High Accuracy Characterization of Geodetic GPS Antennas Using Anechoic Chamber and Field Tests

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BIOGRAPHIES

Bruce Schupler is the Program Manager for Satellite Laser Ranging and Very Long Baseline Interferometry (VLBI) at Honeywell Technology Solutions Inc. He has been involved in the development of space geodetic instrumentation and data analysis since 1977 with particular expertise in VLBI. He has been active in the high accuracy characterization of GPS antennas for geodetic applications since 1989. He is the author of several publications as well as numerous presentations on this subject as well as in the areas radio astronomy and space geodesy.

Dr. Thomas A. Clark joined NASA's Goddard Space Flight Center in 1968 with research interests in developing the techniques of VLBI and GPS for high accuracy geodesy. His GPS "Totally Accurate Clock" ("TAC") has allowed the VLBI and Astronomy communities to achieve global time synchronization of atomic clocks at levels of better than 25 nsec. His research has also involved the characterization of geodetic GPS antenna performance at mm levels and the mitigation of site-specific multipath.

In addition to these research efforts, Dr. Clark was an Adjoint Professor of Physics and Astronomy at the Univ. of MD (1968-76) and a Visiting Professor at Chalmers Univ. in Sweden (1993).

Dr. 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, Goddard's Moe I. Schneebaum Memorial Award for Engineering and the CSVHFS John T. Chambers Memorial Award. He is a Fellow of the American Geophysical Union and the International Association of Geodesy.

ABSTRACT

Since 1987 we have been characterizing GPS antennas using two anechoic chambers at the NASA Goddard Space Flight Center (GSFC) plus the GPS testing facility at the Goddard Geophysical and Astronomical Observatory (GGAO). Our measurement program has concentrated on determining the radiometric phase center, and the phase, amplitude and polarization response of the geodetic GPS antennas used throughout the IGS network, at DGPS base stations, and by commercial surveyors. Recent measurements have stressed the variations of these parameters over the entire range frequencies of GPS and GLONASS from below L5 to above L1. We have also measured a number of other types of antennas including low cost L1 antennas for timing applications, and specialized antennas for spacecraft and aircraft applications.

Measurements have been made to characterize subtle mm-level effects of a number of types of radomes, different types of mountings, structural materials in the near-field of the antenna, and differences between similar antennas made by different manufacturers. During the course of each measurement session we have remeasured one particular antenna to provide a consistency check on our procedures and processing. The phase centers determined from this repeated re-measurement of a single antenna have been consistent at the few millimeter level.

While almost all of the geodetic chokering antennas that we have measured in recent years have very similar phase centers, phase patterns, and amplitude patterns, there are some variants of this design that perform quite differently. In addition, the presence of different radomes, mounting configurations, and surrounding material has a significant effect on these parameters. Also, the antenna amplifier has, in some cases, caused a very significant effect on the frequency domain performance. This last factor is

extremely important for combined GPS+GLONASS measurements, for time synchronization, and when the new L5 frequency is activated.

In this paper we will present a summary of our measurement results for the most common types of geodetic GPS antennas presently in use. These results will focus on the following points:

a) The systematic change with frequency in the phase and amplitude characteristics of these antennas

b) A comparison of the measured performance of several similar antennas by different manufacturers

c) The effect of material near the antenna

d) A comparison of the measured performance of several different designs of geodetic GPS antennas

e) The frequency range over which these antennas may be expected to operate effectively

1. INTRODUCTION

The performance of all GPS user antennas is influenced by many factors. These include factors inherent to the design of the antenna, the effect of material close to the antenna (including the antenna radome, if any), the design of the antenna amplifier, and the frequency range over which the antenna is operated. The user of the antenna 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 number of geodetic quality GPS user antennas using the anechoic chamber of the Goddard Space Flight Center (GSFC) (Schupler and Clark, 1991; Schupler et al., 1994; Schupler et al., 1996). We have recently expanded our test program to address some of these outside influences on the performance of the basic antenna. These include testing a variety of 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 lower than the proposed third civil GPS frequency (L5 at 1176.45 MHz) to higher than the top of the L1 GPS band. (Note that the frequency range that we are spanning includes all of the GLONASS frequencies.)

2. MEASUREMENT PROCEDURES

Previous versions of the measurement and data analysis procedures which we follow have been discussed in some detail (Schupler et al., 1994). This detailed discussion will not be repeated here. However, a brief summary of our measurement process will be useful for those who are unfamiliar with our procedures. Please note that if there is a conflict between our earlier description and the one found here, the description in this paper should be considered to reflect our current practice.

All of our measurements have been performed in the anechoic chamber located in Building 19 at the Goddard Space Flight Center. This chamber was recently rebuilt and is now fully automated. It consists of a large antenna positioner located at the large end of room built in the shape of square horn with a source antenna located 18m away at the throat of the horn. All of the interior surfaces of the anechoic chamber are lined with RF absorbent material. For our purposes, the source antenna is a dipole which can be rotated under computer control to provide a signal which 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). A picture of our range calibration standard GPS antenna mounted on the antenna positioner in the anechoic chamber is shown in Figure 1.

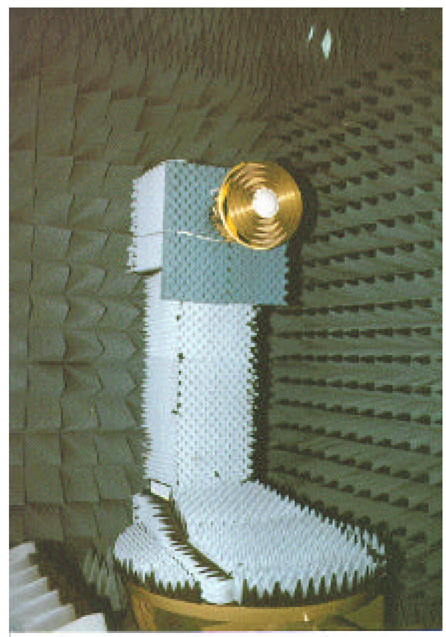

Figure 1 - The Range Calibration Antenna on the Antenna Positioner in the Anechoic Chamber

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 have 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 crosspolarization and axial ratio

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 (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

response functions. The amplitude response is referenced to the response of a well characterized standard gain horn.

In order 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 determined through the use of a laser, an auxiliary table, and a plumb bob as shown in Figure 2.

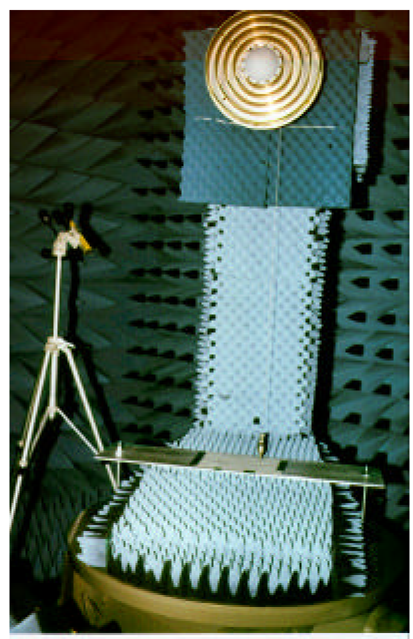

Figure 2 - With the Laser, Auxiliary Table and Plumb Bob Used to Determine the Antenna Offset

Once the data has been collected, sorted, and extracted into usable files of magnitude and phase data, the phase data must be processed to extract the antenna phase center and to generate phase patterns which correspond to the computed phase center. This process consists of fitting the data to a model which 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 produce as the antenna under test 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.

It has been shown previously (Schupler et al., 1996) that 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^o when fitting for the phase center.

3. THE ANTENNAS AND CONFIGURATIONS THAT WILL BE DISCUSSED

Our two most recent antenna measurement sessions occurred in October, 1998 and November, 1999. The geodetic antennas and measurement configurations that we measured during these sessions and that will be discussed in this paper are listed in Table 1. (In addition to the geodetic antennas, we also measured several L1 only and other experimental antennas.)

4. A SELECTION OF RESULTS

The processing of the data obtained from the measurement sessions listed in Table 1 produced results which are far too voluminous to be presented here in other than a summary form. The following sections of this paper show selected results which highlight the effects that various parameters can have on the performance of geodetic GPS user antennas.

4.1 CHANGES IN ANTENNA RESPONSE WITH FREQUENCY

The chokering style GPS antenna exhibits very significant changes in its response as a function of frequency. Figure 3 shows the change in the amplitude response of several chokering antennas as a function of frequency while Figure 4 shows the change in phase response.

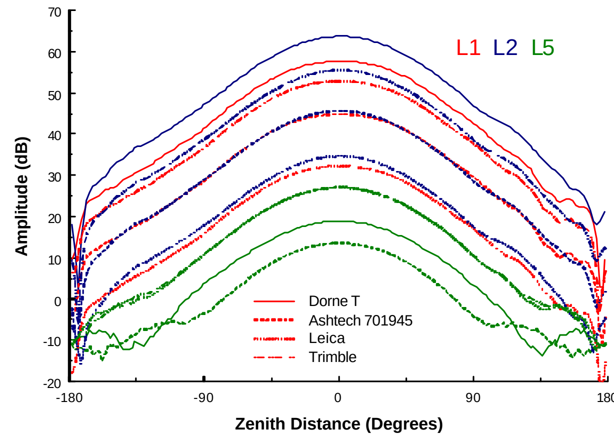

Figure 3 - The Amplitude Response of 4 Chokering GPS Antennas at L1, L2, and L5

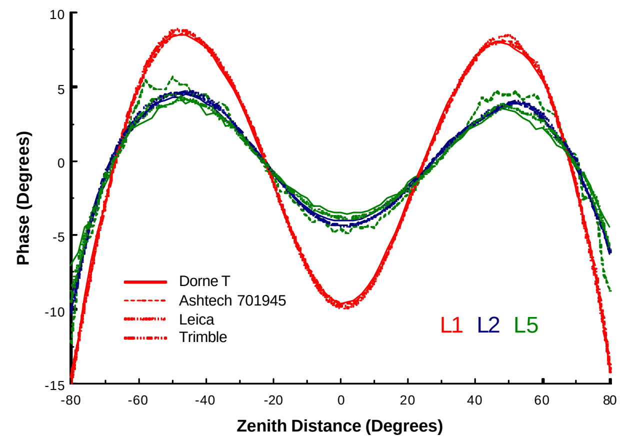

Figure 4 - The Phase Response of 4 Chokering GPS Antennas at L1, L2, and L5

As may be seen from these 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.

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 $\pm 60^o$.

4.2 HOW SIMILAR ARE ANTENNAS FROM DIFFERENT MANUFACTURERS?

While the amplitude and phase response of chokering 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. The absolute value of vertical scale in Figure 5 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 shapes of the curve for each antenna as a function of frequency.

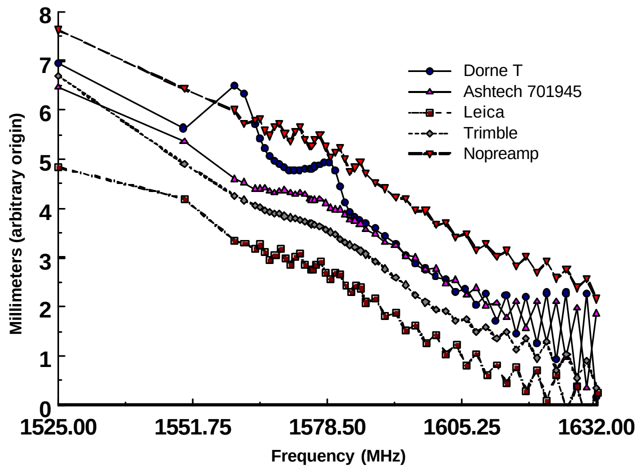

Figure 5 - Different Antennas Exhibit Different Vertical Phase Center Motion as a Function of Frequency

4.3 THE EFFECT OF REFLECTORS AND RADOMES

In order to explore the effect that various reflectors placed in the vicinity of a GPS users 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. The various reflectors which we used are listed in Table 1. Figure 6 shows the cementboard (cement filled panels) used to simulate a concrete monument.

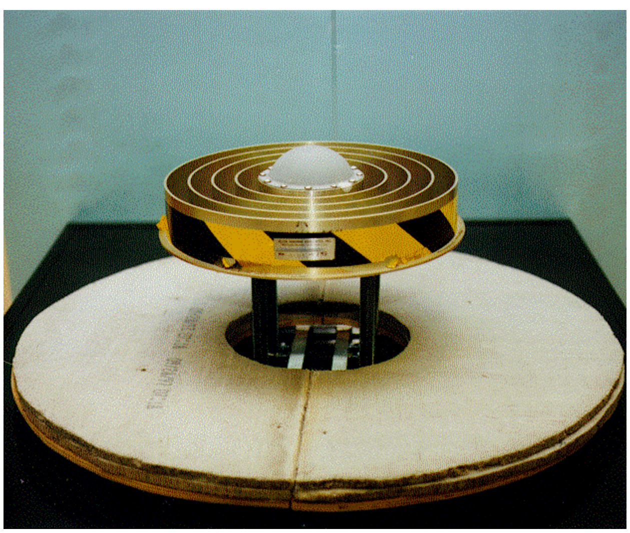

Figure 6 - Modified Antenna Mount Showing the Cementboard Used to Simulate a Concrete Monument

Figure 7 shows the effect that various reflectors have on the L1 phase pattern of the Dorne-Margolin T antenna. 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 Figure 7, the effects of the cementboard and plywood reflectors are very similar and minimal while a quite large effect is obtained (as expected) from the foil-faced insulation. It appears that the absorber which we used over the foil-faced insulation did not completely shield the antenna from the effect of the foil.

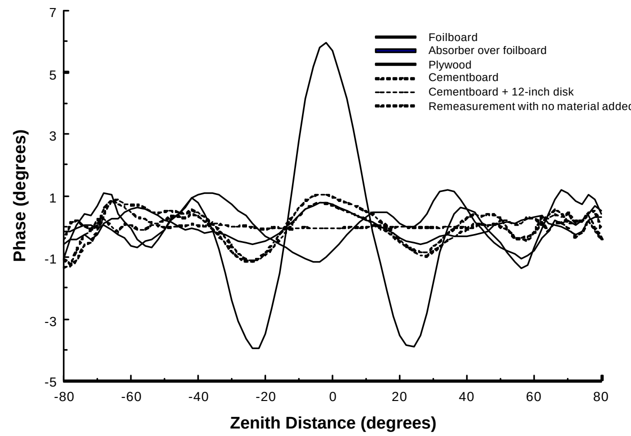

Figure 7 - The Effect of Reflectors on the Phase Pattern of the Dorne-Margolin T Antenna at L1

This is somewhat surprising as the absorber used was the same as that used on the walls of the anechoic chamber.

The metal disk placed in the middle of the cementboard simulated a metal top plate on a concrete pier. While this did have a different impact on the antenna than the cementboard alone, the difference was small.

In order to explore the effect of radomes on the performance of the GPS user antenna, we took an Ashtech Model 701945-1 antenna, mounting adapter, short radome, and tall radome that were kindly lent to us for testing by Ken Hudnutt of SCIGN and performed our series of measurements. While the phase and amplitude patterns do not change noticeably as the various components are added to the basic antenna, the location of the phase center does 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 similar magnitude to the results near L1.)

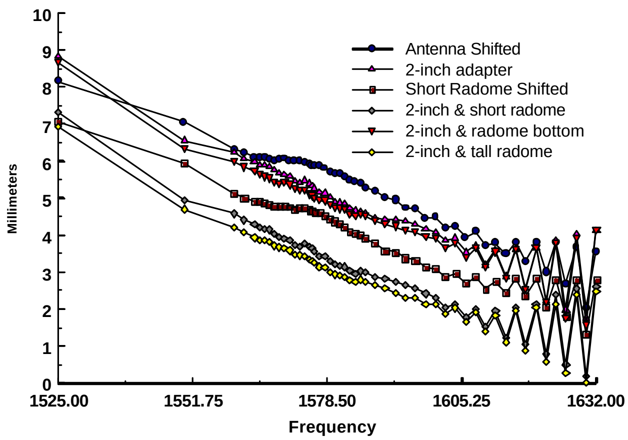

Figure 8 - The Effect of Radomes and Antenna Mounts on the Phase Center Position of the Ashtech 701945 Antenna

In Figure 8 the traces with the word "Shifted" in the label have been translated by the height of the 2-inch pipe adapter in order to 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 an lowering of the phase center position by approximately 2 mm.

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 mm when the radome was installed.

The cause of the oscillation in the phase center vertical position seen at the high frequency end of Figure 8 will be discussed in Section 4.5.

4.4 THE EFFECT OF A CHANGE IN DESIGN

All of the antennas that we have discussed so far have basically been of the same design. The JPS antennas are of a somewhat different design and exhibit somewhat different characteristics than the "normal" chokering antennas. Three JPS antennas (a Regant Single Depth, a Regant Dual Depth, and a Legant) were lent to us for testing by Barry Hogarth of JPS. Test results for the two variants of the Regant will be reported here. Both the single depth and dual depth Regant were tested with and without their integral radome.

The phase patterns of all configurations of the Regant are similar to our range standard Dorne-Margolin T antenna at L2 and L5 and of noticeably smaller magnitude at L1. However, the most striking difference between the performance of the Regant antennas and our range standard antenna is seen when the phase center vertical position is plotted as a function of frequency. This information is shown in Figures 9 and 10.

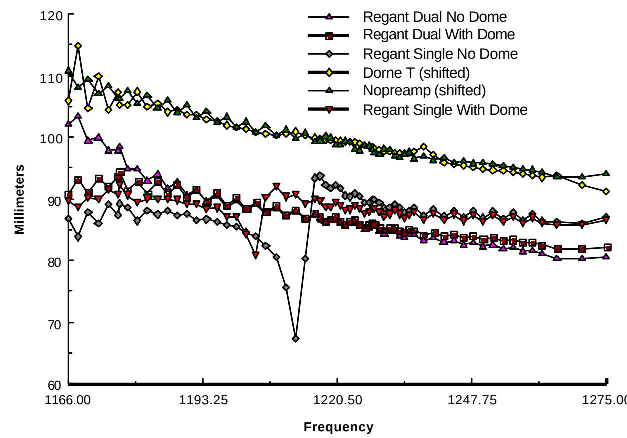

Figure 9 - The Vertical Phase Center Position of the JPS Antennas as Compared to the Dorne T at L2 and L5

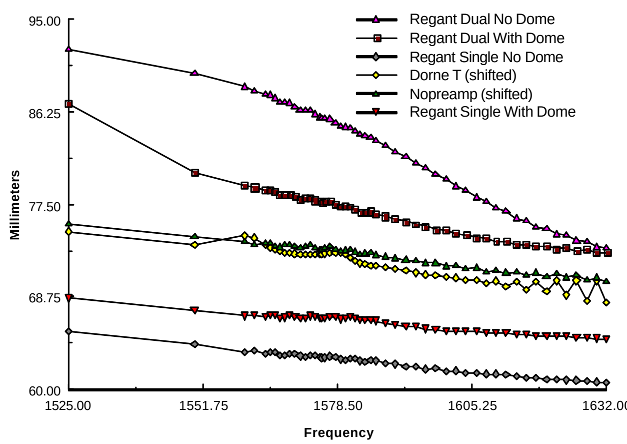

Figure 10 - The Vertical Phase Center Position of the JPS Antennas as Compared to the Dorne T at L1

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 has a significant role to play 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 antennas RF structure. Neither version of the Regant should be operated without its radome.

4.5 WHAT LIMITS THE FREQUENCY RESPONSE OF THESE ANTENNAS?

The effect of the amplifier on the response of otherwise very similar GPS antennas is a question that we wished to address. Based on measurements that we had performed several years ago in preparation for using Dorne-Margolin T antenna for combined GPS and GLONASS measurements, we were suspicious that the response of the amplifier was limiting the bandpass of the antenna. This question needed to be further explored in order to determine whether or not current antennas can be used at L5.

In order 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 that 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 is shown 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 chokerings or the antenna element. While the amplitude response show 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 bandedges at both ends of our frequency range. Indeed, the same rapid change in phase center position can be seen in the frequency space 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 while the response of the Ashtech is similar to that of the Dorne-Margolin T.

5. SUMMARY AND CONCLUSIONS

The data presented here has described the response of several different geodetic GPS user antennas over a wide frequency range and in a number of different configurations. While no attempt has been made to apply the antenna calibrations which can be derived from this data to field-collected GPS data, the effects shown here will doubtless also be seen in such situations.

This data leads 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 L5 performance of many of the current chokering antenna designs is limited by amplifier / bandpass filter response

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

6. ACKNOWLEDGMENTS

This work could not have been performed without the assistance of Steve Seufert of GSFC and his expertise with the GSFC anechoic chamber and 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.

This measurement program is funded under the Solid Earth and Natural Hazards (SENH) NASA Research Announcement (NRA) 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.

7. REFERENCES

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