4 Design and Analysis of Microstrip Elements and Arrays

This chapter will investigate the design and performance of telemetry and GPS circularly polarized microstrip antenna elements and arrays for use on cylinders having 6, 8, and 14-inch diameters. These three diameters are chosen because they represent diameters typical of sounding rockets launched by ASRP.

Although there may be benefits to using a circularly polarized antenna on a sounding rocket, the benefits may not outweigh the design challenges or possible performance limitations. As mentioned in chapter 3, the use of a circularly polarized antenna on a sounding rocket has less polarization mismatch loss than a linearly polarized antenna. While clearly a benefit, there are other design, performance, and cost factors that must be considered. Therefore, to be able to determine whether a circularly or linearly polarized antenna is the better antenna to use on a sounding rocket, this chapter will also investigate the design and performance of linearly polarized antenna elements and arrays. However, the design of the linearly polarized antennas will be limited to only telemetry antennas on a 14-inch cylinder.

This chapter begins with a consideration of linearly polarized antennas because the linearly polarized elements are simpler to design and serve as a basis for the circularly polarized designs. For both the linearly and circularly polarized antenna sections, planar antenna elements are designed first. Then, the designs of the cylindrical elements and arrays are presented. The chapter concludes by comparing the performance of the linearly and circularly polarized elements and arrays.

The material used in all the antenna designs described in this report is 60 mil RT-Duroid 5870 substrate[2]. A summary of the substrate characteristics is listed in table 4.1 For both the linearly and circularly polarized antennas, the design process is the

Table 4.1. Characteristics of RT-Duroid used for this project.

Weight of copper foil (oz.)	0.5
Dielectric constant	3.33
Loss tangent	0.001
Surface resisitivity (Mohm)	3×10^{8}
Substrate thickness (mils)	60
Copper thickness (mm)	0.17

same. The first step is to determine the initial antenna dimensions using simplified planar models or basic CAD programs such as PATCHD, CPPATCH, or Clementine's estimation tool. Then, the design is optimized for a cylinder using the more accurate fullwave CAD program Clementine. For the linearly polarized antenna, the length dimension is optimized such that the resonant input impedance is real. For the circularly polarized elements, a minimum axial ratio is of prime importance. In both cases, once the element dimensions are determined, the matching networks are designed to match 50 ohm feedlines to the patches' input impedance. For the linearly polarized patches, the patch's input impedance is real and can be matched using a quarterwave transformer. For the circularly polarized patches, the input impedance has an imaginary component, which requires the more complicated L-section matching network. If properly matched, the losses due to reflections at the input of the patch are minimized. The final step in the design process is to create an array of elements for a cylinder. This is accomplished by spacing the matched elements equally around its circumference. If the number of patches

[2] RT-Duroid 5870 is available from Rogers Corporation, 100 S. Roosevelt Avenue, Chandler, AZ 85226. The corporation's URL is http://www.rogers-corp.com.

in the array is sufficient, then the radiation pattern will be nearly omnidirectional and have minimum ripple.

4.1 Design of Linearly Polarized Element

Three linearly polarized antennas will be investigated: a single element, a large wraparound patch, and an array of patch elements. In all these cases, antennas for only a 14-inch diameter cylinder will be considered. The first antenna designed will be a linearly polarized patch element, because it is the simplest to design.

In this section, the linearly polarized elements are designed using the equations from the simplified models listed in chapter 3. The design results are then compared with the results of PATCHD (based on fullwave data) and Clementine's estimation tool (based on cavity model equations). Finally, the patch and its feed network are optimized for a cylinder by running iterative fullwave simulations using Clementine.

4.1.1 Rectangular Patch – Planar Design

The first step in designing a rectangular patch for a cylinder is to determine its width, effective permittivity, and resonant length using the simple formulas for the planar case. Using equations from the transmission line model, the cavity modal, and the HED model presented in chapter 3, the patch's dimensions and characteristics are determined.

First an efficient patch width is determined,

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{3\times 10^8}{2\cdot 2.2155\,\text{GHz}}\sqrt{\frac{2}{2.33+1}} = 52.47\,\text{mm}. \tag{4.1}$$

After determining the rectangular element's width, then the effective dielectric constant can be determined,

$$\begin{aligned}\varepsilon_{eff} &= \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 10\frac{h}{W}\right)^{-\frac{1}{2}} \\ &= \frac{2.33+1}{2} + \frac{2.33-1}{2}\left(1+10\frac{1.54\,\text{mm}}{52.47\,\text{mm}}\right)^{-\frac{1}{2}} = 2.25,\end{aligned} \tag{4.2}$$

where h is the height of the dielectric substrate. The calculation of the length takes two steps. First, the amount of fringing must be determined,

$$\begin{aligned}L_{fringing} &= \frac{0.412h\left(\varepsilon_{eff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\varepsilon_{eff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)} \\ &= \frac{0.412 \cdot 1.54\,\text{mm}\left(2.25 + 0.3\right)\left(\frac{52.47\,\text{mm}}{1.54\,\text{mm}} + 0.264\right)}{\left(2.25 - 0.258\right)\left(\frac{52.47\,\text{mm}}{1.54\,\text{mm}} + 0.8\right)} = 0.792\,\text{mm}.\end{aligned} \tag{4.3}$$

Now that the fringing (on both ends of the patch) has been determined, then the actual physical length the rectangular patch is determined,

$$L = \frac{\lambda_g}{2} - 2L_{fringing} = \frac{c}{2f\sqrt{\varepsilon_{eff}}} - 2L_{fringing} \tag{4.4}$$

$$= \frac{3\times10^8}{2\cdot 2.2155\,\text{GHz}\sqrt{2.25}} - 2\cdot 0.792\,\text{mm} = 43.676\,\text{mm}.$$

Now that the patch dimensions are known, the third step in the patch design is to determine the input resistance. Here, the input resistance is determined using the HED analysis equations listed in chapter 3. However, before the resistance can be determined, the quality factor and the effective lengths and widths must first be determined. The dielectric and conductive quality factors are

$$Q_d = \frac{1}{\tan\delta} = \frac{1}{0.001} = 1000 \tag{4.5}$$

and

$$Q_c = \frac{1}{2}\frac{\eta\mu_r k_0 h}{R_s} = \frac{1}{2}\frac{377\,\Omega\cdot 1\cdot 46.40132\,\mathrm{m}^{-1}\cdot 0.00154\,\mathrm{m}}{0.01707\,\Omega} = 780.677, \tag{4.6}$$

where the surface resistivity is

$$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}} \tag{4.7}$$

and the free space wave number is

$$k_0 = \frac{2\pi}{\lambda_0}. \tag{4.8}$$

The space and surface wave quality factors, determined using the HED formulas, are

$$\begin{aligned} Q_{sp} &= \frac{3}{16}\left(\frac{\varepsilon_r}{p\cdot c_1}\right)\left(\frac{L_e}{W_e}\right)\left(\frac{\lambda_0}{h}\right) \\ &= \frac{3}{16}\left(\frac{2.33}{0.8311\cdot 0.5029}\right)\left(\frac{45.13\,\mathrm{mm}}{53.82\,\mathrm{mm}}\right)\left(\frac{135.41\,\mathrm{mm}}{1.524\,\mathrm{mm}}\right) = 77.892, \end{aligned} \tag{4.9}$$

and

$$\begin{aligned} Q_{sw} &= Q_{sp}\left(\frac{e_r^{hed}}{1-e_r^{hed}}\right) \\ &= 77.892\left(\frac{0.9419}{1-0.9419}\right) = 1263.3, \end{aligned} \tag{4.10}$$

where the effective length and width are,

$$L_e = L + 2L_{fringing} \quad \text{and} \quad W_e = W + 2W_{fringing}. \tag{4.11}$$

The width of the fringing fields along the width edges are approximated by

$$W_{fringing} \approx \frac{h\ln(4)}{\pi}. \tag{4.12}$$

The total quality factor is determined using these four individual quality factors,

$$\begin{aligned} Q_t &= \frac{1}{\dfrac{1}{Q_d}+\dfrac{1}{Q_c}+\dfrac{1}{Q_{sp}}+\dfrac{1}{Q_{sw}}} \\ &= \frac{1}{\dfrac{1}{1000}+\dfrac{1}{780.68}+\dfrac{1}{77.892}+\dfrac{1}{1263.3}} = 62.85. \end{aligned} \tag{4.13}$$

In order to determine the input resistance using the HED resistance formula, the radiation efficiency must also be determined. The radiation efficiency is,

$$\begin{aligned} e_r &= \frac{e_r^{hed}}{1+e_r^{hed}\left(\tan\delta+\dfrac{R_s}{\pi\eta_0\mu_0}\cdot\dfrac{\lambda_0}{h}\right)\left(\dfrac{3}{16}\cdot\dfrac{\varepsilon_r}{p\cdot c_1}\cdot\dfrac{L_e}{W_e}\cdot\dfrac{\lambda_0}{h}\right)} \\ &= \frac{0.94192}{1+0.942\left(0.001+\dfrac{0.0171}{\pi\cdot 377\cdot 1}\cdot\dfrac{0.1354}{0.00154}\right)\left(\dfrac{3}{16}\cdot\dfrac{2.33}{0.831\cdot 0.503}\cdot\dfrac{0.04513}{0.05382}\cdot\dfrac{0.1354}{0.001524}\right)} \\ &= 0.81. \end{aligned} \tag{4.14}$$

Using the quality factor and radiation efficiency, the input resistance for the rectangular microstrip patch is determined,

$$\begin{aligned} R_{in} &= \frac{4\mu_r\eta_0}{\pi\cdot\tan\delta_{eff}}\cdot\frac{L_e}{W_e}\cdot\frac{h}{\lambda_0}\cos^2\left(\frac{\pi x_0}{L_e}\right) \\ &= \frac{4\cdot 1\cdot 377}{\pi\cdot 0.1591}\cdot\frac{0.04513}{0.05382}\cdot\frac{0.001524}{0.13541}\cos^2\left(\frac{\pi\cdot 1.00082}{0.04513}\right) = 207\,\Omega. \end{aligned} \tag{4.15}$$

The patch's directivity, gain, and bandwidth can be determined using the HED formulas covered in chapter 3. The directivity and gain are

$$
\begin{aligned}
D &= \frac{\eta}{40\pi} \cdot \frac{1}{p \cdot c_1} \\
&= \frac{377}{40\pi} \cdot \frac{1}{0.8312 \cdot 0.5029} = 7.19
\end{aligned} \tag{4.16}
$$

and

$$
G = e_r D = 0.81 \cdot 7.19 = 5.8. \tag{4.17}
$$

The bandwidth of the rectangular element is

$$
\begin{aligned}
BW &= \frac{1}{\sqrt{2}} \left(\tan\delta_{eff} + \frac{R_s}{\pi\eta_0} \cdot \frac{\lambda_0}{h} + \frac{16}{3} \cdot \frac{p \cdot c_1}{\varepsilon_r} \cdot \frac{h}{\lambda_0} \cdot \frac{W_e}{L_e} \cdot \frac{1}{e_r^{hed}} \right) \\
&= \frac{1}{\sqrt{2}} \left(\frac{1}{62.85} + \frac{0.0171}{\pi 377} \cdot \frac{0.1354}{0.00154} + \frac{16}{3} \cdot \frac{0.831 \cdot 0.503}{2.33} \cdot \frac{0.001524}{0.1354} \cdot \frac{0.05382}{0.04513} \cdot \frac{1}{0.94192} \right) \\
&= 0.022
\end{aligned} \tag{4.18}
$$

In addition to using these formulas, the DOS CAD program PATCHD and Clementine's estimation tool were also used to determine the patch's dimensions and characteristics. A summary of the results of these planar cases is listed in table 4.2.

4.1.2 Rectangular Patch – Cylindrical Design

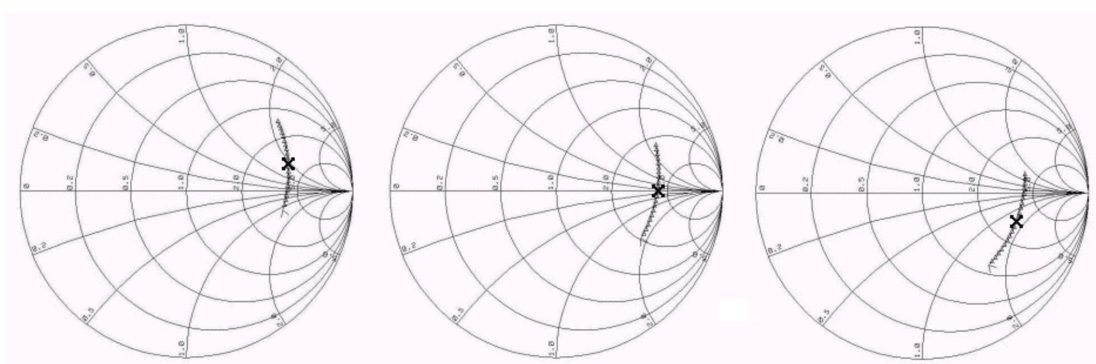
Using the width from the planar case that was determined in the previous section, the rectangular patch length was optimized for a 14-inch cylinder using Clementine's fullwave CAD program. Roughly five simulations were required to determine the optimum length. The optimum length is the resonant length when the input impedance is real. The characteristics of this optimized patch are listed in table 4.2.

The impedance of this optimized patch is plotted on the Smith chart shown in figure 4.1.b. On the chart, the S_{11} parameters over the frequency range of 2.1405 to 2.2905 GHz are plotted, with 'x' marking the design frequency of 2.2155 GHz. As seen

Table 4.2. Summary of planar and cylindrical rectangular patch parameters.

Method of Analysis	Simple Models	PATCHD	Clementine (estimated result)	Clementine (fullwave result)
Substrate Height (mm)	1.524	1.524	1.524	1.524
Dielectric Constant	2.33	2.33	2.33	2.33
Effective Dielectric Constant	2.25	-	-	-
Substrate Loss Tangent	0.001	0.001	0.001	0.001
Patch Length (mm)	43.676	42.78	43.53	43.27
Patch Width (mm)	52.47	52.47	52.18	52.47
Frequency (GHz)	2.2155	2.2153	2.2155	2.2155
Input Resistance (Ohms)	207	223.23	233	206.79
Patch Total Q	63	47.207	-	-
Efficiency	81%	95.41%	95.41	-
Patch Bandwidth	2.20%	2.45%	2.22%	2.71%

in the figure, the patch has real input impedance for only a narrow range of frequencies. Any change in the patch length will change the resonant frequency of the patch and its input impedance. The impedance characteristics that result from changing the resonant length by +/- 0.25 mm are shown in figures 4.1.a and 4.1.c. The first length is slightly less than optimum while the second is slightly greater. When the length is less than the resonant length, the patch input impedance is slightly inductive. In contrast, when the length is greater than the resonant length, the input impedance is slightly capacitive.

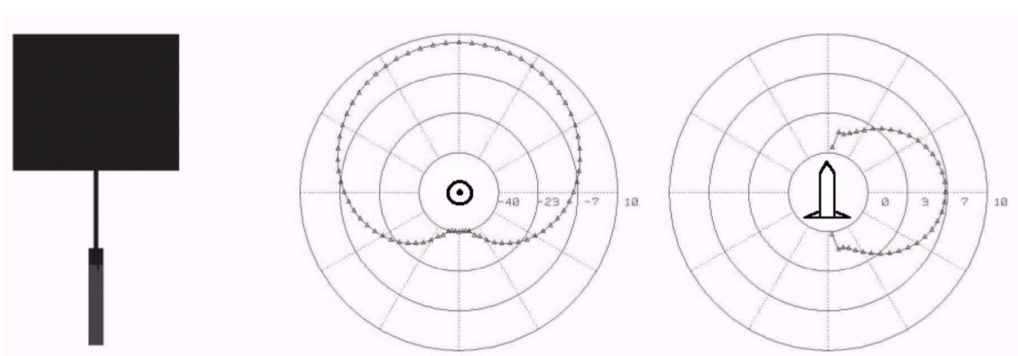


a. L = optimum – 0.25mm **b.** L = optimum length **c.** L = optimum + 0.25mm

Figure 4.1. Impedance performance of rectangular patch at and near resonance.

Once the patch's impedance is known, then the patch can be matched to a microstrip feed line using a quarterwave transformer. Obviously, since the quarterwave transformer is designed specifically for the resonant resistance, the efficiency of the match will degrade for other frequencies or patch lengths. To match the patch input resistance to the 50 ohm microstrip feed line, a quarterwave microstrip line transformer was designed having a width of 1.254 mm and a length of 24.97 mm.

This matched rectangular patch on a 14-inch cylinder was analyzed using Clementine. The patch with its feeding network, its radiation pattern, and S_{11} plot are shown in figures 4.2 and 4.3. Its radiation pattern is similar to the radiation pattern for the planar rectangular patch (see figure 2.2). However, due to the curvature of the cylinder, its pattern width is slightly larger, where some of the radiated energy extends around the cylinder. The 3 dB beamwidth of the patch in the azimuth plane is approximately 80 degrees, which is roughly the same as the planar case. The 3 dB beamwidth in the elevation plane is approximately 95 degrees. As shown in figure 4.3, the 3 dB bandwidth is about 90 MHz, or 4.0%. A summary of both the planar and cylindrical rectangular patches' parameters and performances are listed in table 4.2. As expected for a large radius, the cylindrical patch is similar to the planar patch.



a. rectangular patch antenna **b.** azimuth plane gain pattern **c.** elevation plane gain pattern

Figure 4.2. Rectangular microstrip antenna and its radiation pattern.

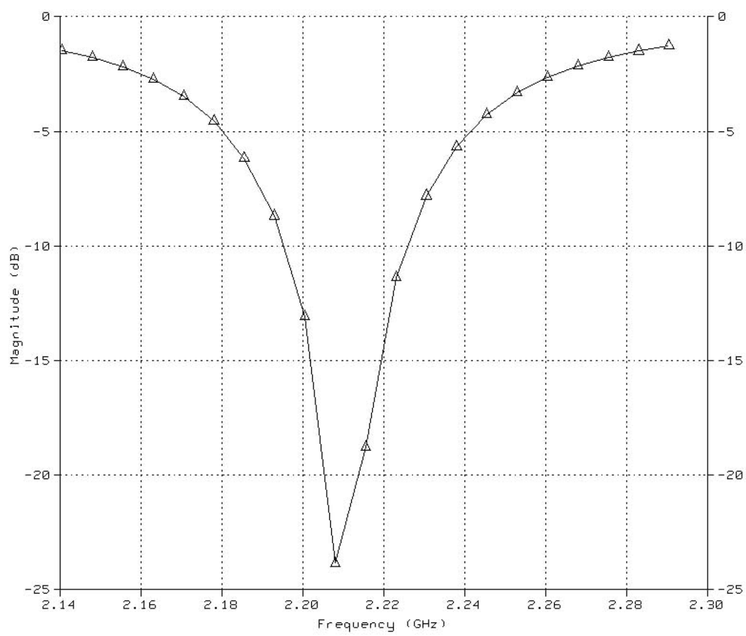


Figure 4.3. Rectangular microstrip antenna's S_{11} plot.

To relate resonant length of a rectangular patch to frequency, five different antennas were designed at 2.1155, 2.1655, 2.2155, 2.2655, and 2.3155 GHz. As before, the resonant length of each patch was determined by adjusting their lengths until the input impedance was purely real. The patch dimensions and input resistance at these five frequencies is listed in table 4.3. A plot of the resonant length versus resonant frequency is shown in figure 4.4. As seen in the graph, resonant length for the rectangular patch decreases 0.0204 mm for a 1 MHz increase in resonant frequency.

Table 4.3. Summary of five rectangular patches tuned at different frequencies.

Frequency (GHz)	Width (mm)	Length (mm)	Rin (Ohms)
2.1155	52.47	45.40	220.5
2.1655	52.47	44.31	212.5
2.2155	52.47	43.27	207.7
2.2655	52.47	42.27	200.0
2.3155	52.47	41.32	193.5

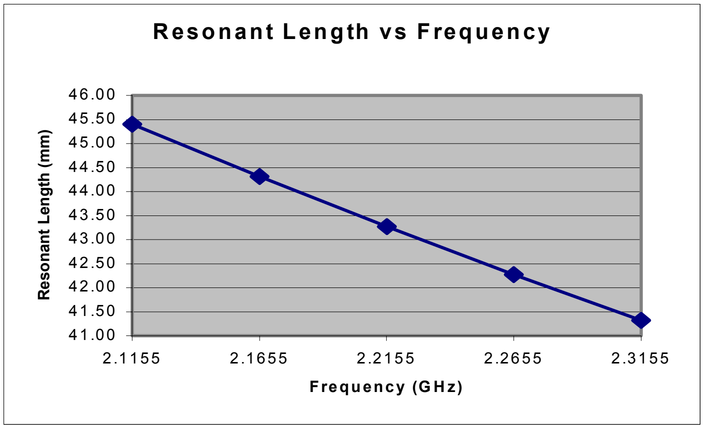


Figure 4.4. Resonant lengths for five linearly polarized patches.

4.2 Design of Wraparound Patch Element

The next microstrip antenna investigated is the wraparound patch. The wraparound patch is simply a single linearly polarized patch that is wrapped around the entire surface of the cylinder. As in the case of the linearly polarized patch element discussed in the previous section, the length of the wraparound patch is approximately half the guided wavelength. However, the width is much longer, being equal to the circumference of the cylinder. Because it wraps around the cylinder, its radiation pattern is omnidirectional. The wraparound patch is fed at evenly spaced points along the circumference of the cylinder. The distance between the feeds must less than the effective wavelength. This ensures that higher order transverse modes are not excited.

4.2.1 Wraparound Patch – Planar Design

Using basic design formulas, the patch dimensions, number of feed points and impedance can quickly be determined. The length of the wraparound patch is calculated using the simple transmission line formula,

$$L \approx 0.49\frac{\lambda}{\sqrt{\varepsilon_r}} = 0.49\frac{3\cdot 10^8\,\text{m/s}}{2.2155\,\text{GHz}\cdot\sqrt{2.33}} = 43.47\,\text{mm}. \tag{4.19}$$

The width of the wraparound patch is the circumference of the cylinder,

$$W = 2\pi r = \pi D = \pi\cdot\left(14\,\text{in} - 2\cdot 60\,\text{mils}\right) = 1107.58\,\text{mm}\,. \tag{4.20}$$

The number of feed points is determined by calculating the effective wavelengths around the circumference of the payload,

$$\begin{aligned} N_\lambda &= \frac{W\sqrt{\varepsilon_r}}{\lambda_0} = \frac{W\,f\sqrt{\varepsilon_r}}{c} \\ &= \frac{1107.58\,\text{mm}\cdot 2.2155\,\text{GHz}\cdot\sqrt{2.33}}{3\times 10^8\,\text{m/s}} = 12.5. \end{aligned} \tag{4.21}$$

The number of feeds, N_F, must be greater than N_λ. Ideally, N_F is also a power of 2 to facilitate the design corporate feeds, e.g.,

$$N_F = 2,\ 4,\ 8,\ 16,\ \ldots \tag{4.22}$$

The total input resistance of the band is calculated using transmission line model,

$$R_{in} = \frac{1}{2W\,G_s} = \frac{377\cdot 2.2155\,\text{GHz}}{2\pi\cdot 1107.58\,\text{mm}\cdot 3\cdot 10^8\,\text{m/s}} = 7.34\,\Omega, \tag{4.23}$$

where the conductance G_s is

$$G_s = \frac{\pi}{\lambda\eta_0}\left(1 - \frac{\left(k_0 h\right)^2}{24}\right). \tag{4.24}$$

The input impedance of the wraparound patch at each feed point is

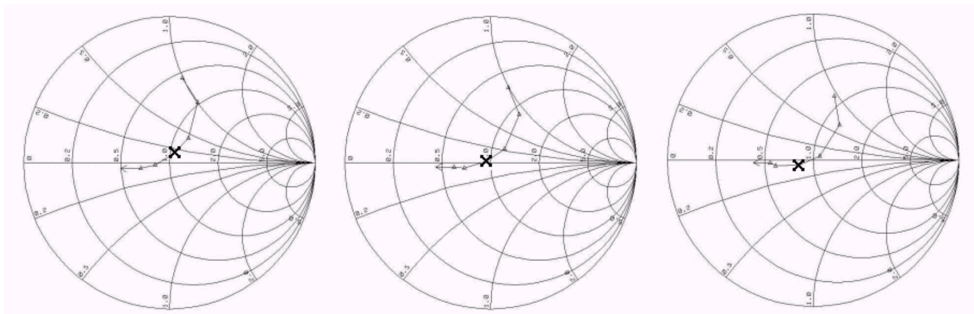
$$\begin{aligned} R_F &= N_F\cdot R_{in} \\ &= 16\cdot 7.34\,\Omega = 117\,\Omega. \end{aligned} \tag{4.25}$$

In addition to using these basic transmission line formulas, the wraparound patch was analyzed using the DOS CAD program WRAPPAT. The results for both these analyses are listed in table 4.4 on page 61.

4.2.2 Wraparound Patch – Cylindrical Design

The length of the wraparound patch was then optimized for the 14-inch cylinder using Clementine. After several iterations, the wraparound patch length yielding a real input impedance at each feed point was found. Its parameters are shown in table 4.4. The impedance characteristics of this optimized wraparound patch are plotted on the Smith chart shown in figure 4.5b over the frequency range of 2.1405 to 2.2905 GHz, where 'x' marks the design frequency of 2.2155 GHz. As with the smaller rectangular patch discussed in the previous section, two wraparound patches having lengths offset by +/- 0.25 mm from the resonant length were analyzed to observe the input impedance changes from the resonance length (see figures 4.5a and 4.5c). When the length is less than the resonant length, the patch input impedance is slightly inductive. In contrast, when the length is greater than the resonant length, the patch input impedance is slightly capacitive. Once the wraparound patch's impedance is known, then the patch can be matched to 50 ohms. To match the patch input resistance (at each feed point) of 47.4 ohms to the 50 ohm microstrip feed line, a quarterwave transformer was designed having a width of 4.66 mm and a length of 24.09 mm.

The matched wraparound patch was analyzed using Clementine. The patch feeding network, radiation pattern, and S_{11} plot are shown in figures 4.6, 4.7 and 4.8, respectively.



a. L = optimum – 0.25mm **b.** L = optimum length **c.** L = optimum + 0.25mm

Figure 4.5. Impedance performance of wraparound patch at and near resonance.

As seen in figure 4.7, the pattern of the wraparound patch is omnidirectional with a gain of approximately -1 dB in the azimuth plane. The ripple in the pattern is less than 1.5 dB. In the elevation plane, the radiation pattern also shows a gain of approximately -1 dB broadside from the patch; however, off of broadside, the gain of the wraparound patch increases to greater than 2 dB. In terms of a sounding rocket in flight, this pattern implies that the gain is actually greater underneath the rocket (in the direction of the ground

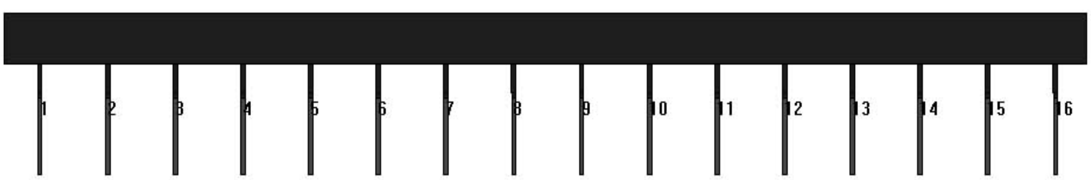
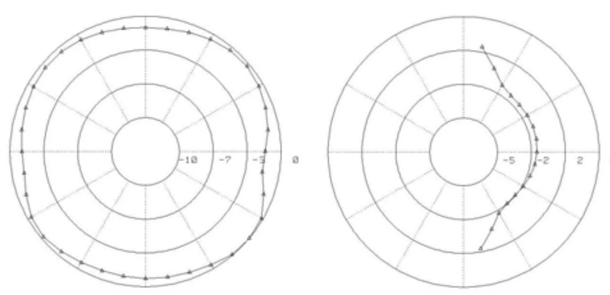


Figure 4.6. Wraparound patch with quarterwave transformer matching sections.



a. Azimuth plane gain pattern. **b.** Elevation plane gain pattern

Figure 4.7. Linearly polarized patch and its radiation pattern.

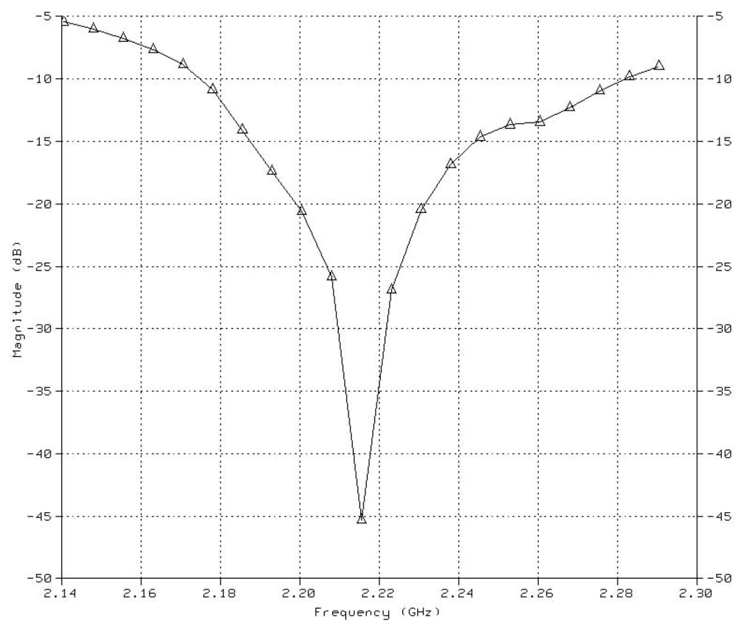


Figure 4.8. S_{11} for linearly polarized wraparound patch with quarterwave matching section.

station) than to broadside. The S_{11} performance of the wraparound patch, as shown in figure 4.8, shows that the 3 dB bandwidth of the patch is greater than 8%, which is much larger than the results of the single rectangular patch. This wide bandwidth is likely because Clementine's calculated input impedance was approximately the same impedance as the 50 ohm feed line. In other words, the antenna is essentially already matched to the feed lines and the limiting effects of the quarterwave transformer frequency selectivity do not have much of an effect.

To conclude the analysis of the wraparound patch, it was analyzed at five different resonant lengths to get an idea how resonant length changes with frequency. The results are summarized in table 4.5 and figure 4.9. As in the previous cases, the resonant lengths correspond to input impedances with no reactive component. As seen from the results, the resonant length for the wraparound patch decreases 0.019 mm for a 1 MHz increase in resonant frequency. This is slightly less than the rectangular patch, which varied 0.021 mm for each 1 MHz.

Table 4.4. Summary of wraparound analysis results using simple models and Clementine.

	Basic Equations	WRAPPAT	Clementine
Frequency (GHz)	2.2155	2.2155	2.2155
Radius (mm)	176.276	176.276	176.276
W (mm)	1107.58	1107.58	1107.58
L (mm)	43.47	42.23	44.11
NF	16	16	16
Impedance (ohms)	88	117	47.4
BW	-	-	>7.5%

Table 4.5. Summary of five wraparound patches tuned at different frequencies.

Frequency (GHz)	Width (mm)	Length (mm)	Rin (ohms)
2.1155	1107.58	46.15	50.9
2.1655	1107.58	45.20	50.3
2.2155	1107.58	44.11	47.4
2.2655	1107.58	43.23	49.4
2.3155	1107.58	42.36	43.2

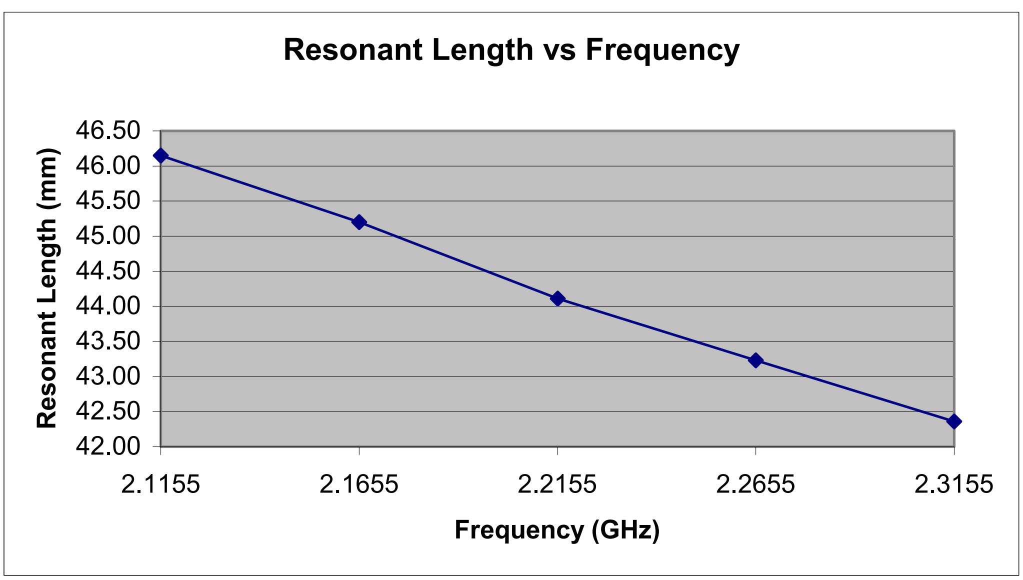
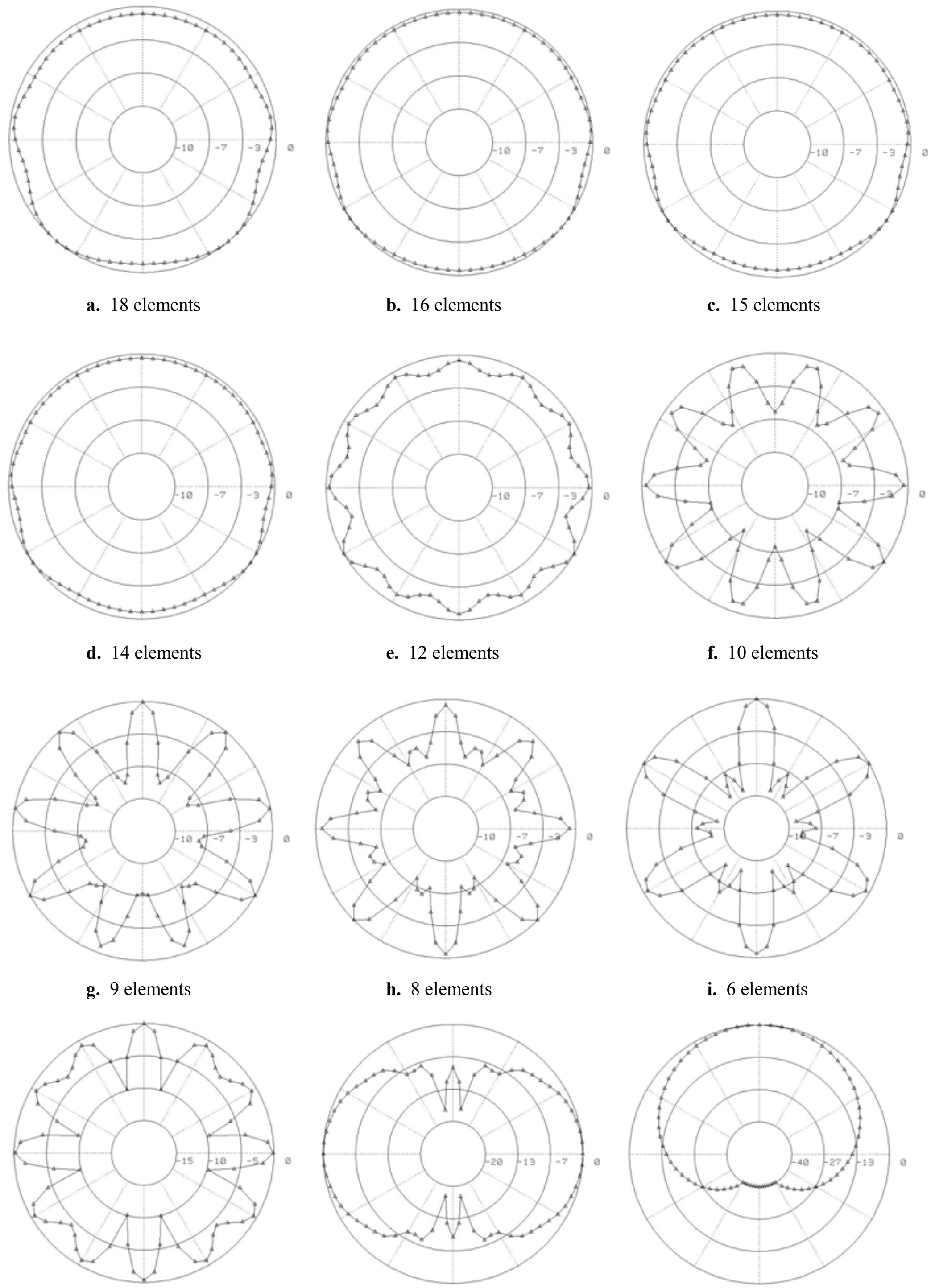


Figure 4.9. Resonant lengths for 5 wraparound patch antennas.

4.3 Design of Linearly Polarized Array

As was seen in the previous section, nearly omnidirectional radiation can be achieved by wrapping a single patch completely around a cylinder. However, a more efficient method is to place an array of individual patches around the circumference of a cylinder. In designing an antenna array of this type, it is necessary to determine the number of elements necessary to achieve minimum pattern ripple. To have an efficient antenna, the element spacing should also minimize the mutual coupling between the individual patch elements. The effects of mutual coupling have been investigated in the literature. From these studies, the design rule of thumb to minimize mutual coupling is to space the array elements by $0.6\lambda_g$ to $0.9\lambda_g$, where the spacing is measured from the patch centers. For the telemetry frequency of 2.2155 GHz, λ_0 is 135 mm while λ_g is roughly 88 mm for the RT-Duroid substrate used in this report. This section will present Clementine simulations to investigate how varying the number of rectangular patch elements on the cylinder affects the ripple in the radiation pattern of the array.

Arrays comprised of the rectangular patch elements designed in section 4.1 were simulated with Clementine. Their electric field radiation patterns are shown in figure 4.10. The arrays with 18, 16, 15, and 14 elements clearly have omnidirectional patterns with very little ripple. As mentioned before, the rule of thumb to minimize mutual coupling is to space the elements $0.6\lambda_g$ to $0.9\lambda_g$, or in this case, approximately 45 to 71 mm. Arrays having either 18, 16, or 15 elements fit in this category.



a. 18 elements b. 16 elements c. 15 elements

d. 14 elements e. 12 elements f. 10 elements

g. 9 elements h. 8 elements i. 6 elements

j. 4 elements k. 2 elements l. 1 element

Figure 4.10. Radiation patterns for rectangular patch arrays on a 14-inch diameter cylinder.

To obtain an omnidirectional pattern, each patch element must be fed with signals having equal magnitude and phase. These are largely affected by the feed network design. A 16-element feed network is the simplest to implement because it can be designed using 2-way power dividers throughout the entire corporate feed network. Due to its symmetrical layout, each element will have equal signals at their input ports. The 18-element array's feed network is more complicated because it requires a combination of 2-way and 3-way power dividers. The 14 and 15-element arrays' feed networks are more complicated. In cases like these, where the sub-arrays have unequal elements that require non-symmetrical feed lines, it is important to ensure that each patch element is fed with signals having equal magnitude and phase. As a result, special attention is required in the line width (impedance matching), line length (phase matching), and T-junction designs (impedance and phase matching). The matter is further complicated by the feed line corner discontinuities.

Figure 4.11 shows the mutual coupling for arrays shown in figures 4.10a – f. The plots show the power coupled from one patch to the other patches around the cylinder (S_{21}, S_{31}, S_{41}, etc.). As expected, the coupling is largest to the first adjacent patch. The power coupled to the first adjacent patch is below -25 dB for all the arrays. The mutual coupling for the each of the four omnidirectional arrays (18, 16, 15, and 14 element) fall within –25 dB to -32 dB.

The parameters of the patch arrays shown in figure 4.10 are listed in table 4.6 and 4.7. In table 4.7, the amount of ripple for each array is related to the radius, element spacing, and guided wavelength. The data shows that an omnidirectional pattern on a 14-

inch diameter is achieved when the spacing is less than 1λ_g.

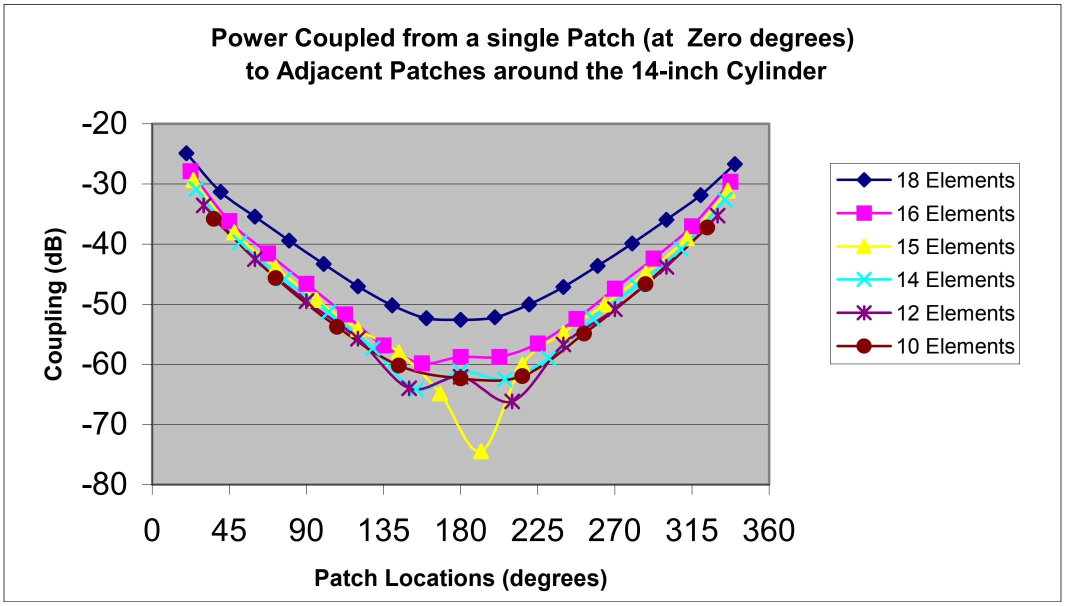


Figure 4.11. Mutual coupling effects of linearly polarized array on a cylinder.

Table 4.6. 14-inch cylinder parameters at 2.2155 GHz.

λ_0	λ_g	$0.6\lambda_g$	$0.9\lambda_g$	Radius
(mm)	(mm)	(mm)	(mm)	(mm)
135.41	88.71	53.23	79.84	176.28

Table 4.7. Ripple of 2.2155 GHz rectangular patch arrays on a 14-inch cylinder.

Elements	Spacing	Ripple	Spacing/radius	Spacing/ λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
18	61.53	1.2	0.35	0.69
16	69.22	0.7	0.39	0.78
15	73.84	0.7	0.42	0.83
14	79.11	0.7	0.45	0.89
12	92.30	2	0.52	1.04
10	110.76	7	0.63	1.25
9	123.07	8	0.70	1.39
8	138.45	8	0.79	1.56
6	184.60	9	1.05	2.08
4	276.90	10	1.57	3.12
3	369.20	18	2.09	4.16
2	553.80	40	3.14	6.24

4.4 Design of Single Fed, Circularly Polarized Element - Planar Surface

The following sections investigate the design of single fed circularly polarized microstrip patches. Specifically, the nearly square and truncated corner circularly polarized elements are investigated because they are small in size and their dimensions can be calculated quickly using simple models. In this section, simple models will be used to determine the dimensions of planar nearly square and truncated corner patches for telemetry and GPS frequencies. In the following sections, these dimensions will be used to optimize elements and arrays for 6, 8, and 14-inch cylinders.

The circularly polarized elements can be designed easily using the variational method discussed in chapter 3. However, in order to use these formulas, the quality factor of a square patch must be determined. Using the HED equations, the quality factor of a square patch was calculated as 70.67.

The first patches designed are the nearly square and truncated patch elements for the telemetry frequency 2.2155 GHz (see figure 3.3). The area of both patches is

$$\begin{aligned} S &= L \cdot W \\ &= 43.37\,\text{mm} \cdot 43.37\,\text{mm} \\ &= 1908\,\text{mm}^2. \end{aligned} \tag{4.26}$$

The c segment area for the nearly square patch is

$$\begin{aligned} \Delta s &= \frac{S}{Q_t} \\ &= \frac{1908\,\text{mm}^2}{71.51} \\ &= 26.68\,\text{mm}^2, \end{aligned} \tag{4.27}$$

while the truncated patch's perturbation segment area is

$$\begin{aligned}\Delta s &= \frac{S}{2\cdot Q_t} \\ &= \frac{1908\,\text{mm}^2}{2\cdot 71.51} \\ &= 13.34\,\text{mm}^2.\end{aligned} \tag{4.28}$$

The width of the nearly square's perturbation segment is

$$\begin{aligned}c &= \frac{\Delta s}{L} \\ &= \frac{26.68\,\text{mm}^2}{43.68\,\text{mm}} \\ &= 0.61\,\text{mm},\end{aligned} \tag{4.29}$$

while the side length of the truncated corner is

$$\begin{aligned}c &= \sqrt{\Delta s} \\ &= \sqrt{13.34\,\text{mm}^2} \\ &= 3.65\,\text{mm}.\end{aligned} \tag{4.30}$$

The circularly polarized GPS (1.57542 GHz) nearly square and truncated elements are designed following the same steps above. The area for these patches is

$$\begin{aligned}S &= L\cdot W \\ &= 61.74\,\text{mm}\cdot 61.74\,\text{mm} = 3812.0\,\text{mm}^2.\end{aligned} \tag{4.31}$$

The area of the nearly square patch's perturbation segment is

$$\begin{aligned}\Delta s &= \frac{S}{Q_t} \\ &= \frac{3812.0\,\text{mm}^2}{93.24} = 40.88\,\text{mm}^2,\end{aligned} \tag{4.32}$$

while the area of the truncated patch's perturbation segment is

$$\begin{aligned}\Delta s &= \frac{S}{2 \cdot Q_t} \\ &= \frac{3812.0\,\text{mm}^2}{2 \cdot 93.24} = 20.44\,\text{mm}^2.\end{aligned} \tag{4.33}$$

The width of the nearly square's perturbation section is

$$\begin{aligned}c &= \frac{\Delta s}{L} \\ &= \frac{40.88\,\text{mm}^2}{61.74\,\text{mm}} = 0.66\,\text{mm},\end{aligned} \tag{4.34}$$

while the side length of the truncated corner is

$$\begin{aligned}c &= \sqrt{\Delta s} \\ &= \sqrt{20.44\,\text{mm}^2} = 4.52\,\text{mm}.\end{aligned} \tag{4.35}$$

The planar telemetry and GPS elements were also analyzed using the DOS CAD program CCPATCH and Clementine's estimation tool, (see tables 4.8 and 4.9). The results show that accurate results can be achieved with the simple models.

Table 4.8. Nearly Square CP Patch – Planar Design.

	Telemetry			GPS		
	Equations	CCPATCH	Clementine Est.	Equations	CCPATCH	Clementine Est.
Frequency (GHz)	2.2155	2.2155	2.2155	1.57542	1.57542	1.57542
Height(mm)	1.524	1.524	1.524	1.524	1.524	1.524
Permittivity	2.33	2.33	2.33	2.33	2.33	2.33
Loss Tangent	0.001	0.001	0.001	0.001	0.001	0.001
Length (mm)	44.292	43.28	44.14	61.402	61.3079	62.32
Width (mm)	43.68	42.46	43.17	61.74	60.45	61.09
c (mm)	0.612	0.819	0.97	0.662	0.8579	1.23
Zin (ohms)	-	613-j5.7	-	-	572-j4	-

Table 4.9. Truncated Corner CP Patch – Planar Design.

	Telemetry			GPS		
	Equations	CCPATCH	Clementine Est.	Equations	CCPATCH	Clementine Est.
Frequency (GHz)	2.2155	2.2155	2.2155	1.57542	1.57542	1.57542
Height(mm)	1.524	1.524	1.524	1.524	1.524	1.524
Permittivity	2.33	2.33	2.33	2.33	2.33	2.33
Loss Tangent	0.001	0.001	0.001	0.001	0.001	0.001
Length (mm)	43.68	42.462	43.66	61.74	60.45	61.7
Width (mm)	43.68	42.462	43.66	61.74	60.45	61.7
c (mm)	3.653	4.1676	3.926	4.521	5.0922	4.647
Zin (ohms)	-	613-j5.7	-	-	572-j4	-