Flag Theory II

Dallas Lankford, 11/20/2010, rev. 12/9/2010

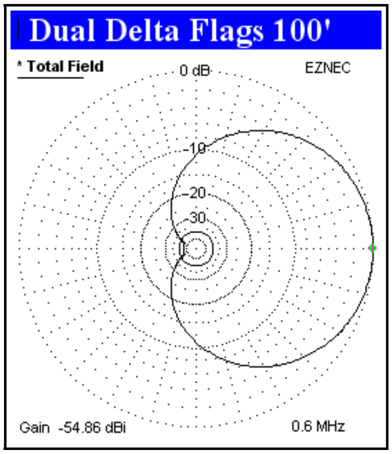
It has been said that dBi means gain relative to an isotropic radiator. But what does that mean? For example, for a receiving antenna with -50 dBi gain, how much preamp gain will be needed between the antenna and receiver? Some insight into such questions can perhaps sometimes be gotten from a certain not so well known formula.

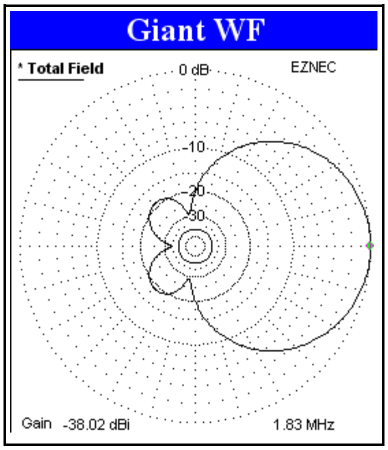
The formula, which is stated in Field Intensity Units by Anonymous and which can be derived from the antenna factor formulas stated by Robert Richards and on the web site http://en.wikipedia.org/wiki/Antenna_factor is:

$V_{dB\mu V} = E_{dB\mu V/m} + G_{dBi} - 20\log(f_{MHz}) + 29.8$ – any additional loss, due to, say, SWR and/or combiners,

where $V_{dB\mu V}$ is the RMS voltage at the receiver antenna input in dB relative to 1 µV, assuming a 50 ohm antenna input, $E_{dB\mu V/m}$ is the field strength RMS voltage in dB relative to 1 µV/m, G_{dBi} is the antenna gain in dBi, and f_{MHz} is the frequency in MHz. In other words, $V_{\mu V}$ and $E_{\mu V/m}$ are in dBµV and dBµV/m respectively.

The two EZNEC plots below provide two examples to illustrate the formula above. The dual delta flag array is one of the delta flag arrays which were tested at Grayland, while the Giant Waller Flag array is NX4D's latest evolution of his and N4IS's remarkable rotatable 160 meter high RDF dual flag phased arrays.





Dual Delta Flag: For a 1 µV/m field at 600 kHz, $V_{\mu V} = 0 - 54.86 + 4.4 + 29.8 = -20.6$ dBµV, or 0.093 µV at the antenna input of a receiver with a 50 ohm antenna input, assuming no other gain or loss.

Giant WF: For a 1 µV/m field at 1.83 MHz, $V_{\mu V} = 0 - 38.42 - 5.2 + 29.8 = -13.8$ dBµV, or 0.20 µV at the antenna input of a receiver with a 50 ohm antenna input, assuming no other gain or loss.

In the first case, for a Perseus receiver having a 1.8 µV sensitivity for 6 kHz bandwidth 10 dB (S + N)/N AM (MW DX), about 26 dB of preamplification would be in order for a man made noise floor of 1 µV, say at Grayland, which is often a low noise site, with most noise man made noise sources in the null of the dual delta flag array. This is consistent with my observations at Grayland where at the low end of the MW band 20 dB of preamplification (which was all I took) seemed inadequate. I do not know enough about CW DXing on top band to knowledgeably discuss that case. Nevertheless, anecdotal information from NX4D suggests that the Giant WF requires no preamplification in an urban area when using a sensitive CW receiver.

For those who prefer dBm units for receiver antenna inputs, the basic formula can be gotten by adding –107 (or subtracting 107) dBm (1 µV) to (from) the right hand side of the original Anonymous formula above:

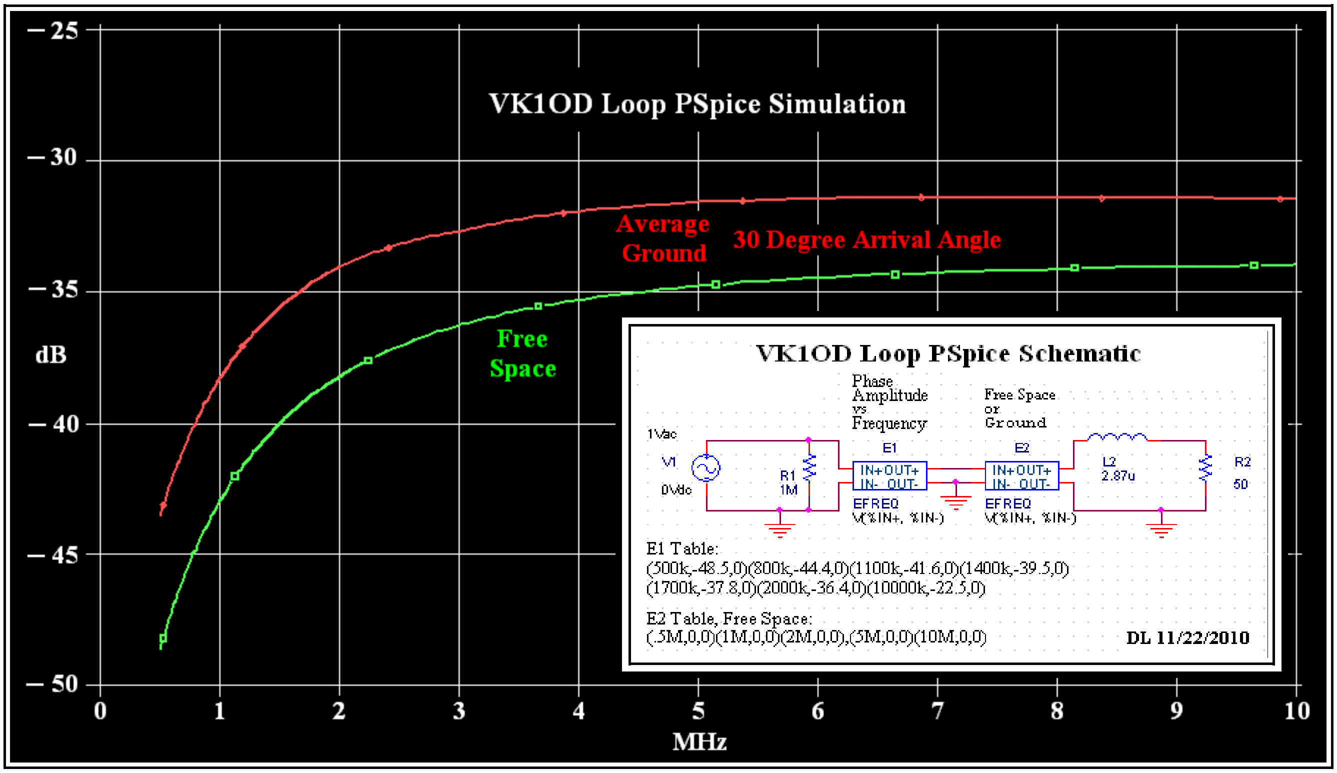
$V_{dBm} = E_{dB\mu V/m} + G_{dBi} - 20\log(f_{MHz}) - 77.2$ – any additional loss.

Thus the Dual Delta Flag and Giant WF example values above are –127.6 dBm and –120.8 dBm respectively.

For antennas and antenna arrays which have no additional loss, the above approach seems entirely satisfactory. However, for antennas and antenna arrays which have substantial additional loss, such as mismatched loops, the above approach does not seem entirely satisfactory because SWR losses must be included, and EZNEC does not give accurate large value SWR losses. I do not know how EZNEC includes combiner loss, so that aspect is unclear to me.

It seemed that if these kinds of antennas could be simulated with PSpice, then high SWR losses might be included in the PSpice simulations.

A small loop for free space was derived by VK1OD directly from physics equations, not from EZNEC, and so it provides a bench mark independent of EZNEC for comparison with the PSpice simulation methods developed here. The VK1OD loop PSpice simulation schematic embedded in the PSpice simulation below provides a simple introduction to the PSpice antenna simulation method for loop antennas which I have developed. The PSpice simulation output is in dBµV units. PSpice antenna simulations are inherently for free space. This means that PSpice simulations are independent of EZNEC only for the free space case. Earth grounds can be included in the PSpice simulations by using EZNEC as will be explained later.

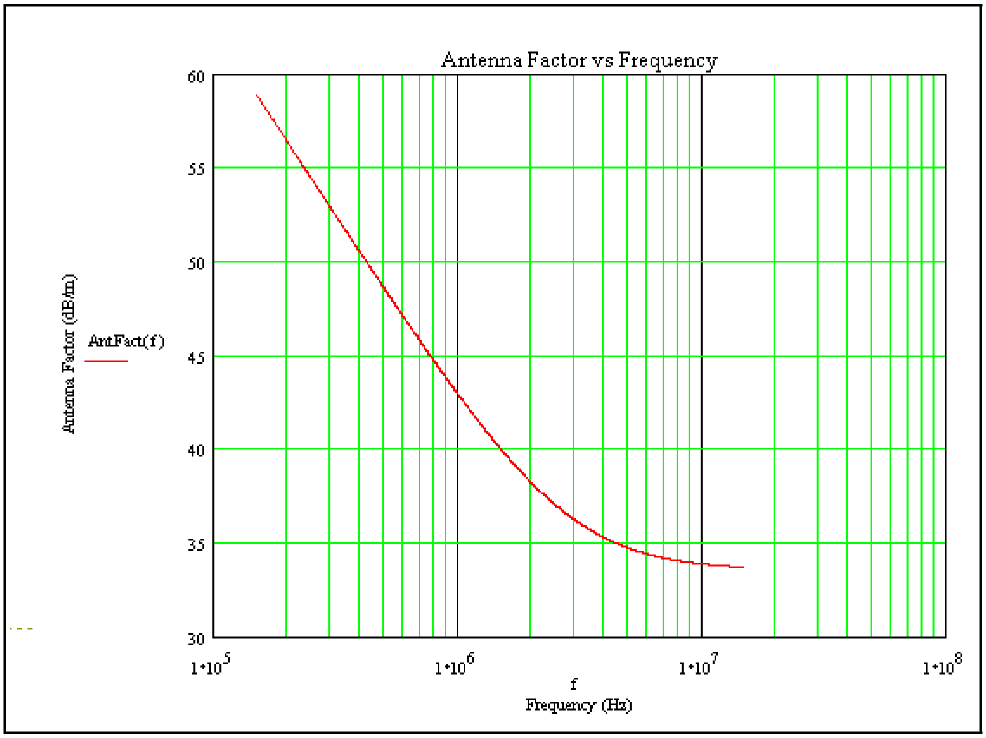


The VK1OD loop was a square single turn loop with area 0.36 square meters. It was connected directly to a 50 ohm antenna input of a receiver, so the loop impedance was not matched. The loop inductance of 2.87 µH was calculated from a formula, not measured. The PSpice schematic models a 2.87 µH inductor in series with a 50 ohm resistor (the receiver input). The open circuit voltage induced in the loop by a passing electromagnetic wave is simulated by a 1 volt RMS sine wave V1 whose amplitude an phase are processed by an PSpice EFREQ part E1 followed by a second PSpice EFREQ part which simulates free space or ground. The 1M resistor R1 is an artifact of PSpice which is required to make PSpice run. Ditto for the three grounds. R1 and the three grounds are not part of the loop antenna simulation, and may be regarded as not being there. In PSpice EFREQ varies an input voltage amplitude an phase with respect to frequency using a linear table of triples (frequency, amplitude, phase). The frequencies of the triples are monotonically increasing; that is, the frequency increases as the points go from left to right. The table need not be depicted as a horizontal line of triples; when the line is broken into several horizontal lines of points, the single linear line of triples is the line gotten by placing the lines of triples beside each other, beginning with the top line, followed by the second line placed to the right of the top line, and so on. The triples may be regarded as points in 3 dimensional space connected in order by line segments which approximate a curve in 3 dimensional space. PSpice apparently curve fits a curve to the points because the traces on the simulation graphs are curves, not a sequence of straight line segments. The points of EFREQ E1 are: (500k,-48.5,0) (800k,-44.4,0) (1100k,-41.6,0) (1400k,-39.5,0) (1700k,-37.8,0) (2000k,-36.4,0) (10000k,-22.5,0) (20000k,-16.4,0). The frequencies are 500 kHz to 10MHz. Units can be k (for kHz) and M (for MHz). I used k throughout for no particular reason. For table E2 I used M throughout for no particular reason. Because the simulation is for a single loop, the phases were all set to 0. For an array of loops, with phase shifters and combiners, the phases would be varied to simulate the delays among the antenna elements of loop array. The amplitude of the open circuit voltage V(θ) induced in a planar loop antenna with respect to the angle θ between the plane of the loop and a passing electromagnetic wave is

$$V(\theta) = 2\pi\ E\ A\ \mathrm{COS}(\theta)\ /\ \lambda\ ,$$

where E is the field strength of the wave in volts per meter, A is the area of the one turn loop in square meters, θ is the angle between the the plane of the loop and the electromagnetic wave, and λ is the wavelength in meters. For example, at 500 kHz, for θ = 0 (maximum loop pickup), V = 2π x 1 x 0.36 x 1 / 600 = 3.77 x 10^– 3, and 20 log(V) = – 48.5 dB. Thus the first triple in the table for EFREQ E1 is (500k,-48.5,0). The table shown for EFREQ E2 is for free space, so all triples have the form (f,0,0); the amplitude change due to ground is 0 because there is no ground, and the phase is 0 for the reason given above. All simulations are for the plane of the loop unless otherwise stated.

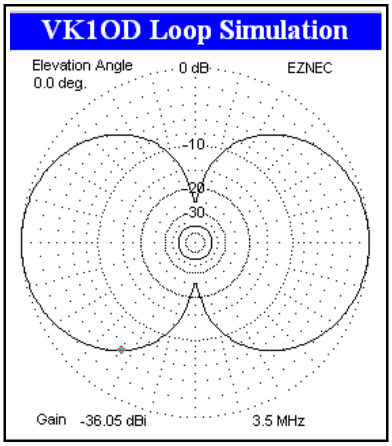
One of Roberts' formulas is $AF = -G_{dBi} + 20\log(f_{MHz}) - 29.8$ from which it follows that $AF = -V_{dBm}$, when $E_{\mu V/m} = 0$. Thus the antenna factor graph in the VK1OD article should be the negative of my PSpice simulation graph above, and it is to within 1 dB at the high frequency end and to within 2 dB at the low frequency end; compare the VK1OD graph below with the PSpice simulation graph above.

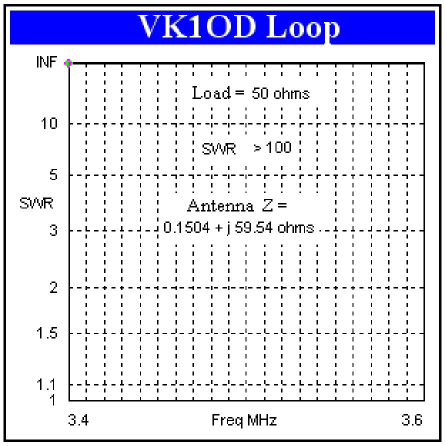


This may be regarded as establishing the validity of the PSpice antenna simulation method for free space.

Earth grounds, good, average, or bad, can often be included in PSpice simulations by using EZNEC as follows. Choose a fixed arrival angle, say 30 degrees. For various frequencies, run EZNEC for free space and for the type of ground desired. Note the difference in EZNEC dBi for each frequency. Construct a EFREQ table based on those differences at those frequencies. In the case of the VK1OD loop, for a 30 degree arrival angle the free space dBi is less than the average ground dBi by about 5.1 dB at 0.5 MHz, 4.7 at 1 MHz, 4.2 at 2 MHz, 3.6 at 3 MHz, 3.2 dB at 5 MHz, and 2.5 dB at 10 MHz. From these values an EFREQ E2 Table for average ground and 30 degree arrival angle is (0.5M, 5.1,0) (1M,4.7,0) (2M,4.2,0) (3M,3.6,0) (5M,3.2,0) (10M,2.5,0). In the case of a loop antenna, no correction is needed for arrival angle when the arriving ray is in the plane of the loop.

The red trace in the VK1OD simulation graph above is for average ground and 30 degree arrival angle.





At left is an EZNEC simulation for the VK1OD loop for free space. Using Anonymous' formula, V = – 16.15 dBμV at 3.5 MHz. This is very different from the – 35.5 dBμV of the PSpice simulation above at 3.5 MHz and from the 35 antenna factor of the VK1OD graph at 3.5 MHz. At right is an EZNEC SWR simulation for the VK1OD loop attached directly to a receiver with a 50 ohm antenna input impedance. The exact value of the SWR is not stated by EZNEC, only that it is greater than 100. It appears that the SWR loss accounts for the difference of about 19 dB between the EZNEC simulation value and the PSpice value and antenna factor value. In general, EZNEC does not seem to provide a way to adjust for SWR loss when the SWR value is extremely high. Only when the SWR is near 1:1 is it easy to correct for; no SWR correction is required in that case.

As stated above, the amplitude of the open circuit voltage induced in a single turn loop antenna by a passing electromagnetic wave is

$$V(\theta) = 2\pi\ E\ A\ COS(\theta) / \lambda.$$

Thus the voltage with respect to time and θ is

$$V(\theta,t) = [2\pi\ E\ A\ COS(\theta) / \lambda]\ COS(\omega\ t)$$

where t is time in seconds, $\omega = 2\pi f$, and f is frequency in Hertz.

If a resistor R is added in series with a small (relative to wavelength) loop, then an open circuit voltage voltage

$$V_E(t) = k(R)\ E\ SIN(\omega\ t + \varphi\ )$$

is added to the loop open circuit voltage where k(R) is a function of R and φ is the phase between $V(\theta,t)$ and $V(\theta,t)$. This kind of antenna is called a flag antenna. If $\varphi = \pi /2$ and $k(R) = 2\pi A / \lambda$, then the open circuit voltage induced in the flag antenna due to the addition of R is

$$V_{flag}(\theta,t) = V(\theta,t) + V_E(t)$$

$$= [2\pi\ E\ A / \lambda]\ [(COS(\theta)COS(\omega\ t) + COS(\omega\ t)]$$

$$= [2\pi\ E\ A / \lambda]\ [(COS(\theta) + 1]\ COS(\omega\ t)\ .$$

Thus if the pattern of a loop antenna can be adjusted in this way, then the pattern is a cardioid. It is fortuitous that in some cases R can be adjusted so that a cardioid or near cardioid pattern results for a particular arrival angle. This is the basis for flag antennas and flag arrays. For maximum pickup, $\theta = 0$, and the amplitude of the flag antenna is seen to be twice the amplitude of a loop antenna of the same size, namely

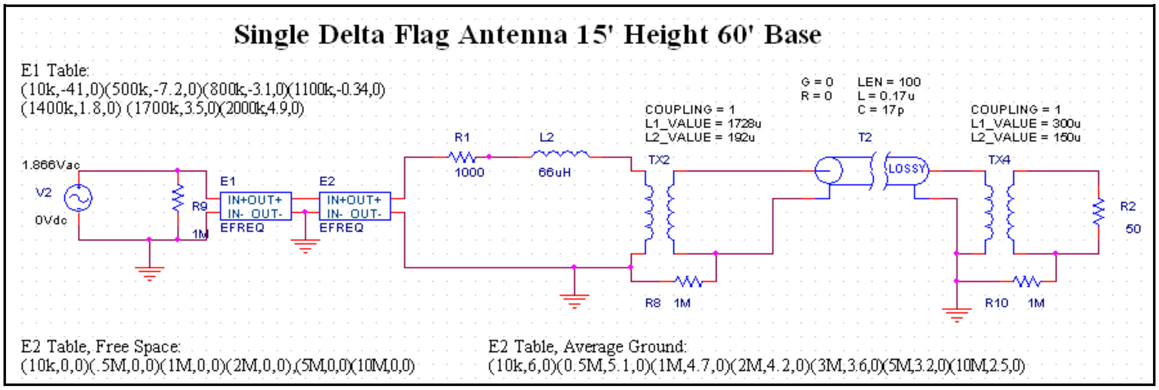
$$V_{flag}(0^\circ,t) = 2[2\pi\ E\ A / \lambda]\ \ \mathrm{COS}(\omega\ t)$$

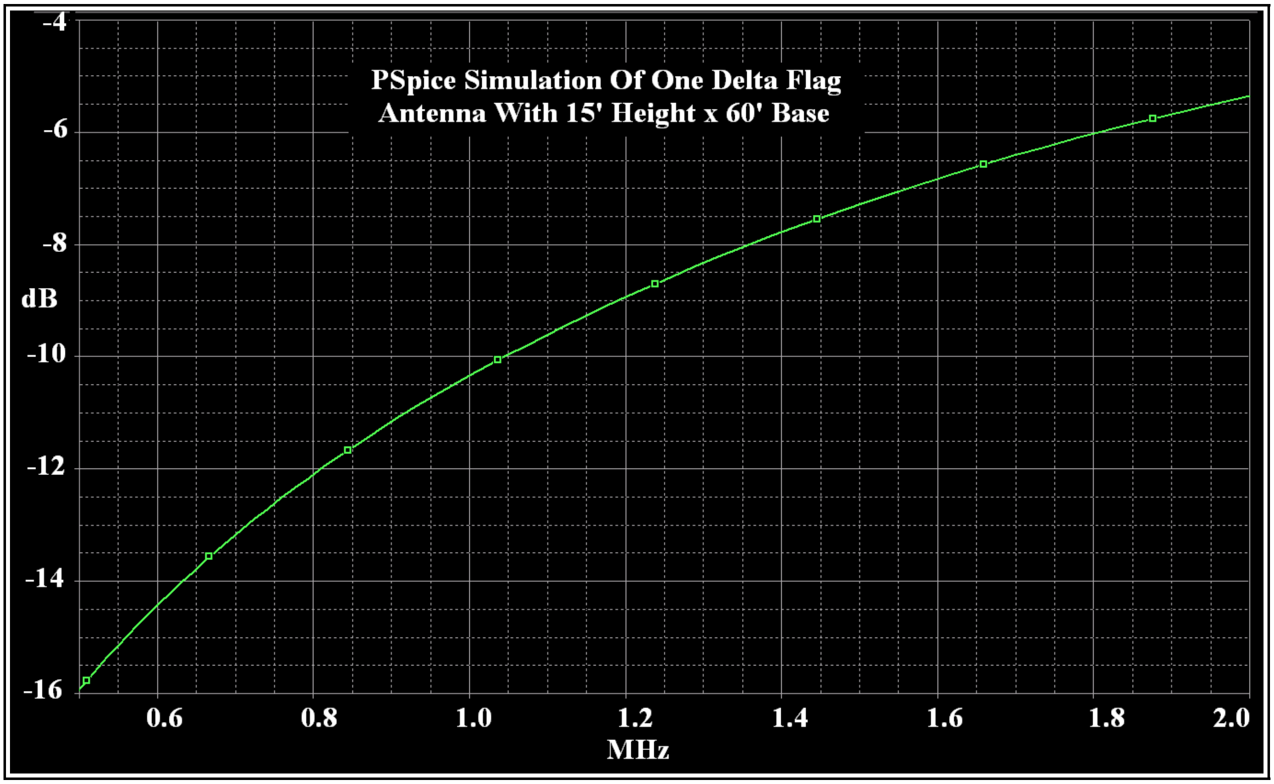
for free space. For a 30 degree arrival angle, $\theta = 30$ degrees, so

$$V_{flag}(30^\circ,t) = 1.866[2\pi\ E\ A / \lambda]\ \ \mathrm{COS}(\omega\ t)$$

the coefficient is COS(30) + 1 = 1.866 in free space. For average ground, EZNEC simulation indicates the coefficient is about the same.

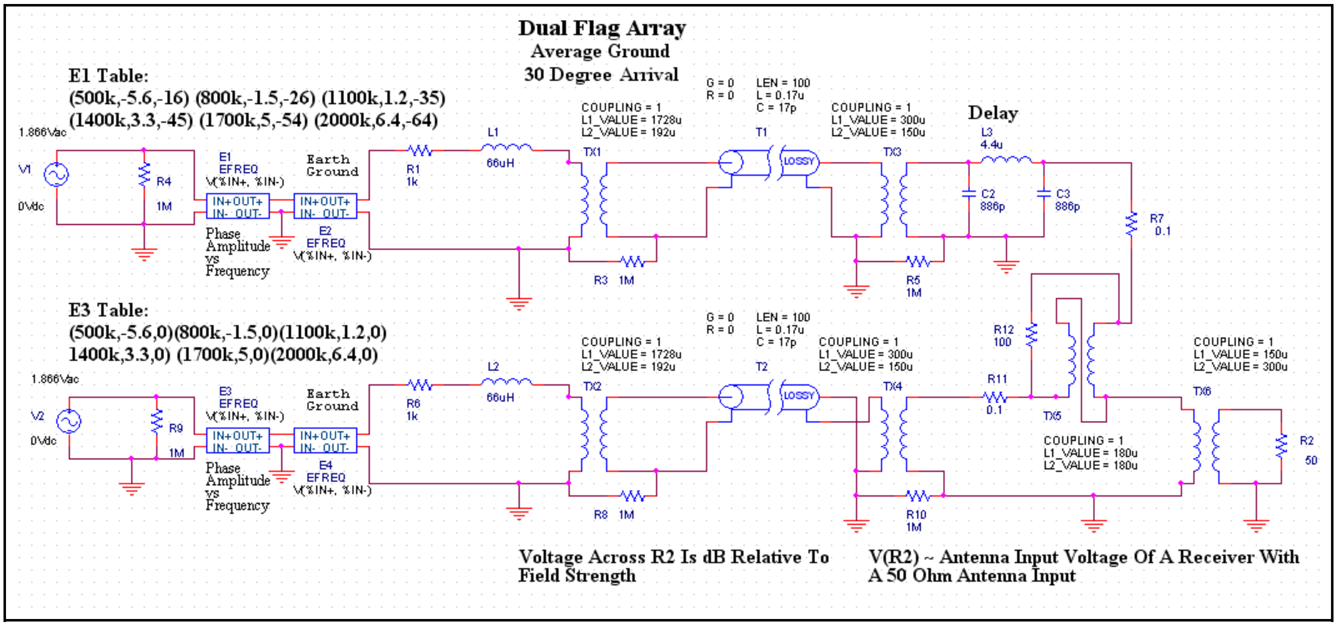
The following is a PSpice schematic for a single delta flag antenna with base 60' and height 15' (41.8 square meters) close to average ground and with a 30 degree arrival angle, followed by a PSpice simulation of this schematic.

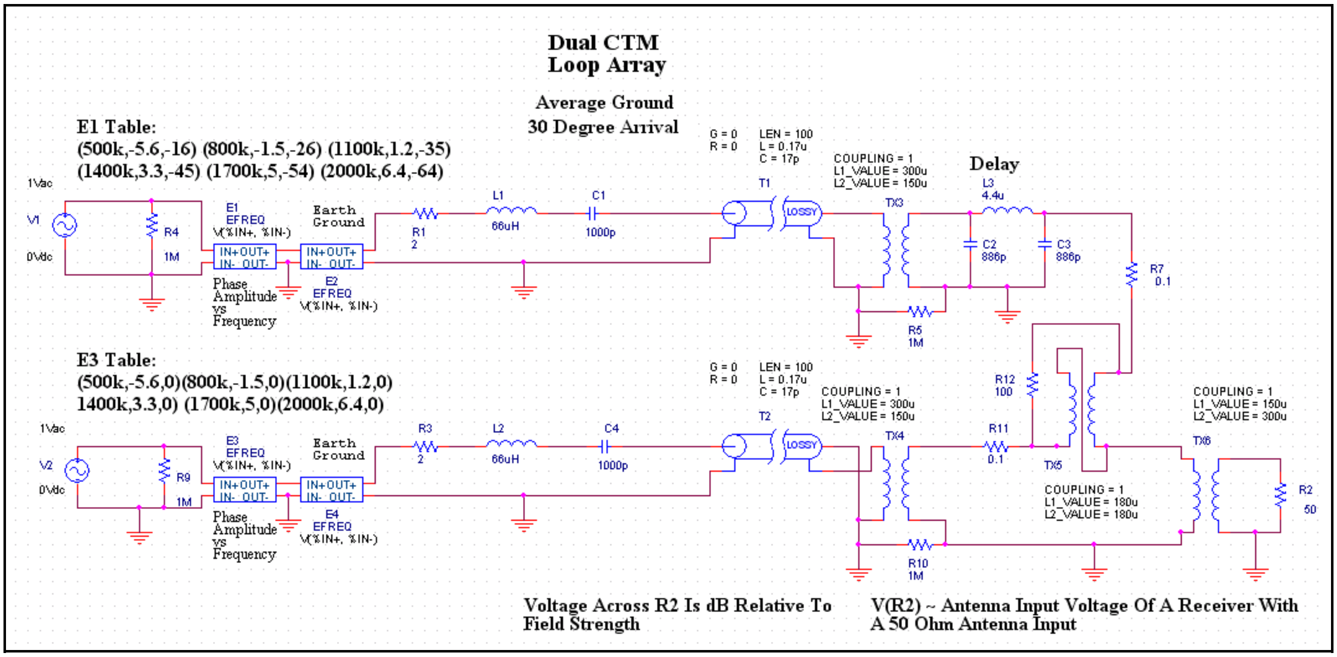




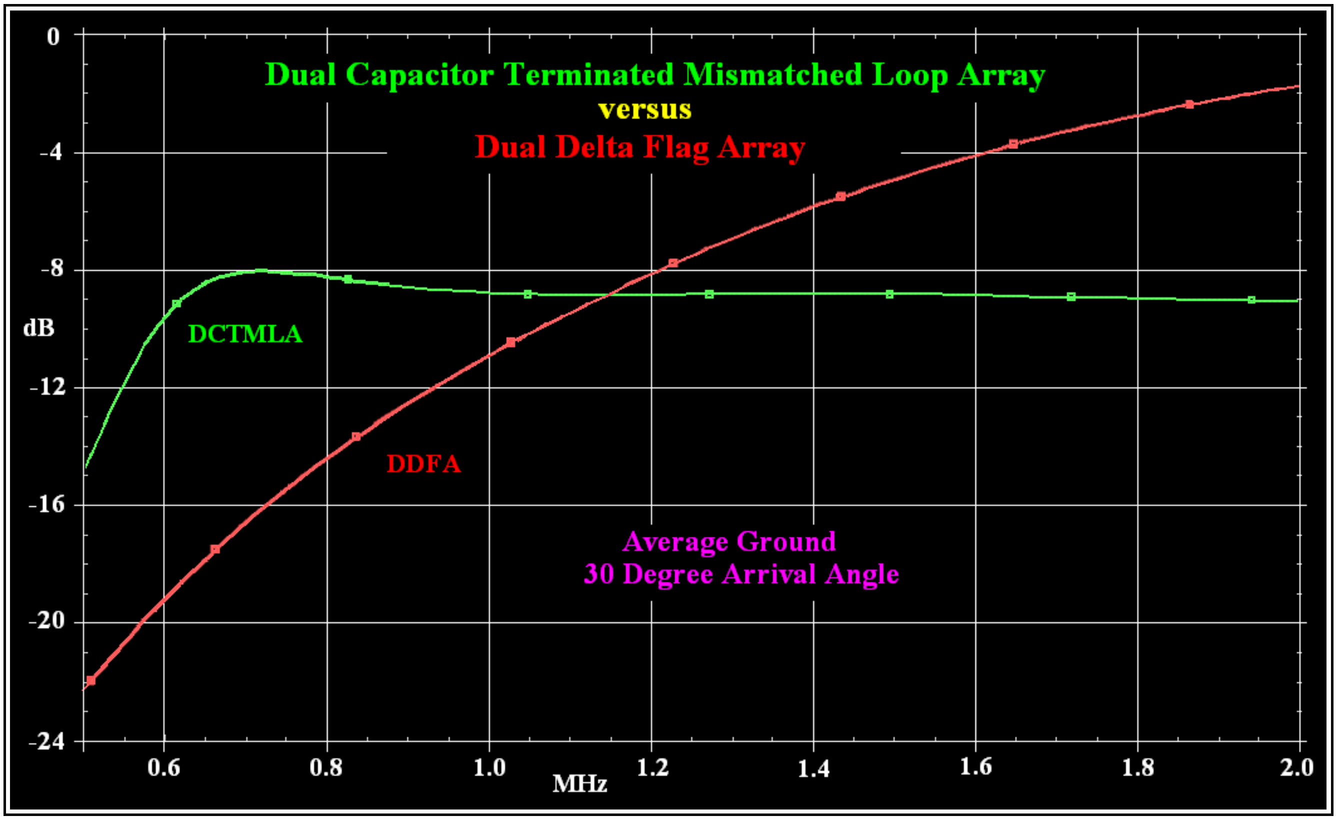
The simulation agrees with EZNEC to within 1 dB, assuming that the single flag antenna which EZNEC models is impedance matched to the receiver (which can easily be done with a broadband transformer). The PSpice schematic already includes impedance matching. This may be regarded as establishing the validity of the PSpice antenna simulation method for average ground and arrival angles in the neighborhood of 30 degrees.

Below is a PSpice schematic which is a model of my 60' x 15' dual delta flag array, followed by a PSpice schematic of a dual capacitor terminated mismatched delta loop array. One of the two main reasons the PSpice antenna simulation methods were developed was to model capacitor terminated loop arrays which are not easy to model with EZNEC due to their high SWR losses.



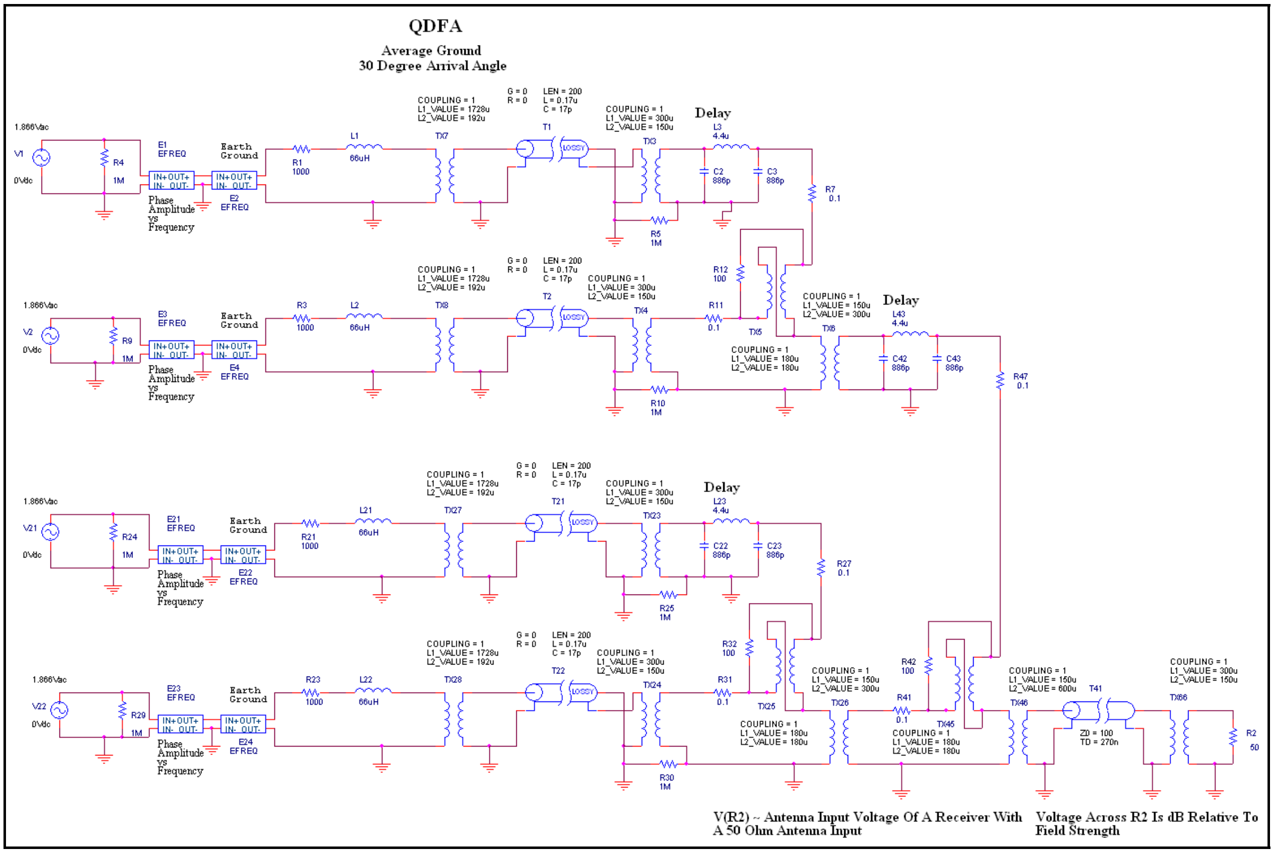


The following figure is a comparison of the dual delta flag array and the dual capacitor terminated mismatched loop array for average ground and 30 degree arrival angle. For an account of the discovery of dual capacitor terminated mismatched loop arrays see "(Broadband) Capacitor Terminated Loop Arrays." Ground wave signal level measurements of a dual capacitor terminated mismatched delta loop array prototype have shown that it has almost as good null depth and null aperture as a dual delta flag array while having about 10 dB gain increase at the lower end of the MW band and about 3 or 4 dB gain loss at the high end of the MW band compared to a dual delta flag array. The more or less flat MW response of a dual capacitor terminated mismatched loop array with appropriately chosen capacitor values appears to be an improvement over the low end MW roll off of a dual delta flag array. A quad capacitor terminated mismatched loop array, as yet untested, may have similar characteristics compared to a quad delta flag array, which may reduce or or eliminate low band MW insensitivity while not significantly degrading high band MW sensitivity. The PSpice simulation of the dual capacitor terminated mismatched array can not be compared with the EZNEC simulation because accurate SWR values were not available from EZNEC. The PSpice and EZNEC dual delta flag array simulations were within 1.5 dB of each other at 600 kHz and within 0.5 dB of each other at 1500 kHz. Because of this and the close agreement of the PSpice and EZNEC simulations of the VK1OD loop, the comparison below is considered valid. The differences between the two simulation traces also agrees reasonably well with measurements of ground wave signal levels at my location in North Louisiana.



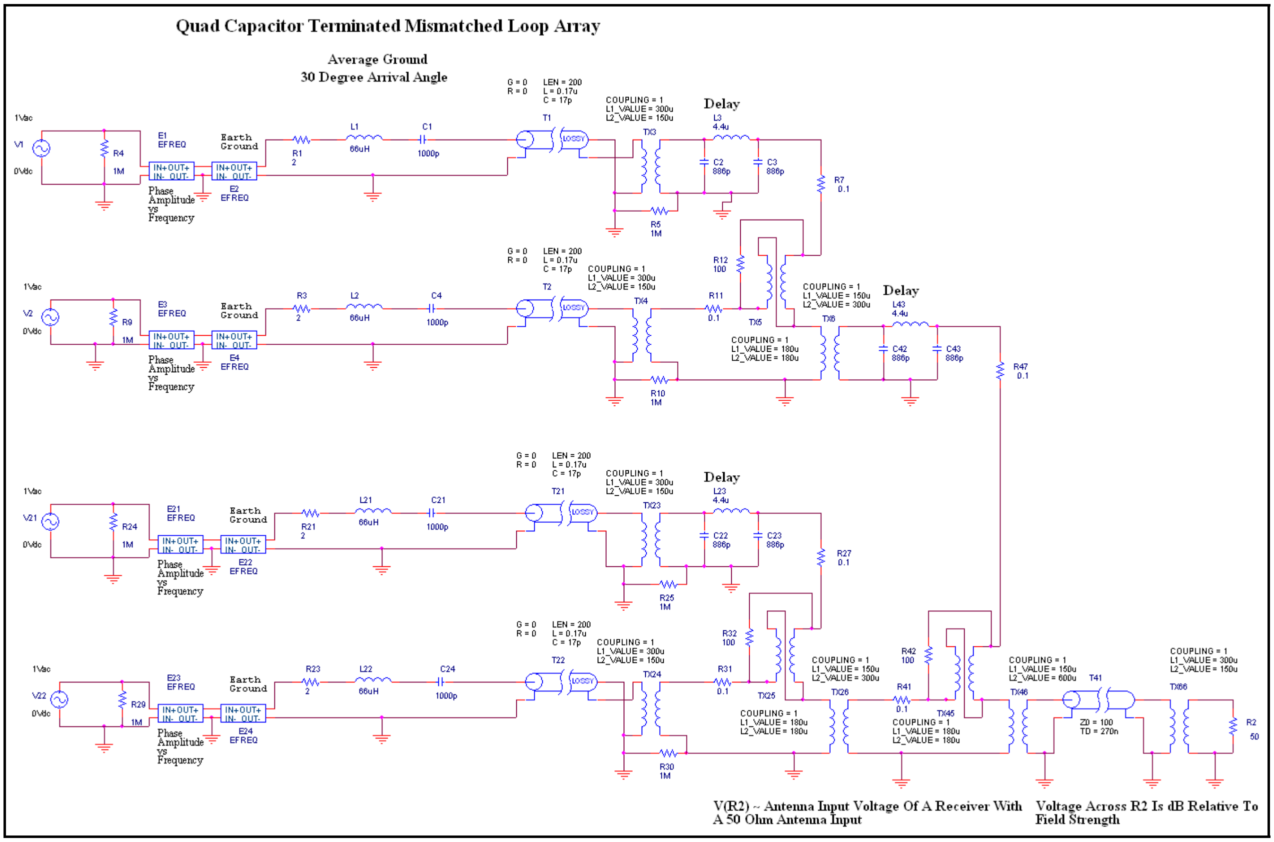
The second main reason the PSpice antenna simulation methods were developed was to model quad capacitor terminated mismatched loop arrays which also are not easily modeled with EZNEC due to their high SWR losses. Moreover, while the dual capacitor terminated mismatched loop array was easy to test in the limited space available, the quad version was not because it requires about 400' of linear space.

Below are PSpice schematics of my quad delta flag array which was tested at Grayland in April 2009 and my yet to be built quad capacitor terminated mismatched loop array. You may magnify them in Adobe Reader for better viewing. Following the PSpice schematics is a figure with PSpice simulations of the two arrays. The QDFA PSpice simulation agrees with an EZNEC simulation of a QDFA with the same dimensions and same 1000 ohm terminating resistors to within 0.5 dB at the high end and to within 2.0 dB at the low end of the MW band. This may be regarded as establishing the validity of the PSpice antenna simulation method for QDFA's and QCTMLA's with 30 degree arrival angle and average ground.



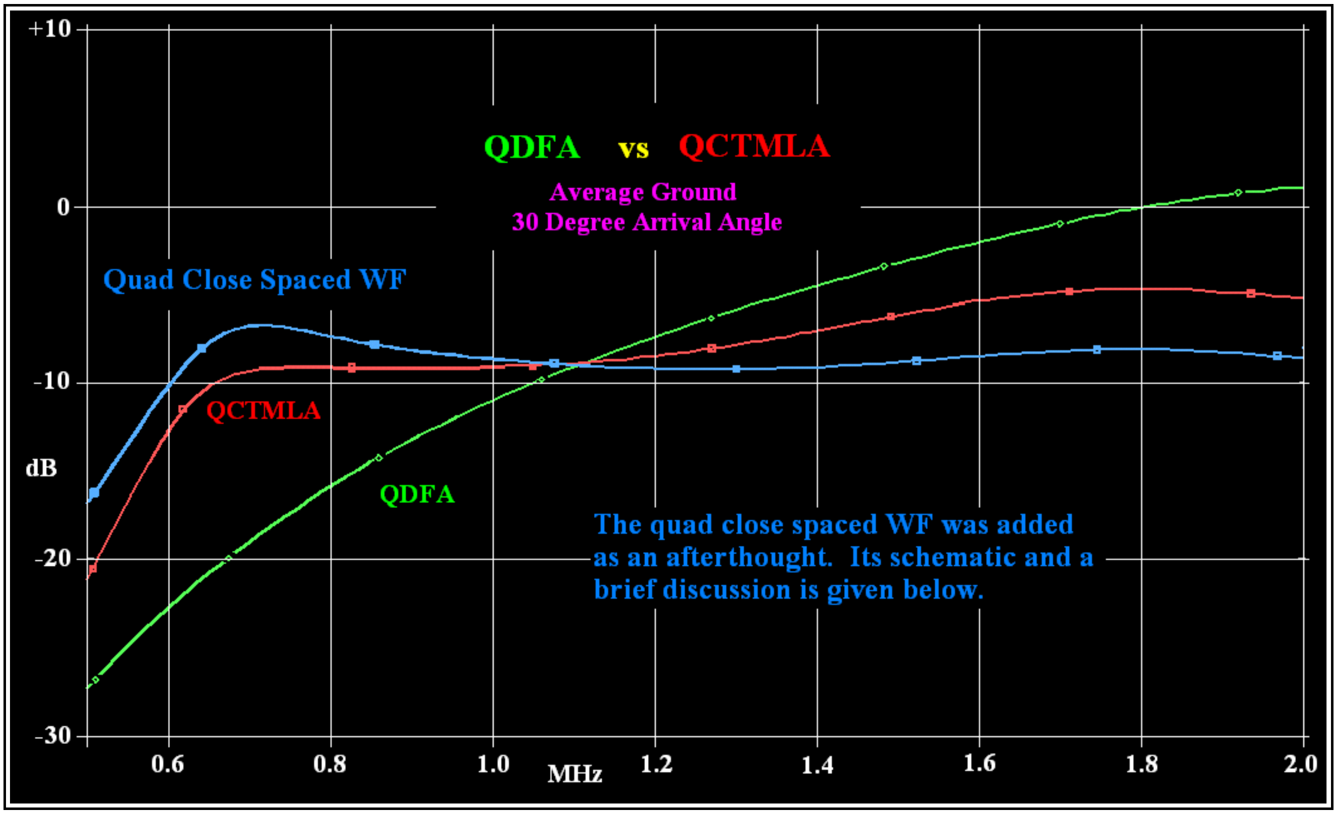
V(R2) -- Antenna Input Voltage Of A Receiver With A 50 Ohm Antenna Input

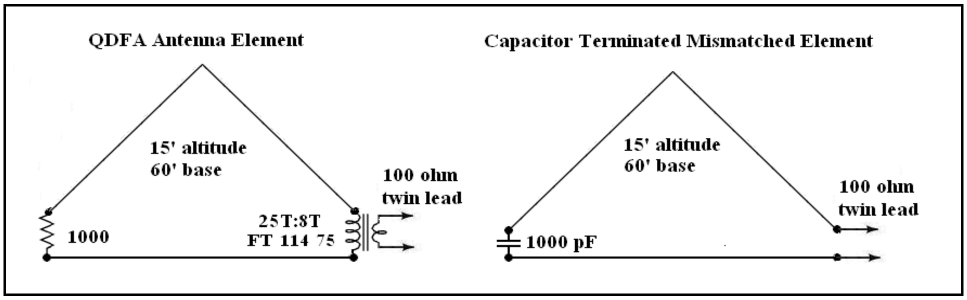
Voltage Across R2 Is dB Relative To Field Strength



V(R2) -- Antenna Input Voltage Of A Receiver With A 50 Ohm Antenna Input

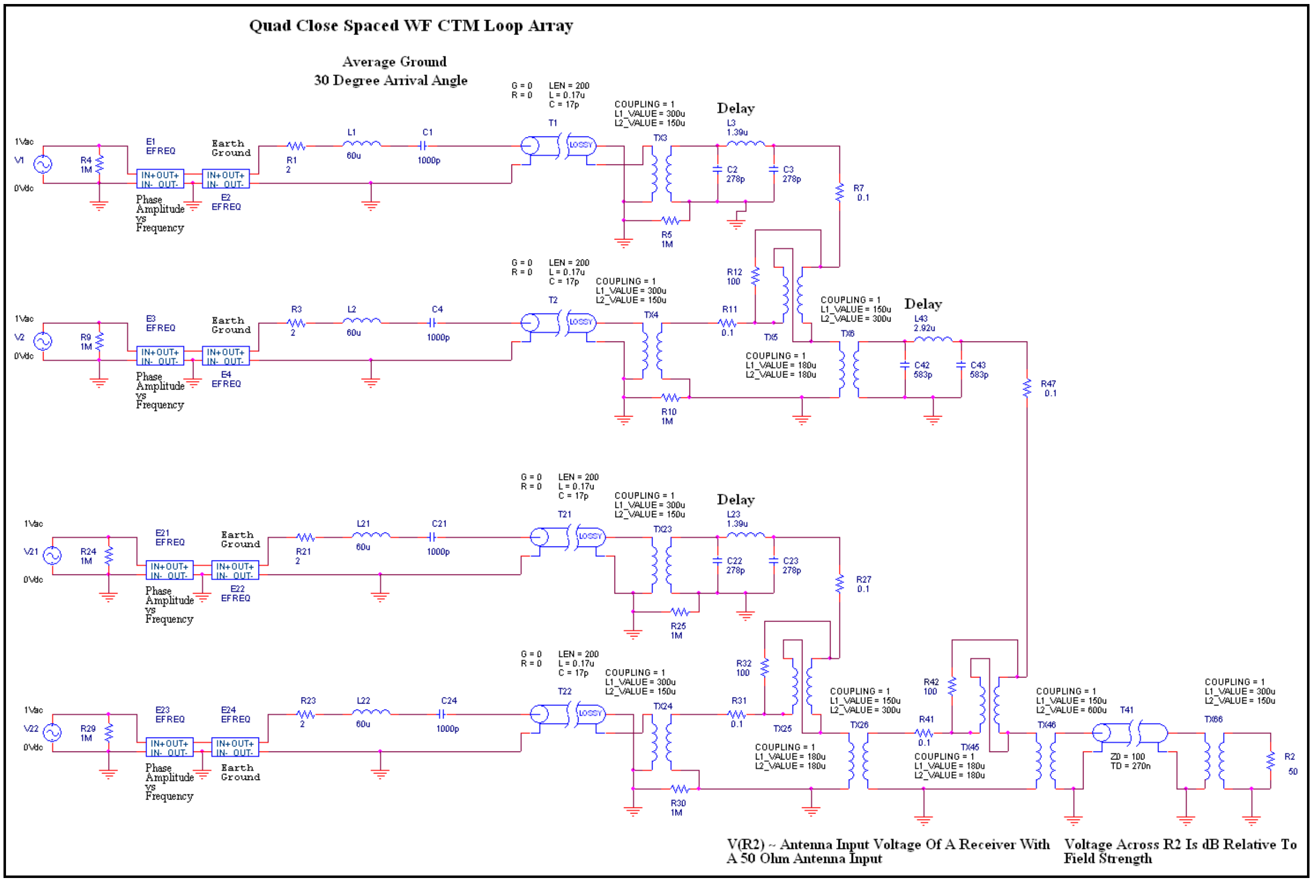
Voltage Across R2 Is dB Relative To Field Strength





The only difference between the QDFA and the capacitor terminated mismatched version is the antenna elements, shown at right. It is trivial to convert a QFDFA to a capacitor terminated mismatched version. Replace the resistors with 1000 pF capacitors, and delete the antenna transformers and connect the 100 ohm twin leads directly to the loop elements. For detailed information about the QDFA see “Phased Delta Flag Arrays.”

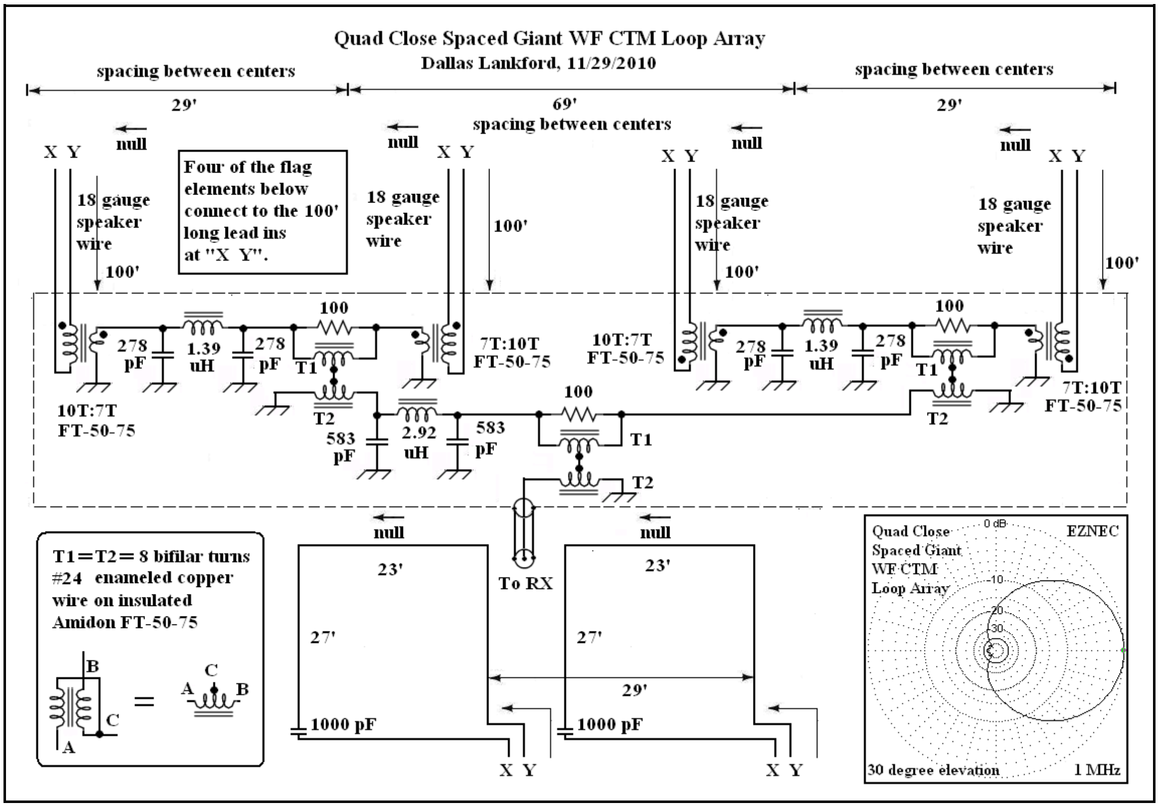
The close spaced giant quad flag array was inspired by various versions of the Waller Flag, the original (NX4D), the big (N4IS), and the giant (NX4D). In the past I had tried and failed to develop quad versions of those dual WF arrays. My usual approach always resulted in poor patterns, not at all like the QDFA pattern that I wanted. While developing these PSpice methods, I tried again, and succeeded. A traditional schematic is given below the PSpice schematic. In the bottom right hand corner below is an EZNEC simulation of this close spaced array. The total length required for the close spaced quad is 150', less than half the 360' length of the original QDFA. Its MW band gain is about the same as the 360' long quad capacitor terminated mismatched loop variant of the QDFA; its low end gain is a little greater, while its high end gain is a little less (see the blue trace in the graph above). Taller masts are required for the close spaced array, and because the elements are rectangular loops, 8 masts will probably be required. Variants with half height rectangle elements, or half height delta elements should have virtually identical patterns, albeit less gain, so a small delta version first will be built first to determine if the pattern is as EZNEC simulations suggest. Close spacing may make the desired patterns difficult, if not impossible, to achieve. We will see.


Quad Close Spaced WF CTM Loop Array

Average Ground
30 Degree Arrival Angle

V(R2) ~ Antenna Input Voltage Of A Receiver With A 50 Ohm Antenna Input

Voltage Across R2 Is dB Relative To Field Strength


Quad Close Spaced Giant WF CTM Loop Array
Dallas Lankford, 11/29/2010

Four of the flag elements below connect to the 100' long lead ins at "X Y".

T1=T2= 8 bifilar turns #24 enameled copper wire on insulated Amidon FT-50-75

Concluding Remarks

The PSpice methods developed here are satisfactory for modeling the forward gain for capacitor terminated mismatched loop arrays, as well as flag and delta flag arrays, and for flag and variant arrays which are too large for easy construction and testing. Other examples, not included in this article, have been simulated with the PSpice methods, including various WF arrays, compared to EZNEC simulations, and it has been found that also in each of these cases PSpice simulation agrees with the equivalent EZNEC simulation to within about 1 dB. This is more evidence that the PSpice methods provide models from which accurate graphs of forward gain versus frequency can be computed for various loop antennas and loop arrays, including resistor terminated flags and delta flags, both single and arrays, capacitor terminated flags and delta flags, both single and arrays, and broadband loops without resistor or capacitor terminations. Additional PSpice simulation methods have also been developed for generating patterns for these kinds of arrays. Some PSpice pattern simulations have been checked against EZNEC pattern simulations, and agreement is good to excellent. The actual patterns of flags and their variants are usually limaçons, not cardioids, which could account for some of the disagreement between the EZNEC and PSpice gain and pattern simulations of this article.