GPS Microstrip Antenna Array on a Resistivity Tapered Ground Plane for Multipath Mitigation

Basrur Rama Rao, *The MITRE Corporation*
Jonathan H. Williams *The MITRE Corporation*
Eddie N. Rosario, *The MITRE Corporation*
Robert J. Davis, *The MITRE Corporation*

BIOGRAPHY

B. Rama Rao is a Principal Engineer at The MITRE Corporation. He received his Ph.D. degree from Harvard University in Applied Physics. Prior to joining MITRE he held technical staff positions at the Sperry Research Center and at MIT Lincoln Laboratory. He has also served as an Assistant Professor of Applied Physics at Harvard University and as a Research Associate at MIT Dr. Rama Rao holds seven U.S. patents.

Jonathan Williams is a Lead Engineer at MITRE. He received his BS and MS degrees, both in Electrical Engineering from Clemson University. He worked as an Antenna Engineer at E-Systems in St. Petersburg, Florida from 1994-96 testing prototype GPS antennas including the CRPA. From 1996-97 he worked as a Design Engineer at M/A-COM in Amesbury, Massachusetts, where he designed pico-cell antennas for the consumer market. He joined The MITRE Corporation in January 1998.

Eddie N. Rosario is a Technical Assistant in the Antenna & Electromagnetics Section at The MITRE Corporation. He assisted in the design, assembling and testing of the two-element microstrip antenna array described in this paper.

Robert J. Davis is a Communications Engineer at The MITRE Corporation. He received his AS degree from Northeastern University and manages the Near Field antenna range where the two element antenna array described in this paper was tested. Since joining MITRE in 1981 he has tested antennas ranging in frequency from VLF to EHF and also conducted EMI, SATCOM and scale model investigations.

ABSTRACT

GPS Carrier Multipath is a major source of error in Differential GPS that cannot be removed through signal processing in the receiver; it occurs from a variety of structural and ground reflections and is common to both land based and airborne GPS systems. In this paper we describe a new type of low profile, lightweight two-element microstrip antenna array used in combination with a resistivity tapered ground plane for reducing multipath in GPS systems. The concentric two-element array consists of an outer annular ring microstrip antenna enclosing a centrally located circular microstrip antenna. This antenna array is used as a polarization filter for adaptive cancellation of the cross polarized multipath signals; the function of the resistivity tapered ground plane is to reduce the back radiation lobes of the antenna by attenuating the signals that are either diffracted or reflected from the edges of the ground plane. A Proof of Concept (POC) version of this antenna that operates in the GPS L_1 band has been built and tested to demonstrate feasibility of this concept. A dual band version that operates at both the GPS L_1 and L_2 frequency bands can be built by using stacked microstrip patch antenna elements. This new antenna offers significant advantages in terms of size, weight and cost over other multipath mitigation antennas such as the choke ring ground plane antenna or the three element vertical linear array. It is especially attractive for installation on airborne platforms because of its low profile, which is not possible with the much taller multi-element array. The microstrip antenna elements can be manufactured using printed circuit technology to reduce cost; the resistivity tapered ground plane can be made from different types resistive material that are currently available such as textiles, composites, paints or thin films sputtered on thin plastic sheets. Since it does not need stamped or machined metallic parts like the choke ring ground plane, it is easier and less expensive to manufacture and also lighter in weight.

INTRODUCTION

GPS carrier multipath is a significant source of error that limits the positioning accuracy of a Differential GPS (DGPS) [1–3]. Since multipath is caused by interaction between the individual GPS antenna and its unique surrounding environment it is not common to both the reference station and the remote user receivers since they could be separated by distances of up to 150 km in a local DGPS; hence, multipath errors at the user terminal are uncorrelated with those measured at the reference and cannot be eliminated through differential processing like other bias errors that generally affect the GPS system. If the multipath signal is delayed in time relative to the direct satellite signal by more than 1.5 chips it can be rejected through decorrelation processing; this delay corresponds to an increased path length of 450 meters for the C/A code and 45 meters for the P (Y) code. However, multipath with shorter delays may cause range errors that are unacceptable in a high precision GPS systems. Unfortunately, it is generally scattering from sources closest to the antenna that produce the strongest multipath. In addition to receiver processing techniques, a well-designed antenna can help greatly in reducing the effects of multipath in DGPS.

In this paper we describe a new type of light weight, low profile GPS antenna system consisting of a two element concentric microstrip antenna array on a resistivity tapered ground plane that is effective in suppressing multipath through adaptive cross polarization filtering and antenna pattern shaping. This antenna system can be used for both land based and airborne GPS systems and offers significant advantages over existing multipath mitigation antennas in terms of size, weight and cost.

Sources and Types of Multipath in GPS Systems

Multipath can affect GPS receivers used in both ground station as well as airborne terminals. In a ground system multipath signals can be picked up by the GPS receiving antenna in two different ways as shown in Figure 1.

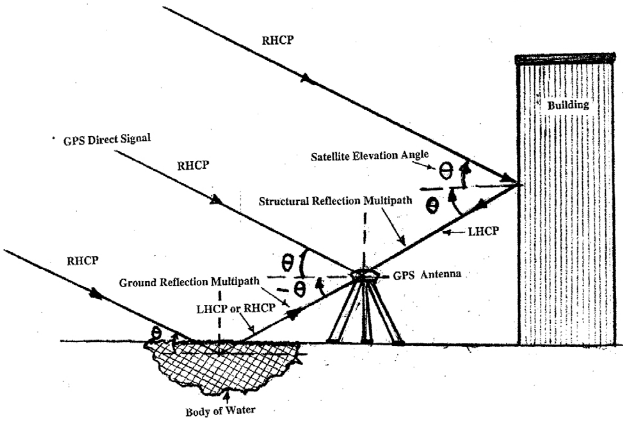

Figure 1. Structural and Ground Reflection Multipath Effects on GPS Antenna

It can be generated by a “structural reflection” caused by a specular reflection of the satellite signal off numerous scattering sources common to an urban environment such as buildings, large vehicles, aircraft or a ship; the reflected multipath signal would be incident on the antenna at an elevation angle **above** the horizon. Alternatively, it can also be caused from a “ground reflection” at a low grazing angle off the moist ground, roof top, sea surface or a large body of water close to the antenna. The grazing angle is the angle that the incident ray makes with the surface of the ground; ground reflections are strongest at grazing angles below the Brewster angle, which for moist soil conditions is around 15° [4]. The multipath signal in this case would be incident on the antenna at a negative elevation angle, **below** the horizon as shown in Figure 1. The amplitude, phase shift and depolarization of the multipath signal would depend on the complex reflection coefficient of the type of reflecting surface and the incident-grazing angle.

Multipath can affect the accuracy of an airborne GPS system through either a “structure reflection” or a “ground reflection” depending on the altitude of the aircraft. When the aircraft is at high altitudes, multipath is caused primarily through reflection or diffraction of the satellite signal from scattering sources such as the wings, tail or any other large appendage of the aircraft fuselage; this is illustrated in Figure 2.

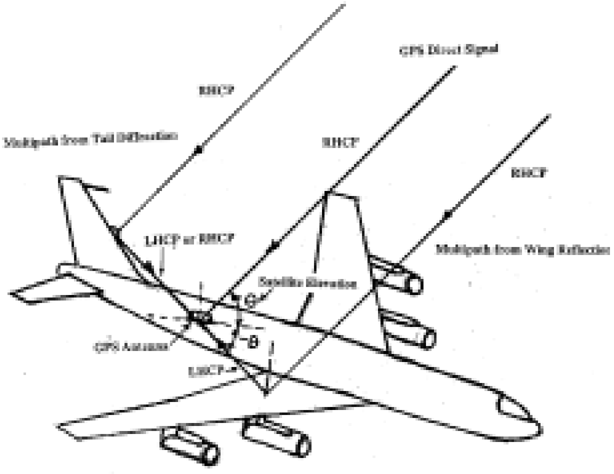

Figure 2. Sources of Multipath in a GPS Airborne System

These multipath effects are similar to structure bounce multipath problems experienced by a ground based GPS antenna. The direction of incidence of the multipath signal would be very dependent on the location of the antenna on the aircraft and the geometry of the aircraft fuselage. In large aircraft like a Boeing 777 or 747 -- 400, reflections off its large wing span have been identified as the primary cause of multipath positioning errors [5]. When the aircraft approaches the airport, ground multipath from the runway can affect the position accuracy of the GPS system during precision approach and landing. A recent study [5] has shown that multipath effects in an airborne platform such as the Boeing 777 are generally smaller than in land based systems. Large multipath reflections from the sea surface could also be a problem when landing fighter aircraft on an aircraft carrier although this problem does not appear to have been investigated in detail so far.

Multipath Mitigation through Polarization Discrimination and Reduction of Antenna Backlobes

The polarization of the multipath signal after reflection from a large metallic object or the sea surface is normally reversed. Since the direct satellite signal is Right Hand Circularly Polarized (RHCP), the multipath signal incident on the antenna after reflection is Left Hand Circularly Polarized (LHCP) as shown in Figures 1 and 2. This difference in polarization between the direct and the multipath signal can be used as an effective discriminant for rejecting single bounce multipath signals in a GPS system; this is normally done by selecting an antenna system with a high circular polarization ratio $\rho_C = E_{RHCP}/E_{LHCP}$ where ρ_c is defined as the ratio of the magnitude of the principal (RHCP) component E_{RHCP} of the radiated field of the antenna over its cross polarized (LHCP) component E_{LHCP} in the direction of the multipath signal received by the antenna. This is done by ensuring that the GPS receiving antenna has a good RHCP axial ratio $AR = |(E_{RHCP} + E_{LHCP})/ (E_{RHCP} - E_{LHCP})|$. However, the sense of polarization keeps reversing after each reflection, so the final state of the polarization of the multipath signal depends on whether the number of reflections suffered by it before it reaches the antenna are odd or even. However, with each successive reflection the amplitude of the multipath is reduced, hence, multipath signals arriving at the antenna after multiple bounces are generally too weak to be of concern to GPS systems.

For reflections off the “ground,” such as moisture laden earth or a concrete runway, which can be considered as a lossy dielectric surface, the multipath signal is elliptically polarized with both RHCP and LHCP components at incidence angles smaller than the Brewster’s angle. Hence, elimination of ground multipath by using just polarization discrimination will not be as effective; this can be done by reducing the antenna back-lobes for both types of polarization or by improving the so called “Up/Down Gain Ratio” of the antenna [9] at low elevation angles. Hence, a good GPS receiving antenna for effective multipath mitigation needs to have both a high cross polarization rejection ratio at low elevation angles for rejecting structural multipath and simultaneously also have low antenna back lobes to reduce ground multipath. Reflections off the sea surface can be considered similar to that from a good conductor and leads to a full polarization reversal.

If multipath in an airborne platform is caused by reflection off a large metallic surface such as the wing, we can expect polarization reversal; hence, polarization discrimination would work well in suppressing the amplitude of the multipath signal. However diffracted signals from edges of the fuselage can in general be elliptically polarized making multipath rejection from polarization discrimination alone much less effective.

Current Antenna Technology for Multipath Mitigation

Various types of antenna designs have been proposed for mitigating multipath, including choke ring ground planes [6–8] and multi-element antenna arrays [9]. Choke ring ground planes are circular ground planes with quarter wavelength slots cut into them to present a high impedance to currents flowing on the ground plane to prevent their interference with the antenna radiation. Typical diameter of a choke ring ground plane is 14” to 16”, with a height about 3” or higher and a weight of 10 to 20 lbs. They are not suitable for airborne applications because of their construction and weight. A three-element array consisting of interleaved turnstile elements for L1 and L2 spaced 1/3 wavelength apart has been designed by Counselman for suppressing multipath. It is about 12.75" high and 5" wide. While this antenna does not have a ground plane it is too high for airborne applications or for other systems where a low profile antenna is needed.

PROPOSED MICROSTRIP ANTENNA ARRAY ON A RESISTIVITY TAPERED GROUND PLANE FOR GPS MULTIPATH MITIGATION

In this paper we describe a new type of conformal, lightweight and low cost GPS antenna system consisting of a two element concentric microstrip antenna array on a resistivity tapered ground plane where we have combined two separate techniques for multipath mitigation:

- The two element concentric antenna array, consisting of an outer annular ring microstrip antenna enclosing an inner circular microstrip patch antenna, is used as a polarization filter for adaptive cancellation of the LHCP multipath signal caused by "structural reflections" that are incident on the antenna. Adaptive cross polarization cancellation techniques have been used successfully for many years for reducing interference in satellite communication systems that use frequency re-use for increasing channel capacity and also in radar systems for detecting weak targets in the presence of rain and ground clutter [10-11]. In this paper a modified version of this type of cross polarization cancellation technique has been used to reduce multipath effects in GPS systems.

- A resistivity tapered ground plane [12] is used in conjunction with the two-element antenna array to reduce the back radiation lobes of the antenna to suppress contributions from "ground reflection" multipath. This is accomplished by attenuating signals diffracted or reflected from the edge of the ground plane which are primary contributors to high antenna back lobes.

This type of antenna can be used in both ground terminals and also airborne GPS terminals for reducing position errors caused by multipath. In an airborne system, the antenna array can be used either with or without a resistivity tapered ground plane since the predominant source of multipath is "structural reflections" from sources on the aircraft itself which are incident on the airborne GPS antenna at incidence angles in the vicinity of the horizon or slightly above it. A "Proof Of Concept" (POC) antenna that operates in the GPS L_1 band has been built and tested to demonstrate its potential for significant multipath mitigation. Tests were conducted on the antenna array both with a resistivity tapered ground plane and also with a conventional metallic ground plane– the former is suitable for both land based and airborne systems whereas the latter is only suitable for airborne applications.

This new antenna has significant advantages over other multipath mitigation antennas such as the choke ring ground plane antenna or the three-element array described previously. The resistivity tapered ground plane is made from a thin kapton film with a tapered resistive film of Indium Tin Oxide (ITO) sputtered on it. This resistive film is bonded to a thin plastic plate and hence, can be made very light in weight because of the absence of any metallic parts. Since it does not need quarter wavelength deep choke rings it also has a very low profile. The absence of any machined or stamped metal parts makes this type of ground plane very cost effective and lightweight for many commercial GPS applications. The resistive film can be protected from scratching or other types of mechanical damage by sandwiching it between two plastic protective films. A variety of different tapered resistive material that are currently commercially available can be used for making this type of resistivity tapered ground plane in addition to the sputtered thin films used in our POC antenna; these other material that can be used include resistive textiles, resistive composite materials used for RCS reduction in aircraft, and specially developed resistive paints. Since the antenna uses microstrip elements it has a low profile and can be made conformal to the surface of an aircraft unlike the three element array described above which has a protrusion height of nearly 12".

Description of the Antenna Design

The antenna is a concentric two-element array consisting of an outer annular ring microstrip antenna enclosing an inner circular microstrip patch antenna. A schematic diagram of this antenna is shown in Figure 3. A picture of this array antenna is shown in Figure 4. The prototype model that was built and tested to prove feasibility of this antenna concept were single frequency band microstrip patch antennas that operated in the GPS L_1 band only; however, a dual band antenna element that operates on both the L_1 and L_2 band can be built by stacking the microstrip patches as shown in Figure 3.

Both microstrip antennas were machined on a 0.1-inch thick dielectric substrate made from Roger's 6010LM material. This substrate has a dielectric constant of 10.2 and a loss tangent of 0.0028. The outer annular ring patch antenna is used as the main reference antenna element to receive signals from the GPS satellites, whereas the inner

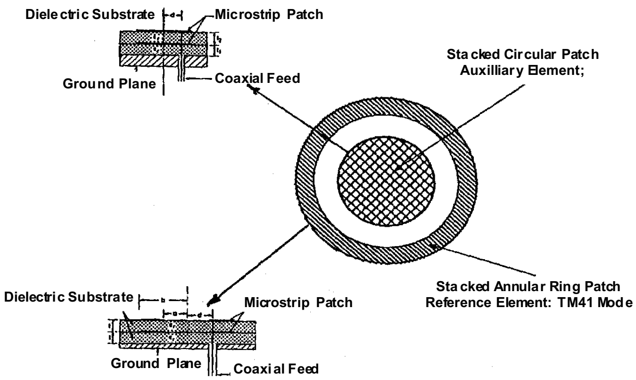

Figure 3. Schematic Sketch of the Two Element Antenna Array Using Annular Ring & Circular Microstrip Antennas for Reducing GPS Multipath Effects

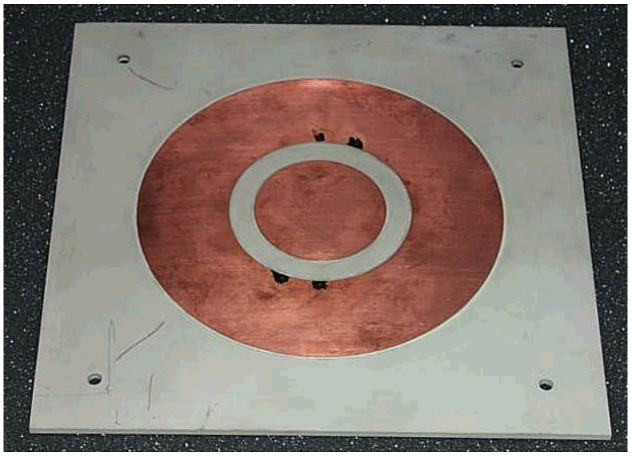

Figure 4. Picture of Concentric Two Element Antenna Array for Reducing Multipath Consisting of an Outer Annular Ring Microstrip Antenna (Reference) and a Central Circular Microstrip Antenna (Auxiliary)

patch antenna is used as the auxiliary element to cancel out the cross polarized LHCP multipath signals received by the outer ring antenna at a pre-selected low elevation angle, generally the horizon. Since the outer annular ring needs to have a diameter that is larger than the central circular patch antenna, it was designed to be resonant in the TM_{41} higher order mode. The ring was excited by four symmetrically located coaxial probes located at 90° intervals around the antenna. The four probes had a relative phase difference of 0°, 90°, 180° and 270° to generate Right Hand Circular Polarization (RHCP) for best reception of GPS signals. By selecting the azimuth location of the four probes and their relative phase difference the annular ring antenna was forced to radiate in the lower order TM_{11} mode even though its larger physical dimensions correspond to resonance at the higher order TM_{41} mode. The lower order mode was excited to obtain a symmetric radiation pattern in the azimuth plane for the annular ring antenna and to allow its radiation pattern to "phase track" the radiated signals from the inner circular patch antenna to allow cancellation of the cross polarized multipath signal over an entire 360° circle in azimuth at some pre-selected elevation angle, normally the horizon. The location of each coaxial probe was close to the inner radius of the annulus to obtain the best return loss across the GPS L_1 frequency band. This location of the probe yields an input impedance close to 50 ohms at resonance. The inner and outer radii of the annular ring were 1.01" and 2.25" inches, respectively. The inner circular microstrip patch antenna is resonant in the fundamental TM_{11} mode and was also excited by four coaxial probes symmetrically arranged at their resonant locations around the circle with relative phase differences of 0°, 90°, 180°, and 270° to generate RHCP and to allow co-modal phase tracking with the fields of the annular ring in the azimuth plane. The cross-polarized LHCP gain of the central circular patch antenna at the horizon is nearly 4.5 dB higher than the gain of the outer annular ring antenna. Signal from the central circular patch antenna, after appropriate phase and amplitude weighting, can be combined with the signal from the outer ring patch antenna to cancel the cross polarized radiation at the pre-selected elevation angle.

Description of the Resistivity Tapered Ground Plane

Ground plane edge diffraction effects that contribute to the back lobes of a microstrip antenna can be reduced by the use of resistivity tapered ground planes whose surface resistance gradually increases from the center to the outer edge of the ground plane. This has already been demonstrated by Rama Rao, et al. [12]. This is similar to a well-known technique for reducing the radar cross section of a target where resistive cards are placed at the edges of the target to eliminate edge diffraction effects.

The annular ring/circular patch antenna array was placed at the center of a 26" square resistivity ground plane for multipath reduction. The ground dimension is 3.47 wavelengths square at 1.5754 GHz, the L_1 center band frequency. The ground plane was formed by using resistivity tapered thin films of Indium Tin Oxide (ITO) sputtered on a kapton film substrate; the resistive film was bonded to a thin plastic sheet to form the ground plane for the antenna. The surface resistivity of the film varies increases from 0 (perfect conductor) at the center to about 2000 ohms per square at the outer edge in an exponential manner. Figure 5 shows the resistivity profile of the 26" square ground plane.

Antenna patterns of the two element array on the resistivity tapered ground plane were measured to demonstrate suppression of cross polarized radiated signals at low elevation angles from adaptive polarization cancellation by the array and also to confirm the reduction in the antenna back-lobes from the resistivity tapered ground plane.

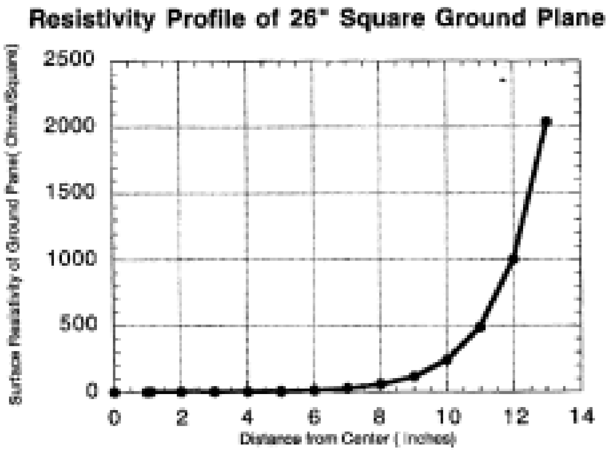

Figure 5. Resistivity Tapering Profile of the 26" Square Ground Plane used for the Two Element Antenna Array

MEASURED ANTENNA PATTERNS OF THE ANTENNA ARRAY ON RESISTIVITY TAPERED GROUND PLANE AND METAL GROUND PLANE

Antenna patterns were measured in the Near Field Antenna Range at MITRE using a 6' feet high cylindrical scanner. Figure 6 shows the measured radiation pattern of the annular ring patch antenna when it is placed on a conventional 26" inch square **metallic ground plane before cancellation** of the cross polarized LHCP; the annular ring is the outer element in this concentric two element array and is the **reference antenna** element that is used to receive the GPS signals.

Figure 7 shows the measured radiation pattern of the inner circular patch antenna element when placed on the same metallic ground plane. Both patch antennas are polarized RHCP.

An examination of Figures 6 and 7 indicates that the polarization ratio ρ_C of both antennas degrades at elevation angles below 15°, with the cross polarized LHCP component of the radiated field having an amplitude comparable to that of the principal polarized component RHCP. Hence, the ability of this antenna to reject cross-polarized signals from structural multipath reflections is very poor. Furthermore this antenna also has significant back lobes in both types of polarization making it susceptible to multipath caused by ground reflections.

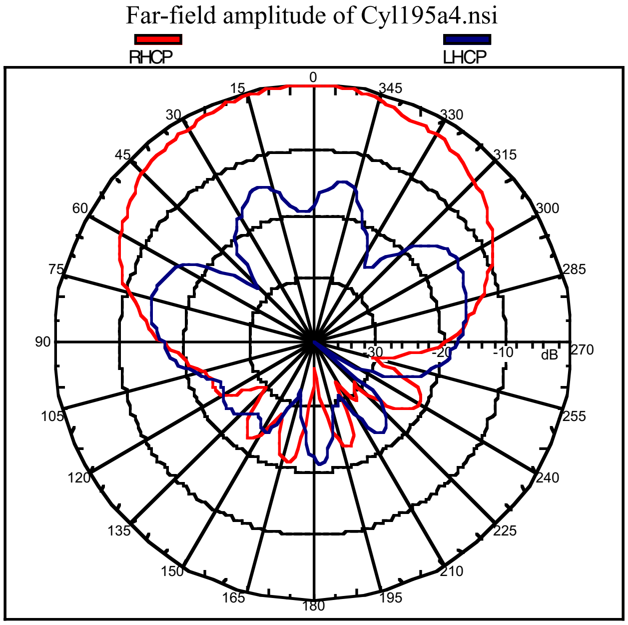

Figure 6. Measured Antenna Pattern in the Elevation Plane of the Outer Annular Ring Microstrip "Reference" Antenna on a 26" Square Metallic Ground Plane <u>Before</u> Cross Polarization Cancellation

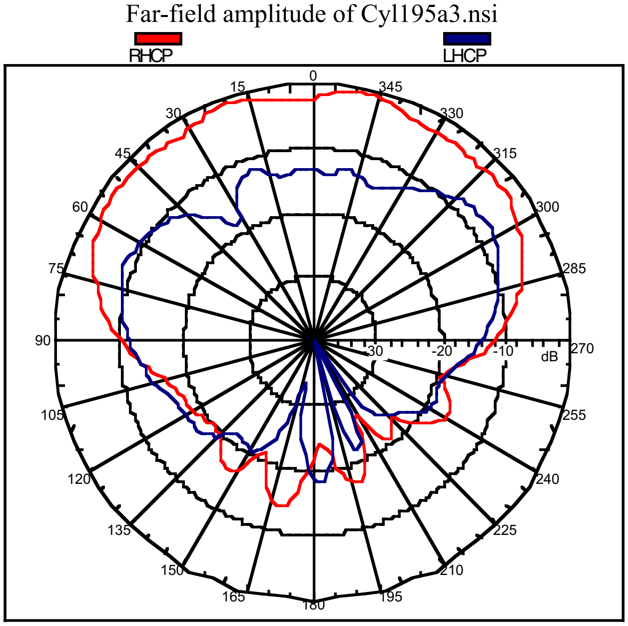

Figure 7. Measured Antenna Pattern in the Elevation Plane of the Central Circular Microstrip "Auxiliary"Antenna on a 26" Square Metal Ground Plane <u>Before</u> Cross Polarization Cancellation

Figure 8 shows the measured **adapted** radiation pattern of the annular ring patch antenna after the following two modifications were made:

- The metallic ground plane was replaced by the resistivity tapered ground plane whose taper profile is shown in Figure 5.
- The signals from the inner patch, after appropriate phase and amplitude weighting, were combined with signals received by the outer ring to cancel the LHCP signal received by the annular ring antenna at an elevation angle of 0° (horizon) and an azimuth angle of 275°.

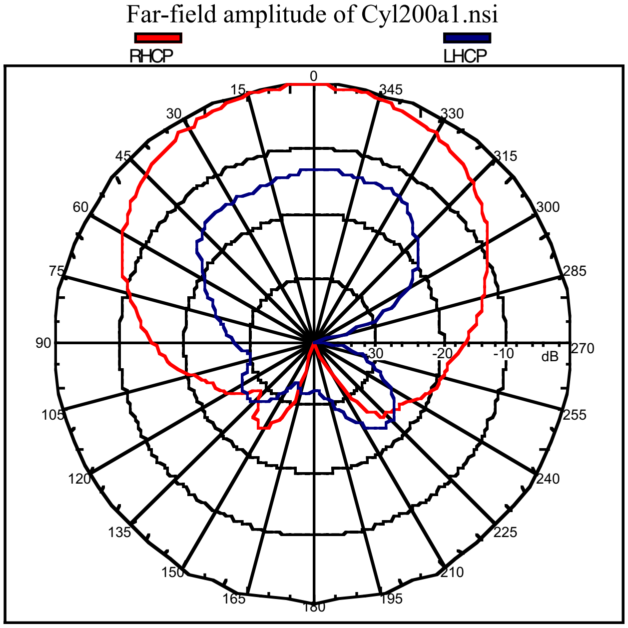

Figure 8. Measured Antenna Pattern of the Outer Annular Ring "Reference" Antenna on a Resistivity Tapered Ground Plane with Cross Polarization Cancellation at Elevation Angle of 0° in Elevation (Horizon) and Azimuth Angle = 275°

A comparison of Figures 6 and 8 shows the improvement in the rejection capability of this modified antenna against cross -- polarized multipath signals from structural reflections that are incident at low positive elevation angles. A significant reduction in the LHCP component is seen over the entire upper hemisphere and even down to elevation angles below the horizon, as low as –15°. Since the signals of the two antennas are combined to cancel only the cross polarized component at the horizon, there is negligible impact on the RHCP gain of the annular ring antenna necessary for efficient reception of GPS signals; this can be determined by comparing the antenna patterns shown in Figures 6 and 8. Furthermore, the resistivity tapered ground plane has also suppressed the amplitudes of the backlobes of the adapted antenna pattern, further improving its ability to reject multipath generated by ground reflections as well. It has also smoothed out the ripples in the antenna pattern in the main antenna beam caused by interaction between the antenna signals and the signals diffracted from the edge of the metallic ground plane. An examination of Figure 8 also shows that the null in the cross-polarized pattern at the horizon results in increased cross-polarized side lobe at a lower elevation angle below the horizon. The radiated energy in the cross-polarized null placed at the horizon is channeled in a different direction and appears as a noticeably larger sidelobe. This distortion in side lobe level can be minimized by taking an average value of the weights over a range of azimuth angles at the horizon rather than a specific fixed azimuth angle of 275° as was done in the example shown in Figure 8.

Both elements of this antenna array have the same polarization (RHCP) and are also excited in the same mode (TM_{11}). This co-modal phase alignment between the far fields generated by these two antennas allows cancellation of the cross-polarized far field component at the pre-selected elevation angle over a complete 360° circle in azimuth. This is shown in Figure 9 where the measured azimuth plane patterns for the cross-polarized LHCP component of the annular ring antenna have been compared for three different cases.

The plot shown in red color is the azimuth pattern at an elevation of 0° (horizon) of the annular ring "GPS reference" antenna on a conventional metal ground plane before any adaptive polarization cancellation. The plot in blue is the corresponding measured azimuth pattern at the same angle of the annular ring placed on a resistivity tapered ground plane before polarization cancellation. The third plot shown in brown is the measured antenna pattern of the annular ring antenna on the resistivity tapered ground plane **after cancellation** of the cross polarized signal at the horizon; the amplitude and phase weights for the antenna elements for this case were those measured at a specific azimuth angle of 275° were we see the largest reduction in the cross polarized LHCP signal radiated by the annular ring antenna. The difference between the red and brown color patterns shown in this figure is the overall reduction in cross polarized signal that is achieved by this antenna array over a complete 360° circle in azimuth angle. The degree of reduction in LHCP level varies from a maximum of 20 dB for the selected azimuth angle of 275° where the specific amplitude and phase weights for polarization cancellation were estimated to a minimum of approximately 5 dB at an azimuth of 180° due to the pattern distortion caused by the placement of the null at 275° as explained earlier. The symmetry of the null as a function of the azimuth angle can be improved by averaging the amplitude and phase weights required for LHCP cancellation over a wider range of azimuth angles rather than at a single specific angle as shown in Figure 9.

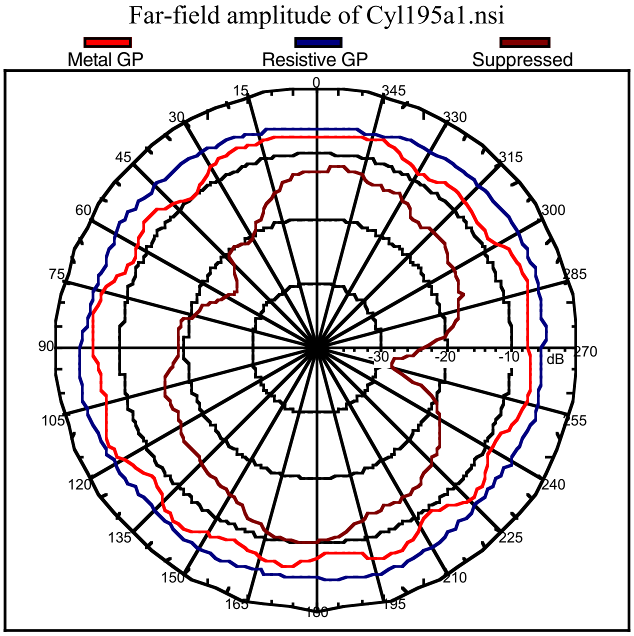

Figure 9. Comparison of the Azimuth Plane Patterns (at Horizon) of the Outer Annular Ring "Reference" Antenna for Three Cases: 1) On Metal Ground Plane Before Cross Polarization Cancellation (Red); 2) On Resistivity Tapered Ground Plane Before Cross Polarization Cancellation (Blue); 3) On Resistivity Tapered Ground Plane After Cross Polarization Cancellation (Brown)

Antenna patterns of the annular ring antenna were also measured by selecting an elevation angle lower than the horizon for canceling the cross polarized signal; this is illustrated in Figure 10, where the selected elevation angle was -30° in elevation and 270° in azimuth. This corresponds to a case where the antenna pattern needs to be adapted to cancel out a strong "ground reflection" multipath signal, such as scattering from a sea surface.

Since a resistivity tapered ground plane may not be feasible for some airborne platforms we also measured the antenna pattern of this two element microstrip antenna array placed on a metal ground plane to simulate the aircraft fuselage and cancelled the cross polarized component of the radiation pattern at the local horizon. The measured radiation pattern after cross polarization cancellation is shown in Figure 11; it can be compared to Figure 6, the patterns of this antenna measured before cross polarization cancellation, to determine the degree of improvement in the multipath rejection capabilities of this antenna at the lower elevation angles.

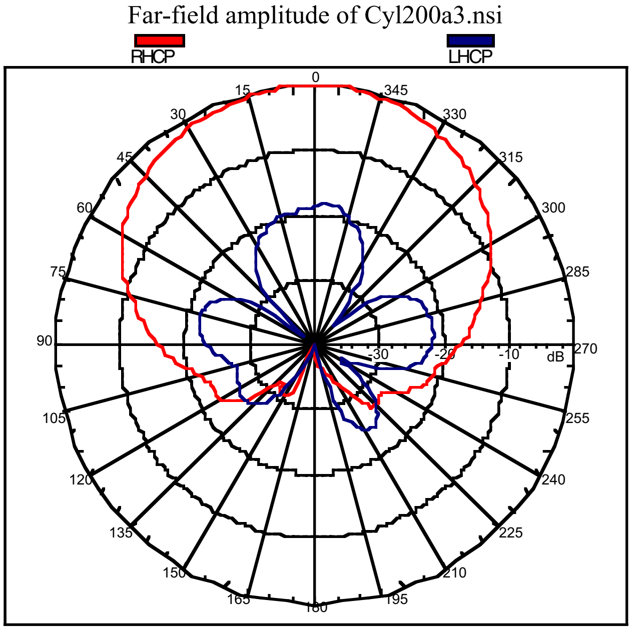

Figure 10. Measured Elevation Plane Pattern of the Outer Annular Ring "Reference" Microstrip Antenna on a 26" Square Resistivity Tapered Ground Plane with Cross Polarization Cancellation at Elevation = -30° and Azimuth = 270°

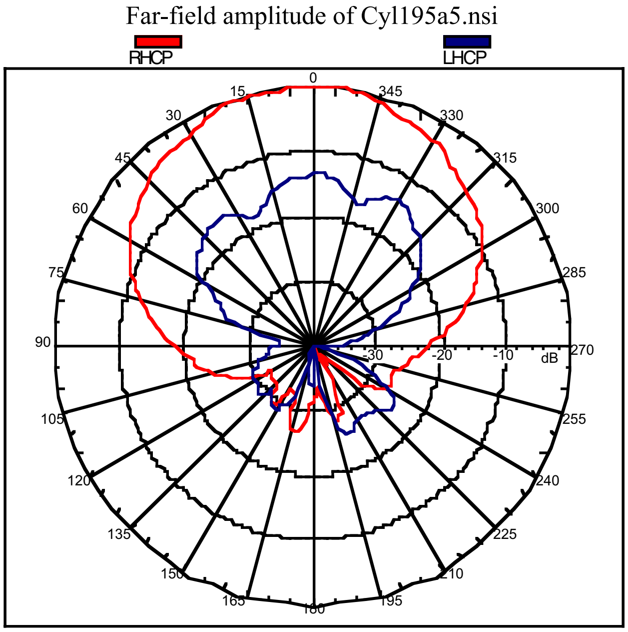

Figure 11. Measured Elevation Plane Pattern of the Outer Annular Ring "Reference" Microstrip Antenna on a 26" Square Metal Ground Plane with Cross Polarization Nulling at Elevation Angle = 0° (Horizon) and Azimuth = 270°

The plot shown in red color is the principal RHCP pattern and the one in blue is the cross-polarized LHCP pattern. As can be seen from this figure we obtain a significant improvement in the circular polarization ratio at low elevation angles between +30° and -30° due to the significant reduction in the LHCP radiation. The multipath is strongest at these lower elevation angles in an airborne platform.

The RHCP gain of the annular ring antenna element, measured by using a standard gain horn antenna was 2.5 dBic. The gain of this antenna can be increased by increasing the thickness of the dielectric substrate to 0.2" from its current thickness of 0.1" to improve radiation efficiency and bandwidth. The prototype antenna was built from Rogers 6010 LM substrate, whose dielectric constant is 10.2; the gain can be improved by using a lower dielectric constant substrate such as TMM6 (dielectric constant of 6). The size of the annular ring antenna can also be reduced by designing the outer annular ring to resonate either at the TM31 or TM_{21} mode instead of the TM_{41} mode as in the existing antenna.

Acknowledgement

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