Project Report
ATC-238

GPS Antenna Multipath Rejection Performance

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16. Abstract

A GPS antenna multipath rejection performance evaluation was conducted at Lincoln Laboratory. Ground reference station antennas and aviation patches were tested for their ability to reject a multipath signal. Different types of ground plane structures were used such as choke rings, ground planes, and mock sections of fuselage. Frequencies transmitted were L1 (1575 MHz), L2 (1227 MHz), and the median GLONASS frequency (1609 MHz). Receive amplitude and phase were measured on each antenna. Subsequently, these data were converted to absolute gain for a right-hand and left-hand circularly polarized signal as a function of satellite elevation angle.

Two types of multipath signals were considered: ground bounce multipath and building or structure bounce multipath. Ground bounce multipath typically occurs at low satellite elevation angles while structure bounce multipath can occur at any satellite elevation angle. Separate analysis methods were used to assess an antenna's ability to reject either type of multipath.

This report describes the data collection methods, data reduction and analysis, and the results.

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EXECUTIVE SUMMARY

BACKGROUND

This report documents a performance evaluation of GPS antennas typically used in real-time aircraft navigation applications. The study was conducted in order to determine the ability of an antenna to reject multipath signals. Since our GPS application was aircraft navigation, the antennas we tested were either aircraft antennas or ground station antennas typical of what would be used in a GPS differential navigation system.

STUDY METHOD

Data were collected by mounting the test antenna on a pedestal in an anechoic chamber. The test antenna was then illuminated with a linearly polarized source whose frequency was 1575 MHz (L1). The amplitude and phase of the test antenna while it was being illuminated were measured. Variations in source elevation angle with respect to the test antenna and test antenna azimuth angle with respect to the source were introduced in order to simulate the variability of GPS satellite elevation and azimuth angles. Receive amplitude and phase of the test antenna were then converted to absolute gain, for both a right-hand and a left-hand circularly polarized signal. Absolute gain for both polarizations was plotted as a function of elevation angle.

Three of the antennas tested were capable of receiving at frequencies other than L1 (1575 MHz). Accordingly, they were tested at L2 (1227 MHz) and the median GLONASS frequency (1609 MHz).

One of the purposes of this study was to determine if mounting antennas on different ground plane structures improved their ability to reject multipath signals. Again, a typical GPS differential navigation scenario was created by mounting ground-based antennas on choke rings or ground planes and aircraft antennas on a mock section of a 727 fuselage. Some antennas were tested on more than one ground plane structure.

Two types of multipath signals were considered: ground bounce multipath and building or structure bounce multipath. Ground bounce multipath typically occurs at low satellite elevation angles. Structure bounce multipath can occur at any satellite elevation angle. We measured rejection of ground bounce multipath by determining the antenna's cross polarization ratio at a five-degree satellite elevation angle. The larger the cross polarization ratio, the better the antenna would be at rejecting ground bounce multipath. Conversely, minimum cross polarization ratios at all satellite elevation angles were considered when determining an antenna's ability to reject a structure bounce multipath signal. In our analysis, it was assumed that GPS signals would, upon reflection from a perfectly conducting surface, switch polarizations from right-hand to left-hand circular polarization.

RESULTS

The choice of antenna ground plane structure was important for improving an antenna's ability to reject ground bounce and structure bounce multipath signals. When antennas were mounted in choke rings, there were better at rejecting both types of multipath than when they were mounted on ground planes. Variations in antenna type (i.e., crossed dipoles, patch, quadrahelix) also affected multipath rejection ability.

The broad-band antennas performed roughly as well at L2 (1227 MHz) or the GLONASS frequency (1609 MHz) as they had at L1 (1575 MHz). Antennas tested on both a choke ring and ground plane were better at rejecting ground bounce and structure bounce multipath when they were mounted on the choke ring.

RECOMMENDATIONS

Since multipath is typically the largest source of error in a differential GPS system, great care should be taken when choosing the type of antenna as well as the antenna location for the ground-based station.

Future studies should focus on characterizing the environment surrounding specific locations to allow the user a means of minimizing the effects of multipath. With a site specific multipath profile, the user could determine whether most of the multipath signals would be ground bounce or structure bounce. Accordingly, one could choose an antenna whose multipath rejection performance matched the type of multipath predominant at that site.

ACKNOWLEDGMENTS

I would like to thank the following people in the Air Traffic Surveillance Group for their help on this project: Raymond LaFrey for supervision; Edward Bayliss, for creating the parameters of this study and guiding me through it from start to finish; Richard Ferranti, for technical and editorial advice; George Knittel, for help in defining and interpreting this study; Michael Burrows, for technical clarification; Ralph Halvorsen, for building the hardware; Timothy Borge, for collecting the data; and Katharine Krozel, for editing, artwork, and creative suggestions.

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1. INTRODUCTION

The Global Positioning System (GPS) is a satellite-based navigation system that allows users to determine their location with meter-level accuracy. In the recent past, the aviation community has become increasingly interested in using GPS for aircraft navigation and, in combination with a data link, for surveillance. Though the inherent accuracy of the GPS signal is sufficient for many phases of flight, terminal approach and surface surveillance require that the satellite signals be differentially corrected by ground stations providing precision references.

GPS signals are transmitted in L-band at 1227 MHz and 1575 MHz. Since satellites can appear anywhere from the horizon to the zenith, satellite signal reception by both aircraft and differential ground stations can be corrupted by multipath interference. Multipath occurs when the GPS signal is reflected from the ground or a structure large compared to its wavelength (such as a building, another aircraft, or parts of the aircraft itself). Depending on the signal path difference between the direct and bounced signal, the multipath constructively or destructively adds with the direct signal. The result of this addition is either signal fading or a signal so corrupted that it cannot be used by the GPS receiver.

Three factors influence how much multipath interference will affect a particular GPS receiver: the antenna's ability to discriminate between a direct and a reflected signal, its location, (the surrounding ground environment or an aircraft's position), and what, if any, signal processing techniques the receiver uses to mitigate multipath interference.

The Air Traffic Surveillance Group conducted a study to assess the first of these factors. As is shown in this report, multipath signals may be mitigated on the basis of polarization: GPS signals are right-hand circularly polarized while multipath is often left-hand circularly polarized. Thus, the study's focus was to measure key polarization parameters of six commercial GPS antennas and to assess the effects of mounting these antennas on different ground plane structures (choke ring, fuselage section, or flat ground plane). Data were analyzed to determine the multipath susceptibility of these antennas at elevation angles likely to produce either ground bounce or structure bounce multipath.

This report describes the data collection methods, the data reduction and interpretation techniques, and the results of these antenna measurements.

2. MULTIPATH

GPS receivers use multilateration techniques to determine their location based on the time of arrival of the GPS satellite signal. Four satellites are needed to determine a three dimensional position and correct the receiver's clock bias. Since the exact location of each satellite is known, solving for the precise time it takes a signal to propagate to the GPS antenna uniquely determines its location.

Multipath occurs when a direct signal is reflected off of a structure that is large compared to the GPS signal's wavelength, resulting in an inaccurate measure of the propagation time. Figure 1 depicts three satellite-to-ground paths: a direct line-of-site path, structure bounce path to the GPS antenna, and a ground bounce path to the GPS antenna. The angle θ in Figure 1 represents the satellite elevation angle.

Snell's law of reflection states that when an electromagnetic wave undergoes a reflection, the angle of incidence is equal to the angle of reflection. Given Snell's law, and the geometry pictured in Figure 1, it is clear that, with respect to the GPS antenna, a satellite can appear to be transmitting from a negative elevation angle (-θ). With this in mind, this data collection was designed to simulate satellite elevation angles varying from –30 degrees to 90 degrees, where 90 degrees is a satellite at the zenith.

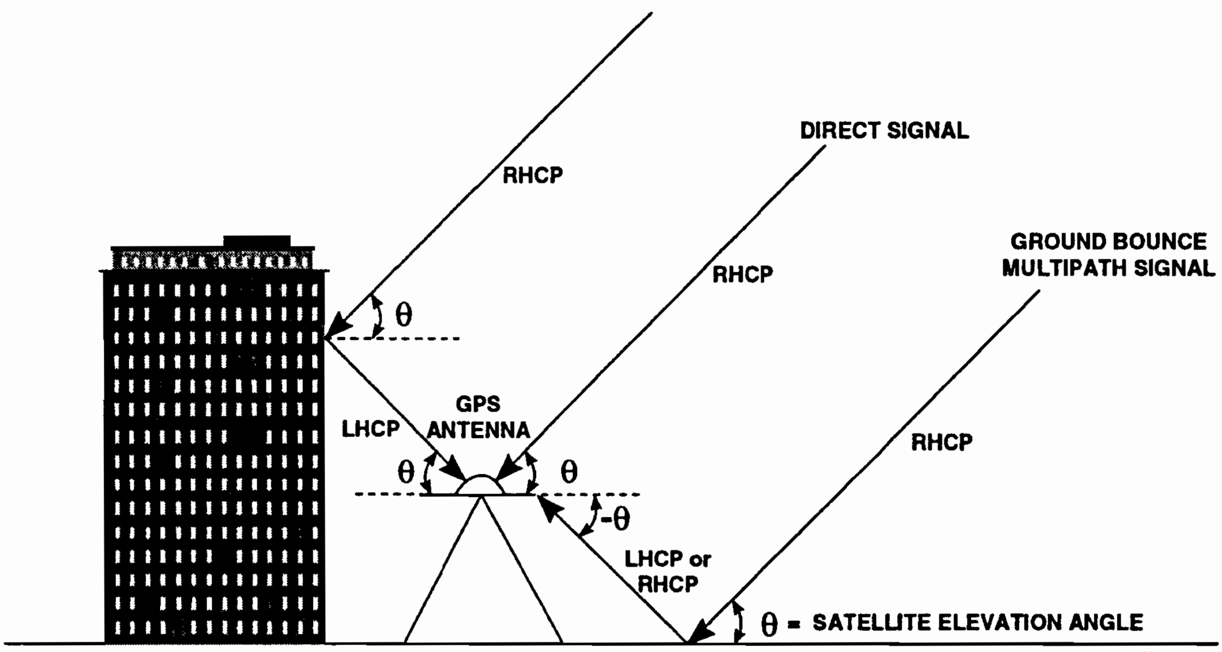

Figure 1. Multipath Bounce Scenario.

When a circularly polarized signal is reflected off of a perfectly conducting reflector, it reverses its polarization sense. Polarization sense continues to be reversed for each subsequent bounce. Therefore, a right-hand circularly polarized signal that has bounced an odd number of times will become a left-hand circularly polarized signal. Similarly, a right-hand circularly polarized signal that has bounced an even number of times will remain a right-hand circularly polarized signal [1].

When a signal bounce off of a surface, amplitude is typically attenuated and phase is shifted. The amount of attenuation and phase shift are determined by the reflection coefficient (Γ) of the reflecting surface. For a perfect reflector, the amplitude remains constant after reflection. That is:

$$|\Gamma| = 1$$

However, for all other surfaces, amplitude is attenuated. In this data collection, it was assumed that all multipath signals were reflected off of a perfect reflector. Additionally, differences in phase between the direct signal and a multipath signal were not computed except for possible circular polarization reversals. The results therefore represent a worst-case estimate of the antenna multipath rejection capabilities.

Circular polarization is the combination of horizontal and vertical polarizations of equal amplitudes and orthogonal phases. Because these two linear polarizations have different reflection coefficients, horizontal and vertical components of a circularly polarized signal undergo different reflections. The result is that circularly polarized signals, upon reflection, off any surface except a perfect conductor, become elliptically polarized signals. The extent of the ellipticity is primarily determined by the reflection coefficient of the vertical component [2]. For simplicity, it was assumed in this study that all reflected multipath signals were circularly polarized. Again, these results represent worst-case examples of the antenna's multipath rejection capabilities.

3. THE DATA COLLECTION

Data were collected with the antennas mounted in one of three different ground plane structures. In all, six antennas were tested (four ground-based and two aviation). Antennas that are capable of performing outside of 1575 MHz (L1) were tested at either 1227 MHz (L2) or a GLONASS[1] frequency depending on the specifications of the antenna. Data were collected in an anechoic chamber simulating a GPS antenna receiving a satellite signal.

3.1 HARDWARE

One of the goals of this study was to determine the role of an antenna's immediate environment in suppressing multipath signals. Three types of ground plane structure were considered: a ground plane, a choke ring, and a mock section of fuselage. Figure 2 shows these three types of ground plane structures. Table 1 lists the diameters of the ground plane structures used in this study. An XX indicates that data were collected with the antenna mounted on that structure. The two antennas mounted on the mock fuselage were the aviation antennas.

Figure 2. Ground Plane Structures Used: Mock Fuselage, Ground Plane, and Choke Ring.

1 GLONASS is the Russian equivalent of GPS, operating at approximately 1609 MHz.

Table 1. Antennas and Ground Plane Structures

Antenna	Ground Plane	Choke Ring	Mock Fuselage
3S (quadrahelix)	XX 15"		
Dome and Margolin (dipoles)	XX 15"		
Litton (patch)			XX
NovAtel (corner fed patch)	XX 18"	XX 18"	
Trimble Aviation (patch)	XX 24"	XX 24"	XX
Turbo Rogue (dipoles)		XX 15"	

3.1.1 Ground Plane

Until recently, ground planes were the only hardware mounting option commercially available for ground-based GPS antennas. Manufacturers used different diameters and metals for their ground planes. For the sake of consistency, all ground-based antennas tested were measured on an aluminum ground plane. Two of these antennas were then measured in a choke ring. As can be seen from Table 1, the diameter of the ground plane was equal to that of the choke ring when measurements were made on both.

3.1.2 Choke Ring

Choke rings are designed to reject ground bounce multipath signals. A choke ring, like a corrugated horn, changes the boundary conditions of the surface the antenna is mounted on. On a flat surface, the boundary conditions for the **E** field are different from those for the **H** field. This makes the antenna sensitive to the predominantly cross polarized multipath signal. Adding quarter–wavelength grooves to that flat surface creates the same boundary conditions for both fields, thereby reducing the antenna's sensitivity to multipath signals [3]. Because of aerodynamic considerations, it is nearly impossible to affix a choke ring onto the fuselage of an aircraft. However, in a differential GPS navigation system, the reference ground station's antenna can be mounted on either a ground plane or a choke ring.

3.1.3 Fuselage Section

Little can be done to minimize the effects of multipath signals being received by an antenna mounted on an aircraft. The chief source of multipath error for an airborne aircraft comes from edge diffraction and signal propagation along the aircraft fuselage [4]. During aircraft approach and landing, however, the dominant multipath is from ground and building reflections. In order to better understand and quantify both types of multipath sources, measurements were taken on two aviation antennas mounted on a mock 727 fuselage. The mock fuselage was built to ARINC standard 743A[2] at Lincoln Laboratory. Figure 3 shows the Litton aircraft antenna mounted on the mock fuselage.

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2 4' X 7' with a radius of curvature of 96 inches; ARINC Characteristic 743A, p. 34.

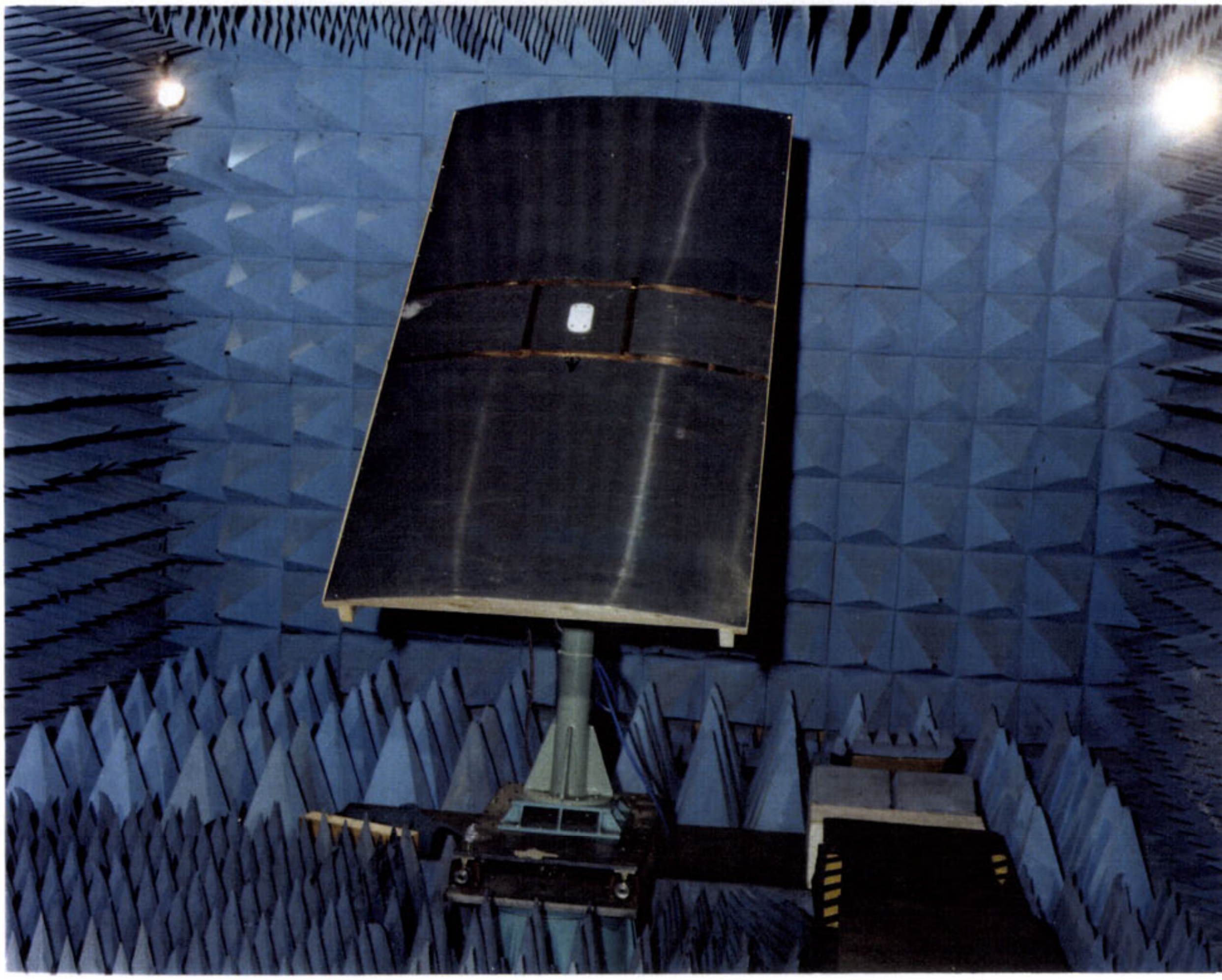

Figure 3. Litton Antenna Mounted on the Mock Fuselage.

3.2 ANTENNAS

In a differential aircraft navigation application, two different types of antennas would be required: a reference ground station antenna and an aircraft antenna. The difference between the two is that the ground station is not a dynamic platform nor is its antenna limited by the size constraints of an aircraft antenna. Most commercially available aircraft antennas are patches. Accordingly, two patch aircraft antennas were tested. Ground station antennas used in this study included a quadrahelix, two crossed dipoles, and a corner fed patch. The antennas tested were a representative sample of the types of ground station antennas commercially available. Table 2 lists the pertinent data on each antenna tested in this experiment while Figure 4 shows the antennas.

Table 2. Antenna Specifications

Antenna	Model Number or P/N	Type of Antenna	Amplifier Gain in dB	Noise Figure
3S	3Snav027014	Quadrahelix	23	1.5
Dorne and Margolin	C146101	Crossed dipoles	passive antenna	N/A
Litton	510116-1	Patch	passive antenna	N/A
NovAtel	GPS-501	Corner Fed Patch	24	3.0
Trimble Patch	1624811	Patch	44	2.0<
Turbo Rogue	7490400-4	Crossed dipoles	54	3.0–3.5

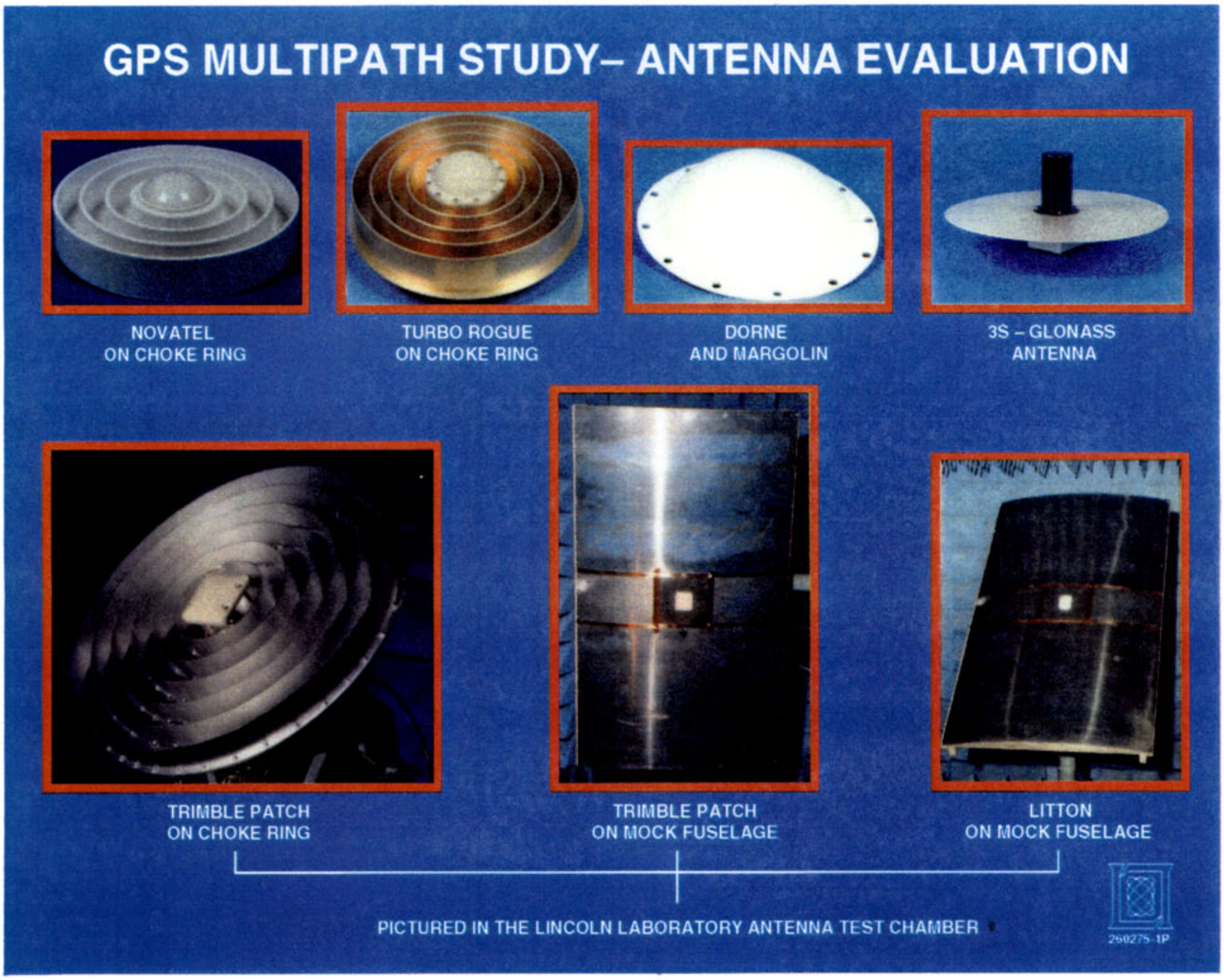

Figure 4. Antennas Tested.

3.3 SET UP

All data for this study were collected in an anechoic chamber at the Laboratory's Antenna Test Range (ATR). Figures 5 shows the anechoic chamber used in this study.

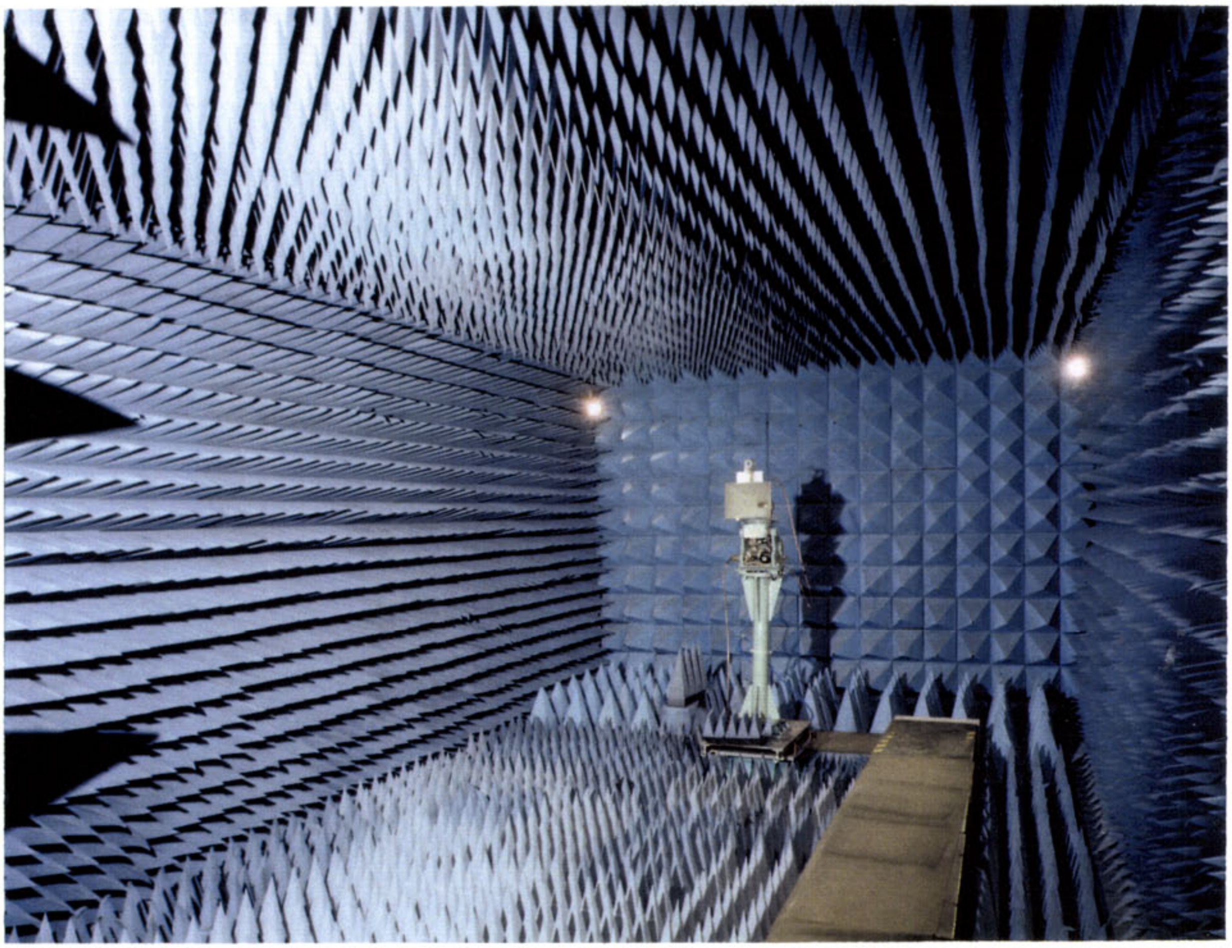

Figure 5. Anechoic Chamber Used to Test Antennas.

Figure 6 is a diagram of the test setup. A linearly polarized source, at frequencies of 1227.60 MHz (L2), 1575.42 MHz (L1), and 1609.00 MHz (GLONASS), was used to illuminate the test antennas. Since a circularly polarized source antenna was not available, we transmitted orthogonal linear polarization and mathematically converted these to right-hand and left-hand circular polarizations. Test antenna amplitude and phase were measured and calibrated by replacing the test antenna with a standard gain horn.

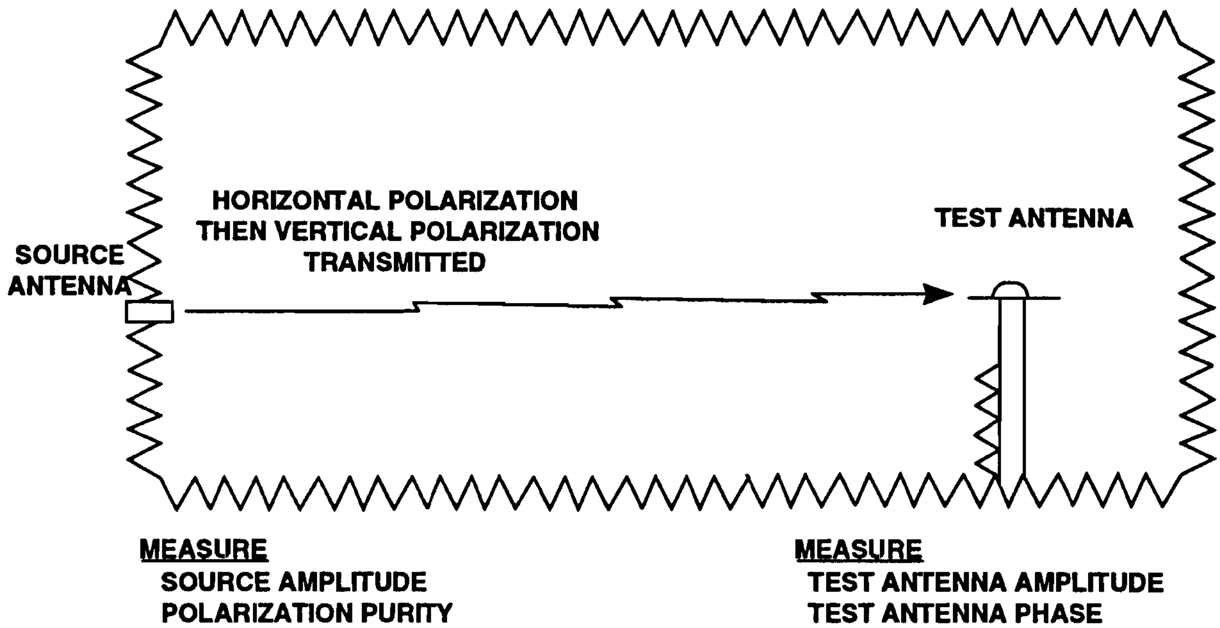

Figure 6. Sketch of Test Setup.

3.3.1 Elevation and Azimuth

GPS satellite elevation angles vary from 0 degrees to 90 degrees (where 90 degrees represents a satellite at the zenith); while azimuth angles vary from 0 degrees to 360 degrees. In this test, we emulated these variations in azimuth and elevation angles by varying the antenna's orientation with respect to the source. In this way, we captured the real-life scenario of the GPS signal moving with respect to the antenna. To take into account aircraft banking angles and multipath received from the ground at negative elevation angles, the test antenna elevation angles were varied from –30 degrees to 90 degrees. Data were collected at 1-degree increments across this range of elevation angles while holding the azimuth angle fixed. Test antenna azimuth angle was varied from 0 degrees to 360 degrees in 45-degree increments because we assumed this would give us an accurate representation of antenna variation due to azimuth angle while not requiring us to collect prohibitively large amounts of data. Figure 7 illustrates the range of azimuth and elevation angles.

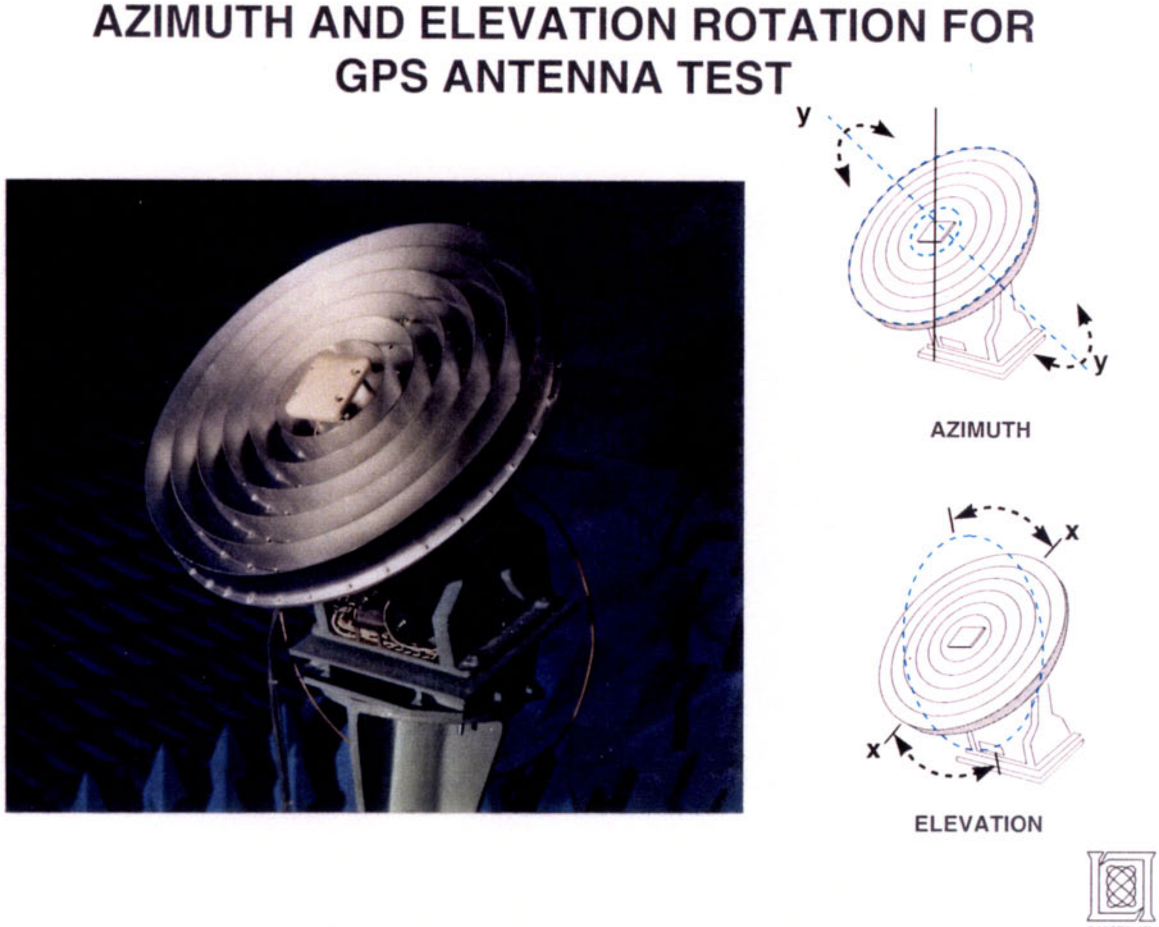

Figure 7. Azimuth and Elevation Variation.

4. RESULTS

To evaluate the antenna's performance in the presence of cross-polarized multipath interference, right-hand circular polarization and left-hand circular polarization absolute gains versus elevation angle were plotted for all azimuths. These results are discussed in the following sections.

4.1 ABSOLUTE GAIN

The two orthogonal linear polarizations were converted to right-hand and left-hand circular polarization using Equation 4.1

$$G_{\pm} = \frac{G_h + G_v}{2} \pm \sqrt{G_h G_v} \sin\delta \tag{4.1}$$

where G = Gain

+ = Right-Hand Circular Polarization (RHCP)

– = Left-Hand Circular Polarization (LHCP)

h = Horizontal Polarization

v = Vertical Polarization

δ = (Horizontal phase –Vertical phase)

Right-hand circular polarization and left-hand circular polarization signal levels were converted to absolute gain using the calibration data from the standard gain horn. The Appendix contains one absolute gain plot for each antenna tested. Though GPS satellites transmit right-hand circular polarization signals, left-hand circular polarization absolute gains were calculated as a means of assessing the antenna's multipath rejection capability.

4.2 GPS ANTENNA MULTIPATH REJECTION PERFORMANCE

Two types of multipath can corrupt a GPS measurement: ground bounce multipath and multipath signals that are reflected off buildings or similar structures (structure bounce multipath). Typically, ground bounce multipath occurs at relatively low satellite elevation angles. In this study we assumed that ground bounce multipath would occur at satellite elevation angles less than 30 degrees. Alternatively, building bounce multipath can occur at any satellite elevation angle, so we considered all positive satellite elevation angles. Given the two different characteristics of these types of multipath, separate methods of quantifying an antenna's performance in either circumstance were used.

4.2.1 Ground Bounce Multipath

Ground bounce multipath occurs at low satellite elevation angles. Because the magnitude of the ground's reflection coefficient increases as the satellite angle decreases, it is assumed that the worst multipath interference occurs at the lowest satellite elevation angles. For this study, a satellite elevation angle of 5 degrees was assumed to be a worst-case multipath. In practice, satellites below 5 degrees of elevation are not typically used for aircraft navigation because of the high likelihood they are corrupted by multipath. Therefore, in this study, we calculated the ratio between the level of a direct signal at 5 degrees of elevation and a ground bounce signal. As was shown in Figure 1, the ground bounce signal is left-hand circularly polarized and has a negative elevation angle. Accordingly, the numbers listed under the smallest ratio column in Table 3 are the worst-case ratio of the direct right-hand circularly polarized signal at 5 degrees of elevation to the ground bounce left-hand circularly polarized signal at negative 5 degrees of elevation.

Changing the azimuth angle of the test antenna affected the antenna's performance. Table 3 also lists the largest or best ratio of direct to ground bounce signal for each antenna tested. Azimuth angles are not included in Table 3 because their orientations were arbitrarily assigned at the start of the data collection. Again, Table 3 shows the data used to assess an antenna's ability to reject a ground bounce multipath signal. Structure bounce multipath will be discussed in Section 4.2.2.

Table 3. Peak Azimuth Variation of Ground Bounce Multipath Signal Rejection

Antenna	Ground Plane Structure	Smallest Ratio Direct/Ground Bounce (dB)	Largest Ratio Direct/Ground Bounce (dB)
3S (quadrahelix)	ground plane	13.9	23.1
Dome and Margolin(dipoles)	ground plane	2.8	5.3
Litton (patch)	mock fuselage	3.6	10.8
NovAtel (corned fed patch)	choke ring	10.3	23.0
NovAtel (comer fed patch)	ground plane	3.9	10.8
Trimble Aviation (patch)	choke ring	9.4	20.3
Trimble Aviation (patch)	ground plane	4.1	14.3
Trimble Aviation (patch)	mock fuselage	2.8	8.0
Turbo Rogue (dipoles)	choke ring	9.8	15.3

A comparison of smallest to largest minimum ratio of the direct signal to a ground bounce multipath signal shown in Table 3 indicates that satellite azimuth angle plays a significant role in an antenna's ground bounce multipath rejection performance. For example, there was a 13 dB difference in the smallest and largest ratios for the NovAtel (corner fed patch) on a choke ring. Figure 8 shows more clearly the variation in direct to ground bounce ratios due to azimuth angle changes. In Figure 8 the direct to ground bounce ratio is plotted for all azimuth angles tested for the NovAtel antenna on a choke ring. As can be seen in Figure 8, variations in azimuth angle had a significant effect on this antenna's ability to reject a ground bounce multipath signal. As previously mentioned, direct signal to ground bounce multipath signal ratios were calculated at a 5-degree satellite elevation angle.

Azimuth angle was not the only factor which affected the antenna's ability to reject multipath signals. Ground plane structures can enhance an antenna's performance. For example, the Trimble aviation patch mounted on a choke ring measured 6.6 dB higher than when mounted on a fuselage section and 5.3 dB higher than when mounted on a ground plane. Section 5 discusses ground plane structures in more depth.

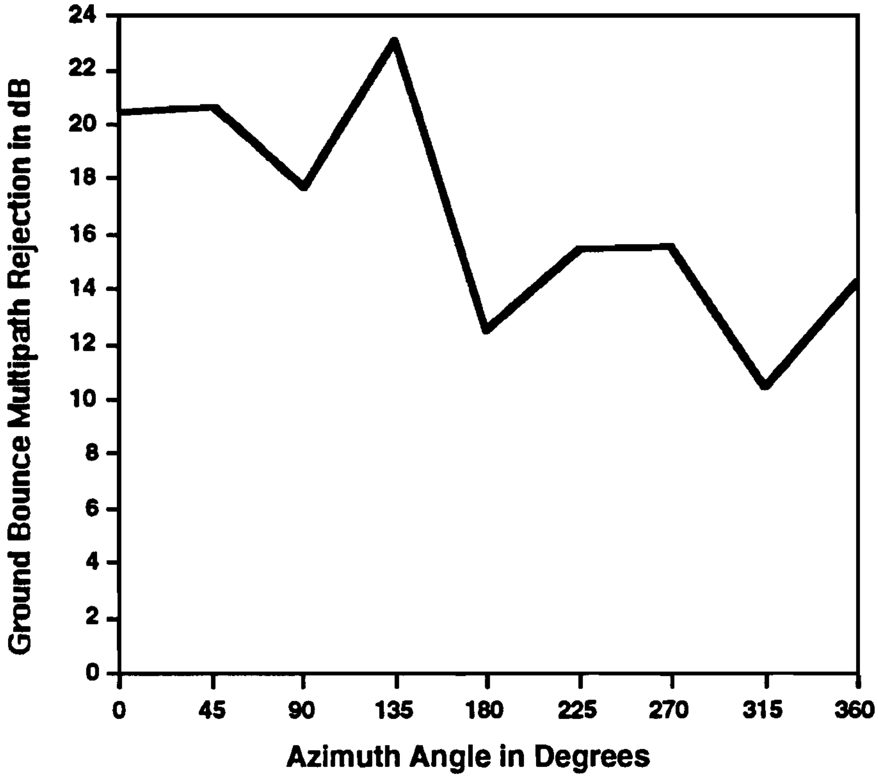

Figure 8. Azimuth Multipath Rejection Variation for NovAtel Antenna on a Choke Ring, 5-degree Elevation Angle.

4.2.2 Structure Bounce Multipath and Cross Polarization Ratio

Our means of evaluating an antenna's structure bounce multipath performance is to determine its minimum cross polarization ratio over the entire gain pattern. Cross polarization ratio is the ratio between right-hand circular polarization gain and left-hand circular polarization gain. All satellite elevation angles, above 5 degrees, are considered in this analysis because structure bounce multipath can occur at any satellite elevation angle. The larger the cross polarization ratio, the better the antenna will be at rejecting a multipath signal that has bounced off of a structure.

Nine satellite azimuth angles were tested; minimum cross polarization ratios were determined for each azimuth angle. Since these antenna minima varied, figures and tables are presented to provide the reader with a sense of the range of variation due to azimuth angle. Figure 9 shows the absolute gain for the NovAtel antenna on a choke ring at a relative azimuth angle of 135 degrees. The minimum cross polarization ratio for this azimuth angle was smaller than any other azimuth angle tested. Thus, Figure 9 is referred to as the smallest minimum cross polarization ratio. Similarly, Figure 10 shows the largest minimum cross polarization ratio for the NovAtel antenna on a choke ring, occurring at a relative azimuth angle of 45 degrees.

Table 4 and Table 5 list the smallest and largest minimum cross polarization ratios, respectively, for all antennas tested. Also listed are the elevation angles where the minimum cross-polarization ratio occurred. In this computation, only elevation angles greater than 5 degrees were used because generally satellites below 5 degrees of elevation are not used for navigation.

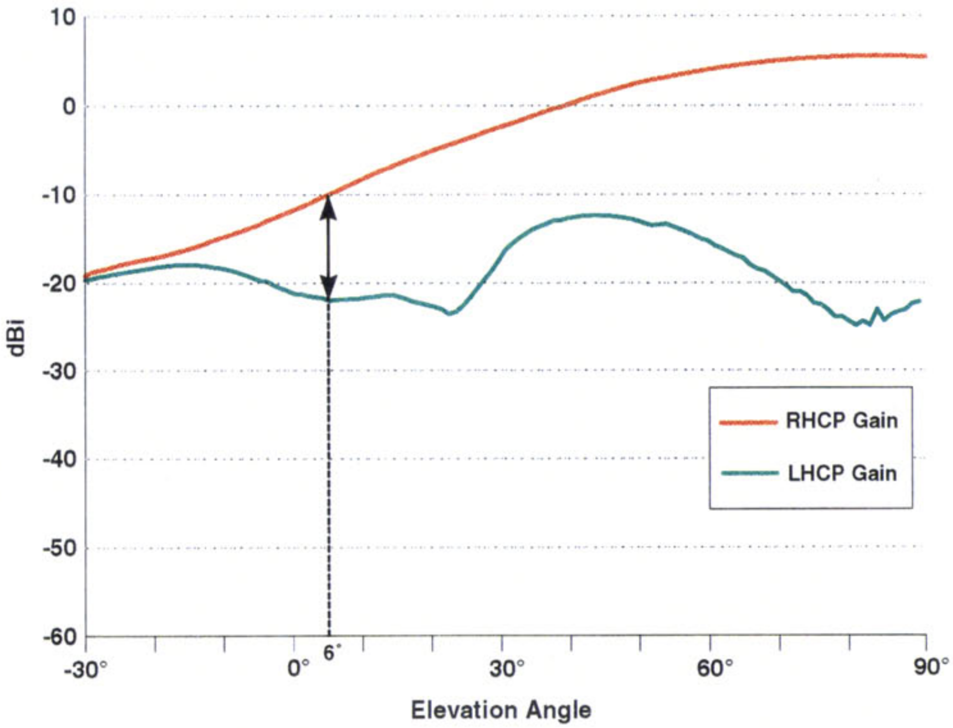

Figure 9. Smallest Minimum Cross Polarization Ratio Determined From Absolute Gain, NovAtel (corner fed patch) Antenna on a Choke Ring; Azimuth Angle = 135 degrees.

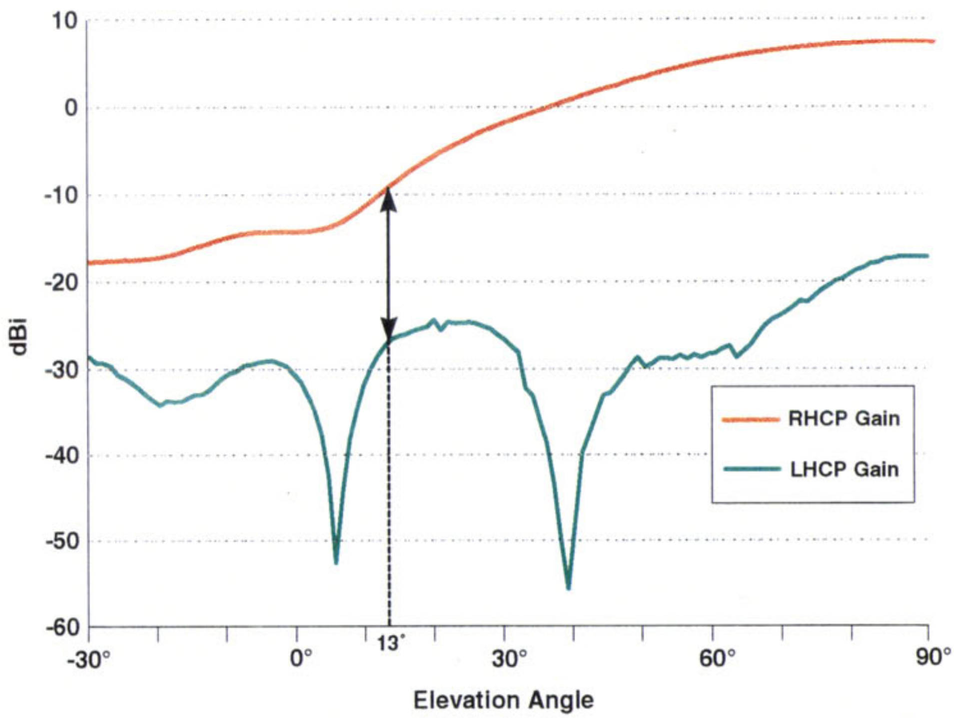

Figure 10. Largest Minimum Cross Polarization Ratio Determined From Absolute Gain, NovAtel (corner fed patch) Antenna on a Choke Ring; Azimuth Angle = 45 degrees.

Table 4. Smallest Minimum Cross Polarization Ratio

Antenna	Ground Plane Structure	Minimum Cross Pol Ratio (dB)	Elevation Angle
3S (quadrahelix)	ground plane	10.4	14°
Dorne and Margolin (dipoles)	ground plane	3.2	5°
Litton (patch)	mock fuselage	–0.4	5°
NovAtel (corner fed patch)	choke ring	11.1	6°
NovAtel (corner fed patch)	ground plane	1.4	14°
Trimble Aviation (patch)	choke ring	4.9	5°
Trimble Aviation (patch)	ground plane	–0.2	5°
Trimble Aviation (patch)	mock fuselage	0.2	5°
Turbo Rogue (dipoles)	choke ring	6.9	5°

Table 5. Largest Minimum Cross Polarization Ratio

Antenna	Ground Plane Structure	Minimum Cross Pol Ratio (dB)	Elevation Angle
3S (quadrahelix)	ground plane	15.1	84°
Dorne and Margolin (dipoles)	ground plane	5.5	5°
Litton (patch)	mock fuselage	5.0	5°
NovAtel (corner fed patch)	choke ring	17.3	13°
NovAtel (corner fed patch)	ground plane	10.5	85°
Trimble Aviation (patch)	choke ring	12.5	5°
Trimble Aviation (patch)	ground plane	10.3	5°
Trimble Aviation (patch)	mock fuselage	10.4	69°
Turbo Rogue (dipoles)	choke ring	12.1	12°

A comparison of Table 4 and Table 5 shows the choke ring improved both the NovAtel's (corner fed patch) and the Trimble's (patch) performance. Improvements between 2 and 10 dB were measured. Section 5 discusses the effects of these ground plane structures on the antenna's performance in more detail.

5. GROUND PLANE VERSUS CHOKE RING

A closer look at the NovAtel (corner fed patch) and Trimble (patch) antennas' performances shows a significant improvement in cross polarization ratio when these antennas were mounted on choke rings. Figure 11 represents the absolute gain for the NovAtel antenna on two different ground plane structures; a choke ring and a ground plane. For these absolute gain plots, the azimuth angle of the antenna when it was tested was the same. It can be seen that the cross polarization ratio was greatly improved by mounting this antenna on a choke ring. As previously discussed, increasing the cross polarization ratio increases the antenna's multipath rejection capabilities. Figure 12 shows a similar gain plot for the Trimble antenna on two different ground plane structures; a choke ring and a ground plane. Again, cross polarization ratio was improved across all elevation angles when the antenna was mounted on a choke ring.

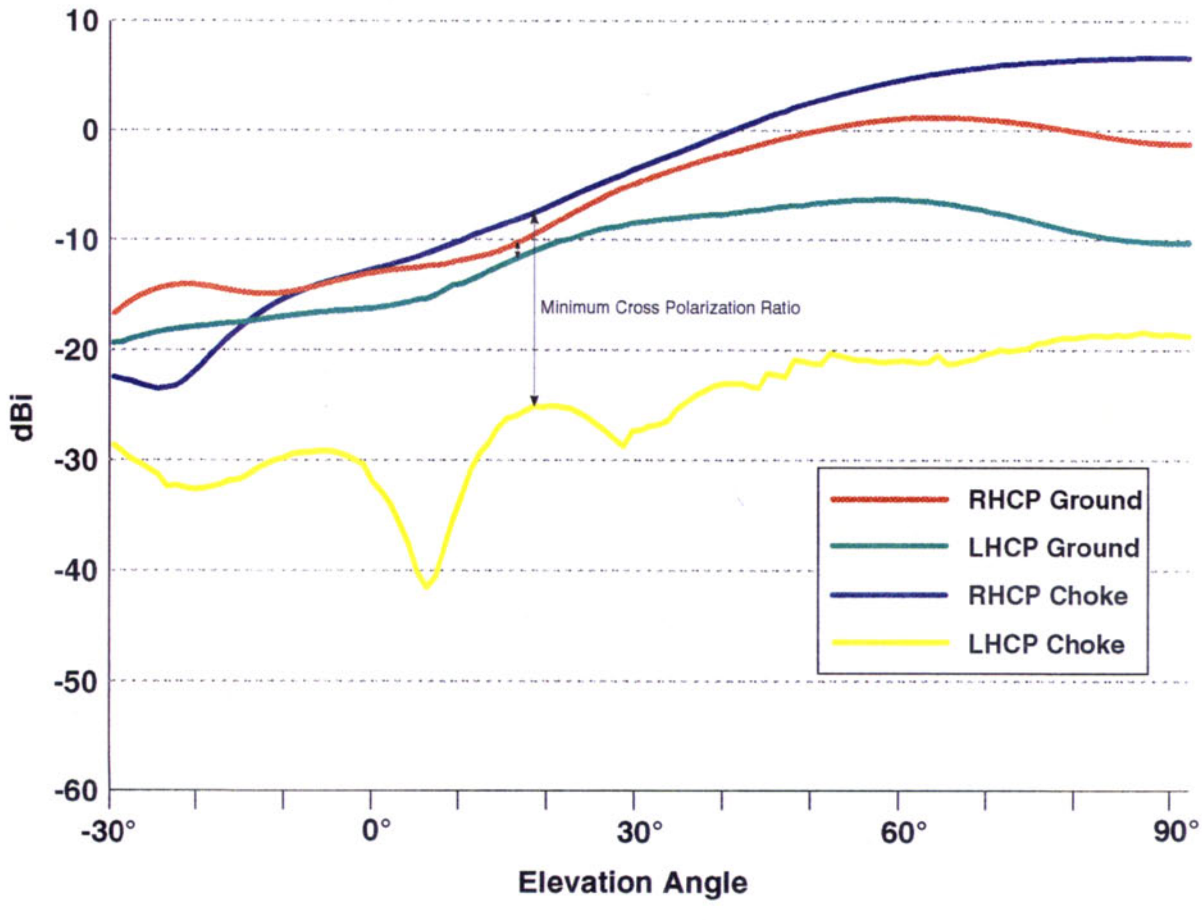

Figure 11. Ground Plane Structure Comparison for NovAtel (corner fed patch) Antenna, Ground Plane vs. Choke Ring.

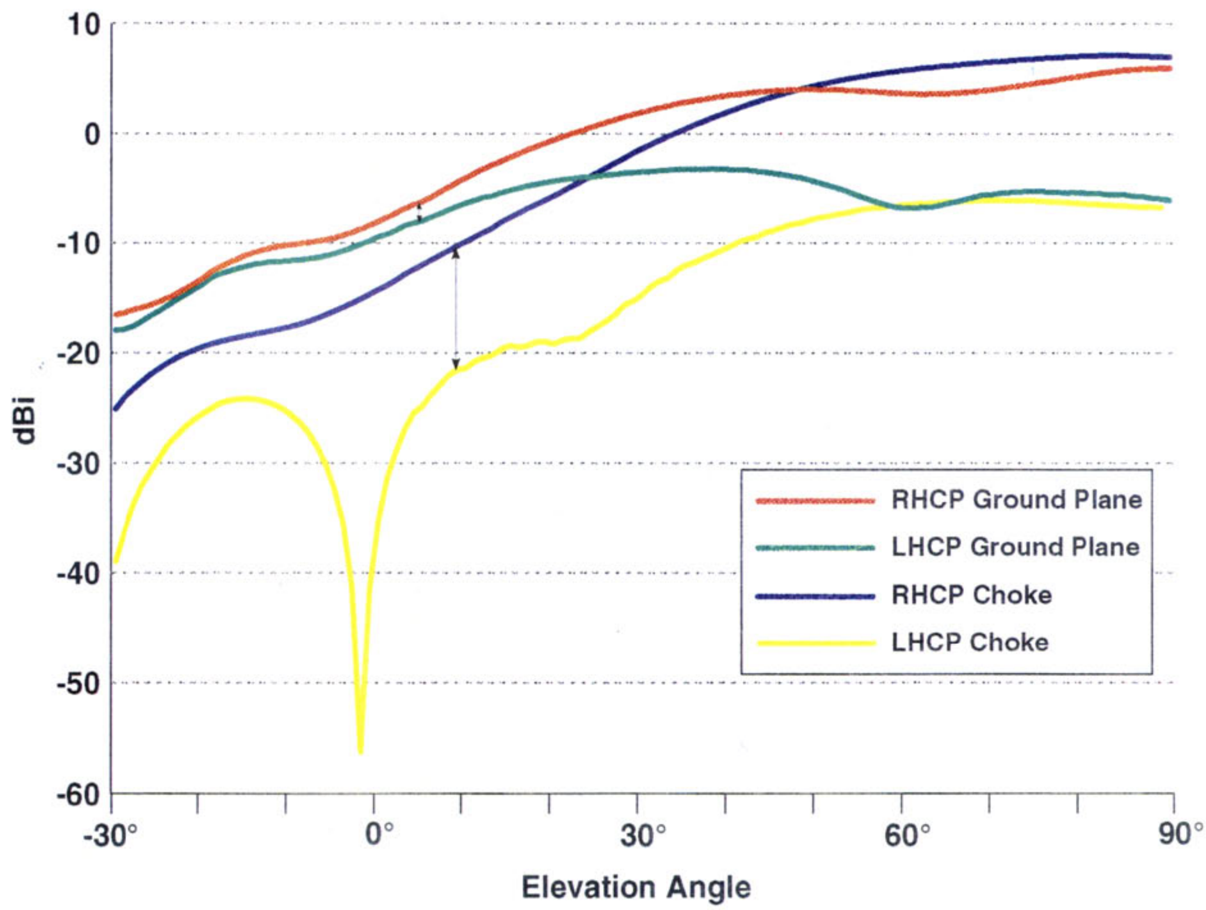

Figure 12. Ground Plane Structure Comparison for Trimble (patch) Antenna, Ground Plane vs. Choke Ring.

6. OTHER FREQUENCIES

Three of the antennas were tested at frequencies other than L1 (1575 MHz). Aside from changing the frequency, these data were collected in exactly the same manner as described in Section 3. The 3S (quadrahelix) antenna (a GLONASS antenna) was tested at 1609 MHz, which is the median frequency in the GLONASS frequency allocation. The Dorne and Margolin (crossed dipoles) and Turbo Rogue (crossed dipoles) antennas were tested at L2 (1227.60 MHz). Absolute gain computations were made on these data in the same fashion as described in Section 4 for data collected at L1 (1575.42 MHz). Figures 12 through 14 are the absolute gain plots where the smallest minimum cross polarization ratio was measured. These plots represent the worst-case cross polarization ratio for each antenna. Cross polarization ration is used to determine an antenna's ability to reject a structure bounce multipath signal.

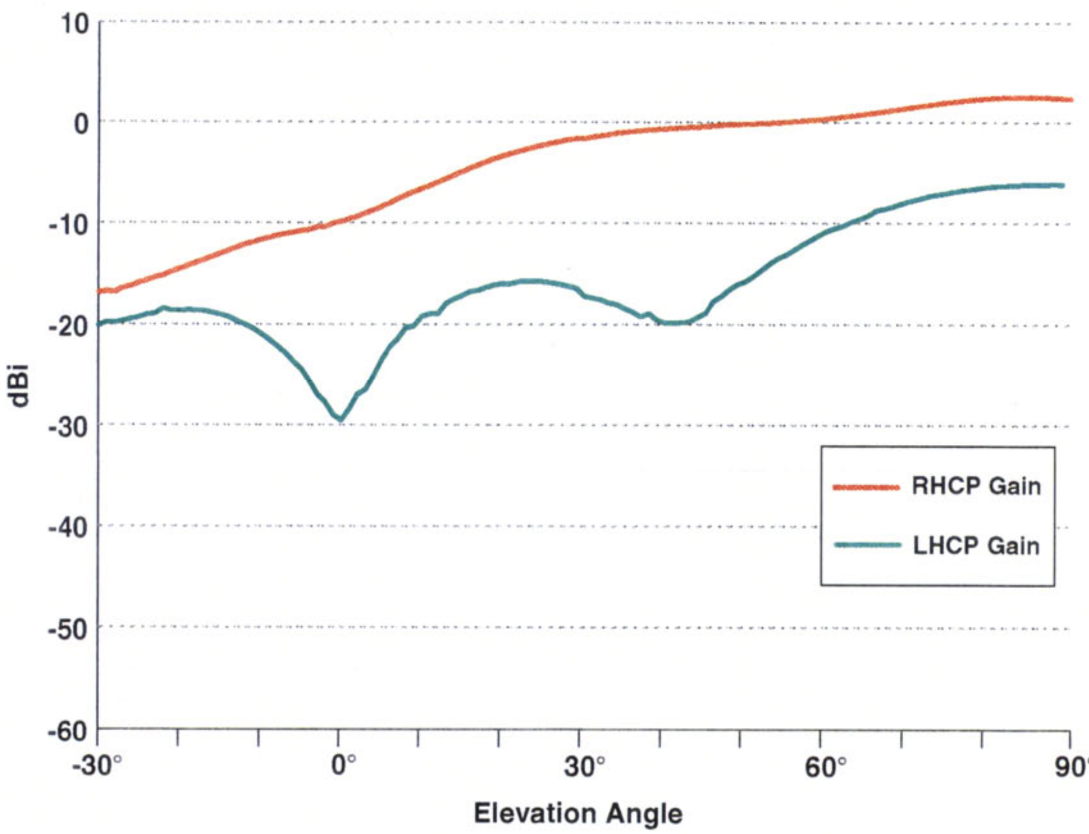

Figure 13. Absolute Gain for 3S (quadrahelix) Antenna on a Ground Plane at 1609 MHz: Minimum Cross Pol. Ratio = 8.4 dB at 89-degree Elevation.

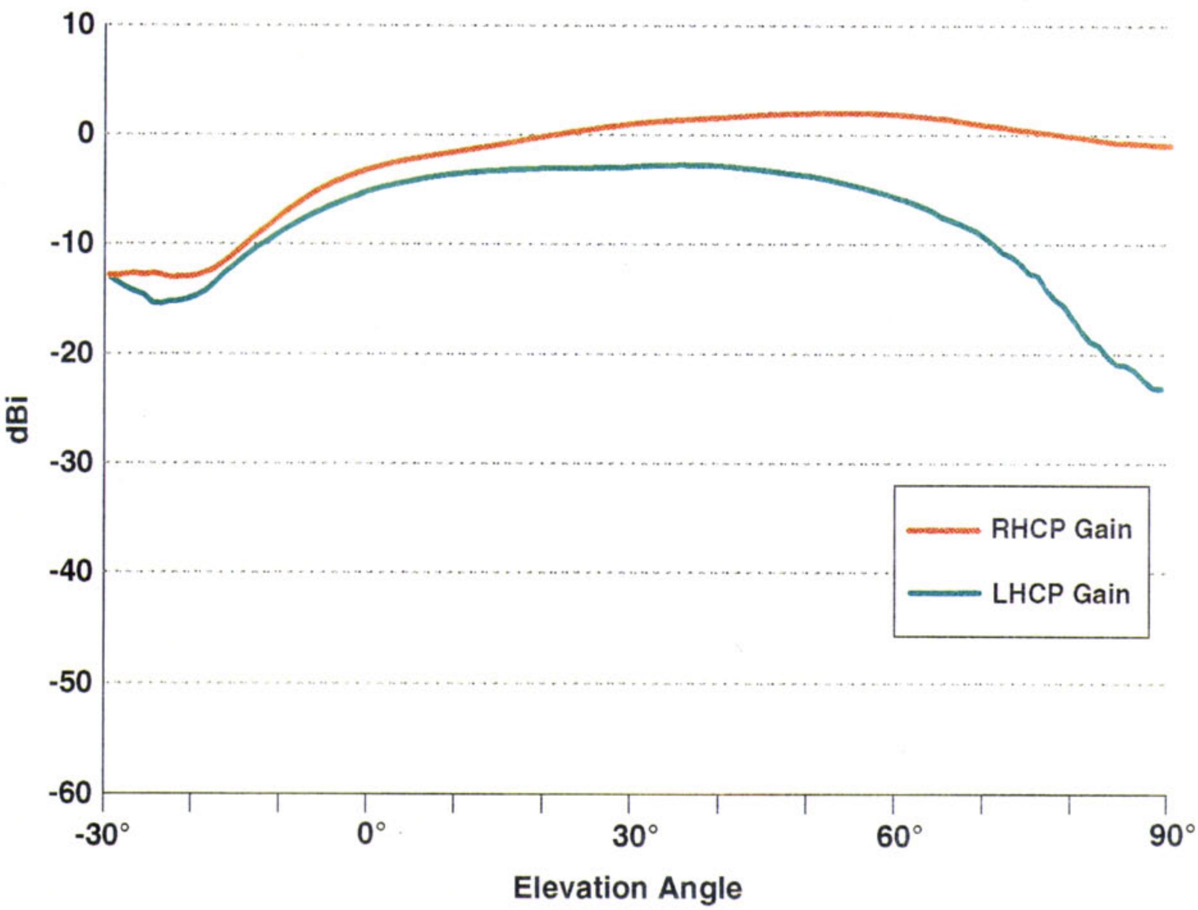

Figure 14. Absolute Gain for Dorne & Margolin (crossed dipoles) Antenna on a Ground Plane at 1227 MHz: Minimum Cross Pol. Ratio = 1.9 dB at 6-degree Elevation.

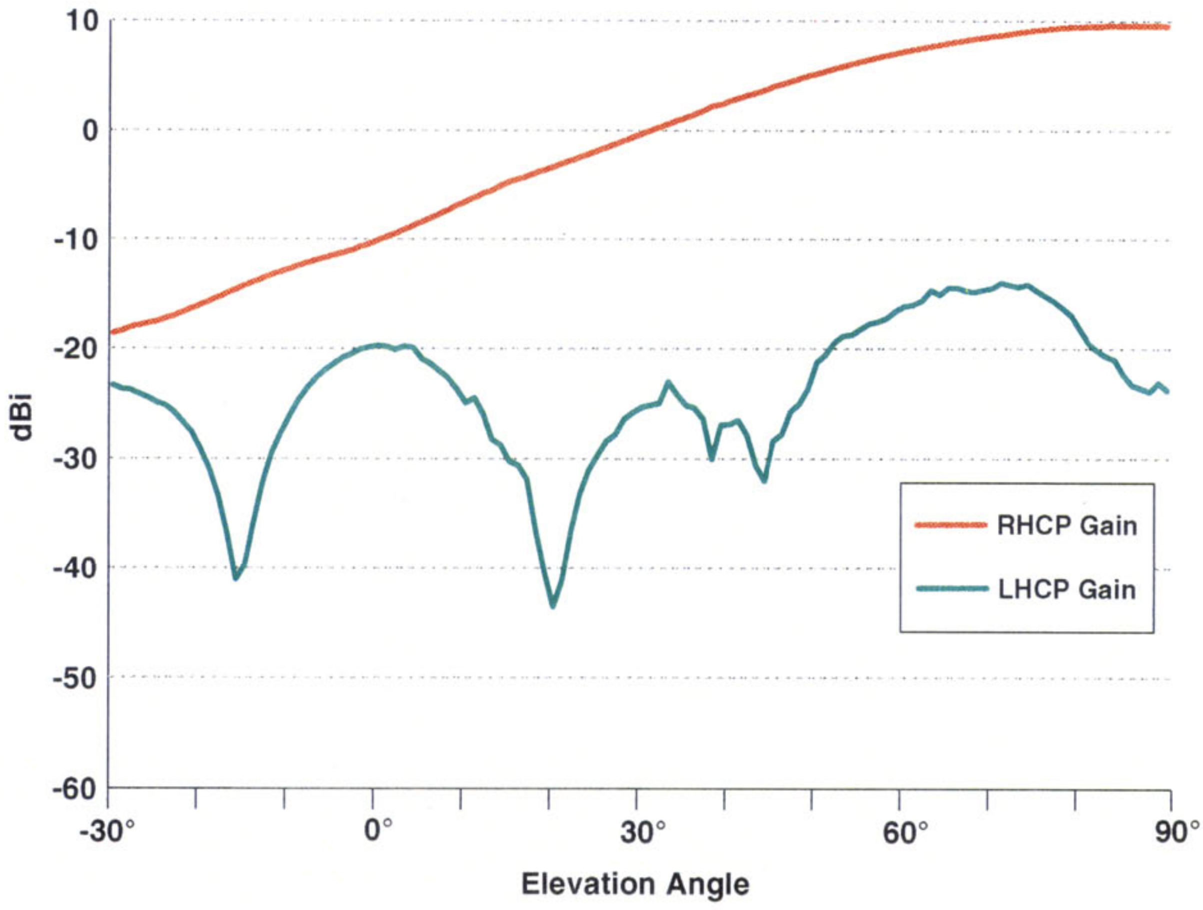

Figure 15. Absolute Gain for Turbo Rogue (crossed dipoles) Antenna on a Choke Ring at 1227 MHz: Minimum Cross Pol. Ratio = 12.6 dB at 5-degree Elevation.

7. CONCLUSIONS

The GPS antenna evaluation conducted at Lincoln Laboratory tested a total of six antennas mounted in various ground plane structures. The antennas were evaluated on the basis of their ability to reject two different types of multipath: ground bounce and structure bounce. Antennas were tested in an anechoic chamber. Linearly polarized orthogonal polarizations were transmitted; receive amplitudes and phases for each antenna were recorded. These data were converted to right-hand and left-hand circularly polarized signals using well-known mathematical methods.

Antenna performance evaluations were made based on each antenna's absolute gain properties. To asses an antenna's ground bounce multipath rejection performance, ratios of direct to ground bounce signals at a 5-degree elevation angle were calculated. Structure bounce rejection performance was determined by computing a minimum cross polarization ratio of elevation angles from 5 degrees to 90 degrees from an absolute gain data. Different ground plane structures were also used to see if changing the mounting environment for an antenna improved its overall performance.

Each antenna's performance was assessed using the ratios of direct signal gain to ground bounce signal gain at a 5-degree elevation angle and the minimum cross polarization ratio for all satellite elevation angles greater than 5 degrees. The antennas that performed best were the NovAtel (corner fed patch) on a choke ring and the 3S (quadrahelix) on a ground plane. Both had direct to ground bounce signal ratios and cross polarization ratios of 10 dB or greater for all azimuth angles. Therefore, these two antennas would be very good at rejecting either type of multipath.

The antennas that performed fairly well were the Turbo Rogue (crossed dipoles) on a choke ring and the Trimble (patch) on a choke ring. These antennas had minimum direct to ground bounce ratios of nearly 10 dB and minimum cross polarization ratios of approximately 5 dB. All other antennas tested did not perform as well as these.

Ground plane structure did improve an antenna's ability to reject a multipath signal. For instance, the NovAtel (corner fed patch) antenna increased its smallest minimum cross polarization ratio by nearly 9 dB when it was mounted on a choke ring instead of a ground plane. Similarly, the Trimble (patch) antenna gained 5 dB in its smallest cross polarization ratio when mounted on a choke ring. Though cross polarization is a measure of ability to reject structure bounce multipath, similar results were attained when evaluating ability to reject ground bounce multipath. The NovAtel and Trimble antennas improved 6 dB and 5 dB, respectively, when mounted on a choke ring rather than a ground plane, when assuming a ground bounce multipath signal occurred at a 5-degree elevation angle.

In addition to varying the ground plane structure, three of the antennas were tested at frequencies other than 1575 MHz. The Turbo Rogue (crossed dipoles) and the Dorne and Margolin (crossed dipoles) were tested at 1227 MHz. The Turbo Rogue antenna performed very well at 1227 MHz. Minimum cross polarization ratios exceeded 12 dB for all azimuths. The Dorne and Margolin antenna did not perform as well, providing minimum cross polarization ratios ranging from 2 to 5 dB. The 3S (quadrahelix) antenna was tested at 1609 MHz, and performed as well at this GLONASS frequency as it did at L1 (1575 MHz). Minimum cross polarization ratios at 1609 MHz ranged from 9 to 17 dB.

This study was designed to determine which of the GPS antennas provided the best reduction of multipath signals. Future studies will focus on characterizing environmental multipath at any given GPS reference location. The latter study, combined with the present GPS antenna evaluation should allow the user to determine the best antenna type and GPS reference station location to mitigate the effects of multipath.

APPENDIX

Plots of absolute gain in dBi versus satellite elevation angle are shown in Figures A-1 through A-9. In practice, satellite elevation and azimuth angles vary with respect to the GPS antenna. Since it was not practical in a testing environment to move the source all over the anechoic chamber, the antenna was rotated in azimuth and moved at 1-degree increments in elevation. For each sweep through elevation angle, azimuth angle was held fixed. Azimuth orientation was varied from 0 degrees to 360 degrees in 45-degree increments. Reference marks were made on each antenna to allow antenna testing personnel to realign the antenna to a 0-degree relative azimuth angle.

Each plot in this appendix represents the absolute gain for the worst-case azimuth orientation, that is, the orientation with the smallest minimum cross polarization ratio. For a comparison of worst-case to best-case cross polarization ratios, see Table 3. Since the initial marking of a 0-degree azimuth was arbitrary, azimuth information is not included with these plots. What is important to note is antenna performance fluctuates depending upon satellite heading and elevation angle. These plots represent the worst-case scenario in that fluctuation.

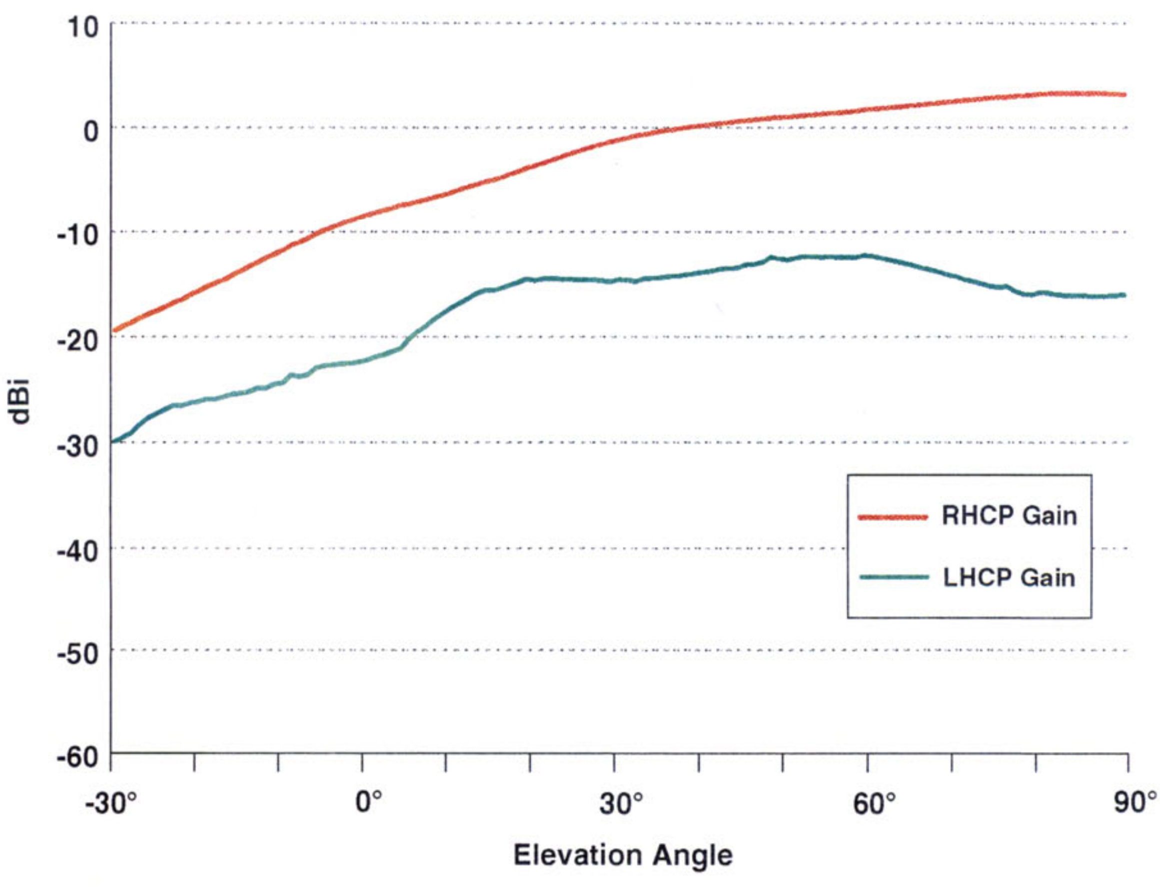

Figure A-1. Absolute Gain for 3S (quadrahelix) Antenna on a Ground Plane: Minimum Cross Pol. Ratio = 10.4 dB at 14-degree Elevation.

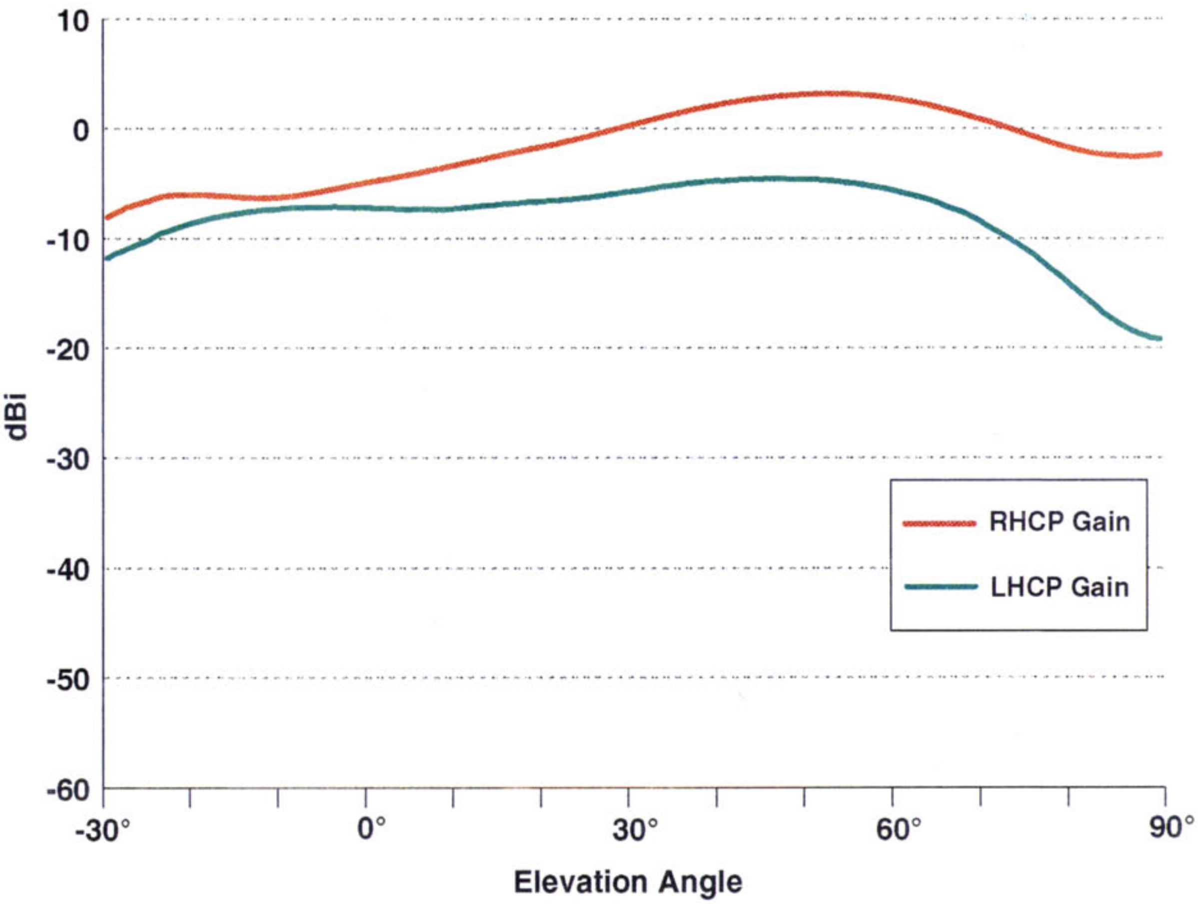

Figure A-2. Absolute Gain for Dorne & Margolin (crossed dipoles) Antenna on a Ground Plane: Minimum Cross Pol. Ratio = 3.2 dB at 5-degree Elevation.

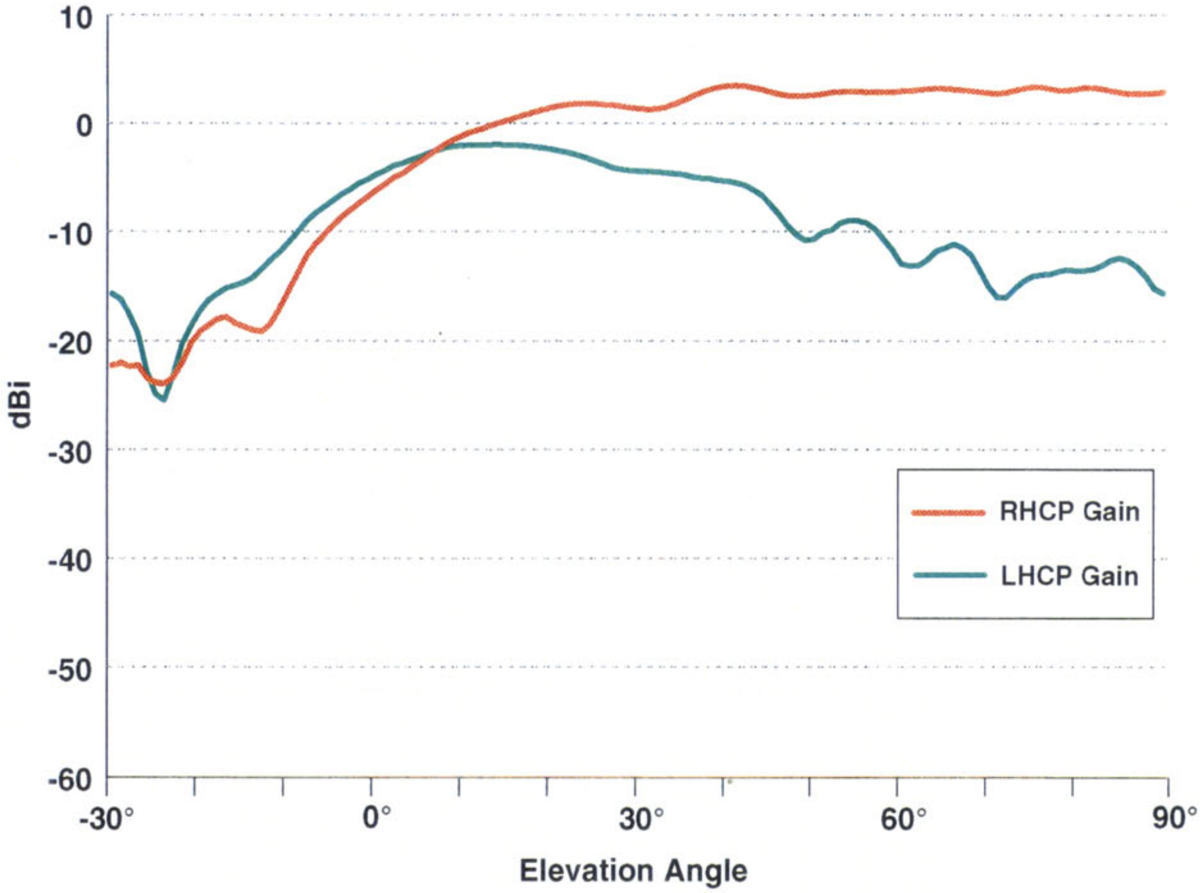

Figure A-3. Absolute Gain for Litton (patch) Antenna: Minimum Cross Pol. Ratio = -0.4 dB at 5-degree Elevation.

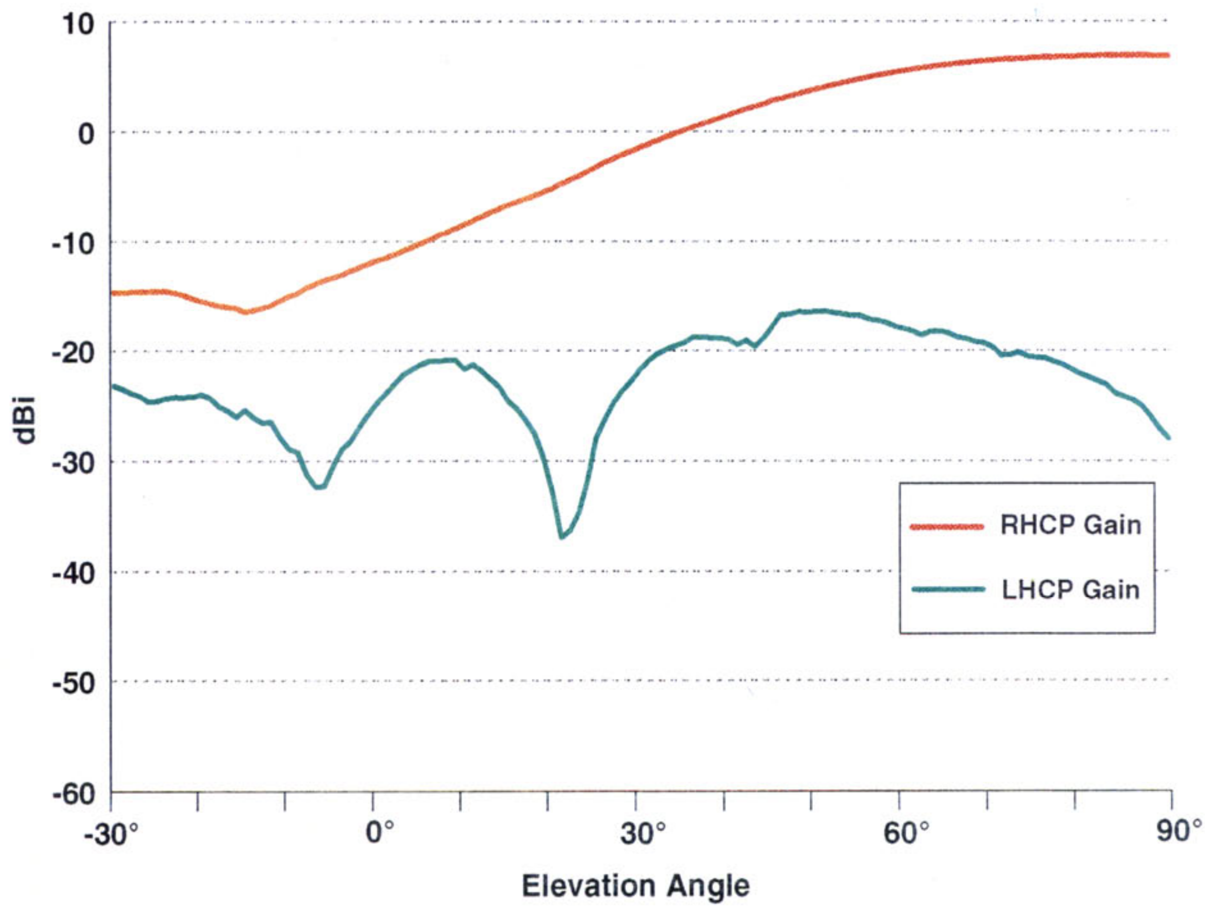

Figure A-4. Absolute Gain for NovAtel (corner-fed patch) Antenna on Choke Ring: Minimum Cross Pol. Ratio = 11.1 dB at 6-degree Elevation.

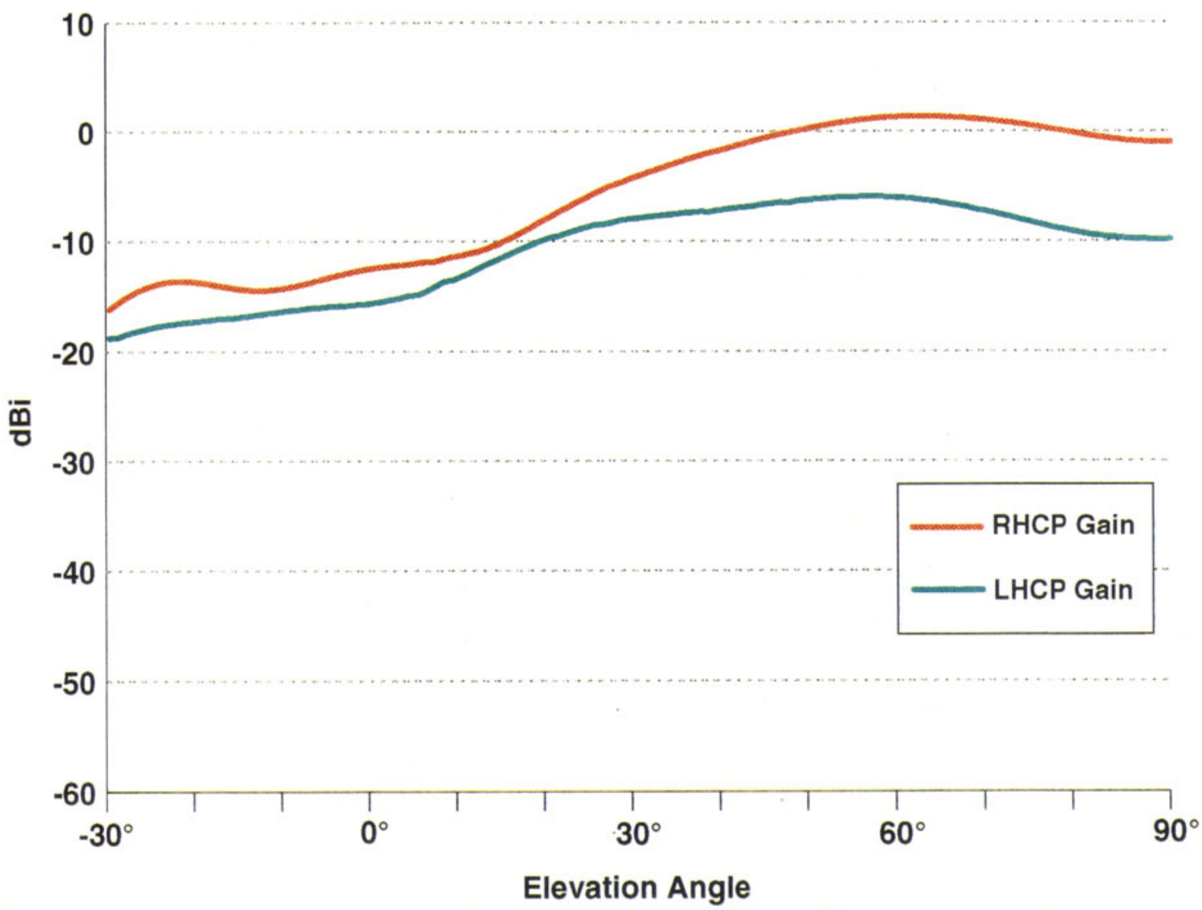

Figure A-5. Absolute Gain for NovAtel (corner-fed patch) Antenna on Ground Plane: Minimum Cross Pol. Ratio = 1.4 dB at 14-degree Elevation.

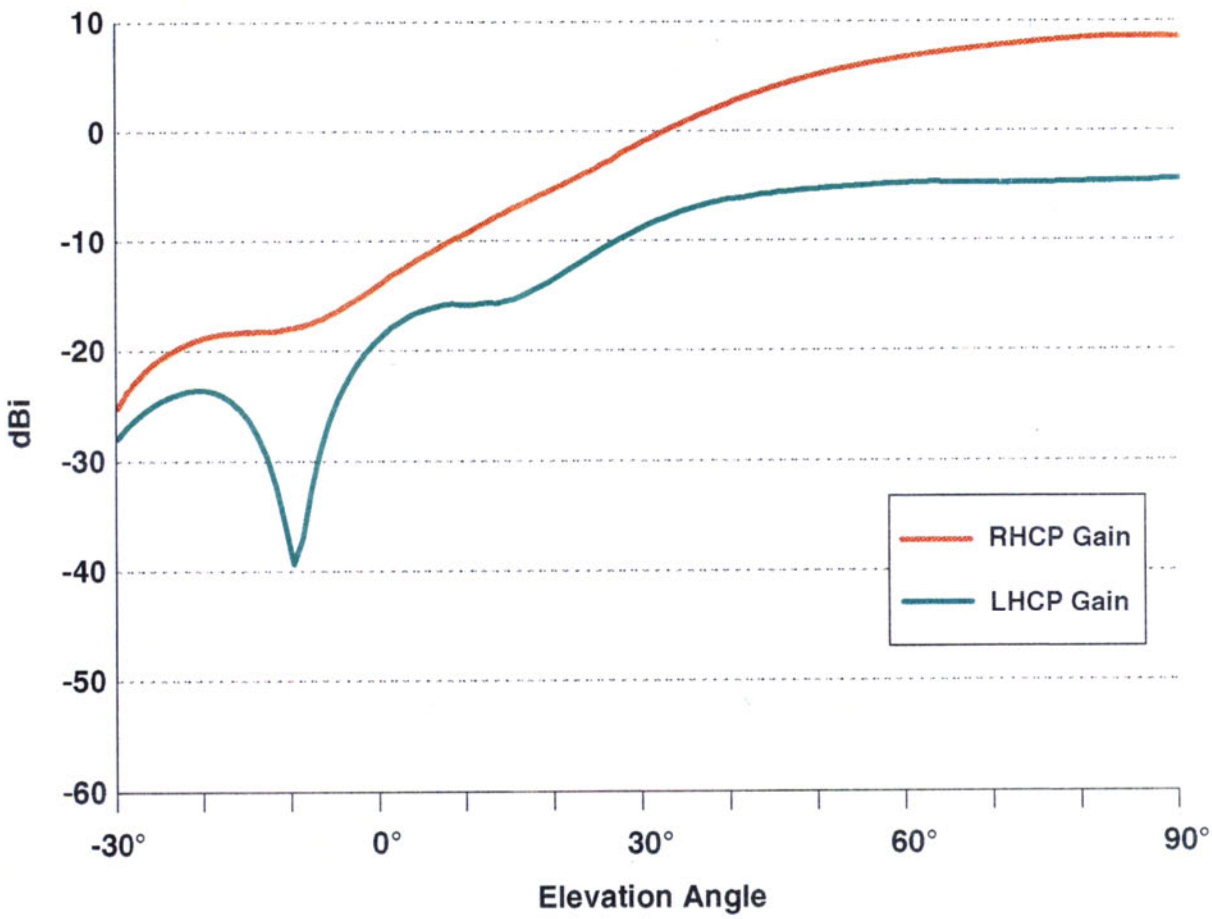

Figure A-6. Absolute Gain for Trimble (patch) Antenna on Choke Ring: Minimum Cross Pol. Ratio = 4.9 dB at 5-degree Elevation.

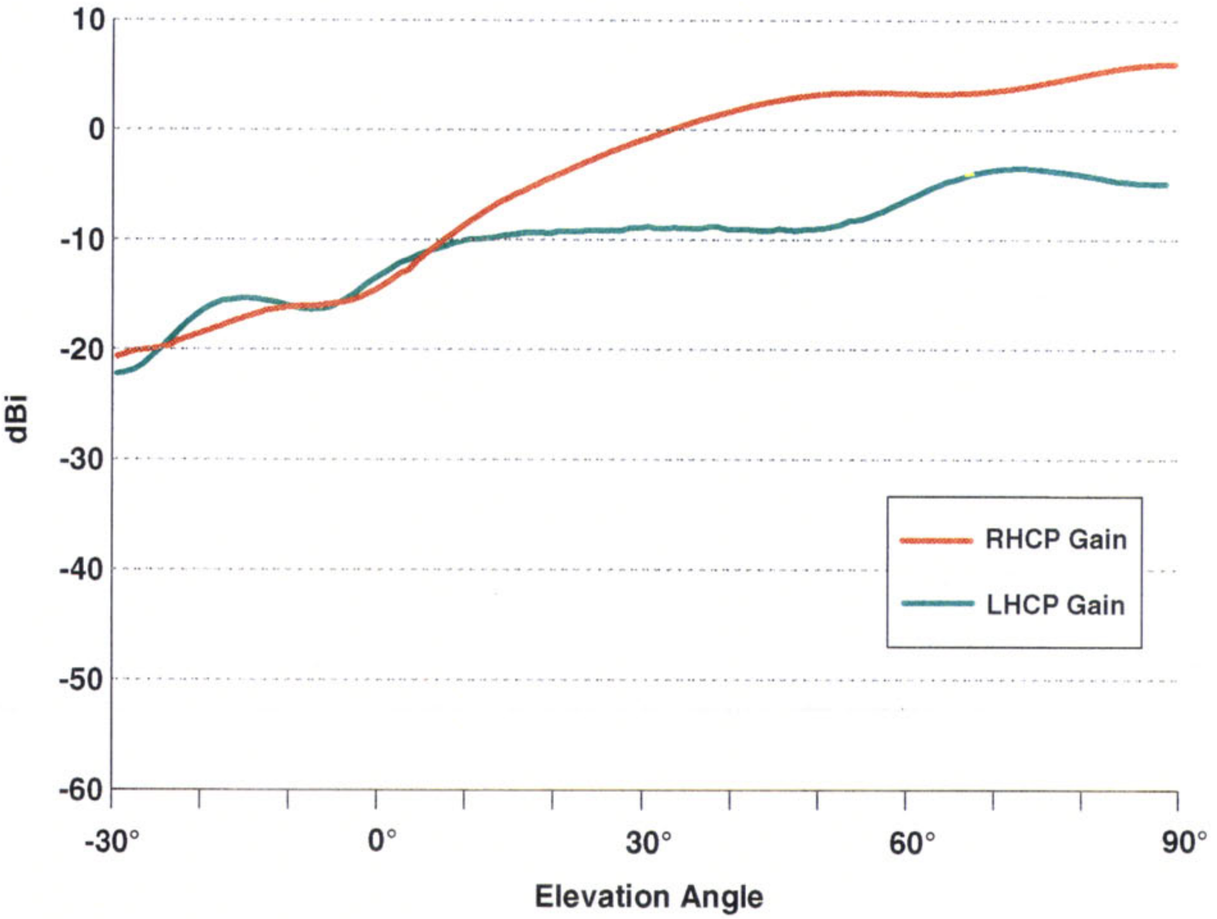

Figure A-7. Absolute Gain for Trimble (patch) Antenna on Ground Plane: Minimum Cross Pol. Ratio = -0.2 dB at 5-degree Elevation.

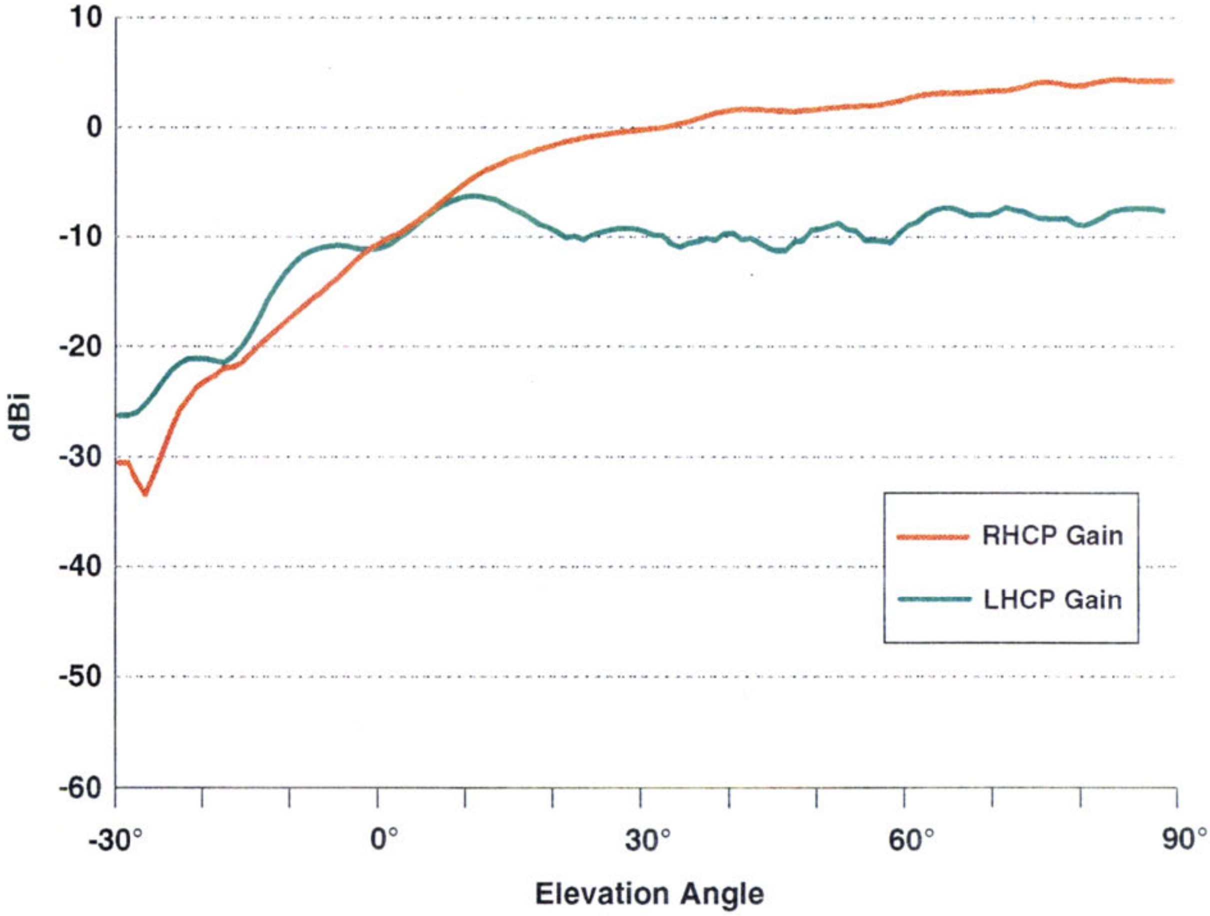

Figure A-8. Absolute Gain for Trimble (patch) Antenna on Fuselage: Minimum Cross Pol. Ratio = 0.2 dB at 5-degree Elevation.

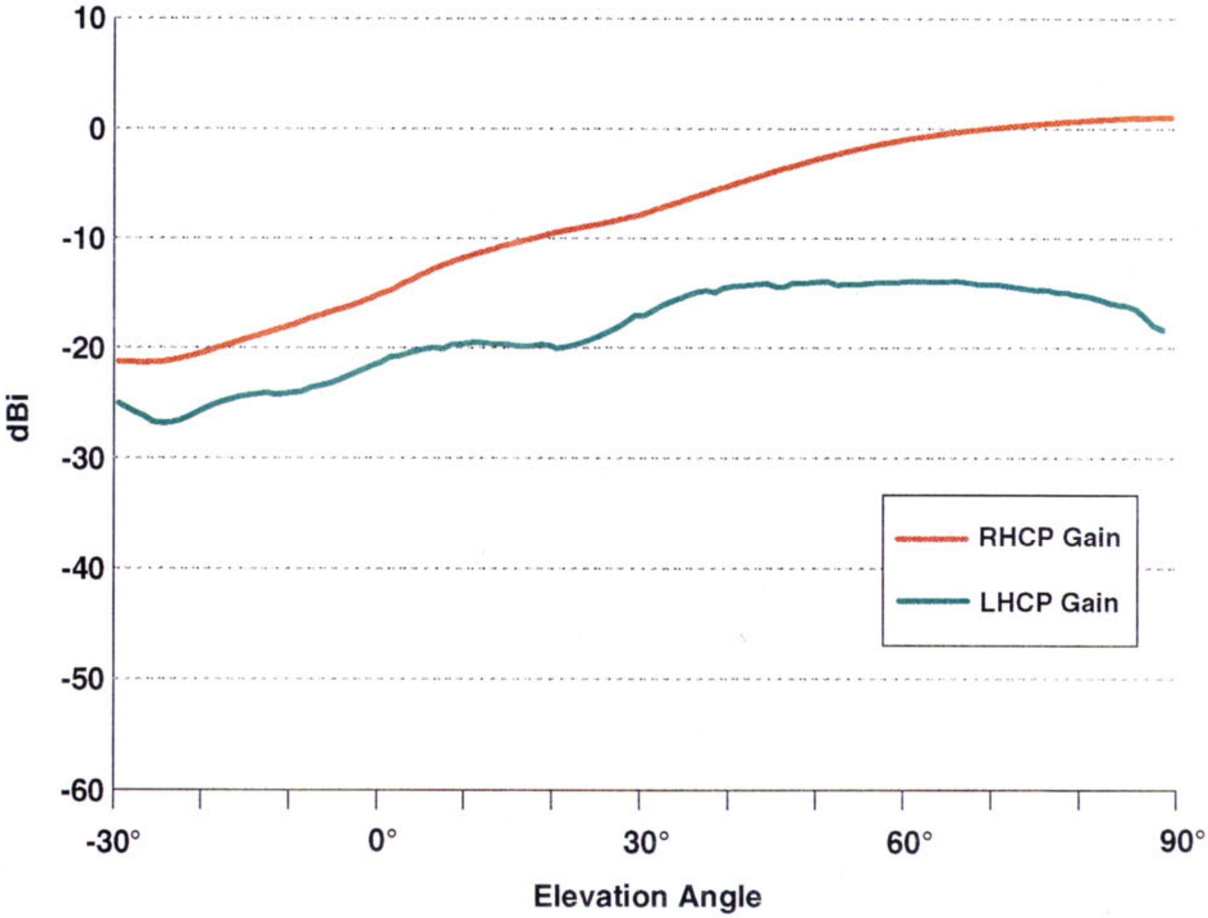

Figure A-9. Absolute Gain for Turbo Rogue (crossed dipoles) Antenna: Minimum Cross Pol. Ratio = 6.9 dB at 5-degree Elevation.

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[1] Skolnik, Merrill I., “Introduction to Radar Systems,” Second Edition, McGraw-Hill Book Company, New York, 1980, p. 505 .

[2] Ibid, p. 506.

[3] Lo, Y. T.. and S. W. Lee; “Antenna Handbook,” Van Norstrand Reinhold Company, New York; 1988, p. 8-50.

[4] Braasch, Michael S., “On the Characterization of Multipath Errors in Satellite–based Precision Approach and Landing Systems,” Dissertation Presented at Ohio University, June 1992, p. 9.