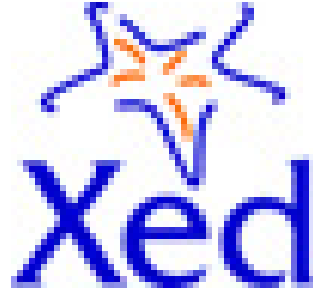


RG3 UHF Antenna



XED Limited

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2

Document Information Revision History Reviewers

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Author	Tamer TEMEL
Technical Lead	Ian Harvey
Contributors	...

Table 2.1: Release Notes

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Table 2.2: Revision History

Reviewed by	Name	Review date

Table 2.3: Review Notes

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2.1 document convention

Throughout this document we use the term **radiation** to describe displacement of radio waves towards or away from the radiating antenna element. The terms receiver and transmitter refer

to radio frequency transmitting and receiving equipment, specifically in the sub-gigahertz radio spectrum.

2.2 copyright

and **copyleft** rights may apply to images and illustrations used in this document. Where possible original creators have been attributed.¹

¹https://commons.wikimedia.org/wiki/Commons:Reusing_content_outside_Wikimedia

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3 Overview

3.1 Introduction

Identification and design of an optimal antenna solution for the RG3 Tesla-System™ of mobile radio networks like any other radio system is a RF-Design challenge beyond an antenna, purely because of the nature of how radio systems work, are used and located. A holistic approach is needed to include technical performance of the antenna system as well as training commissioning installations on the basis of quality of installation from a radio systems perspective. With immediate concerns to system susceptibility to direct and indirect surrounding solid and metallic objects. The first order choice of antenna type is between directional and omnidirectional kind. The dipole which serves as a reference for the quarterwave monopole design matter of this report serves as reference throughout this document as most antennae for sub giga hertz communications are derivatives of the dipole and in common have ratio-metric geometries reflecting their frequency of operation. A standard 915MHz dipole yields a 2.15dBi, decibels of gain over the theoretical ideal isotropic source. This translates to the antenna's ability to radiate a level of power as well as its' sensitivity in detecting low level RF signals.

Considerations taken into account during the process of designing an antenna solution as replacement for an existing third party product. Improvements brought about by a tuning process to granular bands of frequencies that the company's equipment operate on.

Benefits of a tuned antenna compared to a generic one include sharpened response curves with a relatively narrow band of frequencies, effectively filtering others out, picking up fewer false triggers and making more effective use of energy resources through improved network utilisation. AS demonstrated, deviating from generic solutions allow a more selective bandwidth antenna to be formed.

Whilst illustrations and solutions detailed in this document focus specifically on radio bands centred at 450 and 470 MHz, ideas and models developed can be adapted to build antennae for operation at any other sub-giga Hertz frequency desired.

Furthermore, this document aims to show through illustrations that commissioning plays an important part in establishing radio links between end points and base stations. Each unit must be installed in accordance with the same principles used in the conceptual design process to be effective. Accordingly, some bias towards the actual physics of how an antenna works, elevation and other factors are included to underline the broad scope of considerations required for antenna design and deployment.

3.2 Ubiquitous antenna

Ubiquitous antenna components of radio systems play the critical role of converting electrical impulse energy streams into patterns of radiated electromagnetic waves that can travel at the speed of light. Once airborne, the radio waves' existence persist until energy carried by the waves is converted into other forms.

In the ideal world, we prefer to see fully recovered radio waves as buoyant electrical signals at the receiver end of our radio link but, radio waves can stray and become converted into other forms of energy such as sound or heat as they inevitably collide with permanent or momentary obstructions in their paths.

One of the magical characteristics of an antenna is the radiating element's conjugate functionality and purpose. That is, the energy conversion is reversible so that an antenna may be used as a transmitter or as a receiver, of radio waves. For instance, on the way out, radio waves are generated due to oscillations of controlled levels of magnetic fields formed proportional to concentration and rate of electrons flowing in the conducting elements of the antenna ¹. Radio waves emanate then propagate from the radiator during transmissions. At the other end and on the way in, electronic signals are absent until the waves are absorbed by the antenna converting to electrical energy and signal. An antenna is essentially a magical gateway where energy transformation takes place from one form to another. The antenna itself does not generate baseband or modulation signals but is characterized by the same operating frequencies and their physical interface.

Choice of antenna Choice of antenna is heavily governed by the chosen technology, compliance with regional EMC/EMI regulations and application specifics such as physical size and budgetary constraints. All things considered, we have identified the Quarter-wave Monopole Antenna for our chosen structure type with a novel approach of establishing a more distinct ground plane, which is typically served by the ground planes of electronic circuits responsible for generating and amplifying signals for transmission over the air. Our tests suggests that the traditional approach to antenna integration may well be improved through a review of the fundamentals of this type of antenna and it's adaptation to relatively smaller form factor radio systems such as the RG3 Truck base station and Eco range of end-points.

A well designed antenna doesn't present an end to end solution. Other factors must be considered in context of the radio network infrastructure and high in this list should be the antenna's installation procedure. If there is a choice, where and how it should be anchored. Else, a clear definition of best practices and efforts needed in selection of location, elevation and physical alignment of the system all need consideration to commissioning.

3.3 Definition of an Antenna System

The antenna system of a radio link includes all the components that lie in between a transmitter and the actual RF radiator. The same principles apply to the receiver end. We must therefore the antenna radiator element, transmission lines and matching elements will be considered.

Having identified the type of antenna this application, we begin with an abstract review of the project's aims in preparation of applying well defined principles to tailor the solution by modelling and engineering constituent elements and materials towards characterizing and tuning the antenna for desired radio frequency bands of operation.

As part of the design process we consider interconnections between the conductive radiating element of the antenna system back to the RF amplifier and axillary electronic circuits as a transmission line and mitigate losses caused by mismatched lines and reflections.

Figure 3.1 shows a theoretical landscape in which a radio network is established across a rural landscape. In the ideal world, the **receiver** or base station would be positioned on a hill at the centre of the map. The **transmitters** or end-points could then be scattered at any distance and any direction from the origin or base station at the centre. Also there would be no trees, skyscrapers or solid objects in between.

environment

¹in accordance with Michael Faraday's Laws of electro magnetics

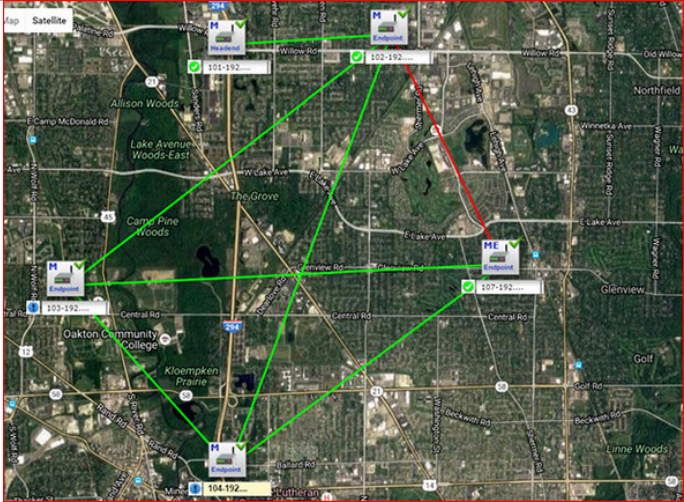
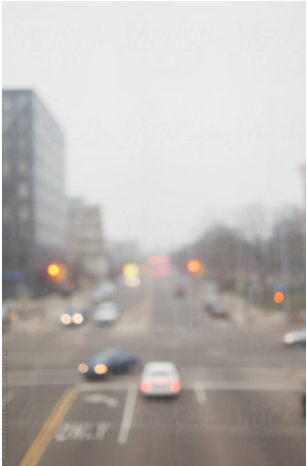
range	landscape
	

Table 3.1: Environment

In this application dozens possibly hundreds of end points periodically transmit data packets over the air. Their ability to project data packets as far as the base station may be effected by factors including a reduction in signal strength due to losses in transmission lines, deviation of antenna from its' optimal frequency of resonance, the climate and atmospheric conditions, physical obstructions of wavefronts travelling from transmitter to receiver. Whilst this report is focused on the design of an optimal antenna solution, practical tips for installation and commissioning are highlighted for the reader's consideration.

4 Practical Considerations

Ground planes Pole antennas by definition require a ground plane, which should ideally be of infinite size for it plays a critical role as a return path and in achieving resonance at desired frequencies. The following image illustrates two port bode plots with different size of ground planes and their effects on transmitted or received signal quality in a monopole antenna.

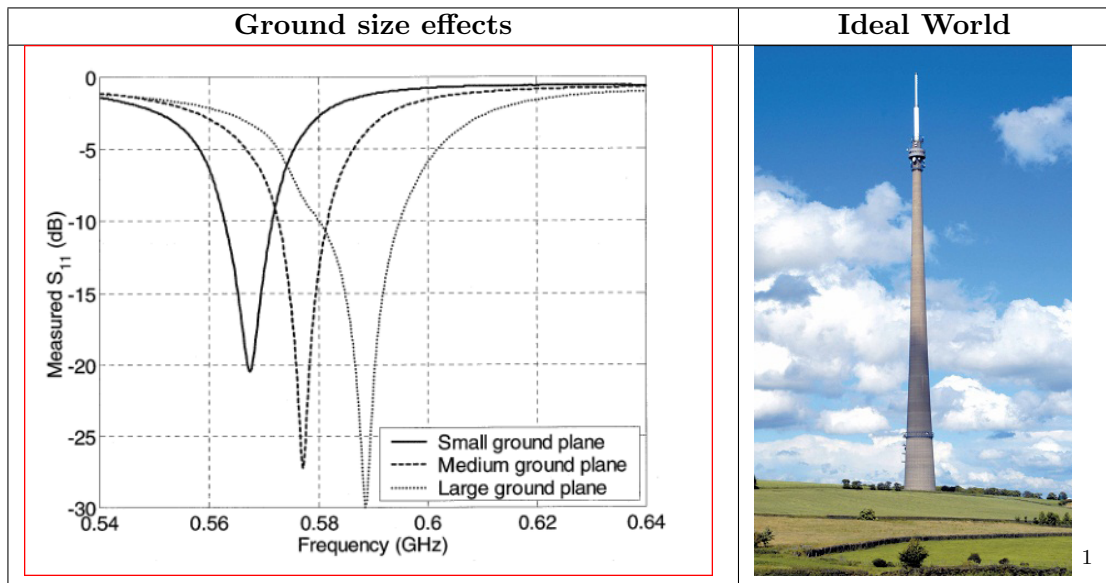


Table 4.1: Ground planes

4.1 Antenna orientation and radiation patterns

Unlike directional antennas, omni-directional antennas radiate their energy in all-directions. In real terms the ideal source of light inside a bubble is somewhat different and radiation workspace resembles more of a doughnut shape with signal strength boundaries of points and curves forming the boundaries of reach.

The doughnut shape of Figure ?? is representative of a monopole antenna's radiation pattern. Conversely a vertical alignment results in wavefront radiation in the horizontal magnetic-plane, perpendicular to direction of a monopole antenna and the electric-field.

A typical situation where the omnidirectional antenna type is desirable is a cellular radio network. Where the antenna is fixed to a central mast and nodes that are in-range and located anywhere to the north, south, east or west of the antenna must all be able to communicate with it, irrespective of the direction they're facing.

The Quarter-wave omnidirectional antenna type is suited to applications where the direction of the receiving and transmitting antennae are not constrained and propagate in all directions

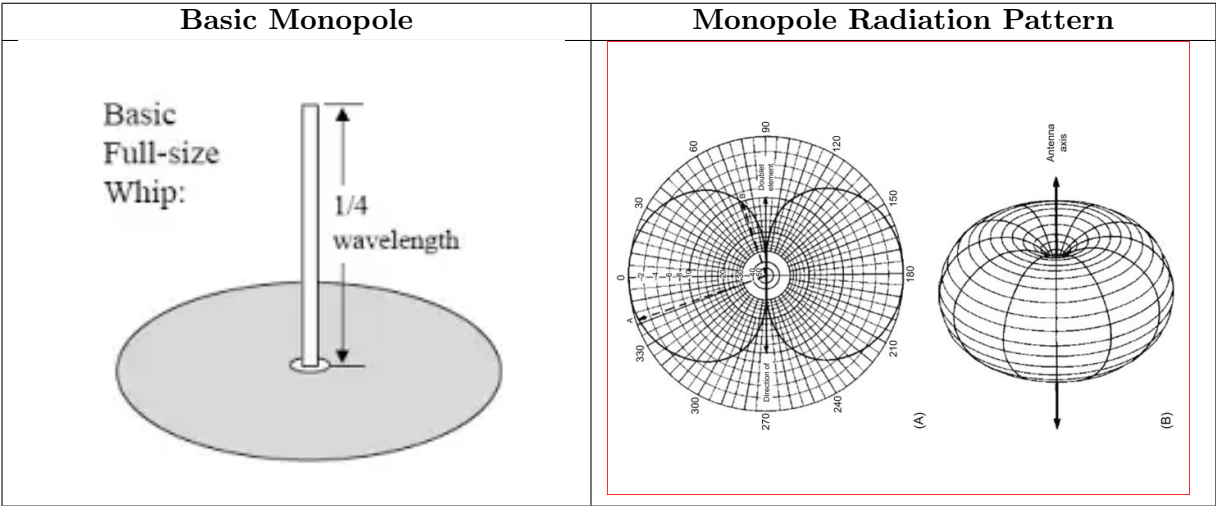


Table 4.2: Basic Monopole antenna and 1/4 wavelength radiation patterns

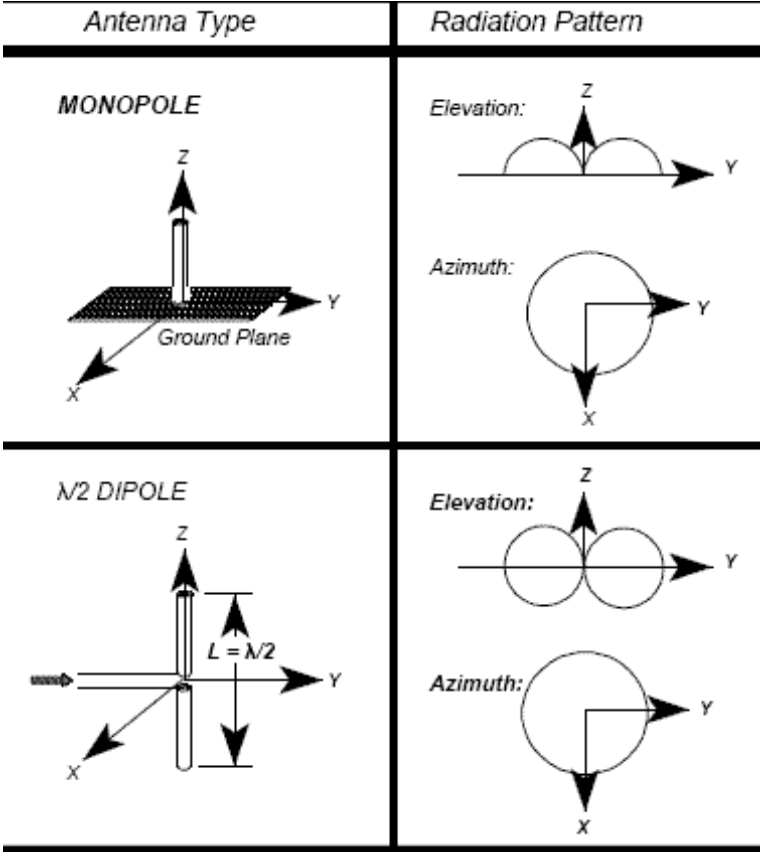


Figure 4.1: Comparison of Monopole and Dipole Radiation Patterns

covering a 360° scope. Compared to directive and static, point to point radio links such as microwave satellite dishes in which the transmitter and receiver antennae that operate on the principle of pointing towards one another.

4.2 Polarization

A typical situation where the omnidirectional antenna type is desirable is a cellular radio network. Where the base station antenna is fixed to a central mast and nodes that are in-range and located in any direction north, east, south or west must all be able to communicate with it, irrespective of the direction they themselves are facing.

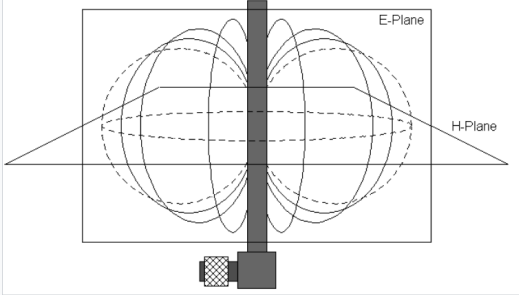
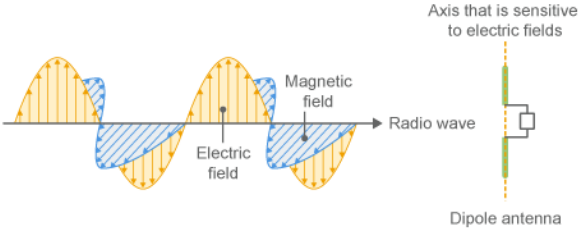
Electric (E) and Magnetic (H) Planes	Waves
	

Table 4.3: Electric and Magnetic fields

2

If the quarter-wave antenna in Figure ?? was tilted 45 degrees with respect to ground plane, then the radiating antenna would concentrate most of its' radiated energy towards the ground to one side and up into the sky on the other. Likewise, any deviation from vertical alignment would tilt the antenna's field of vision from the ideal horizontal propagation to something in between. In contrast a perfectly aligned vertical antenna would radiate its' energy laterally and in all horizontal directions as shown in Figure 4.2. The image on the left in Table ?? shows a cross sectional radiation pattern and a representative beam form or lobe by a monopole antenna. The issue of antenna alignment and elevation from ground plane plays a major factor in the antenna's performance in terms of signal strength and range of coverage.

4.3 Omnidirectional

Omni-directional antennas radiate their energy in **all-directions** The Quarter-wave Marconi omnidirectional antenna is preferred in applications where the direction of the receiving and or transmitting antenna is not known. This can be compared to static, point to point radio links such as microwave satellite dishes in which the transmitter and receiver antennae must point in the direction of one another.

The distance or magnitude from the center to the antenna to any point an the surface of the doughnut represents the signal strength or the range of the radio link for the antenna.

4.4 The dipole antenna

or **half-wave antenna** principles help comprehend rationale for fundamental operation of the monopole, **quarter-wave antenna**.

The dipole is characterized by two radiating rods connected 180 degrees out of phase to each other, forming a synthetic ground plane between the symmetric radiator elements. The signal

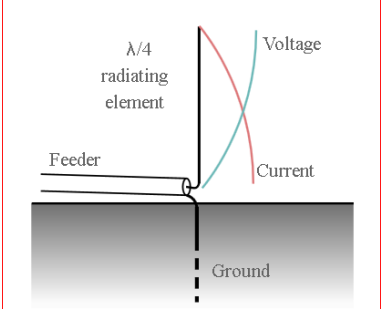
Dipole	Monopole
	

Table 4.4: Physical difference between a Dipole and Monopole

feed point in between the two radiators. Figure ?? to the left in Table 4.4 shows how the monopole is physically one-half of a dipole antenna and Figure ??

TABLE XXX shows radiation patterns of the monopole and the concept a monopole antenna’s **image antenna** section that resembles a dipole, half-wavelength antenna. The quarter-wave monopole antenna operates similar to a dipole above ground plane but, no radiation is emanated from the image antenna beneath the ground plane.

4.4.1 The concept of an Image Antenna

In context of telecommunications and antenna design, an **image antenna** is an electrical mirror-image of an antenna element. As illustrated by Figure to the right in Table 4.6 An image is formed from radio waves reflected from a conductive surface called the ground plane, which is generally represented by the surface of the earth for large antenna installations but other substitutes in mobile applications and is used as a geometrical technique in calculating the radiation pattern of the antenna³.

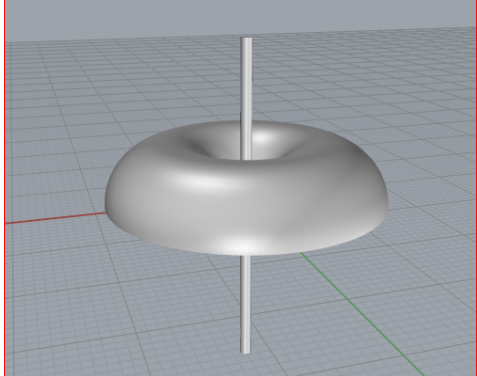
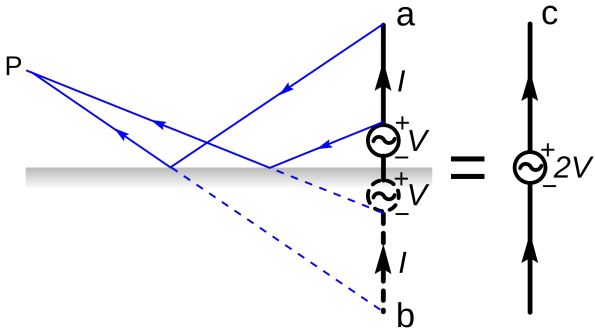
Radiation pattern	Ground plane effect
	

Table 4.5: The Monopole Radiation pattern and Ground Plane effects.

Consideration of antenna alignment and radiation patterns and their direction, it can be see that the ideal antenna should be fixed to a location elevated free from obstructions and clear line of sight and in the case of a monopole that’s vertically aligned and radiating horizontally a

³https://en.wikipedia.org/wiki/Image_antenna

significant tilting of the vertical alignment may lead to loss of connection due to higher dependence on reflected waves than those that are directly absorbed and arriving perpendicular to the antenna.

Figures A and B in Table 4.6 show the radiation pattern of the monopole, which resembles a doughnut shape. We note that the antenna is vertically polarized to ensure that radiated radio signals propagate in the horizontal direction, parallel to the ground plane of the earth’s surface.

This is achieved through the use of the **image-antenna** concept and is illustrated by Figure (C) of Table 4.6 below.

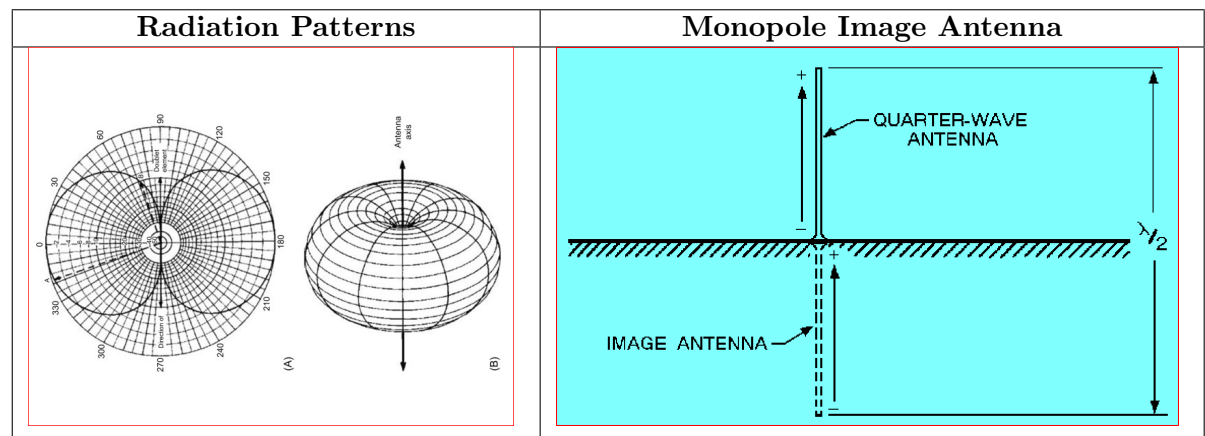


Table 4.6: Marconi (A) 2D and (B) 3D doughnut radiation pattern with relative direction of propagation (C) Image Antenna.

4.5 Monopole characteristics

The monopole antenna is defined by a single radiating element that can be used with an unbalanced feed line such as coaxial cable. The monopole uses the theory of a conjugate reflection of the pole in a ground plane, which leads us to the conclusion that directional characteristics of a grounded quarter-wave antenna are similar to that of a half-wave antenna in free space.

4.5.1 Simulated Earth

Despite the absence of a physical ground reference plane that is intrinsic to the Dipole antenna, the monopole can be designed to deliver comparable performance to a dipole type, based on the theory of a **simulated earth connection** to provide the image for the absent radiating element in the monopole antenna.

4.6 Monopole radiation pattern

The radiation pattern of a monopole antenna resembles a doughnut shape but due to the absence of an anti phase radiator rod, no radiation takes place beneath simulated earth as shown in Figure

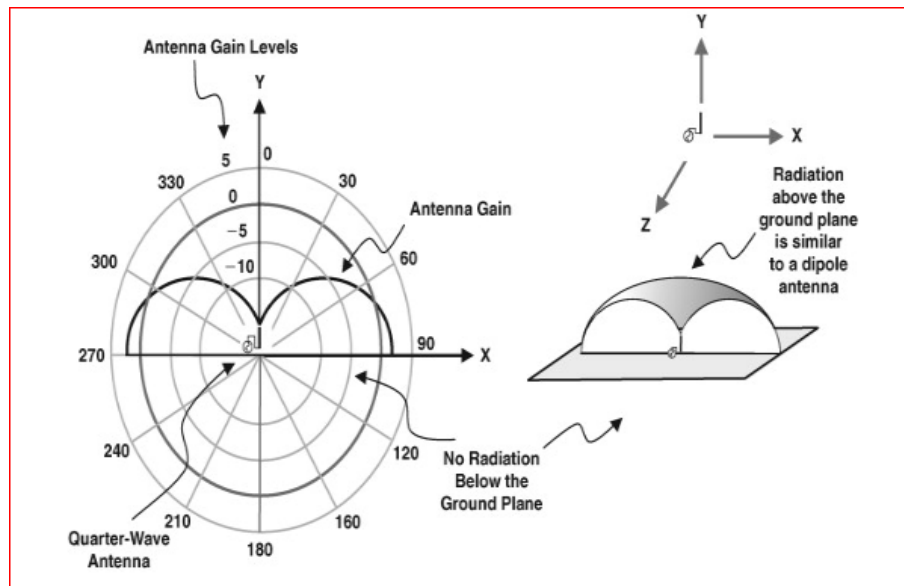


Figure 4.2: Quarterwave antenna radiation pattern

4.7 Dipole radiation pattern

4.8 Monopole and Dipole

The basic quarter wavelength antenna is relatively simple to implement and better suited to mobile applications than alternatives, particularly in UHF radio band applications where the physical size of the antenna and an infinite size ground plane is not available, reducing the overall physical geometry of the antenna considerably.

Radiation pattern of an antenna is largely determined by the number of elements of and antenna, their physical lengths, shape as well as their proportionate geometry and alignment with the ground plane. Whip antennas radiate RF signal patterns perpendicular to the direction of alignment. That is, a vertically aligned antenna radiates in the horizontal direction. With a doughnut shaped radiation pattern

5 360MHz Monopole Antenna Design

5.1 Conductor size

Whilst it is true that any conductor may be considered as an RF radiator element. A transmission line from an RF generator to the load must be impedance matched with the loading antenna so that standing wave ratios are minimized and only the radiator element does the transmitting, for maximum efficiency and performance.¹

whilst length of the antenna is of significance, **diameter of the radiating conductor** plays a critical role on the feed-point impedance of the antenna. In the frequency domain diameter of the radiator has the effect of sharpening or broadening the sensitivity to a band of frequencies. An increase in diameter increases capacitance per unit length and inductance per unit length decreases. This doesn't effect the radiation resistance of the antenna but with a reduced L/C ratio, Quality Factor, Q the antenna resonance curve loses it's sharpness in exchange for a plateau shape.

This directly relates to the characteristic impedance of a transmission line: $Z_o = \sqrt{L/C} \Omega$ per unit length.

K-factor relates to radiating conductor diameter and serves as an optimizing offset factor when calculating antenna length for the desired frequency of operation. It does so by taking into account a change in antenna Resistance which contributes to signal degradation through some of the energy converting into heat at resonance and can vary from 10 Ω to hundreds of Ω .

Test results at the end of this document show improvement in sensitivity of our antenna through the change in diameter of our radiator element.

5.2 Velocity factor, v

Electric field responsible for causing current through the transmission lines can not form faster than the speed of light. This latency or lag is proportional to the length of the transmission line is to the load antenna.

$$v = \frac{1}{\sqrt{\epsilon_r}} * 100$$

where ϵ_r = relative dielectric constant.

In practical applications energy travels slower than the speed of light. Accordingly, a **velocity factor** of 0.65 to 0.97 is applied to calculations based on application specific transmission line characteristics incorporated into the **antenna system**. The phenomena is prominent in and effects the interface sections between the RF amplifier and antenna connection terminals in the PCB and connections leading up to the antenna itself, often through no 12 coaxial cable feed mechanisms in single ended feed topologies.

¹1990 edition ARRL Handbook section 16-4

For a monopole antenna, the essential ground plane must be formed by other means. In cases where coaxial cable is used to make a monopole antenna, the reference ground plane of the transmission line is typically formed using the feeder, the woven screen between the core signal wire and the outer sleeve.

This means that transverse waves applied to the base of the antenna result in magnetic radiation perpendicular to the direction that the antenna is pointing.

5.3 Laboratory Tests

Using a 1mm tinned copper wire as the radiating element initially cut to theoretical length plus 10 percent. We proceeded to observing the antenna performance on the network analyzer. Using the analyzer's two-port S11 parameters functions to monitor the antenna's sensitivity at the desired frequency of operation. We trimmed the antenna's length one milli-meter at a time, noting changes in performance in anticipation of improvements as we tend towards theoretical length.

The following Magnitude(dB) vs. Frequency plots show how well or otherwise the antenna is resonating. A triangular **marker** indicates the magnitude of the antenna under test at 460MHz. A sharp point and lower the dip on the vertical scale indicates better antenna performance.

The title of each table shows the diameter of the synthetic copper ground plane created for the tests.

Table 5.1 shows a curiosity look at the performance of an off the shelf antenna for 433 MHz operation. Image 1 shows it's sensitivity at 433MHz that it is tuned to. Image 2 shows how this antenna might perform at 460MHz. We had no control over the length of this antenna.

We note that if we were to employ this antenna in a 433MHz application, it would perform at best with a sensitivity level of of -12.92dB and since all antennae have a bandwidth of frequencies where their operation may be acceptable, using this antenna for our 460MHz application would return -7.89dB of performance.

5.4 Conclusions

We then go on to test various lengths of 1mm diameter and 0.5mm diameter radiator elements, leading us to the conclusion that as per the **image antenna** theory, the monopole benefits from a ground plane by concentrating the antenna's ability absorb reflected radio waves improving performance significantly. Again larger surface area gives greater performance.

Whilst a 1mm diameter wire does perform a shade behind the 0.5mm diameter type, using the same size ground plane with a 0.5mm wire resulted in comparable performance but with the 0.5mm antenna at a shorter length. That is, the 0.5mm antenna outperformed the 1mm antenna by -3dB even though it was almost 10mm longer.

The 0.5mm ethernet wire used at a length very close to theoretical value with a 70mm diameter sythetic ground plane gave the best results. Outperforming the reference antenna by a margin on a scale of each operating at their designed frequencies.

5.5 Random sample

The following table shows the performance of a random commercially available antenna.

It can be seen that combinations of wire diameter and Ground plane area for each wire type that the Ethernet wire with 0.5mm diameter together with a 70mm diameter ground plane gives best results with an optimal antenna length of 175mm for 460MHz UHF operation with measured results of better than -27dB.

Some test results have been omitted for brevity.

5.6 Implementation tests and results

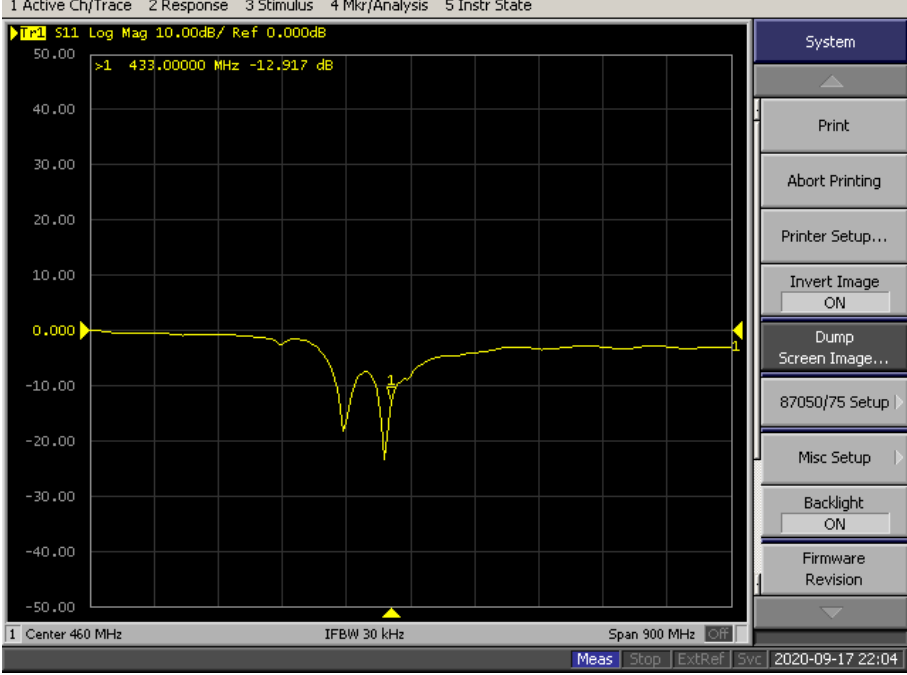
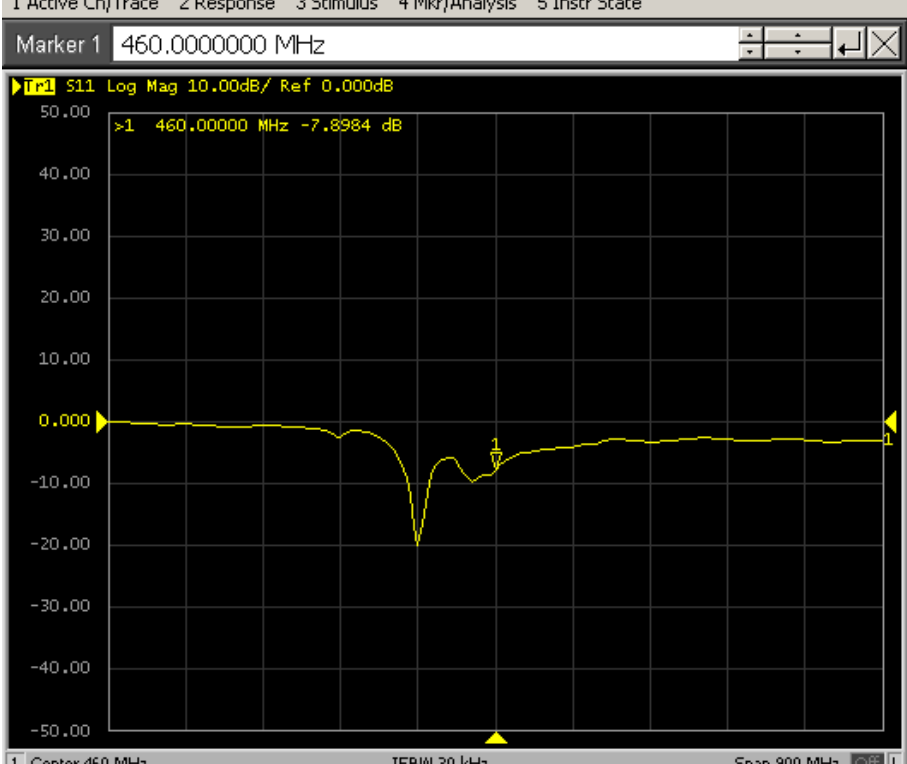
Reference Antenna	S11 (dB)
	-12.92
	-7.89

Table 5.1: An off the shelf 433MHz monopole antenna

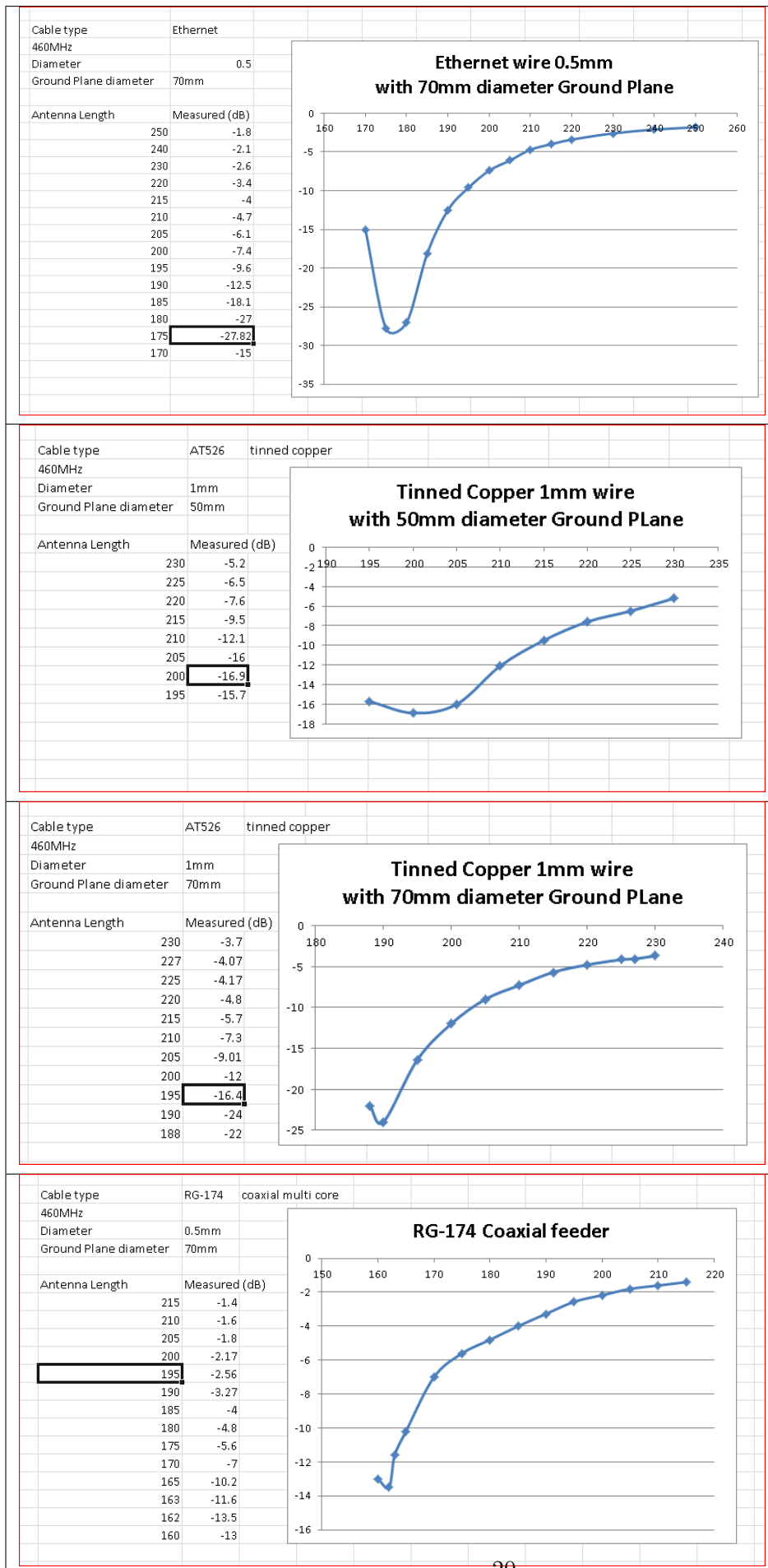


Table 5.2: Radiator element types compared

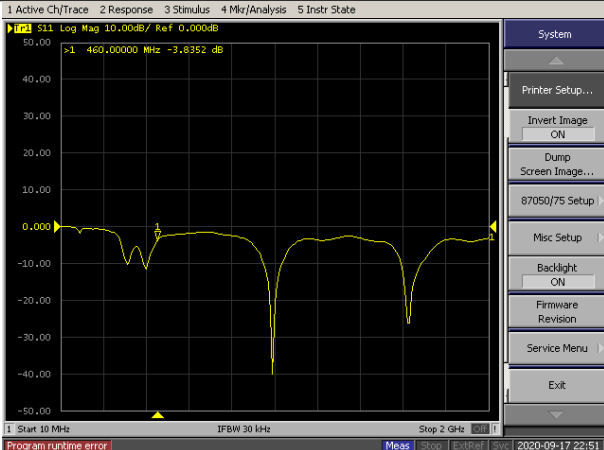
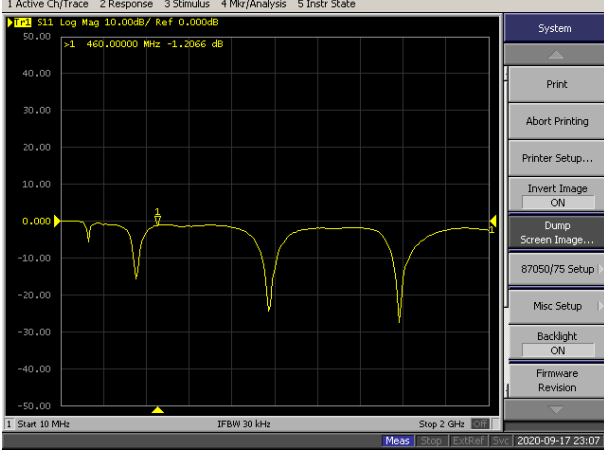
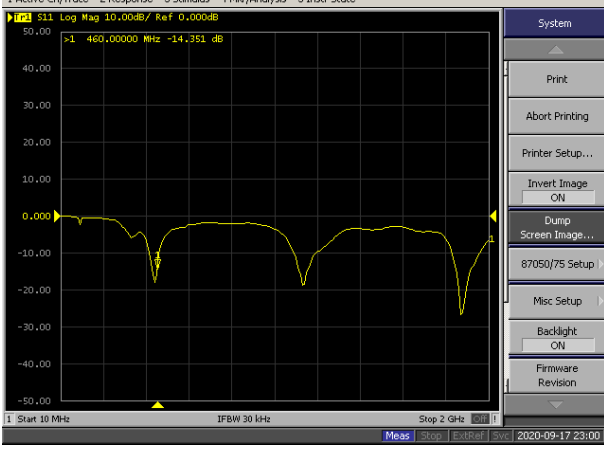
1mm radiator and 70mm Ground	S11 (dB)	Length(mm)
	-3.83	227
	-1.26	220
	-14.35	195

Table 5.3: Antenna matching with 1mm diameter radiator and 70mm diameter artificial ground plane

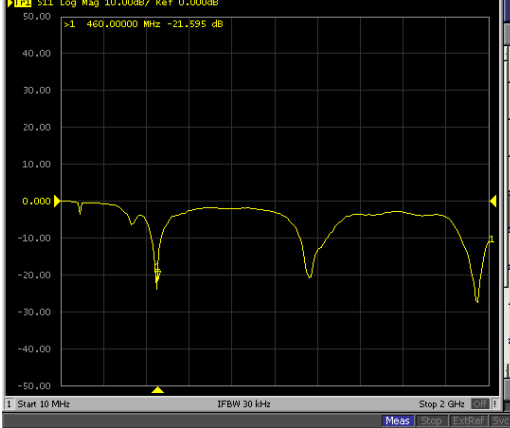
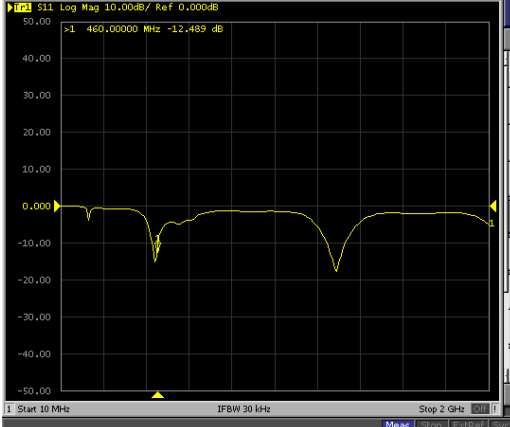
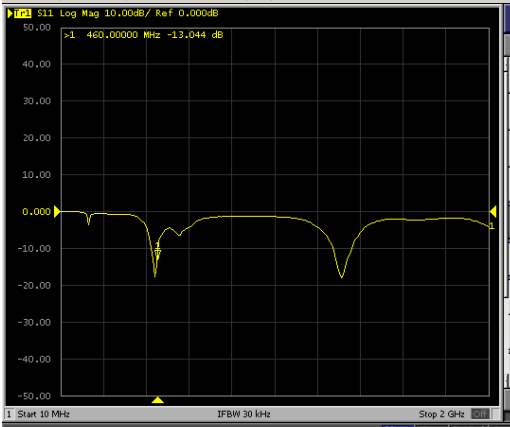
RG174 Coax and 70mm Ground	S11 (dB)	Length(mm)
 1 Active Ch/Trace 2 Response 3 Stimulus 4 Mkr/Analysis 5 Instr State Log Mag 10.00dB/ Ref 0.000dB >1 460.00000 MHz -21.595 dB Start 10 MHz IFBW 30 kHz Stop 2 GHz Meas Stop Extr Ref Sys 2020-09-17 23:03	-21.59	190
 1 Active Ch/Trace 2 Response 3 Stimulus 4 Mkr/Analysis 5 Instr State Log Mag 10.00dB/ Ref 0.000dB >1 460.00000 MHz -12.489 dB Start 10 MHz IFBW 30 kHz Stop 2 GHz Meas Stop Extr Ref Sys 2020-09-17 23:14	-12.48	162
 1 Active Ch/Trace 2 Response 3 Stimulus 4 Mkr/Analysis 5 Instr State Log Mag 10.00dB/ Ref 0.000dB >1 460.00000 MHz -13.044 dB Start 10 MHz IFBW 30 kHz Stop 2 GHz Meas Stop Extr Ref Sys 2020-09-17 23:15	-13.04	160

Table 5.4: continued - Antenna matching with 1mm diameter radiator

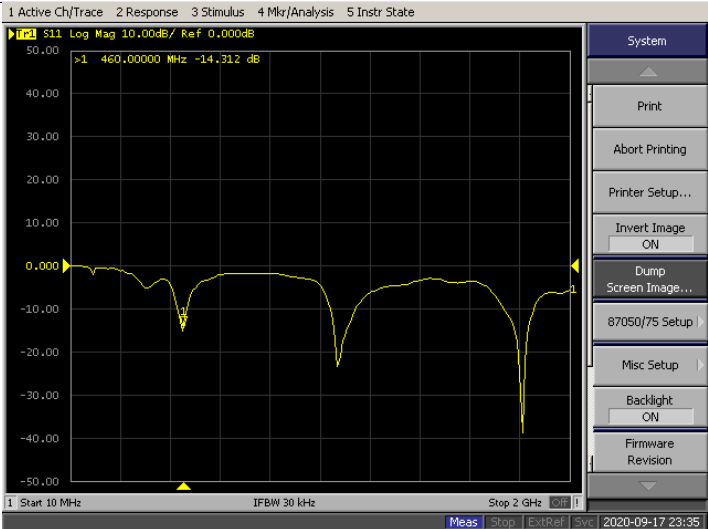
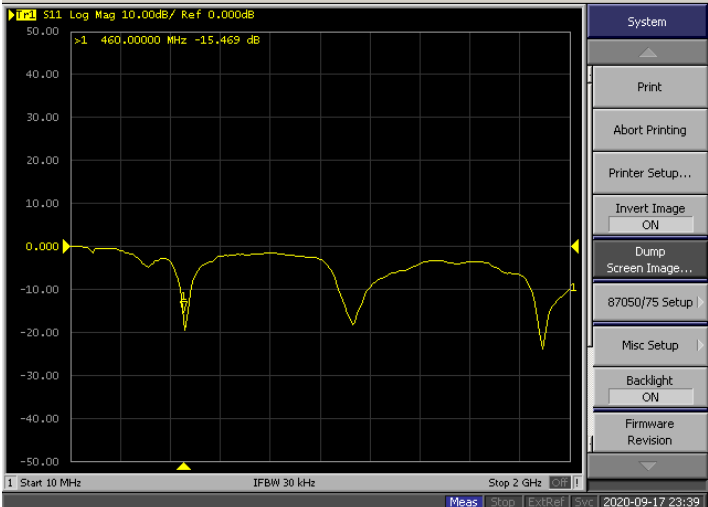
1mm radiator and 50mm Ground	S11 dB	length (mm)
	-14.31	205
	-15.46	195

Table 5.5: Antenna matching with 1mm diameter radiator and50mm diameter artificial ground plane

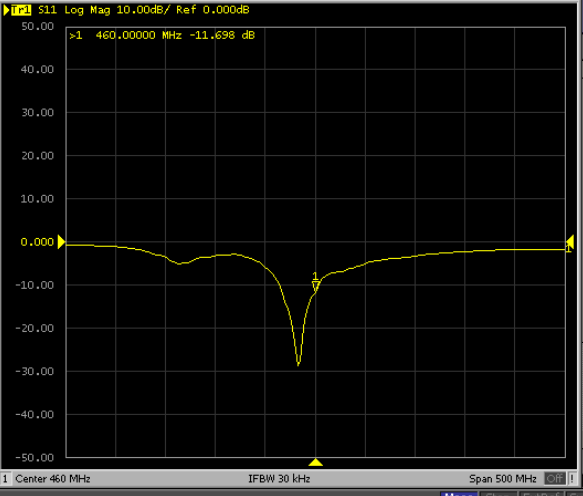
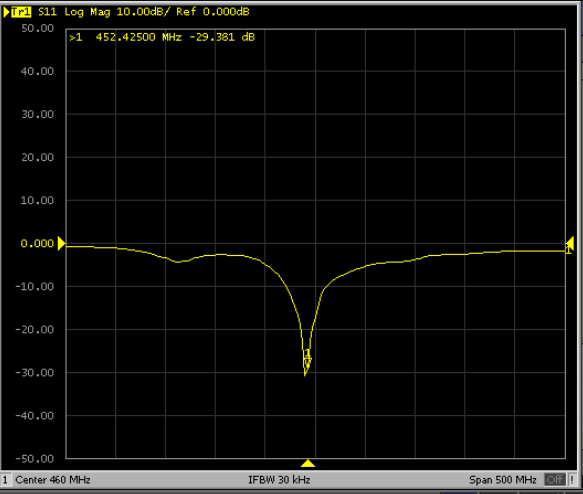
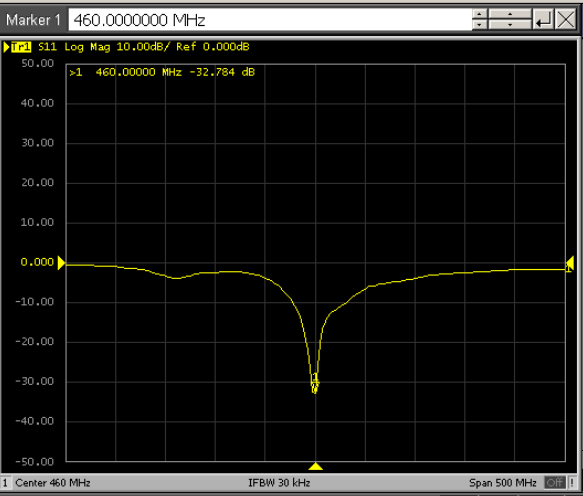
0.5mm radiator with 70mm Ground		S11 (dB)	length (mm)
		-11.69	185
		-29.31	180
		-32.78	175mm

Table 5.6: Antenna matching with 0.5mm Ethernet wire and 70mm diameter artificial ground plane

6 Design considerations

6.1 VSWR

is defined as the reflected power from the antenna back into the generator due to mismatched impedance between the generator and the loading antenna. The symbol Γ is used to denote reflection coefficient.

6.2 Voltage Standing Wave Ratio

$$VSWR = \frac{1 + \rho}{1 - \rho} \quad (6.1)$$

where ρ = reflection coefficient.

$$\rho = \frac{VSWR - 1}{VSWR + 1} \quad (6.2)$$

where VSWR = Voltage Standing Wave Ratio.

$$|T|^2 = 1 - |\Gamma|^2 \quad (6.3)$$

$$|\Gamma|^2 = \frac{VSWR - 1}{VSWR + 1} \quad (6.4)$$

6.3 Antenna Bandwidth

is defined as the range of frequencies over which the VSWR is $\leq 1.5:1$. This translates to 96% power transmission with the remaining fraction becoming reflected.

7 Laboratory Test Logs

7.1 Equipment Under Test



Figure 7.1: Antenna Test samples

The following list shows parts and test equipment were used in tests:

- Agilent **E5062A** Network Analyzer.
- Rowan Cable Products **TCW 18** Copper, Tinned 1mm diameter wire.
- Amphenol RF, Coax, RF Cable Assemblies SMA STR/SMA STR PLG **RG-174** CBL 1.00 MET.
- Advance, Ref. **AT526** Copper tape (used to create artificial Ground plane over cardboard substrate.)
- One strand of Twisted Pair wire taken from a length of CAT6 Network cable.

7.2 Abbreviations

- **ERP** Effective Radiated Power, synonymous with **equivalent radiated power**, is an IEEE standardized definition of directional radio frequency (RF) power. It compares the actual antenna to a half-wave dipole antenna.
- **EIRP** Effective Isotropic Radiated Power, compares it to a theoretical isotropic antenna
- **dB** Decibels
- **UHF** Ultra High Frequency
- **AMR** Automatic Meter Reading
- **RF** Radio Frequency

- **PCB** Printed Circuit Board
- **SNR** Signal to Noise Ratio

References <http://www.antenna-theory.com/>
<https://www.electronics-notes.com/articles/antennas-propagation/vertical-antennas/quarter-wave-vertical.php>
<https://www.rfwireless-world.com/calculators/Whip-Antenna-Calculator.html>

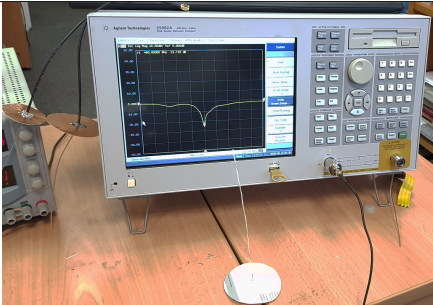
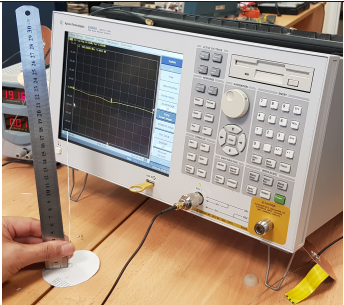
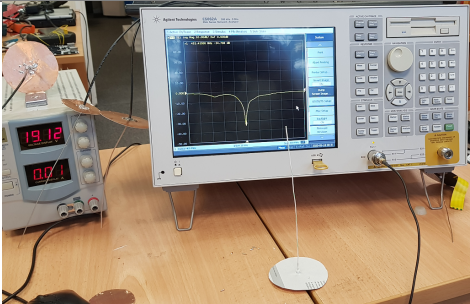
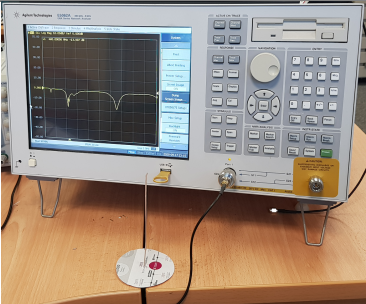
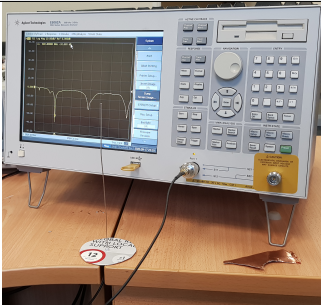
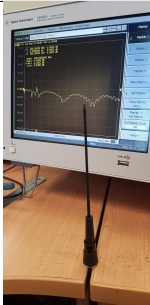
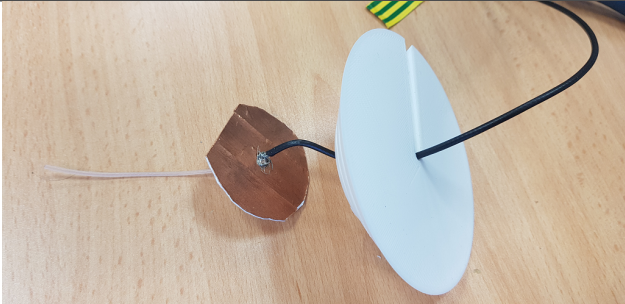
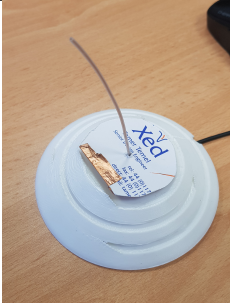
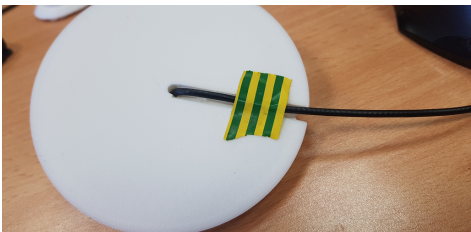
	
	
	
	
	

Table 7.1: Antenna prototypes