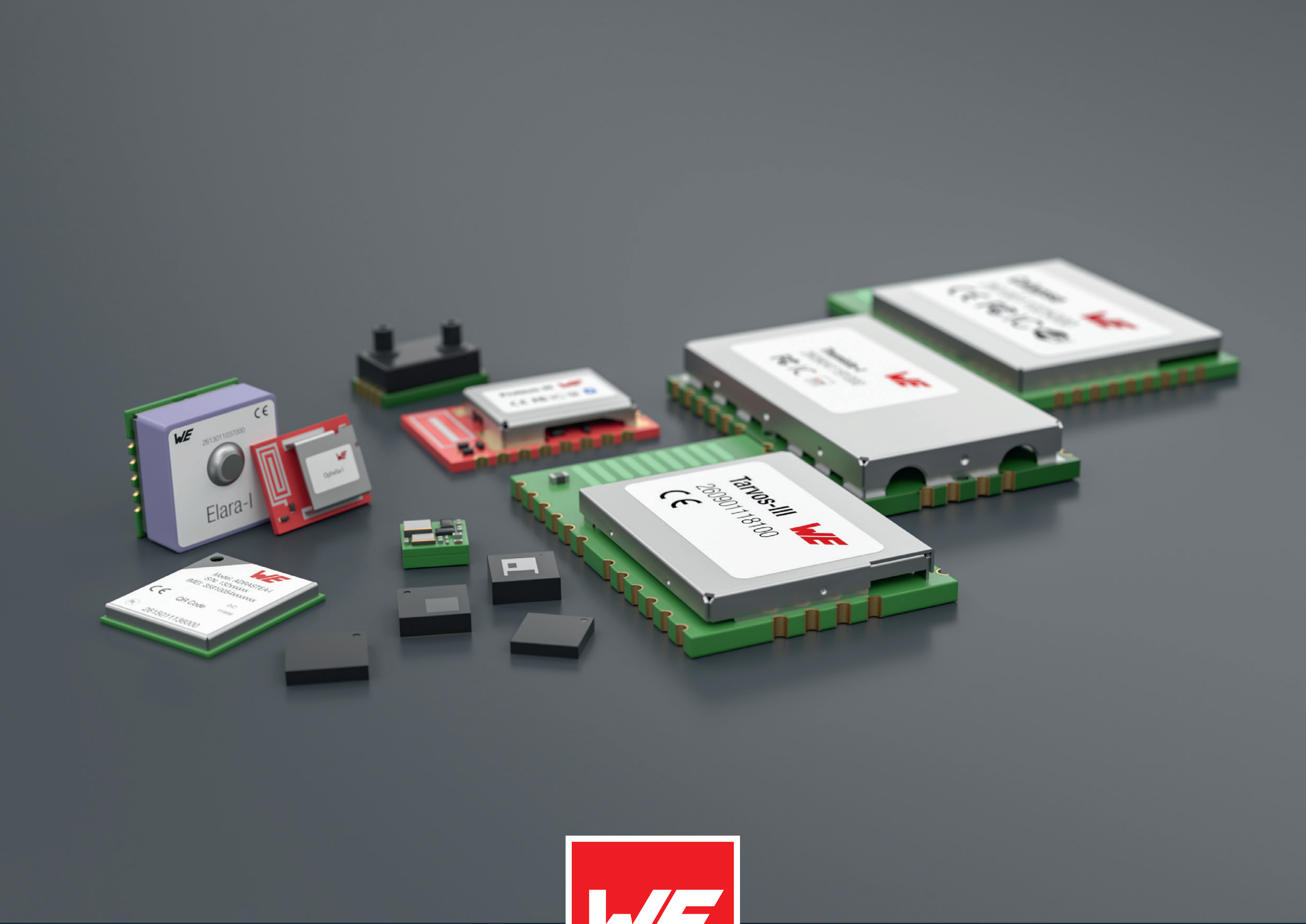


ANR017

GNSS Antenna Selection

Version 1.2

July 19, 2023

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

Revision history

Manual version	Notes	Date
1.0	• Initial version	March 2020
1.1	• Effective dielectric constant formula corrected	April 2020
1.2	• Updated `Important notes`, meta data and document style	July 2023

Abbreviations

Abbreviation	Description
AR	Axial Ratio
BDS	BeiDou navigation System
CP	Circular Polarization
FR4	Flame Retardant 4
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LHCP	Left Hand Circular Polarization
LNA	Low Noise Amplifier
RF	Radio frequency
RHCP	Right Hand Circular Polarization
SAW	Surface Acoustic Wave
SMD	Surface Mounted Device
THT	Through Hole Technology
TM	Transverse Magnetic
VSWR	Voltage Standing Wave Ratio

Contents

1 Introduction 4

2 Basic Antenna Theory 5
2.1 Antenna Radiation Pattern . . . 5
2.2 Efficiency . . . 6
2.3 Directivity . . . 6
2.4 Antenna gain . . . 7
2.5 Bandwidth . . . 7
2.6 Input impedance and VSWR . . . 7
2.7 Polarization and Axial ratio . . . 9

3 General Antenna Consideration 12
3.1 Passive Antenna Types . . . 13
3.1.1 Wire Antennas . . . 14
3.1.2 Loop Antennas . . . 14
3.1.3 Helix Antennas . . . 16
3.1.4 Spiral Antennas . . . 17
3.1.5 Microstrip Patch Antenna . . . 19
3.1.6 Slot Antenna . . . 23
3.1.7 Ceramic Antenna . . . 24
3.1.7.1 Ceramic Chip Antenna . . . 24
3.1.7.2 Ceramic Patch Antenna . . . 25

4 Ceramic Patch Antenna Analysis 27

5 Practical Implementation 32

6 Summary 39

7 Important notes 40

1 Introduction

This application note provides an understanding of antenna theory, antenna design considerations and implementation for GNSS solutions. The first chapter of the document covers basic antenna theory to provide better understanding of the following chapters. The later chapters of the document focus on

- Types of antenna
- Design considerations
- Requirements and specifications
- Simulated analysis
- Practical implementation

Information provided in this application note are intended for GNSS solutions.

2 Basic Antenna Theory

An antenna can be described as a device used to radiate and absorb electromagnetic waves. It transforms the electromagnetic waves from the free space into electrical voltages and currents in conductors and vice versa. The antenna is an essential component in any RF communication system.

In GNSS applications, signals from satellites have very low power level at the earth surface. This imposes a significant importance in selection, design and implementation of an antenna.

2.1 Antenna Radiation Pattern

The radiation pattern is simply defined as the representation of the electromagnetic field or energy radiated from the antenna. All radiation characteristics of an antenna can be represented by a function in 2D or 3D coordinate systems. These patterns are created by measuring the fields radiated from the antenna. They are commonly used to investigate the radiation field characteristics of the antenna in detail.

The radiation patterns vary based on the antenna types and specification such as isotropic, omnidirectional and directional.

Isotropic radiation is exhibited by an ideal antenna that radiates equally on all directions, however these antennas do not practically exist. Omnidirectional and directional are commonly found radiation patterns. Omnidirectional antennas radiate equally in all directions perpendicular to an axis. They exhibit a radiation pattern shaped like a donut in three dimensional representation.

Antennas radiating in a specific direction apart from omnidirectional antennas are referred as directional antennas. The radiation pattern of a directional antenna varies according to the power distribution in different directions.

The radiation pattern is used to describe most antenna parameters in graphical representation for better understanding and interpretation.

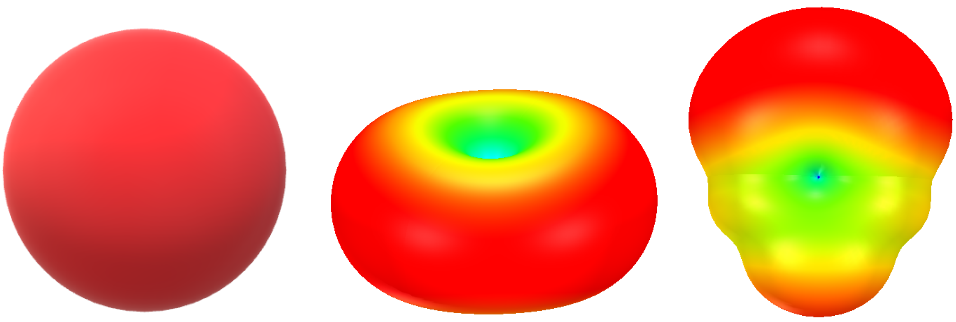


Figure 1: Isotropic, Omnidirectional and Unidirectional radiation pattern

The radiation performance of antenna can be described through some important antenna parameters as follows:

- Efficiency
- Directivity
- Gain
- Bandwidth
- Polarization
- Axial ratio

Some of these parameters are further explained below.

2.2 Efficiency

Antenna efficiency is defined as a combination of radiation, conduction and reflection. The radiation efficiency is simply the ratio of the total power transmitted into space to the input power of the antenna provided by the source. The non-radiated input power accepted by the antenna is lost in form of heat dissipation, dielectric and ohmic losses.

$$\eta = \frac{P_{rad}}{P_{in}} \tag{1}$$

$$P_{in} = P_{rad} + P_l \tag{2}$$

P_{rad} = Radiated power
P_{in} = Input power accepted by the antenna
P_l = Power loss
η = Radiation efficiency

The total efficiency takes the power losses as well as the effect of impedance matching into account. Both total and radiation efficiency can be used to express antenna gain.

2.3 Directivity

Directivity of an antenna is given by the ratio of radiation field density of an antenna in a given direction to the average field density in all other directions.

Depending on the antenna design, direction of the radiation changes. In some cases the antenna radiation is high in one direction relative to other directions. The front to back ratio of the radiation also varies depending on the antenna design. Similar to Gain, the directivity of an antenna is expressed in dB and it can be also expressed in dBi if it is defined relative to an isotropic radiator.

2.4 Antenna gain

Antenna gain is one of the important parameters used to describe antenna performance. In general, antennas are passive components and do not possess gain by itself similar to an amplifier power gain. Antenna gain can also be stated as a factor of radiation efficiency multiplied by directivity. In practice, no antenna can transfer input power completely into radiated output power resulting in radiation efficiency always less than a hundred percent. This results in the antenna gain being always lower than directivity. Gain of an antenna is expressed in dB and it can be also expressed in dBi if it is defined relative to an isotropic radiator.

$$G = D \times \eta \tag{3}$$

G = Antenna gain
D = Directivity
η = Radiation efficiency

2.5 Bandwidth

Bandwidth is defined as a range of frequencies in which the antenna characteristics meets certain specification. These specification are defined based on the end application.

Each characteristic of an antenna varies over the frequency in a different manner. This results in several bandwidth definitions depending on antenna characteristics like Efficiency bandwidth, polarization bandwidth, directivity bandwidth, gain bandwidth and impedance bandwidth. Commonly the antenna bandwidth is referred to impedance bandwidth or return loss bandwidth. The specification is to achieve pure resistive impedance at antenna resonant frequency and to get a minimum of -10dB return loss for the specified bandwidth.

As all the satellites signals are circularly polarized, GNSS application requires maintaining a axial ratio below 3dB in the operating bandwidth of an antenna.

2.6 Input impedance and VSWR

As already discussed an efficient antenna radiates most of its power and has minimum loss to provide better efficiency. Some of the reasons for power loss include reflection of the waves and impedance mismatch in the transmission line.

To maximize power transfer in an antenna, output impedance of the transmission line should match the input impedance of the antenna. In this way, the transmission line maintains the same level of impedance, which is usually the characteristic impedance of the transmission line. This is achieved by the process called impedance matching. In practice, the input impedance of an antenna is affected by many external factors like nearby objects, conducting materials and other antennas. In theory, for purposes of simplification, an isolated antenna composed of real and imaginary parts is considered.

$$Z_{in} = R_{in} + X_{in} \tag{4}$$

R_{in} = Input Resistance
X_{in} = Capacitive or Inductive reactance

The characteristic impedance widely used in the coaxial cables is 50 Ω, which provides best trade-off between loss dissipation and power handling in RF systems. For this reason RF systems commonly work with 50 Ω transmission line.

Transmission lines with improperly matched impedance results in loss of power. Reflection in the transmission line and related phenomena are further defined by some parameters such as reflection coefficient, Voltage Standing Wave Ratio (VSWR) and return loss.

Reflection Coefficient is defined as the ratio of reflected wave voltage to the incident wave voltage.

$$\Gamma = \frac{(Zin - Zout)}{(Zin + Zout)} \tag{5}$$

Zin - Input impedance of the antenna
Zout - Characteristic impedance of the transmission line

Return loss of the antenna is given by

$$RL = 20\log_{10}(|\Gamma|) \tag{6}$$

VSWR is the ratio of maximum voltage to the minimum voltage on the transmission line.

$$VSWR = \frac{(1 + |\Gamma|)}{(1 - |\Gamma|)} \tag{7}$$

2.7 Polarization and Axial ratio

Unlike other parameters, polarization is one of the least explained parameters in antenna characteristics. It is used to describe the vectorial nature of the electric fields radiated by an antenna. Based on the orientation of the electric field expressed by the antennas, the polarization of an antenna is classified into linear and circular and elliptical polarization.

In linear polarization, the electric and magnetic field vectors do not change their direction during wave propagation. If the electric field vectors are perpendicular to earth surface, the wave is vertically polarized. If the electric field vectors are parallel to earth surface, then the wave is horizontally polarized. Figure 2 shows the linear vertically polarized wave propagating in the direction Z. The electric field vectors are represented in straight lines and the magnetic field vectors are represented in dashed lines. Figure 3 shows the direction of the electric field vectors in horizontal and vertically polarized waves respectively. In figure 3, direction of propagation is away from the reader.

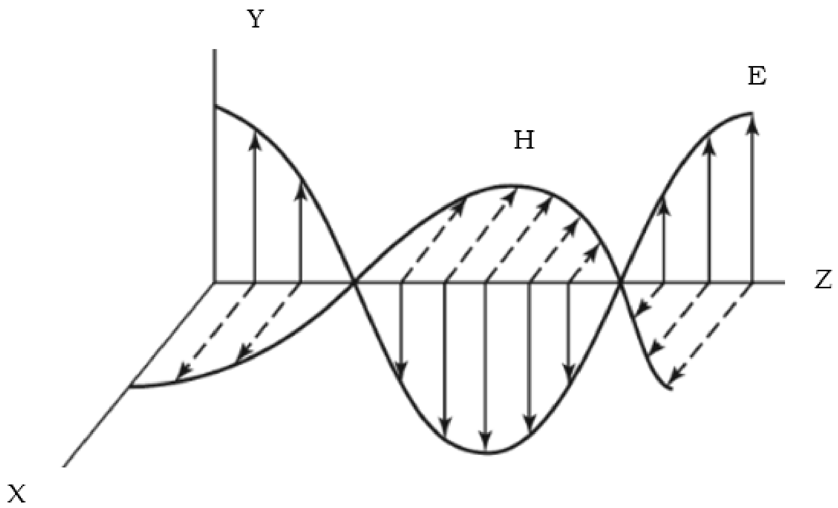


Figure 2: Linear polarization

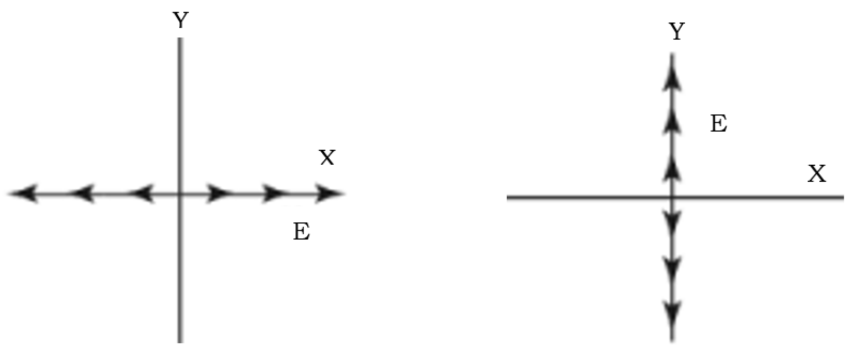


Figure 3: Horizontal and vertical linear polarization

In circular polarization the electric and magnetic vectors do not point in the same direction. They rotate 360° per wavelength during wave propagation. The rotation is achieved by the specific excitation of the orthogonal modes. If the phase delay between the two orthogonal modes is 90°, then circular polarization is achieved. Depending on the direction of rotation, right hand or left hand circular polarization is determined. Figure 4 shows the right hand circular polarized wave propagating in the direction Z. Figure 5 shows the direction of electric field vector rotation in left and right hand circular polarized waves respectively. In the figure 5, direction of propagation is away from the reader.

Due to the relative antenna orientation and high to multipath interference, satellite communication applications tend to use circular polarization.

In practice, it is impossible to obtain a perfect circular polarization, which mostly results elliptical polarization. The ratio of major to minor axis of the ellipse is called the axial ratio. In case of proper circular polarization, the minor and major axis are equal which gives an axial ratio of unity or 0dB. Therefore, it is recommended to design an antenna with an axial ratio as close as possible to 0dB. Depending on the type of antennas various methods are used to achieve circular polarization.

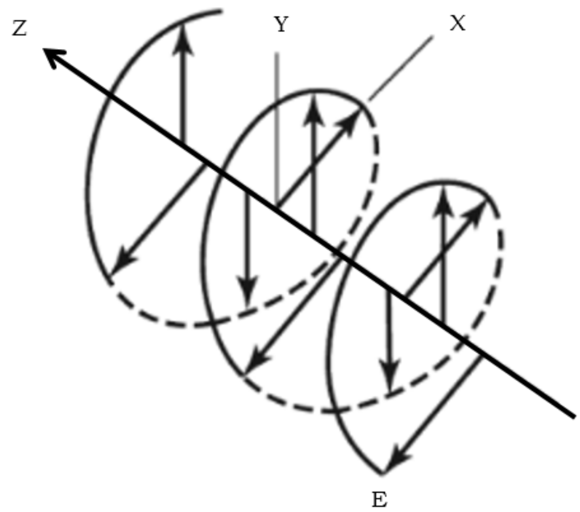


Figure 4: Circular polarization

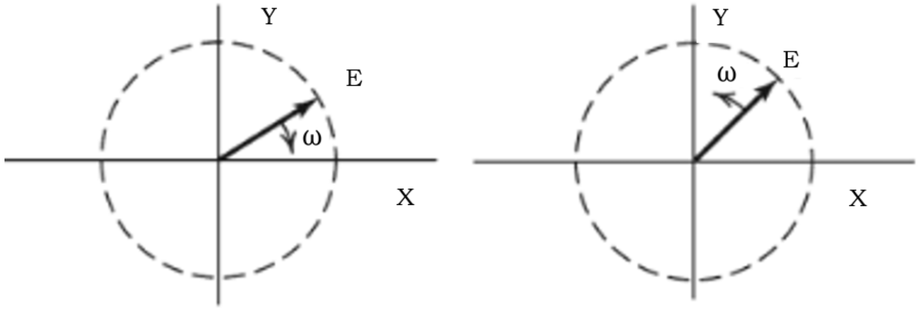


Figure 5: Left hand and right hand circular polarization

3 General Antenna Consideration

Based on the antenna theory described in the previous section, important antenna parameters influencing the performance of the antennas can be understood. The requirements for antenna design and selection are defined by those parameters. In addition to the technical requirements derived from antenna parameters, other factors have to be taken into account in the antenna selection process, such as

- Antenna placement
- Ground plane size and design
- Interference on the application board
- Impedance matching to the system
- Antenna exposure to sky
- Noise factor
- Power consumption
- End application

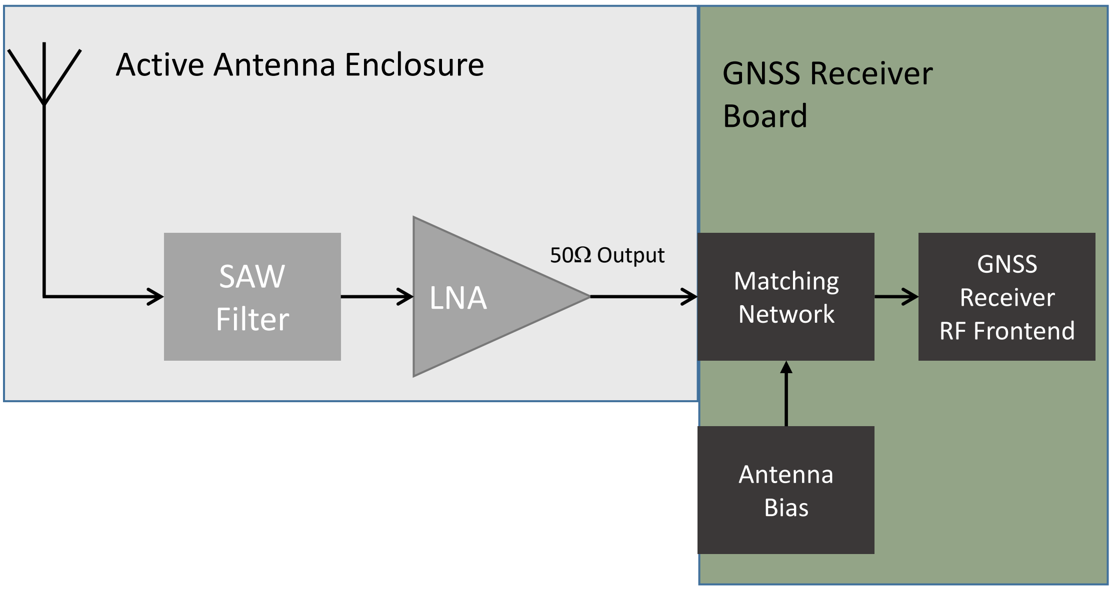


Figure 6: Active antenna implementation

Different GNSS systems are used worldwide for positioning and navigation applications. In general, the GNSS signal has a signal power level of -120dBm to -140dBm at the earth surface, which implies that the GNSS receiver needs minimum carrier to noise ratio approximately in the range from 35dBHz to 50dBHz for optimal performance.

A standard active antenna used for GNSS purpose commonly integrated with a LNA, SAW filter along with 50 Ω matched input connection. So it provides higher gain, sensitivity and reduced noise figure for an optimal performance to the receiver.

However, integration of an active antenna might be critical in applications with low power consumption requirements. A proper gain selection of an active antenna is also necessary as an antenna gain higher than receiver input specification might overload some GNSS receivers.

In the following chapters, this application note focuses on passive antenna types and related considerations.

3.1 Passive Antenna Types

The typical technical antenna requirements of a passive antenna preferred for GNSS application include

- High Gain towards zenith
- Low Noise Figure
- Axial Ratio close to unit
- LHCP signal rejection
- RHCP signal susception
- Properly matched impedance

As the GNSS signals are circular polarized, only circularly polarized antennas are described. It is important for the passive antenna to use circular polarization. This demands RF expertise for design and implementation. The circulation polarization can be obtained in passive antennas through different methods based on the types of antenna.

Common passive antenna types which can provide circular polarization and can be used in GNSS applications are

- Wire Antenna
- Loop Antenna
- Helix Antenna
- Spiral Antenna
- Slot Antenna
- Microstrip Patch Antenna
- Ceramic Antenna

Antennas listed here are originally linearly polarized. Their base designs can be modified to achieve circular polarization.

3.1.1 Wire Antennas

Basic form of commonly used wire antennas are dipole wire antennas which support linear polarization.

Designing a crossed dipole antenna using normal dipole wire antenna is a common method used to obtain circular polarization. The crossed dipole is created by placing two dipole antennas perpendicular to each other. Each dipole antenna is fed with 90° phase shift which results in circular polarization. The crossed dipole antenna is large in size and radiation pattern of the antenna is mostly omnidirectional due to the dipole antenna behaviour.

A crossed dipole to operate at frequency of 1.575GHz has the dimension:

- Dipole length = 71.2mm
- Width = 1.8mm
- Feed gap = 1.8mm
- Ground plane = 142mm x 142mm

It has a RHCP gain of -0.6dBi and Return loss of -13.4dB. Because of the omnidirectional radiation and large dimension of the antenna, it is commonly not preferred for GNSS application.

3.1.2 Loop Antennas

A loop antenna is implemented generally by a bent metallic conductor to form different shapes. Depending on the shapes, number of turns in the loop, structures as well as feeding techniques the performance can be altered to achieve circular polarization.

Loop antennas are commonly used for its directional radiation pattern. The circular polarization in loop antennas is achieved using different methods such as parasitic loop, dual loops

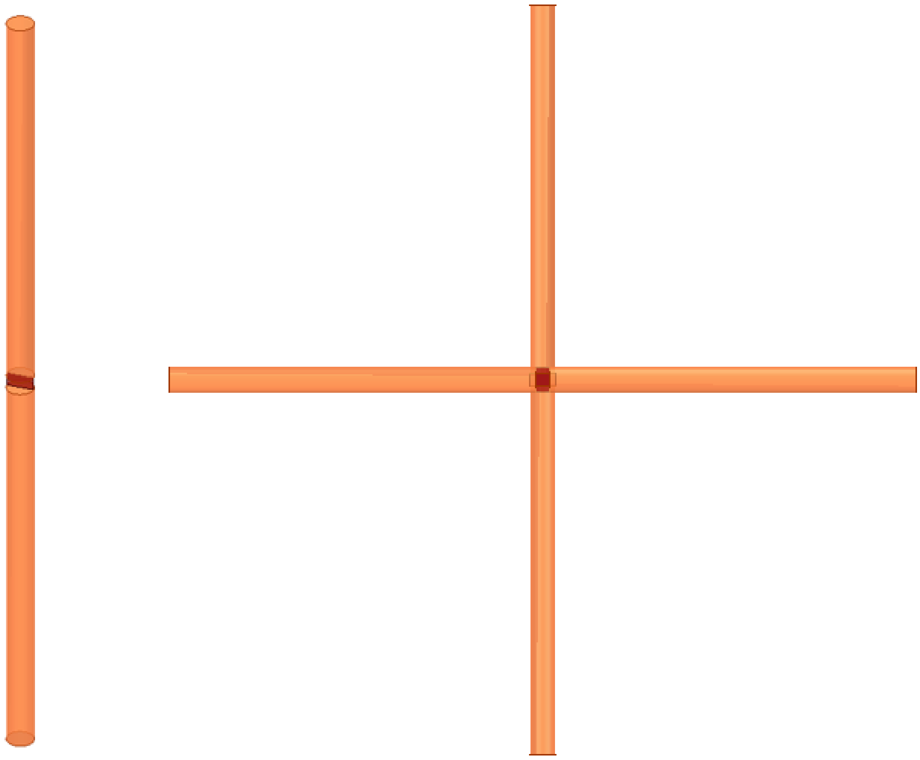


Figure 7: Normal dipole and cross dipole wire antenna

and different types of feeds.

Figure 8 shows a circular loop antenna with two concentric circular loops, among which the inner loop is parasitic loop and the outer loop is a driven loop which is excited by a probe feed. There are gaps in the loops, gap1 and gap2 placed at an angle 45° and 60° respectively. Gap1 of outer loop produces circular polarized fields which is coupled with the inner loop to provide circular polarization. The antenna is designed on an 40x40mm^2 ground plane at a height of 13mm and provides unidirectional radiation pattern. The gain of this antenna is about 7 to 8dBi and VSWR of 3 over the operating frequency at 1.5GHz.

All the parameters of the antenna can be altered to manipulate the antenna characteristics to achieve best performance.

In case of figure 9, a dual rectangular loop antenna is designed on a ground plane of 200mm x 150mm at an height of 53mm excited at the middle through dipole antenna in series. The gaps in the loops are situated symmetrically with respect to the feed. In comparison with single loop antennas, a dual loop antenna significantly increases the AR Bandwidth.

Similar to parasitic loop, all antenna parameters can be optimized for specific performance. The optimized parameters values are x=48.3mm, y=96.7mm, g=5.9mm, L=157.4mm, d=10mm and t=2mm.

At the operating frequency of 1.5GHz and with the optimized parameters the VSWR is 1.07,

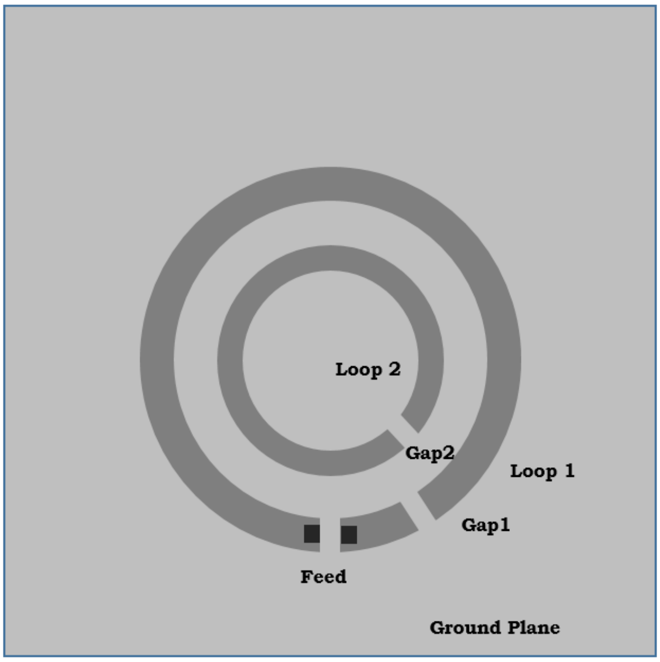


Figure 8: Parasitic loop antenna

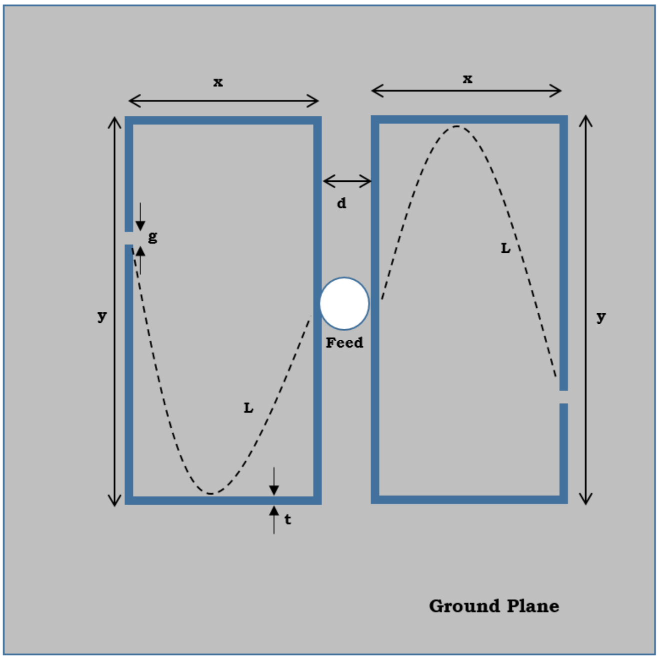


Figure 9: Dual rectangular loop antenna

with minimum AR of 0.03dB and similar gain as parasitic loop antenna.

3.1.3 Helix Antennas

Helix Antenna is a widely preferred antenna structure for the circular polarization. It is designed by a metallic wire wound to form a screw thread like structure. The major parameters to design the helix antenna which significantly influences the antenna performance are

- Number of turns (N)
- Pitch angle (α)
- Separation between turns (S)
- Diameter (D)
- Length of the antenna (L)
- Circumference of one turn (C)

The circumference of the turns defines the mode of operation. If the circumference of one turn (C) is small compared to the wavelength then the mode of operation is referred as normal mode. In normal mode the antenna exhibits linear polarization. If the circumference of one turn is same or nearly equal to the wavelength then the mode of operation is referred as Axial mode.

Axial mode is the preferred operation mode because of its circular polarization and unidirectional gain. One other mode of operation called higher-order radiation mode occurs when the circumference exceeds the wavelength. This results in splitting the major lobe of the radiation pattern.

For optimal performance in axial mode, the design equations of the key parameters are given by

$$\frac{3}{4} < C < \frac{4}{3}\lambda \tag{8}$$

$$S \approx \frac{1}{4} \tag{9}$$

$$12^\circ \leq \alpha \leq 14^\circ \tag{10}$$

An axial mode helical antenna with minimal possible dimension to operate at 1.575GHz is given as: L=19.3cm, C=21.2cm, D=6cm, S=4.2cm and N=4. The antenna is designed on a ground plane of 21.5cm x 21.5cm. It has a RHCP gain of 11.6dBi and return loss of -13.8dB. Despite having good characteristics, these antennas have some limitations such as high dimension and complex integration. Ceramic helical antenna are also designed in order to reduce antenna size.

3.1.4 Spiral Antennas

Spiral antennas provide frequency-independent performance in terms of radiation pattern, impedance and polarization which is independent of frequency. This behaviour allows to operate over a wide range of frequencies.

Figure 11 shows different types of planar spiral antennas like sinusoidal log and archimedean spiral antenna respectively. The antenna has two conducting arms flaring outwards from the center. The structure of the arms flaring out depends on the type of spiral. For instance a typical planar archimedean spiral antenna arm is defined by the equation

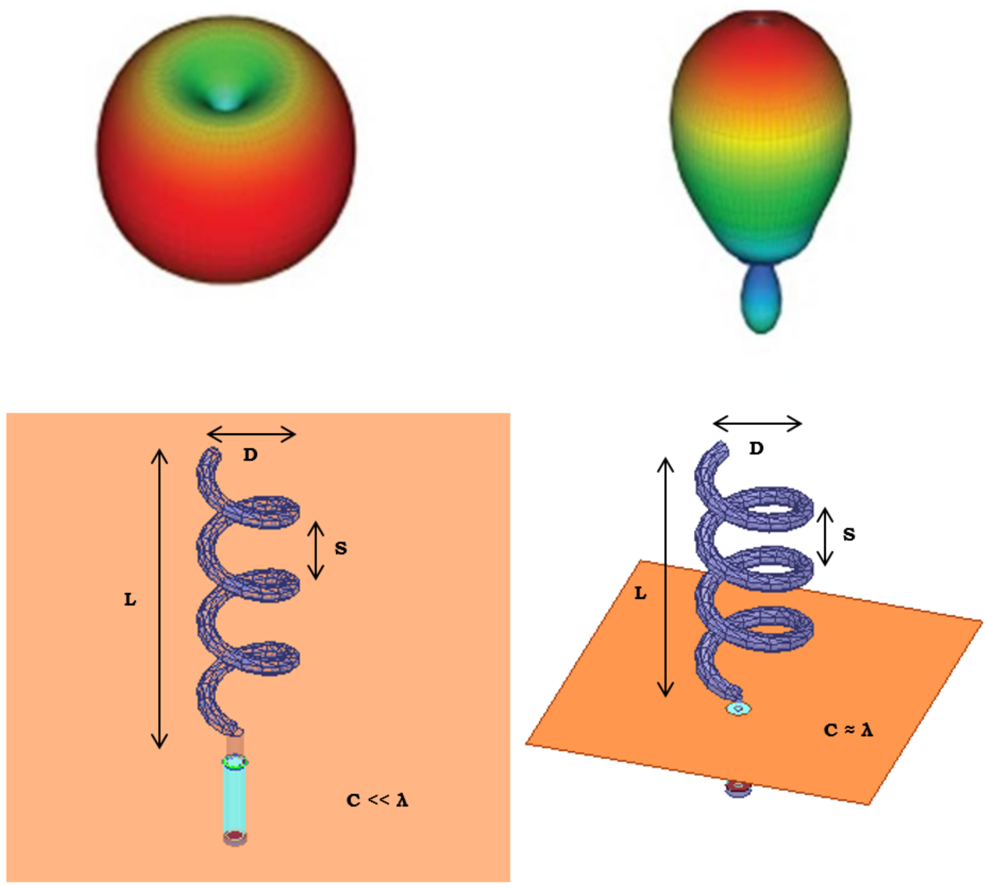


Figure 10: Helix antenna normal and axial mode

$$r = r_0 a \phi^{(\frac{1}{b})} \tag{11}$$

r- Inner radius
a - Expansion Coefficient
b - Spiral Coefficient
ϕ - Angle at radius linearly increase

The arms are excited in balanced mode with equal amplitude and with phase difference of 180°. This design results in the radiation of circularly polarized waves.

The characteristics of different planar spiral antenna types with minimum possible dimension to operate at frequency 1.575GHz are displayed in the Table 1.

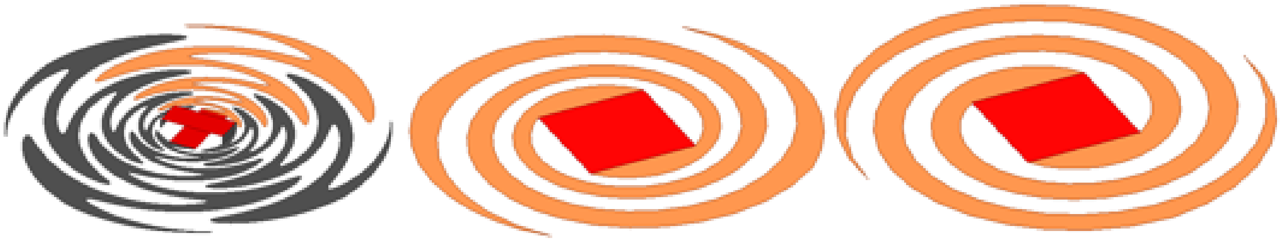


Figure 11: Different types of spiral antenna

Patch type	RHCP Gain(dBi)	Return Loss(dB)	Antenna Dimension
Planar Spiral-Log	2.1	-5.56	90mm x 90mm
Planar Spiral-Archimedean	0.92	-2.86	70mm x 70mm
Planar Spiral-Sinuous	4.8	-3.92	120mm x 120mm

Table 1: Spiral antenna characteristics

3.1.5 Microstrip Patch Antenna

Microstrip patch is one of the popular PCB antennas. It is well known for its low profile, low cost, compact design and easy implementation. Patch antennas provide many design possibilities to manipulate antenna behaviour. The required performance of the antenna can be achieved by modifying the

- Structure
- Feed technique
- Patch design

During the design process, very common shapes of patch considered are rectangular and circular patches. Depending on the dimensions of base patch, the shape further changes. Some of basic shapes are shown in the figure 12

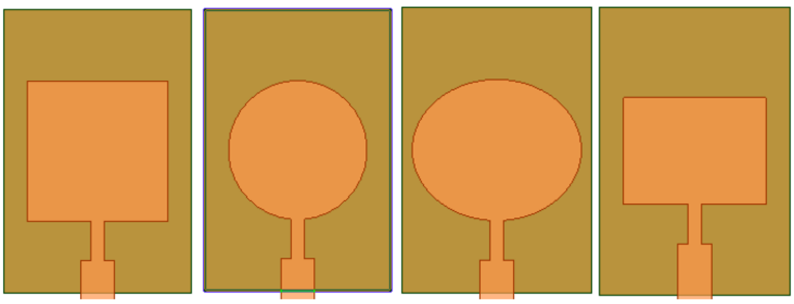


Figure 12: Microstrip patch antenna shapes

Once the shape of the patch is decided, the next important step is the feeding type to be used. Generally, there are four types of feeds used for the excitation. These feed types are

1. Edge feed
2. Inset feed
3. Probe feed
4. Slot Feed

The above listed feed types are shown in the figure 13 respectively.

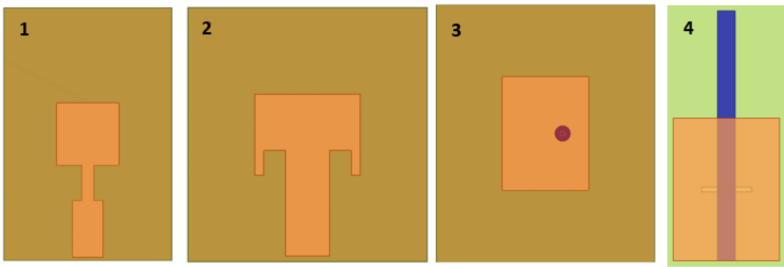


Figure 13: Feed types in microstrip patch antenna

A specific performance can be achieved using different designs, producing different patch antenna solutions. During the design process, all requirements of the end application shall be taken into account. Design considerations relevant to circular polarization shall also be taken into account. Centre operating frequency depends on the dimension of the patch.

The width of the patch is determined approximately by the equation.

$$W \approx \frac{c}{2fc\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{12}$$

The effective dielectric constant is given by the equation

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(\frac{1}{\sqrt{1 + \frac{12h}{W}}}\right) \tag{13}$$

Effective length of the patch is given as

$$L_{eff} \approx \frac{c}{2fc\sqrt{\varepsilon_{eff}}} \tag{14}$$

Actual length of the patch is

$$L = L_{eff} - 2\Delta L \tag{15}$$

From the equation it can be seen that the length and width of the patch are inversely proportional to the relative permittivity of the substrate. If size of the patch decreases, the relative

permittivity increases.
In case of circular patch the approximate radius is given by the equation

$$r \approx \frac{F}{\sqrt{1 + \frac{200h}{\pi \varepsilon_r F}[ln(\frac{\pi h}{200h}) + 1.7726]}} \tag{16}$$

$$F = \frac{8.791 \times 10^9}{fc\sqrt{\varepsilon_r}} \tag{17}$$

c - Velocity of light in vacuum
fc - Centre operating frequency
ε_r - Relative Permittivity of the substrate
h - Thickness of substrate
△L - Length extension of patch during operation
r - Radius of the Patch

Even though the circular patch antenna has the advantage of wider bandwidth compared to rectangular patch, the fabrication of circular patch is more challenging compared to the rectangular patch. Therefore rectangular patch is preferred in practical application.

Antenna characteristics of different Microstrip patch antenna types with minimal possible patch dimension without optimization to operate at frequency of 1.575GHz are given in the Table 2. Further optimization and impedance matching is possible in the end application.

Patch type	RHCP Gain(dBi)	Return Loss(dB)	Patch Dimension	Ground Dimension
Rectangular-Probe fed	2.7	-6.26	58mm x 45mm	97mm x 77mm
Rectangular-Inset fed	1.87	-10.32	58mm x 45mm	97mm x 138.7mm
Rectangular-Edge fed	1.7	-3.25	58mm x 45mm	97mm x 196.2mm
Circular-Probe fed	0.1	-0.3	45mm x 45mm	55mm x 55mm
Elliptical-Inset fed	-4.2	-0.72	58mm x 45mmm	97mm x 138.7mm
Elliptical-Edge fed	-4.3	-0.74	58mm x 45mmm	97mm x 196.2mm

Table 2: Microstrip patch antenna characteristics

After creating the basic design, the tuning of an antenna to achieve optimal performance is made by further detailed design process. This tuning optimizes the antenna characteristics. As already discussed, the basic concept of circular polarization is the excitation of two orthogonal modes (TM01,TM10) equally but with a 90° phase difference. In case of microstrip patch antenna, circular polarization phenomena is obtained by means of several feeding techniques and combinations. One important condition to be always considered is to maintain 50 Ω impedance microstrip lines in the feed networks.

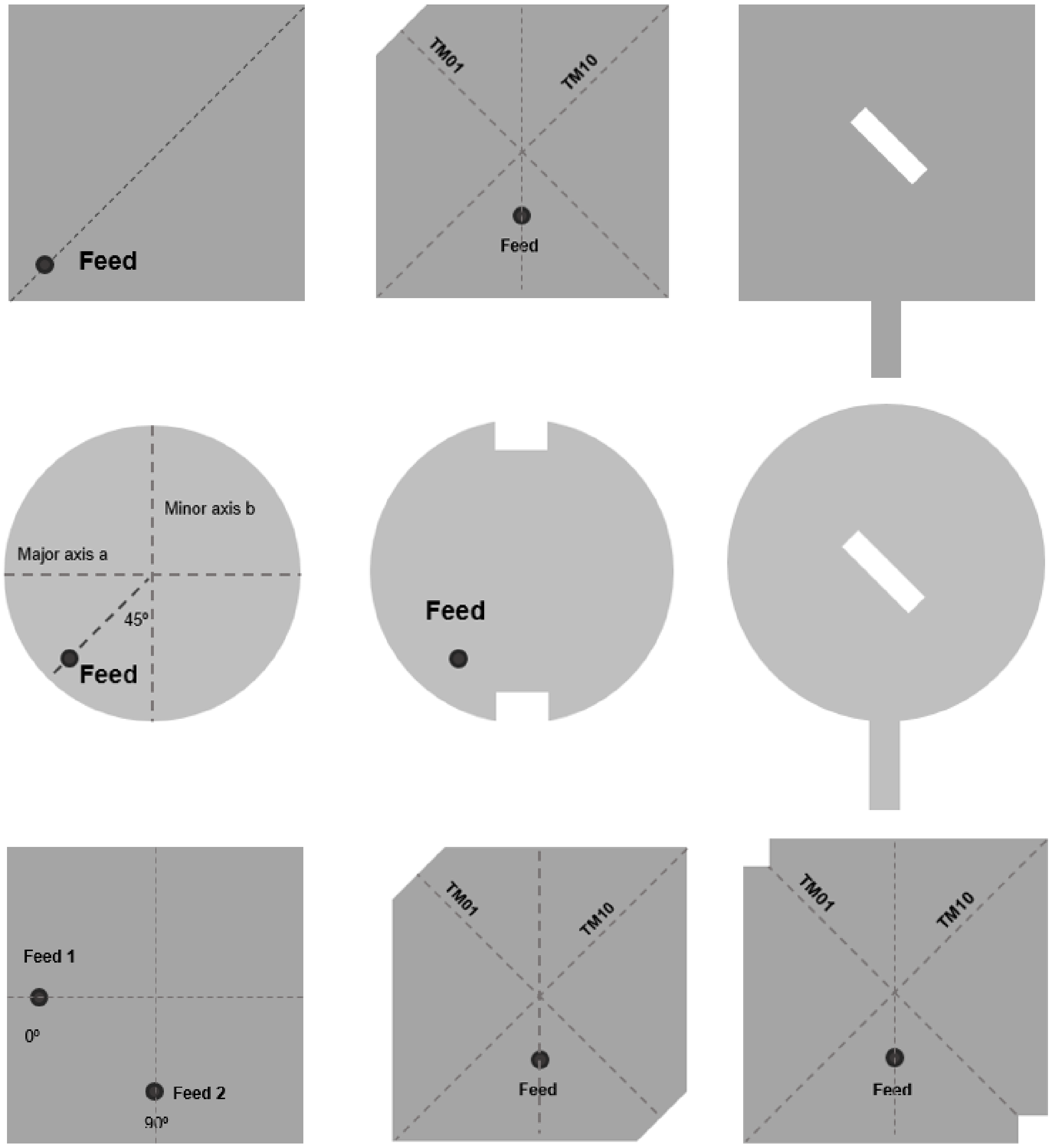


Figure 14: Circular polarization feed techniques

The feeding techniques include

- Single feed with different excitations
- Excitation at specific angles
- Combination with slots
- Corner truncation
- Perturbation
- Dual or multi feeds
- Different feed network

Few of these feed techniques are shown in figure 14

3.1.6 Slot Antenna

Slot antennas are very simple PCB-based antennas. Their design is based on the concept of microstrip patch antenna. Generally the slot antenna has a microstrip feed on bottom layer of the PCB and a slot above on the top layer. The electromagnetic energy is coupled to the slot through micro strip which enables the slot to radiate as an antenna. They are simpler to design and can be easily integrated along with other active and passive devices. A broader bandwidth relative to a normal microstrip patch can be achieved.

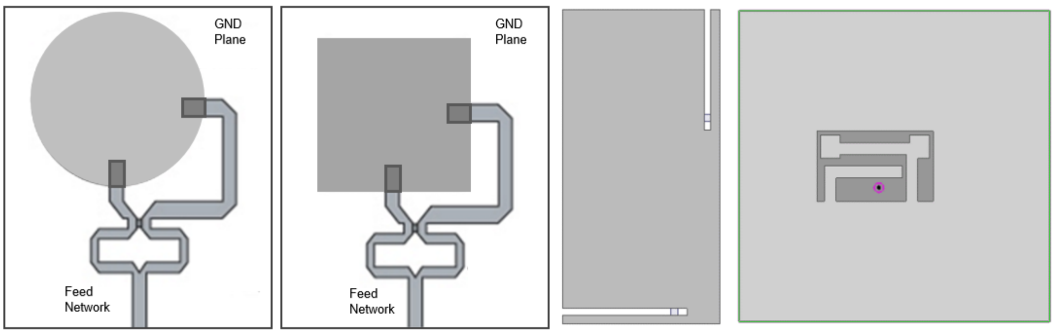


Figure 15: Different types of slot antennas

Circular polarization in the slot antenna is achieved by modifying the feed. Typical feed technique is to design a power divider in the microstrip line, so that two feeds with a quarter wavelength excited at two orthogonal modes with a phase shift of 90°. To operate at 1.575GHz, a microstrip fed slot antenna has a length=89mm, width=4.5mm and designed on a 134mm x 178mm ground plane. It provides a RHCP Gain of 2.1dBi and Return loss of -17.6dB.

The slots and feed shapes as well as structures can be varied in numerous ways to achieve circular polarization. Some of such slot antenna types are shown in the figure 15

3.1.7 Ceramic Antenna

Ceramic antenna as indicated by the name itself, is an antenna created using ceramic as its core material. The main reason of using ceramic material is strict size requirements in some applications. As ceramic has higher relative permittivity compared to commonly used FR4 PCB substrate, size of the ceramic antenna is relatively small. The size reduction also results in reduced gain, directivity and bandwidth of the antenna. Nevertheless, comparing to the similar antenna design in FR4 substrates of same dimension, ceramic antennas provide the better gain and directivity.

There are three major types of ceramic antennas. The first is the ceramic resonator or dielectric resonator antenna which is commonly a ceramic cuboid or cylinder block used to radiate energy. A single ceramic block cannot produce efficient results in all required antenna applications, they need to be adapted to the end application.

The second type is the ceramic patch antenna which is widely used for GNSS application

The third type is ceramic chip antenna which is well known for the small size and high efficiency.

3.1.7.1 Ceramic Chip Antenna

Ceramic chip antenna presents advantages in size, high gain and ease of implementation. It is therefore one of the good choices of antenna for GNSS solutions. This type of antenna is mostly used in relatively small like mobile applications.

Ceramic chip antenna provides relatively high gain in comparison to other antennas of similar size, but does not provide optimal circular polarization and its performance is highly affected by the ground plane. Commonly chip antenna comes under the monopole antenna classification. In this classification, antenna together with the ground plane exhibit a dipole antenna characteristic. The high gain of the chip antenna is achieved by a sufficiently large ground plane. Some ceramic chip antenna manufacturers represent antennas with no ground plane requirement which is not exactly true.

The linear polarization characteristics, ground plane influence, design consideration like isolation distance, footprint and mounting of ceramic chip antenna shall be always taken into consideration during design. To achieve much higher performance, the size of the antenna is relatively increased which leads to further increase in ground plane size. Due to these difficulties, chip antennas are only considered for suitable applications.

Some of the ceramic chip antennas available in the market and their typical characteristics are given in the Table 3. All antennas listed in the table are linearly polarized and have own specific layout recommendations. Impedance matching is possible in the end application.

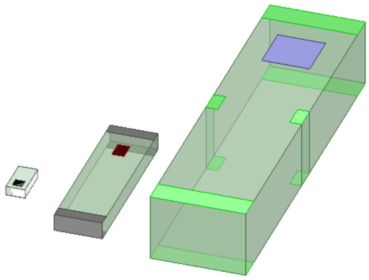


Figure 16: Ceramic chip antenna

Dimension	Gain(dBi)	Bandwidth(MHz)	Return Loss(dB)	Ground Plane
3.2x1.6x0.5mm	-2	10	< -10	80mm x 40mm
10x3.2x1.5mm	-1.6	20	< -10	80mm x 37mm
10x10x0.9mm	1.2	45	< -10	70mm X 40mm
12x3mm x 2.4mm	1.6	45	< -10	70mm x 50mm
15x4mm x 3.2mm	1.6	45	< -9.5	100mm x 50mm

Table 3: Ceramic chip antenna characteristics

3.1.7.2 Ceramic Patch Antenna

Ceramic patch antenna is a patch antenna designed on ceramic substrate instead of the common printed circuit board. Due to nature of the ceramic material and flexible design solution of microstrip patch antenna, Ceramic patch antennas provide optimal performance and are suitable for GNSS application. As discussed in the section 3.1.5, possible microstrip patch antenna designs apply to ceramic patch antennas as well. Because of the implementation of the patch design on the ceramic substrate, the size of antenna can be reduced depending on the ceramic material.

A typical dimension of microstrip patch for GNSS application is approximately 60mm x 40mm, whereas ceramic patch antennas are available from dimension of 10mm x 10mm. Although the characteristics change depending on size, they can be optimized by tuning the antenna. Usage of ceramic substrate supports size reduction of the antenna.

If properly implemented, a ceramic patch antenna is circularly polarized and possess a hemispherical radiation pattern. This leads to directivity almost twice the directivity of omnidirectional antenna.

The high directivity from radiation pattern allows higher antenna visibility to sky and reduces the interference from other devices nearby. Although the peak gain of the antenna even with small ground plane would be high, the bandwidth reduces and also the Axial ratio gets affected. The flexible design possibilities of the patch allow fine tuning of the antenna.

As of a very small ceramic patch, the performance reduces considerably. The typical preferred size of the ceramic patch antenna range from 10 to 35mm.
Some of the typical characteristics of ceramic chip antennas for different sizes are given in

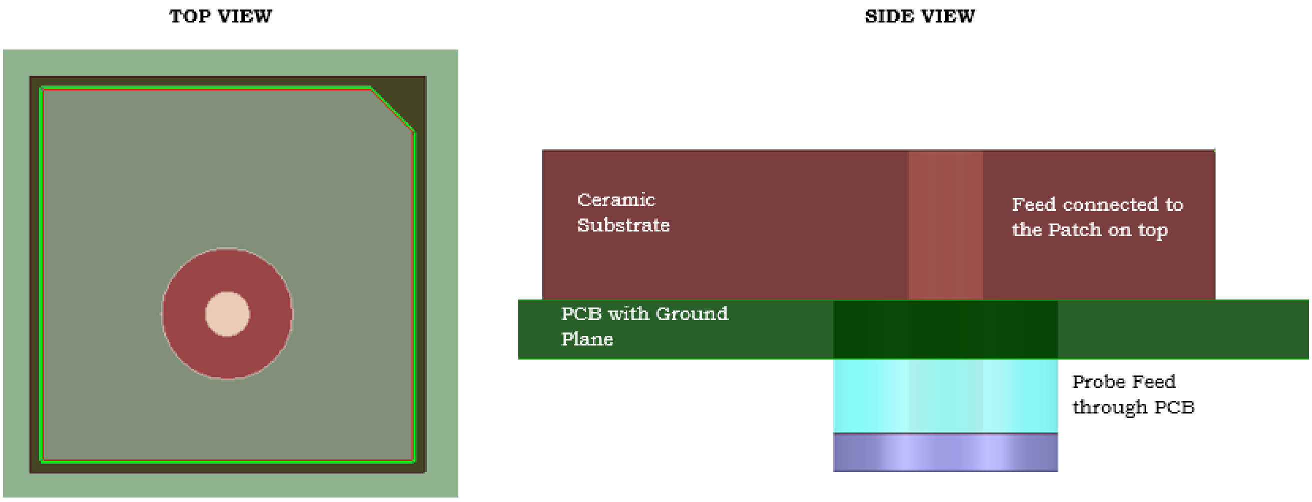


Figure 17: Ceramic patch antenna

Table 4. All antennas listed in the table are right hand circularly polarized with an axial ratio of 1-2.5 dB and the characteristics are displayed for the ground plane size of 75mm x 75mm.

The antenna tuning and impedance matching can be done in the end application for further improvement in the characteristics.

Dimension	RHCP Gain(dBic)	Bandwidth(MHz)	Return Loss(dB)	Efficiency
10x10x4mm	2	10	< -10	45%
13x13x4mm	3	15	< -10	50%
15x15x4mm	3-4	15	< -10	70%
18x18mm x 4mm	4.5-5.5	20	< -10	70%
25x25mm x 4mm	5.5	25	< -9.5	80%

Table 4: Ceramic patch antenna characteristics

4 Ceramic Patch Antenna Analysis

As described in the previous section, the ceramic patch antenna is one of the most suitable antenna for GNSS application and provides flexible designing to optimize the antenna performance. This section allows to understand the antenna behaviour and design considerations to be taken care before implementation of the antenna in practical application.

The smallest and most suitable ceramic patch antenna dimension is 18mm x 18mm, as this antenna size has a bandwidth to provide required performance at all the interested frequency of the GNSS application with the same design optimization. If the size of the antenna is smaller, complex optimization is needed for different operating frequency.

There are two types of common mountings used in the ceramic patch antenna: SMD and THT. The typical ground plane size of the 18mm x 18mm ceramic patch antenna for optimal performance is 75mm x 75mm. Although by designing the patch the antenna performance can be tuned, it has to be done by antenna design engineers and requires RF expertise. For an already designed antenna the performance can also be manipulated by the ground plane size, positioning and impedance matching.

To get a general overview and observe the behaviour of the already designed antenna, an 18mm x 18mm through hole mount antenna is simulated with two different conditions.

Firstly the antenna ground plane is varied from 20 mm^2 to 75 mm^2 throughout the simulation. In the second setup, the position of the antenna is varied based on distance between the edge of the ceramic patch antenna and the edge of the ground plane.

For a 75 mm^2 standard ground plane shown in figure 18 the value of L is varied from 0mm to 28.5mm, moving the antenna in a diagonal path from the corner to the center of the ground plane.

The antenna is already tuned to the center frequency of 1576MHz and due to the change in the size of the ground plane, the center frequency is shifted which results in detuning of antenna. Although results for the antenna with different dimensions are subjected to change, the behaviour of the antenna remains similar.

The analysis shows the importance of understanding the behaviour, design consideration and implementation of the ceramic patch antenna. Figure 19 shows that, if the condition of antenna implementation changes, the characteristics like center frequency, bandwidth, gain and axial ratio change as well. The size of the ground plane is modified by the parameter G.

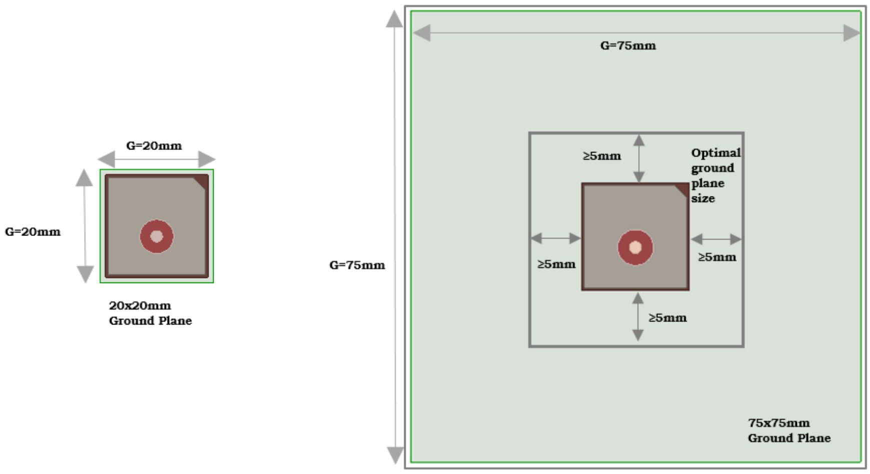


Figure 18: Ceramic patch antenna simulation - different ground plane

As from the results, it can be observed that the change in the ground plane influences all the important parameters. Once the ground plane size decreases from the required size G=75mm to 20mm, the antenna gets detuned to lower frequency. The rapid drop in center frequency occurs around G=28mm, when the ground plane size becomes very small. On a typical ceramic patch antenna implementation, it is better to have at least a ground size 10mm larger than the antenna size, so that all sides of the antenna edge have distance of 5mm to the edge of the ground plane.

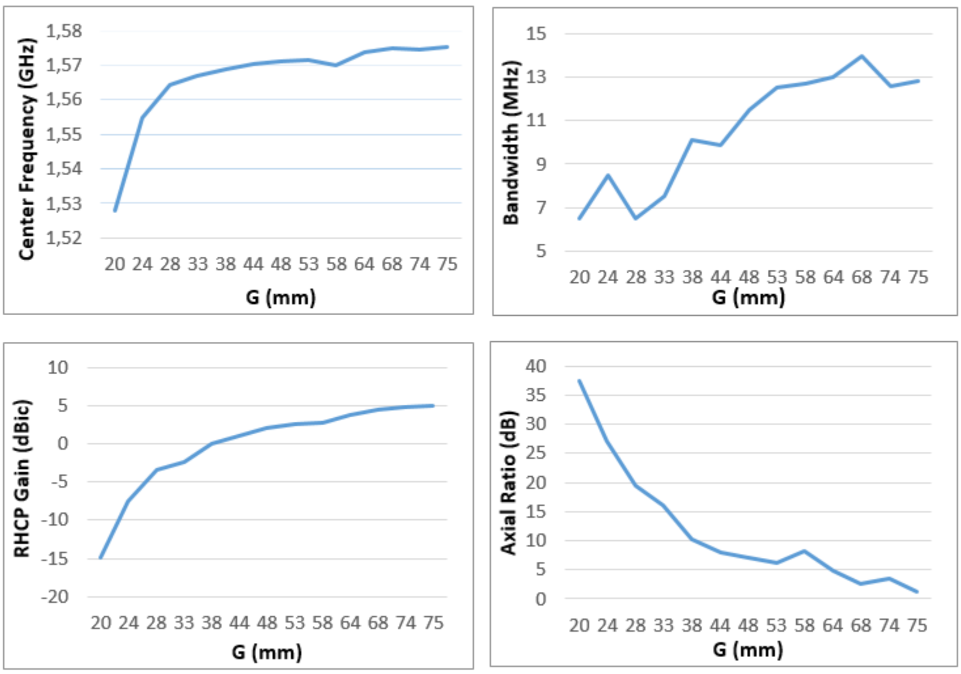


Figure 19: Antenna performance for different ground plane

Design or implementation of other components in the near 5mm distance around the antenna can affect the antenna performance. So generally, a minimum of 5mm keep out distance from antenna to other components is recommended in layout design

The bandwidth becomes narrower with reduction in ground size reduction. The most affected parameters are the RHCP Gain and Axial ratio, as seen in the results there is a phenomenal change by the ground plane size reduction.

Similar to the size of the ground, the position of antenna on the ground plane also changes the antenna characteristics. This is due to the change in the asymmetrical distribution of the ground plane created by the change in antenna position. To observe the changes in antenna characteristics in response to the change in antenna position on ground plane, a simulation is executed. On the standard ground plane of 75x75 mm^2 size, the position of the antenna is moved from the corner to the center of the ground plane in a diagonal path by varying the value of the parameter L from 28.5mm to 0mm. This setup can be seen in figure 20. The simulation results are shown in figure 21.

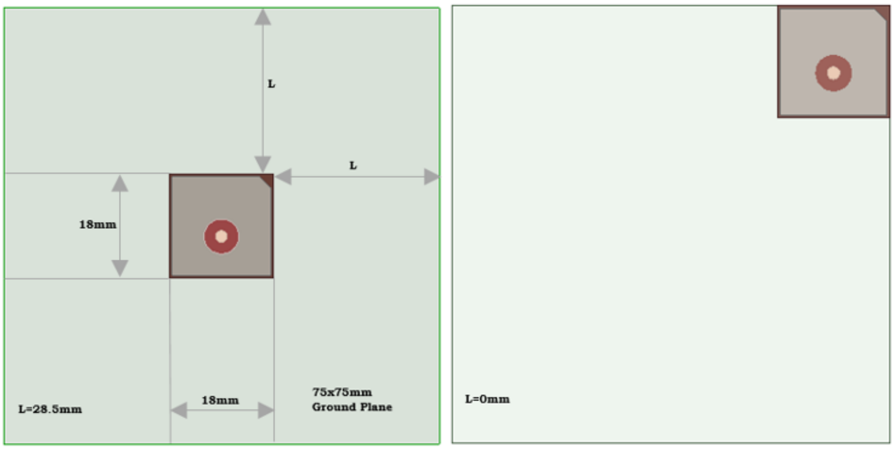


Figure 20: Ceramic patch antenna simulation - different antenna position

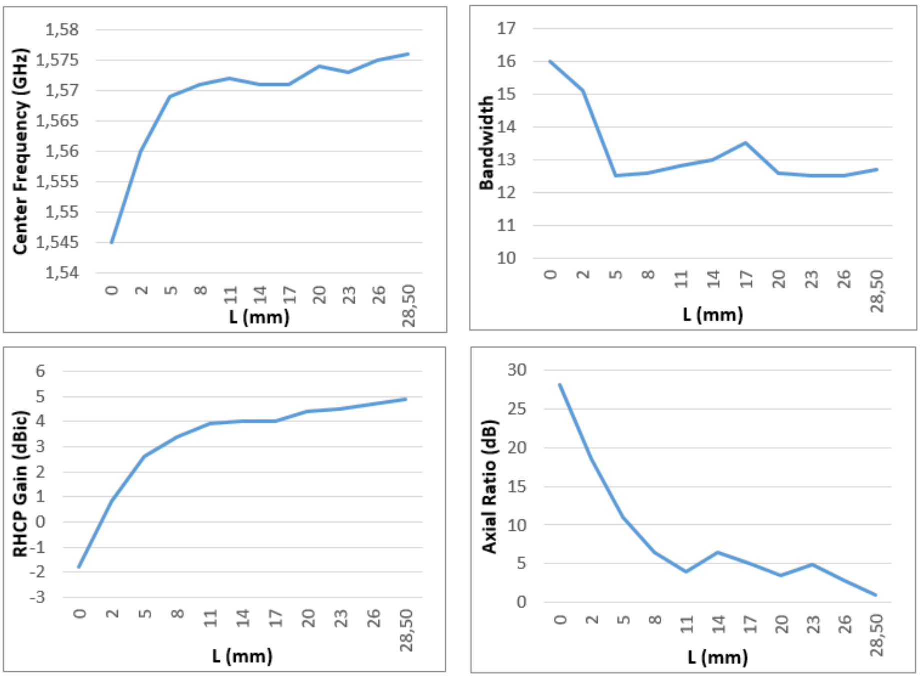


Figure 21: Antenna performance for different antenna position

In the results, the center frequency, bandwidth and RHCP gain show small variation until the antenna approaches the corner of the ground plane. Once the antenna moves very near approximately 5mm to the corner, the center frequency and RHCP gain are affected significantly which is seen by the reduced antenna performance. Although the bandwidth increases approaching the corner, other parameters are drastically affected with the antenna positioned near the corner of the ground plane. Most significantly the axial ratio is affected with the change in position resulting in depolarization. This indicates that during the design process, the antenna shall not be positioned near the edges or corner of the ground plane, as it results in antenna performance degradation.

5 Practical Implementation

From the previous chapters, it can be understood that to implement the ceramic patch antenna on a printed circuit board, certain design considerations should be taken into account. In order to understand the antenna behaviour in real life scenario, the practical implementation of a ceramic patch antenna is further explained in this section.

A ceramic patch antenna of size 18mm x 18mm with the through hole mount is designed on two different Boards. PCB-A is a four layer PCB with dimension 60mm x 90mm. The ground plane in PCB-A is distributed on layer 2 and layer 4. Layer 1 and layer 3 of the PCB are dedicated for signal and power traces. Antenna feed is connected to the coplanar stripline on the bottom layer.

PCB-B is also a four layer PCB with dimension 60mm x 118mm. The ground plane in PCB-B is separated between the antenna and main ground plane. The main ground plane of the PCB has a dimension of 60mm x 90mm distributed on the layer 2 and layer 4. Layer 1 and layer 3 of the PCB are dedicated for signal and power plane. The ceramic patch antenna has a dedicated ground plane underneath on all the four layers with a dimension of 24mm x 24mm. The antenna ground plane is connected to the main ground plane on layer 3 and layer 4. This connection also supports the coplanar strip line feed connection to the antenna pin on the bottom layer.

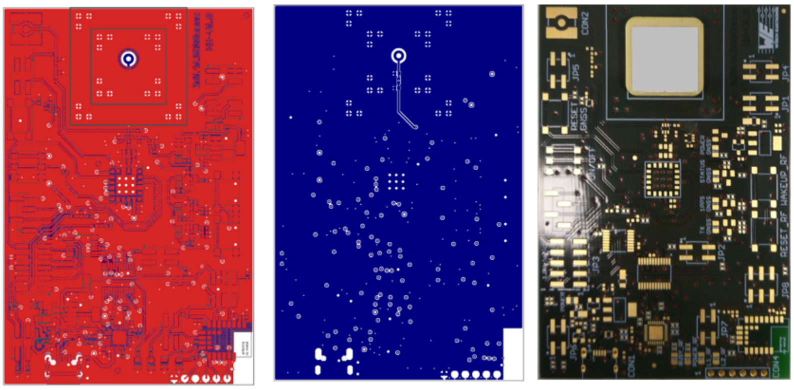


Figure 22: PCB-A

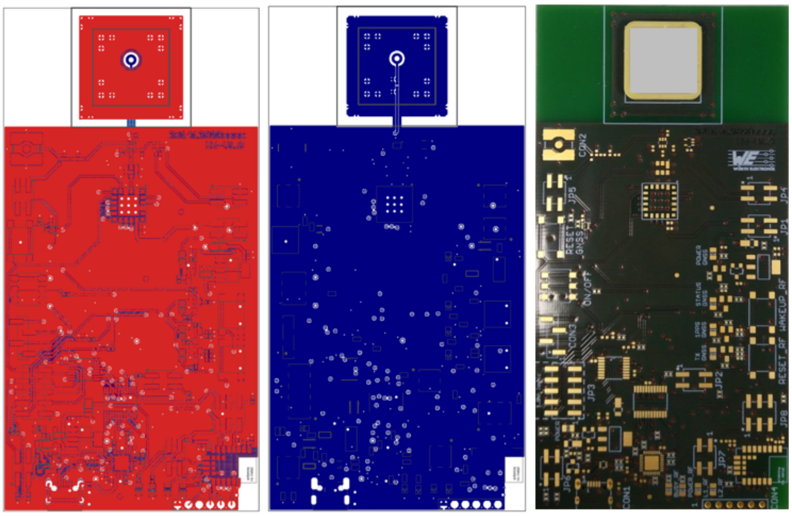


Figure 23: PCB-B

As described already, tuning an antenna for a specified ground can be done on the ceramic patch antenna through the modification handled on the patch. Apart from tuning the antenna through the patch modification, the impedance matching method is the most commonly used tuning method which allows to a set the antenna in optimal performance for certain frequency range. Impedance matching allows to match the antenna input impedance to a characteristic impedance of the transmission line. Using impedance matching the antenna can be set into resonance at operating frequency, achieve low return loss and better signal reception.

To have a 50 Ω impedance matched coplanar line from the receiver output to antenna input, the input impedance of the antenna should be known. It can be seen from figure 24 that four different through hole ceramic patch antennas (A1, A2, A3, A4) of dimension 18mm x 18mm are soldered on both PCB-A and PCB-B.

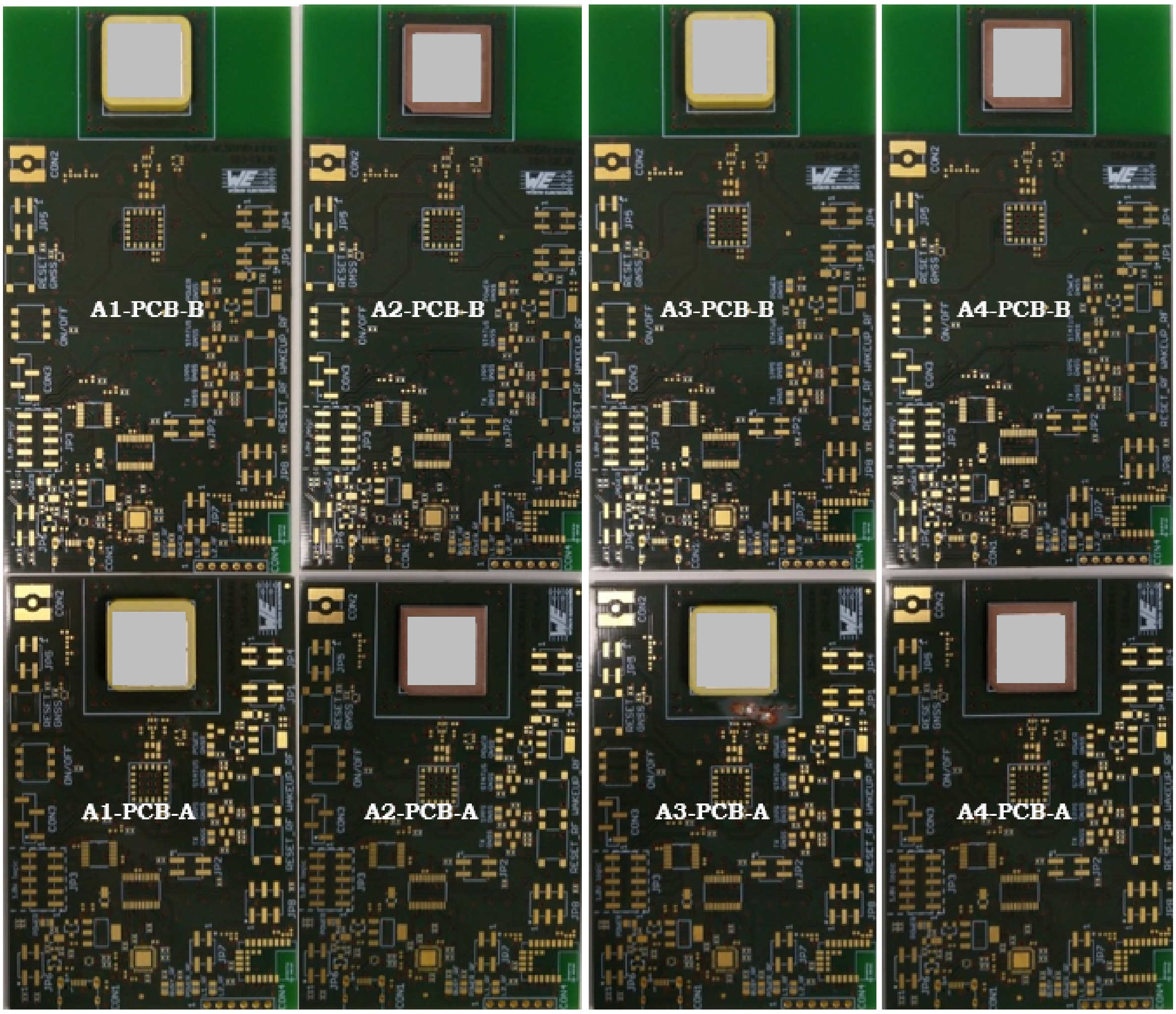


Figure 24: Antennas assembled on PCB-A and PCB-B

The antennas are from different manufacturers and have similar characteristics. Firstly, the impedance characteristics and return loss of the antenna on two PCB variants are observed using a network analyzer which is shown in the figure 25.

In figure 25, there can also be seen the markers are placed on the frequencies representing the important GNSS systems as GPS, Galileo, GLONASS and BeiDou.

- Marker 1: 1.561 GHz (BeiDou)
- Marker 5: 1.609 GHz (GLONASS)
- Marker 6: 1.575 GHz (GPS, Galileo)

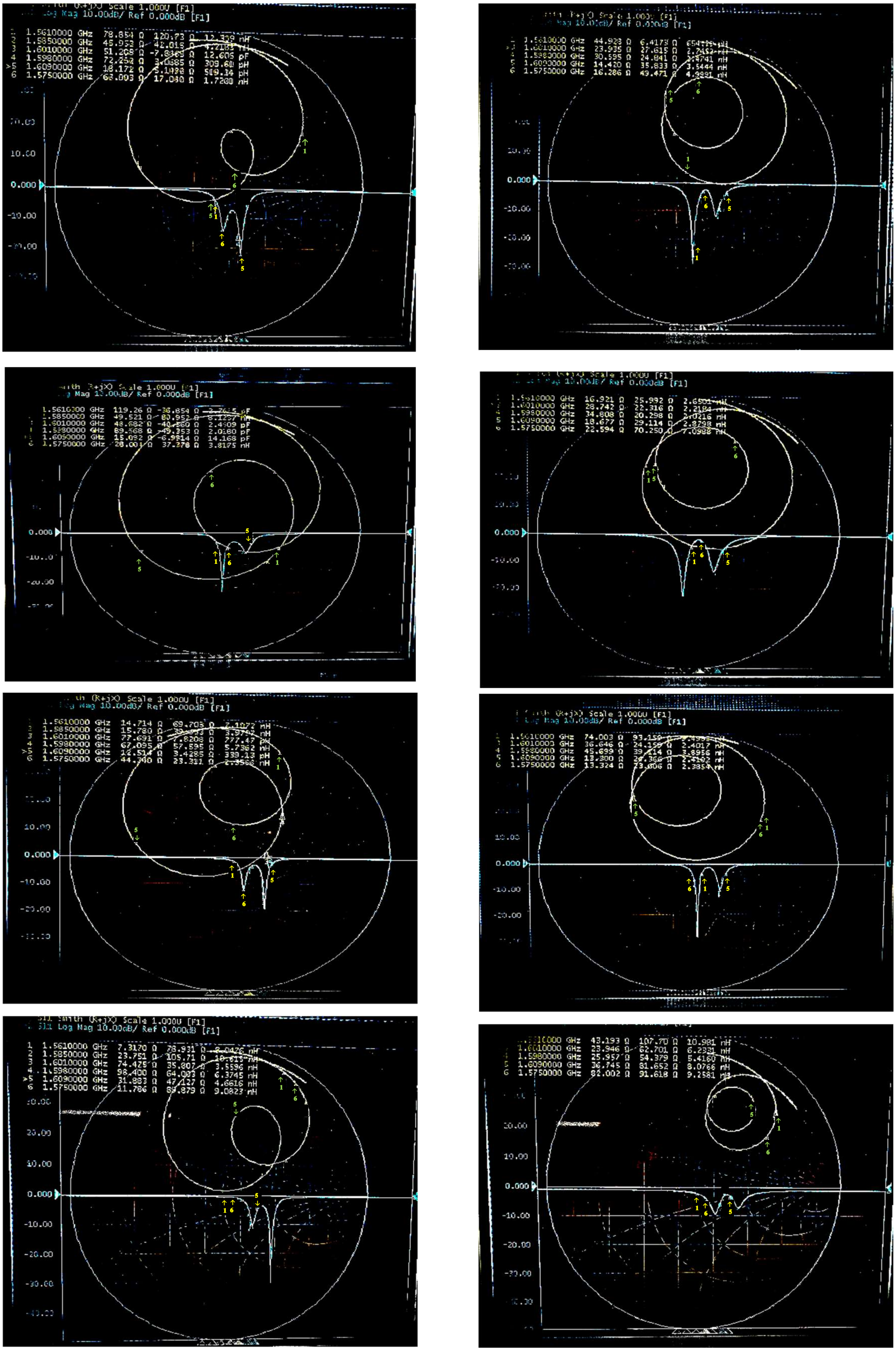
The green markers are used in the impedance trace and the yellow markers are used in return loss trace.

As per the technical data from manufacturers, the antennas have an input impedance of 50 Ω. However, the input impedance varies according to the ground plane which can be observed from network analyzer measurment in figure 25. It can be seen the green markers in figure 25 changes between PCB-A and PCB-B, exhibiting different input impedance.

PCB-A provides input impedance close to 50 Ω. PCB-A is also less susceptible to external influence than PCB-B.

Figure 25 also denotes that the operating frequency range of the different GNSS systems vary and not all the frequencies can be covered for the optimal performance, thus resulting in a trade-off between the performance and operating frequency. Based on the navigation system on the end application, impedance matching is done for a particular system or favouring some systems over other.

PCB-A PCB-B



A1

A2

A3

A4

Figure 25: Input impedance of antennas on PCB-A and PCB-B

Impedance matching can be done using different methods. Most common method is using Π-filter matching circuit composed of capacitive and inductive elements. Along with the help of the Smith chart, the values of components in the pi filter are modified to determine the proper impedance matching circuit. On both PCB-A and PCB-B, a pi filter circuit is designed using a coplanar strip on the bottom layer where the components can be assembled to provide 50 Ω matched output for the antenna feed pin.

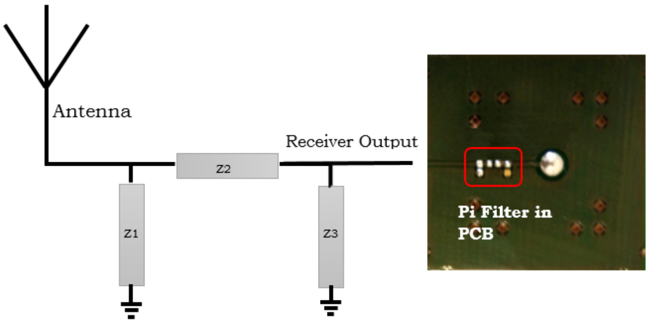


Figure 26: Pi-filter on PCB

PCB-A providing the better antenna input impedance is used for further experimentation. The antennas along with the other circuitry are assembled on PCB-A and taken into operation. All the boards are tuned to have optimal 50 Ω matched impedance from output of the GNSS receiver to antenna input. To compare antenna performance, the GNSS signals which are received by the GNSS receiver through the implemented antenna are analysed and the mean carrier to noise ratio of four strong satellite signals are plotted over time, which can be seen in the figure 27.

The antenna A2 shows better signal reception for all the important frequencies and systems in comparison to other antennas. Based on the result from the figure 27, antenna variant 'A2', an 18mm x 18mm through hole ceramic patch antenna from the manufacturer Abracon, is selected as the most suitable option for implementation on our GNSS Evaluation boards.

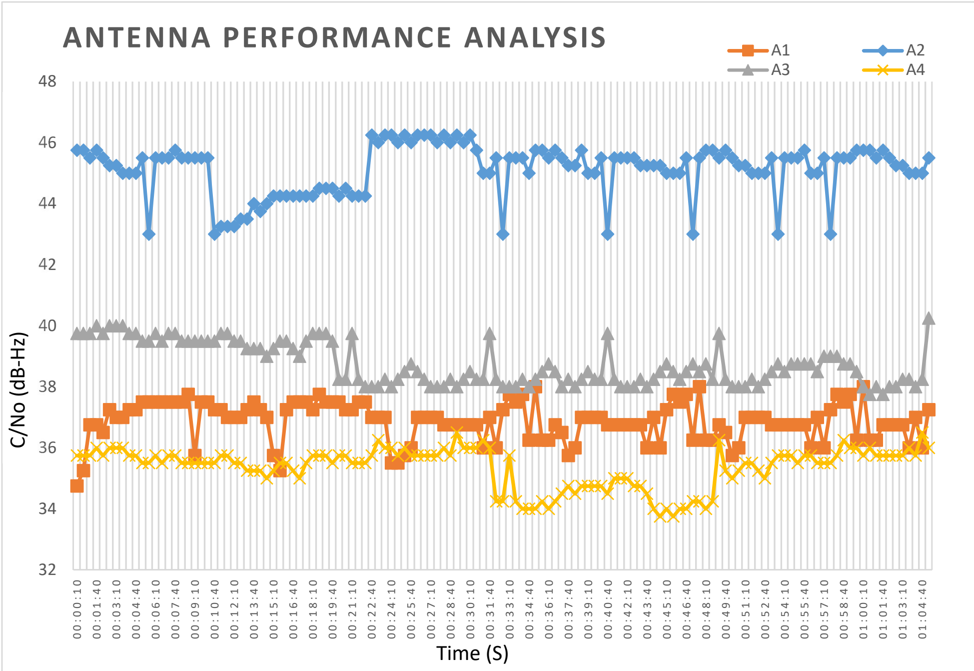


Figure 27: Antenna performance analysis

6 Summary

This application note provides recommendations and guidelines for GNSS antenna selection as well as implementation.

An introduction section covers fundamentals of antenna theory (Chapter 2). Chapter 2 provides the necessary basics to understand concepts, terms and details of the rest of the analysis.

Followed by that, challenges of antenna selection, design and implementation for GNSS antennas are discussed. Advantages and disadvantage of the different antenna solutions are highlighted.

Critical steps of the integration, such as:

- Tuning the patch
- Optimized antenna dimension
- Implementation

and their impact on the end application are explained in detail and shown with several examples. Provided examples also shows the change in characteristics for different antenna implementations of same type.

Being one of the most used antennas, a simulated analysis of ceramic patch antennas was performed and described for different test conditions. The results explains the effect of external influence on the ceramic patch antenna implementation. The guidelines for practical implementation are also discussed based on analysis.

Discussing the practical implementation of different ceramic patch antennas in real life scenarios emphasized major design challenges, such as:

- Antenna detuning
- Influence of ground plane
- Influence of antenna position
- Change in performance

In the last part of the application note, the performance analysis of the different antennas are represented graphically. The results display the signal reception capabilities of the antenna. Although the antennas used have similar characteristics, the performance on the implemented PCB is different. Based on the performance of the antennas, the antenna with best signal reception is selected for the end application. The end application in this case is the evaluation boards of our GNSS modules $Elara - II$ and $Erinome - II$.

Considerations and outcomes of this work concerning antenna selection, design, and integration are decisive for the performance of the GNSS end application.

7 Important notes

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List of Figures

1 Isotropic, Omnidirectional and Unidirectional radiation pattern . . . 5
2 Linear polarization . . . 9
3 Horizontal and vertical linear polarization . . . 9
4 Circular polarization . . . 10
5 Left hand and right hand circular polarization . . . 11
6 Active antenna implementation . . . 12
7 Normal dipole and cross dipole wire antenna . . . 15
8 Parasitic loop antenna . . . 16
9 Dual rectangular loop antenna . . . 16
10 Helix antenna normal and axial mode . . . 18
11 Different types of spiral antenna . . . 19
12 Microstrip patch antenna shapes . . . 19
13 Feed types in microstrip patch antenna . . . 20
14 Circular polarization feed techniques . . . 22
15 Different types of slot antennas . . . 23
16 Ceramic chip antenna . . . 25
17 Ceramic patch antenna . . . 26
18 Ceramic patch antenna simulation - different ground plane . . . 28
19 Antenna performance for different ground plane . . . 28
20 Ceramic patch antenna simulation - different antenna position . . . 30
21 Antenna performance for different antenna position . . . 30
22 PCB-A . . . 32
23 PCB-B . . . 33
24 Antennas assembled on PCB-A and PCB-B . . . 34
25 Input impedance of antennas on PCB-A and PCB-B . . . 36
26 Pi-filter on PCB . . . 37
27 Antenna performance analysis . . . 38

List of Tables

1 Spiral antenna characteristics . . . 19
2 Microstrip patch antenna characteristics . . . 21
3 Ceramic chip antenna characteristics . . . 25
4 Ceramic patch antenna characteristics . . . 26

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