also quite similar for all of the antennas at a given frequency. The only exception to this is the slightly noisy appearance of the Ashtech antenna at L5 around a zenith distance of ±50 degrees.

How Similar Are Antennas from Different Manufacturers?

Although the amplitude and phase response of choke ring style GPS antennas from various manufacturers are generally similar, the change in the vertical component of the phase center location with frequency does vary somewhat — see Figure 5. The absolute value of the vertical scale in the figure is arbitrary for each antenna and has been adjusted independently for each antenna for plotting purposes. What is significant in this plot is the differing shape of the curve for each antenna as a function of frequency.

TABLE 1 Geodetic GPS Antenna Configurations Recently Measured in the GSFC Anechoic Chamber

Antenna	Configuration
Ashtech Model 701945-01	With no added material
Ashtech Model 701945-01	With 2-inch pipe adapter
Ashtech Model 701945-01	With short radome
Ashtech Model 701945-01	With 2-inch pipe adapter and short radome
Ashtech Model 701945-01	With 2-inch pipe adapter and radome bottom
Ashtech Model 701945-01	With 2-inch pipe adapter, radome bottom, and tall radome
Dorne & Margolin T	Amplifier removed
Dorne & Margolin T	Foil placed over choke rings, amplifier removed — test of element only
Dorne & Margolin T S/N 198	Range standard antenna in normal configuration
Dorne & Margolin T S/N 198	Cementboard simulating a monument 11.5 cm behind antenna
Dorne & Margolin T S/N 198	30-cm-diameter reflecting disk mounted on cementboard behind antenna
Dorne & Margolin T S/N 198	Cementboard behind antenna and conical radome
Dorne & Margolin T S/N 198	Cementboard behind antenna and hemispherical Goddard East GPS site (GODE) radome.
Dorne & Margolin T S/N 198	Foil-faced insulation as reflector 11.5 cm behind antenna
Dorne & Margolin T S/N 198	Absorber over foil-faced insulation 11.5 cm behind antenna
Dorne & Margolin T S/N 198	Plywood 11.5 cm behind antenna
Dorne & Margolin T S/N 198	Plywood behind antenna and conical radome
Dorne & Margolin T S/N 198	Plywood behind antenna and hemispherical (GODE) radome
JPS RegAnt Dual Depth	With radome
JPS RegAnt Dual Depth	Without radome
JPS RegAnt Single Depth	With radome
JPS RegAnt Single Depth	Without radome
Leica AT504	No radome
Leica AT504	With Leica radome

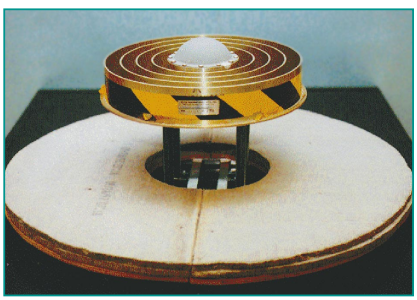


FIGURE 6 Modified antenna mount showing the cementboard used to simulate a concrete monument

Effect of Reflectors and Radomes

In order to explore the effect that various reflectors placed in the vicinity of a GPS user's antenna could have on the data collected by the antenna, we modified the antenna mounting structure shown in Figure 1 so that it could support a variety of reflectors, as listed in Table 1. Figure 6 shows the cementboard (cement filled panels) we used to simulate a concrete monument.

Figure 7 shows the effect that various reflectors have on the L1 phase pattern of the Dorne & Margolin T antenna — a Dorne & Margolin antenna element on a JPL-designed choke ring with integral amplifier. The data plotted in Figure 7 is the change in measured phase between the described configuration and the antenna with no added reflector.

As can be seen in the figure, we obtained very similar and minimal effects with the cementboard and plywood reflectors, and we obtained a quite large effect (as expected) from the foil-faced insulation. We also examined the effect of placing an absorber over the foil-faced insulation. It appears that the absorber did not completely shield

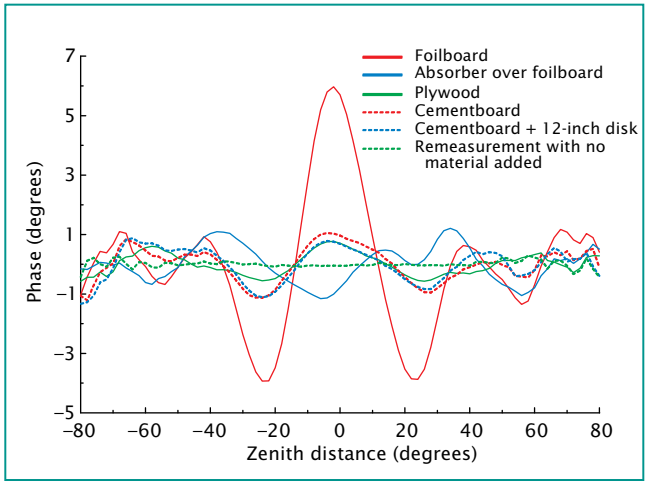


FIGURE 7 The effect of reflectors on the phase pattern of the Dorne & Margolin T antenna at L1

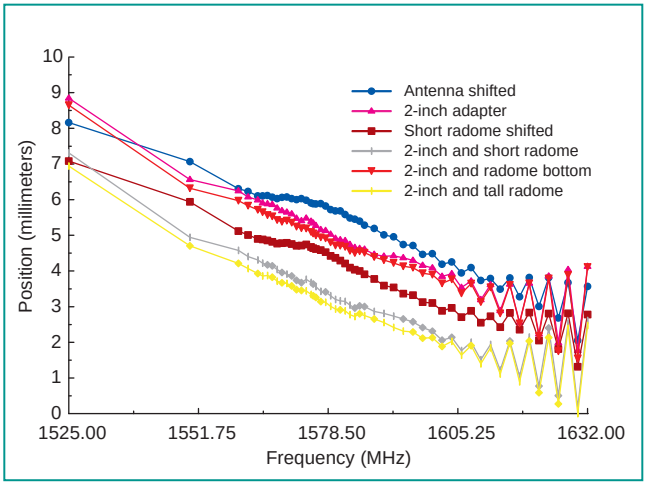


FIGURE 8 The effect of radomes and antenna mounts on the phase center position of the Ashtech 701945-01 antenna

the antenna from the effect of the foil. This is somewhat surprising, because we used the same absorber that we used on the walls of the anechoic chamber.

The 12-inch (30.48 centimeters) metal disk we placed in the middle of the cementboard simulated a metal top plate on a concrete pier. Although this did have a different effect on the antenna than the cementboard alone, the difference was small.

To explore the effect of radomes on the performance of the GPS user antenna, we performed our series of measurements using an Ashtech Model 701945-01 antenna, mounting adapter, short radome, and tall radome. Although the phase and amplitude patterns did not change noticeably as we added the various components to the basic antenna, the location of the phase center did vary. This variation in the frequency range around L1 is shown in Figure 8. (The results in the frequency range near L2 and L5 have a magnitude similar to those near L1.)

In Figure 8 we translated the traces with the word "shifted" in the label by the height of the 2-inch (5.08 centimeters) pipe adapter to make them fit onto the same scale as the other traces. The origin of the phase center position in this plot is arbitrary and is not tied to any physical feature of the antenna. The vertical scale is meant only to show the effect that adding components to the basic antenna has on the variation of the phase center vertical component with frequency.

As expected, the most significant changes in the vertical position occur when either radome is added. This effect appears to be a lowering of the phase center position by approximately 2 millimeters.

In addition to performing this test on the Ashtech antenna, we also tested a Leica Model AT504 antenna with and without its radome. This antenna also showed a lowering of its phase center by 2 to 3 millimeters when the radome was installed. (We will discuss later the cause of the oscillation in the phase center vertical position seen at the high-frequency end of Figure 8.)

The Effect of a Change in Design

So far we have discussed antennas of basically the same design. The Javad Positioning Systems (JPS) antennas are of a somewhat different design and exhibit somewhat different characteristics than the "normal"

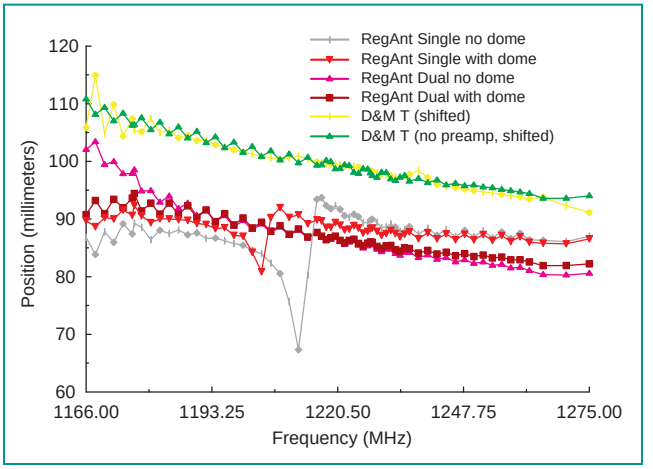


FIGURE 9 The vertical phase center position of the JPS antennas as compared with the Dorne & Margolin T near L2 and L5

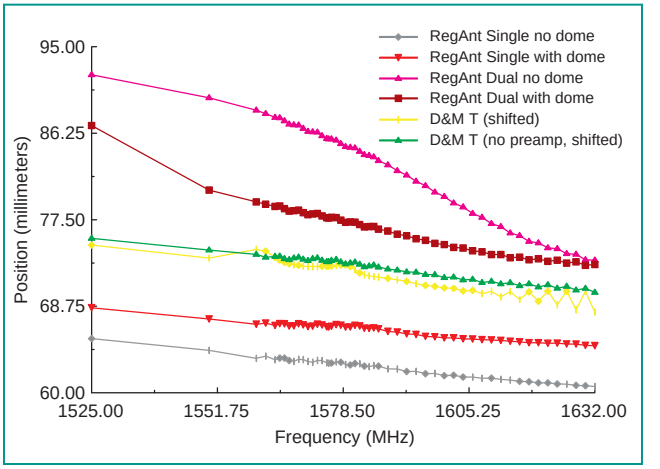


FIGURE 10 The vertical phase center position of the JPS antennas as compared to the Dorne & Margolin T near L1

choke ring antennas. We tested three JPS antennas: a RegAnt Single Depth, a RegAnt Dual Depth, and a LegAnt. We will report here the test results for the two variants of the RegAnt, both of which we tested with and without their integral radomes.

The phase patterns of all configurations of the RegAnt are similar to those of our range standard Dorne & Margolin T antenna at L2 and L5 and of noticeably smaller magnitude at L1. However, the most striking difference we saw between the performance of the RegAnt antennas and that of our range standard antenna was when we plotted the phase center vertical position as a function of frequency. We show this information in Figures 9 and 10.

The most obvious feature of Figure 9 is the rapid change in the phase center position of the RegAnt Single Depth antenna in the vicinity of 1200 MHz. When the radome is not installed on this antenna, this change occurs within the L2 passband. When the radome is installed, this feature is reduced in magnitude and shifted out of the L2 passband. This clearly shows that the radome in this antenna is not an auxiliary item. Rather, it is part of the RF structure of the antenna. Interestingly, for the RegAnt Single Depth antenna, Figure 10 shows that in the L1 area the addition of the radome makes the phase center move up rather than down. This clearly indicates that the radome plays

ANTENNA TERMINOLOGY

Anechoic chamber. An enclosure ranging in size from a few meters to tens of meters on a side used for the testing of antennas and other RF devices. The interior walls of the chamber are covered with RF-absorbing material that reduces signal reflections or "echoes" to a minimum.

Axial ratio. A measure of the polarization ellipticity of an antenna designed to receive circularly polarized signals. An axial ratio of unity, or 0 dB, implies a perfectly circularly polarized antenna.

Choke ring. An antenna ground-plane consisting of several concentric metal hoops, or thin-walled hollow cylinders, mounted on a circular base at the center of which is placed an antenna element such as a microstrip patch. It significantly attenuates ground-bounce and low-elevation angle multipath.

Cross-polarization response. A measure of the degree to which an antenna designed for, say, right-hand circularly polarized signals, responds to left-hand circularly polarized signals.

Dipole. A simple directional antenna which consists of a linear conductor, often wire or thin metal tubing, approximately one half-wavelength long, with the feed point in the middle. It is often used as a reference antenna.

Gain. For a transmitting antenna, the ratio of the radiation intensity in a given direction to the radiation that would be obtained if the power accepted by the antenna was radiated isotropically. For a receiving antenna, it is the ratio of the power delivered by the antenna in response to a signal arriving from a given direction compared to that delivered by a hypothetical isotropic reference antenna.

Gain (amplitude) pattern. The spatial variation of an antenna's gain.

Horn antenna. An aperture antenna, typically in the shape of a truncated cone or pyramid, used at microwave frequencies. It is essentially a waveguide that is flared toward the open end from which electromagnetic waves are launched (or received, in the case of a receiving antenna). The simple geometry of the horn antenna permits accurate calculation of its gain pattern and is noted for its low level of backlobes.

Phase center. The apparent source of radiation of a transmitting antenna. If the source is an ideal point source, the phase center is the center of the radiating spherical wavefronts (of equal phase). For a GPS receiving antenna, it is the point to which the receiver's phase measurements actually refer. Since a real antenna is not an ideal point source, its equiphase contours will not be perfectly spherical, and hence the center of curvature may vary with the azimuth and elevation angle of an arriving signal.

Phase pattern. The spatial variation of an antenna's phase center.

Polarization. The sense of vibration of electromagnetic radiation. There are two main types of polarization: linear, in which the radiating wave's electric field vector is confined to a particular direction (typically vertical or horizontal); and circular, where the electric vector rotates as the wave propagates through space. Depending on the sense of rotation, a signal's waves may be left-hand or, as with GPS signals, right-hand circularly polarized. For maximum response, the polarization of a receiving antenna must match the polarization of the signals.

Radome. An electromagnetically transparent cover intended to protect an antenna from the effects of its physical environment.

RF absorber. Material, such as carbon-impregnated foamed plastic, that absorbs (rather than reflects) incident radio signals.

a significant role in the RF design of this antenna.

The RegAnt Dual Depth antenna shows almost no effect from the radome in the L2 area and a small effect near L5. However, the radome has a significant impact on the antenna in the L1 region. Once again, the radome forms a portion of the antenna's RF structure. Neither version of the RegAnt should be operated without its radome.

What Limits the Frequency Response of the Antennas?

We wished to address the question of the effect of the integral amplifier on the response of otherwise very similar GPS antennas. Based on measurements that we performed several years ago in preparation for using a Dorne & Margolin T antenna for combined GPS and GLONASS measurements, we suspected that the response of the amplifier was limiting the bandpass of the antenna. We needed to explore this question further to determine whether or not we could use current antennas at L5.

To determine the effect of the amplifier, we removed it from a Dorne & Margolin T antenna, ran the antenna through our measurement process, and compared the results with those of our standard range antenna with an amplifier installed. When we examined the results of this test, the effect of the amplifier became quite clear. As we show in Figure 5, the rapid oscillations in the phase center vertical position result from the response of the amplifier rather than being an inherent characteristic of the choke rings or the antenna element. Although the amplitude response shows a very significant, albeit smooth, decrease at the extreme frequencies and the phase patterns still appear to be well-behaved, the phase center in the case with the amplifier is not well behaved. We suspect that this is caused by the bandpass filters within the amplifier being used at or beyond their designed band edges at both ends of our frequency range. Indeed, the same rapid change in phase center position can be seen in the frequency range between L2 and L1. The Leica antenna uses a different amplifier design and does not exhibit this phase center vertical oscillation to nearly as great a degree as the Dorne & Margolin T does, whereas the response of the Ashtech is similar to that of the Dorne & Margolin T.

Conclusions

We presented here the data on the response of several different geodetic GPS user antennas over a wide frequency range and in many different configurations. Although we have made no attempt to apply the antenna calibrations that can be derived from this data to field-collected GPS data, the effects shown here will doubtless also be seen in such situations.

Our measurements lead us to the following conclusions:

- Similar antenna designs from different vendors perform in a generally similar manner.
- Almost anything you put near an antenna affects its response.
- A change in an "auxiliary" portion of an antenna assembly (radome, amplifier, etc.) can significantly change the response.
- The performance of some antenna designs depends critically on the coupling between the antenna and its radome.
- The amplifier/bandpass filter response limits the L5 performance of many of the current choke ring antenna designs.

FURTHER READING

For an introduction to GPS antennas and their characteristics, see

"A Primer on GPS Antennas," by R.B. Langley in *GPS World*, Vol. 9, No. 7, July 1998, pp. 50–54.

For discussions about the effects antennas have on GPS observations, see

"How Different Antennas Affect the GPS Observable," by B.R. Schupler and T.A. Clark, in *GPS World*, Vol. 2, No. 10, November 1991, pp. 32–36.

"Signal Characteristics of GPS User Antennas," by B.R. Schupler, R.L. Allshouse, and T.A. Clark, in *Navigation*, Vol. 41, No. 3, 1994, pp. 277–295.

"Characterizations of GPS User Antennas: Reanalysis and New Results," by B.R. Schupler, T.A. Clark, and R.L. Allshouse in *GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, the Proceedings of the International Association of Geodesy Symposium No. 115, pp. 328–332, Springer-Verlag, Berlin, 1996.

The International Association of Geodesy established a Special Study Group to investigate antenna and site effects on GPS measurements. For its final report, see

<http://maia.usno.navy.mil/gpst/refs/ssg1158.html>.

Additional results for the test configurations described in this article are available on request.

Acknowledgments

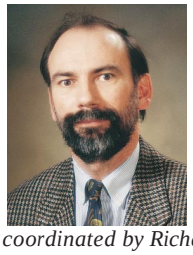
We could not have performed this work without the assistance of Steve Seufert of GSFC and his expertise with the GSFC anechoic chamber and without the resourcefulness of Charles Kodak of Honeywell in finding just the right item to make the tests possible. In addition, we would like to thank those manufacturers and organizations who lent us antennas to test (see next section).

This measurement program is funded under the Solid Earth and Natural Hazards NASA Research Announcement to improve the inherent accuracy of GPS measurements used in Earth science research. We eagerly seek the cooperation of industry and academia to sample new antenna, radome, and mounting technologies for the science community.

This article is based on the paper "High Accuracy Characterization of Geodetic GPS Antennas Using Anechoic Chamber and Field Tests" presented at 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.

Manufacturers

The antennas discussed in this article are manufactured by **Dorne & Margolin** (now **EDO Corporation**, New York, NY); **Javad Positioning Systems (JPS)**, (now **Topcon Positioning Systems**, San Jose, CA); **Ashtech Precision Products Division** of **Magellan Corporation**, Santa Clara, CA); and **Leica Geosystems Inc.** (Torrance, CA).



"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 4 of this issue.