

Fidel Amezcua

Professor: Ray Kwok

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## Design of a 915 MHz Patch Antenna with structure modification to increase bandwidth

### 1. Introduction

The objective presented in this report is to outline the steps followed to design a 915 MHz rectangular patch antenna with a modification in the structure to increase its bandwidth. The patch antenna is easy to fabricate and due to its low profile structure. The patch antenna is widely used in aircraft because of its planar structure. Due to its low profile it is easily conformed to a curved shape such as an airplane tip.

One disadvantage of the patch antenna is its inherent narrow band characteristic. Due to the economics and competitive effort among telecommunication companies, the need for high bandwidth antennas is a requirement to modern communication systems that need to cover an entire band of the frequency spectrum without the need to purchase and maintain multiple narrow band antennas; it's desirable for a single antenna to cover all the frequencies in the assigned band. The method to increase bandwidth is to cut a U-Shaped cutout to the patch antenna and the design procedure is outlined in the next sections.

Although the accuracy is not as good as the cavity model, the patch antenna is best analyzed using transmission line theory because it's easy to understand and most undergraduates are familiar with it. The patch antenna can be thought as a transmission line of width  $W$ . The

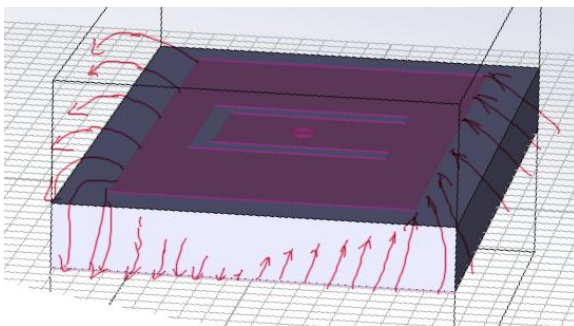
radiation occurs at the edges of the width of the antenna and can be thought as the radiating of two narrow apertures. For proper impedance match, the feed point is found by varying the feed point along the length of the antenna.

Fringing occurs at the edge of the antenna due to the finite length of the patch. To take into account the fringing effect the dielectric constant is modified to get an effective dielectric constant given by

$$e_{reff} = \frac{e_r + 1}{2} + \frac{e_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (1)$$

The effective dielectric constant is a combination of the substrate's dielectric constant and the one of its surroundings and is given by Equation 1 and is valid for when  $W/h > 1$ . For low frequencies the dielectric has negligible effect on fringing, but at high frequencies the fringing effect has a major role.

One of the effects of the dielectric constant is the increase of the effective length of the antenna. Figure 1 shows that the effective length of the antenna is larger than its physical size.



**Figure 1** Effective length of the rectangular patch antenna. Fringing occurs on top and at the bottom of the U-slot.

The effective length is the electrically larger than the physical length [3]; this increase in length is given by Equation 2.

$$\frac{\Delta L}{h} = 0.412 \frac{(e_r + 0.3) \left( \frac{W}{h} + 0.264 \right)}{(e_r - 0.258) \left( \frac{W}{h} + 0.8 \right)} \quad (2)$$

The length of the antenna is now

$$L_{eff} = L + 2\Delta L \quad (3)$$

For proper radiation the resonant frequency is selected such that it corresponds to a half wavelength; thus, without taking into account the fringing effect, the resonant frequency is given by Equation 4, where  $c$  is the free-space velocity of light.

$$f_r = \frac{c}{2L\sqrt{e_r}} \quad (4)$$

And Equation 4 is modified to take into account the fringing effect the resonant frequency is given now by

$$f_{rc} = \frac{c}{2L_{eff}\sqrt{e_{reff}}} \quad (5)$$

The width of the patch antenna with good radiation efficiency is [3]

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{e_r + 1}} \quad (6)$$

With  $e_r$ ,  $f_r$ , and  $h$ , specified, the design procedure is summarized as determining the effective dielectric constant using Equation 1, then find  $W$ . Once  $W$  is known, the length is found using Equation 2. The actual length is found using Equation 7

$$L = \frac{c}{2f_r\sqrt{e_{reff}}} - 2\Delta L \quad (7)$$

In terms of measurements, there are some fundamental parameters that can characterize an antenna and can be measured directly or indirectly in the laboratory. One characteristic of an antenna is the radiation power density  $W_d$  given by

$$W_d = E \times H \quad (8)$$

, which in turn is related to the radiation intensity by

$$U = R^2 W_{rad} \quad (9)$$

where  $W_{rad}$  is the radiation density ( $\frac{W}{m^2}$ )

The directivity is related to the directional patterns. The beamwidth is the angle where the power is reduced by three dB on each side of the maximum beam and it is measured in the phi- and theta-direction to specify the elevation and azimuth angles. Those angles can be calculated from the directional patterns that are measurable in the lab. An approximation [3] of directivity for planar antennas is

$$D_o = \frac{32400}{\theta \cdot \varphi} \quad (10)$$

where  $\theta$  and  $\varphi$  are the half power beamwidths of the theta and phi direction measured in degrees.

Another useful relation that helps compute the gain of an antenna is the power received to power transmitted ratio, with  $G_t$  and  $G_r$  being are the maximum gains of the transmitting and receiving antennas respectively. This relation is given by

$$\frac{P_r}{P_t} = \left[\frac{\lambda}{4\pi R}\right]^2 G_t G_r \quad (11)$$

,where the term  $\left[\frac{\lambda}{4\pi R}\right]^2$  is known as the free-space loss factor. Usually  $P_r$  can be measured with a Vector Network Analyzer with a known  $P_t$  which is set by the VNA and is part of the measuring setup shown in Figure 3 .The transmitter antenna gain, $G_t$  ,can be selected from a known antenna.

Finally, an equation that would be helpful is the relation between directivity and gain.

$$G_o = e_o D_o \quad (12)$$

Equation 12 says that if the gain and directivity are in dB, the total efficiency  $e_o$  is just the gain minus the directivity. The total efficiency takes into account other losses such as the reflection mismatch,  $e_r$  ,conduction efficiency,  $e_c$  , and dielectric efficiency,  $e_d$  .

$$e_o = e_r e_c e_d \quad (13)$$

The conduction and dielectric efficiency are difficult to compute and are determined experimentally. Since the efficiency is close to 1, or a small number in dB, the gain and directivity are often, erroneously, used interchangeably when the substrate is air.

## 2. Experimental Procedure:

The design stage starts with the selection of the tools for simulation and, once having the initial dimensions, start the drawing of the model in turn. For this patch antenna, Microwave

Studio from CST is the option best fitted since there is a myriad of examples of patch antenna design on the internet. Microwave Studio from AWR and HFSS from Ansoft are the other choices for electromagnetic simulation.

The first approach to increase the fractional bandwidth is to increase the height of the substrate. An initial height of 0.61 cm is chosen because that is the size of the plastic available at the machine shop. The dielectric constant of the substrate,  $\epsilon_r = 2.77$ , is found experimentally using the capacitance formula. Figure 2 shows the initial design of the patch antenna with height 0.61 cm, length 6.22 cm and width 12.24 cm. The simulation shows that the antenna's fractional bandwidth is quite narrow, even with an increased substrate height a mere 2% is achieved in this initial design.

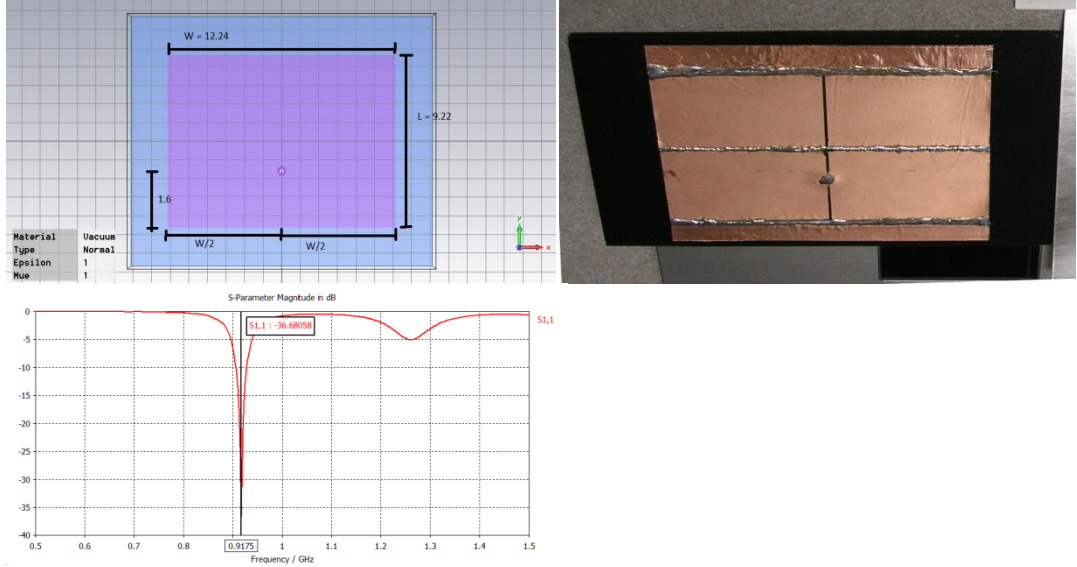


Figure 2 Initial design of a patch antenna shown on the left with dimensions in centimeters and its return loss shown on the right.

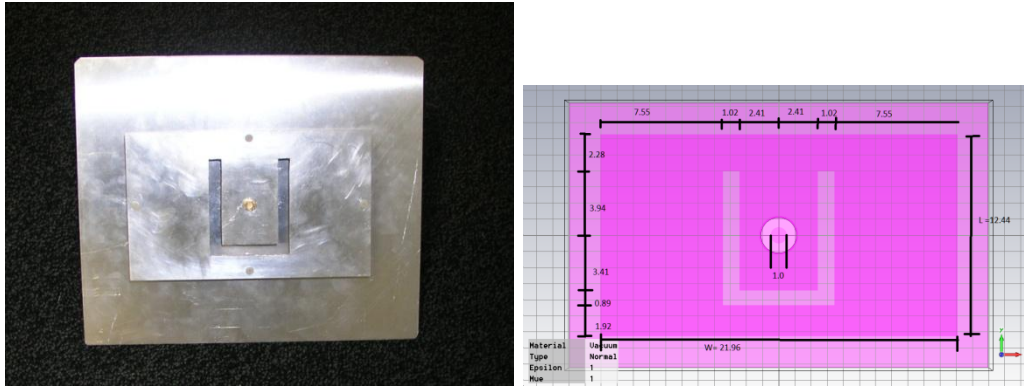
The first antenna was build and tested to verify that indeed the simulation matched the physical world. The work to complete the design specifications is then to increase its bandwidth to meet the goal to increase the fractional bandwidth to 25% or more.

A lower dielectric constant and a larger substrate height,  $h$ , can further increase the bandwidth of the antenna, but that comes at a cost, the size of the antenna increases. The antenna is suspended in air, which has the lowest dielectric constant, but it the bandwidth is not sufficiently wide to satisfy the specifications.

The approach followed was to find literature in the IEEE website and implement a suitable technique to increase bandwidth. One method was to apply an inset cut to the patch; and feed that point with a quarter wave transmission line. Another method was to stack two patches one on top of the other. The former method was a good choice and it is in fact an example of it in CST's site but that would require a 50 Ohm transmission line. With the current dielectric height it would be difficult to realize such transmission line. Inset feeds with a quarter wave transmission lines are more suitable to patch antennas of height dimensions close to the available printed circuit dimensions. Stacking patches to increase bandwidth would increase demand a more experienced technique not yet achieved, so it was not an option at this point.

Searching for other options, it was found that a U-Slot cut would increase the bandwidth of a patch antenna [1].

With satisfactory results during simulation, the antenna dimensions are taken to the machine shop and the model is build using available materials. Aluminum sheet was available and was selected since it is less expensive than copper. The finished result is shown in Figure 3 with the dimensions outlined.



**Figure 3 Finished patch antenna prototype with given dimensions in centimeters**

Once the simulated results are satisfactory, the next step is to measure the finished product. The last step of the design procedure is the verification and comparison of the simulated results with the results measured on the laboratory. The measurement setup is shown in Figure 4.



**Figure 4 Setup of the radiation measurement with the transmitting antenna in the background.**

One important measurement that characterizes the antenna is the return loss. The measurement is done by measuring the S11 parameter with a calibrated Vector Network Analyzer such as the HP 8753.

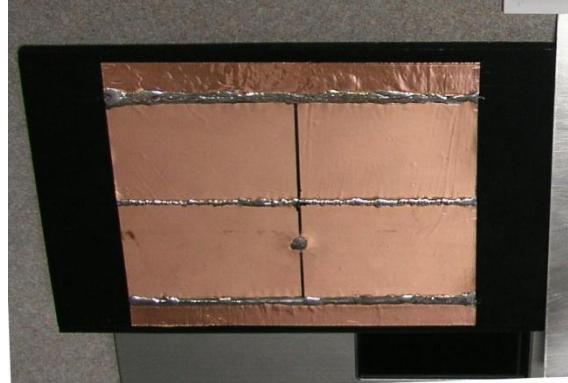
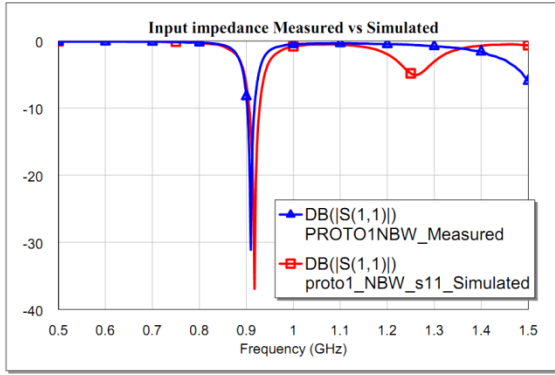


The other measurement is the transmission and reception characteristics of the antenna. The measurement is done by measuring the S21 parameter with a calibrated radiating source provided by the HP 8753 VNA connected to the transmitting antenna. The receiving port is connected to the antenna under test. These calibrated measurements are useful when doing calculations of gain and directivity of the antenna.

To make radiation pattern measurements, the antenna shown in Figure 4 is swept 360 degrees, the phi angle, and the amplitude versus frequency is plotted on a polar chart. A similar chart is plotted in the theta direction, but in this case the angle is swept 180 degrees because the floor covers half the hemisphere. The theta direction is swept 180 degrees, the theta angle, and a similar chart is plotted. With the help of a graduated chart as a guide to monitor the rotation angle, the measurements are taken every 5 degrees and care is taken to assure that the measurements are consistent by activating the averaging function of the VNA. The measurement is done in two locations to find the best spot such that unwanted reflections are spotted and rejected if a suspected bad measurement falls off the expected pattern.

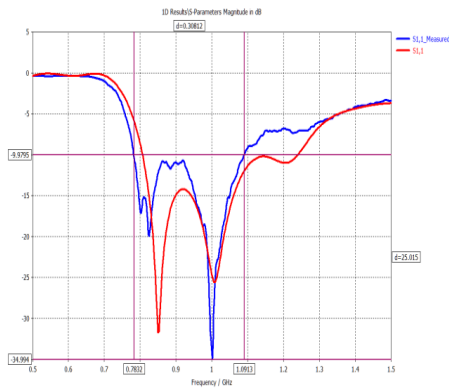
### 3. Results:

Figure 5 shows the return loss of the first prototype. The measurement values follow closely to the results obtained during simulation using CST. This agreement increased the confidence about the simulator setup. As expected, the sharp drop of the return loss value is an indication that the antenna has a narrow band frequency response.



**Figure 5 Comparison of the measured and simulated return loss of the first design PROTO1 show the narrow band characteristics**

The return loss is measured again after increasing the height and replacing the dielectric with air and the cutout in place. The results shown in Figure 6 show a large percentage increase in bandwidth. With the frequency of operation ranging from 783 to 1091 MHz as shown in the figure, the design goal to increase the bandwidth has been achieved. The fractional bandwidth is over 33% with this numbers.



**Figure 6 Comparison of the measured and simulated return loss after applying the U-Slot cutout shows the increase in bandwidth**

From the results shown in Figure 7, we find shows the radiation pattern, the plot in red color shows a large lobe and it might be an indication that a wave is reflected from the wall of the laboratory and is picked up

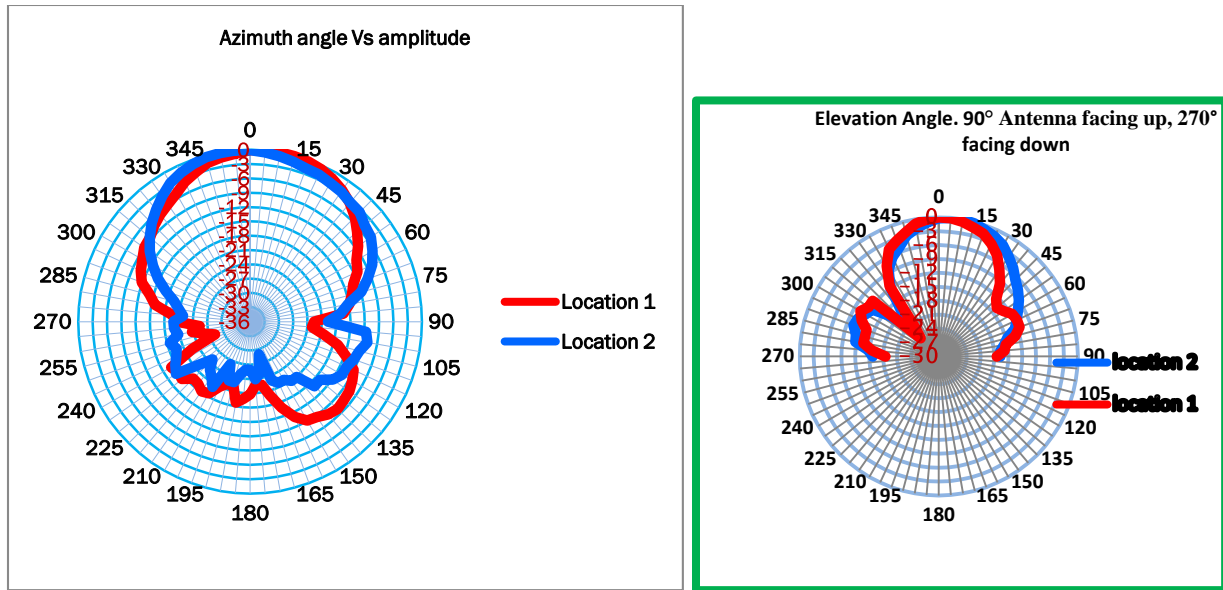


Figure 7 Radiation pattern of the patch antenna in the theta- and phi- direction respectively.

Table 1 shows the power received from a transmitter located at a distance 3.96 meters away from the receiving antenna.

Table 1 Power measurements and gain

Distance (in)	Distance (m)	Input power (dBm)	Output power(dBm)
156	3.96	0	-25.1
<u>Gains from simulation.</u>			
Tx-Ant Gain (dB)	Rx-Ant Gain (dB)	Combined gain (dB)	
5.97	9.27	15.2	

Table 2 shows a sample calculation using the results from Table 1. With the input power to the transmitting antenna is 0 dBm, the receiving power is -25.1 dBm. Using Equation 11, reprinted

here as  $\frac{P_r}{P_t} = \left[\frac{\lambda}{4\pi R}\right]^2 G_t G_r$ , and having all the power levels in dB, the relation  $P_r - P_t = -25 \text{ dBm} - 0 \text{ dBm} = -40.6 + 5.97 + G_r$  gives the gain of our receiving antenna  $G_r = 9.5 \text{ dB}$ . In the calculation  $\lambda = 300/900 = .33$  meters, the distance between the antennas  $R = 3.96$  meters, the gain of the transmitting antenna  $G_t = 5.97$  (from simulation), and the free-space radiation loss  $\left[\frac{\lambda}{4\pi R}\right]^2 = 0.0000434 = 10 \log(0.0000434) = 43.6 \text{ dB}$  but since the loss is only on the half hemisphere, the radiation loss is 40.6 dB

Another calculation shown in Table 2 is the directivity. With the half power beamwidths taken from the polar charts, also tabulated in Table 2,  $\varphi = 65$  and  $\theta = 50$ , the directivity is calculated using Equation 10, so  $D_o = \frac{32400}{\theta \cdot \varphi} = \frac{32400}{50 \cdot 65} = 9.96 \text{ dBi}$ .

**Table 2 Power measurements and radiation angles**

Power transmitted (dBm)	Free-space radiation loss (dB)	Power Received (dB)	Patch Antenna gain (dBi)
0	-40.6	-25.1	9.5
Angle $\theta$	Angle $\varphi$	$D = 32400/(\theta \cdot \varphi)$	
50	65	9.96	

Table 3 shows a comparison of the measured and the simulated results. The gain and directivity of the patch antenna were calculated as indicated before. All other parameters shown in Table 3 are either values by design or are taken directly from the radiation pattern charts.

**Table 3 Simulated and measured results**

	Simulated	Measured

Directivity	9.41 dBi	9.96 dBi
Cross Polarization	n/a	14.4
Fractional BW	48.6%	33.6%
Polarization	Linear H	Linear H
Impedance	50	50
Return Loss	10 dB	10 dB
VSWR	2	2
Front to back ratio	n/a	12 dB
HPBW Phi	73°	65°
HPBW Theta	51°	50°
Operating Frequency	811 MHz – 1200 MHz	783 MHz – 1091 MHz
Gain	9.27 dBi	9.53 dBi

#### 4. Discussion:

Comparing the measured and simulated return loss, the results show a close agreement. In terms of return loss the measurements show a high degree of confidence. The problem arises when doing radiation pattern measurements. From the results shown in Figure 7, the plot of the theta versus amplitude, red curve for the first location, shows a big lobe around 135 degrees which is not shown in the blue curve. The large lobe in the red curve might be an indication that a wave is reflected from a wall of the laboratory and is picked up by the face of the antenna since

it is directly facing one wall and also facing the door at 45 degrees from this angle. The radiator is behind the antenna at this time. To sort out this uncertainty, a third location might be required and from the 3 curves, sort out the minimum amplitudes for angles between 180 to 360 degrees.

Other than that, the front radiation agrees with the simulation results.

The calculations of gain and directivity are in close agreement with the results shown in the simulator. The results are tabulated in Table 3 with the major antenna characteristics.

As a last comparison, Figure 8 and Table 4 show appearance and design specification for an antenna of similar characteristics and dimensions found on Pasternak's web site [5]. The site does not specify whether the antenna is a patch antenna but the picture shown indicates that it might be a patch antenna



**Figure 8** Characteristic of PE51024 antenna from Pasternak Enterprises

**Table 4 Specification for Outdoor antenna PE51024 from Pasternak Enterprises**

**Specifications <sup>(1)</sup>**

Parameter	Value	Units	Description
Impedance	50	Ohms	
Frequency Range	902-928MHz	MHz	
Input VSWR	≤ 1.2	ratio	
Gain	8.5	dBic	
Polarization	RHC		Right Hand Circular
HPBW	68	deg	@E-plane
(3dB Beam width)	64		@H-plane
Height/Length	260 □	mm	(10.24"□)
Width	44	mm	(1.74")
RF Connector		N- Female	
Mast Diameter	23-46	mm	Diameter(.9-1.8 inches)
Operating Temperature	-40 to +85	Deg C	
Weight	855.5	grams	(est.)

**Ordering Information**

Part Number	Description
PE51024	902 TO 928 MHz OUTDOOR ISM & RFID ANTENNA; 8.5 dBi; RHCP

Comparing both antennas, it's noted that the PE51024 antenna is a narrow band with a fractional bandwidth of only 26 MHz, as opposed to the wide bandwidth presented in this report. Further on, the beamwidths are similar on both antennas. Pasternak's antenna has a better VSWR, but that is expected since in this design, the VSWR is sacrificed in order to gain bandwidth. The last parameter that both antennas agree is the front to back ratio. In the brochure, Pasternak's antenna promote a better than 15 dB front to back ratio. The calculation of the front to back ratio from the radiation charts for the antenna presented in this design is 12 dB, but it's believed that the front to back measurement can be improved with better isolation on the laboratory walls in order to prevent reflections and multi-path effects that affect the antenna measurements.

5. Conclusion:

The results show that the experimental results are in accordance with results published by textbooks and white papers found during research. Furthermore, the results closely match to a

commercial antenna in spite of the errors faced during the measurements in a lab that has no capability to absorb wave radiations.

As a first experience, designing, building, and testing an antenna has been a rewarding experience. The software is a helpful tool to avoid going back and forth between the desk and the machine shop. As better models are implemented in software, the accuracy of the simulations increases avoiding then the expense of discarding prototypes that did not work.

As the education background progresses, new reading material and theory will ease the antenna design. Also, as more experience is gained handling multiple chores with simulator and macros, more complex tasks can be programmed to further characterize an antenna. The design cycle can be further reduced, and a gain is achieved when one better understands the underlying microwave and electromagnetic principles.

Future work will include reading more about antenna theory in order to apply a more rigorous mathematics when solving electromagnetic problems as an aid to confidently apply modifications to the antenna such as, to make the antenna resonate at two or more frequencies and to fully understand the cutout done on this antenna. Other areas of improvement would include protecting the antenna against the wear so that the antenna withstands rain, heat, moisture, and snow for example.

## 6. References:

- [1] T. Huynh and K.F Lee, "Single-Layer single patch wideband microstrip antenna", Electronic Letters 1995, pp. 1310-1321



[2] R.Garg, P.Bharthia, I.Bahl, and A.Ittipiboon, Microstrip Antenna Design Handbook. Boston, Artech House, 2001.

[3] Constantine A. Balanis, Antenna Theory and Design. John Wiley & Sons, Inc., 1997.

Web sites:

[4] <http://www.ksmetals.com/retail.html>

[5] <http://www.pasternack.com/product-Outdoor-ISM-and-RFID-Antenna-RHCP-260mm-X-260mm-X-44mm-N-Female-902-928-MHz-8.5-dBi-PE51024-87579.html>

7. Appendix: