Compact Co-Planar Dual-Band Microstrip Patch Antennas for Modernized GPS

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BIOGRAPHY

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Mohamed S. Mahmoud is an independent consultant. He received his Ph.D. from Ohio State University in 1999. During the past ten years, he has held several technical positions at The MITRE Corporation, Advanced Technology Center of the Lockheed Martin Corporation, Space Systems Loral, and the ElectroScience Laboratory at Ohio State University. His work is related to research and development of wireless and sensor products for satellite communications, GPS, and Radar.

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ABSTRACT

A new navigational signal designated as L_5 with a center frequency of 1176 MHz and a bandwidth of 20 MHz has been introduced as part of GPS Modernization. This new signal is in the Aeronautical Radio Navigation Service Band and will primarily benefit aviation users by allowing precision navigation when used with the existing L_1 signal for ionospheric corrections. In addition, U.S. military users will be primary beneficiaries of the new M code signal with a bandwidth of 24 MHz introduced into the L_1 and L_2 bands. The unique feature of this code is its spectral separation from the civil signals in these two bands. New antennas will be needed to support both civil and military users of a modernized GPS system when it becomes fully operational. The L_1/L_5 antenna used in avionics has to meet stringent size and performance requirements imposed by the RTCA. Military antennas also need to have adequate bandwidth and gain to allow high fidelity reception of M code signals. This paper describes two new microstrip antenna designs for very compact, co-planar dual-band antennas suitable for operation in either the L_1/L_5 bands for civil avionics applications or in the L_1/L_2 bands for use in small CRPA antenna arrays used for military applications. Both antenna designs meet their expected performance requirements and offer significant advantages over conventional GPS microstrip antenna designs that are currently being used.

INTRODUCTION

Modernization of GPS will enhance its civilian and military applications by offering signal diversity. Aviation users will be primary beneficiaries of a new "safety of life" signal designated as L_5 with a center frequency of 1176 MHz and a bandwidth of 20 MHz which is located in the protected Aeronautical Navigation Service band (ARNS) band. When used in conjunction with the existing L_1 signal, it will enable precision navigation in avionics by correcting for propagation errors introduced by the ionosphere through dual frequency processing. The L_5 test payload was successfully launched by the Block IIR-20(M) satellite in March 24, 2009; the first signal transmission occurred on April 10, 2009. The new M code signal introduced by GPS modernization will benefit the military users. An important characteristic of this military code will be its spectral separation from the civil signals in the GPS L_1 and L_2 bands. This separation is achieved through the use of M code's binary off-set carrier BOC(10,5) modulation which will have a bandwidth of 24 MHz. The signal spectrum of M code will have two main lobes located 6 to 9 MHz above and below the L_1 and L_2 band centers located at 1575 MHz and 1227 MHz, respectively. The M code signal was first broadcast by the GPS Block IIR-14(M) satellite launched in September 2005.

New antennas will be needed to support both civil and military users of a modernized GPS system when it becomes fully operational. Microstrip antennas are popular for many GPS applications because their small size, low profile, and low cost are hard to match with other antenna designs. One major drawback is their narrow bandwidth. To keep pace with GPS modernization, future GPS antennas will need to receive signals in at least two frequency bands, if not in all three bands of the system. The antennas also need to meet the size, height, gain, bandwidth, and axial ratio requirements imposed by the civil avionics and military systems. The requirements for antennas used in avionics systems are particularly stringent. They need to comply with the ARINC 743, a size requirement shown in Figure 1. In addition, these antennas are also required to meet the gain profile as a function of elevation angle set by the RTCA, from zenith down to a minimum elevation angle of 5 degrees. These gains are specified for the L_5 band by RTCA/DO-292 [2] and for the L_1 band by RTCA/DO-228 [1]. These documents also impose an axial ratio requirement for circular polarization of 3 dB above an elevation of 10 degrees.

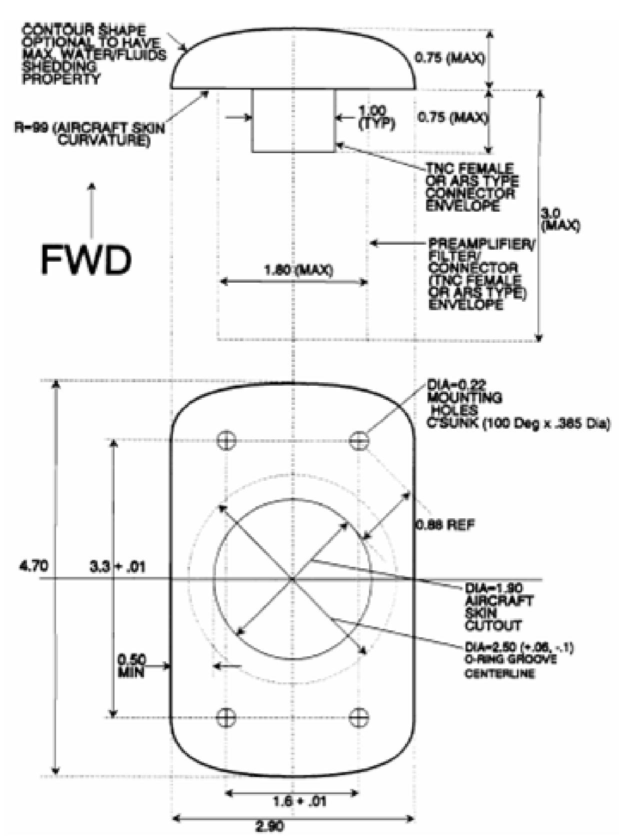


Figure 1. ARINC 743A Antenna Size Requirement for GPS Avionics Antenna

This paper describes two new designs for very compact, co-planar dual-band; right-hand circularly polarized microstrip antennas capable of providing high quality of performance in either the L_1/L_5 bands for civilian avionics applications and in the L_1/L_2 bands for adaptive antenna arrays used in military applications. The goal in these antenna designs is to achieve optimum performance that meets requirements in both of these bands, rather than on a broader triple band design where performance in some frequency bands may be compromised. The MITRE Corporation was recently awarded a U.S. patent for this new antenna design [3].

ANTENNA DESIGNS

CONVENTIONAL STACKED PATCH DUAL-BAND MICROSTRIP ANTENNAS

Dual-band operation in microstrip antennas that are currently used in GPS systems is generally obtained by “stacking” two patch antennas one on top of the other, with each antenna tuned to a different frequency band. The lower frequency antenna with the wider dimensions is generally at the bottom; the smaller size, higher frequency antenna is at located at the top. The lower frequency patch acts as a small ground plane for the upper patch. Two types feed techniques using orthogonally placed coaxial probes are used to obtain right-hand circular polarization; the location of the feed probes is optimized to provide a good impedance match to the receiver at both frequency bands; the relative phase of the two probes are 0 and -90 degrees, respectively. In the first method called the “top feeding” method, shown in Figure 2(a), the inner conductor of each feed probe proceeds through the lower patch without making contact and is connected to the top patch. A second method is the “bottom feeding” technique illustrated in Figure 2(b); the feed probe in this method is connected only to the lower patch. A disadvantage in both of these conventional designs is that the antennas for the two bands do not share a common dielectric substrate; the substrate for the top antenna also acts as a superstrate for the bottom antenna affecting its performance differently; this makes it difficult to optimize the design for obtaining optimum gain profile and bandwidth at both bands. The top patch also partially shields the bottom patch which can degrade its performance. When used in miniaturized adaptive antenna arrays, stacked patch antennas also suffer from increased mutual coupling from surface waves generated in the dielectric substrate that can affect gain and pattern symmetry.

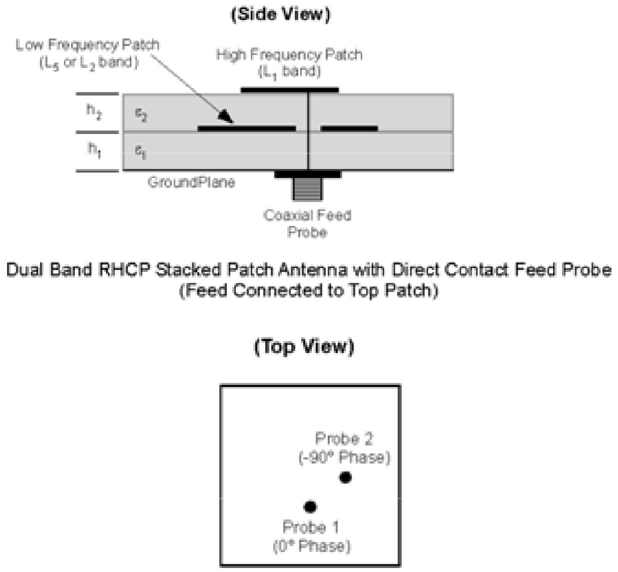


Figure 2(a). Dual-Band RHCP Stacked Microstrip Antenna with "Top Feed"

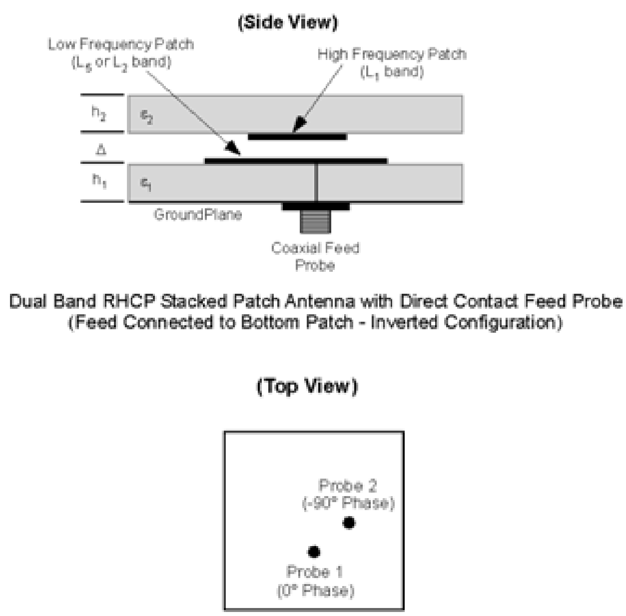


Figure 2(b). Dual-Band RHCP Stacked Microstrip Antenna with "Bottom Feed"

DESCRIPTION OF THE TWO NEW CO-PLANAR ANTENNA DESIGNS

Figures 3(a) and 3(b) show the cross-section of the two new dual-band microstrip antenna designs described in this paper; both designs avoid stacking the patch antennas by using a co-planar geometry. The antenna consists of two concentric patch antennas. The inner circular patch antenna is designed for operation in the GPS L_1 band; it is fed by two orthogonally located coaxial probes which are excited with a relative phase of 0 and -90 degrees through a quadrature hybrid to generate right-hand circularly polarized radiation (RHCP). The location of these two probes is selected to provide a good impedance match to the GPS receiver in both frequency bands. Surrounding this central patch is a thin annular ring patch antenna that is parasitically coupled to the central patch antenna; the diameter and width of the outer annular ring is tuned so that when coupled to the center patch, it resonates either in the L_5 band for avionics applications or in the L_2 band for military applications. The outer annular ring is also RHCP by virtue of parasitic coupling to the central patch. Antennas for both bands share a common dielectric substrate and a common dual feed probes for generating right-hand circular polarization. This common substrate, if needed, can include two different types of substrate materials with different dielectric constants and thickness to afford the antenna designer with extra design parameters to achieve optimum performance in both frequency bands. The antenna design can also be simplified, if necessary, by using a substrate made from single material. Very compact co-planar L_1/L_2 antennas, only 0.98 inches in diameter have been built and tested using a ceramic substrate with a dielectric constant of 20.

In the first design shown in Figure 3(a), the co-planar patch antennas with their substrate layers are located above the ground plane. The second design shown in Figure 3(b) is a cavity backed design where the co-planar antennas are located inside and at the center of a metal cavity; this design allows the antenna to be flush mounted below the ground plane. They have been designed for operation in the GPS L_1/L_2 bands, largely for use in military systems. Since these antennas are recessed inside a flush mounted cavity, they allow thicker dielectric substrates to be used for improving the bandwidth and gain without increasing antenna protrusion above the ground plane, although this would increase the intrusion depth below the ground plane. A second advantage is that this design reduces mutual coupling between adjacent antenna elements caused by the surface waves generated in the dielectric substrate. This type of surface wave coupling between adjacent elements in an adaptive array is illustrated in Figure 4. The lowest order TM_0 surface wave generated inside the dielectric substrate has no cut off frequency; hence, it is present even in very thin substrates. Its effects can be mitigated only by using a cavity backing around the microstrip antenna. This second antenna design is particularly attractive for use in densely packed adaptive antenna arrays, since it prevents surface wave coupling between adjacent antenna elements. Because of its flush mounting, this design is also attractive for use in high performance, tactical military platforms which require antennas with very low aerodynamic drag.

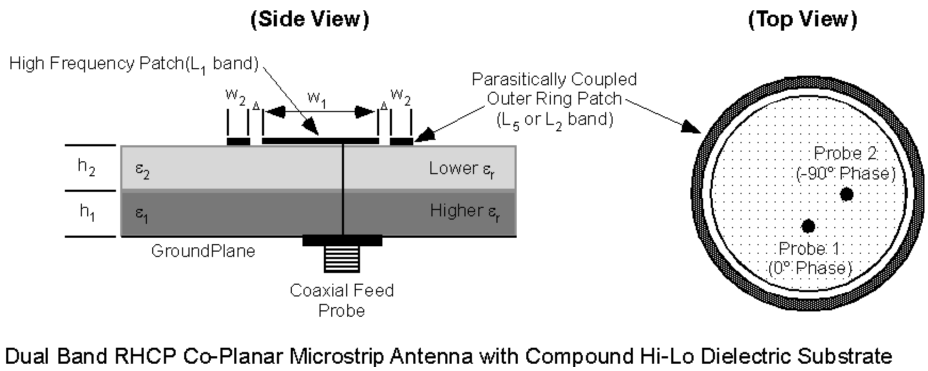


Figure 3(a). Co-Planar Dual-Band RHCP Patch Antenna Design with No Cavity Backing. Antenna is Mounted on Top of Ground Plane

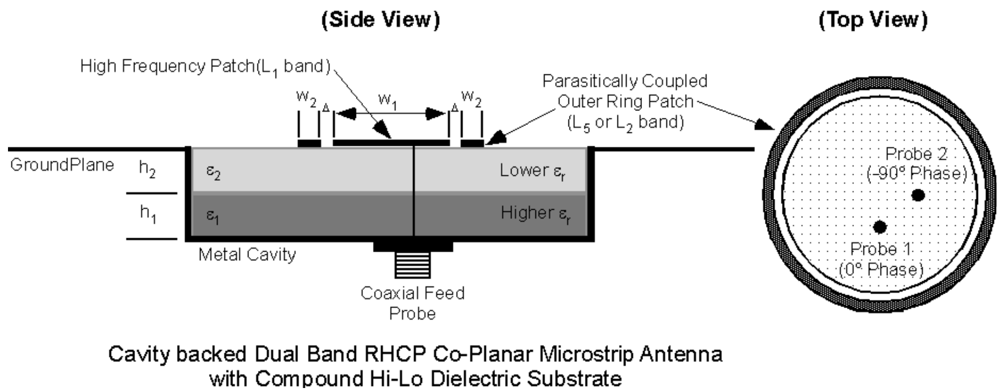


Figure 3(b). Co-Planar Dual-Band RHCP Patch Antenna Design With Metal Cavity Backing. Antenna is Flush Mounted Below the Ground Plane

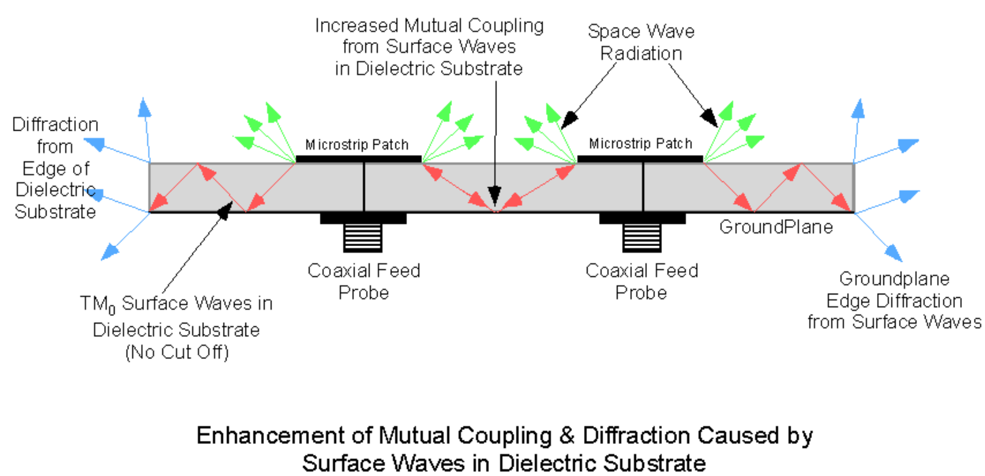
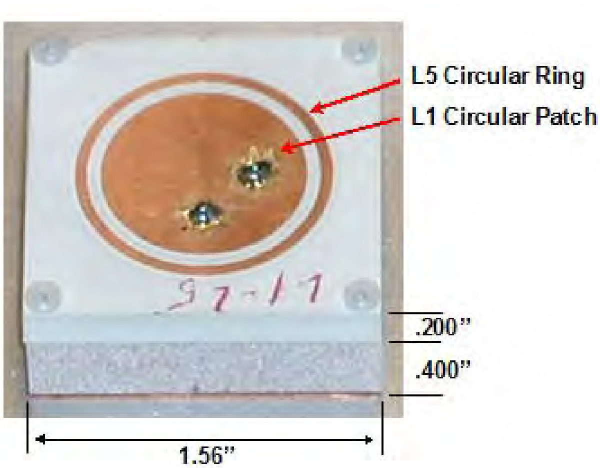


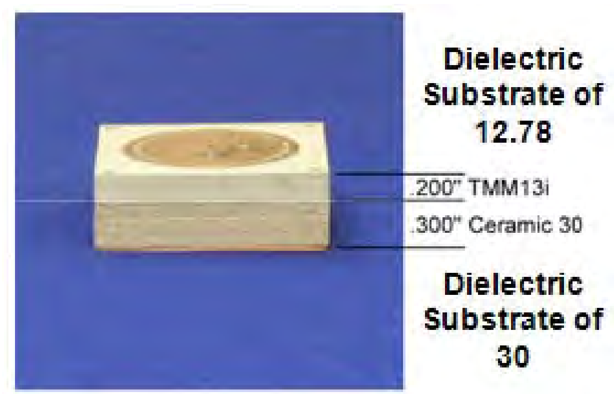
Figure 4. Mutual Coupling Between Adjacent Antenna Elements in a GPS Adaptive Antenna Array and Diffraction from Edge of Ground Plane Caused By Surface Waves in the Dielectric Substrate

CO-PLANAR L_1/L_5 ANTENNA FOR AVIONICS APPLICATIONS

A picture of co-planar dual-band antenna operating in the L_1 and L_5 bands for use in avionics systems using modernized GPS is shown in Figure 5. The diameter of the centrally located circular patch antenna is 0.9 inches. The inner and outer diameter of the outer annular ring patch antenna are 1.030 and 1.130 inches, respectively. The co-planar patches are located on top of a multi-layer dielectric substrate, the top layer of which is 0.2 inches thick and is made from Roger's TMM13i material with a dielectric constant ε_r = 12.78; the bottom layer is 0.4 inches thick and is made from a ceramic material with a dielectric constant ε_r = 30.0; this ceramic is made by the Emerson-Cummings Corporation. The substrate is 1.56 inches square. Figure 6 shows the measured return loss of this antenna showing good dual-band resonances in the GPS L_1 and L_5 bands. Figure 7 shows the measured RHCP and LHCP elevation plane patterns for this antenna at f_c = 1.176 GHz, 1.164 GHz, and 1.188 GHz, respectively; these three frequencies correspond to the center frequency f_c of the GPS L_5 band and f_c ± 12 MHz. Note that band edge frequencies where the patterns were measured are even wider than the 20 MHz bandwidth required by the L_5 band. The patterns were measured at two different azimuth angles at 0 and at 90 degrees in the Near Field antenna range at The MITRE Corporation. The antenna under test was mounted at the center of a rolled edge ground plane 51 inches in diameter. These measured patterns are a good indication of the wide pattern and axial ratio bandwidths provided by this antenna design. Figure 8 shows the measured gain profile of this antenna versus elevation angle at 1.176 GHz. The corresponding gain limits at both low and high elevation angles imposed by RTCA/DO-292 are also shown in this figure; this requires the antenna to have a minimum RHCP gain of +1 dBic from zenith down to an elevation of 25 degrees; in addition, the antenna should have a minimum gain of -5.5 dBic at an elevation of 5 degrees. The antenna seems to meet these gain requirements as shown in this figure. Figure 9 shows the measured RHCP and LHCP patterns at 1.575 GHz, the center frequency of the GPS L_1 band and at the two band edge frequencies of 1.587 GHz and 1.563 GHz, respectively. Figure 10 shows the measured gain profile of this antenna versus angle at 1575 MHz. The corresponding gain limits imposed by RTCA/DO-228 are also shown in this figure for comparison. Note that the antenna meets the gain requirement of -4.5 dBic at an elevation of 5 degrees.



Top View



Side View

Figure 5. Top and Side Views of the L_1/L_5 Co-Planar RHCP Microstrip Avionics Antenna

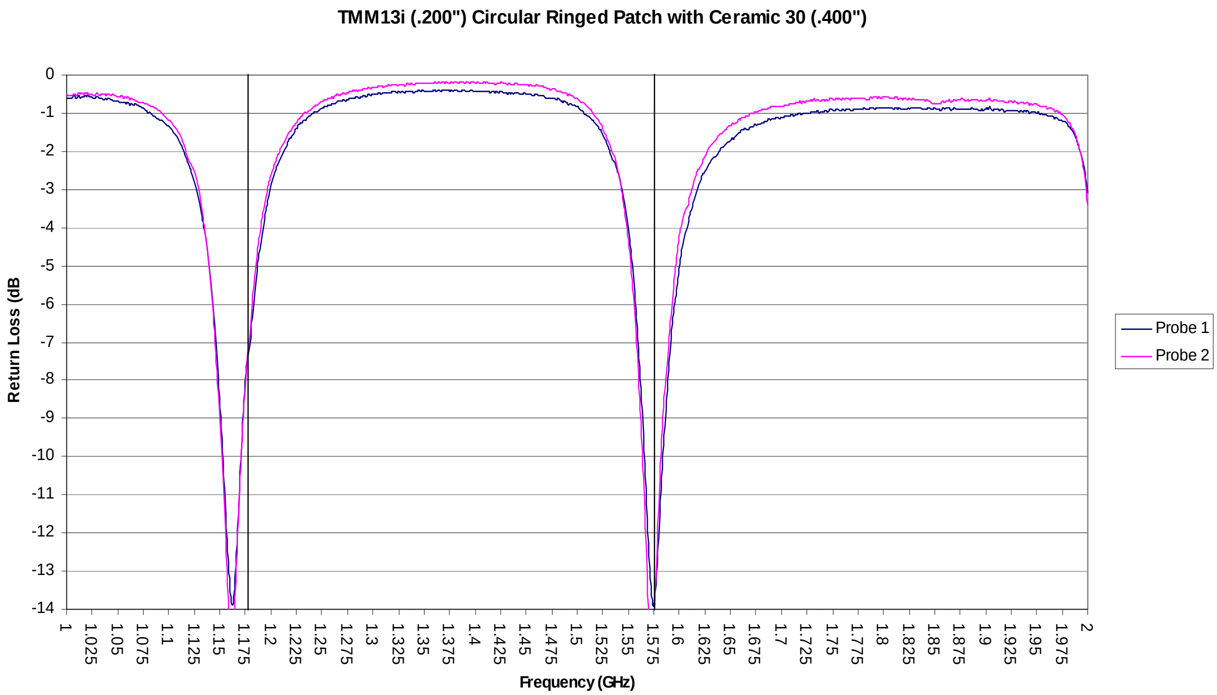


Figure 6. Measured Return Loss of the L_1/L_5 Co-Planar Microstrip Avionics Antenna

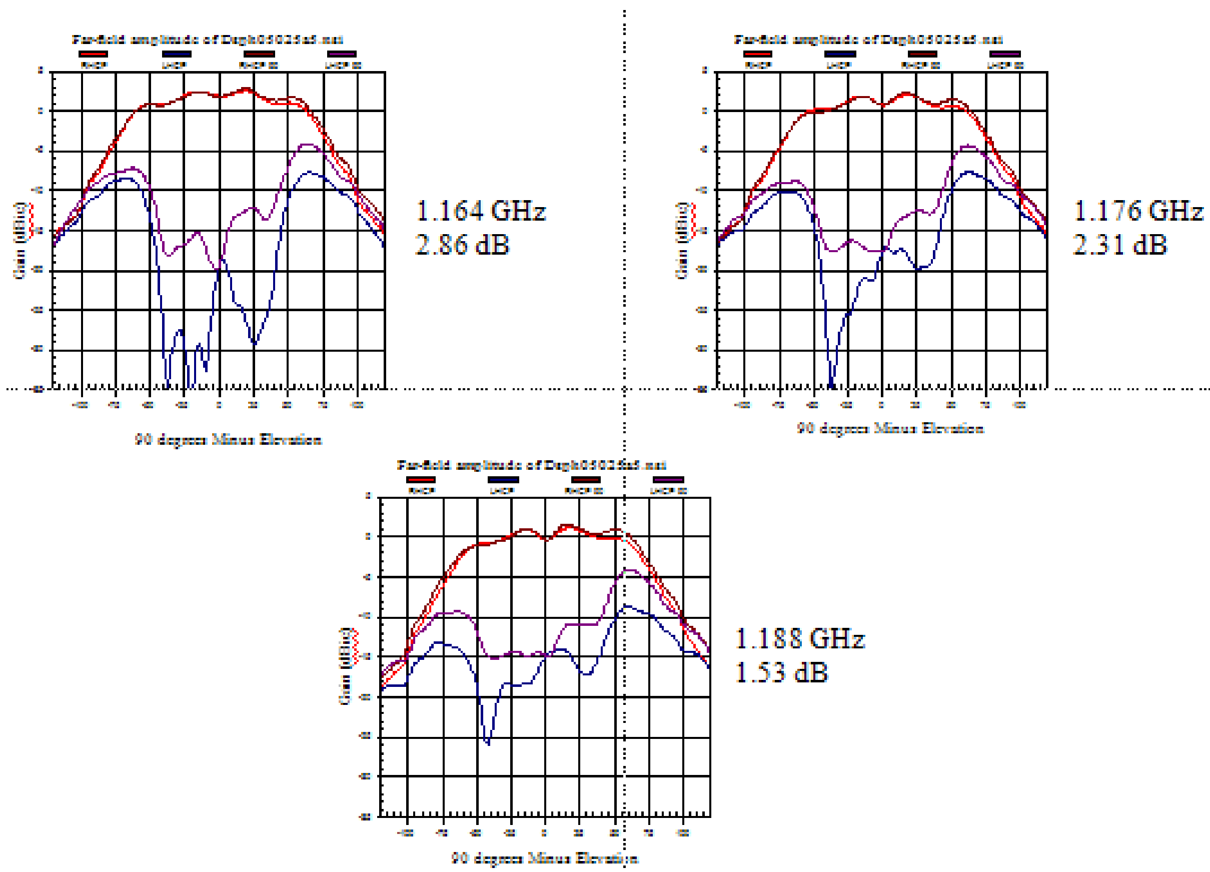


Figure 7. Radiation Pattern of L_1/L_5 Co-Planar Microstrip Avionics Antenna Measured at Frequencies of 1.164, 1.176, and 1.188 GHz

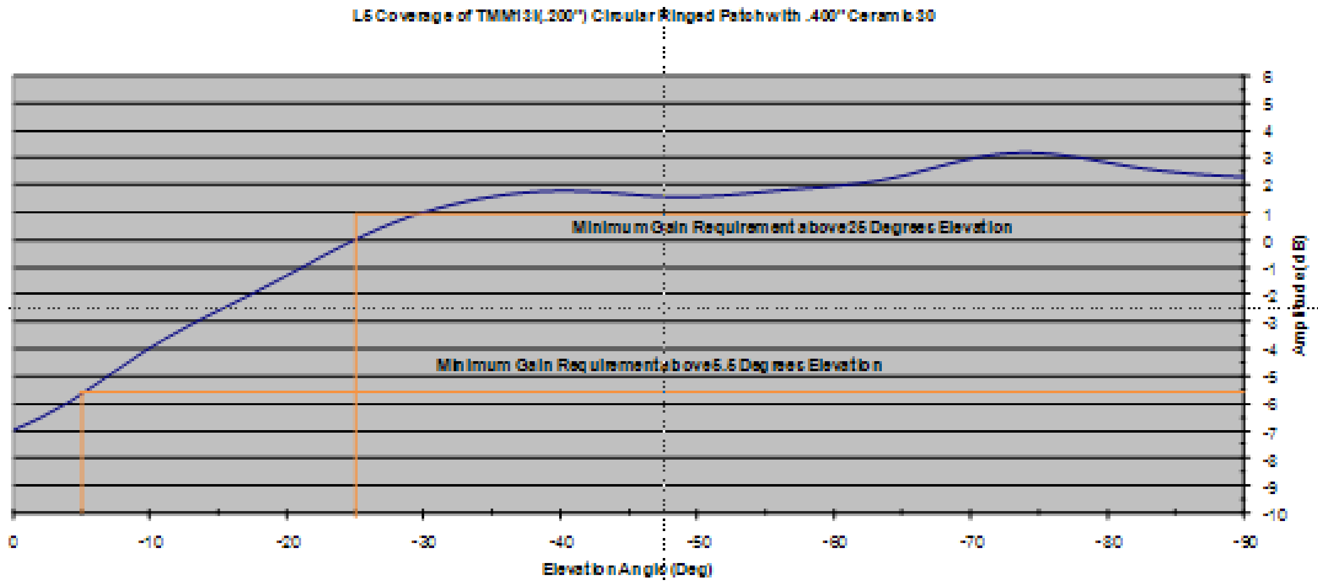


Figure 8. RHCP Gain versus Elevation Angle of L_1/L_5 Co-Planar Avionics Antenna Measured at a Frequency of 1.176 GHz and Comparison with RTCA/DO-292 Gain Requirements

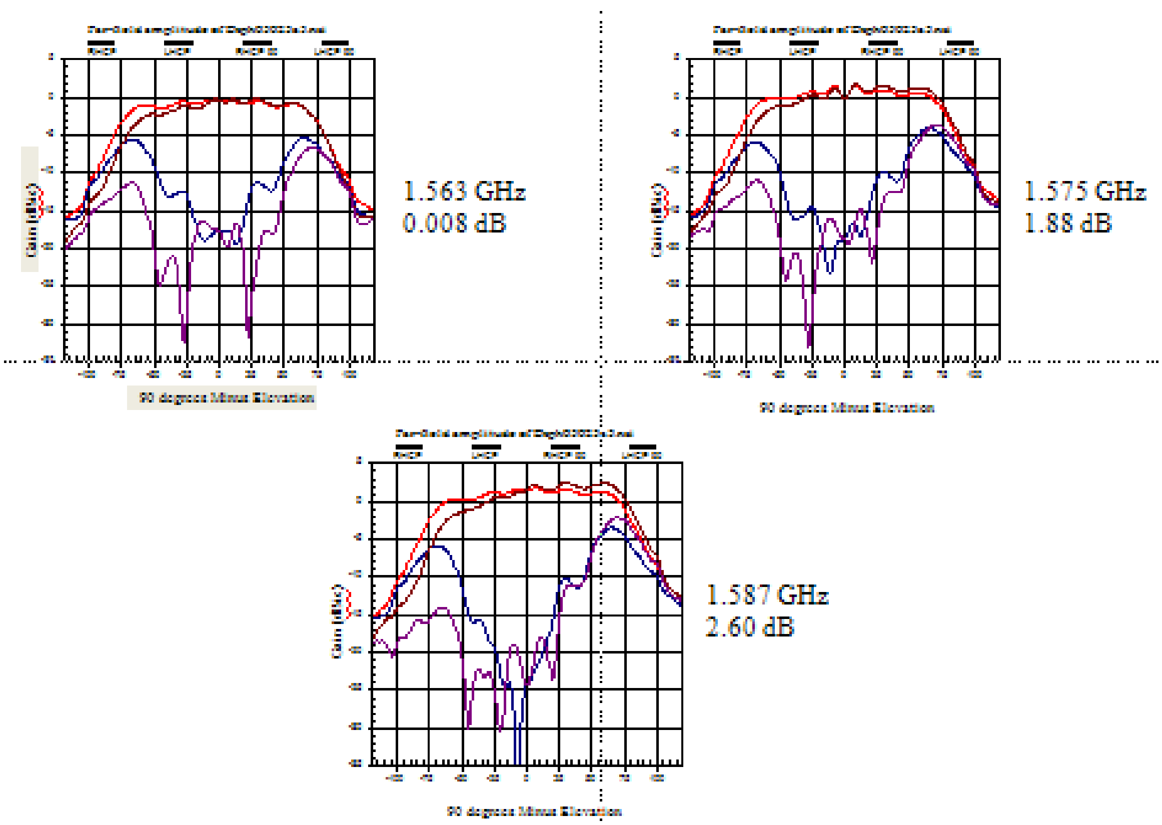


Figure 9. RHCP Gain versus Elevation Angle of L_1/L_5 Co-Planar Microstrip Avionics Antenna Measured at Frequencies of 1.563 GHz, 1.575 GHz, and 1.587 GHz

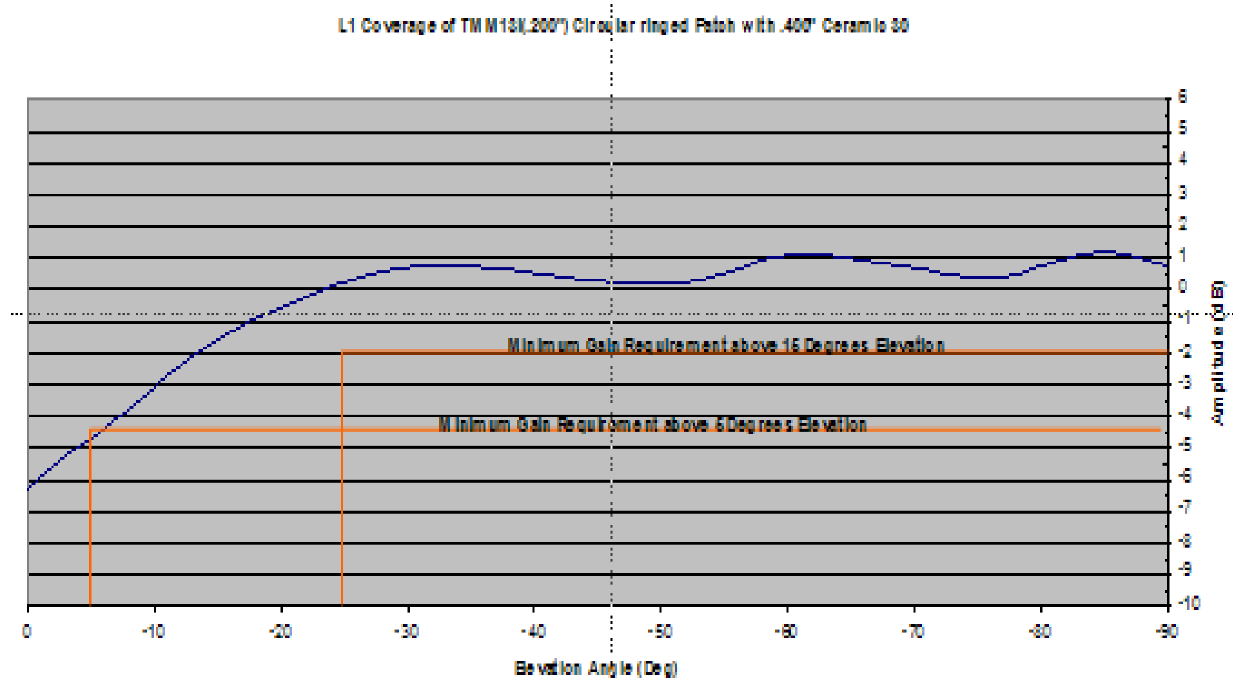
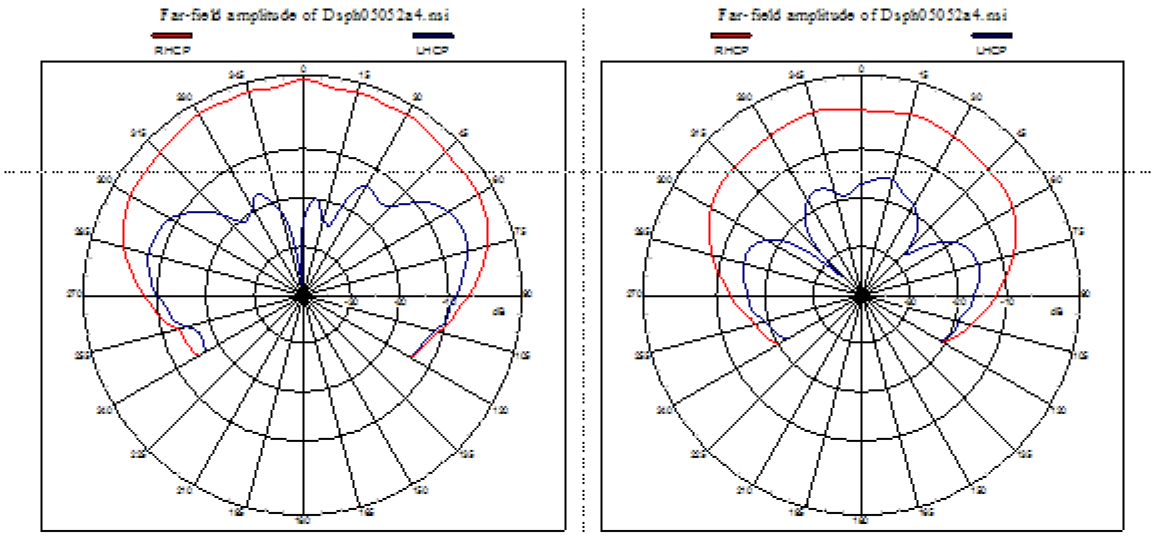


Figure 10. RHCP Gain versus Elevation Angle for L_1/L_5 Co-Planar Microstrip Avionics Antenna Measured at 1.575 GHz and Comparison with RTCA/DO-228 Gain Requirements

CO-PLANAR CAVITY BACKED L_1/L_2 MICROSTRIP ANTENNAS FOR MILITARY SYSTEMS

Figure 11 shows a picture of an antenna with the second type of design. It is a co-planar, L_1/L_2 dual-band microstrip antenna located inside a square shaped metallic cavity that is flush mounted inside the ground plane. The cavity is a 1.63-inch square and 0.6 inches deep – the same as the thickness of the dielectric substrate used in the patch antenna. The antenna uses a multi-layer dielectric substrate similar to the one previously shown in Figure 5. The top layer of the substrate is 0.2 inches thick and made from Roger's TMM 13i with a dielectric constant of 12.78. The bottom layer of the substrate is made from a ceramic material and is 0.4 inches thick; it has a dielectric constant of 30. The substrate is a 1.56-inch square. Figure 12 shows the measured elevation plane patterns for RHCP and LHCP of this antenna; the frequency of measurements was near the center band frequencies of the L_1 and L_2 frequency bands. Figure 13 shows this antenna being used as an antenna element inside a flush mounted adaptive antenna array consisting of the four antenna elements. The array aperture is approximately a 3.5 inch square, but is entirely level with the top surface of the ground plane mounting bracket. This illustrates the advantages of this antenna design; it allows the entire GPS array of four elements to be flush mounted. This antenna design is especially attractive when multi-element GPS adaptive antenna arrays are installed in tactical military platforms, since it has minimal impact on aerodynamic drag.

Figure 11. Picture of Cavity Backed Co-Planar L_1/L_2 Microstrip Antenna Element for Miniaturized GPS Adaptive Antenna Array



L_1 Band **L_2 Band**

Figure 12. Radiation Pattern of Co-Planar L_1/L_2 Microstrip Antenna with Metal Cavity Backing Measured Near the Center Band Frequencies of the GPS L_1 and L_2 Bands

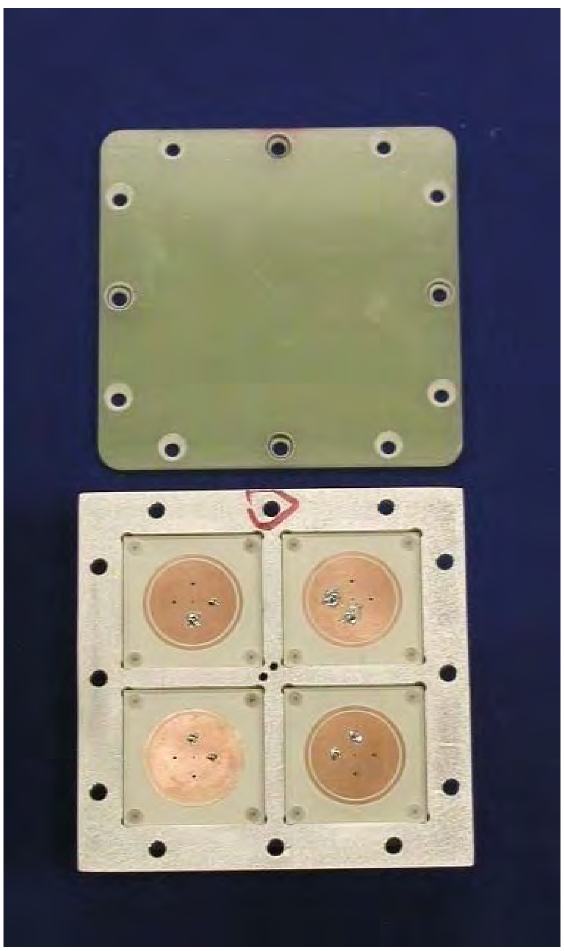


Figure 13. Flush Mounted Four-Element Array of Cavity Backed Co-Planar Dual-Band Patch Antennas

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2. "Minimum Operational Performance Standards for the Global Navigation Satellite System (GNSS) Airborne Antenna Equipment," RTCA/DO-228, RTCA, Inc., Washington D.C., October 20, 1995, pp. 6-7.

3. "System for a Co-Planar Dual-Band Microstrip Patch Antenna," U.S. Patent 7,385,555, June 10, 2008.