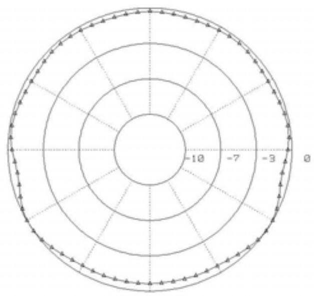
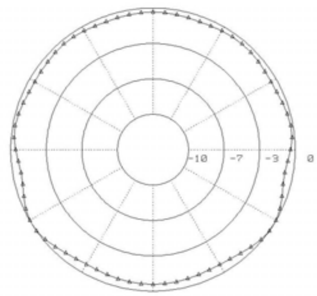
4.8 Design of Nearly Square Cylindrical Antenna Array for Telemetry

To achieve a circularly polarized omnidirectional pattern, an array of circularly polarized elements is wrapped around the circumference of the cylinder. To achieve this omnidirectional pattern, it is important to choose the correct number of elements to minimize pattern ripple. This section presents Clementine simulations to investigate how the number of nearly square circularly polarized patch elements for 14, 8, and 6-inch cylinders affect the ripple in the omnidirectional radiation pattern.

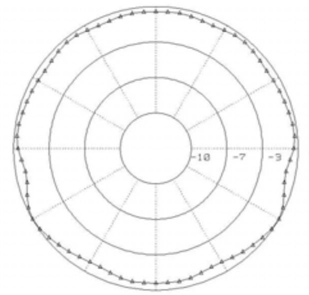
The electric field radiation patterns for these three diameters are shown in figures 4.36 – 4.38. The ripple characteristics of these arrays are summarized in tables 4.22 – 4.25. As in the case of the linearly polarized arrays, the ripple is kept below 3 dB when the element spacing is slightly less than a guided wavelength. The mutual coupling factors (S_{21}, S_{31}, S_{41}, …) of these arrays are shown in figure 4.39, where each point of the graph represents a patch element.



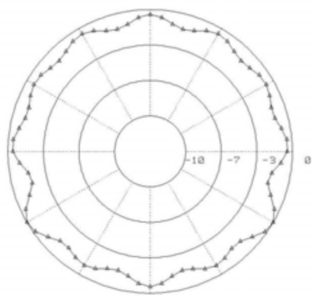
a. 16 elements



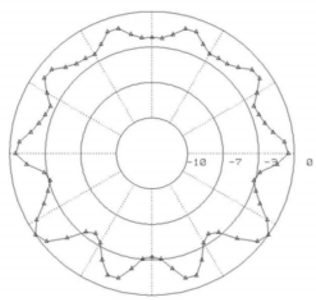
b. 15 elements



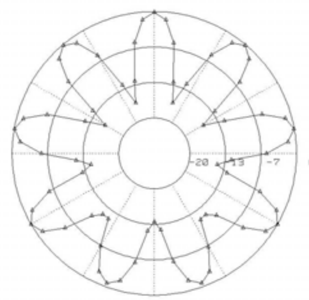
c. 14 elements



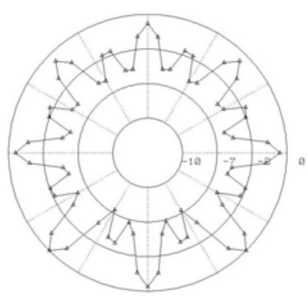
d. 12 elements



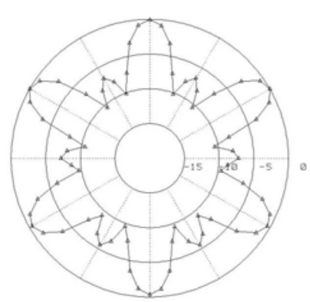
e. 10 elements



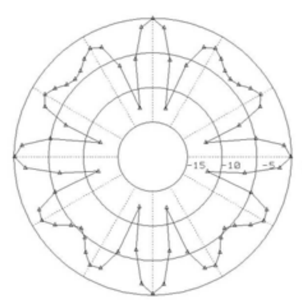
f. 9 elements



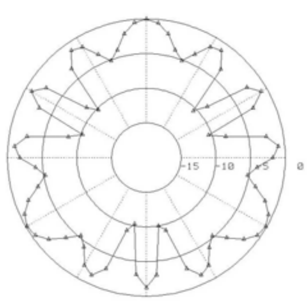
g. 8 elements



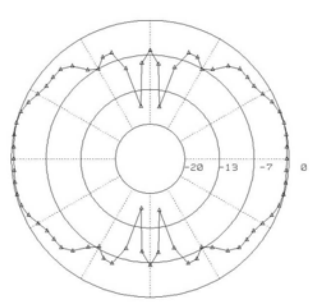
h. 6 elements



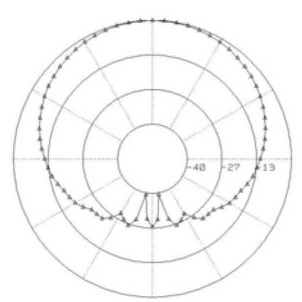
i. 4 elements



j. 3 elements

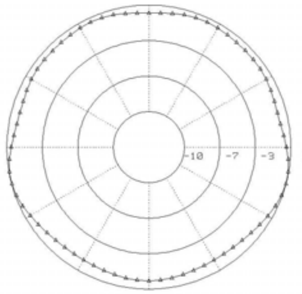


k. 2 elements

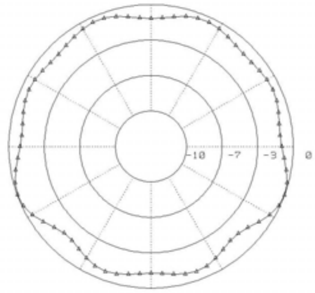


l. 1 element

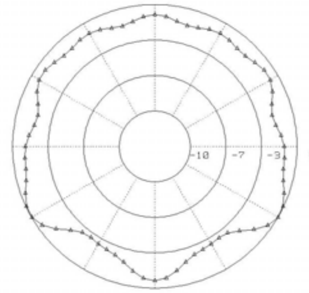
Figure 4.36. Normalized electric field patterns for nearly square telemetry array – 14-inch diameter.



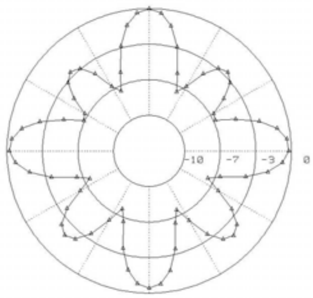
a. 9 elements



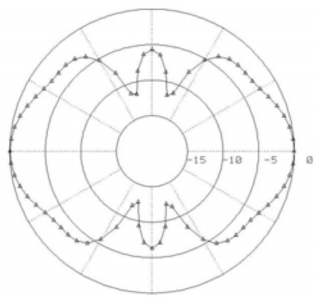
b. 8 elements



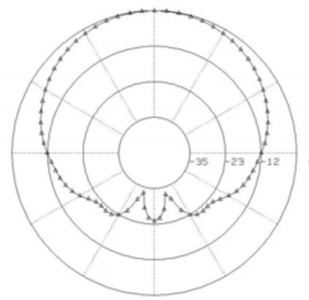
c. 6 elements



d. 4 elements

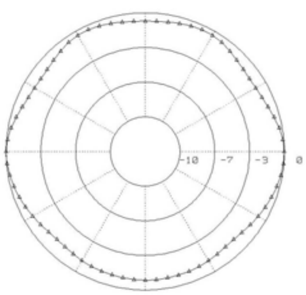


e. 2 elements

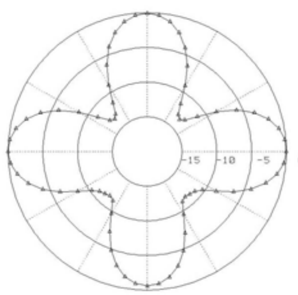


f. 1 element

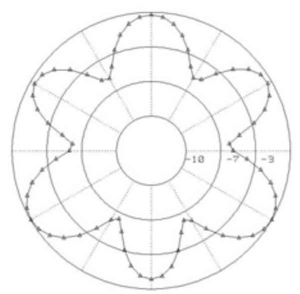
Figure 4.37. Normalized electric field patterns for nearly square telemetry array – 8-inch diameter.



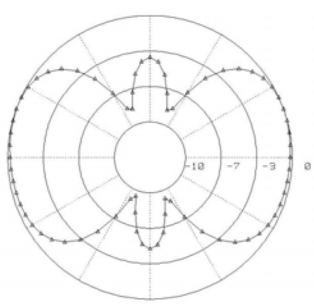
a. 6 elements



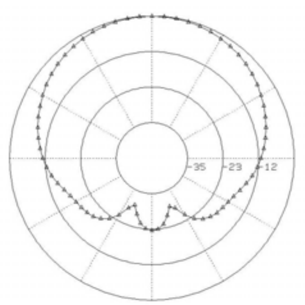
b. 4 elements



c. 3 elements



d. 2 elements



e. 1 element

Figure 4.38. Normalized electric field patterns for nearly square telemetry array – 6-inch diameter.

Table 4.22. Nearly square patch array parameters at 2.2155 GHz.

Wavelengths				Radii		
λ_0	λ_g	$0.6\lambda_g$	$0.9\lambda_g$	14 Dia. Cyl.	8 Dia. Cyl.	6 Dia. Cyl.
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
135.41	88.71	53.23	79.84	176.28	100.08	76.68

Table 4.23. Ripple of nearly square patch arrays on a 14-inch cylinder at 2.2155 GHz.

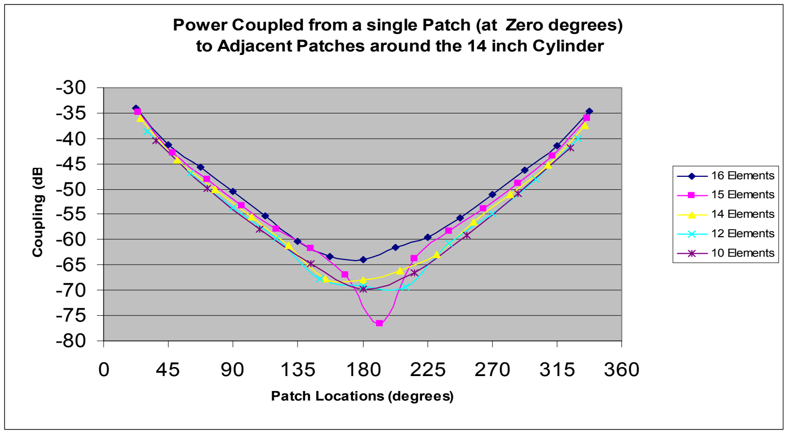
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
16	69.22	0.6	0.39	0.78
15	73.84	0.8	0.42	0.83
14	79.11	1	0.45	0.89
12	92.30	2	0.52	1.04
10	110.76	4	0.63	1.25
9	123.07	17	0.70	1.39
8	138.45	7	0.79	1.56
6	184.60	10	1.05	2.08

Table 4.24. Ripple of nearly square patch arrays on an 8-inch cylinder at 2.2155 GHz

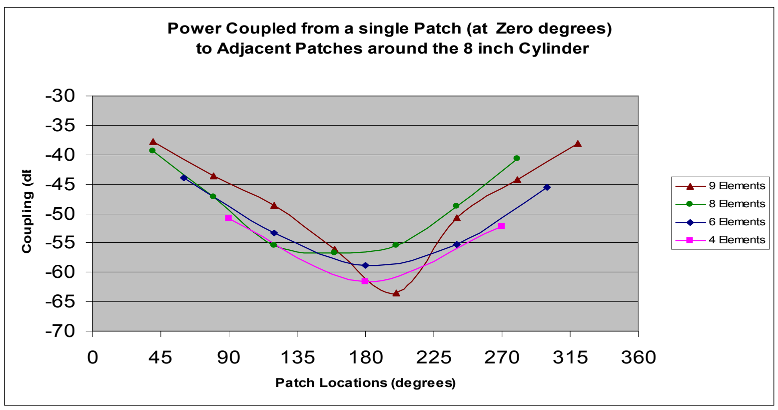
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
9	69.87	1	0.70	0.79
8	78.60	2	0.79	0.89
6	104.80	2.8	1.05	1.18
4	157.21	8	1.57	1.77
2	314.41	12	3.14	3.54

Table 4.25. Ripple of nearly square patch arrays on a 6-inch cylinder at 2.2155 GHz

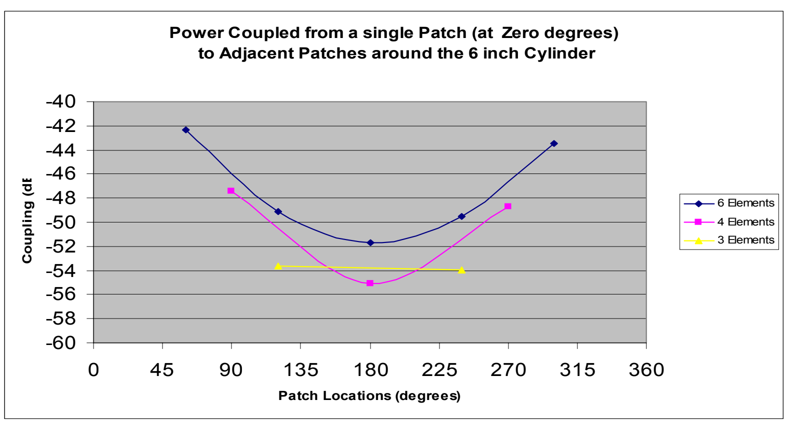
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
6	80.30	1.5	1.05	0.91
4	120.45	13.5	1.57	1.36
3	160.60	6	2.09	1.81
2	240.90	10	3.14	2.72



a. 14-inch diameter cylinder



b. 8-inch diameter cylinder



c. 6-inch diameter cylinder

Figure 4.39. Mutual coupling for nearly square patch arrays at 2.2155 GHz.

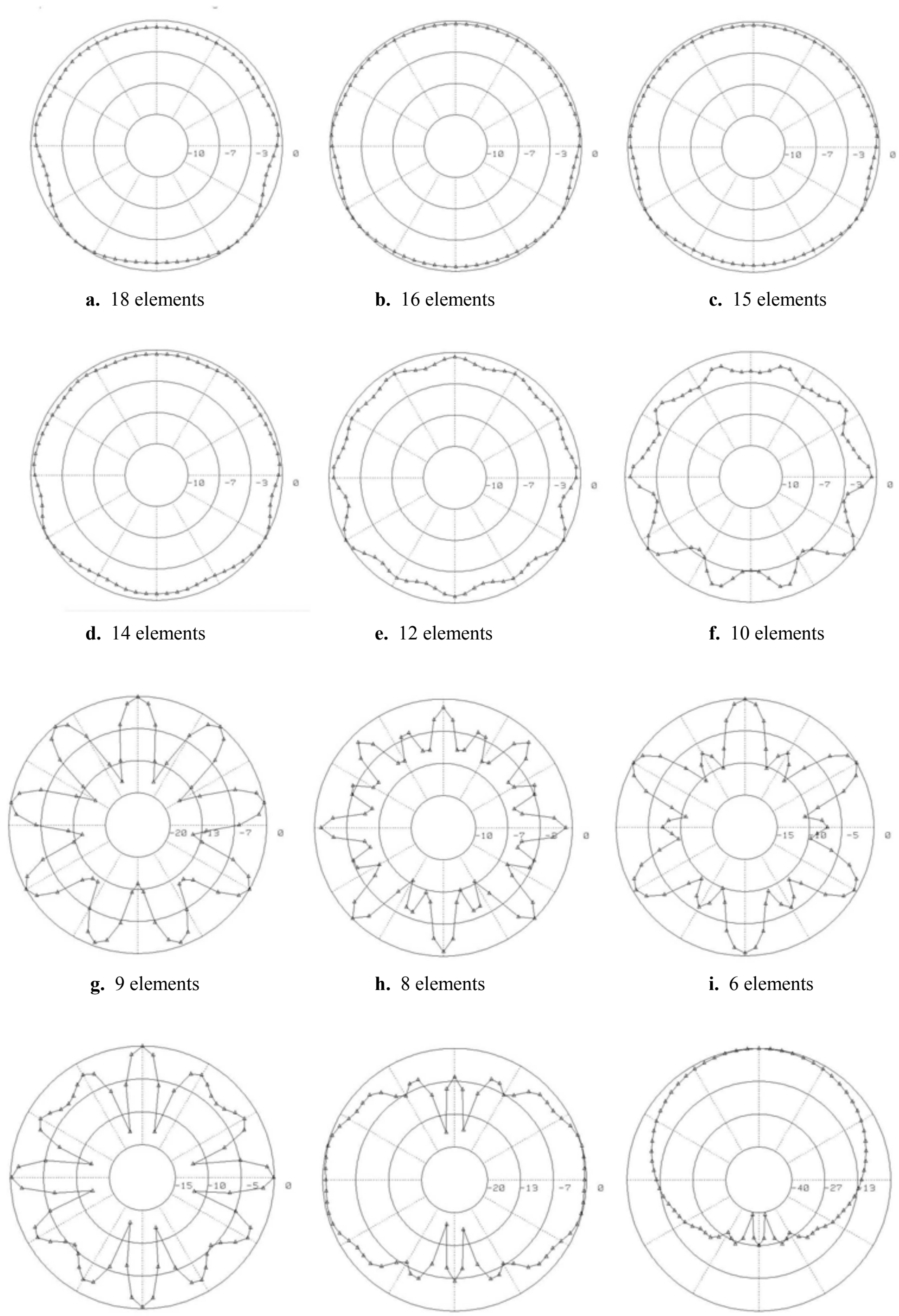
4.9 Design of Truncated Corner Cylindrical Antenna Array for Telemetry

To achieve a circularly polarized omnidirectional pattern, an array of circularly polarized elements is wrapped around the circumference of the cylinder. To achieve this omnidirectional pattern, it is important to choose the correct number of elements to minimize pattern ripple. This section presents Clementine simulations to investigate how the number of truncated corner circularly polarized patch elements on the 14-, 8-, and 6-inch cylinders affect the ripple in the omnidirectional radiation pattern.

The electric field radiation patterns for these three diameters are shown in figures 4.40 – 4.42. The ripple characteristics of these arrays are summarized in tables 4.26 – 4.29. As in the case of the linearly polarized and nearly square arrays, the ripple is kept below 3 dB when the element spacing is slightly less than a guided wavelength. The mutual coupling factors (S_{21}, S_{31}, S_{41}, …) of these arrays are shown in figure 4.43, where each point of the graph represents a patch element.

4.9.1 Comparison of Nearly Square and Truncated Corner Patch Arrays

The ripple in radiation patterns for the nearly square and truncated corner patch arrays are almost exactly the same when they have the same number of elements in their arrays. The only difference in these arrays is that the truncated corner patch can fit more elements on a cylinder than the nearly square patch. This is because the nearly square patch is fed on the diagonal and must be orientated diagonally while the truncated corner is orientated horizontally.



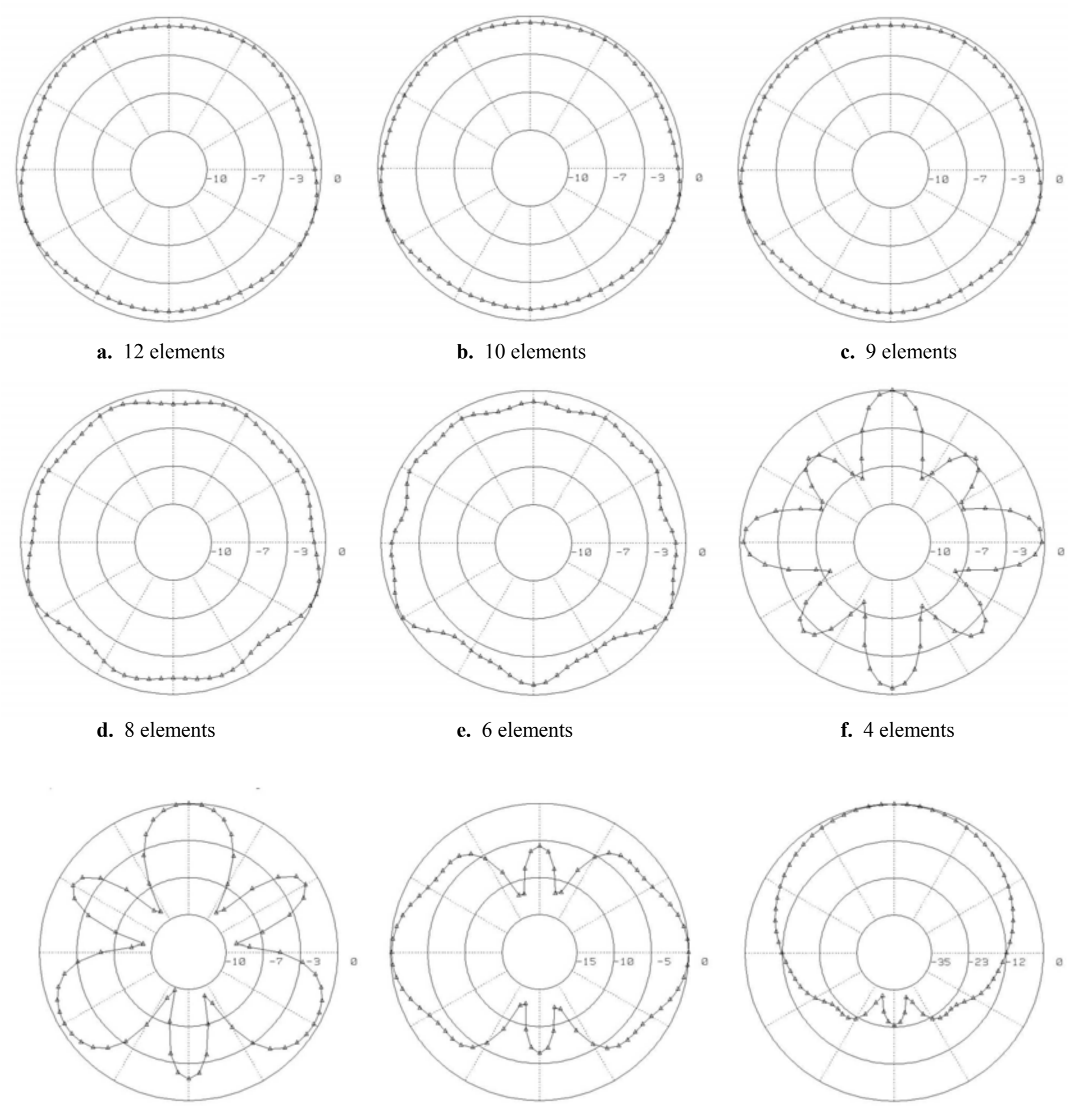
a. 18 elements **b.** 16 elements **c.** 15 elements

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 4.40. Normalized electric field patterns for truncated corner telemetry array - 14-inch diameter.

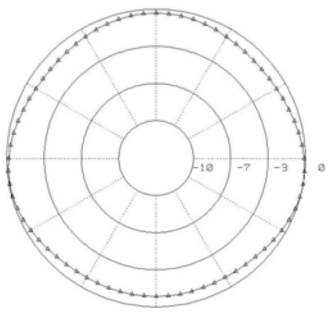


a. 12 elements **b.** 10 elements **c.** 9 elements

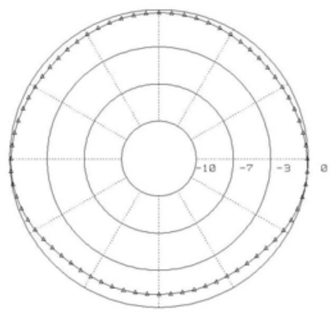
d. 8 elements **e.** 6 elements **f.** 4 elements

g. 3 elements **h.** 2 elements **i.** 1 element

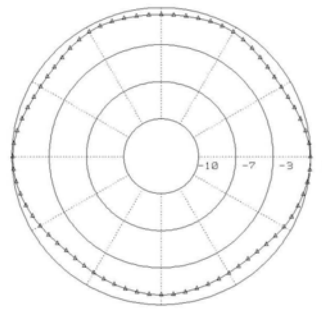
Figure 4.41. Normalized electric field patterns for truncated corner telemetry array - 8-inch diameter.



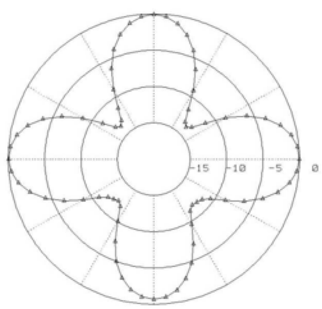
a. 9 elements



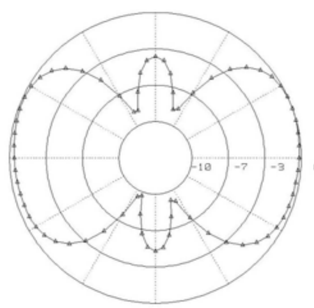
b. 8 elements



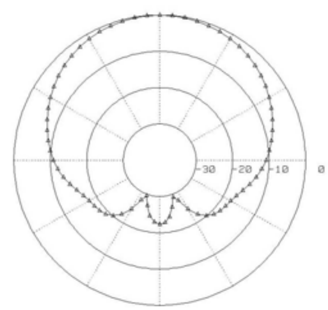
c. 6 elements



d. 4 elements



e. 2 elements



f. 1 element

Figure 4.42. Normalized electric field patterns for truncated corner telemetry array - 6-inch diameter.

Table 4.26. Truncated corner patch array parameters at 2.2155 GHz.

Wavelengths				Radii		
λ_0	λ_g	$0.6\lambda_g$	$0.9\lambda_g$	14 Dia. Cyl.	8 Dia. Cyl.	6 Dia. Cyl.
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
135.41	88.71	53.23	79.84	176.28	100.08	76.68

Table 4.27. Ripple of truncated corner patch arrays on a 14-inch cylinder at 2.2155 GHz .

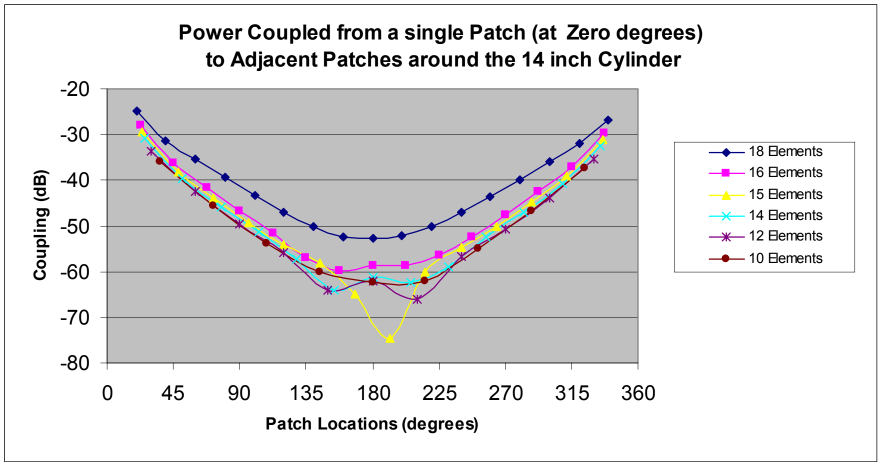
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
18	61.53	1.5	0.35	0.69
16	69.22	0.7	0.39	0.78
15	73.84	0.8	0.42	0.83
14	79.11	1	0.45	0.89
12	92.30	2	0.52	1.04
10	110.76	3.5	0.63	1.25
9	123.07	17	0.70	1.39
8	138.45	7	0.79	1.56
6	184.60	11	1.05	2.08

Table 4.28. Ripple of truncated corner patch arrays on an 8-inch cylinder at 2.2155 GHz.

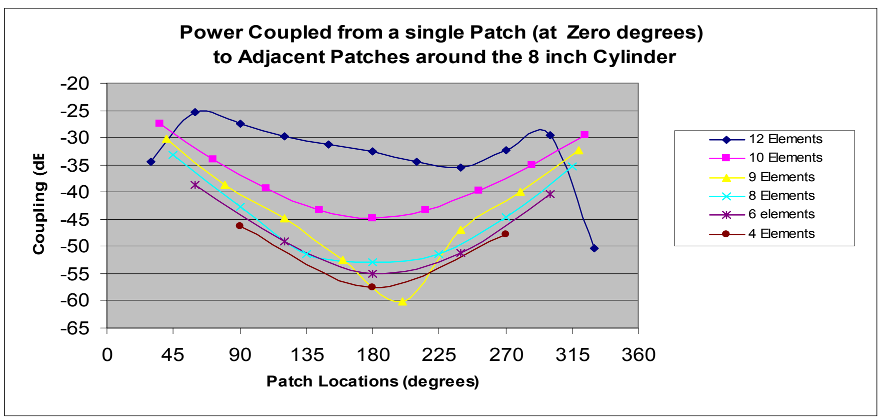
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
12	52.40	1	0.52	0.59
10	62.88	1	0.63	0.71
9	69.87	1	0.70	0.79
8	78.60	1.8	0.79	0.89
6	104.80	2.5	1.05	1.18
4	157.21	8	1.57	1.77
3	209.61	10	2.09	2.36

Table 4.29. Ripple of truncated corner patch arrays on a 6-inch cylinder at 2.2155 GHz.

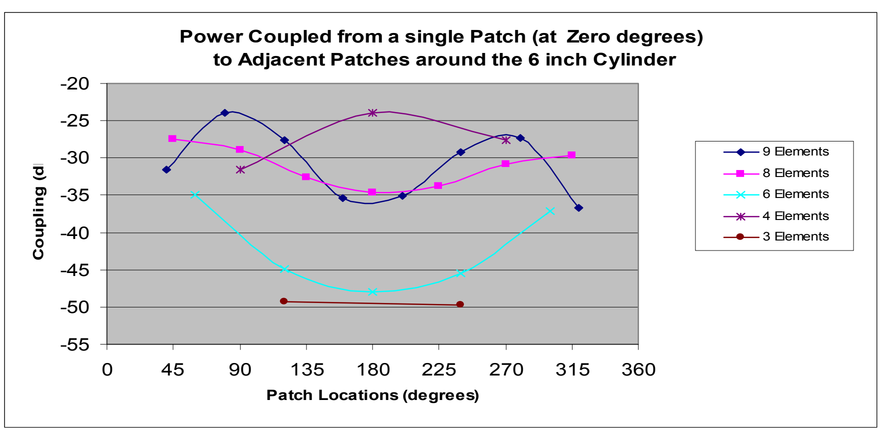
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
9	53.53	1	0.70	0.60
8	60.22	1.2	0.79	0.68
6	80.30	1.3	1.05	0.91
4	120.45	13	1.57	1.36
2	240.90	10	3.14	2.72



a. 14-inch diameter cylinder



b. 8-inch diameter cylinder



c. 6-inch diameter cylinder

Figure 4.43. Mutual coupling for truncated corner patch arrays at 2.2155 GHz.

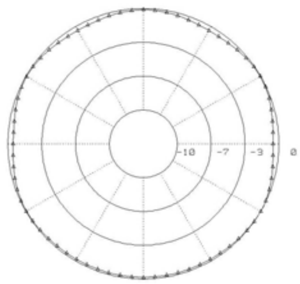
4.10 Design of Truncated Corner Cylindrical Antenna Array for GPS

This section will use Clementine simulations to investigate how the number of truncated corner circularly polarized patch elements on the 14-, 8-, and 6-inch cylinders affect the ripple in the omnidirectional radiation pattern.

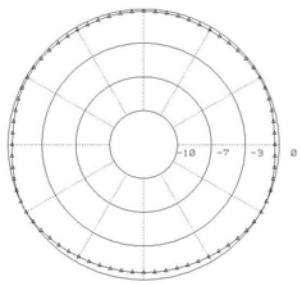
The electric field radiation patterns for these three diameters are shown in figures 4.44 – 4.46. The ripple characteristics of these arrays are summarized in tables 4.30 – 4.33. As in the case of the telemetry arrays, the ripple is kept below 3 dB when the element spacing is slightly less than a guided wavelength. The mutual coupling factor of these arrays are shown in figure 4.47, where each point of the graph represents a patch element (S_{21}, S_{31}, S_{41}, …).

4.10.1 Comparison of Telemetry and GPS Truncated Corner Patch Array

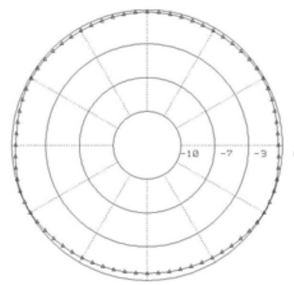
For all but the GPS array on the 6-inch cylinder, the ripple in the radiation patterns for both the telemetry and GPS truncated corner patch arrays are minimized when the element spacing is less than a guided wavelength. The GPS array on the 6-inch cylinder has a ripple of 3.5 dB when the spacing is just less than the guided wavelength. This behavior is likely a result of curvature effects because, in this particular case, the guided wavelength is almost twice as large as the cylinder's radius. For this case, the ripple is not minimized until the spacing is about $0.7\lambda_g$



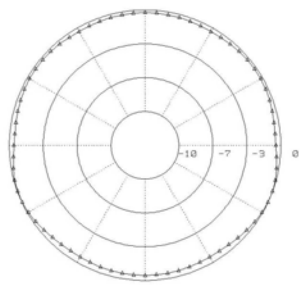
a. 16 elements



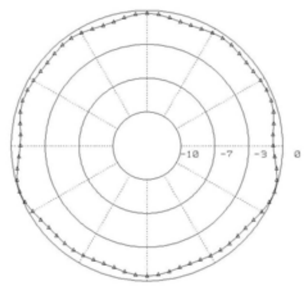
b. 15 elements



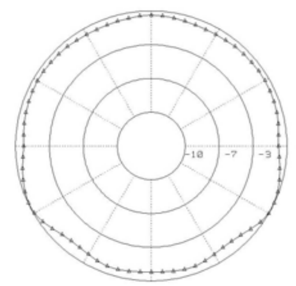
c. 14 elements



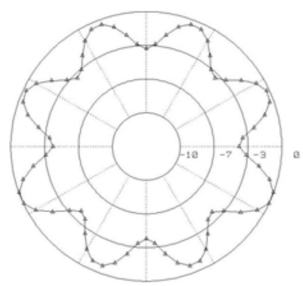
d. 12 elements



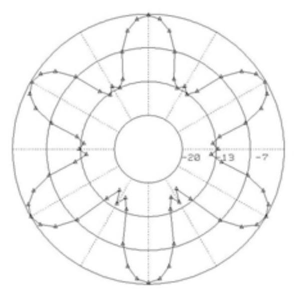
e. 10 elements



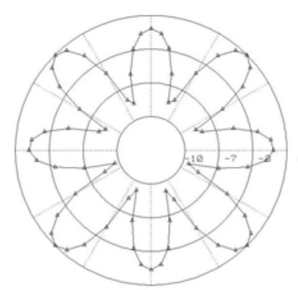
f. 9 elements



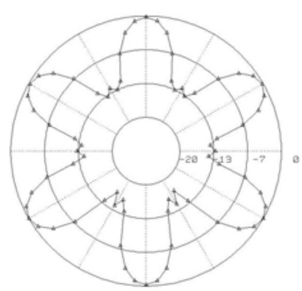
g. 8 elements



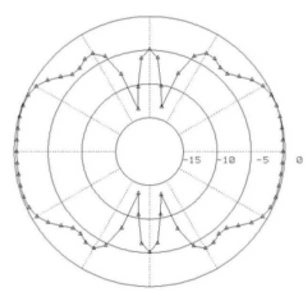
h. 6 elements



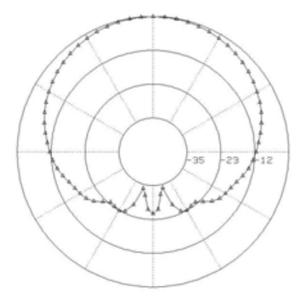
i. 4 elements



j. 3 elements

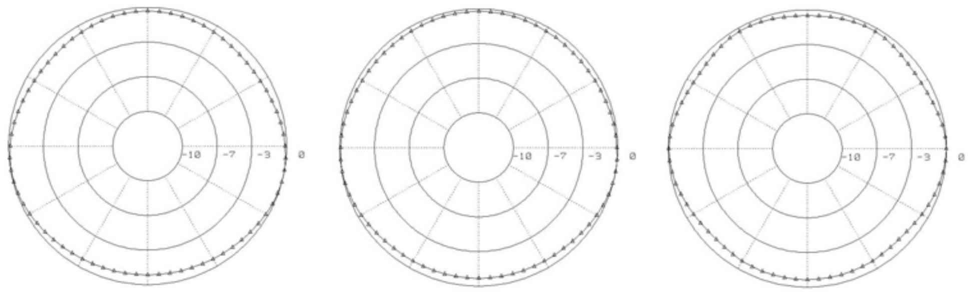


k. 2 elements

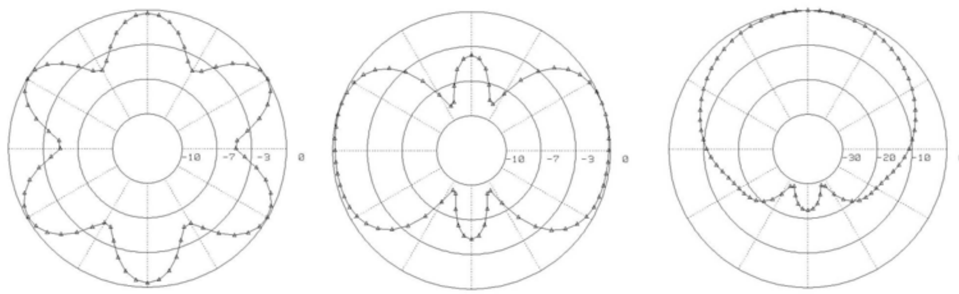


l. 1 element

Figure 4.44. Normalized electric field patterns for GPS truncated corner array – 14-inch diameter.

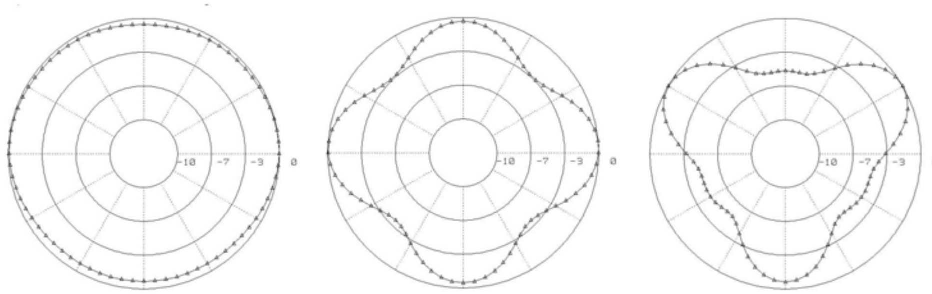


a. 9 elements **b.** 8 elements **c.** 6 elements

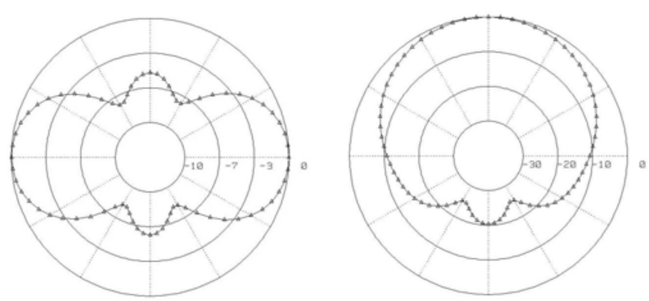


d. 4 elements **e.** 2 elements **f.** 1 element

Figure 4.45. Normalized electric field patterns for GPS truncated corner array – 8-inch diameter.



a. 6 elements **b.** 4 elements **c.** 3 elements



d. 2 elements **e.** 1 elements

Figure 4.46. Normalized electric field patterns for GPS truncated corner array – 6-inch diameter.

Table 4.30. Truncated corner patch array cylinder parameters at 1.57542 GHz.

Wavelengths				Radii		
λ_0	λ_g	$0.6\lambda_g$	$0.9\lambda_g$	14 Dia. Cyl.	8 Dia. Cyl.	6 Dia. Cyl.
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
190.43	124.75	74.85	112.28	176.28	100.08	76.68

Table 4.31. Ripple of truncated corner patch arrays on a 14-inch cylinder at 1.57542 GHz.

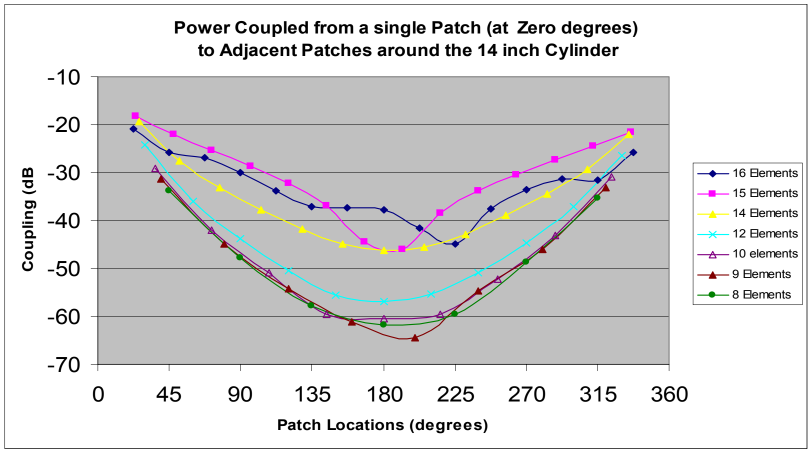
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
16	69.22	0.5	0.78	0.55
15	73.84	0.5	0.83	0.59
14	79.11	0.5	0.89	0.63
12	92.30	0.5	1.04	0.74
10	110.76	1	1.25	0.89
9	123.07	1	1.39	0.99
8	138.45	4	1.56	1.11
6	184.60	17	2.08	1.48
4	267.90	10	3.02	2.15
2	553.80	14	6.24	4.44

Table 4.32. Ripple of truncated corner patch arrays on an 8-inch cylinder at 1.57542 GHz.

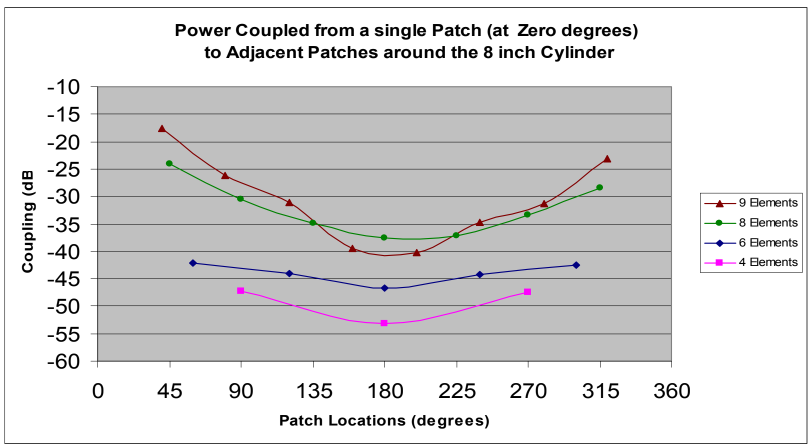
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
9	69.87	1	0.70	0.56
8	78.60	0.8	0.79	0.63
6	104.80	0.9	1.05	0.84
4	157.21	5	1.57	1.26
2	314.41	4	3.14	2.52

Table 4.33. Ripple of truncated corner patch arrays on a 6-inch cylinder at 1.57542 GHz.

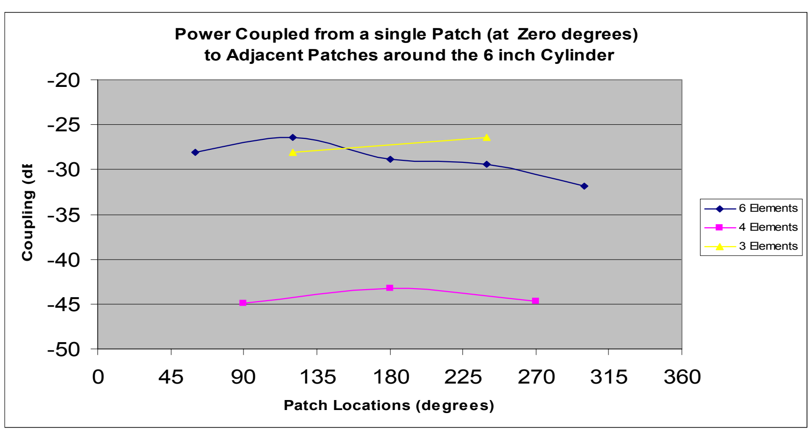
Elements	Spacing	Ripple	Spacing/radius	Spacing/λ_g
	(mm)	(dB)	(mm/mm)	(mm/mm)
6	80.30	0.8	1.05	0.64
4	120.45	3.5	1.57	0.97
3	160.60	5	2.09	1.29
2	240.90	8.5	3.14	1.93



a. 14-inch diameter cylinder



b. 8-inch diameter cylinder



c. 6-inch diameter cylinder

Figure 4.47. Mutual coupling for truncated corner patch arrays at 1.57542 GHz.

4.11 Antenna Element and Array Comparisons – Cylindrical Surface

In this final section, the performance of linearly and circularly polarized antennas mounted on cylinders will be investigated by comparing the performance of the telemetry antennas discussed previously in this chapter. The performance of both antenna elements and arrays will be compared.

4.11.1 Element Comparison

The analysis results for the telemetry elements mounted on 14-inch cylinders previously presented in this chapter are summarized in table 4.34. The beamwidths and gains of the elements are essentially the same for all cases. The impedance bandwidths

Table 4.34. Patch performances on a 14-inch diameter.

Microstrip Patch	Diameter	Azimuth Plane		Elevation Plane		Broadside		
		3 dB Beamwidth	6 dB AR Beamwidth	3 dB Beamwidth	6 dB AR Beamwidth	Gain	Impedance Bandwidth	6 dB AR Bandwidth
	(inches)	(degrees)	(degrees)	(degrees)	(degrees)	(dB)	(MHz)	(MHz)
Rectangular	14	80	-	105	-	6.5	90	-
Nearly Square	14	90	180	90	145	6.6	112	24.9
Truncated Corner	14	95	180	90	140	6.7	125	24.3

of the circularly polarized antenna elements are greater than the linearly polarized element by at least 22 MHz. Because these elements are matched using different types of matching networks, it is difficult to know whether the differences in impedance bandwidths result from the performance of the antenna elements or the matching networks.

Assuming that the increase in antenna bandwidth for the circularly polarized antennas are a result of their element performance, then the circularly polarized antenna out performs the linearly polarized antenna. This is true, even though the axial ratio bandwidths of the circularly polarized antennas are much narrower than the impedance bandwidths. For narrowband signals, or for signals within a few MHz from the center frequency of the antenna, the circularly polarized antennas will out perform the linearly polarized antenna by approximately 3 dB. This is because the axial ratio is low, meaning the polarization loss is very low for the circularly polarized antenna. However, farther from the antenna's center frequency, the circularly polarized antenna becomes more like a linearly polarized antenna.

At the center frequency of the antennas, the axial ratio degrades in the directions along the longitudinal axis of the cylinder. As shown in figure 3.6, an axial ratio of 6 dB equates to a loss of approximately 0.5 dB, when the ground station's antenna is circularly polarized. But, even when the axial ratio becomes large, say AR = 30 dB, the performance of the circularly polarized antenna presents no more mismatch loss than a linearly polarized antenna. With this in mind, the impedance bandwidth results listed in table 4.35 show that even with an AR of 30 dB, the circularly polarized antenna has roughly 25 MHz greater bandwidth than the linearly polarized antenna. Unfortunately, this data is only broadside to the patch and does not allow for comparisons in other regions.

4.11.2 Array Comparison

To compare the performance of the linearly and circularly polarized omnidirectional array antennas, the telemetry antennas discussed in previous sections will be analyzed and their simulation results compared. The Clementine results for the wraparound patch, rectangular patch array, and truncated corner patch array mounted on 14-inch cylinders are shown in figure 4.48 – 4.53 and summarized in table 4.35. For a wraparound patch on a 14-inch cylinder, 16 feed points are required. To provide an accurate comparison, both the rectangular patch and truncated corner patch arrays in this comparison have 16 patch elements in their arrays.

Figure 4.48 shows the impedance bandwidth versus frequency of the omnidirectional antennas. The bandwidth of the wraparound patch is greater than the bandwidths of both the linearly and circularly polarized patch array. As mentioned in section 4.2, this is likely a result of the wraparound patch having an input impedance near 50 ohms. Figure 4.48 also shows that the truncated corner patch array has about 25 MHz greater bandwidth than the rectangular patch array. This corresponds to the results in the previous section, where the circularly polarized element had roughly 25 MHz greater impedance bandwidth than the linearly polarized element.

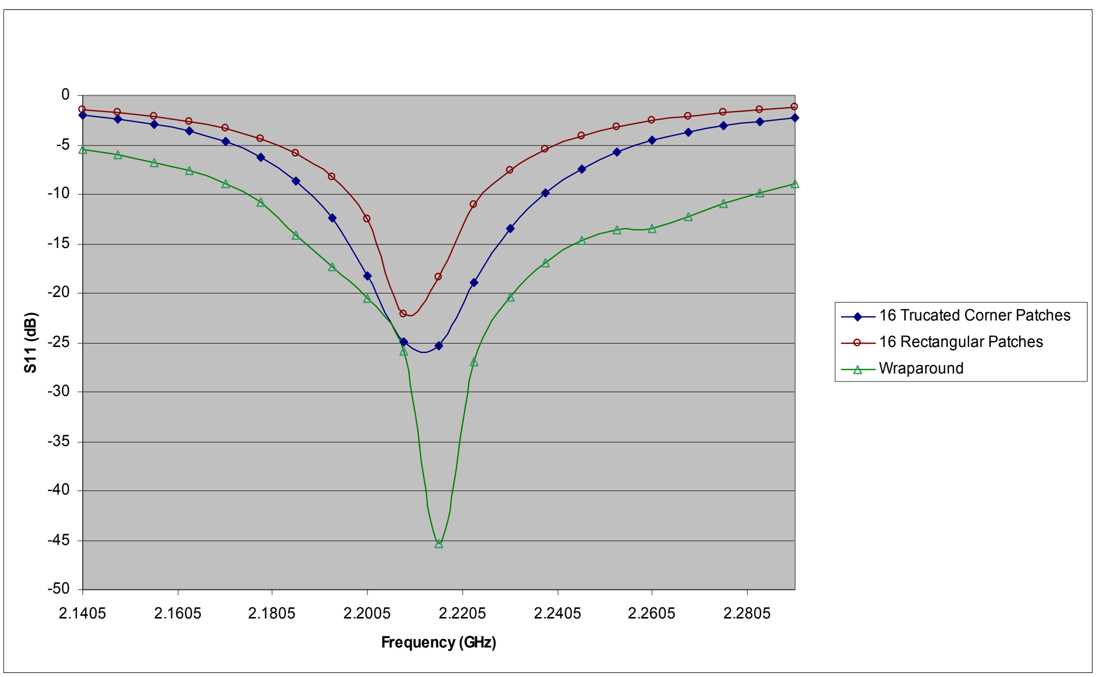
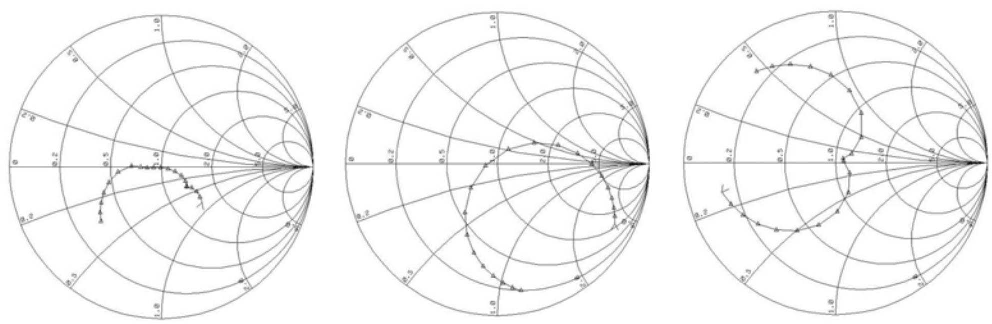


Figure 4.48. S_{11} comparison plot for omnidirectional antennas on 14-inch cylinders.

The antennas' impedance characteristics can be further compared by viewing their Smith chart results, as shown in figure 4.49. The data in each plot is taken over the same frequency ranges and increments. It can be seen that the wraparound patch has more frequency points near the 50 ohm region of the Smith chart than the other two antenna patch arrays. Additionally, it can be seen that the truncated corner patch array is matched for more frequencies near the 50 ohms region than the rectangular.

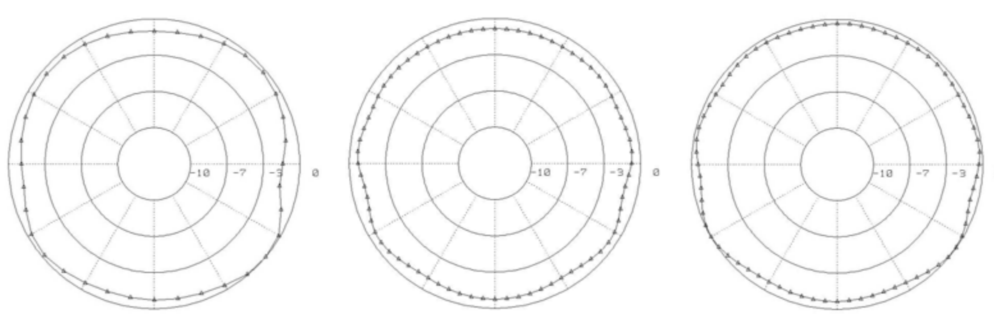


a. wraparound **b.** rectangular patch array **c.** truncated corner array

Figure 4.49. Smith charts plots showing impedance characteristics from 2.1455 to 2.2955 GHz.

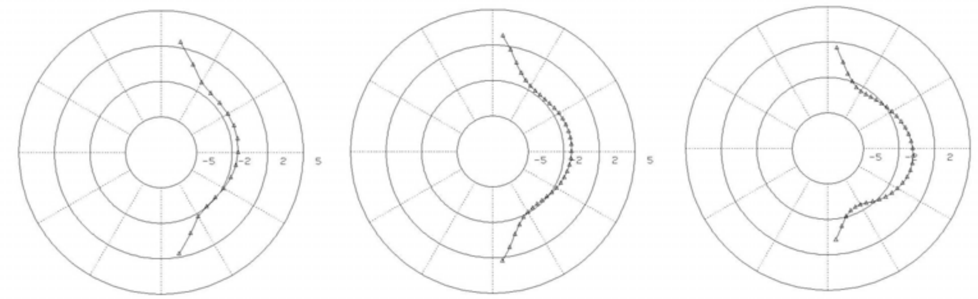
The antennas' gain characteristics are shown in figures 4.50 – 4.51 and tabulated in table 4.35. Both the azimuth and elevation gain patterns of the three antenna types are essentially the same. The gains are approximately 1.5 to 0 dB broadside to the cylinder, which is expected for antennas having omnidirectional radiation patterns. The broadside gain of the wraparound patch is slightly less than the patch arrays. This may imply that the surface wave loss is greater with the single element of the wraparound patch. The broadside gain of the circularly and linearly polarized patch arrays are about 0.5 to 1.0 dB. A visible difference between these two arrays is that the truncated corner patch has a slight increase in directivity in its elevation plane radiation pattern. This may be the result of the larger surface area required for the L-section matching network.

Since the impedance and gain characteristics of these antennas are similar, the main difference between the antennas is their polarizations characteristics. The circularly polarized truncated corner patch array will result in minimal polarization losses, except near the top and bottom regions of the rocket where the polarization losses will approach 3 dB. In contrast, the linearly polarized rectangular patch array, or the linearly polarized wraparound patch, will result in a 3 dB polarization mismatch loss for all regions surrounding the cylinder. The axial ratio of the circularly polarized truncated corner patch array antenna is shown in figures 4.52 and 4.53. The axial ratio broadside of the cylinder is approximately 0.5 to 1 dB. In the regions between 70 to 90 degrees from broadside the axial ratio performance results in significant polarization mismatch loss. Applying equation (3.33) to the axial ratio plots provides a quantitative relationship between the losses of the circularly and linearly polarized antenna arrays. These mismatch losses are tabulated in table 4.36.



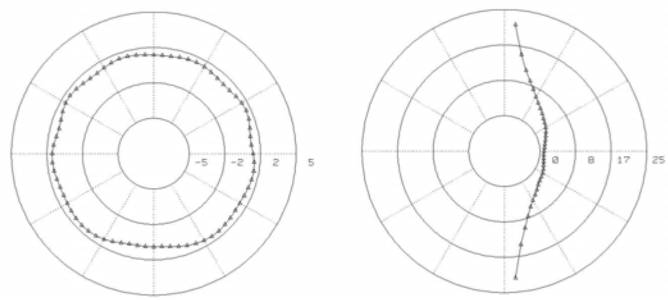
a. wraparound **b.** rectangular patch array **c.** truncated corner array

Figure 4.50. Azimuth plane gain plots at 2.2155 GHz.



a. wraparound **b.** rectangular patch array **c.** truncated corner array

Figure 4.51. Elevation plane gain plots at 2.2155 GHz.



a. azimuth plane **b.** elevation plane

Figure 4.52. Axial ratio of the truncated corner array.

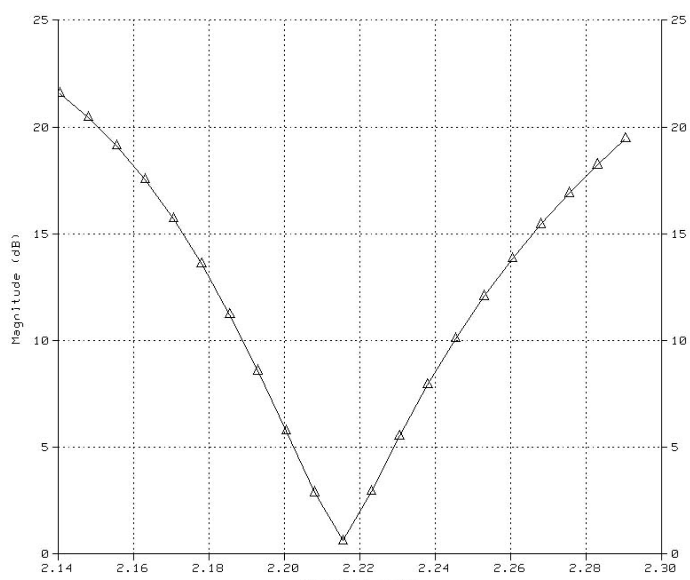


Figure 4.53. Broadside axial ratio of the truncated corner array.

Table 4.35. Comparison of wraparound patch and arrays on 14-inch cylinder.

Antenna	Diameter	Azimuth Plane	Elevation Plane	Broadside			
		Ripple	6 dB AR Beamwidth	Gain	Impedance Bandwidth	6 dB AR Bandwidth	Mismatch Loss at fo +/- 15 MHz
	(inch)	(dB)	(degrees)	(dB)	(MHz)	(MHz)	(dB)
Wraparound (LP) Patch	14	1.5	-	0	> 150	-	3
Rectangular (LP) Patch	14	0.5	-	-0.5	101	-	3
Truncated Corner (CP) Patch Array	14	0.5	140	0	133	30 MHz	0.5

Table 4.36. Polarization mismatch loss comparison of the linearly and circularly polarized antenna arrays.

	Truncated Corner Patch Array				Rectangular Patch Array				
Angle	AR	AR	Loss	Loss	AR	AR	Loss	Loss	Circular Polarized Improvement
(degrees)	(dB)	(linear)	(linear)	(dB)	(dB)	(linear)	(linear)	(dB)	(dB)
0	0	1.00	1.00	0.00	Infinite	Infinite	0.50	3.00	3.00
15	1	1.12	1.00	0.01	Infinite	Infinite	0.50	3.00	2.99
30	2	1.26	0.99	0.06	Infinite	Infinite	0.50	3.00	2.94
45	4	1.58	0.95	0.22	Infinite	Infinite	0.50	3.00	2.78
60	6	2.00	0.90	0.45	Infinite	Infinite	0.50	3.00	2.55
75	12	3.98	0.74	1.33	Infinite	Infinite	0.50	3.00	1.67
90	30	31.62	0.53	2.74	Infinite	Infinite	0.50	3.00	0.26

The results of this section show that for narrowband signals radiating broadside to the rocket, the circularly polarized antenna will provide greater performance than the linearly polarized antenna. However, at angles greater than about 70 degrees from broadside, the performance of the circularly and linearly polarized antennas can be considered equal. For broadband signals, or when narrowband signals drift significantly away from the operating frequency, the circularly polarized patch array also out performs the linearly polarized patch array. The linearly polarized wraparound patch has about 1 dB less gain than the patch arrays, but it has the advantage of a much broader impedance bandwidth.