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Tall Vertical Arrays

The author presents his EZNEC *analysis of a variety of vertical antenna arrays for 80 m.*

Many hams use phased-vertical arrays, such as the two-element cardioid or the popular 4 Square, for communications on the low bands from 40 through 160 meters. Designs for larger, more complex arrays (employing from 5 to 9 elements) are available if improved performance is desired.[1] Typically, these antennas use ¼ λ monopoles in conjunction with ground screens composed of ¼ λ radials. I was curious to see what would happen if taller (⅝ λ) monopoles and/or radials were substituted. This article discusses the results of that investigation.

Computer Simulations

The computer analysis was done on the 80 meter band at a frequency of 3650 kHz. Each vertical monopole is built from no. 12 AWG copper wire, and the ground screen includes 60 radials made of no. 16 AWG copper wire. These radials were buried to a depth of just 3 inches, in "average" soil having a conductivity of 0.005 Siemens per meter and a dielectric constant of 13. I simulated all of the antennas described in this article using the *EZNEC* software package, which is available from Roy Lewallen, W7EL.[2]

[1]Notes appear on page 35.

Results for a Single Vertical Element

Table 1 shows what happens when an isolated monopole, whose height is either ¼ λ or ⅝ λ, is installed over a buried ground screen composed of 60 radials, whose length may also be either ¼ λ or ⅝ λ. In free space, an actual quarter wavelength is 67.37 feet, while ⅝ λ amounts to 168.42 feet, so those lengths were used for the buried radials. For the vertical element, however, the height of the "¼ λ" monopole was adjusted to resonate the antenna (input reactance equal to or close to zero) at 3650 kHz. In a similar fashion, the height of the "⅝ λ" element was trimmed to produce maximum gain at the lowest elevation angle, in combination with the shortest possible monopole. (Throughout this analysis, radial lengths and radiator heights were always varied in increments of 0.01 foot.)

Table 1 displays some interesting results. First, we see that the resonant height of a nominal "¼ λ" element is slightly shorter when longer radials are employed. Also, the height of the "⅝ λ" monopole that generates maximum gain is significantly reduced when it is placed over a ground screen using longer radials.

When the nominal element height is fixed, the installation of a larger ground screen yields more gain: from 0.39 dBi to 1.00 dBi for the ¼ λ monopole, and from 0.73 dBi to 1.00 dBi for the ⅝ λ radiator. Figures 1 and 2 show the elevation plane radiation patterns for the two cases.

When the radius of the ground screen is fixed at 0.25 λ, then upgrading to a taller ele-

Table 1

Performance of a single vertical monopole antenna with ground screen, as a function of radiator height and radial length. Each antenna is designed to operate at 3650 kHz. Antennas with ¼ λ monopoles have their element height adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	¼ λ Monopole ¼ λ Radials	*¼ λ Monopole ⅝ λ Radials*	*⅝ λ Monopole ¼ λ Radials*	*⅝ λ Monopole ⅝ λ Radials*
Radiator Height (ft)	65.46	65.38	151.32	142.48
Radial Length (ft)	67.37	168.42	67.37	168.42
Resonant Frequency (kHz)	3650	3650	1586	1679
Maximum Gain (dBi)	0.39	1.00	0.73	1.00
Take-off Angle (°)	24.9	26.3	15.2	16.5
Z_{input} (Ω)	38.1	40.56	281.6 – *j* 990.5	769.3 – *j* 1479

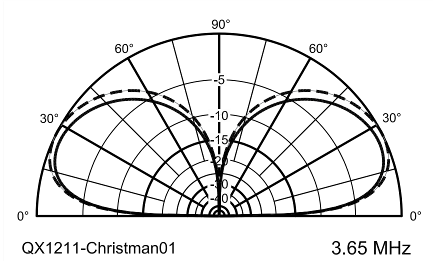

Figure 1 — Elevation-plane radiation patterns for a resonant ¼ λ vertical-monopole antenna, when placed over a ground screen composed of 60 buried radials. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 0.39 dBi at 24.9° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft). Peak gain = 1.00 dBi at 26.3° take-off angle.

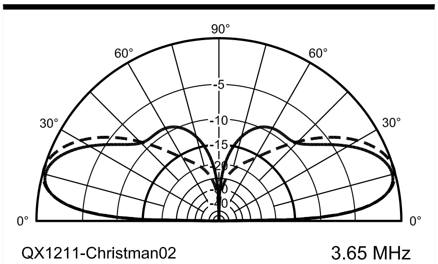

Figure 2 — Elevation-plane radiation patterns for a nominal ⅝ λ vertical-monopole antenna, when placed over a ground screen composed of 60 buried radials. The height of each element was adjusted for maximum gain. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 0.73 dBi at 15.2° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft), peak gain = 1.00 dBi at 16.5° take-off angle.

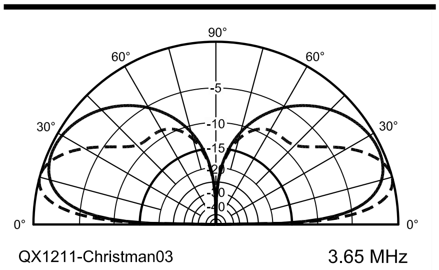

Figure 3 — Elevation-plane radiation patterns for nominal ¼ λ and ⅝ λ vertical-monopole antennas, when placed over a ground screen composed of 60 buried ¼ λ radials (L = 67.37 feet at 3650 kHz). The ¼ λ element was tuned to resonance at 3650 kHz, while the height of the 5/8 λ radiator was adjusted for maximum gain. Solid trace = ¼ λ monopole (H = 65.46 feet), peak gain = 0.39 dBi at 24.9° take-off angle. Dashed trace = ⅝ λ monopole (H = 151.32 feet), peak gain = 0.73 dBi at 15.2° take-off angle.

ment gives us both an increase in peak gain and a lower take off angle (from 0.39 dBi at 24.9° to 0.73 dBi at 15.2°), as revealed in Figure 3. If a larger ground screen (radius = 0.625 λ) is present, installing a taller monopole still provides a lower elevation angle (from 26.3° to 16.5°), but the peak gain remains unchanged at exactly 1.0 dBi (see Figure 4).

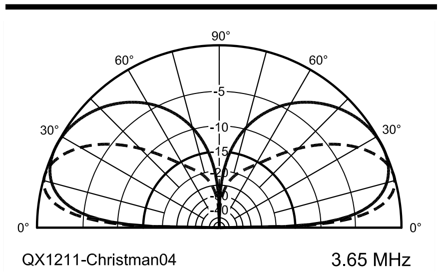

Figure 4 — Elevation-plane radiation patterns for nominal ¼ λ and ⅝ λ vertical-monopole antennas, when placed over a ground screen composed of 60 buried ⅝ λ radials (L = 168.42 feet at 3650 kHz). The ¼ λ element was tuned to resonance at 3650 kHz, while the height of the ⅝ λ radiator was adjusted for maximum gain. Solid trace = ¼ λ monopole (H = 65.46 feet), peak gain = 1.00 dBi at 26.3° take-off angle. Dashed trace = ⅝ λ monopole (H = 151.32 feet), peak gain = 1.00 dBi at 16.5° take-off angle.

Results for a Two element Cardioid Array with 90° Current Phasing

Figure 5 is a plan view of the ground screen for a 2 element array with ¼ λ spacing (67.37 feet) between the radiators. Each monopole has 60 radials in its ground screen, and their maximum length is also ¼ λ. Notice that this antenna uses a "broadcast style" ground screen, where none of the radials overlap one another. Instead, the radials are truncated and bonded together at those locations where they intersect, and a "common bus" links these points together, as shown in the drawing.

Table 2 lists the outcome for each combination of element height and radial length,

Table 2

Performance of a 2 element cardioid array with 90° spacing and phasing, as a function of radiator height and radial length. Each antenna is designed to operate at 3650 kHz. Arrays with ¼ λ monopoles have their element heights adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	¼ λ Monopole *¼ λ Radials*	*¼ λ Monopole* *⅝ λ Radials*	*⅝ λ Monopole* *¼ λ Radials*	*⅝ λ Monopole* *⅝ λ Radials*
Radiator Height (ft)	65.45	65.42	158.73	158.03
Resonant Frequency (kHz)	3650	3650	1512	1514
Radial Length (ft)	67.37	168.42	67.37	168.42
Endfire Mode:	*I_{front} = 1<–90° and I_{back} = 1<0°)*			
Maximum Gain (dBi)	3.49	3.87	3.26	3.45
Take-off Angle (°)	24.8	25.5	14.5	14.6
Elevation Plane F/B Ratio (dB)	13.60	12.26	12.88	12.84
Azimuth Plane F/B Ratio (dB)	22.92	22.76	13.18	13.09
Azimuth Plane Half Power Beamwidth (°)	177.2	182.0	198.2	197.4
Z_{input} (Ω) (Front Element)	55.04 + *j* 17.49	57.58 + *j* 18.85	172.7 – *j* 604.8	185.9 – *j* 621.6
Z_{input} (Ω) (Back Element)	21.99 – *j* 17.68	22.55 – *j* 18.96	148.3 – *j* 799.8	157.2 – *j* 828.7
Broadside Mode:	*(I_{front} = I_{back} = 1<0°)*			
Maximum Gain (dBi)	1.72	2.31	2.12	2.31
Take-off Angle (°)	24.9	26.3	14.8	14.8
Azimuth Plane F/S Ratio (dB)	2.27	2.51	2.75	2.74
Z_{input} (Ω) (Both Elements)	56.09 – *j* 16.62	58.97 – *j* 17.57	258.0 – *j* 714.5	275.1 – *j* 739.5

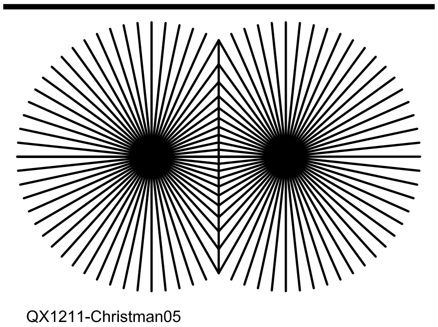

Figure 5 — Plan view of the ground screen for a 2 element vertical array. Spacing between the elements is ¼ λ, and each element has 60 buried radials, whose maximum length is also ¼ λ (67.37 feet at 3650 kHz).

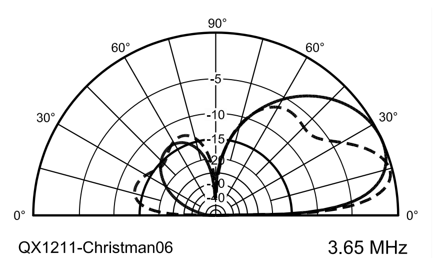

Figure 6 — Elevation-plane radiation patterns for 2 element cardioid arrays with quadrature phasing (I_{front} = 1<–90°, I_{back} = 1<0°), when using either ¼ λ or ⅝ λ monopoles. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz). The ¼ λ monopoles were tuned to resonance at 3650 kHz, while the height of the ⅝ λ radiators was adjusted for maximum gain. Solid trace = ¼ λ monopoles (H = 65.45 feet), peak gain = 3.49 dBi at 24.8° take-off angle. Dashed trace = ⅝ λ monopoles (H = 158.73 feet), peak gain = 3.26 dBi at 14.5° take-off angle.

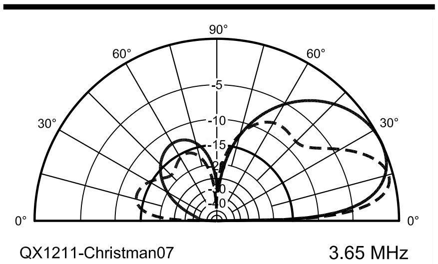

Figure 7 — Elevation plane radiation patterns for 2 element cardioid arrays with quadrature phasing (I_{front} = 1<–90°, I_{back} = 1<0°, when using either ¼ λ or 5/8 λ monopoles. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz). The ¼ λ monopoles were tuned to resonance at 3650 kHz, while the height of the ⅝ λ radiators was adjusted for maximum gain. Solid trace = ¼ λ monopoles (H = 65.42 feet), peak gain = 3.87 dBi at 25.5° take off angle. Dashed trace = ⅝ λ monopoles (H = 158.03 feet), peak gain = 3.45 dBi at 14.6° take off angle.

when the array is driven in the classic cardioid fashion, utilizing equal magnitude currents that are 90° apart in phase angle. Again we find that ¼ λ resonance occurs with a somewhat shorter monopole height (from 65.45 ft to 65.42 ft) when a larger ground screen is employed. Note that resonance was achieved by placing a *single* (isolated) radiator over the *entire* ground screen, and then adjusting its height to minimize the input reactance at 3650 kHz. For a "⅝ λ" element, maximum gain occurs at a slightly lower height (from 158.73 feet to 158.03 ft) if longer radials are used.

Surprisingly, we find that, for *either* ground screen, switching to the much taller "⅝ λ" radiator actually generates *less* gain (from 3.49 dBi to 3.26 dBi when using ¼ λ radials, and from 3.87 dBi to 3.45 dBi for ⅝ λ radials), although the take off angle still falls by roughly 10°. (As we shall see in a moment, a phase lag of 90° is far too small to generate very much gain from such tall elements.) See Figures 6 and 7 for the plots.

As expected, installing longer radials under either monopole leads to an increase in the peak forward gain: from 3.49 dBi to 3.87 dBi for the ¼ λ radiator, and from 3.26 dBi to 3.45 dBi for the ⅝ λ element. The corresponding elevation-plane patterns are displayed in Figures 8 and 9, respectively.

Table 2 also provides information for the case where the two monopoles are driven with equal-amplitude in-phase currents, which generates a *broadside* (rather than an *endfire*) radiation pattern. Using longer radials generates more gain from either the ¼ λ or the ⅝ λ element, while substituting a taller radiator (over a ground screen of either size) reduces the take-off angle by 10° or more.

Two-element Cardioid Array with Modified Current Phasing

One way to improve the performance of the traditional cardioid array is to increase the phase-lag of the current delivered to the front element. When optimized for maximum end-fire gain at the lowest-possible take-off angle, the results are as shown in Table 3. For resonant ¼ λ vertical monopoles, changing the phase-lag from 90° to 136° yields about 0.8 dB of extra gain. The taller "⅝ λ" elements generate around 1.4 dB of additional gain, although the phase-lag needs to be further increased, to around 144°. As usual, there is no "free lunch." These significant improvements in forward gain are achieved at the expense of great reductions in the front-to-back ratio, which falls to less than 10 dB in both the elevation and azimuth planes.

Using a larger ground screen under an array with elements of a fixed height leads to more end-fire gain, but at a slightly higher take-off angle (see Figures 10 and 11). Employing a taller monopole over a ground screen whose radius is held constant produces both more gain and a lower take-off angle, which can be seen in Figures 12 and 13.

As before, a *broadside* radiation pattern can be created when the two vertical elements are driven with equal-amplitude in-phase currents. (Note that the lower portion of Table 3 is nearly identical to that of Table 2, since only minor changes were made in the height of the "⅝ λ" monopoles to achieve maximum gain.) Once again, the use of longer radials generates more gain from either the ¼ λ or the ⅝ λ element, while substitut-

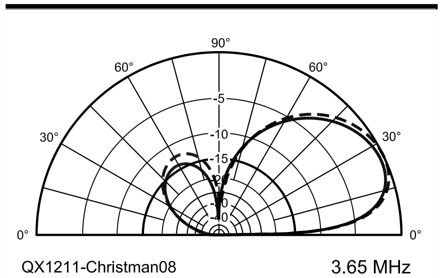

Figure 8 — Elevation-plane radiation patterns for cardioid arrays using two ¼ λ elements with quadrature phasing (I_{front} = 1<–90°, I_{back} = 1<0°), when the ground screens are composed of 60 buried radials whose maximum length is either ¼ λ or 5/8 λ. The monopoles were tuned to resonance at 3650 kHz. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 3.49 dBi at 24.8° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft), peak gain = 3.87 dBi at 25.5° take-off angle.

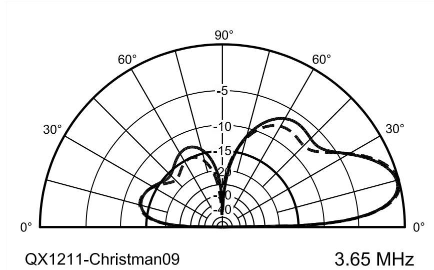

Figure 9 — Elevation-plane radiation patterns for cardioid arrays using two ⅝ λ elements with quadrature phasing (I_{front} = 1<–90°, I_{back} = 1<0°), when the ground screens are composed of 60 buried radials whose maximum length is either ¼ λ or ⅝ λ. The height of the monopoles was adjusted for maximum gain. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 3.26 dBi at 14.5° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft), peak gain = 3.45 dBi at 14.6° take-off angle.

ing a taller radiator (over a ground screen of either size) reduces the take-off angle by 10° or more.

Results for a 4-Square Array with ¼ λ Elements and ¼ λ Radials

The classic four-square phased-vertical array utilizes ¼ λ elements spaced ¼ λ apart, with a large number of ¼ λ radials in the ground screen. In this article I will examine 4-squares with monopole heights of approximately ¼ and ⅝ λ, installed over ground screens composed of radials whose maximum length is either ¼ λ or ⅝ λ (60 radials per radiator). Figure 14 is a plan view of a ground screen made from ¼ λ (max) radials. Traditionally, the antenna is designed to fire along the diagonals of the square (through the corners), but it can also be configured to beam through the sides.

The first 4-square design to be reviewed is a typical array with ¼ λ monopoles and ¼ λ (max) radials. Table 4 lists the performance parameters for this antenna, when we vary the phase-angles of the equal-amplitude currents which are driven into the bases of the radiators. To begin the analysis, a single (isolated) element was placed over the entire ground screen, and its length was adjusted for resonance at 3650 kHz, which required an overall height of 65.43 feet.

The left column in Table 4 is for a normal corner-fire feed system, which employs

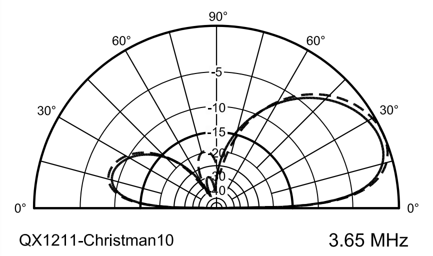

Figure 10 — Elevation-plane radiation patterns for cardioid arrays using two ¼ λ elements with phasing adjusted for maximum end-fire gain (I_{front} = 1<–136°, I_{back} = 1<0°), when the ground screens are composed of 60 buried radials whose maximum length is either ¼ λ or ⅝ λ. The monopoles were tuned to resonance at 3650 kHz. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 4.25 dBi at 23.1° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft), peak gain = 4.71 dBi at 23.6° take-off angle.

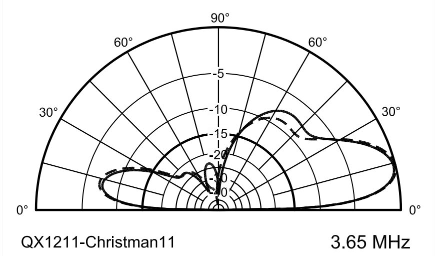

Figure 11 — Elevation-plane radiation patterns for cardioid arrays using two ⅝ λ elements with phasing adjusted for maximum end-fire gain (I_{front} = 1<–143° or 1<–144°, I_{back} = 1<0°), when the ground screens are composed of 60 buried radials whose maximum length is either ¼ λ or ⅝ λ. The height of the monopoles was adjusted for maximum gain. Solid trace = ¼ λ radials (L = 67.37 ft at 3650 kHz), peak gain = 4.63 dBi at 13.9° take-off angle. Dashed trace = ⅝ λ radials (L = 168.42 ft), peak gain = 4.81 dBi at 14.1° take-off angle.

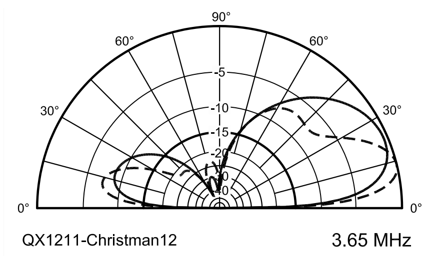

Figure 12 — Elevation-plane radiation patterns for 2 element cardioid arrays with phasing adjusted for maximum end fire gain (I_{front} = 1<–136° or 1<–143°, I_{back} = 1<0°), when using either ¼ λ or ⅝ λ monopoles. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz). The ¼ λ monopoles were tuned to resonance at 3650 kHz, while the height of the ⅝ λ radiators was adjusted for maximum gain. Solid trace = ¼ λ monopoles (H = 65.45 feet), peak gain = 4.25 dBi at 23.1° take-off angle. Dashed trace = ⅝ λ monopoles (H = 158.73 feet), peak gain = 4.63 dBi at 13.9° take-off angle.

Table 3

Performance of a 2 element cardioid array, as a function of radiator height and radial length. Again, the monopole spacing is 90°, but this time the current phase angles are adjusted for maximum gain at the lowest-possible elevation angle. Each antenna is designed to operate at 3650 kHz. Arrays with ¼ λ monopoles have their element heights adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	¼ λ Monopole ¼ λ Radials	*¼ λ Monopole ⅝ λ Radials*	*⅝ λ Monopole ¼ λ Radials*	*⅝ λ Monopole ⅝ λ Radials*
Radiator Height (ft)	65.45	65.42	159.17	157.97
Resonant Frequency (kHz)	3650	3650	1508	1515
Radial Length (ft)	67.37	168.42	67.37	168.42
Endfire Mode:	*(I_{back} = 1<0°)*			
I_{front}	1<–136°	1<–136°	1<–143°	1<–144°
Maximum Gain (dBi)	4.25	4.71	4.63	4.81
Take-off Angle (°)	23.1	23.6	13.9	14.1
Elevation Plane F/B Ratio (dB)	8.32	8.21	7.19	6.91
Azimuth Plane F/B Ratio (dB)	8.58	8.50	7.24	6.95
Azimuth Plane Half Power Beamwidth (°)	129.6	132.4	130.6	130.0
Z_{input} (Ω) (Front Element)	37.34 + *j* 24.0	38.64 + *j* 25.68	87.79 – *j* 623.0	96.56 – *j* 654.2
Z_{input} (Ω) (Back Element)	14.39 – *j* 0.42	14.3 – *j* 0.58	72.33 – *j* 736.7	79.79 – *j* 776.4
Broadside Mode:	*(I_{front} = I_{back} = 1<0°)*			
Maximum Gain (dBi)	1.72	2.31	2.12	2.31
Take-off Angle (°)	24.9	26.3	14.8	14.9
Azimuth Plane F/S Ratio (dB)	2.27	2.51	2.75	2.74
Z_{input} (Ω) (Both Elements)	56.09 – *j* 16.62	58.97 – *j* 17.57	250.1 – *j* 702.9	276.3 – *j* 741.1

Table 4

Performance of a 4 Square array using ¼ λ monopoles and ¼ λ radials, as a function of the phase angles of the base currents. The height of the elements was adjusted to 65.43 feet, for resonance at 3650 kHz, while the radials have a length of 67.37 feet. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials per element. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	Traditional Phasing	*W8JI Phasing*	*Maximum Gain Phasing*
Firing through the corners of the square:			
I_{front}	1<–180°	1<–240°	1<–250°
I_{sides}	1<–90°	1<–120°	1<–125°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	5.89	6.36	6.36
Take-off Angle (°)	23.7	22.2	22.0
Elevation Plane F/B Ratio (dB)	17.99	30.3	33.96
Azimuth Plane F/B Ratio (dB)	23.35	36.99	38.35
Azimuth Plane F/S Ratio (dB)	N.A.	15.9	14.1
Azimuth Plane Half Power Beamwidth (°)	100.6	80.0	76.8
Z_{input} (Ω) (Front Element)	67.17 + *j* 54.22	30.97 + *j* 52.63	26.14 + *j* 50.08
Z_{input} (Ω) (Side Elements)	43.19 – *j* 18.82	25.54 – *j* 2.48	22.94 – j 0.08
Z_{input} (Ω)(Back Element)	1.82 – *j* 16.38	7.06 – *j* 0.99	8.08 + *j* 0.41
Firing through the sides of the square:			
I_{front}	1<–90°	1 <–105°	1<–131°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	4.90	5.22	5.42
Take off Angle (°)	25.0	24.4	23.4
Elevation Plane F/B Ratio (dB)	13.93	17.71	9.41
Azimuth Plane F/B Ratio (dB)	23.6	21.65	9.76
Azimuth Plane Half Power Beamwidth (°)	130.0	118.2	104.1
Z_{input} (Ω) (Front Elements)	91.7 + *j* 5.71	84.81 + *j* 14.07	68.64 + *j* 23.41
Z_{input} (Ω) (Back Elements)	21.28 – *j* 38.29	16.79 – *j* 28.42	15.49 – *j* 9.79

progressive 90° phase-shifts between the back, side, and front monopoles (I_{back} = 1<0°, I_{sides} = 1<–90°, I_{front} = 1<–180°). The middle column is for the design suggested by Tom Rauch W8JI, which incorporates larger current phase-angles (I_{back} = 1<0°, I_{sides} = 1<–120°, and I_{front} = 1<–240°).[3] Finally, the right-hand column is for the situation where the phase-shifts have been optimized for *maximum* forward gain at the lowest-possible take-off angle. The outcome for this trial-and-error solution was: I_{back} = 1<0°, I_{sides} = 1<–125°, and I_{front} = 1<–250°. Notice that the W8JI phase-angles actually yielded the *same* amount of gain as the "max gain" set, although the take-off angle and front-to-back ratio obtained in the W8JI case could be improved just a bit by including a few additional degrees of phase-lag.

See Figures 15 and 16 for a comparison of the principal-plane radiation patterns which are produced by the three different sets of current phase-angles. Tom's recommended values produce noticeably smaller side lobes (in the azimuth plane) than the "max gain" set, while generating exactly the same amount of peak gain, along with front-to-back ratios that are nearly as good, in both the elevation and azimuth planes.

One advantage of utilizing the traditional 0°/–90°/–90°/–180° phase-angles is the fact that the resulting half-power beamwidth in the azimuth plane is more than 100°, which allows good coverage of all points of the compass with only four directions of fire. Employing larger phase-shift values (such as those shown in Table 4) provides more gain in the bore-sight direction, but narrows the beamwidth by more than 20°. So, it may be desirable to include a provision to allow such an array to beam through the *sides* of the square, as well as through the *corners*.

The latter portion of Table 4 covers this option. In the left column, the front pair of monopoles are fed in quadrature with those in the back (I_{back} = 1<0°, I_{front} = 1<–90°).

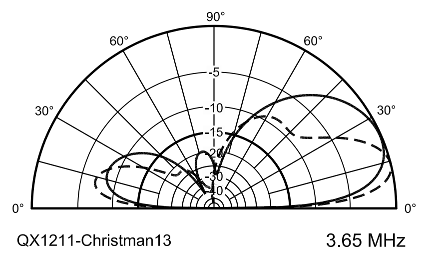

Figure 13 — Elevation-plane radiation patterns for 2 element cardioid arrays with phasing adjusted for maximum end fire gain (I_{front} = 1<–136° or 1<–144°, I_{back} = 1<0°), when using either ¼ λ or ⅝ λ monopoles. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz). The ¼ λ monopoles were tuned to resonance at 3650 kHz, while the height of the ⅝ λ radiators was adjusted for maximum gain. Solid trace = ¼ λ monopoles (H = 65.42 feet), peak gain = 4.71 dBi at 23.6° take-off angle. Dashed trace = ⅝ λ monopoles (H = 158.03 feet), peak gain = 4.81 dBi at 14.1° take-off angle.

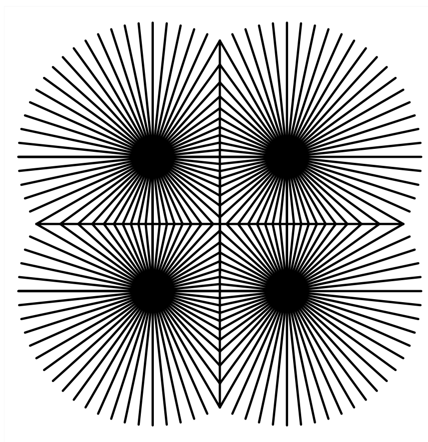

Figure 14 — Plan view of the ground screen for a 4-Square vertical array. Each side of the square has a dimension of ¼ λ, and each element has 60 buried radials, whose maximum length is also ¼ λ (67.37 feet at 3650 kHz).

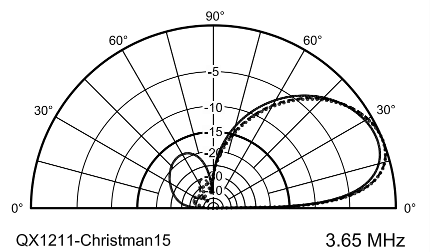

Figure 15 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°, –90°, –90°, –180°), peak gain = 5.89 dBi at 23.7° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.36 dBi at 22.2° take-off angle.
Dotted trace = "max gain" angles (0°, –125°, –125°, –250°), peak gain = 6.36 dBi at 22.0° take-off angle.

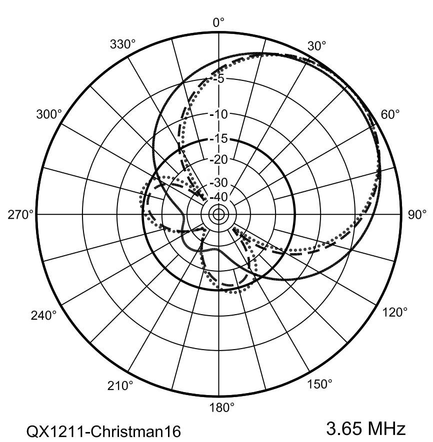

Figure 16 — Azimuth-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, –90°, –90°, –180°), peak gain = 5.89 dBi at 23.7° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.36 dBi at 22.2° take-off angle.
Dotted trace = "max gain" angles (0°, –125°, –125°, –250°), peak gain = 6.36 dBi at 22.0° take-off angle.

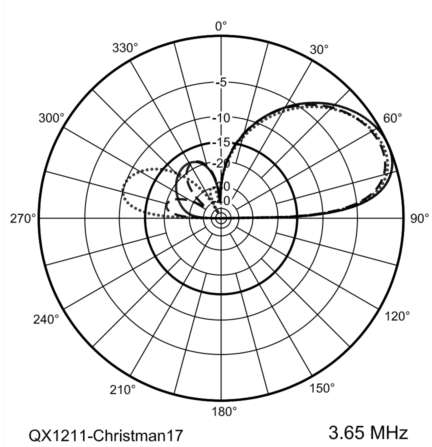

Figure 17 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the sides of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, 0°, –90°, –90°), peak gain = 4.90 dBi at 25.0° take-off angle.
Dashed trace = arbitrary angles (0°, 0°, –105°, –105°), peak gain = 5.22 dBi at 22.4° take-off angle.
Dotted trace = "max gain" angles (0°, 0°, –131°, –131°), peak gain = 5.42 dBi at 23.4° take-off angle.

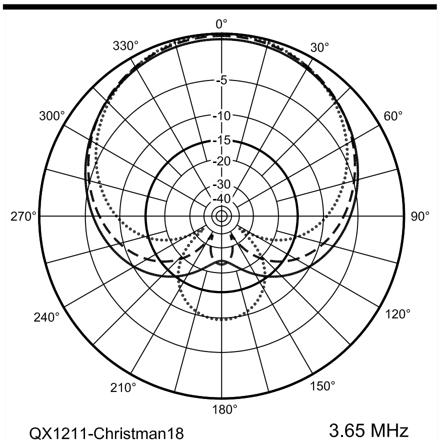

Figure 18 — Azimuth-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the sides of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, 0°, –90°, –90°), peak gain = 4.90 dBi at 25.0° take-off angle.
Dashed trace = arbitrary angles (0°, 0°, –105°, –105°), peak gain = 5.22 dBi at 24.4° take-off angle.
Dotted trace = "max gain" angles (0°, 0°, –131°, –131°), peak gain = 5.42 dBi at 23.4° take-off angle.

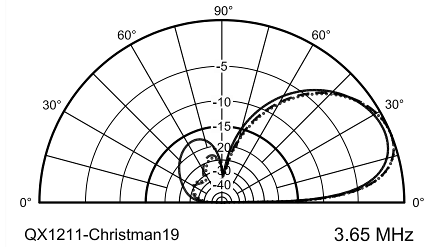

Figure 19 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, –90°, –90°, –180°), peak gain = 6.34 dBi at 24.1° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.81 dBi at 22.5° take-off angle.
Dotted trace = "max gain" angles (0°, –125°, –125°, –250°), peak gain = 6.81 dBi at 22.3° take-off angle.

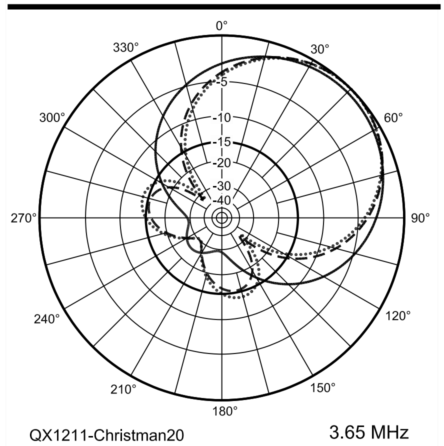

Figure 20 — Azimuth-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°, –90°, –90°, –180°), peak gain = 6.34 dBi at 24.1° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.81 dBi at 22.5° take-off angle.
Dotted trace = "max gain" angles (0°, –125°, –125°, –250°), peak gain = 6.81 dBi at 22.3° take-off angle.

Table 5

Performance of a 4 Square array using ¼ λ monopoles and ⅝ λ radials, as a function of the phase angles of the base currents. The height of the elements was adjusted to 65.42 feet, for resonance at 3650 kHz, while the radials have a length of 168.42 feet. Each monopole is built from no. 12 AWG copper wire, and the ground system is composed of 60 no. 16 AWG wire radials per element. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	Traditional Phasing	*W8JI Phasing*	*Maximum Gain Phasing*
Firing through the corners of the square:			
I_{front}	1<–180°	1<–240°	1<–250°
I_{sides}	1<–90°	1<–120°	1<–125°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	6.34	6.81	6.81
Take-off Angle (°)	24.1	22.5	22.3
Elevation Plane F/B Ratio (dB)	16.48	22.76	23.85
Azimuth Plane F/B Ratio (dB)	24.26	30.12	30.63
Azimuth Plane F/S Ratio (dB)	N.A.	15.51	13.85
Azimuth Plane Half Power Beamwidth (°)	100.8	80.2	77.2
Z_{input} (Ω) (Front Element)	69.65 + j 56.56	31.52 + j 55.1	26.42 + j 52.42
Z_{input} (Ω) (Side Elements)	43.75 – j 20.11	25.66 – j 2.99	23.0 – j 0.47
Z_{input} (Ω) (Back Element)	1.16 – j 15.76	7.29 – j 0.31	8.39 + j 1.01
Firing through the sides of the square:			
I_{front}	1<–90°	1<–105°	1<–131°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	5.34	5.67	5.89
Take-off Angle (°)	25.5	24.9	23.9
Elevation Plane F/B Ratio (dB)	12.94	15.49	9.07
Azimuth Plane F/B Ratio (dB)	24.57	20.95	9.41
Azimuth Plane Half Power Beamwidth (°)	129.4	118.6	103.8
Z_{input} (Ω) (Front Elements)	95.03 + j 5.28	88.0 + j 14.19	71.27 + j 24.34
Z_{input} (Ω) (Back Elements)	20.28 – j 39.23	15.79 – j 28.8	14.84 – j 9.25

Table 6

Performance of a 4 Square array using ⅝ λ monopoles and ¼ λ radials, as a function of the phase-angles of the base currents. Maximum gain at the lowest take-off angle always occurred at an element height of about 165.6 feet (where the monopole was resonant at 1448 kHz), and the radials have a length of 67.37 feet. Each monopole is built from no. 12 AWG copper wire, and the ground system is composed of 60 no. 16 AWG wire radials per element. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	Traditional Phasing	*W8JI Phasing*	*Maximum Gain Phasing*
Firing through the corners of the square:			
I_{front}	1<–180°	1<–240°	1<–270°
I_{sides}	1<–90°	1<–120°	1<–135°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	5.45	6.57	6.82
Take-off Angle (°)	14.0	13.4	13.1
Elevation Plane F/B Ratio (dB)	11.1	17.11	20.1
Azimuth Plane F/B Ratio (dB)	11.27	17.33	20.18
Azimuth Plane F/S Ratio (dB)	N.A.	13.43	10.7
Azimuth Plane Half Power Beamwidth (°)	109.6	82.8	72.0
Z_{input} (Ω) (Front Elements)	63.65 – j 360.9	6.71 – j 426.3	– 0.78 – j 460.3
Z_{input} (Ω) (Side Elements)	157.6 – j 524.7	85.88 – j 524.6	56.06 – j 524.4
Z_{input} (Ω) (Back Elements)	61.02 – j 648.3	21.93 – j 593.0	17.5 – j 568.5
Firing through the sides of the square:			
I_{front}	1<–90°	1<–105°	1<–147°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	4.25	4.72	5.56
Take off Angle (°)	14.5	14.3	13.6
Elevation Plane F/B Ratio (dB)	9.31	11.25	6.76
Azimuth Plane F/B Ratio (dB)	9.44	11.27	6.84
Azimuth Plane Half Power Beamwidth (°)	149.2	133.0	99.6
Z_{input} (Ω) (Front Elements)	192.5 – j 395.8	161.4 – j 397.5	87.52 – j 441.8
Z_{input} (Ω) (Back Elements)	171.1 – j 634.8	140.9 – j 628.7	75.98 – j 572.1

W8JI's website does not reveal the phase-angle he uses in this application, so I have selected a value of –105° (I_{back} = 1<0°, I_{front} = 1<–105°).

As before, the right-hand column is where the phase-shifts have been optimized for *maximum* forward gain at the *lowest* take-off angle. This time, the outcome was: I_{back} = 1<0° and I_{front} = 1<–131°. The "max gain" phasing yields an extra 0.2 dB of forward gain (in comparison to using a phase-lag of 105°), but the front-to-back ratios fall considerably. A study of the elevation- and azimuth-pattern plots (Figures 17 and 18) indicates that choosing an intermediate phase-shift value, such as 105° or thereabouts, may be a good compromise between maximum gain and low side-lobe levels.

Results for a 4-Square Array with ¼ λ Elements and ⅝ λ Radials

If we have installed ⅝ λ radials beneath our 4-square, but the monopoles themselves are trimmed to a height which yields quarter-wave resonance (at 3650 kHz), what kind of performance can we expect? Refer to Table 5 for the answers. It appears that the classic (0°/–90°/–90°/–180°) current phase-angles will yield well over 6 dBi of forward gain when beaming along the diagonals of the square. Larger phase-lags, such as the W8JI and "max gain" values, can produce nearly half a decibel of additional gain. The key radiation-pattern plots appear in Figures 19 and 20.

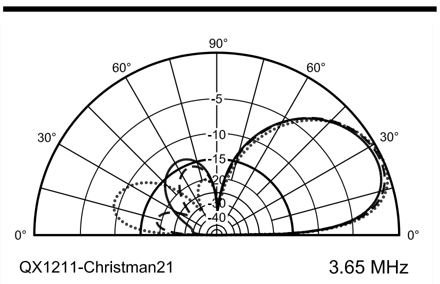

Figure 21 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the sides of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, 0°, –90°, –90°), peak gain = 5.34 dBi at 25.5° take-off angle.
Dashed trace = arbitrary angles (0°, 0°, –105°, –105°), peak gain = 5.67 dBi at 24.9° take-off angle.
Dotted trace = "max gain" angles (0°, 0°, –131°, –131°), peak gain = 5.89 dBi at 23.9° take-off angle.

When adjusted to fire through the sides of the square, the traditional quadrature-fed (0°/–90°) array generates more than 5 dBi of gain, while larger phase-lags providing an extra ⅓ to ½ dB in the favored direction. Figures 21 and 22 display the elevation and azimuth-plane patterns.

If we compare the data in Tables 4 and 5, we can determine how the performance of the array will change if we modify a conventional 4-square by simply *extending* the maximum length of its radials from ¼ λ to ⅝ λ. When firing through the diagonals of the square, the peak forward gain rises by 0.45 dB, no matter which set of current phase-angles we choose. On the down side, the front-to-back ratio also deteriorates in most cases. When firing through the sides of the square, the gain increases once again, by about 0.44 and 0.47 dB (depending upon the current phase-angles), but the front-to-back ratios don't suffer this time. So, we can pick up nearly half a decibel of forward gain by increasing the maximum length of the radials from ¼ λ to ⅝ λ, no matter what set of current phase-angles we pick.

Results for a 4-Square Array with ⅝ λ Elements and ¼ λ Radials

On the other hand, what if we don't have enough room to put in a larger ground screen? Is it worthwhile to make the radiators themselves taller? Let's examine Table 6, which lists the performance parameters for an array of "⅝ λ" monopoles working in conjunction with a normal ground screen whose

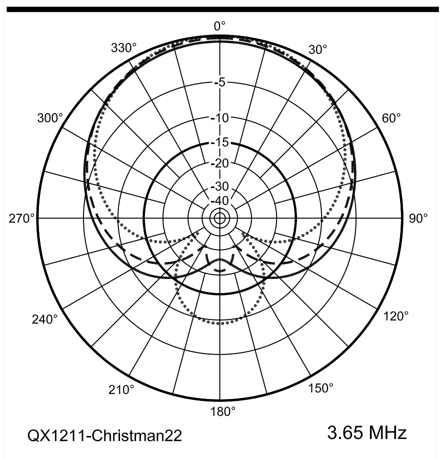

Figure 22 — Azimuth-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the sides of the square, using ¼ λ monopoles that were tuned to resonance at 3650 kHz. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, 0°, –90°, –90°), peak gain = 4.90 dBi at 25.0° take-off angle.
Dashed trace = arbitrary angles (0°, 0°, –105°, –105°), peak gain = 5.22 dBi at 22.4° take-off angle.
Dotted trace = "max gain" angles (0°, 0°, –131°, –131°), peak gain = 5.42 dBi at 23.4° take-off angle.

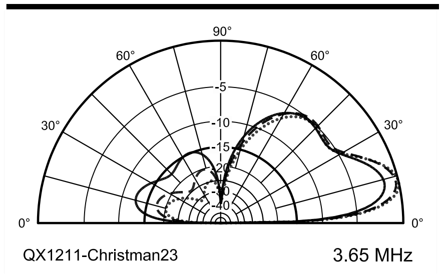

Figure 23 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, –90°, –90°, –180°), peak gain = 5.45 dBi at 14.0° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.57 dBi at 13.4° take-off angle.
Dotted trace = "max gain" angles (0°, –135°, –135°, –270°), peak gain = 6.82 dBi at 13.1° take-off angle.

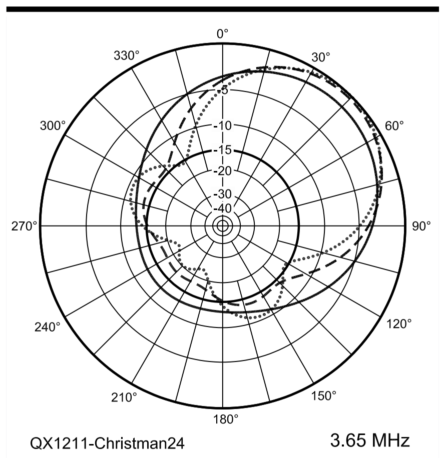

Figure 24 — Azimuth-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the corners of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, –90°, –90°, –180°), peak gain = 5.45 dBi at 14.0° take-off angle.
Dashed trace = "W8JI" angles (0°, –120°, –120°, –240°), peak gain = 6.57 dBi at 13.4° take-off angle.
Dotted trace = "max gain" angles (0°, –135°, –135°, –270°), peak gain = 6.82 dBi at 13.1° take-off angle.

radials are (at most) ¼ λ long.

The first thing we notice is that the normal drive-current phase-angles don't work very well, if applied to the bases of "⅝ λ" elements. Adjusting the current phase-angles from (0°/–90°/–90°/–180°) to something on the order of (0°/–120°/–120°/–240°), or even (0°/–135°/–135°/–270°), allows us to easily obtain more than a full decibel of additional gain, as well as increasing the front-to-back ratio, when beaming through the diagonals of the square. Figures 23 and 24 illustrate the patterns. Utilizing larger-than-normal current phase-angles (–105° to –147°) for the front elements can also be advantageous when firing through the sides of the square (see Figures 25 and 26 for the plots).

By comparing Tables 4 and 6, we can find out if it makes sense to extend the height of existing ¼ λ monopoles to ⅝ λ, when the radials in the ground-screen are no longer than ¼ λ. With ⅝ λ radiators, the chief area of improvement is a reduction (by roughly 9°) in the take-off angle of the main lobe. If we insist upon keeping the traditional current phase-angles, then the peak forward gain *decreases* if we switch to taller elements. But, there is an incremental *increase* in gain of 0.21 dB with W8JI phase-angles, and 0.46 dB with the "max gain" values, when beaming through the corners of the square. While firing through the sides of the square, a significant phase-lag in the front monopoles (about 147°) is needed in order to produce an improvement. Thus, a decision to employ ⅝ λ radiators in this situation should definitely be accompanied by a change in the phase-angles of the base currents supplied to the elements.

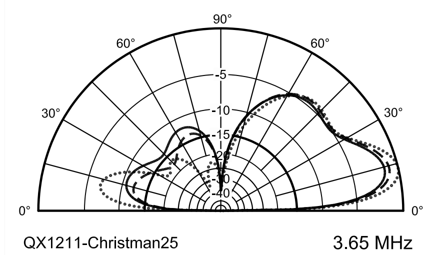

Figure 25 — Elevation-plane radiation patterns for 4-Square arrays with 3 different sets of current phase angles, when firing through the sides of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ¼ λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase angles (0°, 0°, –90°, –90°), peak gain = 4.25 dBi at 14.5° take-off angle.
Dashed trace = arbitrary angles (0°, 0°, –105°, –105°), peak gain = 4.72 dBi at 14.3° take-off angle.
Dotted trace = "maxgain" angles (0°, 0°, –147°, –147°), peak gain = 5.56 dBi at 13.6° take-off angle.

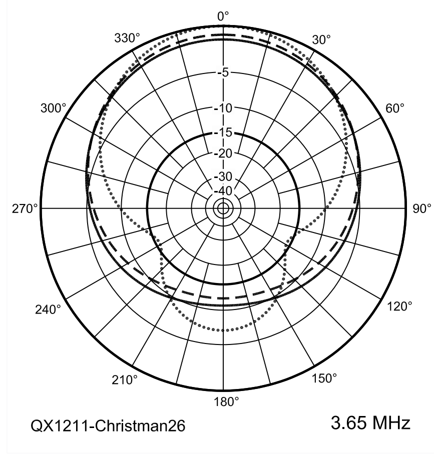

Figure 26 — Azimuth-plane radiation patterns for 4-square arrays with 3 different sets of current phase-angles, when firing through the sides of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is 1/4 λ (L = 67.37 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°,0°,-90°,-90°)
Peak gain = 4.25 dBi at 14.5° take-off angle
Dashed trace = arbitrary angles (0°,0°,-105°,-105°)
Peak gain = 4.72 dBi at 14.3° take-off angle
Dotted trace = "max-gain" angles (0°,0°,-147°,-147°)
Peak gain = 5.56 dBi at 13.6° take-off angle

Table 7

Performance of a 4 Square array using ⅝ λ monopoles and ⅝ λ radials, as a function of the phase-angles of the base currents. Maximum gain at the lowest take-off angle always occurred at an element height of about 165.6 feet (where the monopole was resonant at 1445 kHz), and the radials have a length of 168.42 feet. Each monopole is built from no. 12 AWG copper wire, and the ground system is composed of 60 no. 16 AWG wire radials per element. The soil is "average" (conductivity = 0.005 Siemens/meter and dielectric constant = 13).

	Traditional Phasing	*W8JI Phasing*	*Maximum Gain Phasing*
Firing through the corners of the square:			
I_{front}	1<–180°	1<–240°	1<–272°
I_{sides}	1<–90°	1<–120°	1<–136°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	5.62	6.73	6.97
Take-off Angle (°)	13.9	13.4	13.1
Elevation Plane F/B Ratio (dB)	11.13	16.95	19.75
Azimuth Plane F/B Ratio (dB)	11.29	17.16	19.83
Azimuth Plane F/S Ratio (dB)	N.A.	13.56	10.56
Azimuth Plane Half Power Beamwidth (°)	109.4	82.6	71.2
Z_{input} (Ω) (Front Element)	68.1 – *j* 361.5	9.32 – *j* 425.5	0.72 – *j* 461.5
Z_{input} (Ω) (Side Elements)	157.7 – *j* 527.9	86.0 – *j* 526.2	54.41 – *j* 525.2
Z_{input} (Ω) (Back Element)	58.61 – *j* 649.0	20.88 – *j* 593.0	16.89 – *j* 567.0
Firing through the sides of the square:			
I_{front}	1<–90°	1<–105°	1<–146°
I_{back}	1<0°	1<0°	1<0°
Maximum Gain (dBi)	4.42	4.89	5.71
Take-off Angle (°)	14.4	14.2	13.6
Elevation Plane F/B Ratio (dB)	9.31	11.22	6.97
Azimuth Plane F/B Ratio (dB)	9.43	11.24	7.05
Azimuth Plane Half Power Beamwidth (°)	149.0	132.6	100.0
Z_{input} (Ω) (Front Elements)	196.1 – *j* 399.9	165.0 – *j* 400.8	91.48 – *j* 441.5
Z_{input} (Ω) (Back Elements)	168.7 – *j* 638.0	138.7 – *j* 631.2	76.22 – *j* 574.9

Results for a 4-Square Array with ⅝ λ Elements and ⅝ λ Radials

The final configuration incorporates monopoles whose height is approximately ⅝ λ, in combination with buried radials with a maximum length of ⅝ λ. This array would be the most expensive to construct, requiring the largest amount of land as well as the tallest radiators. Table 7 provides the critical data we need. Notice that the application of larger-than-normal phase-shifts (either the W8JI or "max-gain" values) to the drive currents can generate at least a full decibel of extra gain, along with more front-to-back ratio, when compared to the typical (0°/–90°/–90°/–180°) angles. The key radiation-pattern plots are shown in Figures 27 and 28. Greater current phase-shifts are also beneficial when the array is firing through the sides of the square (see Figures 29 and 30).

Reviewing Table 4 together with Table 7 permits us to see the "margin of superiority" that the biggest 4-square array (⅝ λ elements and radials) enjoys over the smallest one (¼ λ elements and radials). With normal current phasing (0°/–90°/–90°/–180°) the results are disastrous when we look at forward gain — the smaller array works better! With larger phase-lags, however, we calculate 0.37 dB of extra gain for W8JI phasing, and 0.61 dB with "max gain" phasing. However, the taller monopoles in the big array will always give us a main-lobe take-off angle that is lower by about 9°. If we are beaming through the sides of the square, only the "max gain" phase-angles provide additional gain, versus the small array.

Keeping the Current Phase-angles Constant

In this section, we will examine what happens if the phase-angles of the base currents are held fixed, while the length of the radials and the height of the radiators is varied. The results for "traditional" phase angles (0°/–90°/–90°/–180°) are presented in Table 8. The highest gain is achieved when ¼ λ elements are placed over a ground screen composed of radials whose maximum length is ⅝ λ. This set of current phase-angles doesn't work too well when combined with ⅝ λ monopoles, but the taller radiators *do* generate a much-lower main lobe, which may be preferable. In that case, an array using ⅝ λ elements and ⅝ λ radials would be the one to pick. The elevation-plane patterns for both of these alternatives are given in Figure 31.

If the "W8JI" current phase-angles are applied to the input terminals of the radiators, the outcome will be as displayed in Table 9. Once again, a system of ¼ λ elements combined with ⅝ λ (max) radials produces the most gain. If a lower take-off angle is

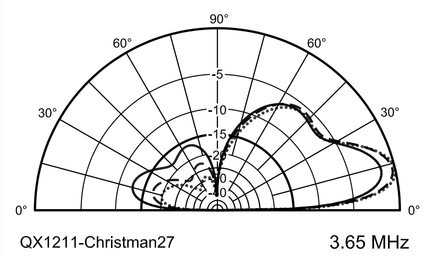

Figure 27 — Elevation-plane radiation patterns for 4-square arrays with 3 different sets of current phase-angles, when firing through the corners of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°,-90°,-90°,-180°)
Peak gain = 5.62 dBi at 13.9° take-off angle
Dashed trace = "W8JI" angles (0°,-120°,-120°,-240°)
Peak gain = 6.73 dBi at 13.4° take-off angle
Dotted trace = "max-gain" angles (0°,-136°,-136°,-272°)
Peak gain = 6.97 dBi at 13.1° take-off angle

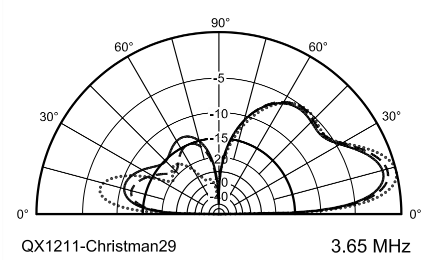

Figure 29 — Elevation-plane radiation patterns for 4-square arrays with 3 different sets of current phase-angles, when firing through the sides of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°,0°,-90°,-90°)
Peak gain = 4.42 dBi at 14.4° take-off angle
Dashed trace = arbitrary angles (0°,0°,-105°,-105°)
Peak gain = 4.89 dBi at 14.2° take-off angle
Dotted trace = "max-gain" angles (0°,0°,-146°,-146°)
Peak gain = 5.71 dBi at 13.6° take-off angle

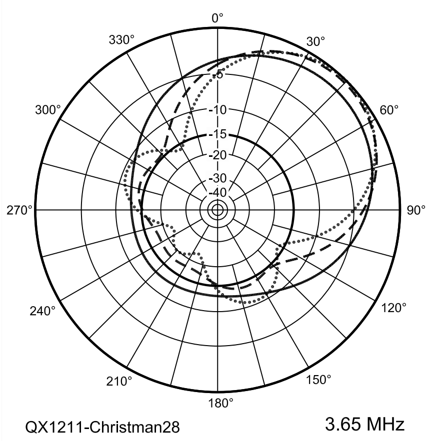

Figure 28 — Azimuth-plane radiation patterns for 4-square arrays with 3 different sets of current phase-angles, when firing through the corners of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°,-90°,-90°,-180°)
Peak gain = 5.62 dBi at 13.9° take-off angle
Dashed trace = "W8JI" angles (0°,-120°,-120°,-240°)
Peak gain = 6.73 dBi at 13.4° take-off angle
Dotted trace = "max-gain" angles (0°,-136°,-136°,-272°)
Peak gain = 6.97 dBi at 13.1° take-off angle

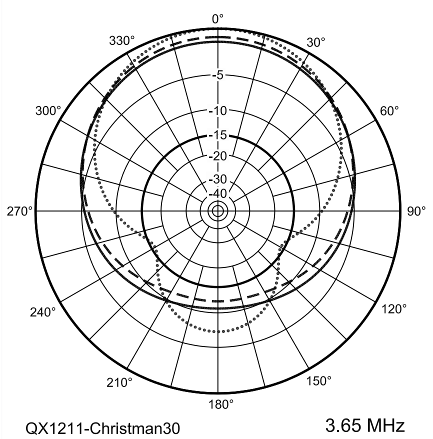

Figure 30. Azimuth-plane radiation patterns for 4-square arrays with 3 different sets of current phase-angles, when firing through the sides of the square, using ⅝ λ monopoles whose height was adjusted for maximum gain. Each element has a ground screen composed of 60 buried radials, whose maximum length is ⅝ λ (L = 168.42 feet at 3650 kHz).
Solid trace = "Normal" phase-angles (0°,0°,-90°,-90°)
Peak gain = 4.42 dBi at 14.4° take-off angle
Dashed trace = arbitrary angles (0°,0°,-105°,-105°)
Peak gain = 4.89 dBi at 14.2° take-off angle
Dotted trace = "max-gain" angles (0°,0°,-146°,-146°)
Peak gain = 5.71 dBi at 13.6° take-off angle

Table 8

Performance of a 4 Square array when the elements are driven with traditional current phase angles (0°/–90°/–90°/–180°), as a function of radiator height and radial length. Each antenna is designed to operate at 3650 kHz. Arrays with ¼ λ monopoles have their element heights adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens per meter and dielectric constant = 13).

	¼ λ Monopole ¼ λ Radials	*¼ λ Monopole ⅝ λ Radials*	*⅝ λ Monopole ¼ λ Radials*	*⅝ λ Monopole ⅝ λ Radials*
Radiator Height (ft)	65.43	65.42	165.62	165.62
Resonant Frequency (kHz)	3650	3650	1448	1445
Radial Length (ft)	67.37	168.42	67.37	168.42
Firing through the corners of the square:				
	(I_{back} = 1<0°, I_{sides} = 1<–90°, and I_{front} = 1<–180°)			
Maximum Gain (dBi)	5.89	6.34	5.45	5.62
Take-off Angle (°)	23.7	24.1	14.0	13.9
Elevation Plane F/B Ratio (dB)	17.99	16.48	11.1	11.13
Azimuth Plane F/B Ratio (dB)	23.35	24.26	11.27	11.29
Azimuth Plane Half Power Beamwidth (°)	100.6	100.8	109.6	109.4
Firing through the sides of the square:				
	(I_{back} = 1<0° and I_{front} = 1<–90°)			
Maximum Gain (dBi)	4.90	5.34	4.25	4.42
Take-off Angle (°)	25.0	25.5	14.5	14.4
Elevation Plane F/B Ratio (dB)	13.93	12.94	9.31	9.31
Azimuth Plane F/B Ratio (dB)	23.60	24.57	9.44	9.43
Azimuth Plane Half Power Beamwidth (°)	130.0	129.4	149.2	149.0

Table 9

Performance of a 4 Square array when the elements are driven with W8JI current phase angles (0°/–120°/–120°/–240°), as a function of radiator height and radial length. Each antenna is designed to operate at 3650 kHz. Arrays with ¼ λ monopoles have their element heights adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens per meter and dielectric constant = 13).

	¼ λ Monopole ¼ λ Radials	*¼ λ Monopole ⅝ λ Radials*	*⅝ λ Monopole ¼ λ Radials*	*⅝ λ Monopole ⅝ λ Radials*
Radiator Height (ft)	65.43	65.42	165.59	165.59
Resonant Frequency (kHz)	3650	3650	1448	1445
Radial Length (ft)	67.37	168.42	67.37	168.42
Firing through the corners of the square:				
	(I_{back} = 1<0°, I_{sides} = 1<–120°, and I_{front} = 1<–240°)			
Maximum Gain (dBi)	6.36	6.81	6.57	6.73
Take-off Angle (°)	22.2	22.5	13.4	13.4
Elevation- Plane F/B Ratio (dB)	30.30	22.76	17.11	16.95
Azimuth-Plane F/B Ratio (dB)	36.99	30.12	17.33	17.16
Azimuth-Plane F/S Ratio (dB)	15.90	15.51	13.43	13.56
Azimuth-Plane Half Power Beamwidth (°)	80.0	80.2	82.8	82.6
Firing through the sides of the square:				
	(I_{back} = 1<0°and I_{front} = 1<–105°)			
Maximum Gain (dBi)	5.22	5.67	4.72	4.89
Take-off Angle (°)	22.4	24.9	14.3	14.2
Elevation-Plane F/B Ratio (dB)	17.71	15.49	11.25	11.22
Azimuth-Plane F/B Ratio (dB)	21.65	20.95	11.27	11.24
Azimuth-Plane Half Power Beamwidth (°)	118.2	118.6	133.0	132.6

our goal, then an antenna utilizing both ⅝ λ monopoles and ⅝ λ radials works best. (See Figure 32 for the elevation-plane plots.)

Table 10 provides the performance data for 4-square arrays in which the current phase-angles have been adjusted to supply the maximum-possible amount of forward gain at the lowest-attainable take-off angle. If we must limit ourselves to relatively-short (¼ λ) radiators, then they should be combined with ⅝ λ radials, as usual. However, a system of ⅝ λ radiators and ⅝ λ radials is the overall winner, yielding almost 7 dBi of gain at an elevation angle of just over 13°. The radiation-pattern plots are shown in Figure 33.

Conclusions

This article has discussed the use of extended-height radiators and extended-length radials in vertical antenna systems. Designs composed of a single element have been reviewed, along with both 2- and 4-element arrays. Computer analysis reveals that in many cases, normal ¼ λ monopoles can be combined with longer radials and modified current phase-angles to provide better performance. If lower take-off angles are important, then taller radiators must be employed.

Notes

[1]John Devoldere, ON4UN, *ON4UN's Low-Band DXing* (*4th edition)*, ARRL, Newington, CT, 2005; see Chapter 11 for details.

[2]Roy Lewallen, W7EL, *EZNEC* antenna-simulation software; available from Roy Lewallen, W7EL, PO Box 6658, Beaverton OR 97007.

[3]Tom Rauch, W8JI, "Four-Square," **w8ji.com/tx_four_square.htm**.

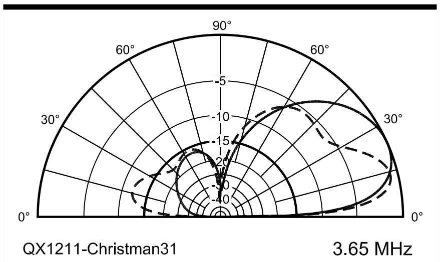

Figure 31 — Elevation-plane radiation patterns for the two best- performing 4-square arrays, when firing through the corners of the square, using traditional current phase-angles (0°,-90°,-90°,-180°).
Solid trace = 1/4 λ elements and ⅝ λ radials
Peak gain = 6.34 dBi at 24.1° take-off angle
Dashed trace = ⅝ λ elements and ⅝ λ radials
Peak gain = 5.62 dBi at 13.9° take-off angle

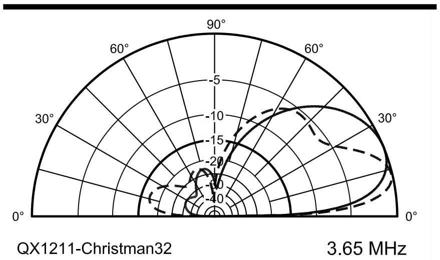

Figure 32 — Elevation-plane radiation patterns for the two best performing 4-square arrays, when firing through the corners of the square, using "W8JI" current phase angles (0°,-120°,-120°,-240°).
Solid trace = 1/4 λ elements and ⅝ λ radials
Peak gain = 6.81 dBi at 22.5° take-off angle
Dashed trace = ⅝ λ elements and ⅝ λ radials
Peak gain = 6.73 dBi at 13.4° take-off angle

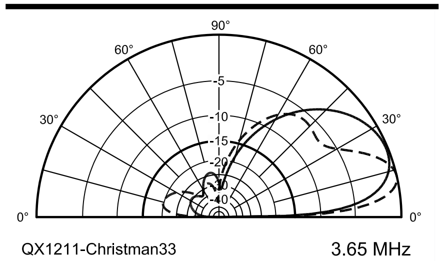

Figure 33 — Elevation-plane radiation patterns for the two best- performing 4-square arrays, when firing through the corners of the square, using "max-gain" current phase- angles, (0°,-125°,-125°,-250°) or (0°,-136°,-136°,-272°)
Solid trace = 1/4 λ elements and ⅝ λ radials
Peak gain = 6.81 dBi at 22.3° take-off angle
Dashed trace = ⅝ λ elements and ⅝ λ radials
Peak gain = 6.97 dBi at 13.1° take-off angle

Table 10

Performance of a 4 Square array when the phase angles of the element currents are selected to produce maximum forward gain, as a function of radiator height and radial length. Each antenna is designed to operate at 3650 kHz. Arrays with ¼ λ monopoles have their element heights adjusted for resonance at 3650 kHz, while those with ⅝ λ elements are adjusted for maximum gain and lowest take-off angle at the same frequency. Each monopole is built from no. 12 AWG copper wire, while the ground system is composed of 60 no. 16 AWG wire radials. The soil is "average" (conductivity = 0.005 Siemens per meter and dielectric constant = 13).

	¼ λ Monopole ¼ λ Radials	*¼ λ Monopole ⅝ λ Radials*	*⅝ λ Monopole ¼ λ Radials*	*⅝ λ Monopole ⅝ λ Radials*
Radiator Height (ft)	65.43	65.42	165.59	165.59
Resonant Frequency (kHz)	3650	3650	1448	1445
Radial Length (ft)	67.37	168.42	67.37	168.42
Firing through the corners of the square:				
			(I_{back} = 1<0°)	
I_{sides}	1<–125°	1<–125°	1<–135°	1<–136°
I_{front}	1<–250°	1<–250°	1<–270°	1<–272°
Maximum Gain (dBi)	6.36	6.81	6.82	6.97
Take-off Angle (°)	22.0	22.3	13.1	13.1
Elevation Plane F/B Ratio (dB)	33.96	23.85	20.10	19.75
Azimuth Plane F/B Ratio (dB)	38.35	30.63	20.18	19.83
Azimuth Plane F/S Ratio (dB)	14.10	13.85	10.70	10.56
Azimuth Plane Half Power Beamwidth (°)	76.8	77.2	72.0	71.2
Firing through the sides of the square:				
			(I_{back} = 1<0°)	
I_{front}	1<–131°	1<–131°	1<–147°	1<–146°
Maximum Gain (dBi)	5.42	5.89	5.56	5.71
Take-off Angle (°)	23.4	23.9	13.6	13.6
Elevation Plane F/B Ratio (dB)	9.41	9.07	6.76	6.97
Azimuth Plane F/B Ratio (dB)	9.76	9.41	6.84	7.05
Azimuth Plane Half Power Beamwidth (°)	104.1	103.8	99.6	100.0

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