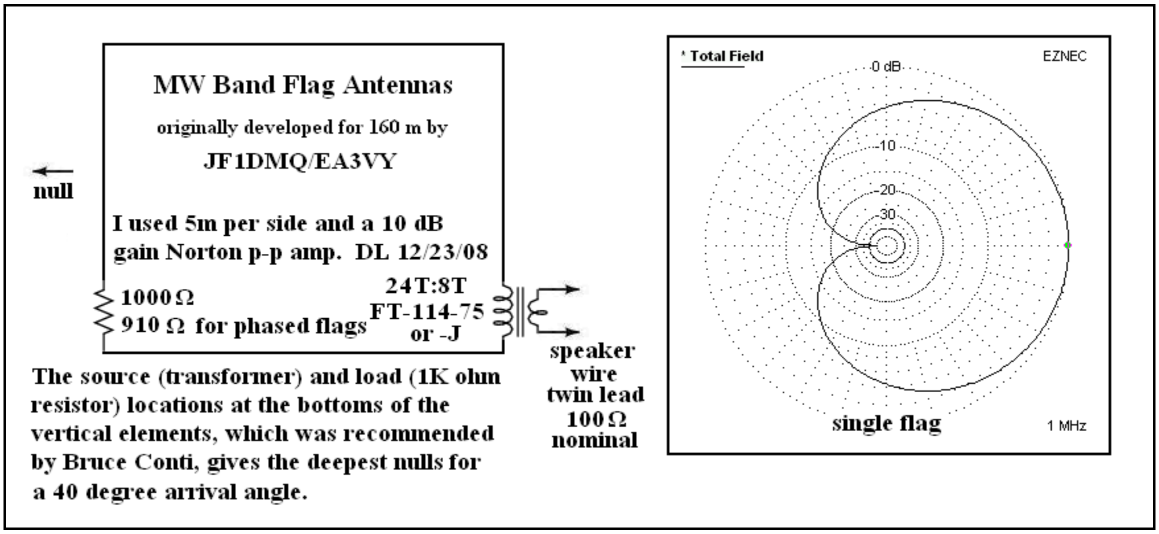
Phased Flag Arrays

Dallas Lankford, 12/25/08, rev. 3/15/09



The software defined radio Perseus which can record the entire MW band places new demands on antennas for MW DXing. A MW antenna with a mechanically steerable null (e.g., a loop rotated with a rotor or by hand) or a MW antenna array with electronic steerable null will not provide satisfactory splatter reduction for the entire MW. Clearly antenna arrays with wider null aperture than provided by previous rotated or electronically null steered MW arrays is needed. This note describes such arrays with two and four phased flag elements.

The flag antenna was developed as a ground independent EWE-type antenna which avoids ground conductivity issues. I had never used a flag myself until a few days ago, but found its null considerably better than a EWE I tried a few years ago. The size I chose for my flag tests was 5 meters per side, which is about right for use with a 10.8 dB gain Norton transformer feedback amplifier described in The Dallas Files here . The size can be decreased if an amplifier with greater gain is used, but carried to extremes this can limit flag and flag array sensitivity. At a location of low man made noise the flags should be at least twice the area given above, or even three or four times the area. Some have said that 940 ohms is the optimal termination resistance.. But no difference in null pattern was observed between 940 and 1000 ohms termination with EZNEC simulations, so I used 1000 ohms for convenience. The single flag EZNEC simulation above was done for 40 degree elevation angles. Some have user remote variable resistors to deepen the depth of a single flag antenna. But varying a remote resistor does not steer the null of a single flag element either vertically or horizontally, and so it is ineffective for null steering a single flag antenna.

I arranged my flag so that the null was pointed due North, the direction of most of my strong clears. During the first night of testing a single flag sometimes nulled the clears to the North as well as a (variable) phased pair of verticals spaced 33 meters apart. But at other times the single fixed flag did not null nearly as well as the phased verticals, due presumably to changing ionospheric conditions and the small null aperture of a single flag (about 7 degrees). A pair of phased flag antennas described in the following effectively resolves those issues.

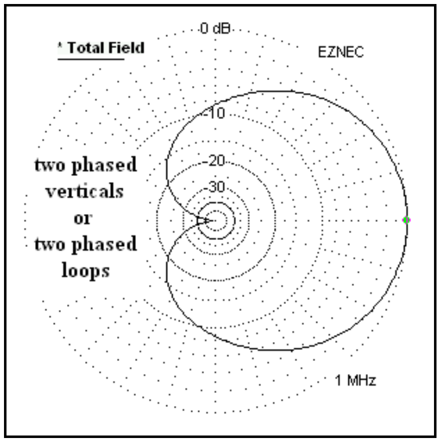
The following is a slightly edited account of the invention and development of dual phased flag arrays given by Carlos DaSilva, N4IS in a posting to the Top Band reflector in May 2007.

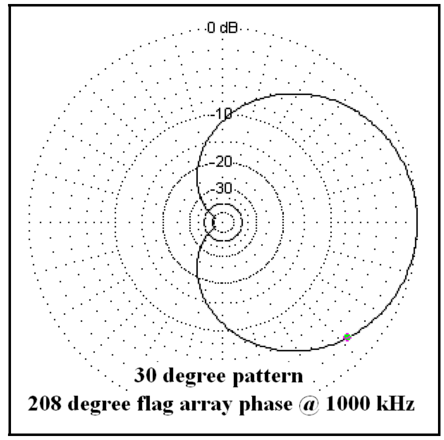
"… the Waller Flag, as I called it (after Doug Waller, N4XD), is not a new antenna project, the idea of it started with WA2WVL articles QST Feb, 1995, "Is this EWE for you?" At the end of the second article, Floyd mentioned the new design of a dual EWE in end-fire, but no constructions or practical evaluations details.

Few years later, Earl K6SE QST July 2000, working with EA3VY come up with an improved project ground independent Low Band Receiving Antenna and Earl K6SE called it a Flag Antenna. Earl also presented the project of two flags in phase with a nice diagram. ON4UN also mentioned the project idea on his book.

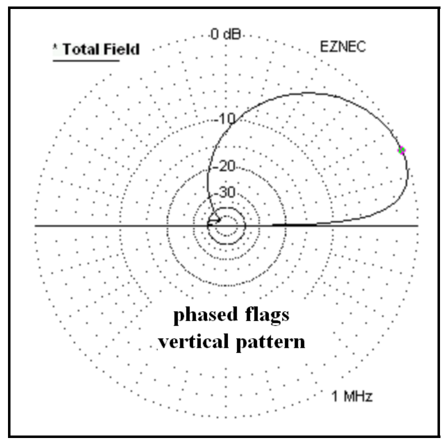
The Waller Flag is basically two flag antennas phased 180 degrees. In 2003 Doug Waller, NX4D living on 1/3 city lot set himself the goal to work as many DXCC on low bands as possible from his limited size lot.

First Doug built a single rotatable flag antenna and then improved that by building a dual rotatable flag array in end fire configuration. He followed most of Earl's recommendations. Removal of common mode currents is mandatory. You don't want to receive signals form your feed line shield. We use RF chokes of 15 turns of RG174 on FT-140-77 ...” For further information see N4IS .





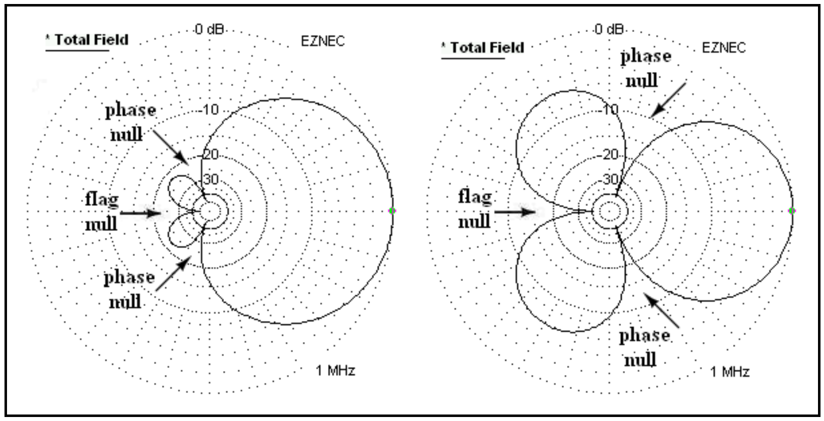
My phased two element flag arrays described here are somewhat different from the Waller flag arrays because mine are designed to generate the widest possible 30 dB null aperture, while the Waller arrays were designed for maximum RDF. A pair of phased flags (with the dimensions given above, separated by 100 feet, with the planes of both flags in the same plane and suitably phased) has a much wider 30 dB or greater null aperture than a single flag, generally about 90 degrees as can be seen in the figure above far right. For comparison the cardioid pattern of two loops or two verticals is given in the figure above at near right. The 30 dB null aperture for two phased loops or two phased verticals is about 30 degrees which is quite good, much better than a single flag, but much worse than two phased flags At coastal sites with low levels of man made noise the flag elements should, perhaps, have at least twice the area given above (or larger?), namely rectangles 15 feet high by 30 feet long (or longer?). Otherwise the phased flag array may be preamp noise limited even with very low noise Norton transformer feedback preamplifiers. EZNEC simulation has also shown that 910 ohm load resistors for two phased flags gives slightly better and deeper nulls than the 1000 ohm load used for a single flag, and, of course, is better matched to 100 ohm nominal twin lead using a 9:1 Z transformer. The null in the vertical plane of the flag is equally deep from about 0 degrees up to about 50 degrees. This can and does improve both long term null stability and adjacent channel splatter when DXing MW splits, especially if most undesired signals are in or near the 30 dB null aperture. My dual flag array is necessarily larger than the NX4D and N4IS flag arrays because mine is designed to cover the entire MW band. And because of its large size, my flag array is not rotatable.



The first dual flag array I implemented used a variable phaser. (You have to start somewhere.) But a variable phaser was immediately found to be undesirable for two reasons: (1) How can a variable phaser be adjusted for the widest possible 30 dB or greater null aperture? (2) If a variable phaser can be adjusted for the widest possible 30 dB or greater null aperture at a particular frequency, does it follow that the the widest possible 30 dB or greater null aperture is also obtained at all other frequencies in the MW Band? I never did find a way to adjust a variable phaser for the best dual flag array pattern at a single frequency. And I was never able to show that a variable phaser was “linear,” that when it was adjusted to the best null pattern at a single frequency, the same best null pattern was maintained at all frequencies throughout the MW band.

A Variable Phaser Would Be A Mistake For Maximum Splatter Reduction

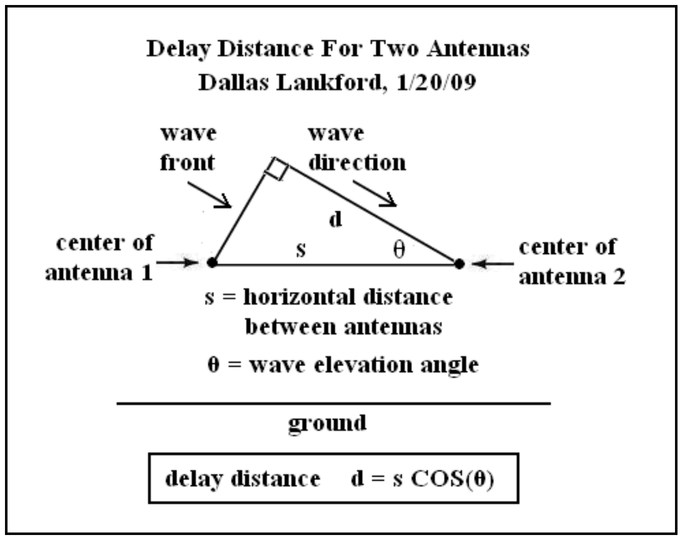
Even if the above two problems could be solved, a more serious reason for not using a variable phaser with a dual or quad flag array was discovered. When EZNEC simulations of null steering were done, it was discovered that as the nulls are steered, “blips” appear inside the 30 dB null aperture which progressively degrade the 30 dB or greater null aperture angle, which in turn degrade the splatter reduction performance of the phased flags. The 30 dB or greater null aperture decreases to about 10 degrees when the steered nulls are about 45 degrees from the flag null. The steered null apertures of phased loops and phased verticals decrease similarly as the nulls are steered away from the fundamental cardioid null, so a phased flag array is no worse than a phased loop or phased vertical array in that regard, and is actually slightly better than them because of the 3rd flag null. The figure at right contains EZNEC simulations which show how null steering degrades the nulls of two flag array.



Clearly, when maximum splatter reduction is the goal, it would be a mistake to use a variable phaser to null steer a two flag or a four flag array. To obtain maximum splatter reduction the phaser should be fixed and the flag array should be oriented for best splatter reduction.

Delay

The first fixed phasers I developed were coax delay line phasers. Coax delay line phasers are supposed to be linear provided the coax used is good quality and matched to its characteristic impedance. The principals of coax phasers are straightforward; see the diagram at right.



For an arrival angle θ, the delay distance d = s COS(θ), where s is the spacing between the centers of the individual flag antennas. For s = 100', d = 100 COS(30°) = 86.6'. There are 3.28 feet per meter, so d = 86.6/3.28 = 26.4 meters.

The time delay T is the time difference between the arrival of a wave front at antenna 1 and the arrival of that same wave front at antenna 2. The speed of electromagnetic radiation is approximately 2.99 x 10^8 meters per second in air, so the time delay per meter in air is 1/(2.99 x10^8) = 3.34 nS/m. Thus the time delay T = 3.34 x 26.4 = 88.3 nS.

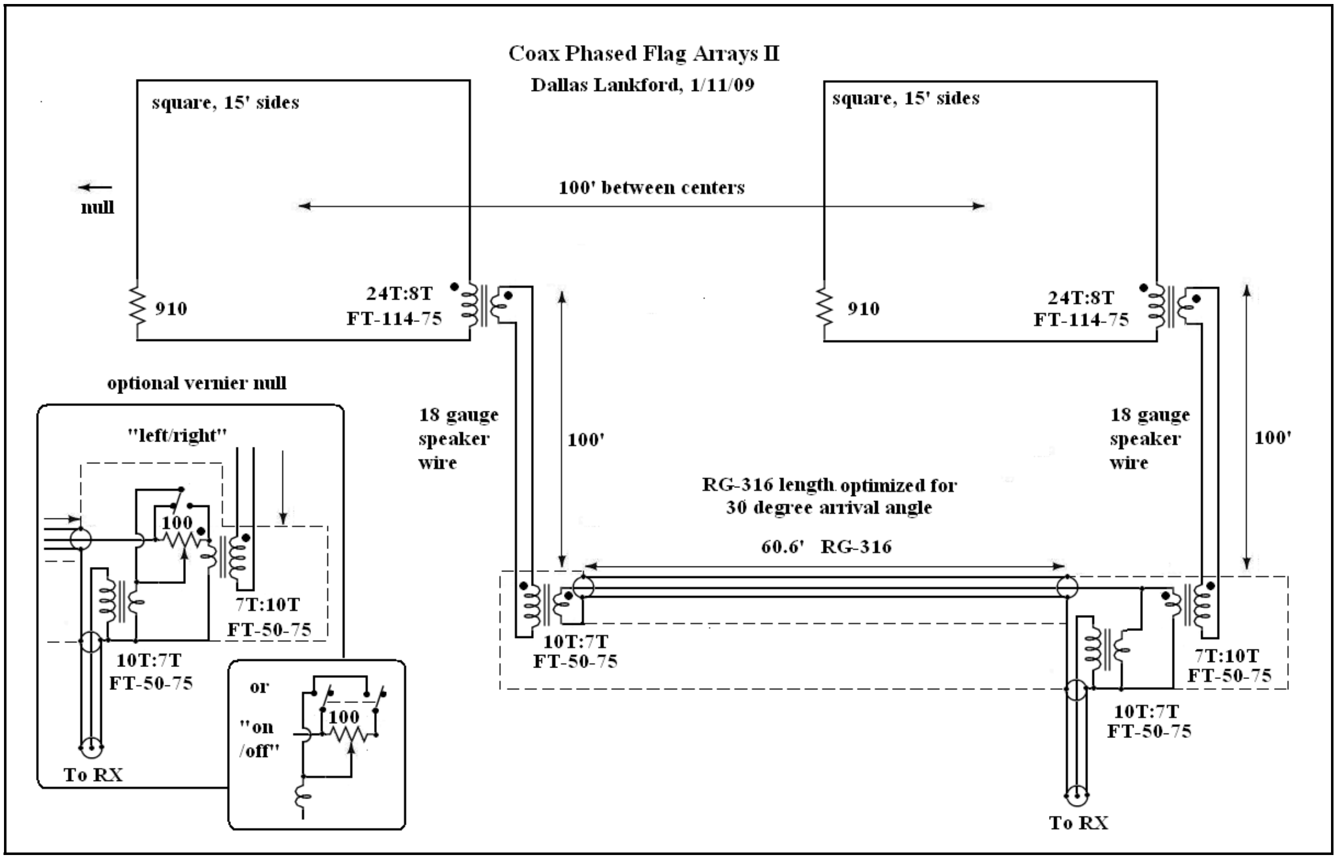
Null Generation

Now if the output of antenna 1 is delayed by the same amount of time T, phase shifted 180 degrees, and combined with the output of antenna 2, without any change in amplitudes of the two combined waves, then in theory the combination of the two resulting signals adds to 0, and a null is formed in the direction θ. Generally the null is not perfect, but nevertheless very good.

Coax Delay

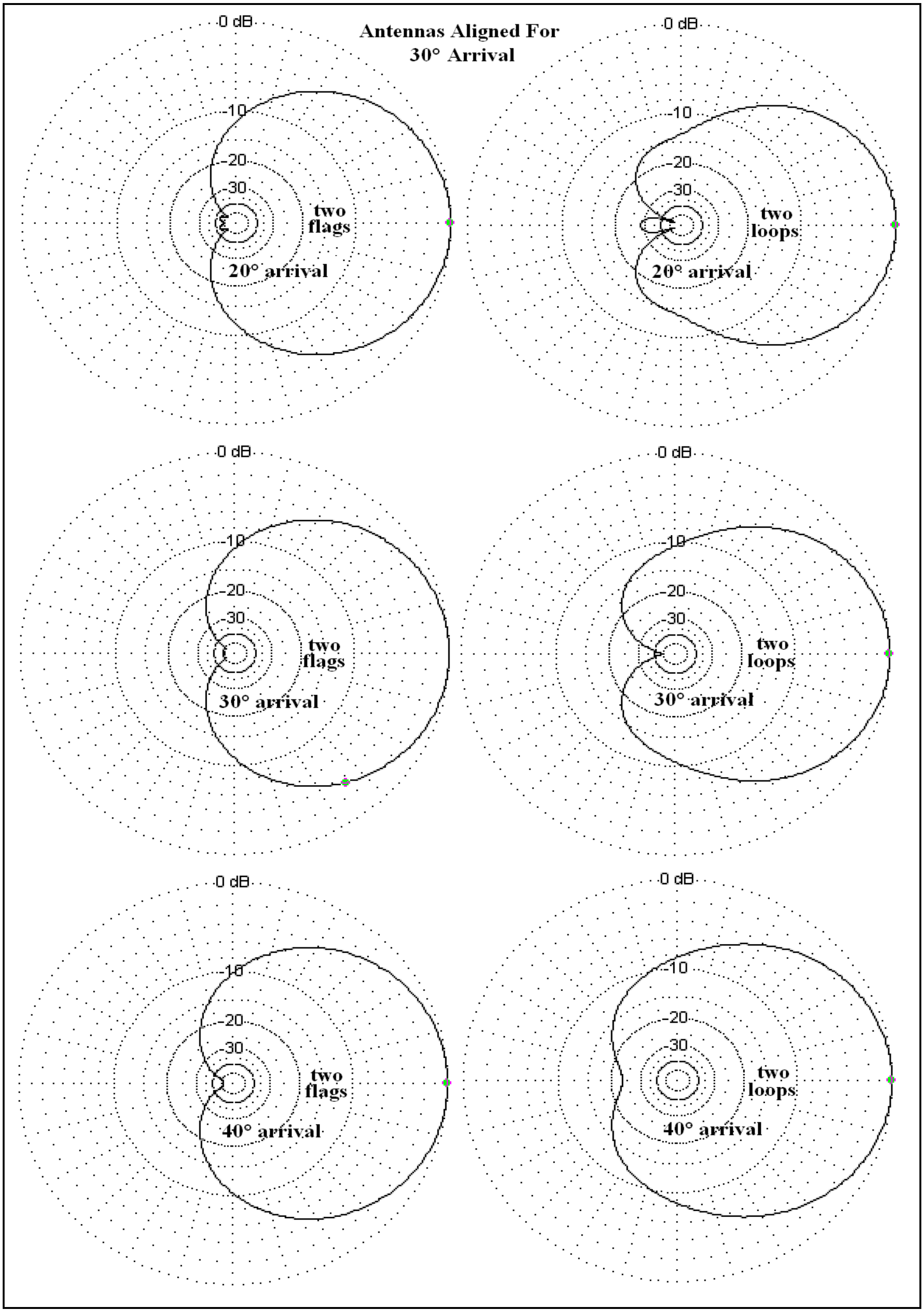
The time delay per meter of electromagnetic radiation in coax is 3.34/VF nS per meter, where VF is the velocity factor of the coax. The velocity factor of coax varies from one type of coax to another, and even from one manufacturer to another. RG-316 is typically more uniform than other kinds of coax, and its VF = 0.7 nominally. Thus the time delay per meter of RG-316 is 3.34/0.7 = 4.77 nS/m. From this it follows that the length L of RG-316 required for a 88.3 nS delay is L = 88.3/4.77 = 18.51 m = 18.51 x 3.28 = 60.7' I used twin lead lead from each antenna to connect the antennas to a fixed phaser consisting of the coax delay line and a combiner. The twin leads also add delay to each of the two signals. Consequently, equal lengths of the same kind of twin lead must be used so that the delays through each of the twin lead segments are identical (and so do not have to be taken into account). This is especially important in the case of speaker wire and zip cord twin lead because their delays are generally not frequency independent. In other words, speaker wire and zip cord do not have well defined velocity factors. I chose 100' lengths of speaker wire because that allows the flags to be located far enough away from my house (where my receiver is located) so that near field man made noise from the house is reduced or virtually eliminated. If your house is especially noisy, you could locate the flags as far away as 150' (or longer) lengths of speaker wire allow, as long as you use equal lengths of speaker wire.

When null depths using the coax phaser with broadband loops (not flags) were not as deep as EZNEC simulation predicted, it occurred to me that the attenuation due to the 60.6' length of RG-316 causes the signal levels through that path to be slightly lower than the signal levels through the other path. So I decided to insert a 100 ohm pot at the junction of the two signal paths to compensate for the two ways that I implemented the 100 ohm pot as shown in the schematic below. Results with the pots were inconclusive, so the pots were deleted. I also implemented a variable coax delay, but it was not useful either and was deleted.

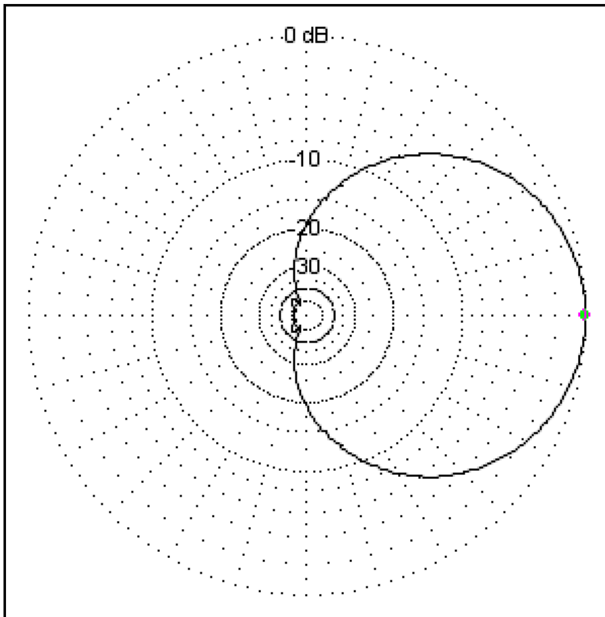


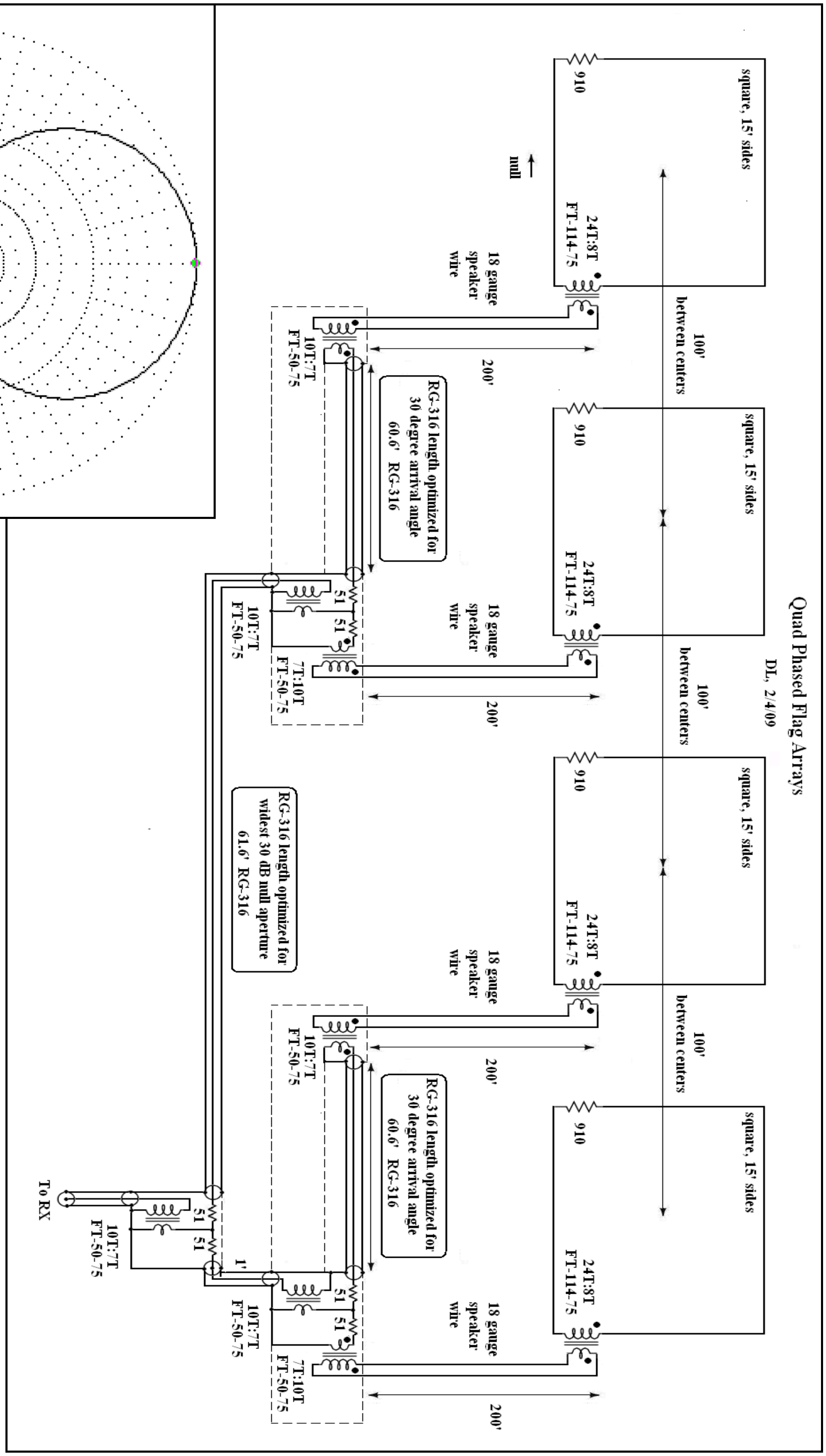
The collection of EZNEC antenna patterns below shows how the nulls of two phased flag compare with the nulls of two phased broadband loops. The loop array was aligned for maximum null depth at a 30 degree arrival angle. Then the flag array was set to the same phase delay as the loop (EZNEC uses phase delay rather than time delay; of course, one can easily convert between phase and time delay). Then patterns for 20, 30, and 40 degree arrival angles were generated and copied. As can be seen from the patterns below, the flag array has a much wider 30 dB null aperture than the loop array, and the flag array clearly has a better vertical null pattern than the loop array. Also, EZNEC simulations show that the rate of change of the loop array vertical pattern with respect to phase is much greater than the rate of change of the flag array vertical pattern with respect to phase, which is another reason why the flag array is fundamentally better than the loop array. The nulls of vertical arrays are similar to the nulls of the loop arrays, so a flag array also has a similarly better null pattern than a vertical null pattern.

The dual flag array above and subsequent dual flag arrays have been set up so that by changing a few jumpers it can be quickly converted back and forth between a flag array and a broadband null array. Listening comparisons at night indicated that the dual flag array nulls were better than the dial broadband loop nulls, but perhaps not as much better as the EZNEC simulations suggest. On the other hand, the dual flag array nulls were generally as good as and in some cases better than two null steered verticals for nighttime signals to the North of my location where the flag array nulls were pointed.



Antennas Aligned For
30° Arrival
0 dB
-10
-20
-30
two
flags
20° arrival
two
loops
20° arrival
two
flags
30° arrival
two
loops
30° arrival
two
flags
40° arrival
two
loops
40° arrival





Quad Flag Arrays

Would you like a phased array which has a 30 dB or more attenuation aperture of 150 degrees? I would. And EZNEC simulation says it is possible. In principle a quad phased flag array will produce the pattern given as an inset above to the quad flag array with details at right. That, of course, remains to be seen. Careless implementation will probably not achieve the desired result. That includes loop planes which are not coplanar, and perhaps excessive lead in signal pickup.

Normally a quad phased flag array would be implemented by spacing the flags 100' between centers, phasing the 1st and 2nd pairs identically (say, for a 30 degree arrival null), and then phasing the two pairs as if they were two single flags spaced twice as far apart (also for a 30 degree arrival null). However, EZNEC simulation shows a disappointing 120 degree 30 dB attenuation aperture for such an array... hardly worth the effort compared to a single pair of phased flags. But a better ZNEC pattern with a 150 degree 30 dB attenuation aperture was obtained when the phasing between the two pairs corresponded to the 100' distance between each adjacent pair of the flags (with the same 30 degree arrival null as before). There is about a 3 dB loss for the "non-standard" phasing compared to the "standard" phasing, but that seems like a small price to pay for an additional 30 degrees of 30 dB or more null aperture.

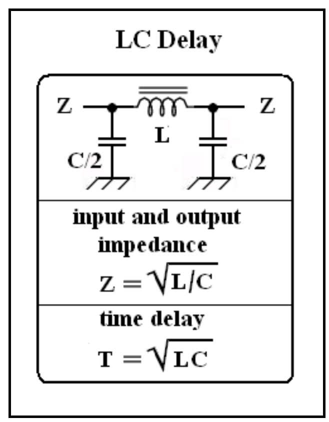
The quad flag array described earlier has not been implemented. Instead, an equivalent delta flag array was implemented because it required only four masts instead of eight. A discussion of the development, implementation, and testing of a quad delta flag array is found in "Phased Delta Flag Arrays" in The Dallas Files .

Appendix

LC Delay, 3/15/09

When I began to consider testing a quad flag array with its potentially better nulls, the prospect of multiple coax delay lines was not attractive. In theory, two capacitors and an inductor can be used to do the same thing as a long length of coax, provided the right power combiner is used. The first time I tried the LC delay circuit with the combiner used for the coax delay circuit, the LC delay circuit was a failure... the nulls were variously unstable or shallow. So a new combiner based on a schematic in the 1992 MiniCircuits RF/IF Designer's Handbook was designed. This combiner is sometimes called a magic T. After the new combiner was tested, the LC delay circuit worked very well with dual flag arrays, and later with dual and quad delta flag arrays.

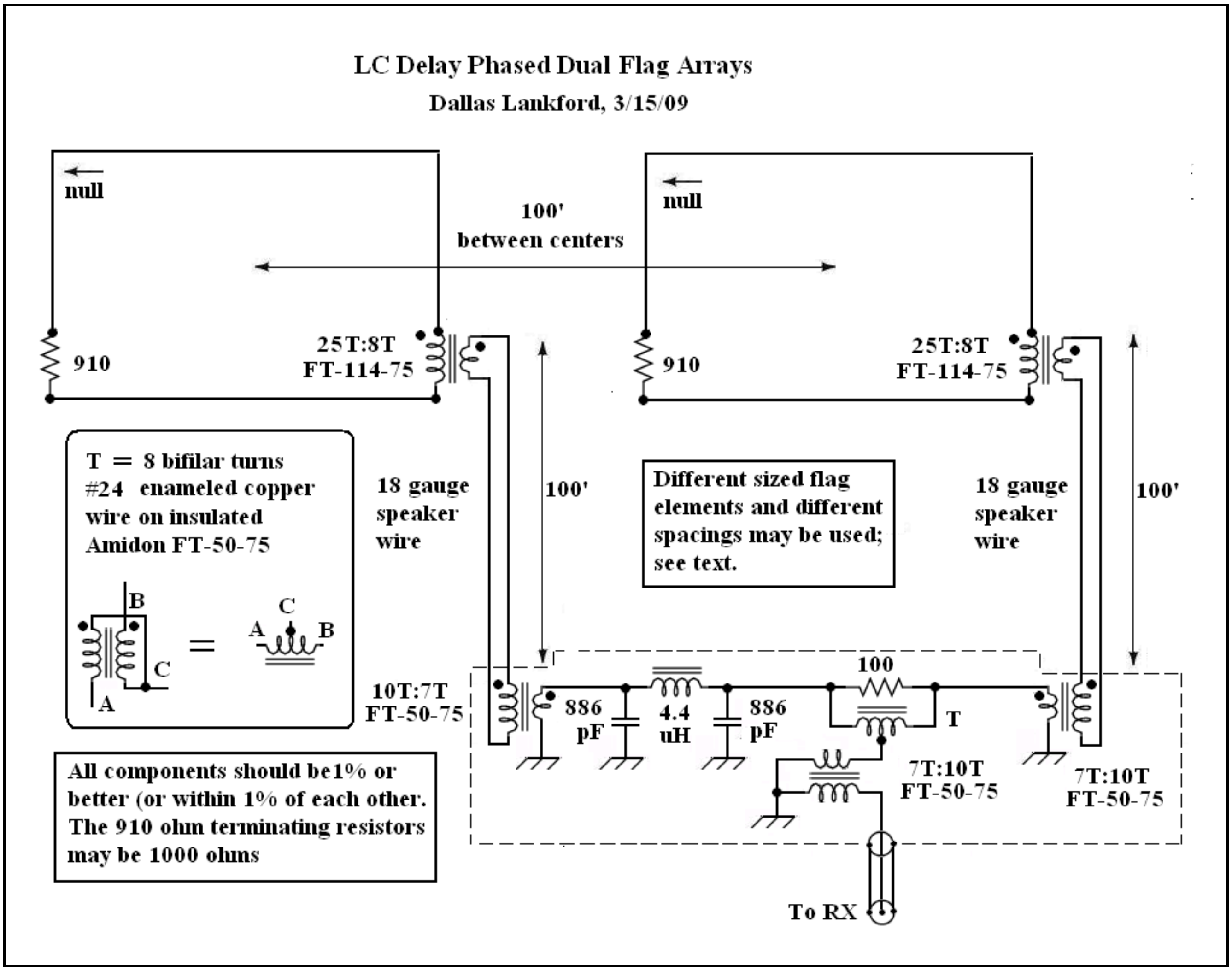
Note that the LC delay phaser has no controls. This is because, as pointed out above, steering the null degrades the splatter reduction of a dual flag or delta flag array. The antenna array is optimized for maximum splatter reduction by orienting the array. It does not matter if the array maximum is not pointed exactly in the desired direction because the beam width is quite broad. The goal is to orient the array so that as many undesired signals as possible are nulled as deeply as possible.



The time delay T in nanoseconds along a ray with arrival angle θ connecting two antennas with centers spaced a distance s apart in feet is T = 1.02 s COS(θ) (nanoseconds), which is a simplification of several formulas above. For a 30 degree arrival angle and 100' spacing T = 88.3 nS, as already shown above. Previously this was converted (above) into a length of coax to provide the necessary delay for phasing. Now, however, the coax length is replaced by an LC delay circuit at right above, which resembles a low pass LC filter. Its input and output impedances Z are the same. For a 50 ohm system, take Z = 50 which gives 2500 = L/C, or L = 2500 C. Taking T = 88.3 x 10^–9, which was calculated above, both sides of the time formula at right are squared, namely 7796 x 10^–18 = LC, after which substitution of 2500 C for L by the equation above gives 7796 x 10^–18 = 2500 C^2, or C = 1766 pF. Thus C/2 = 883 pF, and L = 2500 x 1766 x 10^–12 = 4.4 µH. The capacitors should be mica, and the inductor may be two series 2.2 µH inductors. Or use FT-50-61 toroids and an accurate inductance meter to make the required 4.4 µH inductors. L and C/2 values for other frequencies can be obtained by multiplying the values for 100' spacing by the ratio of the spacings. For example, for 70' spacing, L = (70/100) x 4.4 = 3.1 µH, and C = (70/100)883 = 620 pF. The values of the inductor and capacitors need not be exact provided a capacitor meter is used to match the capacitor values.

The diagram with schematic below shows a dual flag array with LC delay and a combiner based on a schematic in the 1992 MiniCircuits RF/IF Designer's Handbook.

A similar dual flag array has been in operation near my house in North Louisiana since March 2009 (with other phasers since 2008). It works very well with a 10 dB gain push-pull Norton transformer feedback amplifier and 15'x15' flags. At a low noise location it might be worthwhile to double or even quadruple the areas of the flags which would give about 6 or even 12 dB additional sensitivity. The phaser does not need to be changed when the areas of the flags are changed, provided both areas are changed by identical amounts. Additional sensitivity can be obtained by increasing the separation between the centers of the antenna element, but in that case the values of the capacitors and inductors of the phaser must be changed according the the formulas given above. Doubling the separation will improve the sensitivity by about 6 dB, but in that case the null aperture will be slightly decreased. The lengths of the lead ins may be increased up to 200' provided both lengths are identical. If longer lead ins are desired, a push-pull Norton amplifier may be used at the output of the phaser, and then up to 300' of lead in may be attached to the output of the push-pull Norton.



Dual and quad delta flag arrays are described in my article “Phased Delta Flag Arrays” in The Dallas Files .