Technical Correspondence

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THE IMPACT OF CURRENT DISTRIBUTION ON ARRAY PATTERNS

☐ An assumption underlying much of the Amateur Radio literature on phased-array antennas is invalid for some types of arrays used by amateurs. As a result, patterns of these arrays can deviate dramatically from predictions.

The assumption is that, if an array is made of physically identical elements, *the current distribution is the same on all elements as it is on an isolated element.*[1] This assumption also is made in *The ARRL Antenna Book* section on phased arrays (much of which I authored).[2] Because it plays a major role in determining the pattern to be expected from an array and how the array should be fed to produce that pattern, this assumption is important.

If identical current distributions are assumed on all elements, the total field from each element is proportional to the current flowing at each of the element's feed points. But this won't be true if the distributions are different, because the field from an element is determined by the current distribution as well as the magnitude and phase of the current at a given point on the element. A second consequence of the equal-current-distribution assumption is that element self-impedances don't change as a result of the presence of other elements (although the feed-point impedances do change—more about this topic later).

The fact is that *the current distributions on elements in an array are different than for the same elements when the elements are isolated.* Fortunately, in some cases, the effect of this impedance on array performance is minor. In other cases, however, it's dramatic. I'll briefly describe some of each. The following discussion assumes vertical elements over ideal ground, although the conclusions are equally valid for any type of array.

When two equal-length elements are fed with in-phase or 180° out-of-phase currents, current distributions on the two elements are the same, even though each is different than on an isolated element. This is true regardless of element length and spacing. As a result, the azimuth patterns from these arrays aren't affected by the invalidity of the equal-current-distribution assumption, although there can be (usually minor) differences in gain and vertical pattern caused by the changed distributions. Feed-point impedances can be much different than expected if the elements are significantly longer than resonant length, however.

The patterns of all arrays of three or more elements are potentially affected, but for simplicity I'll use some two-element vertical arrays as examples.[3] Placing two very short elements 1/4 λ apart and driving them with currents equal in magnitude and phased 90 degrees apart produces the familiar cardioid pattern. Longer elements also generate a cardioid pattern if their current distributions are equal. The effect of unequal current distribution is visible, but minor, on thin quarter-wavelength elements; the pattern is a cardioid, but with a lobe to the rear about 30 dB down from the forward lobe. The ratio of element currents is $1 \angle -90$ degrees at the bases, but steadily changes to about $1.1 \angle -93$ degrees at the tops. (Thicker elements are affected more. The rear lobe is only 20 dB down with an element length/diameter ratio of 25). For most applications, *the assumption is adequately accurate for thin elements 1/4 wavelength long and shorter.* Fortunately, this encompasses the majority of amateur arrays.

The arrays most profoundly affected are those made from longer elements (for example, 1/2- or 5/8-λ verticals or 1- or 1-1/4-λ dipoles). If the equal-current-distribution assumption were valid, arrays with two identical elements of any length would have a cardioid pattern if fed as mentioned earlier. But, Figs 1 through 4 show what actually happens: The current distributions are vastly different, and the patterns bear only a vague resemblance to a cardioid! Patterns of arrays with antiresonant (0.459-λ) and 1/2-λ elements are very different (Fig 1), showing an undesirably high sensi-

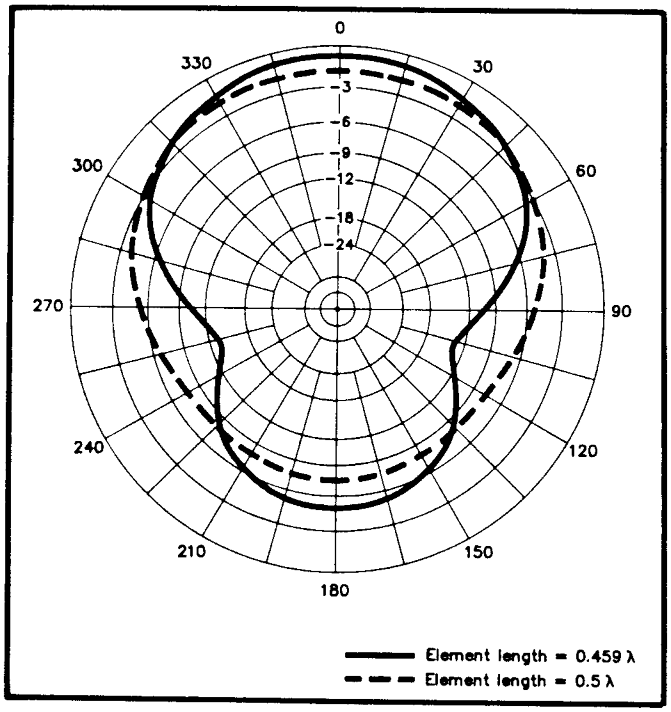

Fig 1—Patterns of two-element arrays fed at the bases with equal currents of 90-degree relative phase. Element spacing is 0.25 λ. The two patterns are for antiresonant elements (0.459 λ) and 1/2 λ-long elements above a perfect ground plane. The outer ring of the plot is +11 dBi.

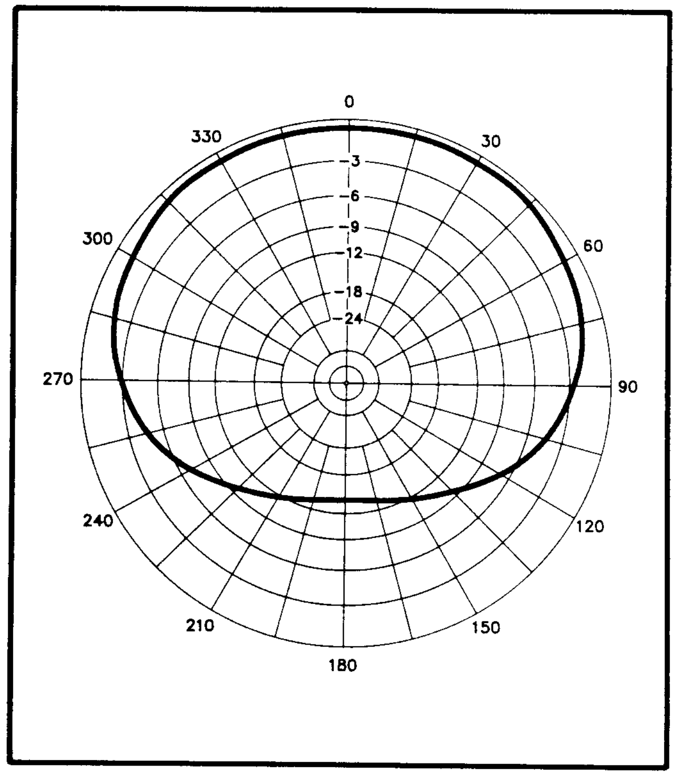

Fig 2—Same setup as Fig 1, but element length is 5/8 λ.

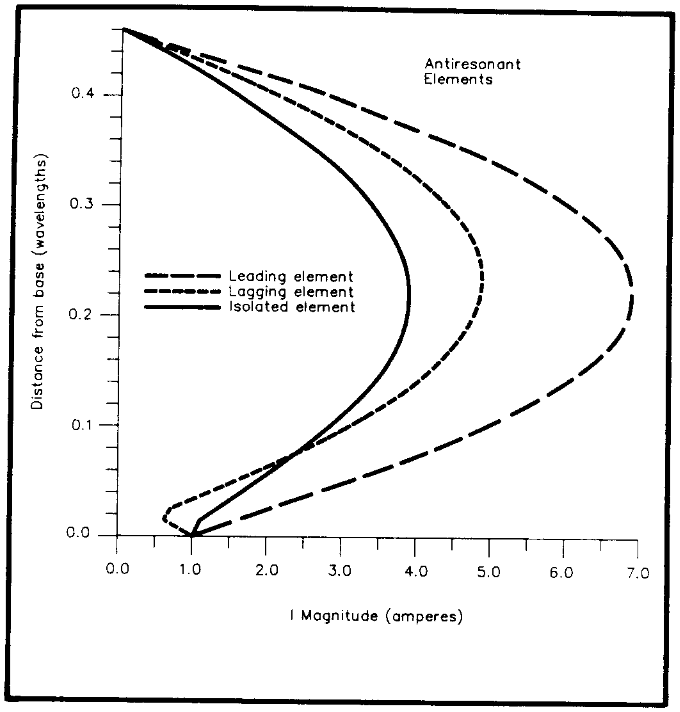

Fig 3—Magnitude of currents on antiresonant vertical elements as a function of distance from the base. The current distribution on an isolated element is shown for reference.

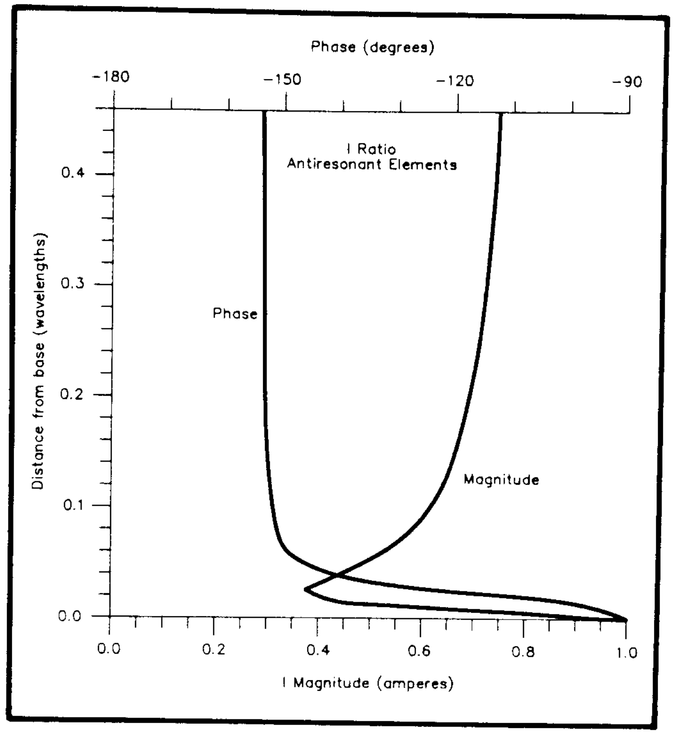

Fig 4—Magnitude and phase of the ratio of currents on two antiresonant elements.

tivity to element length.

Changes in current distribution also change feed-point impedances. If one begins with the familiar equations (shown for two elements)[4]

$$V_1 = I_1Z_{11} + I_2Z_{12}$$
$$V_2 = I_1Z_{12} + I_2Z_{22}$$

self-impedances Z_{11} and Z_{22} and mutual impedance Z_{12} can be derived by observing the feed-point impedances when the elements are driven in phase and out of phase with equal currents. $Z_{11} = Z_{22} = 1/2 \times (Z_0 + Z_{180})$ and $Z_{12} = 1/2 \times (Z_0 - Z_{180})$ where Z_0 and Z_{180} are the feed-point impedances of either element (V_1 / I_1 and V_2 / I_2) when the elements are fed in and out of phase respectively. If element 1 is isolated, $Z_{11} = V_1 / I_1$, so the feed-point impedance becomes the self-impedance. However, the value of Z_{11} calculated from Z_0 and Z_{180} will give a different value—sometimes, a very different value—because of changed current distribution. Although Z_{11} is the "self-impedance" of element 1, I'm uncomfortable with saying the self-impedance has changed because of my long association of the term with the impedance of an isolated element. However, two of the foremost authorities on antenna theory clearly make this interpretation.[5]

How pronounced is the self-impedance change? It's virtually unmeasurable with elements up to 1/4 λ long, but extreme with element lengths near 1/2 λ. An isolated antiresonant vertical element (0.459 λ long, length/dia = 1000) over a ground plane has a base impedance of $1574 - j13.26\ \Omega$. When in an array like those of the preceding examples, Z_{11} calculated from Z_0 and Z_{180} = $2006 + j707.5$. Z_{12} differs even more from the value calculated assuming identical current distributions: $-1055 - j703.5$ versus $+895.6 - j625.2\ \Omega$.[6]

The existence of dissimilar current distributions was reported and analyzed as early as 1944, and figures prominently in papers and texts by King, Harrison, Tai, and undoubtedly others.[5,7-10] Yet during the period of mid-1920s to 1960s, during which many papers on antenna theory appeared, sinusoidal distribution frequently was assumed, as not doing so made mathematical analysis of the general case virtually impossible (see Note 6). The papers not making the equal-current-distribution assumption generally dealt only with two elements in phase or 180° out of phase, cases that could be relatively easily dealt with mathematically. Designers of large arrays, such as those used in phased-array radars, frequently can make the assumption of similar current distribution on all elements. Broadcast-array-design techniques have evolved to the use of method-of-moments programs such as NEC and MININEC, which show results similar to those presented here. However, I'm not aware of any literature that directly addresses the impact of unequal current distribution on typical amateur arrays.

I hope this brief correspondence saves some people from the frustration of trying to phase arrays of longer elements. Much more study is needed to assess the impact of this phenomenon on other types of arrays (how about collinear arrays?) and to learn how best to deal with it.—*Roy Lewallen, W7EL, ARRL TA, 5470 SW 152 Ave, Beaverton, OR 97007*

Notes

[1] *Current distribution* refers to the way current varies along an element. For example, the current distribution is nearly sinusoidal on an isolated, resonant dipole—greatest at the center and tapering to near zero at the ends.

[2] G. Hall, Ed., *The ARRL Antenna Book*, 15th ed (Newington: ARRL, 1988), Chapter 8.

[3] All currents and patterns were calculated with ELNEC, a MININEC-based program that permits the use of true current sources. Twenty segments per element were specified for element lengths of 1/2 λ and less, 40 segments for longer elements. The diameter of each element is 1/1000 its length. A perfect ground is assumed, and plots are for a zero-degree elevation angle.

[4] See Note 2.

[5] R. King and C. Harrison, Jr, "Mutual and Self-Impedance for Coupled Antennas," *Journal of Applied Physics*, Vol 15, Jun, 1944, pp 481-495.

[6] For example, see C. Cox, "Mutual Impedance Between Vertical Antennas of Unequal Heights," *Proceedings of the I.R.E.*, Nov 1947, pp 1367-1370. His equations assume sinusoidal current distributions on both elements. The equations and graphs based on them apparently have appeared in texts and in publications by the National Association of Broadcasters and other organizations related to the broadcast industry.

[7] C. Tai, "Coupled Antennas," *Proceedings of the I.R.E.*, Apr 1948, pp 487-500.

[8] R. King, "Self- and Mutual Impedances of Parallel Identical Antennas," *Proceedings of the I.R.E.*, Aug 1952, pp 981-988.

[9] R. King, *Theory of Linear Antennas* (Cambridge, MA: Harvard University Press, 1956), p 275ff.

[10] C. Harrison, Jr, and R. King, "Theory of Coupled Folded Antennas," *IRE Transactions on Antennas and Propagation*, Mar 1960, pp 131-135.

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