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AN-002

Application Note

A COMPARISON OF LOOP AND ADCOCK ANTENNAS FOR SINGLE-FREQUENCY FIXED-SITE DF APPLICATIONS

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SECTION I - INTRODUCTION

This paper discusses the relative performance of loop and Adcock Watson-Watt radio direction finding systems with emphasis on system sensitivity and bearing accuracy. Although the focus of this discussion is on a hypothetical 30 MHz DF system, the general conclusions are applicable at any frequency where loops might be considered.

The discussion begins with a brief history of the use of both types of systems, followed by a brief review of antenna fundamentals as relevant to topics at hand. Loop antennas are then discussed in considerable detail, including an analysis of sensitivity for both tuned and untuned loops. Adcocks are then similarly analyzed. Direct comparisons are then made between the two. Finally, factors influencing bearing accuracy are considered.

Readers wishing to postpone studying the discussions leading up to direct sensitivity comparisons between loops and Adcocks can go to Tables I and II in Section V-E (Adcock Versus Loop Sensitivity Comparison) for a succinct summary of these comparisons. As can be seen in those Tables, the Adcock yields far superior sensitivity. It is also shown that Adcocks offer certain qualitative advantages as well that ultimately yield superior bearing accuracy under practical operating conditions, and in general are a far better choice where operational constraints permit their larger size.

SECTION II - HISTORICAL BACKGROUND

A. LOOPS

The earliest DF systems took advantage of the bi-directional properties of loop antennas to ascertain the azimuth of received signals. These early systems (built during the early part of the 20th century) worked at low and medium frequencies, and eventually into the HF range as vacuum tube technology improved. Perhaps the most famous of these DF systems was the Bellini-Tosi system used during the First World War. These loop-based systems were particularly applicable for low frequency operation, since phased-array systems such as Adcocks (even if they had existed at that time) would have been far too large for many applications.

B. ADCOCKS

A major drawback of loop antennas for DF applications observed during that period was the so-called "night effect". Although loops generally worked reasonably well during the day, bearings obtained during hours of darkness exhibited large and violent fluctuations, resulting in major bearing errors and uncertainty. This night effect was eventually correctly attributed to the fact that night-time reception was predominated by sky-wave propagation, resulting in horizontally-polarized signal components which caused severe distortion of the loop gain patterns (and thus major bearing errors).

F. Adcock of Great Britain solved this problem by designing a phased-array bi-directional antenna employing two spaced vertical aerials with difference-phased outputs. Although similar to the loop antenna in that the same bi-directional figure-of-eight azimuthal gain pattern was achieved, this vertically-polarized "Adcock" aerial pair was nearly impervious to bearing errors induced by horizontally-polarized signal components. Adcock patented his design in 1919 (British Patent No. 130490), and the Adcock antenna array was hailed as a major step forward in DF technology. The Adcock remains the best available narrow-aperture DF antenna to this day.

C. WATSON-WATT DF SYSTEM

The Watson-Watt, or "twin-channel" DF system was also invented during this same period by Sir R. A. Watson-Watt, also of Great Britain. The Watson-Watt system comprised two orthogonally-oriented co-located bi-directional antennas having figure-of-eight azimuthal gain patterns with circular lobes. In practice, these antennas were either loops or Adcocks. The output of each bi-directional array was then fed to its own radio receiver. The outputs of the two receivers were then in turn fed to an indicating device (at first, a two-phase mechanical pointer was employed, later to be replaced by a CRT display during the 1930s).

Since such a system inherently suffered from a 180 degree ambiguity, a third omni-directional "sense" antenna (co-located with the two bi-direction arrays) was added to resolve this ambiguity. This sense antenna was usually a vertical rod, and fed a third receiver.

Since having three receivers was expensive, and considerable difficulty was encountered in maintaining gain and phase tracking, a modulation scheme was eventually devised to encode the signal from each of the two bi-directional arrays with different audio tone frequencies so that only one receiver was required. Most modern-day Watson-Watt DF systems employ this tone encoding scheme to permit the simplicity and economy of using a single receiver instead of three. A few high-end Watson-Watt DF systems employing the original three-receiver design concept are still available, although their cost is prohibitive for most commercial applications. All RDF Products DF systems employ this latter "single-channel" Watson-Watt technique, and can be used with either loop or Adcock DF antennas.

A more detailed discussion of the basics of the Watson-Watt DF technique can be found in RDF Products Web Note WN-002 ("Basics Of The Watson-Watt DF Technique"). WN-002 can be downloaded from the RDF Products Web Site and is also available on the RDF Products Publications CD.

D. MODERN APPLICATIONS OF LOOPS AND ADCOCKS

Although the invention of the Adcock was considered to be a major technological improvement over loops, Adcocks did not entirely supplant loops, and both types of antennas are widely used today. As a general rule, where space constraints are not a problem, Adcocks are highly preferred due to their superior sensitivity and bearing accuracy. At lower frequencies where Adcocks become too large and cumbersome, loops must be employed in the interest of compactness, even though significant (and often serious) performance trade-offs must be accepted.

SECTION III - ANTENNA FUNDAMENTALS

A. OVERVIEW

In this Section, certain antenna fundamentals are reviewed for the convenience of the reader, even though it is assumed that the reader already has a certain familiarity with antenna basics. Certain additional antenna concepts relevant to DF antennas are also discussed.

B. BASIC RECEIVING ANTENNA MODEL

1. GENERAL MODEL

A simplified general electrical model of a receiving antenna is illustrated in Figure 1 below. As can be seen, the model comprises a voltage generator, radiation resistance, series reactance, loss resistance, and load resistance. These elements of the model are discussed in the following paragraphs.

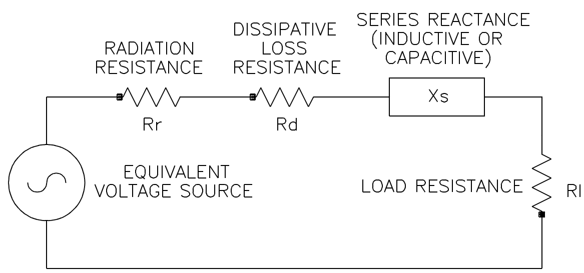

FIGURE 1 – SIMPLIFIED RECEIVING ANTENNA MODEL

2. VOLTAGE GENERATOR

The *voltage generator* represents an equivalent ideal voltage source that accounts for the voltage induced in the antenna when it is illuminated by an electromagnetic field. The magnitude of the voltage generated depends upon the intensity of the illuminating field and the electrical characteristics of the antenna itself.

3. RADIATION RESISTANCE (Rr)

The concept of *radiation resistance* is best understood by momentarily viewing the model illustrated in Figure 1 as that of a transmitting antenna. Since a transmitting antenna in effect is a transducer that converts power from the transmitter (in this case represented by the voltage generator) to electromagnetic radiation, the radiation resistance represents the real component of the "load" through which RF current passes to generate useful output. By the theorem of reciprocity, this radiation resistance must also exist in a receiving antenna.

4. SERIES REACTANCE (Xs)

In the general case, a *series reactance* exists that must be tuned out (offset by an equal but opposite reactance) if maximum power is to be delivered to the load resistance. For naturally resonant antennas, this series reactance is equal to zero. Quarter-wave monopoles and half-wave dipoles are examples of such naturally resonant antennas.

5. LOSS RESISTANCE (Rd)

Loss resistance is an equivalent resistance that models any dissipative loss associated with the antenna. Loss resistance can often be neglected for low-Q naturally resonant antennas, but is of more concern for small high-Q antennas. This loss resistance is caused by ohmic conductor resistance of the antenna itself, as well as the resistance of any associated antenna tuning networks. Signal power dissipated in the loss resistance is converted into heat.

6. LOAD RESISTANCE (Rl)

Since an antenna must ultimately deliver power into a load in order to be useful, the load is represented by an equivalent *load resistance*.

C. POLARIZATION

The *polarization* of an electromagnetic field refers to the orientation of the *electric* lines of force of that field. If these electric lines of force are vertical, the field is said to be *vertically-polarized*. Since most loops and Adcocks are designed to respond to vertically-polarized fields, vertical polarization will be assumed in all the discussions that follow.

D. ELECTRIC FIELD STRENGTH

Electric field strength is the measure of the intensity of an electric field and is expressed in *volts/meter*. An electric field strength of 1 volt/meter is defined as the field intensity required to produce an open-circuit output voltage of 1 volt from a 1 meter long aerial having uniform current distribution along its length. An aerial with such uniform current distribution is known as a *current element*. The current element is actually a hypothetical construct unachievable in practice since current distribution is never uniform along a linear conductor. The concept of the current element is very useful, however, in discussions relating to electric field strength and antenna sensitivity. Overall DF system sensitivity is usually expressed in terms of the number of microvolts per meter (uV/m) electric field strength required to produce a bearing with some minimum threshold signal-to-noise ratio.

For RDF Products DF systems, this minimum signal-to-noise ratio threshold is specified as 20 dB using a receiver IF bandwidth of 15 kHz and a bearing integration time of 200 milliseconds. This 20 dB signal-to-noise ratio corresponds to 6 degrees RMS bearing jitter.

Typical DF sensitivity varies from a fraction of a uV/m for the most sensitive systems to dozens of uV/m for insensitive systems. A word of caution is in order here. When comparing DF system sensitivity specifications among systems provided by different vendors, it is very important to know the specified signal-to-noise ratio threshold and bearing integration time, since sensitivity can be "improved" by specifying unrealistically low signal-to-noise ratios and unrealistically high bearing integration times. The 6 degrees RMS bearing jitter and 200 millisecond integration time criteria were established by this author many years ago on the basis of experimental trials designed to determine a conservative minimum bearing signal-to-noise ratio necessary and maximum bearing integration time allowable for tracking a pulsed vehicle beacon.

E. ANTENNA EFFECTIVE HEIGHT (He)

Antenna *effective height* is the ratio of the antenna open-circuit output voltage to the magnitude (in volts/meter) of the electric field illuminating that antenna. In mathematical terms, effective height is expressed by the equation

$$He = Eo/Fs \tag{1}$$

where He is the effective height in meters, Eo is the antenna open-circuit output voltage, and Fs is the magnitude of the electric field strength in volts/meter. Effective height is a very useful antenna figure-of-merit that is used to calculate antenna open-circuit output voltage when illuminated by an electric field of known strength. In the case of the 1-meter long current element discussed above, since a 1 volt/meter electric field strength produces a 1 volt open-circuit output, the effective height is 1 meter (the same as the physical height).

In general, the effective height is less than the physical height. For electrically short monopoles or dipoles, for example, effective height is very nearly half the physical height.

By simply rearranging equation (1) above, effective height can be used to predict antenna open-circuit output voltage when the antenna is illuminated by an electric field of known strength. Solving for Eo the equation becomes

$$Eo = HeFs \tag{2}$$

where all variables are as defined in equation (1). Effective height is a particularly useful figure-of-merit for antenna sensitivity since it can be computed using simple formulas for basic antennas such as monopoles, dipoles, and loops.

Some caution must be exercised, however, when relying upon effective height alone as the criterion for comparing the sensitivity of two different antennas. Since effective height predicts only antenna open-circuit voltage output without regard to antenna impedance, incorrect conclusions can be drawn. To avoid such erroneous comparisons, some precautions are in order. First, the antenna output voltages should be compared only when applied to the same load resistance (other things being equal, this constraint favors low impedance antennas and penalizes high impedance antennas). Second, the effects of any impedance transformation networks placed between the antennas and the load resistances must also be considered, as these networks can also affect the voltage delivered to the load resistances.

F. ANTENNA NET EFFECTIVE HEIGHT (He')

In order to avoid such confusion caused by differing antenna impedances and impedance transformation networks when comparing the sensitivity of two different antennas, this author uses the concept of *net effective height (He')* so as to allow these factors to be normalized. *Net effective height is simply effective height multiplied by a factor representing the net voltage gain (or loss) imposed by all passive components between the antenna and the load resistance (the input resistance of the first preamplifier)*. Whereas effective height is an open circuit figure-of-merit that ignores tuning and impedance transformation networks, net effective height is a loaded circuit figure-of-merit that accounts for these components.

Using this concept of net effective height allows accurate sensitivity comparisons to be made between two vastly different antennas (such as loops and Adcocks, as is done later in this paper) provided that they ultimately drive the same load resistance.

SECTION IV - LOOP ANTENNA ANALYSIS

A. OVERVIEW

In this Section, a 30 MHz 18" x 18" square loop antenna is modeled and analyzed, using the concept of net effective height (He') as the antenna sensitivity criterion. After a brief discussion of loop basics, He' is computed for a tuned loop driving a high impedance load (such as would be presented by the input of a low-noise JFET cascode preamplifier). Next, He' is computed for a tuned loop driving a low impedance load (such as would be presented by most high-performance 50 ohm input modular amplifiers now available). Following that, He' is computed for an untuned loop driving a low impedance load. Finally, ferrite loops are briefly discussed.

B. LOOP BASICS

As discussed earlier, small loop antennas exhibit the desired bi-directional figure-of-eight azimuthal gain pattern with circular lobes required for Watson-Watt DF systems. The loop exhibits maximum gain along its circular plane, while exhibiting nulls perpendicular to the circular plane.

The literature emphasizes that the classical treatment of such loop antennas is valid only for cases where the total loop conductor length is less than 1/10 of a wavelength (ref. 1). The rationale provided for this restriction is that current through-out the loop remains in-phase when this condition is met. This in turn allows the loop to be treated as a radiating inductor, thus permitting relatively simple analysis.

Since the effective height of the loop is very small (due to its small physical size), many designers ignore the 1/10 wavelength restriction so as to improve sensitivity. Although sensitivity can be improved, it badly diminishes the ability of the loop to reject horizontally polarized signals at and near zero degrees elevation angle, a trade-off that significantly worsens the loop's already serious vulnerability to bearing errors induced by horizontal polarization.

Loops employed for DF applications require an electrostatic shield to prevent E-field pickup (ref. 2). Since the loop exhibits its directional qualities only for the H-field component of the electromagnetic field, it is important that E-field pickup be minimized. Although no E-field pick-up will occur if the loop is perfectly balanced, such ideal balance is very difficult to achieve in practice (the issue of E-field pick-up can also be thought of as a common-mode rejection problem). The presence of the electrostatic shield increases stray capacitance (a factor that limits loop size) and reduces loop Q (a factor that increases losses).

C. 18" x 18" TUNED LOOP ANALYSIS - 1800 OHM LOAD

In the following analysis, net effective height He' is computed as a relative figure-of-merit of antenna sensitivity for an 18" x 18" single-turn tuned loop designed to drive a high-impedance input JFET cascode preamplifier. In a Siliconix application note, a low-noise 30 MHz JFET cascode preamplifier was determined to have an input resistance of approximately 1800 ohms (ref. 3). Since such a preamplifier would be a good choice for a DF loop preamplifier, 1800 ohms is used as a representative load resistance for this design approach.

The effective height of a small loop antenna is given by the equation

$$He = 2\mathbf{B}nA/\mathbf{8} \tag{3}$$

where He is effective height in meters, n is the number of turns, A is loop area of a single turn in square meters, and **8** is the wavelength in meters (ref. 4). For an 18" x 18" square loop, He is 5.172".

The radiation resistance of a small loop antenna is given by the equation

$$Rr = 377(2\mathbf{B}/\mathbf{8})^4(nA)^2 \tag{4}$$

where Rr is the radiation resistance in ohms and the other variables are as defined for equation (3). For an 18" x 18" square loop, Rr is 0.1314 ohms.

Accurate estimates of loop inductance can be found using any one of the many equations that have been derived for this purpose. Using the rather complex equation developed by F. W. Grover of the U. S. National Bureau of Standards (ref. 2), loop inductance for an 18" x 18" loop using 0.1" diameter wire was found to be 1.913 uH (+j360.6 ohms inductive reactance).

Although inductor Q is best determined by actual measurement, a reasonable estimate for Q might be 100 (the presence of the electrostatic shield discussed above induces losses that limit Q). This would result in an equivalent loss resistance Rd of 3.606 ohms

According to A. B. Przedpelski, maximum voltage output from a tuned loop is obtained using parallel tuning (ref. 5). Since the loop is inductive, it is simply resonated using a parallel capacitor Cp. The high impedance load (1800 ohms in the present application) is then placed in parallel with Cp. The complete model is illustrated in Figure 2 below.

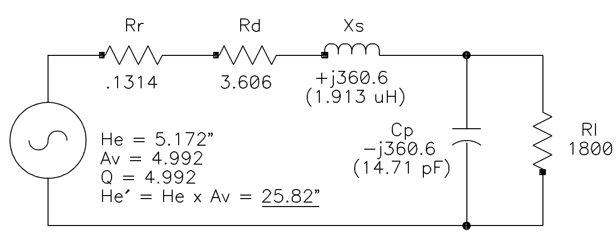

FIGURE 2 – TUNED LOOP MODEL INTO 1800 OHM LOAD

Circuit reactance (Xc or Xl) is 360.6 ohms. Loaded circuit Q is then found using the familiar formula Rl/X, or 1800/360.6 = 4.992. Since the loaded Q is low compared to the inductor Q, voltage gain can be accurately computed using the simple formula Av = Ql, or 4.992.

Net effective height He' is then simply the product of the effective height and the circuit gain, or He x Av, or 5.172" x 4.992 = 25.82".

A word of caution is in order here. Note that the required value of parallel tuning capacitance Cp is only 14.71 pF. In order to make the loop resonate, the loop stray capacitance (effectively in parallel with Cp) must be absorbed into this 14.71 pF, which means that this stray capacitance must not exceed 14.71 pF.

Although the assumption is made that stray capacitance can be held to within 14.71 pF, this is probably an overly generous dispensation, as it is unlikely that this is possible without eliminating the electrostatic shield (an omission that would badly compromise bearing accuracy). If the stray capacitance did in fact exceed 14.71 pF, the actual net effective height He' computed above would be less than 25.82".

D. <u>18" x 18" TUNED LOOP ANALYSIS - 50 OHM LOAD</u>

In the following analysis, net effective height He' is computed for the case where the preamplifier input impedance is 50 ohms. The model for this configuration is illustrated in Figure 3 below. Note that He, Rr, Rl, and L are the same as illustrated in Figure 2 above.

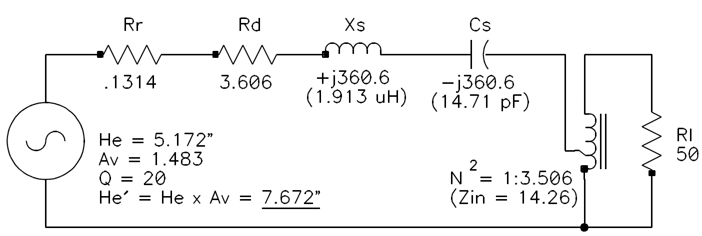

FIGURE 3 – TUNED LOOP MODEL INTO 50 OHM LOAD

Ideally, it would be desirable to simply transform the 3.737 ohm source resistance (Rr + Rd) up to 50 ohms. The voltage gain obtained in such a transformation would be equal to 3.658 (the square root of the load resistance divided by the source resistance). Unfortunately, this would result in an excessively high value of loaded Q (48.25).

High values of loaded Q result in critical tuning adjustments that are difficult to accurately set. Furthermore, component value instability (which causes mistuning) becomes more of an issue with high loaded Q. The problem is compounded in a DF antenna because it is outdoors in an uncontrolled temperature environment.

In order to avoid such mistuning problems that would cause bearing errors, this author suggests that the maximum loaded Q should not exceed 20. By winding the transformer in Figure 3 such that its input is 14.26 ohms (an impedance transformation ratio of 3.506:1), a circuit Q of 20 is achieved. The transformer could be the same type of low-loss ferrite transformer presented by this author in a technical paper published in 1981 (ref. 6).

The voltage gain Av of the circuit can then be shown to be 1.483, and the net effective height equal to He x Av, or 5.172" x 1.483 = 7.672". Although this value is much lower than the 25.82" net effective height calculated in the high impedance case above, it does not necessarily imply that the high-impedance amplifier is a better choice than the low-impedance pre-amplifier - in reality, system sensitivity would be established primarily by the noise figure of the amplifier rather than by the voltage transformation ratio in the tuning networks.

E. 18" x 18" UNTUNED LOOP ANALYSIS

In the following analysis, net effective height He' is computed for the case where no loop tuning is employed. In such applications, the loop output is normally fed directly into a 50 ohm amplifier. The model for this configuration is illustrated in Figure 4 below. Again note that He, Rr, Rl, and L are the same as above.

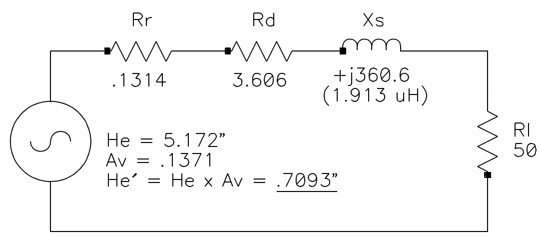

FIGURE 4 – UNTUNED LOOP MODEL INTO 50 OHM LOAD

Again ignoring loop stray capacitance (the inevitable presence of which will make this analysis optimistic), the resulting voltage gain Av of this network is .1371, and the net effective height He' equal to He x Av, or 5.172" x .1371 = .7093".

This value of He' is much lower (by 20.7 dB) than that computed above for a tuned loop driving the same 50 ohm preamplifier. Since He' is computed for the same preamplifier input impedance in both cases, it is a valid figure-of-merit for directly comparing the performance of the two loop configurations. Since the untuned loop suffers such a major loss in sensitivity, it is normally employed only in broadband applications where tuning is not feasible.

F. FERRITE LOOPS

Ferrite loops are employed where the ultimate in compactness is required. Because of their very small size, however, the effective height of ferrite loops is very low. A typical 30 MHz ferrite loop has an effective height of 1.5" or so, which compares unfavorably to the 5.172" effective height of the 18" x 18" air loop analyzed above, and is almost microscopic when compared to that of the Adcock that will be presented in the following Section.

The same general model used for the 18" x 18" air loop analyzed above can also be used for ferrite loops. In general, ferrite loops also exhibit a very low value of radiation resistance Rr. In addition, they will tend to have more inductance per inch of effective height, thus making them higher Q antennas. With loaded Q constrained to 20 as discussed above, less voltage gain is achievable in the tuning network. The combination of this lower value of tuning network gain and the lower effective height combine to produce a net effective height much lower than that of air loops.

Because of this low net effective height, ferrite loops are confined to DF applications where the operating frequency is very low (making air loops too cumbersome), or where the DF antenna must be small enough to be covert. For a non-covert 30 MHz fixed-site DF application, a ferrite loop would be a very poor choice.

G. LOOPS - SUMMARY AND CONCLUSION

Because of their small size, loops are relatively inefficient, having low effective heights (and thus poor sensitivity). Since they are low impedance antennas, however, tuning networks can be employed that provide significant voltage gain that can substantially improve net effective height to great advantage. The use of such networks, however, confines operation to a very narrow frequency band (due to inherent network selectivity). In addition, the voltage gain that can be obtained from these networks is also constrained by the maximum permissible loaded circuit Q. For DF applications, this loaded Q should not exceed 20 for reliable and repeatable performance.

It is not strictly necessary to employ tuning networks, although their omission results in much lower net effective height since the associated voltage gain must be sacrificed. Untuned loops are therefore employed only for broadband applications where the use of tuning networks is impractical.

From the standpoint of sensitivity, air loops are far superior to ferrite loops because of their large physical and effective heights. Ferrite loops are useful, however, when compactness is the overriding requirement.

Based on the discussion above, it is clear that if loops are selected for a single-frequency fixed-site DF application where compactness is not a constraint, tuned air loops are the obvious choice.

SECTION V - ADCOCK ANTENNA ANALYSIS

A. OVERVIEW

In this Section, a 30 MHz dipole Adcock antenna employing 96" 5/8" diameter aerials and 1/8 wavelength spacing is modeled and analyzed, using the concept of net effective height (He') as the antenna sensitivity criterion. After a brief discussion of Adcock basics, He' is computed for a tuned Adcock driving a high-impedance load (such as would be presented by the input of a low-noise JFET cascode amplifier). Next, He' is computed for a tuned Adcock driving a low-impedance load (such as would be presented by most high-performance 50 ohm input modular amplifiers now available). Following that, the matter of sense antennas is briefly discussed. Finally, the sensitivity of the tuned Adcock is compared to that of the loop analyzed in the previous Section.

B. ADCOCK BASICS

As discussed earlier, the Adcock is a phased-array antenna that exhibits the desired bi-direction figure-of-eight azimuthal gain pattern with circular lobes required for Watson-Watt DF systems. An Adcock aerial pair comprises two spaced omni-directional aerials (usually monopoles or vertical dipoles) in the same horizontal plane with difference-phased outputs. Maximum gain is exhibited bore-sight, while nulls occur broadside. A minimum of two Adcock aerial pairs is required to construct a non-rotating Adcock DF array. Most Adcock arrays are of the 4-aerial type (two Adcock aerial pairs orthogonally oriented in the horizontal plane).

Sensitivity is improved by increasing the spacing between the two aerials comprising the Adcock aerial pair, as this provides a larger sample of the illuminating field. This spacing cannot be increased without bounds, however, as this results in elongation of the lobes (loss of circularity), which in turn causes bearing errors. This error is periodic and octantal in nature (there is no error at the eight cardinal and intercardinal points of the compass, and a peak error occurs at the eight tertiary points - 22.5 degrees, 67.5 degrees, etc.).

For 4-aerial Adcocks, this spacing error (sometimes referred to in the literature as octantal error) is approximately .25 degrees RMS for 1/8 wavelength spacing, 1.1 degrees RMS for 1/4 wavelength spacing, and 5 degrees RMS for 1/2 wavelength spacing. Spacing error can be eliminated through site calibration, but only over a narrow to moderate range of elevation angles (the effective spacing is reduced by a factor equal to the cosine of the elevation angle of the illuminating field).

4-aerial Adcocks are typically designed for spacing between 0.1 and 0.35 wavelength, the upper limit being constrained by the afore-mentioned spacing error, and the lower limit being constrained by sensitivity requirements and, from a more practical standpoint, the ability to achieve good balance between the opposing aerials.

The spacing error can be greatly reduced by adding more Adcock aerial pairs. 8-aerial

Adcocks, for example, reduce spacing error to the point where 1 wavelength spacing can be employed.

Even so, classical Adcocks (like loops) are inherently narrow-aperture systems that have no inherent ability to discriminate against reflections as wide-aperture systems can.

As with loops, Adcocks can either be tuned or untuned. When the aerials can be made large enough to self-resonate at the frequency of interest, or when operation over a wide frequency range is required, the aerials are untuned. Tuned Adcocks are employed where size constraints require electrically short aerials to be employed at a single frequency.

Adcocks can be further classified as dipole Adcocks or monopole Adcocks. Dipole Adcocks are generally preferred for fixed-site applications, with the array elevated atop a mast. Monopole Adcocks are generally preferred for mobile or airborne applications, where the array is mounted atop a vehicle or on the underside of an aircraft. Ground-mounted monopole Adcocks are sometimes also used for fixed-site applications at lower frequencies where size constraints make mast mounting impractical. In such cases, it is very important that a large and effective ground plane be employed.

C. TUNED ADCOCK ANALYSIS - 1800 OHM LOAD

In the following analysis, net effective height He' is computed as a relative figure-of-merit for an Adcock aerial pair employing tuned 96" vertical dipoles and 49.2" aerial spacing (1/8 wavelength at 30 MHz) driving the same 1800 ohm input JFET cascode amplifier as discussed in the loop antenna analysis.

The effective height of a single dipole antenna is given by the equation

$$He = 2\mathbf{8}\sin^{2}(\mathbf{B}h/\mathbf{8})/(\mathbf{B}\sin(2\mathbf{B}h/\mathbf{8})) \qquad (5)$$

where He is effective height in meters, h is the dipole height in meters, and **8** is the wavelength in meters (ref. 4). For a 96" dipole, He is 50.50 inches using equation (5). The effective height of two difference-phased dipoles is found by vectorial differencing of the two dipole outputs at 1/8 wavelength spacing. The resulting effective height is reduced to 38.65".

Since accurate estimates of dipole series reactance and radiation resistance cannot be provided by simple equations, these quantities were determined by computer modeling (using MN4.5, an antenna analysis program written by Brian Beezley of Vista, California, USA) to be 10.3 ohms and -j495 ohms, respectively. These quantities reflect the effects of mutual coupling among the four Adcock dipoles for best computational accuracy.

The impedance transformation network is a 3-reactance series enhanced-Q type as discussed in detail by this author in a technical paper published in 1983 (ref. 7), and is used to transform Rr + Rd up to the desired 1800 ohm load resistance. Inductor unloaded Qs of 100 are assumed.

The complete model is illustrated in Figure 5 below.

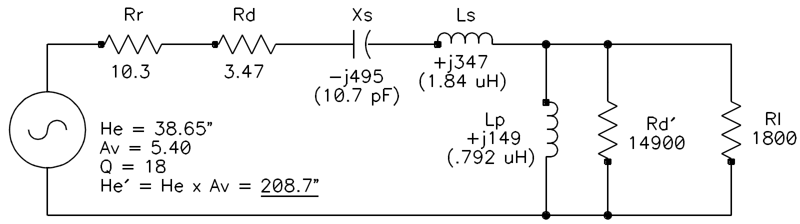

FIGURE 5 – TUNED ADCOCK MODEL INTO 1800 OHM LOAD

Note that Rd is the equivalent series resistance representing the losses of the series tuning inductor and Rd' is the equivalent shunt resistance representing the losses of the shunt tuning inductor.

Modeling the circuit of Figure 5 with NETANL (a computer network analysis program written by this author), the tuning network voltage gain Av was found to be 5.40. Loaded Q was computed to be 18 (using the 3-dB bandwidth method). Net effective height He' is then simply the product of the effective height and the circuit gain, or He x Av, or 208.7".

D. TUNED ADCOCK ANALYSIS - 50 OHM LOAD

In the following analysis, net effective height He' is computed for the Adcock as above, but where the preamplifier input impedance is assumed to be 50 ohms rather than 1800 ohms. The equivalent circuit (illustrated in Figure 6 below) is identical to that for the 1800 ohm load Adcock analysis above, other than for component values. Net effective height (He') is shown to be 35.00".

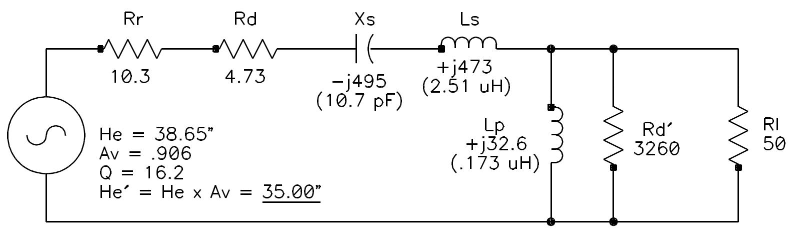

FIGURE 6 – TUNED ADCOCK MODEL INTO 50 OHM LOAD

E. ADCOCK VERSUS LOOP SENSITIVITY COMPARISON

With net effective heights He' computed for both loops and Adcocks for specific load impedances, direct sensitivity comparisons can be made. In Table I below, comparisons are made between the tuned loop and Adcock, while a comparison between an untuned loop and Adcock is made in Table II. Note that each comparison is made for the same load impedance so as to ensure comparative validity.

Table I
Net Effective Height Comparison, Tuned Air Loop Vs. Tuned Adcock

Load	Tuned Loop	Tuned Adcock	Adcock Advantage
50 ohms	He' = 7.627"	He' = 35.00"	+13.2 dB
1800 ohms	He' = 25.83"	He' = 208.7"	+18.2 dB

Table II
Net Effective Height Comparison, Untuned Air Loop Vs. Untuned Adcock

Load	Untuned Loop	Adcock	Adcock Advantage
50 ohms	He' = .7093"	He' = 35.00"	+33.9 dB

The comparisons provided by Tables I and II above clearly show the tremendous sensitivity advantage provided by the Adcock. Particularly noteworthy is the +33.9 dB Adcock advantage over the untuned loop.

The improvement is actually understated somewhat, since the loop analysis ignores the effects of loop parallel capacitance imposed by the electrostatic shield. In effect, the loop analysis assumes that this shield is not present. In practice, this would be very dangerous, since any loop imbalances would result in undesired E-field pickup that would degrade bearing accuracy.

The presence of the loop parallel capacitance constrains the design of the loop tuning networks, the result of which is lowered circuit gain. Loop parallel capacitance is much less of a problem for the untuned loop, since no tuning network is employed.

The comparison provided by Tables I and II also appeals to common sense. With regard to size, even a non-technical observer would intuitively suspect that the larger Adcock array should be more sensitive than the smaller loop. With regard to tuning, the gain-bandwidth trade-off is a very fundamental electronic engineering concept in that gain must be traded-off to obtain more bandwidth, other factors being equal.

F. SENSE ANTENNA CONSIDERATIONS

No mention has been made thus far of the effect of the omni-directional sense antenna on DF sensitivity. In reality, the sense antenna has a very major influence on sensitivity and cannot be ignored.

In general, the sensitivity of the sense antenna should be better than or at least commensurate with that of the bi-directional arrays in a well-designed system. In an Adcock array where the sense signal is derived by summation from the bi-directional arrays, this happens automatically.

In loop arrays, the sense antenna is usually a short vertical monopole co-located with the loops. With tuned loops, it is frequently necessary to also tune the sense antenna as well to ensure commensurate sensitivity. In other cases, sense tuning can be avoided by using an active sense antenna. With untuned loops, the relatively poor loop sensitivity usually permits the use of a similarly insensitive untuned sense antenna.

SECTION VI - BEARING ACCURACY CONSIDERATIONS

A. OVERVIEW

In this final Section, DF bearing accuracy considerations are briefly discussed. Factors causing bearing errors in Adcocks are first discussed, followed by a discussion of the factors causing bearing errors in loops.

B. FACTORS CONTRIBUTING TO ADCOCK BEARING ERRORS

1. ELECTRONIC PROCESSOR ERRORS

Adcocks require electronic circuitry to process the sense and bi-directional signals. Gain and phase imbalances in this circuitry result in bearing errors. With careful design, these errors can be held to under 1 degree RMS. Errors caused by the electronic processor can be reduced to even lower levels by means of site calibration.

2. MECHANICAL ERRORS

Any physical asymmetries will cause bearing errors. These errors can be confined to very low levels by proper construction techniques. Such errors can be reduced by means of site calibration.

3. HORIZONTAL POLARIZATION ERROR

The Adcock exhibits a slight susceptibility to horizontally polarized signals due to the horizontal orientation of the boom supporting opposing vertical dipoles. If the system is well-balanced, however, the resulting induced currents will cancel. In practice, such cancellation is incomplete due to imbalances caused by the mast and the fact that the lower aerials are closer to ground than the upper aerials. The problem can be mitigated by judicious selection of the mast height, as well as by placing a conductive ground screen at the mast base.

The problem is even further mitigated when, as in the case of the Adcock analyzed in the previous Section, tuned aerials and narrow spacing are employed. This results in a much more favorable effective height for the resonant aerials than for the relatively short, non-resonant boom.

Horizontal polarization errors cannot be offset using site calibration due to uncertainties regarding the amount of horizontal signal component present in the illuminating wavefront. In general, however, these errors are ordinarily so slight as not to require action.

4. SPACING ERRORS

As discussed earlier, spacing error is associated with all Adcocks. In the case of the Adcock analyzed in the previous Section, the 1/8 wavelength spacing results in a theoretical RMS spacing error of 0.25 degrees. Spacing error can be reduced (over a modest range of elevation angles) by means of site calibration.

5. SITE ERRORS

As with all narrow-aperture DF systems, classical Adcocks are vulnerable to site errors induced by multi-path reception (reflections) or any other site-related phenomenon that changes the apparent angle-of-arrival of the incoming wavefront. Site error can be mitigated by proper site selection and preparation, but it cannot be reduced by means of site calibration.

C. FACTORS CONTRIBUTING TO LOOP BEARING ERRORS

1. GENERAL

Loops are subject to all the same errors identified above for Adcocks. Loops are far more vulnerable, however, to horizontal- polarization errors. In addition, errors can also be induced by the "antenna effect" as discussed below.

2. HORIZONTAL POLARIZATION ERRORS

Unlike Adcocks, loops inherently respond to horizontally- polarized fields, *with zero degrees elevation angle being the single exception*. This singularity exists, however, as a very sharp null, *with the response to horizontal polarization rapidly increasing as the elevation angle departs from zero*.

Since this response to horizontal polarization is maximum broadside to the loop where its response to the desired vertically-polarized signal component is at a null, *the net effect is that the null becomes "filled", resulting in severe bearing errors*. As discussed earlier, the problem is compounded if the loop is large since it loses its ability to reject horizontally-polarized field components at or near zero degrees elevation angle. The problem often does not appear during a controlled test on a good site where the test transmitter signal is vertically-polarized.

As mentioned earlier, the loop's ability to reject horizontally polarized signals at and near zero degrees elevation angle requires that the loop be very small (that is, the total loop conductor length should be less than 1/10 of a wavelength at the highest operating frequency). Unfortunately, some designers ignore this constraint in an effort to improve sensitivity by increasing loop size well beyond 1/10 wavelength. Informed customers should be wary of such designs.

Of course, the problem for all loops is most severe for sky-wave reception, where the elevation angle is high. This is what was responsible for the night-effect observed during the early days of DF as discussed earlier in this paper. The problem also exists in most other applications as well. As an example, if the DF antenna is placed on a hill, it typically receives signals at negative (non-zero) elevation angles. Another problem that occurs is wavefront "tilt". If the ground is not perfectly conductive (as is usually the case), the received wavefront tends to tilt forward, thus effectively creating an "elevation angle" even though the transmitted signal is nominally at zero degrees elevation angle. Similar perturbations can also result from reflections.

3. "ANTENNA EFFECT" ERRORS

Another factor that can diminish loop bearing accuracy is the so- called "antenna effect". The problem is that although loops are intended to be used as H-field (magnetic field) receptors, they can also respond to the E-field component of the illuminating field if they are not very carefully balanced. The problem is magnified by the fact that loops, being inefficient, produce very low desired output levels, and only a small amount of E-field pickup is necessary to fill in the nulls and cause serious bearing errors. In fact, the problem is usually so severe that it is usually necessary to employ an electrostatic shield to mitigate this antenna effect.

4. CONCLUSION

As a consequence of the above, the actual bearing accuracy of loops is usually far worse than that specified on an ideal test site. In contrast, Adcocks generally yield performance results much closer to those obtainable under ideal siting conditions.

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