Single-Element GNSS Patch Antenna Pattern Control

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This thesis titled
Single-Element GNSS Patch Antenna Pattern Control

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ABSTRACT

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Single-Element GNSS Patch Antenna Pattern Control

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Several Global Navigation Satellite Systems are including the L5 frequency to add additional services. The RTCA Subcommittee 159 (SC-159), World Group (WG-7) is involved in this process and has concerns about the impact that asymmetric ground planes (i.e., aircraft fuselage structures) may have on the performance of the GNSS antenna, most notably the radiation pattern and axial ratio (AR). In this thesis two techniques were investigated to control both radiation pattern and AR of an L5 antenna. To control the radiation pattern a four-fed circular patch antenna was modeled and simulated using a high-fidelity computational electromagnetic model (CEM). Phase and amplitude manipulation of the feeds were used to control the radiation and AR characteristics. This approach has a major advantage by controlling the radiation characteristic to allow for isolation of interfering signals. Control over the asymmetry of a rectangular patch antenna improves the AR on an asymmetrical rectangle ground plane. Several different patch and ground plane shapes were used to demonstrate these advantages: 1) a circular patch antenna with a circular ground plane, and 2) a rectangular patch antenna (element and substrate) with a rectangular ground plane.
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<td>LHCP</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GNSS</td>
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<td>dB</td>
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<td>dBi</td>
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1 INTRODUCTION

Patch antennas are used all over the world, including many communications, navigation, and surveillance systems. They are used in many different devices and are very popular in cell phones, aviation, and automobiles. Patch antennas are also commonly used in Global Navigation Satellite Systems (GNSS). The importance of patch antennas for this functionality should not be downplayed. GNSS patch antennas allow our world to have easy access to navigation via its small size, which could fit in one’s hand, and ease of fabrication. Due to the importance of these antennas it is perforable to improve their performance whenever possible.

Patch antennas are being modernized in civil aviation, were issues degrading the performance of these antennas are being discussed by various organizations. The Radio Technical Commission for Aeronautics Sub Committee (SC) 159, Working Group (WG) 7 helps establish standards for GNSS antennas in the aviation industry. An issue they have concern about is the negative effect an asymmetric ground plane (i.e., the aircraft body) has on the radiation characteristics of the GNSS antenna. It is the goal of this thesis to investigate and research various ways to control the radiation pattern and axial ratio (AR) for a single-element patch antenna to improve performance.
2 BACKGROUND

2.1 GNSS

GNSS is a general term for a satellite navigation system, which may include references to the United States Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the European Galileo satellite navigation system, or other countries satellite navigation satellite system. All GNSSs use multiple frequencies to overcome the delay effects caused by the ionosphere. GPS uses two primary frequencies to provide user position, L1 at 1575.42 MHz and L2 at 1227.60 MHz (Global Positioning Systems Directorate Systems Engineering & Integration, 2012), and is being modernized to include L5 at 1176.45 MHz (Global Positioning Systems Directorate Systems Engineering & Integration, 2014). The L1 signal, in a general sense, is often used to broadcast information about a satellite, while the L2 signal is usually used to remove user position error caused by the ionosphere. Signals consist of three main parts, a Binary Phase Shift Key (BPSK) modulated signal, a code division multiple access (CDMA) code that identify the satellite and helps the receiver estimate a range to the satellite, and the navigational data encoded onto the satellite signal, which is used to help the receiver calculate the satellite’s and user positions (Misra & Enge, 2004).

For civil aviation, the introduction of the L5 frequency at 1176.45 MHz with a wideband L5 CDMA code is planned for safety critical applications and the performance is careful scrutinized. The L5 frequency is in the general aviation frequency bandwidth, and planned for civil aviation use by GPS and the European Galileo (Space Engineering
S.p.A., 2014). New standards are being written for a dual-frequency (L1&L5) antenna in order to accommodate these aviation demands.

2.2 Standards

2.2.1 RTCA


The RTCA is in the process of updating the aviation standards to include the modernizing aspects of GPS and inclusion of the L5 frequency for GNSS, which will specify L1 and L5 performance specifications. The RTCA SC-159, WG-7 is working with the European community to synergistically develop and updated GNSS active antenna performance specification that will be suitable for GPS and Galileo operations. While at the time of this thesis, RTCA WG-7 has not drafted its own dual-frequency (i.e., L1&L5) GNSS active antenna specification, the European MOPS is being used as a
working copy of a draft RTCA MOPS, which is used as a basis for this research (Space Engineering S.p.A., 2014). Throughout this document, reference to the “draft MOPS” is reference to this draft European lead document, which is currently being used as a preliminary draft of an eventual RTCA dual-frequency active GNSS antenna MOPS. In the WG-7 investigation to specify dual-frequency L1 & L5 patch antenna performance, they would like to address the antenna performance asymmetry caused by asymmetric ground plane installations that are typical when the antenna is mounted on top of an aircraft fuselage (i.e., an asymmetric ground plane).

The radiation characteristics (i.e., radiation pattern and AR) of a new GNSS antenna for aviation must meet certain requirements in accordance with the draft MOPS (Space Engineering S.p.A., 2014). The azimuth and elevation angles are specified in increments of 3 and 1 deg, respectively (Space Engineering S.p.A., 2014). The radiation requirements are generally measured with a constant azimuth angle and varying elevation angles. The requirements state that the gain is normalized over the strongest gain in the radiating pattern. The maximum gain allowed at elevation angle 0.0 deg is 0.0 dBi, and the minimum is -2.5 dBi (Space Engineering S.p.A., 2014). At the lower elevation angle of 90 deg the maximum allowed gain is -7 dBi and the minimum gain is -11 dBi (Space Engineering S.p.A., 2014). These requirements will ensure an antenna has good uniform coverage in the upper hemispheres.

The draft MOPS states that when the antenna is placed on circular ground plane with a diameter of 1200 mm, it must be able to receive a Right Hand Circular Polarized (RHCP) signal with an AR of 3 dB at its bore sight or better (Space Engineering S.p.A.,
From the requirements it can be seen how important the AR is for the antenna and how the ability to improve the AR would be useful. When placed on an actual airplane the ground plane will be asymmetric and with a varying shape, which will affect the AR negatively (Zheng & Shen, 2007).

The draft RTCA MOPS also states other minimum performance specifications that address return loss and bandwidth (Space Engineering S.p.A., 2014). The return loss of the antenna must be at the most -14 dB throughout the whole bandwidth, with the voltage source having a 50 ohm impedance (Space Engineering S.p.A., 2014). The bandwidth of the antenna with respect to L5 must be 24 MHz (Space Engineering S.p.A., 2014). The bandwidth will be determined by the smallest and largest frequencies that have a return loss of -14 dB or less (Space Engineering S.p.A., 2014). The -14 dB is equivalent to a 1.5:1.0 VSWR. The RTCA is not the only standard that an antenna must comply to.

2.2.2 ARINC

Other standards exist that the GNSS antenna may have to comply with regarding mounting, i.e., “the ARINC footprint” for mounting a GNSS antenna on an aircraft (Airlines Electronic Engineering Committee, 2001). The patch antenna must have a mounting ground plane that is 11.94 cm by 7.37 cm (Airlines Electronic Engineering Committee, 2001). This is an asymmetrical ground plane, which will have an effect on the performance of the antenna. The height of the antenna above the bottom of the ground plane cannot exceed a height of 1.90 cm. Current single-frequency GNSS L1 antennas satisfies these requirements (NovAtel, Inc., n.d.).
To support dual-frequency and wide bandwidth operations, typically the height of
the antenna increases. Designing dual-frequency patch antennas that meet the ARINC
standard becomes more difficult, because the most common techniques in making a dual-
frequency patch is to stack two patches on top of one another, and for increased
bandwidth, the height of the patch antenna is typically increased. This means that the
allotted maximum height above the bottom of the ground plane, 1.90 cm, is a hurdle to
overcome. The other lateral dimension requirements, length and width must also be met,
but are not as restrictive as the height requirement for wideband dual-frequency patch
antennas.

The ARINC specification (Airlines Electronic Engineering Committee, 2001) also
specifies a relatively large ground plane structure that can be used to test performance of
a GNSS antenna on an emulated surface. This large ground plane structure is curved,
with a radius of 243 cm, and a length of 213 cm meters. This curved ground plane surface
is a good representation to emulate a larger aircraft fuselage; however, this surface is very
large electrically, when compared to the wavelength of the GNSS signals and the
physical size of the GNSS patch antennas. Hence, this large curved ground plane is
difficult to simulate in a computational electromagnetic model (CEM) and increases
simulation times substantially.

2.3 Patch Antennas

2.3.1 Basics of Patch Antenna

Patch antennas in their most simple form can be broken down into four parts:
patch or radiating element, substrate, feed, and ground plane (Balanis, Microstrip
This discussion of patch antennas will focus on patch antennas where the physical dimension in a given direction is half-wave. A patch antenna operates by applying a time varying electrical excitation via a feed with radiation produced at the edges of the patch antenna. (Due to the Theory of Reciprocity, we can consider the characteristics of a transmission and reception antenna equally.) Current will then move across the patch (Pozar, 1992). The distribution of the current will not be even, with the current peaking in the middle of the patch and the current at the edge of the patch being zero (Orban & Meronaut, 2009; Watkins, 1969). The voltage across the antenna is critical because patch antennas are classified as an E field antenna, where the electric fields produce the radiation (Derneryd, 1979). Voltage, like the current, will not be uniform among the patch, it will be zero in the middle and at its highest value on the edges (Orban & Meronaut, 2009). Opposite edges will have opposite polarities as the feed source(s) cycle through its frequency. As the voltage increases and decreases, the electron density on the edges will increase (Orban & Meronaut, 2009). This will have the effect of fringing of electric field lines, and it is this fringing that is responsible for radiation of the patch (Balanis, Microstrip Antennas, 2005). Many of the characteristics discussed can be modified by changing the four basic parameters of a patch antenna (i.e., patch or radiating element, substrate, feed, and ground plane).
2.3.2 Patch Antenna Physical Shape

2.3.2.1 Rectangle Patch Antenna

The two popular forms of patch antennas are the rectangle and circle. Some other unique shapes also exist such as diamonds (Yun, 2008). Rectangular patches are in general the most popular, mostly due to their ease of fabrication and easy modeling with transmission line theory. Various polarizations can also be supported with single or multiple feeds. Rectangular patches have higher gain in their radiation pattern and better radiating efficiency when compared to a circular patch (Nayna, Baki, & Ahmed, 2014). They also have better return loss, lower Voltage Standing Wave Ratio (VSWR) (Nayna, Baki, & Ahmed, 2014). The length and width of the antenna are determined by the design requirements of an antenna.

The length of the radiating element controls at what frequency the patch antenna will resonate. For a half-wave patch antenna, in the simplest form the larger the patch element the lower the resonant frequency, and the smaller the patch element the higher the resonant frequency (Balanis, Microstrip Antennas, 2005; Orban & Meronaut, 2009). An approximation of this relationship is that the length of the patch should be about half the size of the wavelength in the dielectric substrate material (Pozar, 1992; Orban & Meronaut, 2009). The material that makes up the substrate will have a relative permittivity ($\varepsilon_r$), which has the effect of reducing the wavelength of electromagnetic waves within the material (Balanis, Microstrip Antennas, 2005; Orban & Meronaut, 2009). The fact that higher permittivity decreases the wavelength allows for a smaller patch to be used (Balanis, Microstrip Antennas, 2005). The substrate material can also
cause an increase in the fringing, with higher $\varepsilon_r$ causing more fringing (Balanis, Microstrip Antennas, 2005; Pozar, 1992). High amounts of fringing will have the effect of decreasing the resonate frequency of an antenna (Balanis, Microstrip Antennas, 2005; Pozar, 1992; Dahele & Lee, 1983). There is evidence that suggests that fringing can be increased by increasing the thickness of the substrate (Dahele & Lee, 1983). This will have the effect of decreasing the resonate frequency of the patch antenna (Dahele & Lee, 1983). Using the information discussed above, the length of a patch antenna for a given frequency can be found using the transmission line model.

The transmission line model assumes that the patch acts like a microstrip transmission line (Pozar, 1992; Craver & Mink, 1981). The antenna’s fringing and height are calculated using the same equations used for a matched transmission line. This model assumes that some electrical field lines will pass out of the dielectric and into empty space (Pozar, 1992; Craver & Mink, 1981). Because of this the permittivity will not strictly be the relative permittivity of the material it will instead have an effective permittivity ($\varepsilon_{\text{reff}}$). The effective permittivity or reference permittivity is affected by the width of the patch and the height of the substrate. If it can be assumed that the width is greater than the height of the patch then the reference permittivity can be described by equation (1) (Balanis, Microstrip Antennas, 2005).

$$
\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \left( \frac{h}{W} \right) \right]^{-1/2} \quad (1)
$$

Where $h$ and $W$ are the substrate height and patch width respectively. Using equation (1) we can then calculate the length by which the fringing increases the length of the antenna by equation (2) (Balanis, Microstrip Antennas, 2005).
ΔL = 0.412 \left( \frac{W}{h} + 0.264 \right) \frac{\varepsilon_{reff} + 0.3}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} (2)

The additional length by which one radiating slot increases the length of the patch, ΔL, can now be solved for and calculated. Since there are two radiating slots, the length of the patch will increase electrically by 2ΔL (Balanis, Microstrip Antennas, 2005). Using the information gathered via equations (1) and (2), the physical length of the rectangular patch can finally be calculated using equation (3) (Balanis, Microstrip Antennas, 2005).

\[ L = \frac{1}{2f_r \sqrt{\frac{\varepsilon_{reff}}{\varepsilon_0 \mu_0}}} - 2\Delta L \] (3)

Where \( f_r \) is the resonant frequency of the patch, and \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and permeability of free space respectively. While this model is simple to calculate, its accuracy is limited to rectangle patch antennas due to it not accommodating curved edges (Craver & Mink, 1981).

2.3.2.2 Circle Patch Antenna

The other popular form of a patch antenna is the circular patch antenna, which has unique polarization properties due to its symmetry, and tends to have good beamwidth and return loss bandwidth when compared to a rectangle patch antenna. Circular patch antennas do not have the benefit of being circular polarized via one feed, the feed placement on the circumference of the patch will generate linear polarization, regardless of where it is placed; thus, requiring that a minimum of a second feed be added to create other polarizations. However, some studies have been conducted that use one probe feed
but add some elements in the substrate in order to induce circular polarization (Khaleghi, 2008). The beamwidth of a circular patch antenna is wider than that of a rectangular patch, it also has better side lobe suppression (Nayna, Baki, & Ahmed, 2014). Despite this a rectangle patch will have a greater maximum gain (Nayna, Baki, & Ahmed, 2014). A rectangle patch also has the advantage of a minimum return loss and VSWR that is less than that of a circular patch, yet a circular patch’s bandwidth of these values is wider (Nayna, Baki, & Ahmed, 2014). If a matching network is used on a circular patch, then it would have a much better bandwidth than that of a rectangular patch antenna (Nayna, Baki, & Ahmed, 2014).

The radius of a circle antenna has not been determined by the simple transmission model, but instead the more accurate cavity model has been used. The cavity model assumes that the antenna acts as a wave guide with its upper and lower walls as the top patch element and the bottom ground plane; the side walls are the magnetic fields generated by the current in the patch (Balanis, Microstrip Antennas, 2005; Pozar, 1992; Craver & Mink, 1981). The patch antenna is modeled as a lossy waveguide, and it is this loss that acts as radiating element in the circuit (Balanis, Microstrip Antennas, 2005; Pozar, 1992). Because the antennas signal is modeled as a waveguide it is assumed that there are no fringing fields involved in the antenna (Pozar, 1992). Equation (4) (Balanis, Microstrip Antennas, 2005) can used to determine the radius of a circular patch antenna.

\[
a = \frac{F}{\left(1 + \frac{2h}{\pi \varepsilon_r F} \ln \left(\frac{\pi F}{2h} + 1.7726\right)\right)^\frac{1}{z}}
\]
\[ F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}} \]  \hspace{1cm} (5)

Where \( a \) the radius of the patch is in cm, \( h \) is the thickness (i.e., height) of the patch in cm, \( f_r \) is the frequency to be tuned to and \( \varepsilon_r \) is the substrate relative permittivity being used in the patch. The cavity model is accurate for smaller (i.e., thin) substrates, up to around 0.02 times the free space wave lengths, as the larger the model becomes, the less accurate it becomes (Schaubert, Pozar, & Adrian, 1989). One advantage of using a circular patch antenna over a rectangular patch antenna is that a wider bandwidth can be supported with more uniform coverage in the upper hemisphere (Nayna, Baki, & Ahmed, 2014). However, the circular patch antenna has a disadvantages over a rectangular patch antennas in that they are slightly more difficult to fabricate.

2.3.3 Electric Excitations

The method of electrical excitation of a patch antenna are highly diverse. Typical electrical excitation methods come in three primary types: probe fed, microstrip edge fed, and aperture fed (Pozar, 1992). Probe feed electrical excitation was used in this research, and will be concentrated on for the remainder of this document.

2.3.3.1 Probe Feed

The probe fed method consists of an electric wire penetrating up through the bottom of the ground plane, then through the substrate, and then making contact on the patch element on top of the antenna. The hole on the ground plane of the patch antenna should be large enough in diameter for the probe not to touch the wall of the hole, and provide a 50 ohms impedance match at the antenna port. The wall of the hole acts as the return or the ground for the input terminal. The probe feed method often uses a coaxial
cable, with the center conductor of the cable as the probe feed, and the cable shield as the return attached to the ground plane. This method is easy to fabricate and to model, but has the disadvantage of increased reactivity due to the inductance of the exposed probe as the probe passes through the substrate (Pozar, 1992). The reactivity will increase as the length of the wire increases, and as the height (i.e., thickness) of the substrate material increases. Observations have shown that the relationship between the substrate and the feed can make probe feed patch antennas difficult to model once the substrate becomes 0.02 times the free-space wavelengths thick (Schaubert, Pozar, & Adrian, 1989). Many models, such as variants of the cavity model, do not take into account the existence of the probe. This often leads to variables being added in the model that are estimates of the effect of the feed (Schaubert, Pozar, & Adrian, 1989). The input impedance of a probe fed patch will decrease as it moves from the edge of the patch towards the center (Orban & Meronaut, 2009). The input resistance will be zero at the center.

2.3.4 Effect of Feed Placement

2.3.4.1 Input Impedance

The input impedance of the antenna is the impedance that is seen at the terminals of an antenna (Balanis, Antenna Theory: A Review, 1992) and is used to calculate the maximum possible power an antenna can radiate at a given frequency. The input impedance will have two parts, the real part and the imaginary part (Balanis, Antenna Theory: A Review, 1992). The real part or the resistance is associated with the amount of power that is radiated by the antenna (Balanis, Antenna Theory: A Review, 1992). The resonant frequency of the antenna is a fundamental characteristic that can be observed in
the real part of the input impedance, with the peak of the real impedance being at the resonate frequency (Craver & Mink, 1981). The imaginary part or reactivity is the capacitive or inductive part of the antenna (Balanis, Antenna Theory: A Review, 1992). A patch antenna’s reactivity alternates quickly between being inductive and capacitive near the resonate frequency of the antenna.

There are many different parameters that control the value of the input impedance. For a given substrate height, as the relative permittivity of the substrate material increases, so will the input impedance (Craver & Mink, 1981). Another characteristic that controls the impedance of a patch for all feed types is the location of feed with respect to the edge of the patch. The closer to the edge of the patch a feed is, the higher the input resistance of the patch (Lee, et al., 2005). The input resistance can be quite cumbersome to accurately calculate in many models, fortunately the simple transmission line model can calculate an approximation of the input impedance of a patch whose height is less than 0.01 time the free-space wavelengths using equation (6) (Balanis, Microstrip Antennas, 2005).

\[ R_{in}(y = y_0) = \frac{1}{2G_1 \cos^2 \left( \frac{\pi}{L} y_0 \right)} \]  \hspace{1cm} (6)

Where \( L \) the length of the patch, \( y_0 \) is the distance from the edge of the patch, and \( G_1 \) is the conductance on one of the radiation slots and is described using equation (7) (Balanis, Microstrip Antennas, 2005).

\[ G_1 = \frac{W}{120\lambda_0} \left[ 1 - \frac{1}{24} (k_0 h)^2 \right] \]  \hspace{1cm} (7)
Where $W$ is the width of the patch, $\lambda_0$ is the free-space wavelength, $k_0$ is the free-space wave number, and $h$ is the thickness of the patch substrate.

2.3.4.2 S11, Return Loss, Voltage Standing Wave Ratio

The quality of the impedance match between the antenna and input terminals can be characterized by the input impedance, the return loss, and VSWR. The return loss is related to the reflection coefficient at the antenna terminals. Thus, it is related to the input impedance of the antenna, and the transmission line that is connected to the antenna at the antenna terminals; this relationship is shown in equation (8) (Sadiku, 2010).

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S}$$

(8)

Where $\Gamma$ is the reflection coefficient at the antenna terminal, $Z_L$ is the input impedance of the antenna, and $Z_S$ is the impedance of the transmission line feeding the antenna, at the antenna terminal. As can be seen from equation (6), the lowest return is achieved when the input impedance and transmission line are “matched”, and since these values are complex, they must be the complex conjugate of one another. A perfect reflection coefficient would be 0. Converted to decibels the return loss can be expressed in dB format, as shown in equation (9) (Sadiku, 2010).

$$RL = -20\log_{10} |\Gamma|$$

(9)

When the waves that travel down the transmission line toward the antenna terminal are reflected due to a non-perfect impedance match, they are reflected back down the transmission line. These incident and reflected waves can be characterized as a standing wave in the transmission line which can be described, with respect to the voltages as the voltage SWR (VSWR). The VSWR is another measurement of the
quality of the impedance match between the antenna input terminal and the transmission line that feeds it. The VSWR can be calculated using the reflection coefficient as shown in equation (10) (Sadiku, 2010).

\[
VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}
\] (10)

A perfect VSWR is 1.0:1.0, which is often described as just “1”. In the process of designing and analyzing antennas the ideal values for input impedance (i.e., 50 \( \Omega \)) the return loss (i.e., -\( \infty \) dB) and VSWR (i.e., 1) will be used for measuring the quality of the antennas.

2.3.5 Radiation Pattern

The radiation pattern of a patch antenna tends to have good coverage in one hemisphere (i.e., the upper hemisphere) and low coverage in the opposite hemisphere (i.e., lower hemisphere). The coverage is typically omni-directional in the “horizontal” plane, and “mushroom shaped,” in the “vertical” plane. The coverage can be characterized by gain, which is derived from directivity and the radiation efficiency of the antenna. The directivity is defined by the IEEE Standard (IEEE Standard Definitions of Terms for Antennas, 2004) as “the ratio of the radiation intensity in a given direction from the antennas to the radiation intensity averaged over all directions.” The relationship between the gain, the directivity and the radiation efficiency is shown in equation (11) (Balanis, Microstrip Antennas, 2005).

\[
G(\theta, \phi) = e_{cd}D(\theta, \phi)
\] (11)

Where \( e_{cd} \) is the radiation efficiency and \( D(\theta, \phi) \) is the directivity in the direction the angles \( \theta \) and \( \phi \). A patch antenna with good efficiency typically has gain of around 4
to 6 dBi (Howell, 1975). The gain is generally highest at an elevation angle of 90 deg, which is on top of and normal to the radiating element; it is also in the center of the element. The radiation characteristics of a patch antenna can be affected by the shape, size, and configuration of the ground plane. The patterns beam can be brought more towards lower elevation angles by using a large ground plane.

Other steps have been taken to reduce the multipath and interference from lower elevation angles. One such strategy is to have a circular patch antenna with a hole in the middle, with the hole surrounded by grounding vias (Basilio, Chen, Williams, & Jackson, 2007). Probe feeds are placed inside the walled off hole (Basilio, Chen, Williams, & Jackson, 2007). This configuration will increase the minimal elevation angle of the radiation pattern and thus shield it from interfering sources on the horizon (Basilio, Chen, Williams, & Jackson, 2007). Another strategy is to short out the patch using switching diodes. Diodes are placed on the edges of the patch and when enabled will short the patch preventing low elevation angles from being received (U.S. Patent No. 6 930 639 B2, 2005).

The radiation characteristics can also be changed for a circular patch antenna using higher order modes and multiple feeds (Huang, 1984); four probe feeds with various symmetrical configurations were used, along with higher order modes, to change the beam and create conical patterns for a patch antenna (Huang, 1984). However, the ability to change the beam is limited, because the beam can only be changed by physically changing the position of the feeds or using a different dielectric substrate in the patch.
2.3.6 Polarization

2.3.6.1 Basics of Polarization

Polarization is the orientation of the electromagnetic wave field vectors as it moves through space and time, as viewed as the wave travels away from the observation point (IEEE Standard Definitions of Terms for Antennas, 2004; Balanis, Microstrip Antennas, 2005). Elliptical polarization is the most general polarization, with circular and linear being specialized cases. Elliptical and circular polarized waves are either right hand or left hand polarized; this is often called the “sense” of the polarization. RHCP can be described mathematically as shown in equation (12) (Grewal, Andrews, & Bartone, 2013).

\[ E_{RHCP}(\theta, \phi) = \frac{E_{\theta} + jE_{\phi}}{\sqrt{2}} \]  

(12)

Where \(E_{\theta}\) and \(E_{\phi}\) are the spherical coordinate electric field vectors of a wave as it moves radially away from the antenna. Left hand circular polarization (LHCP) is described in equation (13) (Grewal, Andrews, & Bartone, 2013).

\[ E_{LHCP}(\theta, \phi) = \frac{E_{\theta} - jE_{\phi}}{\sqrt{2}} \]  

(13)

The polarization of a wave or antenna can be characterized by the AR, which is the ratio of the maximum electric field value over the orthogonal minimum electric field value. It is defined by IEEE Standard (IEEE Standard Definitions of Terms for Antennas, 2004) as “The ratio of the major to minor axes of a polarization ellipse.” The AR can be mathematically described by equation (14).
\[ AR = \frac{E_{\text{major}}}{E_{\text{minor}}} = \frac{E_{\text{RHCP}}(\theta, \phi) + E_{\text{LHCP}}(\theta, \phi)}{E_{\text{RHCP}}(\theta, \phi) - E_{\text{LHCP}}(\theta, \phi)} \]  

(14)

Where \( E_{\text{major}} \) and \( E_{\text{minor}} \) are the magnitude of the electrical field vectors in the semi-major and semi-minor axis. An antenna that has an axial ratio (AR) that is equal to 1 (i.e., 0 dB) has perfect circular polarization, while an AR of infinity would indicate linear polarization. Any AR in between these values would technically be considered elliptical polarization, but since perfect circular polarization is difficult, especially over a wide geometric volume, small AR values are still typically characterized as circular polarization.

2.3.6.2 Methods of Creating Circular Polarization for a Patch Antenna

Patch antennas can be designed to support circular polarization by feed location with single or multiple feeds. For a single-feed configuration, a common way to obtain circular polarization for a rectangular (i.e., nearly-square) patch is to have the feed offset among the Y and X axis of the patch (i.e., along the diagonal) (Lee, et al., 2005).

Another technique involves truncated edges on a rectangular patch antenna (Orban & Meronaut, 2009). The truncated edges are opposite of each other, while the other edges are left intact. These single-feed techniques work by creating a path difference between signals traveling inside the patch in orthogonal direction to the respective edges and creates circular polarization.

Single-feed patch antennas usually do not have the ability to change their polarization from left to right, yet there has been some research (Yun, 2008) that adds extra features to a single feed patch in order to gain circular polarization. This study uses a diamond antenna with incisions in the radiating element and switching elements in
order to produce a controllable circular polarization (Yun, 2008). There are two ports orthogonal to one another, only one port can be activated at a time via switching mechanism (Yun, 2008). The port that is enabled determines whether it is right or left circularly polarized.

A common way of creating a polarization is to use more than one feed for a perfectly square patch antenna. Two feeds will be placed in an orthogonal manner on the patch. One of the feeds will be 90 deg out of phase of the other when they are combined. This technique quite often provides a quality AR, but requires increased complexity in circuitry of the antenna, and will also require a hybrid combiner, to combine the two out of phase signals into one signal. This technique has the advantage of changing the polarization from left to right or vice versa, if designed into the combining circuitry.

2.4 Ground Plane Effect on Performance

One of the biggest factors on a patch antenna’s performance is the ground plane. The basic effects of the ground plane on antenna performance should be taken into account when designing antenna. The two types of ground planes that are of interest to this thesis are ground planes that are symmetric and/or asymmetrical.

2.4.1 Asymmetrical Ground Plane

Asymmetrical ground planes have been shown to have a negative effect on the AR of a patch antenna. Zhen and Shen have conducted studies to show that when a patch antenna is circularly polarized with a finite sized ground plane, it will perform well if the ground plane is symmetric with respect to the antenna (Zheng & Shen, 2007). Yet, if the ground plane is asymmetric, then it will have significant effects on the AR (Zheng &
Shen, 2007). The designing of the new GNSS patch antennas for aviation should reduce the effects of an asymmetric ground plane on an antennas AR.

2.5 Scope

This thesis investigates the performance of a GNSS L5 patch antenna to obtain control over the radiation characteristics. The first part of this investigation implements a four-feed circular patch antenna over a symmetrical circular ground plane for pattern control. The second part of this investigation implements a four-feed rectangular patch antenna (element or substrate) over an asymmetric rectangular ground plane to investigate the radiation characteristics and AR. Throughout this thesis, only single-frequency L5 patch antennas will be considered to investigate the performance aspects in the two areas listed above: 1) pattern control for circular patch antenna with circular ground plane, and 2) for rectangular patch over asymmetric rectangular ground plane. For all of these investigations, the CEM CST will be used.
3 METHODOLOGY

3.1 Design Discussion

3.1.1 Overview of Requirements

A GNSS antenna with L5 signal support was designed in a CEM CST considering aspects of the ARINC (Airlines Electronic Engineering Committee, 2001) and Draft RTCA (Space Engineering S.p.A., 2014) standards. The GNSS patch antenna would be able to support RHCP, with a maximum AR of 3 dB at boresight. The patch antenna must have a bandwidth of 24 MHz. The areas of the biggest concern were the radiation pattern and the AR of the antenna. The goal was to be able to control these aspects electrically if possible. The antenna also needed to be able to fit the ARINC foot print requiring the length be less than 11.94 cm, the width be less than 7.37 cm and that height be less than 1.90 cm (Airlines Electronic Engineering Committee, 2001). All parameters were designed to meet these requirements.

The ground plane size chosen for all simulations was on the order of 120 mm, which was a compromise between the small ARINC footprint, the large curved ARINC ground plane (Airlines Electronic Engineering Committee, 2001), and the 1200 mm draft RTCA (Space Engineering S.p.A., 2014). In particular, for all circular patch antenna simulations, the flat ground plane was of diameter 120 mm, and for the square patch antenna simulations the flat ground plane was 120 mm square, or 120 mm x 200 mm for the asymmetric simulations.
3.1.2 Analytical Design and Results

From the various theoretical models, analytical designs were performed for the circular patch antenna and the square patch antenna. Due to multiple feeds being able to create circular polarization and because studies had used extra feeds to control the far field (Huang, 1984), it was hypothesized that adding more feeds would allow for better control of the radiation pattern and the AR. It was also thought that a circle patch would help, as it would give a wider beamwidth and would eliminate any artifacts caused by the corners of a square patch. Initial testing showed it was possible to control the radiation pattern and steer the beam on a symmetrical antenna. It was also found that using a patch whose symmetry is related to the ground plane can improve the AR of an antenna. Both techniques were investigated in this thesis.

3.1.3 Circle Patch Antenna with Manipulated Phase

A circular patch with four feeds was modeled in order to control the radiation pattern in the azimuth. The control would be done by using the phase manipulation on the four different feeds. The goal would be for this patch to meet the draft RTCA (Space Engineering S.p.A., 2014) and ARINC (Airlines Electronic Engineering Committee, 2001) standards and operate at the L5 frequency for a given mode of operation. The parameters calculated for the analytical design of the circular patch antenna are shown in table 3.1.
3.1.3.1 Circle Patch Antenna with Manipulated Phase Shape Choice and Reasons

A circle patch was used for the azimuth control in hopes that it would eliminate variables that other shapes would present. The primary concern was the corners of a square patch or the asymmetry of a rectangle patch. A circular patch antenna allows the feed to be placed anywhere on the circumference of patch without negatively affecting the input impedance. A circle patch antenna have been known to have larger beamwidth (Nayna, Baki, & Ahmed, 2014).

Table 3.1

*Analytical Design Parameters for Circle Patch Antenna*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>Rogers TMM 10i</td>
</tr>
<tr>
<td>Substrate Relative Permittivity (unitless)</td>
<td>9.80</td>
</tr>
<tr>
<td>Substrate Height (mm)</td>
<td>5.08</td>
</tr>
<tr>
<td>Substrate Diameter (mm)</td>
<td>46.54</td>
</tr>
<tr>
<td>Feed position from center (mm)</td>
<td>10.0</td>
</tr>
<tr>
<td>Diameter of Circular Patch Element (mm)</td>
<td>46.54</td>
</tr>
<tr>
<td>Diameter of Circular Ground Plane (mm)</td>
<td>120</td>
</tr>
<tr>
<td>Circular Ground Plane Thickness (mm)</td>
<td>0.50</td>
</tr>
</tbody>
</table>
3.1.3.2 Circle Patch Antenna with Manipulated Phase Feed Choice and Location

Calculation

Four probe feeds would be used in order to give more control over the radiation characteristics of the antenna and create circular polarization. The four feeds were 90 deg apart physically on the patch at the same distance from the center. This was done to allow control in all azimuth angles. The feeding mechanism was a probe feed. It was used for its ease of being fabricated and easily being modeled and created in the available CEM. Any induction or losses generated by the use of a probe feed was assumed to be removed via a matching network.

The final positions of the feeds were to be determined experimentally, with the feeds initially being set 10.0 mm from the center of the patch. This position is an estimate and was chosen based upon other similar designs. The feeds locations were to be refined to achieve an input impedance of 50 ohms. A grounding probe was used in the center of the patch antenna in order to help stabilize the AR and protect the aircraft from lightning strikes.

3.1.3.3 Circle Patch Antenna with Manipulated Phase Length and Substrate

Calculations

The substrate of the patch would be thick to support a larger bandwidth; this thickness that was chosen was 5.08 mm, due to availability in the market. The substrate would be a specialized material with a high relative permittivity, this would reduce the size of the antenna allowing it to meet the ARINC (Airlines Electronic Engineering Committee, 2001) standard footprint, a patch no longer and wider than 119.38 mm and
73.66 mm. The substrate material used was the TMM 10i from the Rogers Corporation with a permittivity of 9.8.

The thickness of the patch element was infinitesimally small, this was done due to the thickness on most patch elements being on the sub-micrometers level, and such a thickness would have a similar effect as an infinitesimal thickness on the antenna. The initial diameter of the patch element was calculated analytically using equations (4) and (5) to be 46.54 mm, as listed in table 3.1 and then later refined experimentally using the CEM software. This approach was used due to thickness of the antenna being larger than 0.02 times wave lengths, where the cavity model becomes less accurate. There was also little research on how the length and feed placement will be affected by the existence of multiple feed probes in the substrate of the patch. During refinement with the CEM, the results would be viewed and the appropriate adjustments would be made to the model. This would be repeated and would stop once the patch resonates at 1176.45 MHz, the L5 frequency.

3.1.3.4 Circle Patch Antenna with Manipulated Phase and Circular Ground Plane

The circle patch would use a circle ground plane. This was chosen to avoid corners or asymmetries of a rectangle ground plane, which might have led to irregular performance. The diameter of the ground plane would be 120 mm. This make the distance from the edge of the ground plane to the patch to be more than twice the thickness of the patch’s substrate; a closer proximity of these two parameters would affect the input impedance.
3.1.3.5 Circle Patch Antenna with Phase Manipulation

The phase at each feed probe was to be manipulated and control the radiation characteristics. The feeds would be manipulated in a way that takes into consideration the movement of the waves throughout the antenna. These results would be further used to control the beam in the azimuth. This would be done by assigning all fours feeds similar phases. These results would be graphed and compared to a baseline feed configuration that produces RHCP.

3.1.4 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes

Rectangular patch antennas (both square and rectangular) designs with rectangular (both square and rectangular) ground planes would be simulated. Baseline configurations would be established for comparison. Square patch antenna models with symmetrical and asymmetrical ground planes would be simulated. The antenna would be designed to operate on the L5 frequency with the radiation characteristics of the draft RTCA (Space Engineering S.p.A., 2014) and ARINC (Airlines Electronic Engineering Committee, 2001) specifications in mind. In an attempt to improve the AR performance, adjustments would be made to the length and width of the radiating element and material substrate. In table 3.2 are parameters for analytical design of the square patch antenna, from equations (1), (2), (3), (6), and (7).
3.1.4.1 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes Shape

Choice and Reasons

In order to make the ground planes and the radiating element have a similar geometry, a square patch would be used as the radiating element. It was hypothesized that the distortion of the AR caused by the asymmetric ground plane was due to surface waves and phase delay. A square patch would be used because it was similar to the asymmetric ground plane’s shape and could possibly cancel out these imbalances.

Table 3.2

Analytical Design Parameters for Square Patch Antenna with Symmetrical and Asymmetrical Ground Plane

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>Rogers TMM 10i</td>
</tr>
<tr>
<td>Substrate Relative Permittivity (unitless)</td>
<td>9.8</td>
</tr>
<tr>
<td>Substrate Length (mm) x Width (mm) x Height (mm)</td>
<td>120 x 120 x 5.08</td>
</tr>
<tr>
<td>Feed position from center (mm)</td>
<td>4.7</td>
</tr>
<tr>
<td>Patch Element Length (mm) x Width (mm)</td>
<td>39.8 x 39.8</td>
</tr>
<tr>
<td>Symmetric Ground Plane Length (mm) x Width (mm) x Height (mm)</td>
<td>120 x 120 x 0.50</td>
</tr>
<tr>
<td>Asymmetric Ground Plane Length (mm) x Width (mm) x Height (mm)</td>
<td>120 x 200 x 0.50</td>
</tr>
</tbody>
</table>
3.1.4.2 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes Feed

Choice and Location Calculation

Four probe feeds would be used for all square patches. The feeds will be an equal distance away from the center of the patch and will be 90 deg apart physically. This feed configuration will allow for CP. Four feeds were shown in initial testing to produce a more symmetric radiation pattern, as well as a more symmetric AR. The feed type would be a probe. The probe feed type is easy to model and easy to use to tune the input impedance of the antenna. It is assumed that any reactance or mismatch caused by the probe feed will be removed via a matching network.

The final position of the feeds would be refined experimentally via simulations in CEM software, as the substrate thickness would be greater than 0.02 times the free-spaced wavelengths and because four feeds would be used; there is little research on the how multiple feeds effect feed placement. The feeds would be adjusted to have a 50 Ohm impedance at 1176.45 MHz, the L5 Frequency. The initial placement for the feeds will be 4.7 mm from the center of the patch. This position was calculated using equations (6) and (7). This antenna would also have a grounding probe in the center of the patch in order to stabilize the AR and for lighting strikes.

Once the appropriate feed position is found, the feed location will not be adjusted despite changes that will occur to other parameters. The position of the feeds will not be readjusted when the patch is placed on the asymmetrical ground plane. This is done so the effect the asymmetric ground plane has on the input impedance can be studied. When the dimension of the antenna element and substrate are being manipulated, the feed
location will not be adjusted, as this would add extra variables to account for in improving the AR.

3.1.4.3 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes Length and Substrate Calculations

The thickness of the patches’ substrate would be 5.08 mm. The reason for this choice is that this thickness will provide good bandwidth and a substrate of this thickness can be easily found on the market. The substrate would be composed of a material with a high permittivity in order to meet the ARINC (Airlines Electronic Engineering Committee, 2001) footprint, which requires that the patch antenna be longer than 11.94 cm and no wider than 7.37 cm. The chosen material will have a permittivity of 9.8, it is called TMM 10i, and was created by the Rogers Corporation.

The patch element thickness will have an infinitesimally small size, this was chosen because patch antennas tend to have thicknesses that are sub-micrometer in scale, having an infinitesimal thickness will have a similar effect as a sub-micrometer thickness. The length of the patch element would have to be determined experimentally due to the thickness of this patch, which is greater than 0.02 times the free-space wavelengths and due to the four feeds. Using equations (1), (2), and (3), the initial length of the patch was calculated as 39.8 mm. This initial length would be used in a CEM, which will simulate the antenna. After each simulation, the results will be viewed, the length of the patch element will be adjusted, and the simulation would be run again. This would continue until the patch resonates at L5 frequency, 1176.45 MHz.
3.1.4.4 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes

Ground Plane

The rectangular patch antenna would have two ground plane configuration. One would be a square/symmetrical ground plane, the other would be a rectangle/asymmetrical ground plane. The square ground plane would be the baseline ground plane configuration to compare to the rectangle ground plane. The far field ratio pattern produced by the square ground plane would be highly symmetric. The rectangle ground plane configuration would show how the radiation pattern and AR are affected by an asymmetrical ground plane. The square ground plane’s dimensions were to be 120 mm, which was chosen to be large enough to not affect the input impedance of the patch. The rectangle ground plane would be 120 mm by 200 mm. The 120 mm was used so the effect of the extension of just one dimension on the ground plane could be observed. The 120 mm dimension size was chosen so it would be near the length of the ARINC foot prints mounting plane.

3.1.4.5 Rectangular Patch with Symmetrical and Asymmetrical Ground Planes

Manipulation of Patch and Substrate Dimensions

Both the patch element and the substrates dimensions would be manipulated on a rectangular (square and rectangle) patch on a rectangular ground plane in order to improve the AR of the antenna. They would not be both manipulated at once, each dimension’s manipulation would be seen as a different technique to improve the AR. The substrate would be manipulated because the fringing would be changed, which would have a similar effect as changing the patches dimensions, and also because
substrate material have been shown to have an effect on surface waves. Several small changes to the dimensions of the substrate and patch would be made and then simulated. Once the data was collected, the two different techniques would be compared in the elevation and azimuth angles. They would also be compared to the baseline square antenna whose ground plane was asymmetric, in order to demonstrate an improvement.

3.2 Computation Electromagnetic Models

Since the invention of antennas building prototypes and testing the antennas have been time consuming and costly, but in modern times computer simulation can effectively be used to create and test prototype designs. In the electromagnetics and antenna area, these software simulations are called CEM. They can simulate the electromagnetic properties of antennas and nearby objects. The process of developing an antenna model is generally the similar across the available CEM software. Typically an antenna model is created in a Computer Automated Design (CAD) based environment with material properties assigned. The feed excitation is applied to the antenna model. After the model, with model excitation is completed, a grid system is applied to the model; this gridding system supports points in which the electric fields will be calculated across the grid. The simulation can be executed to produce simulation results. These investigations were performed using three separate CEM programs Remcom, Feko and CST. The experiments were finalized with CST.

3.2.1 CST

CST is very popular CEM and is heavily used in the market. Similar to Remcom (Remcom, 2015) and Feko (Feko, 2015), CST allows the user to build antenna models,
assigned the components within the antenna model materials, apply electric excitations, execute simulations, and produce results. CST was used for the experiment due to the accuracy it showed during initial results and because it’s wide spread use creates large quantities of documentation online. Both the circular patch antenna with circular configuration and the rectangular patch antenna with rectangular asymmetric geometry configurations were simulated in CST. Since the probe feed in the antenna was coming from a coaxial cable, it was concluded that the waveguide port should be used for excitation at each port. The waveport excitation operating principle will attempt to find the fundamental mode in relation to objects touching the waveguide. The waveguide port is accurate at simulating the fundamental modes in transmission lines, such as a coaxial cable. CST produces results for each excitation feed port independently and also allows the combination of data to produce far field radiation characteristics (i.e., pattern and AR).
4 ANTEenna cEM deSigns, reSultS & dISCUSSion

4.1 Circular Antenna and Far Field Pattern Control

4.1.1 Circle Patch on Circular Ground Plane

The circular patch antenna over a circular ground plane was tuned to achieve good performance at the L5 GNSS frequency, which was used to establish baseline (i.e., Baseline 1) performance data. The parameters and dimensions of this final antenna design are shown in table 4.1.

Table 4.1

*Final design parameters of circular patch antenna-baseline 1*

<table>
<thead>
<tr>
<th>Property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>Rogers TMM 10i</td>
</tr>
<tr>
<td>Substrate Relative Permittivity (unitless)</td>
<td>9.8</td>
</tr>
<tr>
<td>Substrate Height (mm)</td>
<td>5.08</td>
</tr>
<tr>
<td>Substrate Diameter (mm)</td>
<td>50.25</td>
</tr>
<tr>
<td>Feed position from center (mm)</td>
<td>10.75</td>
</tr>
<tr>
<td>Diameter of Circular Patch Element (mm)</td>
<td>50.25</td>
</tr>
<tr>
<td>Diameter of Circular Ground Plane (mm)</td>
<td>120</td>
</tr>
</tbody>
</table>

The parameters listed in table 4.1 that resulted from the optimized CEM CST simulations were very close to the parameters estimated from the analytical model.
calculations listed in table 3.1. The only major changes were the diameter of the patch with the final model having a diameter of 50.25 mm and the analytical model a 46.54 diameter; the position of the feed from the center of the patch was different, but the difference was negligible, the position increased by 0.75 mm over the original 10 mm. The significant difference in the estimated size of the patch element, was likely caused by the extra feeds as initial tests showed that models that were single-fed had patch diameters that were closer to the calculated size. It also must be considered that the thickness of the patch is near the cavity model’s limit of 0.02 times the free-space wavelengths, which will cause further deviations from the calculated diameter.

The final CEM CST refined model can be seen in figures 4.1 and 4.2 for the GNSS L5 four-feed circular patch antenna, Rogers TMM 10i substrate, with circular ground plane.
Figure 4.1 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Final Model
4.1.1.1 Circle Patch on Circular Ground Plane S parameters

The S parameters of the GNSS L5 four-feed circular patch antenna over circular ground plane were quite good. The input impedances of the resonate frequency of the patch on port 1 is at the L5 center frequency of 1176.45 MHz. All four ports have approximately the same results so only port 1 will be shown. The input impedances for port 1 are shown in figures 4.3 and 4.4. The real part of the input impedance at the L5 frequency is essentially 50 Ohms and the imaginary part is approximately 14 Ohms. This inductive reactive component of the input impedance is indicative of probe feeds at resonance (the peak in the real part of the input impedance).
Figure 4.3 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane Input Resistance Port 1
The antenna almost perfectly resonates at the L5 frequency, as denoted by the peak of the input resistance being near 1176.45 MHz. (The offset of the peak from L5 was negligible.) Despite the great distance of the feeds from the center of the patch, the input resistance was a near match to the 50 ohm source. A single-fed patch would have required the feed location to be much closer to the center of the patch. The slope of the resistances curve is also shallower than what has been observed in single feed antennas. The reactivity was sufficiently small for the L5 frequency, requiring little tuning from the feed network.

The return loss for the GNSS L5 four-feed circular patch antenna over circular ground plane was good overall but it would require additional tuning if the antenna is to
meet the draft RTCA requirements (Space Engineering S.p.A., 2014). This RL is shown as the magnitude of the S1,1 measurement in figure 4.5.

![Diagram](image.png)

*Figure 4.5 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Return Loss Port 1*

The L5 frequency is denoted by the solid vertical line and the bandwidth of the antenna is between the markers 1 and 2. The L5 frequency itself meets the draft RTCA (Space Engineering S.p.A., 2014) return loss, which must be less than -14 dB, but a bandwidth centered on the L5 frequency, due to the inductive part of the input impedance. It must at least have a minimum frequency of 1164.22 MHz, the results have a minimum frequency of 1166.7 MHz. However, the overall bandwidth of antenna is quite good at 45.9 MHz, which easily surpasses the 24 MHz requirement. This issue could possibly be alleviated by further tuning to the L5 center frequency to shift the entire antenna return loss to the lower frequencies, but would also change the input
resistance, which would decrease maximum power that could be radiated at the L5 frequency. The preferable solution is to use a tuning network to reduce the reactivity at the L5 frequency, which would center the antenna VSWR bandwidth on the L5 frequency.

Another view of the bandwidth for the GNSS L5 four-feed circular patch antenna over circular ground plane is the VSWR in figure 4.6. All the markers are the same as ones in figure 4.5.

\[ \text{VSWR} \]

\[ \text{Frequency / GHz} \]

\[ \text{VSWR} : 1.3068017 \]

\[ (1.1666, 1.4985) \]

\[ (1.2127, 1.5005) \]

\[ 1 \]

\[ 2 \]

Figure 4.6 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, VSWR Port 1

4.1.1.2 Circle Patch on Circular Ground Plane Radiation Characteristics

The radiation characteristics of the GNSS L5 four-feed circular patch antenna over circular ground plane were very good and met the draft RTCA Draft (Space Engineering S.p.A., 2014) requirements. The antenna produced RHCP by giving each of
its four feeds the following phase delays (deg): 0, 90, 180, and 270. This phase delay configuration and its radiation characteristics will be used as the baseline. The antenna’s baseline radiation pattern had a maximum directivity of 6.079 dBi and had very good symmetry. The far field 3D results are shown in figures 4.7 and 4.8. 2D polar plots with phi at 0 and 90 deg are also given in figures 4.9 and 4.10.

Figure 4.7 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Baseline Far Field Radiation Pattern
Figure 4.8 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Baseline Far Field Radiation Pattern (Top View)
Figure 4.9 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Baseline Far Field Radiation Pattern Polar Phi 0 deg
As expected, both 3D and 2D plots illustrate that the circular patch antenna over the circular ground plane exhibits excellent symmetry. The far field pattern nearly meets the draft RTCA specification (Space Engineering S.p.A., 2014), which states that at an elevation angle of 30 deg, the gain, normalized over maximum gain, must be higher than -3.5 dBi. (Though the specification uses gain, which is normalized over the maximum, and is equivalent to directivity which also has been normalized over maximum.) The circular patch antenna at elevation angle 30 deg has a normalized directivity of -4.48 dBi. Despite this, the antenna meets the far field requirement at other elevation angles, most notably at elevation angle 75 deg, where the RTCA minimum accepted directivity is -2.5 dB and the antenna’s directivity is -0.30 dBi. Likewise, at the
lower elevation angle of 5 deg, where the RTCA specification requires the minimal
directivity be -8.5 dBi, the antennas directivity is -8.44 dBi. These results suggest that
the antenna’s far field radiation pattern is too narrow in beamwidth, in the elevation
plane. This effect is likely due to the small size of the ground plane that the antenna is
mounted on. It is hypothesized, that if the antenna was mounted on the ground plane
suggested by the draft RTCA standard, a 1200 mm diameter circle, then the far field
pattern would meet the requirement. In practice the antenna would be mounted on an
airplane, where the airplane ground plane is larger than what was simulated and
asymmetric.

The AR performance of the circular patch antenna with the circular ground plane
will now be investigated. It should be stated that the draft RTCA (Space Engineering
S.p.A., 2014) specification requires that only at boresight should the AR be less than 3
dB. In practice the AR will affect the antenna performance at all angles, thus it is the
opinion of this thesis that the AR specification could be more comprehensive to help
ensure the patch antennas will have adequate operating performance. For the duration of
this thesis a new metric will be used to characterize the AR performance over a geometric
region. This metric will be denoted as the AR beamwidth, where the 3 dB standard of the
RTCA will be applied to geometric angles of the patch antenna in the upper hemisphere.
The AR beamwidth in a given elevation plane will be determined at a given azimuth
angle (i.e., phi angle). The AR beamwidth will be centered about the geometric angle
where the radiation pattern is maximum (e.g., at zenith), and be of width where the AR
falls below the specified metric of 3 dB.
The AR for the GNSS L5 four-feed circular patch antenna over circular ground plane was sufficiently circular polarized. The figure 4.11 shows the AR at various azimuth angles (i.e., various phi angles) around the antenna; in other words this figure represents the AR in the vertical plane, at various azimuth angles. The antenna exhibited an AR at bore sight of 0.008 dB, which is almost ideal.

![Axial Ratio](image)

*Figure 4.11 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Axial Ratio*

Any AR value below 3 dB metric (the solid teal line in figures 4.1.1m), could be viewed as being acceptable. As can be seen in Figure 4.11, all of the upper hemisphere of the antenna has an AR < 3 dB, and approaches linear polarization at theta angle below
the horizon (i.e., > 90 deg). This was expected behavior for a CP patch antenna over a ground plane. The AR beamwidth of the antenna was measured to be 190 deg. The AR is very symmetric with respect to the Z axes. As discussed earlier, the GNSS L5 four-feed circular patch antenna over a circular ground plane generally met the discussed requirements of the RTCA and ARINC specifications. The next section will present the pattern control for this antenna configuration.

4.1.2 Circle Patch on Circular Ground Plane Feed Phase Manipulation

The following sections will demonstrate the ability to manipulate the phase feed distribution to each of the four feeds and control the radiation characteristics of the GNSS L5 four-feed circular patch antenna over a circular ground plane. For these data presentations an “area of high directivity” is considered to be an area where there is relatively high directivity; this is generally a quadrant where the directivity is higher than other quadrants. For these data presentations an “area of low directivity” is considered to be an area where there is relatively low directivity; this is generally a quadrant where the gain is lower than other quadrants.

The pattern control for this GNSS L5 four-feed circular patch antenna over a circular ground plane will be demonstrated in two steps. First, the phase will be controlled on the four-feeds and the area of high directivity will sweep across a quadrant (the area of low directivity will also sweep across a quadrant). Second, the phase will be controlled on the four-feeds and the area of high directivity will sweep across a full 360 deg sweep (the area of low directivity will also sweep across a full 360 deg sweep). The following sections will illustrate the beam control as the area of high and low directivities
move across the respective coverage areas. The feed locations given in 4.12 shows the
feeds port number and its location using the spherical coordinate phi, which will be in
deg, this should not be confused with the phase delay.

Figure 4.12 GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane,
Feeds Port Numbers and Location (Phi, deg)

4.1.2.1 Circle Patch on Circular Ground Plane Feed Phase Manipulation, Sector

Pattern Sweep

To illustrate the beam control over a single sector, the phase is manipulated using
all four feeds. All feeds had the same amplitude. Opposite feeds have a 15 deg phase
difference which will be constant throughout the sweep. One pair of opposite feeds will
incremented with respect to the other pair of feeds. This is progressed until a sector has

been covered. Table 4.2 illustrates the phase at each feed and the respective 2D radiation pattern of each phase configuration. The first entry (i.e., Step# 0) is the baseline feed configuration. The value of the directivity is indicated as color, with the scale being at the bottom right in the 2D plots of table 4.2.
Table 4.2

*GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Sector Sweep*

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>90</td>
<td>180</td>
<td>270</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image)

Frequency = 1.171645

Radi. effic. = 0.578656 dB

Tot. effic. = -5.01738 dB

Dir. = 6.80113 dBi
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
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<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>15</td>
<td></td>
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</tbody>
</table>

![2D Radiation Pattern](image)
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase</th>
<th>Feed 2 phase</th>
<th>Feed 3 phase</th>
<th>Feed 4 phase</th>
<th>2D Radiation Pattern</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern Diagram]

Frequency = 1.17645
Rad. effic. = -1.85695 dB
Tot. effic. = -19.3100 dB
DIR. = 3.12671 dB
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
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<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>20</td>
<td>15</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image-url)

- **2D Radiation Pattern Labels:**
  - Frequency = 1.17645 GHz
  - Rad. effic. = 1.05811 dB
  - Tot. effic. = -19.3624 dB
  - Dir. = 3.26468 dB
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0</td>
<td>30</td>
<td>15</td>
<td>45</td>
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</table>

![2D Radiation Pattern Diagram](image-url)
Table 4.2: continued

<table>
<thead>
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<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>40</td>
<td>15</td>
<td>55</td>
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</table>

![2D Radiation Pattern](image)
Table 4.2: continued

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<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td>50</td>
<td>15</td>
<td>65</td>
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</tr>
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</table>
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
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<tbody>
<tr>
<td>7</td>
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<td>60</td>
<td>15</td>
<td>75</td>
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</tbody>
</table>

![2D Radiation Pattern](image)
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase</th>
<th>Feed 2 phase</th>
<th>Feed 3 phase</th>
<th>Feed 4 phase</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>70</td>
<td>15</td>
<td>85</td>
<td></td>
</tr>
</tbody>
</table>

![Image](image_url)
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0</td>
<td>80</td>
<td>15</td>
<td>95</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern Diagram](image)

- Frequency: 1.17645
- Rad. effic. = -1.88339 dB
- Tot. effic. = -26.3709 dB
- Dir. = 4.68245 dB

[Image of 2D Radiation Pattern Diagram]
Table 4.2: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>90</td>
<td>15</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image-url)
The results show that radiation pattern can be controlled when the phases at the feeds are manipulated. This configuration illustrates the pattern control along the phi axis from approximately 225 to 315 deg. As the phase is controlled on the feeds, the shape and orientation of the radiation pattern differed greatly from the circular patch baseline, illustrated as Step # 0. The symmetric “mushroom” shape and symmetry of the baseline is absent, the shape now varies as the beam (i.e., area of high directivity) moves. The sector of the antenna that contains the beam (i.e., area of high directivity) now has more coverage in lower elevation angles than the baseline circular antenna. When the phase manipulation is at step 10 in Table 4.2 the area of high directivity is pointed in phi direction 300 deg, whereas the opposite sector, phi 125, now has an area of low directivity coverage. This area of low directivity would allow for an unwanted signal to be attenuated, thus providing some anti-jam (i.e., anti-interference) rejection, in the upper hemisphere.

It seemed that certain increments of the sweep of the beam had higher concentrations of directivity. This was especially true in the steps 9, 10 and 11, as seen in Table 4.2. This is illustrated by amount of red in the beam with the initial step 1 having only yellow in the pattern, whereas final step 10 had a large red area. The area of highest directivity Table 4.2 during step 1 had a directivity of 3.07 dBi (at theta 19 and phi 228) and the sector used for isolation has moderate directivity, as highlighted by its slight yellow hue, indicating it is not very isolated. Compare to step 10, the highest directivity is 4.91 dBi (at theta 25 and phi 299), the isolation sector is green indicating it has low
directivity and is well isolated. This suggests that increase in directivity is taken from the isolated area and that the later steps are better at isolating unwanted signals.

The behavior of the areas of high and low directivity areas described did not seem linear. If one considers the position of the beam to be the position of the maximum directivity relative to the (theta, phi) plane then the amount of movement between increments is non-linear. The initial increments appeared to have the largest increase in movement of the beam, while the later changes showed little movement.

One drawback is the low absolute gain of the radiation pattern. The gain of the antenna, when performing the phase manipulation, was low due to low radiation efficiency, as described by equation (11). The radiation efficiency for step 10 in table 4.2 was -20 dB. When compared to the radiation efficiency of the baseline, -5 dB, it becomes clear that the poor efficiency is due to the phase manipulation. This low efficiency could be overcome with amplifier(s) placed at or near the antenna terminals to provide increased gain to all antenna ports.

The AR performance was also affected by the phase manipulation. The baseline created RCHP by making all feeds 90 deg apart in phase. The phase manipulation technique to control the far field pattern also changes the AR and the RCHP performance is degraded by this technique. This means that when this technique is implemented on an antenna, that antenna will not meet the draft RTCA specification with respect to the RHCP performance (Space Engineering S.p.A., 2014). Nevertheless, in the right conditions when interference is present the benefits of the ability to control the beam may outweighs the degradation in RHCP performance.
4.1.2.2 Circle Patch on Circular Ground Plane Feed Phase Manipulation, Full 360 Pattern Sweep

There will now be a full sweep over all sectors of the circular patch antenna to illustrate the pattern control by manipulating the phase at the feeds. This sweep will have higher increments of phase difference of 30 deg for two of the ports, while keeping the phase difference constant for the opposite port pair. The results in the table 4.3 will be arranged in a way to show a clockwise sweep of the antenna as one would see when viewing the antenna looking into the Z axis, as shown in figure 4.12. The baseline will again be present as the first entry (Step # 0) to help put into perspective the pattern control. The results are shown in table 4.3.
Table 4.3

GNSS L5 Four-feed Circular Patch Antenna over Circular Ground Plane, Full Antenna Sweep

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>90</td>
<td>180</td>
<td>270</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image)

Frequency = 1.17645
Rad. effc. = 0.578456 dB
Tot. effc. = -5.01730 dB
Dir. = 6.01113 dBi
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase</th>
<th>Feed 2 phase</th>
<th>Feed 3 phase</th>
<th>Feed 4 phase</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>15</td>
<td>45</td>
<td>0</td>
<td><img src="Image" alt="Graph" /></td>
</tr>
</tbody>
</table>

Table 4.3: continued
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase</th>
<th>Feed 2 phase</th>
<th>Feed 3 phase</th>
<th>Feed 4 phase</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td>(deg)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>15</td>
<td>75</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image)

**Notes:**
- Frequency = 1.17645
- Rad. eff. = -1.07694 dB
- Tot. eff. = -19.9156 dB
- Eirp = 4.18103 dB
Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Step #</th>
<th>Step #</th>
<th>Step #</th>
<th>Step #</th>
<th>Step #</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>90</td>
<td>15</td>
<td>105</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Farfield [shift=1.17645] (full sweep 360°) Directivity_Abs

Frequency = 1.17645
Rad. effc. = -1.00000 dB
Tot. effc. = -20.0000 dB
Dif. = -4.9545 dB
### Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>15</td>
<td>45</td>
<td>0</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern Image]
Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15</td>
<td>75</td>
<td>0</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

2D Radiation Pattern

Farfield ; Farfield [β=1.17645] [full sweep 240°] Directivity_Abs

Frequency = 1.17645
Rad. effic. = -1.00482 dB
Tot. effic. = -19.939 dB
Dir. = 4.20572 dB
### Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>15</td>
<td>105</td>
<td>0</td>
<td>90</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

---

Frequency = 1.17645
Rad. eff. = -1.11715 dB
Tot. eff. = -20.6599 dB
Dir. = -4.54719 dB
Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>45</td>
<td>0</td>
<td>30</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image)
Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>75</td>
<td>0</td>
<td>60</td>
<td>15</td>
</tr>
</tbody>
</table>

2D Radiation Pattern

![2D Radiation Pattern](image-url)

- Frequency = 1.17645
- Radi. eff. = -1.80135 dB
- Tot. eff. = -19.9307 dB
- Dro. = 4.18039 dB

Theta

Phi
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>105</td>
<td>0</td>
<td>60</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image-url)

Frequency = 1.17645
Rad. eff. = -1.19657 dB
Tot. eff. = 20.9521 dB
Dir. = 4.31946 dB
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>30</td>
<td>15</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern Diagram](image)
<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0</td>
<td>60</td>
<td>15</td>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image-url)
Table 4.3: continued

<table>
<thead>
<tr>
<th>Step #</th>
<th>Feed 1 phase (deg)</th>
<th>Feed 2 phase (deg)</th>
<th>Feed 3 phase (deg)</th>
<th>Feed 4 phase (deg)</th>
<th>2D Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0</td>
<td>90</td>
<td>15</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>

![2D Radiation Pattern](image_url)
Table 4.3 clearly shows the efficacy of phase manipulation to steer the beam. The patterns behavior was the same for each sweep from 0 deg to 90 deg of a sector; a small maximum directivity is present then an increase in gain appears near 90 deg. It should be noted that last position of the beam at 90 is close to the next beam position staring at 0 deg. To make up for the small directivity at 0 deg one could also just use the beam at 90 deg from the last sweep. Another solution is to reverse the order of the feed manipulation in order to move the beam counter clockwise. Such a solution would allow for a large gain at near any position of the beam or isolation.

4.2 Rectangle Patch Antenna

4.2.1 Square Patch on Square/Symmetrical Ground Plane

As a baseline a symmetric model was created with a square patch placed over a square ground plane. This antennas performance will be used as the baseline to compare to the square patch with a rectangle/asymmetrical ground plane. It could be considered the 2nd baseline model in this thesis. Using the analytical design parameters presented earlier in table 3.2, the square patch antenna over square ground plane model was refined to obtain a good impedance match at the resonance L5 GNSS frequency. The final refined parameters for the CEM CST model are shown in table 4.4.
Table 4.4

*GNSS L5 Four-feed Square Patch Antenna over Square Ground Plane, Final Model Design Parameters*

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate Material</td>
<td>Rogers TMM 10i</td>
</tr>
<tr>
<td>Substrate Relative Permittivity (unitless)</td>
<td>9.8</td>
</tr>
<tr>
<td>Substrate Length (mm) x Width (mm) x Height (mm)</td>
<td>43.75 x 43.75 x 5.08</td>
</tr>
<tr>
<td>Feed position from center (mm)</td>
<td>10.0</td>
</tr>
<tr>
<td>Square Patch Element Length (mm) x Width (mm)</td>
<td>43.75 x 43.75</td>
</tr>
<tr>
<td>Symmetrical Ground Plane Length (mm) x Width (mm) x Height (mm)</td>
<td>120 x 120 x 0.5</td>
</tr>
</tbody>
</table>

The refined square patch antenna over a square ground plane dimensions are not largely different than the analytical design parameters presented earlier in table 3.2. Any difference is once again mostly caused by the height of the patch and/or the four-feed configuration. Similar to the circle patch, the probe feeds are a good distance away from the center, allowing for easy connection at the antenna feed ports. The substrate material used allowed for the patch to be small enough for it to fit the ARINC (Airlines Electronic Engineering Committee, 2001) foot print, with the foot print being 119.38 mm and 73.66 mm. The final model for the baseline symmetric square configuration is viewable in figures 4.13 and 4.14.
Figure 4.13 GNSS L5 Four-feed Square Patch Antenna over Square Ground Plane, Final Model
4.2.1.1 Square Patch on Square/Symmetrical Ground Plane S Parameters

The S parameters for the baseline symmetric square patch over square ground plane were of good quality. The input impedance was nearly matched to the 50 Ohm source. The input resistance for the 1176.45 MHz is near the peak at 49 ohms meaning this patch antenna resonates at the L5 frequency. The reactance for L5 is 20 ohms; being inductive, is expected with a probe feed, and can be overcome with a capacitor in the matching network. Both the input resistance and reactivity are shown for port 1 in figures 4.15 and 4.16. (All four ports performed similarly; hence data will only be presented for port 1.)
Figure 4.15 GNSS L5 Four-feed Rectangle Patch Antenna over Square Ground Plane, Input Resistance Port 1

Figure 4.16 GNSS L5 Four-feed Rectangle Patch Antenna over Square Ground Plane, Input Reactance Port 1
The return loss and VSWR were small and had a good bandwidth, but were centered slightly above the L5 frequency, as shown in figures 4.17 and 4.18, respectively.

*Figure 4.17* GNSS L5 Four-feed Rectangle Patch Antenna over Square Ground Plane, Port 1 Return Loss
The solid black vertical line marker at the L5 frequency and the 1 and 2 marker are placed to illustrate the bandwidth of the antenna. The return loss was slightly less than -14 dB which can be considered acceptable when compared to the -14 dB specification of the draft RTCA specification (Space Engineering S.p.A., 2014). The RL can be further improved via a matching network. The bandwidth of the antenna was 38.8 MHz which more than meets the 24 MHz requirement of the draft RTCA (Space Engineering S.p.A., 2014), but again, centered slightly above the L5 frequency. With the matching network the square patch will easily meet the return loss, VSWR, and bandwidth requirement.
4.2.1.2 Square Patch on Square/Symmetrical Ground Plane Far Field Radiation Characteristics

The radiation characteristic of the symmetric square patch antenna over a square ground plane exhibited very good symmetric performance. RHCP was produced by this antenna configuration by using the patch’s four feed and giving them the following phase delays (deg): 0, 90, 180, and 270. The far field pattern is illustrated in the 3D far field plots in figures 4.19 and 4.20.

Figure 4.19 GNSS L5 Four-feed Square Patch Antenna over Square Ground Plane, Far Field Radiation Pattern
As displayed in figure, 4.20, the antenna had a high maximum directivity of 6.332 dBi and the radiation pattern has good coverage and symmetry in the upper hemisphere.

In order to gather more in depth data a polar image of the far field in the “elevation plane” is given in figures 4.21 and 4.22.
Figure 4.21 GNSS L5 Four-feed Square Patch Antenna over Square Ground Plane, Far Field Radiation Pattern Polar Phi 0 deg
The far field pattern does not quite meet the draft RTCA specification (Space Engineering S.p.A., 2014), which states that the directivity, normalized to zero, at an elevation angle of 30 deg should be higher than -3.5 dBi, while for this antenna the normalize directivity at that angle is -4.7 dBi. This is probably due to the small ground plane the antenna is mounted on. Due to the goal of this section, to study the effects of an asymmetrical and symmetrical ground planes, a larger ground plane will not be used. With a larger ground plane, it is expected that this requirement could be met. Figures 4.21 and 4.22 help to verify the good symmetry of the pattern as the two figures show that the beamwidths are similar and both have their beam pointed toward an elevation.
angle of 90 deg. The AR for the symmetric square patch antenna is presented in figure 4.23.

![Axial Ratio Graph](image)

**Figure 4.23 GNSS L5 Four-feed Square Patch Antenna over Square Ground Plane, Axial Ratio**

Figure 4.23 shows a solid straight teal 3 dB line to illustrate the RTCA AR limit as specified in the draft RTCA standard (Space Engineering S.p.A., 2014). The boresight AR is 0.01 dB. All azimuth angles presented meet the required 3 dB AR at boresight specification. The AR also appeared to have a large 3 dBi beamwidth of approximately 219 deg.
4.2.2 Square Patch on Rectangle/Asymmetrical Ground Plane

With the symmetric model as a baseline, next the square patch antenna was placed over a rectangular ground plane to illustrate the asymmetric performance of such a configuration. The final CEM CST design parameters for the asymmetrical ground plane antenna are the same as for the symmetrical antenna, as previously shown in table 4.4 with the only difference being that the ground plane has the dimensions 120 mm by 200 mm. (This model is considered a baseline (i.e., Baseline 3) when comparing and contrasting to the patch and substrate manipulations to be shown later, as seen in figures 4.24 and 4.25.)

Figure 4.24 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Final Model
4.2.2.1 Square Patch on Rectangle/Asymmetrical Ground Plane S Parameters

The S parameters of this patch antenna configuration were slightly negatively affected by the asymmetry of the ground plane. For the asymmetric patch antenna configurations data from both port 1 and port 2 will be shown, due to the asymmetric performance. The data at ports 3 and 4 are approximately the same to ports 1 and 2 respectively and thus will not be shown. The input impedance for both ports 1 and 2 are displayed in figures 4.26 and 4.27.
Figure 4.26 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Input Resistance Ports 1 and 2
Figure 4.27 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Input Reactance Ports 1 and 2

The input impedance has not been strongly affected by the change in the ground plane. The resistance and reactance were approximately 50 ohms and 20 ohms, respectively, for the L5 frequency on both ports 1 and 2.

The return loss had its bandwidth slightly affected by the asymmetrical ground plane with the effect being slightly different for each feed as seen in figures 4.28. and 4.29.
Figure 4.28 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Return Loss Ports 1 and 2

Figure 4.29 L5 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, VSWR Ports 1 and 2
The return loss had only gotten slightly higher for feed 1 and had become even less for feed 2. Both feeds have the same bandwidth as the symmetric ground plane antenna, which is 39.5 MHz. If a tuning network is applied then the bandwidth for both feeds allows the antenna to operate within the L5 spectrum of 24 MHz.

For the square patch antenna over the asymmetric rectangle ground plane, the performance at the feed ports in terms of the input impedance, RL, VSWR, and bandwidth did not vary substantially from the baseline 2 symmetric square patch over square ground plane configuration. The radiation characteristics in terms of the radiation pattern and AR were investigated next.

4.2.2.2 Square Patch on Rectangle/Asymmetrical Ground Plane Far Field Radiation Characteristics

The radiation characteristics were the area most affected by the asymmetric ground plane. The radiation pattern maximum directivity was 6.83 dBi, slightly higher than 6.33 dBi exhibited for the symmetric baseline 2 configuration. RHCP was created for the asymmetrical model by making the four feeds have the following phase delays (deg): 0, 90, 180, and 270. Despite this, the radiation pattern of the antenna was distorted from its spherical hemisphere it had when the ground plane of the antenna was symmetric. The radiation pattern for the asymmetric ground plane configuration can be viewed in figures 4.30, 4.31, 4.32 and 4.33.
Figure 4.30 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Far Field Radiation Pattern
Figure 4.31 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Far Field Radiation
Figure 4.32 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Far Field Radiation Pattern Polar Phi 0 deg

Figure 4.33 GNSS L5 Four-feed Square Patch Antenna over Rectangle Ground Plane, Far Field Radiation Pattern Polar Phi 90 deg
The radiation pattern in the upper hemisphere has become oval like and non-uniform in nature. Using a 3 dB beamwidth in the elevation plane to characterize the pattern coverage in the upper hemisphere, it can be seen that the elevation angle coverage of 37.25 deg, at azimuth angle 90 deg is less than baseline 2 coverage of 47.4 deg. When the azimuth angle is 0 deg is considered, the asymmetrical elevation angle coverage is 42.95 deg, compared to the baseline 2 coverage of 47.4 deg. The area which was most negatively affected by this radiation characteristics for the asymmetric ground plane configuration was the AR of the antenna, which is shown in figure 4.34.
The draft RTCA specification (Space Engineering S.p.A., 2014) states the AR at boresight must be 3 dB or less. As can be seen in figure 4.34, the boresight AR of this square patch antenna over the asymmetric ground plane barely met the requirements, which is 2.91 dB. When comparing this AR with the square patch over the square ground plane presented in figure 4.23, it can be observed that the AR has significantly degraded due to the asymmetric ground plane. The immediate elevation angles outside of the boresight were also barely within the 3 dB limit. Outside of that narrow space the only radiation that will have RHCP was the azimuth angle of 90 deg, which has a 3 dB AR.
beamwidth of 124 deg. The lack of RHCP in the antenna will cause there to be polarization mismatch loss. The polarization mismatch loss occurs when an antenna has a different polarization than the incident wave on the antenna (Balanis, Microstrip Antennas, 2005). It is described by the IEEE standard (IEEE Standard Definitions of Terms for Antennas, 2004) as “The magnitude, expressed in decibels, of the polarization efficiency.” The effect will be that RHCP signals received by the antenna will have significantly reduced power.

4.2.3 Rectangular Patch on Asymmetrical Ground Plane with Patch Antenna Manipulations

The asymmetric performance of the square patch antenna over an asymmetric ground plane can be improved by adjusting the patch antenna. This manipulation can be done by making the patch antenna element slightly asymmetric and/or the dielectric substrate material slightly asymmetric. Changing the dimensions of the patch element or the patch substrate have positively affected the AR of the antenna. The results for each method will be presented to illustrate and improvement in AR performance.

4.2.3.1 Rectangular Patch on Asymmetrical Ground Plane with Patch Antenna Manipulations Antenna Element Dimensions Manipulated

Manipulating the dimensions of the radiating patch antenna element were made by increasing/decreasing the dimensions of the antenna patch element along the Y and X axes; see the baseline 3 configuration figure 4.25 for axes orientation. When the dimension of the antenna element were increased/decreased, the substrate dimension were also increased/decreased. There were only significant improvements in AR when
the dimension along the X axis (i.e., short side of the asymmetric ground plane) was increased, thus only the results for the increase in the X dimension will be shown. The X axis dimensions were increased in CST by using variable “move_x.” This variable represents the amount of increase in the baseline 3 configuration X dimension, where the baseline 3’s X dimension is 43.75 mm. Thus, the “move_x” is added to the 43.75 mm for the patch element dimension. The different increments varying from 0 mm to 3 mm were compared. The AR performance (from the directivity data) for each increment will be represented by a different color. The effects of the various increments on the AR are displayed in figures 4.35, 4.36, and 4.37.

Figure 4.35 GNSS L5 Four-feed Rectangle Patch Antenna over Rectangle Ground Plane with Manipulated Antenna Element Dimensions, Axial Ratio Phi 0 deg
Figure 4.36 GNSS L5 Four-feed Rectangle Patch Antenna over Rectangle Ground Plane with Manipulated Antenna Element Dimensions, AR Phi 45 deg
From the data presented in figures 4.35-37, it is clear that manipulating the dimensions of the patch element along the X axis improves the AR. The best improvement seems to be when the patch was increased by 1.25 mm. This value across all figures had the superior AR at boresight which was 1.68 dB approximately. For "move_x" value of 1.25 mm, the smallest AR beamwidth was 104 deg (at phi = 45 deg), and the largest was 240 deg (at phi = 0 deg). For comparison, the baseline 3 AR beamwidth at azimuth angle 90 deg was 124 deg and its boresight AR was 2.87 dB, as shown in figure 4.37. Although, the AR bandwidth for the symmetric baseline 3 configuration is larger than the asymmetric models whose X dimension has been increased by 1.25 mm, it is only larger at azimuth angle 90 deg, at all the other measured
azimuth angles the other model’s AR Beamwidth is wider. Furthermore, the other model’s boresight AR is better than the Baseline Model’ boresight AR.

These improvements in AR are limited as it seems as the patch element continued to increase in the X axis direction the AR became worse at some point. This is mostly visible for the move_x value of 3.0 mm, where its boresight AR increased to 4.31 dB. Comparing figures 4.35-37, only in figure 4.35, when the azimuth angle is 0 deg, the 3.0 mm move_x value (brown line) would have an area of AR that is less than 3.0 dB. Even baseline 3 (move_x = 0.0 mm) has a superior AR bandwidth and AR boresight values than the move_x value of 3.0 mm. This data suggest that there is a “sweet spot” in which the patch element dimension can be increased to in order to improve an axial ratio performance.

4.2.3.2 Rectangular Patch on Asymmetrical Ground Plane with Patch Antenna

Manipulations Substrate Dimensions Manipulated

The dimensions of the substrate on the antenna were manipulated by increasing the substrate dimensions along the Y and X axes. The baseline 3 configuration was used for these manipulations for reference; see the baseline 3 configuration figure 4.25 for axes orientation. As the substrate dimensions increased/decreased the dimensions of the antenna element would remain the same as the baseline 3 configuration dimensions, 43.75 mm by 43.75 mm. Only the results of the increases along the X axis will be given due to little effects that other axes changes had. The X dimensions of the substrate were increased using the variable “move_x” in CST. This variable represents the amount of increase over the baseline 3 configuration. Various “move_x” are added to the X
dimension 43.75 mm (baseline 3) for the patch element dimension. The AR performance (from the directivity data) for increment of the “move_x” is represented by a different color in the plots, as illustrated in figures 4.38-4.40.

Figure 4.38 GNSS L5 Four-feed Rectangle Patch Antenna over Rectangle Ground Plane with Manipulated Substrate Dimensions, AR Phi 0 deg
Figure 4.39 GNSS L5 Four-feed Rectangle Patch Antenna over Rectangle Ground Plane with Manipulated Substrate Dimensions, AR Phi 0 45 deg
From the data in figures 4.38-40, it can be concluded that increasing the substrate dimension along the X axis improved the AR. However, while the AR at boresight generally improved as the substrate dimension increased (i.e., as move_x got bigger), the AR bandwidth decreased at some azimuth angles. For azimuth angle phi=0 deg, the best improvement in the AR performance was observed when the dielectric was extended by 3 mm, as shown in figure 4.38, where the boresight AR was decreased to a value of 1.50 dB, from 2.84 dB the baseline 3 configuration (i.e., move_x = 0 mm). Nevertheless, at the move_x dimensional increase of the substrate by 3 mm, the AR beamwidth was not the widest found, but was an improvement over the baseline. As can be seen in figure 4.40, the only disadvantage observed was at the azimuth angle 90 deg where the patch
antenna with the substrate manipulation (i.e., move_x=3 mm) had a smaller AR beamwidth when compared to other increments and most notably when compared to the baseline (i.e., move_x = 0 mm) AR beamwidth.

As the substrate dimension increase passed 3.0 mm, the AR at boresight started to increase. This can most obviously be seen when the substrate is increased in the X dimension by 6 mm, as illustrated in figures 4.38-40. When move_x is 6 mm, the antenna’s boresight AR is 2.01 dB and its largest AR beamwidth was 220 deg at azimuth angle 0 deg, this is viewable in figure 4.37. Compared to the 3 mm substrate increase whose widest AR beamwidth is 228 deg at azimuth angel 0 deg, as viewable in figure 4.37, there is only a difference of 8 deg. However, the move_x value of 3 mm has an AR boresight value of 1.50 dB, and the boresight value of the 6 mm move_x is 2.01 dB; the difference is 0.5 dB. It should also be noted that the 3 mm substrate increase has the largest AR beamwidth for all azimuth angles measured, this effect can be seen in figures 4.38-4.40. These results show there is a tradeoff in AR at boresight and AR beamwidth performance, as the move_x parameter is varied, and that there may be an optimal value of increase to the substrate dimension to improve the AR.

4.2.3.3 Comparing the Patch Antenna Dimensions Manipulated Techniques

The two techniques to improve AR for the rectangular patch antenna (element vs substrate) over the asymmetric ground plane were compared. The patch element manipulation technique will be compared using the data from the increment 1.25 mm, while the dielectric substrate manipulation will be compared using the data from when the substrate was incremented by 3.0 mm, as these were determined to produce the best
improvement in AR. The AR performances for these patch antenna configurations were compared to the baseline 3 configuration, as presented in figures 4.41 and 4.42, at both the azimuth and the elevation angles. The ARs for the two techniques and baseline 3 were compared at a nominal theta angle of 30 deg (i.e., elevation = 60 deg) as phi (i.e., azimuth) varied from 0 to 360 deg, as shown in figure 4.41; a second AR comparison was made, where phi = 0 deg, and theta varied from -180 to 180 deg, which is illustrated in figure 4.42. While the AR results were viewed in the phi angles, the difference between the two manipulation techniques and baseline 3 would be most pronounced when the elevation angle was 60 deg, as a result, only theta angle 30 deg was shown in figure 4.41. The phi angle of 0 deg was chosen because at this angle the AR saw the largest improvement. The different manipulation techniques and baseline model 3 all had RHCP. The feeds on all patches have the phase configuration of (deg): 0, 90, 180, and 270.
Figure 4.41 Comparing the Patch Antenna Dimensions Manipulated Techniques, Axial Ratio Theta 30 deg
Using the data from figure 4.41, where theta is 30 deg, it was seen that the (minimum, maximum) AR for the patch element dimension extension was (0.77 dB, 2.25 dB) compared to the (minimum, maximum) AR value of dielectric dimension extensions of (0.94 dB, 1.96). The difference between the maximum and minimum AR values was 1.48 dB and 1.02 dB for the patch and substrate extensions, respectively. Both of these patch antenna adjustment techniques provide an improvement in the AR performance, when compared to the Baseline 3 configuration (i.e., square patch antenna (element and substrate) with asymmetric ground plane). These differences and the data displayed in figure 4.41 show that when theta is 30 deg, that the patch extension technique has an AR values that varies larger than substrate extensions technique. At this elevation angle, this
provides evidence that substrate extension technique provides a more uniform AR in azimuth.

The data from figure 4.42 shows that substrate extension technique has an AR boresight value of 1.50 dB, that is smaller than the patch extension technique’s AR boresight value of 1.67 dB. A difference of 0.17 dB. Despite this advantage that the substrate extension technique has, the patch element manipulation technique has AR beamwidth value of 240 deg, which is larger than the substrate extension technique’s AR beamwidth value of 228 deg. It appears that overall AR behavior of the two patches are very similar, and both have advantages, with AR beamwidth of the patch element manipulation technique being the larger of the two, and the substrate manipulation technique having a superior AR boresight and a more uniform AR across its beamwidth at this fixed azimuth (phi = 0 deg) angle.

Both techniques are significant improvements over the baseline 3 AR performance. The boresight AR for baseline 3 is 2.91 dB, compared to the boresight over the dimension manipulation techniques, where was an improvement of 1.24 dB and 1.4 dB for the patch element manipulation and substrate manipulation respectively. There is also improvement in the AR beamwidth for both techniques. Figure 4.42 shows that Baseline 3 has a small AR beamwidth of 54 deg, while the patch element manipulation technique has an AR beamwidth of 240 deg and the substrate manipulation an AR beamwidth of 228 deg. For both of the patch antenna manipulation techniques, there was an overall improvement in the AR of the square patch antenna.
The effect the patch antenna dimensions manipulated techniques had on far field directivity was also investigated. The far field patterns of the baseline 3 configuration, the patch element extension technique, and substrate extension technique were compared in various theta and phi angles. Any increase in dimensions of either technique is based upon baseline 3 configuration. The patch element extension technique will use an increased in X dimension by 1.5 mm, and the substrate extension technique will use an increase of 3 mm in the X dimension. Figure 4.43 has the far field radiation patterns at a constant theta of 30 deg for a varying phi from -180 to 180 deg. In Figure 4.44 the far field radiation patterns has a constant phi at 0 deg and the theta various in range from -180 to 180 deg. All far fields presented had the feeds set to the following phase delays (deg): 0, 90, 180, and 270. The far field comparisons are displayed in figures 4.43 and 4.44.
Figure 4.43 Comparing the Patch Antenna Dimensions Manipulated Techniques, Far Field Directivity Theta 30 deg
From the data shown in figures 4.43 and 4.44, it seemed that both the patch element extension technique and the substrate extension technique have little effect on the far field radiation pattern. There was some small differences to be taken note of in figure 4.43. The patch element extension technique had a maximum directivity of 5.69 dBi, whereas the substrate extension techniques maximum directivity was 5.66 dBi. This small difference means that two patterns radiation pattern could reasonably be considered to be approximately the same.

The different dimension manipulation techniques were also compared in their effect they had on the phase delay in the radiation pattern. The patch element dimension manipulation techniques would again have an increase of 1.5 mm and the substrate...
extensions 3 mm increase. The phase delay in the far field radiation pattern was investigated at a constant theta of 30 deg and a phi range of -180 and 180 deg, this is viewable in figure 4.45. There would also be a comparison done of the far field phase delay at constant phi of 0 deg and theta range of -180 to 180 deg, the results are available in figure 4.46. The feeds that were used to increase the far field radiation pattern phase delay figures had a phase configuration as follows (deg): 0, 90, 180, and 270. All pattern phase changes that occurred due to patch antenna manipulation techniques to improve the AR are shown in figures 4.45 and 4.46.

Figure 4.45 Comparing the Patch Antenna Dimensions Manipulated Techniques, Far Field Phase Theta 30 deg
The baseline 3, patch extension, and substrate extension all had the similar phase delay characteristics shown in figure 4.45, but were shifted to different phi deg. The patch element extension technique had been shifted from the baseline 3 configuration by -11 deg, while the substrate extension technique had been shifted by -22 deg. There may be a connection with how the different techniques affect the phase delay, as the substrate extension’s shift is twice that of the patch extension, which seems similar to the 3 mm being twice that of 1.5 mm. The data is a single observation on these results and more research may be helpful on this characterization.

The data in figure 4.46 shows that dimension manipulation techniques have an effect on the phase delay in the elevation angles. At theta = 0 deg the patch extension
technique has a phase delay of 287 deg, and the substrate extension technique has a phase
delay of 261 deg. Comparing to the baseline phase delay at 0 deg, which is 308 deg,
there is a difference of 21 and 47 deg. The differences could be related to the current phi,
0 deg. The data suggests that no matter which technique or baseline is used, the phase
delay of the radiation pattern is shifted to different phi angles.
5 CONCLUSION

GNSS patch antennas over ground planes were designed considering the draft RTCA (Space Engineering S.p.A., 2014) and ARINC (Airlines Electronic Engineering Committee, 2001) specifications, and interference. This investigation was performed with two primary configurations. Both configurations used four feeds whereby the phase was controlled at each port to affect the radiation characteristics (AR or radiation pattern). The designs concentrated on a GNSS L5 design to illustrate pattern control in an interference environment, and the asymmetric performance that is exhibited when a patch antenna is mounted on an asymmetric ground plane. All antenna configurations were designed using a high fidelity CEM.

The first configuration utilized a circular patch antenna over a 120 mm circular ground plane. For baseline 1, where the phase configuration of the four feeds were 0, 90, 180, and 270 deg, the radiation pattern was very symmetric, had a relatively high directivity of 6.079 dBi, and an AR boresight of 0.008 dB, which was lower than the maximum AR boresight, 3 dB, specified by the draft RTCA (Space Engineering S.p.A., 2014) and RL bandwidth of 45.9 MHz. Manipulating the phase of the four probe feeds of the antenna allowed the radiation far field pattern of the antenna to be controlled in the azimuth; a 360 deg sweep of the antenna was performed using this technique to illustrate the pattern control.

The second configuration utilized a rectangular patch antenna placed on both a square and rectangle ground plane to test the manipulation of the antennas dimensions (patch element and substrate) to affect the antenna radiation characteristics. For baseline
2, a square patch over a square ground plane with the four feeds that had a phase configuration of 0, 90, 180, and 270 deg, the radiation pattern was symmetric, had a relatively high directivity of 6.332 dBi, and an AR boresight of 0.01 dB, which was lower than the maximum AR boresight, 3 dB, specified by the draft RTCA (Space Engineering S.p.A., 2014) and RL bandwidth of 38.8 MHz. When the square patch was placed on an asymmetrical ground plane (baseline 3 configuration) the radiation far field pattern lost its asymmetry and the AR boresight increased to 2.91 dB and the RL bandwidth was 39.5 MHz. The patch elements dimensions were manipulated to help improve the AR. The dimension in the X direction (i.e., short side of the asymmetric ground plane) was increased by 1.25 mm (beyond the baseline 3 configuration), which improved the AR, with AR boresight value being 1.68 dB (improvement from 2.91 dB for the baseline 3 configuration). In another technique to improve the AR, the dimension of the substrate of patch antenna was manipulated to increase in the X dimension by 3.0 mm. This substrate dimension manipulation resulted in an AR boresight value of 1.5 dB at boresight (improvement from 2.91 dB from the baseline 3 configuration). The results of the two different patch antenna dimension manipulation techniques (patch element and substrate) showed an overall improvement in AR for both techniques for a rectangular patch antenna over an asymmetric ground plane.
6  SUGGESTIONS FOR FUTURE RESEARCH

Further research should concentrate on developing an analytical model with expressions for the beam control. It would be productive to have this analytical model, independent of a full CEM, such as CST, to calculate the fields when the beam is being pointed at a particular area. These can then be used to determine where the beam will point without the complexity of a CEM. How the feed placement and dialectic thickness will affect the ability to control the beam could also be included in such an analytical model.

In the same vein as the beam control, an analytical model for controlling the AR by manipulating the dimensions of the patch antenna element and/or antenna substrate would be a ripe area for further investigation.

Viewing the effects that an asymmetrical ground plane has on a patch antenna’s performance suggest that the draft RTCA (Space Engineering S.p.A., 2014) test ground plane, which is a 1200 mm diameter circle, could be specified to be an asymmetric ground plane to better design and test the asymmetric performance effects of GNSS patch antennas. Applications in the field, such as the fuselage of an airplane, will rarely be circular and will most often be asymmetrical. In contrast, the large ARINC (Airlines Electronic Engineering Committee, 2001) test ground plane, which has 2.4438 meters radius and a length of 2.1136 meters, is more applicable to what an antenna will be mounted on in the field; however, more difficult to utilize in CEMs and on test ranges due to its size. The draft RTCA (Space Engineering S.p.A., 2014) ground plane specification could be changed to an asymmetric ground plane to better design and test
the asymmetric performance effects of GNSS antennas that will be installed on aircraft fuselages.
REFERENCES


