Flag Theory

Dallas Lankford, 1/31/09, rev. 9/9/09

The derivation which follows is a variation of Belrose's classical derivation for ferrite rod loop antennas, “Ferromagnetic Loop Aerials,” **Wireless Engineer**, February 1955, 41– 46.

Some people who have not actually compared the signal output of a flag antenna to other small antennas have expressed their opinions to me that the signal output of a flag antenna has great attenuation compared to those other small antennas, such as loops and passive verticals. Their opinions are wrong. One should never express opinions which are based, say, on computer simulations alone, without actual measurements. The development below is based on physics (including Maxwell's equations), mathematics, and measurements.

Measurements have confirmed that the flag signal to noise formula derived below is approximately correct despite EZNEC simulations to the contrary. For example, EZNEC simulation of a 15' square loop at 1 MHz predicts its gain is about +4 dbi, while on the other hand EZNEC simulation of a 15' square flag at 1 MHz predicts its gain is about –46 dBi. But if you construct such a loop and such a flag and observe the signal strengths produced by them for daytime groundwave MW signals, you will find that the maximum loop and flag signal outputs are about equal. Although somewhat more difficult to judge, the nighttime skywave MW signals are also about equal.

Also, the signal to noise ratio formula below for flag arrays has been verified by man made noise measurements in the 160 meter band using a smaller flag array than the MW flag array discussed below. Several years ago a similar signal to noise ratio formula for small untuned (broadband) loop antennas was verified at the low end of the NDB band.

The signal voltage e_s in volts for a one turn loop of area A in meters and a signal of wavelength λ for a given radio wave is

$$e_s = [2\pi A\, E_s/\lambda]\, COS(\theta)$$

where E_s is the signal strength in volts per meter and θ is the angle between the plane of the loop and the radio wave. It is well known that if an omnidirectional antenna, say a short whip, is attached to one of the output terminals of the loop and the phase difference between the loop and vertical and the amplitude of the whip are adjusted to produce a cardioid patten, then this occurs for a phase difference of 90 degrees and a whip amplitude equal to the amplitude of the loop, and the signal voltage in this case is

$$e_s = [2\pi A\, E_s/\lambda]\, [1 + COS(\theta)] .$$

Notice that the maximum signal voltage of the cardioid antenna is twice the maximum signal voltage of the loop (or vertical) alone. A flag antenna is a one turn loop antenna with a resistance of several hundred ohms inserted at some point into the one turn. With a rectangular turn, with the resistor appropriately placed and adjusted for the appropriate value, the flag antenna will generate a cardioid pattern. The exact mechanism by which this occurs is not given here. Nevertheless, based on measurements, the flag antenna signal voltage is approximately the same as the cardioid pattern given above. The difference between an actual flag and the cardioid pattern above is that an actual flag pattern is not a perfect cardioid for some cardioid geometries and resistors. In general a flag pattern will be

$$e_s = [2\pi A\, E_s/\lambda]\, [1 + kCOS(\theta)]$$

where k is a constant less than or equal to 1, say 0.90 for a “poor” flag, to 0.99 or more for a “good” flag. This has virtually no effect of the maximum signal pickup, but can have a significant effect on the null depth.

The thermal output noise voltage e_n for a loop is

$e_n = \sqrt{(4kTRB)}$

where k (1.37 x 10^–23) is Boltzman's constant, T is the absolute temperature (taken as 290), (Belrose said:) R is the resistive component of the input impedance, (but also according to Belrose:) R = 2πfL where L is the loop inductance in Henrys, and B is the receiver bandwidth in Hertz. When the loop is rotated so that the signal is maximum, the signal to noise ratio is

$SNR = e_s/e_n = [2\pi A\ E_s/\lambda]/\sqrt{(4kTRB)} = [66Af/\sqrt{(LB)}]E_s$.

The point of this formula is that the sensitivity of small loop antennas can be limited by internally generated thermal noise which is a characteristic of the loop itself. Even amplifying the loop output with the lowest noise figure preamp available may not improve the loop sensitivity if man made noise drops low enough.

Notice that on the one hand Belrose said R is the resistive component of the input impedance, but on the other hand R = 2πL. Well never mind. Based on personal on hands experience building small loops, I believe R = 2πL is approximately correct. What I believe Belrose meant is that R is the magnitude of the *output* impedance.

For a flag antenna rotated so the the signal is maximum, the signal to noise ratio is

$SNR = e_s/e_n = 2[2\pi A\ E_s/\lambda]/\sqrt{(4kT\sqrt{((2\pi fL)^2 + (R_{flag})^2)}B)} = [322Af/\sqrt{(\sqrt{((2\pi fL)^2 + (R_{flag})^2)}B)}]E_s$.

Now let us calculate a SNR. Consider a flag 15' by 15' with inductance 24 µH at 1.0 MHz with 910 ohm flag resistor, and a bandwidth of B = 6000 Hz. Then A = 20.9 square meters and SNR = 2.86x10^6 E_s . If E_s is in microvolts, the the SNR formula becomes

$SNR = 2.9\ E_s$.

Any phased array has loss (or in some cases gain) due to the phase difference of the signals from the two antennas which are combined to produce the nulls. This loss (or gain) depends on (1) the separation of the two antennas, (2) the arrival angle of the signal, and (3) the method used to phase the two flags. Let φ be the phase difference for a signal arriving at the two antennas. It can be shown by integrating the difference of the squares of the respective cosine functions that the amplitude A of the RMS voltage output of the combiner given RMS inputs with amplitudes e is equal to to $e\sqrt{(1 - COS(\varphi))}$ where e is the amplitude of the RMS signal, in other words,

$$A = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} 2e^2(\cos(t) - \cos(t+\varphi))^2 dt} = e\sqrt{2}\sqrt{1-\cos(\varphi)}$$

The gain or loss for a signal passing through the combiner due to their phase difference is thus $\sqrt{(1 - COS(\varphi))}$.

Let us consider the best case, when the signal arrives from the maximum direction. For a spacing s between the centers of the flags, if the arrival angle is α, then the distance d which determines the phase difference between the two signals is d = s COS(α). If s is given in feet, then the conversion of d to meters is d = s COS(α)/3.28. The reciprocal of the velocity of light 1/2.99x10^8 = 3.34 nS/meter is the time delay per meter of light (or radio waves) in air. So the phase difference of the two signals above in terms of time is T = 3.34 s COS(α)/3.28 nS when s is in meters. The phase difference in degrees is thus φ = 0.36Tf = 0.36 f x 3.34 s COS(α)/3.28 where f is the frequency of the signals in MHz. If additional delay T' is added (phase shift to generate nulls or to adjust the reception pattern), then the phase difference is φ = 0.36(T + T')f = 0.36f(T' + 3.34 s COS(α)/3.28) . If the additional delay is implemented with a length of coax L feet long with velocity factor VF, then the phase delay is

φ = 0.37f(L/VF + s COS(α))

where f is the frequency of the signal in MHz, s is in feet, L is in feet, and α is the arrival angle.

In the case of the flag array above in the maximum direction there are two sources of delay, namely 60.6 feet of coax with velocity factor 0.70, and 100 feet of spacing between the two flag antennas. The phase delay at 1.0 MHz for a 30 degree arrival angle is thus

$\varphi = 0.37 \times 1.0 \times (60.6/0.70 + 100\ \mathrm{COS}(30)) = 64.1$ degrees.

Thus the signal loss in the maximum direction at 30 degree arrival angle due to spacing and the phaser is $\sqrt{(1 - \mathrm{COS}(64.1))} = 0.75$ or $20 \log(0.75/2) = -8.5$ dB.

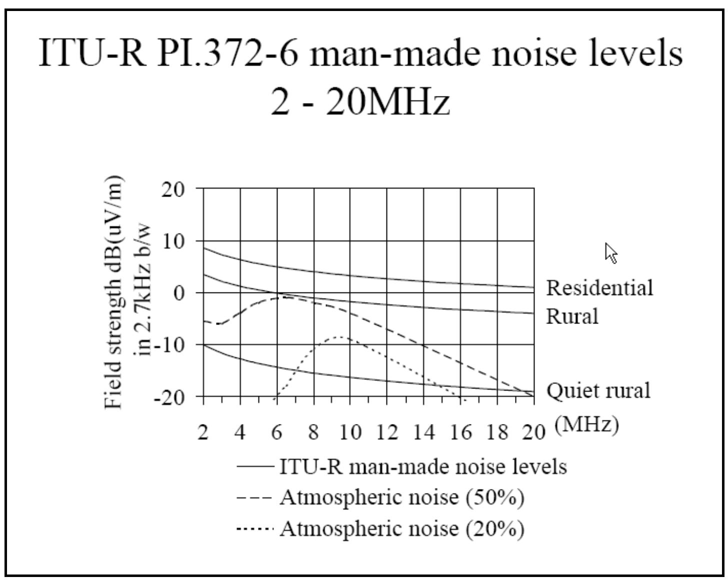
Now comes the interesting part. What happens when we phase the WF array with dimensions and spacing given above? The flag thermal noise output doubles (two flags), and the flag signal output decreases (due to spacing and phaser loss), so the SNR is degraded by 14.5 dB to

$\mathrm{SNR} = 0.55\ E_s$.

So a signal of 1.8 microvolts per meter is equivalent to the thermal noise floor of the flag array.

On some occasions, when man made noise drops to very low levels at my location, it appeared to fall below the thermal noise floor of the WF array. By that I mean that the characteristic “sharp” man made noise changed character to a “smooth” hiss. To determine whether this was the case, I measured the man made noise at my location for one of these low noise events at 1.83 MHz.

To measure man made noise at my location I converted one of the flags of my MW flag array to a loop. The loop was 15' by 15', or 20.9 square meters. I used my R-390A whose carrier (S) meter indicates signals as low as –127 dBm. The meter indication was 4 dB. Then I used an HP-8540B signal generator to determine the dBm value for 4 dB on the R-390A meter. It was –122 dBm. Now the fun begins. The RDF of a loop for an arrival angle of 20 degrees (the estimated wave tilt of man made noise at 1.83 MHz) was 4 dB. So now man made noise after factoring out the loop directionality was estimated as –118 dBm. Field strength is open circuit voltage equivalent, which gives us –112 dBm. I measured MM noise on the R-390A with a 6 kHz BW. The conversion to 500 Hz is –10 log(6000/500) = –10.8, which gives us –122.8 or –123 dBm. The conversion to 500 Hz was necessary in order to be consistent with the SNR above which was calculated for a 500 Hz BW. The loop equation is $e_s = 2\pi A E_s$ /lambda = 0.41 E_s, and 20 log(0.41) = –7.7, rounded off to - 8, so we have -115 dBm, or 0.40 microvolts per meter for my lowest levels of man made noise at 1.83 MHz in a 500 Hz bandwidth. This seemed impossibly low to me until I came across the the ITU graph at right. Man made noise at quiet rural locations may be even lower than 0.40 microvolts per meter at 1.83 MHz. But what about the MW band? From the CCIR Report 322 we find that the man made noise field strength on the average is about 10 dB higher at 1.0 MHz than 1.83 MHz, which would make it 1.26 microvolts per meter at 1.0 MHz. Another 4 dB is added because of impedance mismatch between the R-390A and the loop, which brings man made noise up to 2.0 microvolts per meter at 1.0 MHz. The RDF of one of these flags is about 7 dB, which lowers the man made noise to 0.89 microvolts per meter. Observations in the 160 meter band do not seem to agree exactly with this analysis because flag thermal



noise has never been heard on the MW flag array. But it would not surprise me at all if the flag array thermal noise floor were only a few dB below received minimum daytime man made noise and that measurement error (for example, calibration of my HP 8640B) accounts for the difference between measurement and theory. Also, observations with a flag array having flag areas half the size of the MW flag elements in the 160 meter band do confirm the signal to noise ratio formula; in this case, flag thermal noise does dominate minimum daytime man made noise at my location (0.40 microvolts per meter field strength measured as described above).

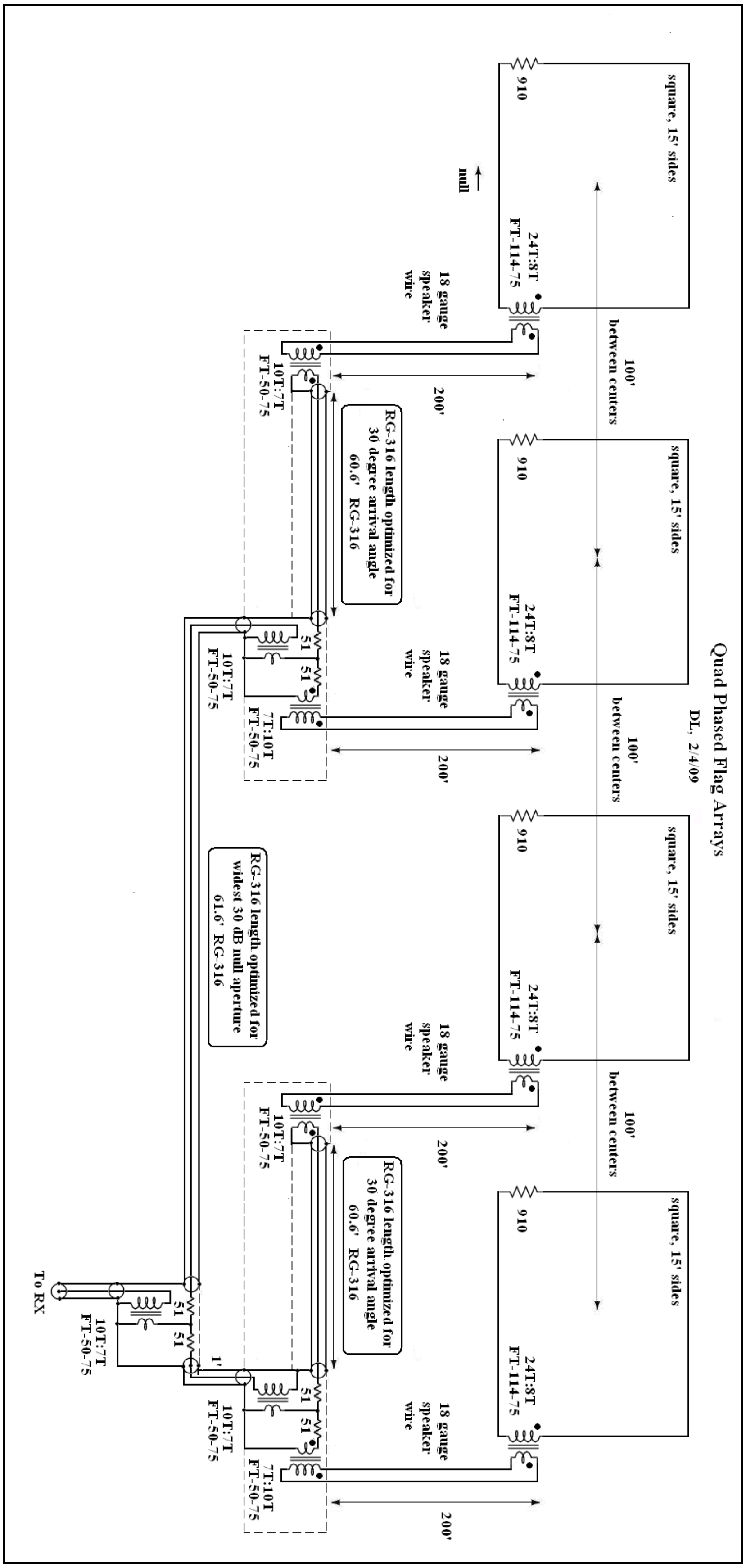
Phaser loss for a dual flag or dual delta flag array varies from about 15.6 to 7.3 dB from about 600 to 1600 kHz respectively, and for a quad flag or quad delta flag from about 35.1 to 13.6 dB. In some cases the loss may be excessive and low noise preamplifiers embedded in the phaser may be required for a satisfactory signal to noise ratio.

The above voltages which are equivalent to signal to noise ratios are open source voltages. They are not the actual signal levels produced by flags or flag arrays. The combiner loss has not been included. The voltage step down for flags to match to 50 ohms is on the order of 3:1, or 10 dB loss, and the combiner at best has 3 dB loss, and perhaps as much as 6 dB loss. Even for sensitive receivers, like the R-390A or my modified IC-746Pro, at least 10 dB of preamplification is needed, and maybe 20 dB would be better.

Because of its theoretically better 30 dB or greater null aperture, a quad flag array for the MW band is to be built and tested. A diagram of the QF array is given in the figure below. It will consist of two flag arrays with sizes, dimensions, and phasing like the MW flag arrays above. The pair of flag arrays is then phased with the same phasing as each pair although the spacing between centers of the pairs is twice the spacing between centers of the two flags which form a pair, namely 200 feet.

Two versions of the quad flag array are given in the following graphics. The second quad array, the narrow diamond version, is a newer array with a better pattern at the low frequency end of the MW band than previous flag and delta flag arrays, and a better SNR because the areas of its flag elements are 4.4 times larger. The first array used coax delay for phasing; the second array uses LC delay for phasing. If long lead in is needed for the first array, then an isolating amplifier like is used for the second array will be needed.

A linear quad delta flag array was tested in April 2009 a few 100 feet from the Pacific Ocean at the Grayland Motel and there it was confirmed that quad delta flag array was a substantially better MW antenna than the beverages and dual loop arrays which have normally been used there. Details of these tests and additional information about flag and delta flag arrays can be found in articles in The Dallas Files at www.kongsfjord.no .



Quad Phased Flag Arrays
DL, 2/4/09
null
square, 15' sides
910
24T:8T
FT-114-75
18 gauge
speaker
wire
100'
between centers
200'
10T:7T
FT-50-75
7T:10T
FT-50-75
51
1'
RG-316 length optimized for
30 degree arrival angle
60.6' RG-316
RG-316 length optimized for
widest 30 dB null aperture
61.6' RG-316
To RX

An Outstanding Narrow Diamond Quad Flag Array

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