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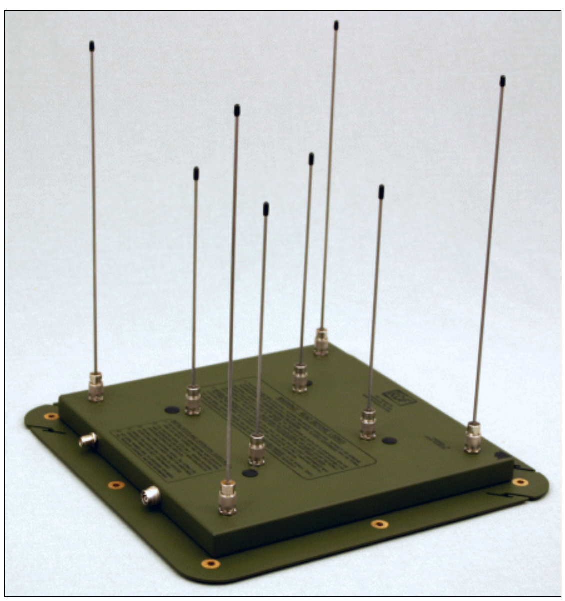
AN-004
Application Note

MEASURING SENSITIVITY OF MOBILE ADCOCK DF ANTENNAS



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About RDF Products Application Notes...

In keeping with RDF Products' business philosophy that the best customer is well informed, RDF products publishes Applications Notes from time to time in an effort to illuminate various aspects of DF technology, provide important insights how to interpret manufacturer' product specifications, and how to avoid "specsmanship" traps. In general, these Application Notes are written for the benefit of the more technical user.

RDF Products also publishes Web Notes, which are short papers covering topics of general interest to DF users. These Web Notes are written in an easy-to-read format for users more focused on the practical (rather than theoretical) aspects of radio direction finding technology. Where more technical discussion is required, it is presented in plain language with an absolute minimum of supporting mathematics. Web Notes and Application Notes are distributed on the RDF Products Publications CD and can also be conveniently downloaded from the RDF Products website at www.rdfproducts.com.

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SECTION I - INTRODUCTION AND EXECUTIVE SUMMARY

This Application Note discusses the various considerations involved in defining and measuring sensitivity of mobile Adcock radio finding (DF) antennas and systems. Since this quality is of paramount interest to most users, specific procedures are discussed that allow technically capable users to conduct their own measurements so that they can independently verify equipment performance. To further facilitate employment of these procedures, easy-to-use menu driven software is provided.

DF vendors frequently cloak information regarding DF system sensitivity measurement procedures under an aura of mystery and arcane technical jargon, the implication being that such measurements can be properly conducted only with the resources and technical expertise of the vendor. Tests conducted by users producing results that appear to be inconsistent with equipment performance specifications are often challenged on the basis of procedural errors, non-ideal sites, non-calibrated test equipment, and various other factors. In some cases, users might even suspect that the real policy driving such challenges is to obfuscate the issue to prevent users from objectively and independently verifying performance specifications.

Although DF system sensitivity measurements do require a certain level of technical expertise and access to specialized test equipment and other material resources, in addition to a certain amount of care and patience, we believe that a policy of obfuscation does not well serve the interests of either the user or the vendor. We thus hope, by means of this Application Note, to provide information that is helpful to users wishing to conduct their own testing programs, or those users who simply want to be able to critically interpret vendor DF sensitivity specifications and evaluate the technical rigor of the measurement procedures employed.

Unlike DF system bearing accuracy specifications (the subject of RDF Products Application Note AN-003 - Measuring Bearing Accuracy Of Mobile Adcock DF Antennas) which are fairly straight-forward, DF sensitivity specifications are much more dependent upon other DF system operating parameters. As a result, there is much more room for "specsmanship" on the part of vendors (that is, there is much greater opportunity for vendors to "improve" sensitivity specifications by invoking favorable but unrealistic assumptions regarding these system operating parameters).

As a corollary to this point, differences in these assumptions can also create difficulty in comparing the specifications of comparable equipment offered by different vendors. It is therefore a primary goal of this Application Note to provide the more technical user with the knowledge necessary to fully interpret DF system sensitivity specifications, as well as to avoid "specsmanship" traps.

Although this paper is primarily oriented to mobile Adcock DF antenna, most of the topics discussed apply to fixed-site DF antennas as well.

SECTION II - DF SENSITIVITY MEASUREMENT CONCEPTS AND DEFINITIONS

A. INTRODUCTION AND OVERVIEW

As is true for any sensitivity specification, DF system sensitivity must be defined in terms of some maximum specified input signal level required to produce a specified output signal-to-noise ratio. It is also important that various other system parameters be specified as well, since these parameters can often greatly influence DF sensitivity.

For a DF system, a proper sensitivity specification should state the maximum required electric field strength of the wavefront illuminating the DF antenna necessary for a specified bearing output threshold signal-to-noise ratio (or bearing-to-noise ratio, to be more precise). It is meaningless, for example, for a vendor to specify the sensitivity of an DF system as "1.0 microvolt", since such a specification excludes the dimensions of both field strength and bearing-to-noise ratio, as well as any mention of wavefront elevation angle, polarization, receiver IF bandwidth, or bearing processor integration time. It is similarly meaningless for a vendor to specify the sensitivity of the DF receiver alone while ignoring the all-important (and in most cases dominant) contribution of the DF antenna.

These important issues are addressed in more detail in the paragraphs that follow.

B. ELECTRIC FIELD STRENGTH

The electric field strength of the electromagnetic wavefront illuminating the DF antenna is quantified in terms of volts per meter (V/m). To better understand this concept, it is first necessary to consider a *current element*. A current element is an aerial (metal rod) that has *uniform current distribution* when illuminated by a wavefront. (Actually, the concept of a current element is a hypothetical construct, since in practice it is not possible to maintain uniform current distribution.)

Wavefront volts per meter electric field strength is then defined as the *open circuit output voltage available from a 1-meter long current element when it is illuminated by that wavefront*. In other words, if the open circuit output voltage available from the 1-meter long current element is 1.0 volt, then the electric field strength of the illuminating wavefront is 1.0 volt per meter.

Typical DF system sensitivity in the HF/VHF/UHF range varies from under one to several dozen microvolts per meter (uV/m), depending upon many factors. Other factors being equal, sensitivity is better for lower rather than higher frequencies, full-size rather than compact antenna arrays, and narrow rather wide frequency coverage antennas.

DF sensitivity is often referred to in terms of "dB microvolts per meter" (dBuV/m). This term simply expresses sensitivity in terms of a voltage ratio (i.e., the number of dB relative to 1.0 uV/m), which is useful when a logarithmic presentation is desired. To convert uV/m to dBuV/m, the following equation is employed:

$$\text{dBuV/m} = 20 \times \log(\text{uV/m}) \qquad (1)$$

where common logarithms are employed. As an example, 100 uV/m would be equivalent to 40 dBuV/m. For the reader's convenience, the DOS utility software program RDFUTIL1 has been written that solves Eq. (1) and most of the other equations presented in this Application Note, as well as performing other conversions and computations that we have found to be useful in DF work. This software is provided on RDF Products Publications CD. This CD is available from any RDF Products sales representative or directly from RDF Products.

C. POLARIZATION AND ELEVATION ANGLE

It is assumed throughout this Application Note that the *polarization* (orientation of the electric lines of force) of the received wavefront matches that of the DF antenna. Most DF antennas are designed to respond to vertically-polarized wavefronts and are specified on that basis.

Most DF antennas are also specified for wavefronts received at zero degrees elevation angle. Adcock DF antennas typically function well for elevation angles up to 30 degrees or so. Loops, on the other hand, suffer pattern distortion that increases rapidly as a function of elevation angle, resulting in very poor performance even at modest elevation angles.

D. ISOTROPIC ANTENNAS AND ANTENNA GAIN

An *isotropic antenna* is one that *radiates (and receives) equally well in all directions*. The concept of the isotropic antenna is a hypothetical construct that is very useful, since the path loss and field strength equations presented below employ this concept.

Practical antennas invariably radiate better in some directions than others. In effect, the radiated power is focused or "beamed" in one or more directions at the expense of others. This results in antenna "gain" in the favored direction(s).

Antenna gain is usually expressed in dBi, or dB referenced to the gain of an isotropic antenna. A beam antenna having a gain of 6 dBi in its most favored direction, for example, would provide 6 dB more radiated power in that direction than would an isotropic antenna driven with equal power (both antennas assumed lossless and matched to the signal source). The gain of an isotropic antenna, by definition, is 0 dBi (unity gain).

E. PATH LOSS COMPUTATION

Path loss is defined as the *attenuation between two isotropic antennas*, and is given by the following equation:

$$\text{Path loss} = 20 \times \log((\mathbf{B} \times d \times f)/75) \qquad (2)$$

where the path loss is expressed in dB, f is in MHz, d is the separation between the two antennas in meters, and common logarithms are employed. To illustrate with an example, the path loss between two isotropic antennas separated by 9 meters (354.3 inches) at 100 MHz is 31.53 dB.

Eq. (2) is a far-field equation that begins to lose accuracy as the distance separating the antennas becomes less than 3 wavelengths at the operating frequency. For most practical purposes, however, this near-field error is small enough to ignore for separations down to 1 wavelength or so.

F. FIELD STRENGTH COMPUTATION

Once path loss has been determined using Eq. (2), electric field strength at the receive antenna can then be computed. To continue with the example from above, assume that the isotropic transmit antenna is driven by a 0 dBm (1 milliwatt) signal source at 100 MHz. Since the 9 meter path loss is known to be 31.53 dB as determined by Eq. (2), the output power from the isotropic receive antenna is then simply 0 - 31.53 = -31.53 dBm. The electric field strength at the isotropic receive antenna can then be computed using the following equation:

$$\text{Field strength} = 7255.197 \times f \times 10^{Po/20} \qquad (3)$$

where the field strength is expressed in uV/m, f is in MHz, and Po is the output power in dBm of the isotropic receive antenna. Using Eq. 3, the field strength is computed to be 19,238 uV/m.

Field strength can also be computed directly by replacing Po in Eq. (3) with transmit power plus transmit antenna gain minus path loss (all in dB or dBi as apprpriate) as follows:

$$\text{Field strength} = 7255.297 \times f \times 10^{(TXP+TXG-PLS)/20} \qquad (4)$$

where field strength is expressed in uV/m, f is in MHz, TXP is transmitter power in dBm, TXG is transmit antenna gain in dBi, and PLS is path loss in dB as computed using Eq. (2).

G. BEARING-TO-NOISE RATIO

1. OVERVIEW

Bearing-to-noise ratio (BNR) is actually *signal-to-noise ratio (SNR) as adapted for DF system sensitivity specification*. Since the primary output of an DF system is the presentation of the bearing, conventional SNR criteria must be modified to account for the "signal" and "noise" attributes unique to the bearing display.

The concept of BNR is best visualized by considering the real-time polar bearing display. This display actually provides a vectorial display of the bearing, with the center of the display being the origin, and the bearing vector (line) emanating from the origin in a direction corresponding to the azimuth of the received signal. (The display is vectorial since both magnitude and angle are projected.) An RDF Products DF processor with a real-time polar bearing display is illustrated in Figure 1.

Figure 1 - DFP-1000B DF Bearing Processor/Display

At high BNRs (i.e., when signals are strong), no bearingvector movement is observable. As the BNR degrades, fluctuations of the CRT trace begin to appear. These fluctuations in turn cause random variations of the indicated azimuth. This latter phenomenon is referred to as *bearing jitter.*

We can thus define the "noise" component of the displayed bearing as bearing jitter. Since noise is a stochastic process, average rather than peak statistical figures-of-merit must be employed to meaningfully quantify it. *RMS (root mean square) averaging* is most frequently employed. RMS averaging is a weighted averaging technique that gives more weight to larger deviations (the magnitude of an RMS average is thus somewhat greater than that of a straight average). A more detailed explanation of RMS averaging is provided in RDF Products AN-003 (Ref. 1)

2. THRESHOLD SENSITIVITY CRITERIA

The *threshold sensitivity* BNR ideally would be specified in a manner that would correspond to some usability threshold for the application of interest. In fact, some vendors specify this threshold simply as being a "usable bearing". Since the concept of a usable bearing is subjective and imprecise, it is very important that the BNR sensitivity threshold criterion be precisely quantified by the vendor.

The astute reader could correctly point out that the criteria for the usability threshold can vary from one application to the next. Even so, this is no different than for other types of sensitivity specifications for which industry-wide standards have been adopted. Examples of this are the 12 dB SINAD standard for FM communications and the 10 dB signal-plus-noise-to-noise ratio standard for AM communications, neither of which represent the true SNR thresholds for many of the applications in which these standards are employed.

Unfortunately, no similar universal usability threshold standard has been adopted in the DF industry. We have therefore set our own threshold standard as *6 degrees RMS bearing jitter*, which, based on our extensive studies and testing, represents a conservative usability standard suitable for mobile tracking and homing DF applications. Expressed in more conventional terms, 6 degrees RMS bearing jitter corresponds to a BNR of 19.57 dB, which compares very favorably to the SNR standards employed for communications applications.

The following equation converts RMS bearing jitter to BNR:

$$BNR = -20 \times \log(\tan(A)) \qquad (5)$$

where BNR is bearing-to-noise ratio (expressed in dB), A is RMS bearing jitter (degrees), and common logarithms are employed. As an example, 10 degrees RMS bearing jitter is equivalent to a 15.07 dB BNR.

3. COMPARING DF SYSTEMS WITH DIFFERENT SENSITIVITY THRESHOLD CRITERIA

A complication arises if the user attempts to compare the DF sensitivity of one DF system with that of another when different BNR threshold criteria are employed. As an example, suppose that DF system "A" is specified as having a DF sensitivity of 5 dBuV/m (decibels relative to an electric field strength of 1 microvolt per meter) for a BNR of 15 dB, while DF system "B" is specified as having a sensitivity of 10 dBuV/m for a BNR of 20 dB (both at the same frequency).

Although informed users would correctly understand that the two specifications could not be directly compared (since different BNRs are specified), they might reasonably (although incorrectly) conclude that the two systems have identical sensitivity since the 5 dB superiority of system "A" (5 versus 10 dBuV/m) is directly offset by the fact the system "A" is specified for a 5 dB worse BNR (15 versus 20 dB).

If the demodulators employed by the two systems were linear (i.e., output SNR linearly proportional to input SNR), input signal levels could be directly offset to accommodate differently specified output BNRs (that is, the 5 dB adjustment used in the above paragraph would be appropriate). Unfortunately, while such demodulator SNR linearity does exist for high SNRs, this linearity vanishes at low SNRs. This phenomenon, known as the "threshold effect", is such that demodulator output SNR degrades much faster than input SNR once the input SNR falls below a certain threshold.

The informed user (now aware of this "threshold effect") would then correctly conclude that system "A" must be more sensitive than system "B", since reducing the input signal to system "B" by 5 dB would result in an output BNR degradation of greater than 5 dB. Additional information, however, would be necessary to quantify the difference.

4. MEASURING BEARING-TO-NOISE RATIO

Fundamentally, there are two methods by which BNR can be measured, one analog and the other digital. With the analog method, the output voltages of the integrators are processed in such a fashion that independent measurements can be made of the signal (DC) and the RMS noise (AC) components. The DF system input signal level is then adjusted until the desired signal-to-noise ratio is established.

If the DF receiver/bearing processor has a computer interface that allows bearing data to be transferred to a computer, software can be written that records the bearings over some period of time and then directly computes RMS bearing jitter. This digital method is much more straightforward than the analog method, and is by far the superior technique provided that the DF receiver/bearing processor has the appropriate computer interface. Fortunately, all RDF Products DF receivers/processors are equipped with RS-232 data outputs.

Regardless of whether bearing jitter is measured by analog or digital means, it is very important that sufficient measurement time is used. Since the bearing integrator bandwidth is ordinarily quite small (typically 1.5 Hz or less), significant measurement time is required to reduce measurement uncertainty (sometimes referred to as fluctuation error) to an acceptable level. If insufficient measurement time is employed, the result tends to vary greatly from one measurement to the next even though nothing in the test setup has changed.

The minimum required measurement time is given by the following equation:

$$t = 1/(2 \times B \times d^2) \qquad (6)$$

where t is the required measurement time in seconds, B is the integrator bandwidth in Hz, and d is the allowable fluctuation error. As an example, if the integrator bandwidth is 1.5 Hz and the permissible fluctuation error is 10% (d = .1), the required measurement time is 33.33 seconds. For a 5% fluctuation error (d = .05), required measurement time is 133.3 seconds.

The default bearing jitter measurement time for RDF Products software is 120 seconds. Since the measurement process for this software uses sampling (rather than continuous as would be the case for analog measurement techniques), it is likely that Eq. (6) is not directly applicable. Based upon experience using 5 samples/second, however, it has been found that 120 second bearing jitter measurements fall within a +/- 0.5 degree window when measuring 6 degrees RMS bearing jitter through an integrator noise equivalent bandwidth of 1.5 Hz.

H. BEARING ACQUISITION TIME

1. OVERVIEW

Bearing acquisition time refers to the *required duration of the received signal necessary to obtain a "usable bearing"*, and is the sum of the receiver automatic gain control (AGC) response time and the bearing integration time. Bearing integration time is of particular relevance to DF sensitivity specification, since sensitivity can be greatly "improved" simply by specifying a longer (though perhaps unrealistic) bearing integration time. It is therefore very important that the user insist that bearing acquisition time be specified along with DF system sensitivity. These issues are discussed in more detail below.

2. AGC RESPONSE TIME

DF systems employing AM axis encoding techniques so that a single receiver can be employed (i.e., single-channel Watson-Watt DF systems) must employ AGC in order to preserve system amplitude linearity. Since bearing errors result if the AGC response time is too short, substantial AGC response time is necessary. AGC response time must therefore be considered as a significant contributor to bearing acquisition time.

Pseudo-Doppler DF systems, in contrast, employ a PM encoding technique. Since amplitude linearity is unnecessary in such systems, AGC need not be employed, thus eliminating AGC considerations from bearing acquisition time. In these systems, bearing acquisition time is composed almost exclusively of bearing integration time.

Regardless of the DF technique employed, bearing integration time comprises the preponderance of bearing acquisition time in a well-designed DF system.

3. BEARING INTEGRATION TIME

Integration (filtering) is included in the circuitry driving the bearing display to reduce noise (bearing jitter). In fact, the bearing integrator effectively establishes the DF receiver post-demodulation bandwidth. From the standpoint of noise reduction then, it is desirable to employ as long a bearing integration time as possible. If integration time is too long, however, ability to respond to short-duration signals is compromised.

The concept of bearing acquisition time is illustrated graphically in Figure 2, with bearing integrator output voltage plotted as a function of time (t). The received signal is assumed to be present beginning at t=0. Initially, no output is observed due to the (assumed) 20 millisecond AGC response time. At t=20 milliseconds, the AGC has completed its response and the integrator begins to charge. Although in theory the integrator never fully charges, some point in time is eventually reached where for all practical purposes the integrator is considered fully charged.

In view of the fact that the integrator never fully charges, a determination must be made regarding the required percentage of full integrator charge that is necessary for a "usable bearing". Although this determination cannot be made completely arbitrarily, it is evident from Figure 2 that the percentage selected has an enormous influence on bearing acquisition time. As an example, if we set 50% maximum output as the criterion, bearing acquisition time is 125 milliseconds, whereas if we set 90% maximum output as the criterion, bearing acquisition time increases to 370 milliseconds. Since this represents an almost 3-to-1 difference in specified bearing acquisition time, the discerning user would certainly want to know which criterion is selected.

Unfortunately, there is no industry standard governing this criterion. We have therefore set our own standard by establishing bearing integration time as the time required for the integrator output voltage to reach 63.2% of maximum. This integration time corresponds to the "time constant" of the simple resistor-capacitor (RC) integrator upon which most integrator circuits are based. The response illustrated in Figure 2 is obtained with an integrator having R = 150,000 ohms and C = 1.0 microfarad, which in turn has a time constant of 150 milliseconds (R x C). Bearing integration time is therefore defined as 150 milliseconds. Bearing acquisition time is then 170 milliseconds (bearing integration time plus the 20 millisecond AGC response time) as illustrated in Figure 2.

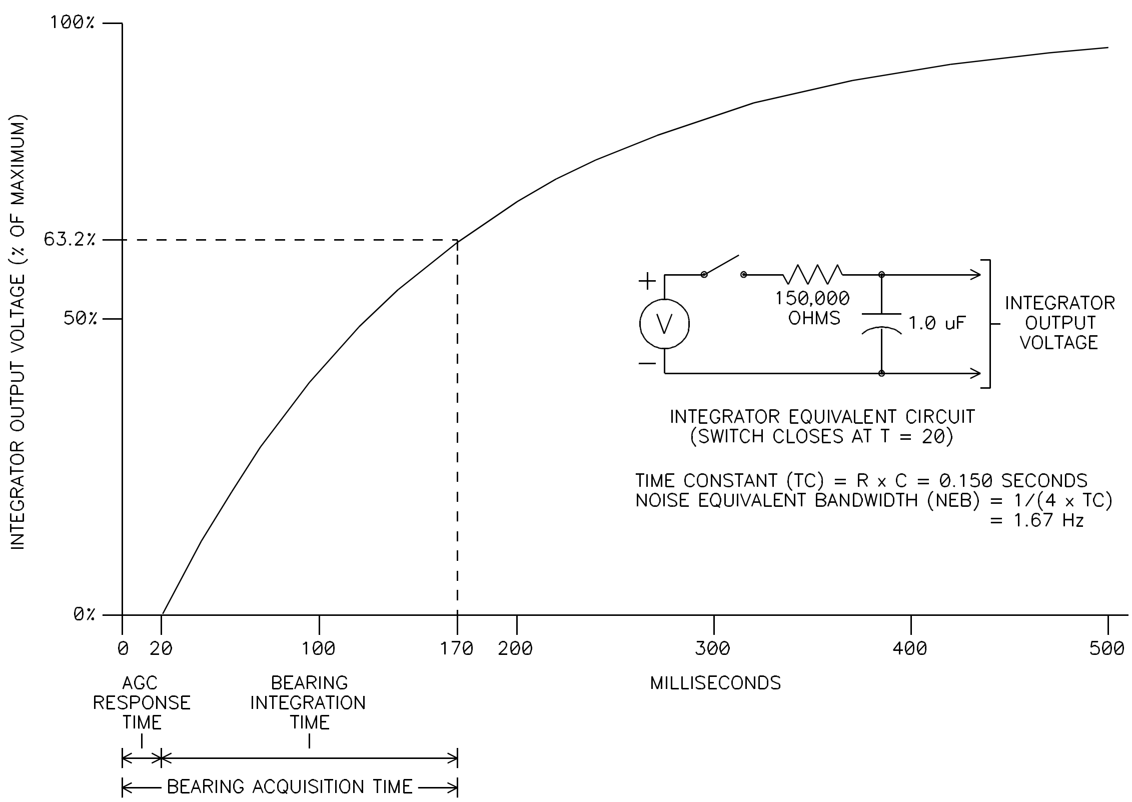

Figure 2 — Integrator Output Voltage Response

4. INTEGRATOR NOISE EQUIVALENT BANDWIDTH

As discussed above, DF system sensitivity is greatly influenced by the specified bearing integration time. Furthermore, the bearing integration time in turn can greatly vary based solely on how it is specified. As a consequence, the astute reader might suspect that some vendors might be tempted to set the criterion for bearing integration time so as to favor the system sensitivity specification.

This can be easily accomplished simply by defining bearing integration time based on a low required percentage of full output voltage. This in turn allows more integrator filtering (larger R or C) for a given specified bearing integration time, which further reduces noise and thereby "improves" sensitivity.

It is therefore very important that the user fully understand the nature of the bearing integrator to avoid falling into such "specsmanship" traps. The user can easily avoid this particular trap by the simple expedient of requiring the vendor to specify the integrator *noise equivalent bandwidth* (NEB) in addition to bearing integration time.

NEB is a succinct means of specifying the bandwidth of a filter (integrator) in absolute terms. If a filter has a perfectly rectangular bandpass characteristic, its specified bandwidth is also its noise equivalent bandwidth. Since practical filters have bandpass characteristics that are more rounded with gradual slopes, they are frequently specified in terms of their 3-dB or 6-dB bandwidths. The noise equivalent bandwidth of a practical filter is equal to the bandwidth of the ideal filter (having a rectangular response) that would pass the same amount of broad-band noise power as that of the practical filter.

For the simple RC integrator filter discussed above, the following equation can be used to compute its NEB:

$$NEB = 1/(4 \times TC) \tag{7}$$

where NEB is the noise equivalent bandwidth in Hz and TC is the time constant in seconds of the integrator RC network (TC = R x C where R is in ohms and C is in farads). For the 150 millisecond time constant integrator used for Figure 2, the NEB is 1.67 Hz.

By requiring the vendor to specify NEB, the above-mentioned subjectivities and ambiguities inherent in defining bearing integration time can be avoided, along with potential "specmanship" traps. Although bearing integration time is a proper specification if realistic criteria are established regarding recovered integrator output voltage, requiring disclosure of NEB allows the user to critically evaluate the bearing integration time specification and thus discourages "specsmanship" on the part of the vendor.

I. DF SYSTEM VERSUS ANTENNA SENSITIVITY

If the DF antenna under evaluation is to be used only with one specific DF receiver/processor, there is no reason to determine its sensitivity independently of that of the complete DF system. In many situations, however, the DF antenna is designed for use with a wide variety of receivers. In such cases, DF antenna sensitivity must be specified on a stand-alone basis.

A proper stand-alone DF antenna sensitivity specification should also specify the assumptions made with regard to the relevant DF receiver/processor operating parameters (noise figure, IF bandwidth, and bearing integrator noise equivalent bandwidth). Furthermore, these assumptions should be realistic (i.e., the potential exists for a "specsmanship" trap by specifying an excessively low receiver noise figure or excessively narrow IF/integrator bandwidths for the intended applications). Standard DF system operating parameters for RDF Products DF antenna sensitivity measurements are discussed below.

J. STANDARD DF RECEIVER OPERATING PARAMETERS FOR DF SENSITIVITY TESTING

The standard receiver/processor operating parameters specified for RDF Products DF antenna sensitivity testing are as follows:

Receiver Noise Figure	-	10 dB
IF Bandwidth	-	15 kHz
Bearing Integrator NEB	-	1.5 Hz

Of the three above parameters, bearing integrator NEB is the most important in that variations directly influence bearing jitter (and thus DF sensitivity). Variations in IF bandwidth also influence bearing jitter, but usually to a lesser extent than bearing integrator NEB. In most instances, variations in receiver noise figure have the least influence on bearing jitter, since most DF antennas employ amplifiers that establish overall DF system noise figure (the presence of these amplifiers greatly mitigates the contribution of the receiver noise figure to overall DF system noise figure).

SECTION III - DF SENSITIVITY GENERAL TEST REQUIREMENTS

A. REQUIRED DISTANCE BETWEEN TEST TRANSMITTER AND DF ANTENNA

For most users, the primary requirement with regard to distance separating the test transmitter and the DF antenna is that it be sufficient to place the DF antenna in the far-field. When this condition is substantially met, the relatively simple field strength formula of Eq. (4) can be employed to determine field strength at the DF antenna. Although equally successful DF sensitivity testing can be conducted in the near-field, much more complex modeling techniques are necessary to compute field strength. Near-field testing should therefore be employed only when the convenience of closer spacing outweighs the complexities of near-field modeling. Near-field testing is advantageous where space is limited. It is particularly attractive when there are nearby reflecting objects in the vicinity and it is desired to move the antennas closer together to reduce errors caused by the resulting reflections.

The near-field versus far-field issue is illustrated in simplified pictorial form in Figure 3. The vertical rod represents a vertically-polarized monopole antenna that is typically employed as the test transmitter antenna. Even though the electric lines of force emanating from this rod ultimately become vertically-polarized in the far-field, this process is incomplete in the near-field. Note that the electric lines of force (illustrated by the arcs in Figure 3) are actually horizontal when they leave the rod, arcing into a more vertical orientation as they strike the ground. As the distance from the rod increases, these lines become progressively more vertical, until finally at some distance the lines become so nearly vertical as to have negligible horizontal components. The distance at which the far-field begins is thus defined as that distance at which the horizontal component is truly negligible. The definition of "negligible" in turn depends upon the application.

Kraus states in Ref. (2) that the near-field error is less than "a few percent" when the distance r separating the antennas is such that

$$r > (d^2 \times f)/150 \qquad (8)$$

where r is the separation in meters, d is the maximum linear dimension of either antenna in meters, and f is in MHz. An equation frequently employed in the electromagnetic interference (EMI) industry is

$$r > 150/(\mathbf{B} \times f) \qquad (9)$$

where r and f are as defined for Eq. (8).

While Eqs. (8) and (9) yield minimum separations that may be suitable for EMI testing, they are inadequate for accurate far-field DF sensitivity testing. In DF applications, the minimum separation should be no less than 10 times the DF antenna aperture (i.e., the distance between the N and S or E and W aerials) or 1.0 wave-length, whichever is greater.

If 1.0 wavelength separation can be maintained, accurate results using relatively straightforward far-field modeling techniques can be obtained, and simple path loss and field strength equations (Eqs. (2-4)) can be employed to accurately predict the electric field strength of the illuminating wavefront. In addition, mutual coupling effects between the two antennas can be safely ignored.

For separations less than 1.0 wavelength, more elaborate near-field modeling techniques should be used for best accuracy, although errors will remain modest for separations down to 0.5 wavelength or so.

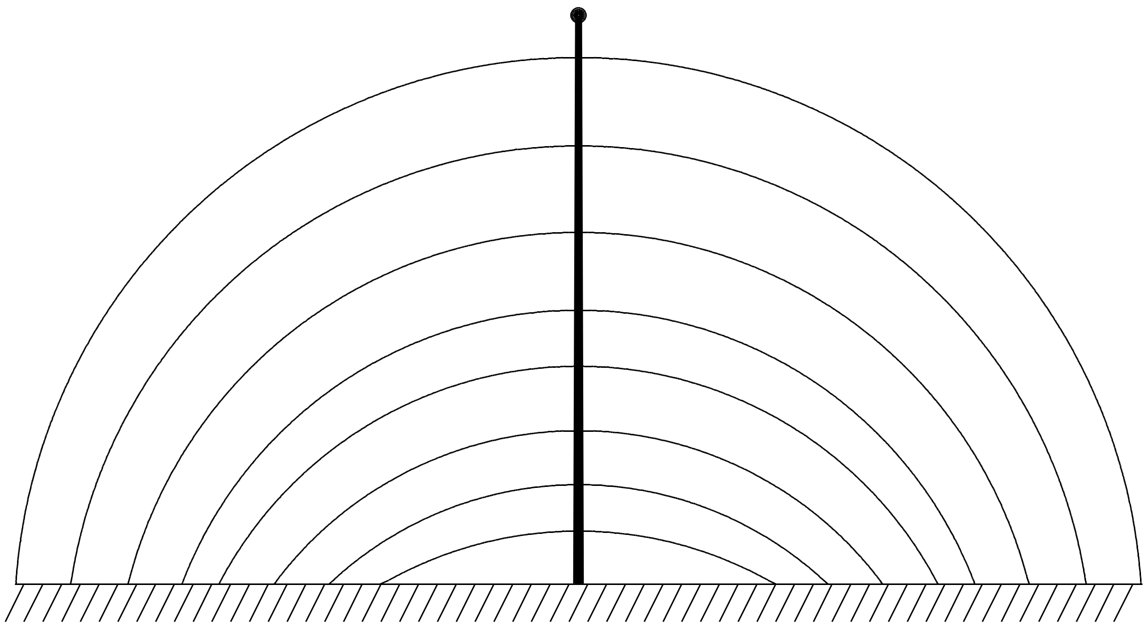

Figure 3 – Representation Of Electric Lines Of Force Near A Vertical Monopole

B. TEST TRANSMITTER REQUIREMENTS

The test transmitter should be a standard RF signal generator capable of covering the frequency range of interest. A synthesized RF signal generator with programmable memory channels is particularly convenient, allowing the user to rapidly change test frequencies. The selected signal generator should have a calibrated wide-range precision variable RF output attenuator. Examples of suitable HF/VHF/UHF units are the HP Models 8640B, 8656B, 8657A/B, and the Marconi Model 2019A.

DF sensitivity testing should be conducted using an unmodulated (CW) signal. Modulation should not be used since it can, under some circumstances, cause additional bearing jitter that would confuse the measurement.

Since it is most convenient to locate the RF signal generator at the operator's console, it is necessary to connect its output to the test transmitter antenna through a substantial length of coaxial cable. Since coaxial cable has losses that usually cannot be ignored, it is necessary to determine these losses at all the test frequencies so that actual power delivered to the test transmitter antenna can be determined. If possible, it is best to directly measure and record cable losses at all frequencies of interest. If this is impractical, manufacturer's data is acceptably accurate provided that the cable has not been exposed to weather for any significant length of time.

For the reader's convenience, the utility program RDFUTIL1 includes a routine that computes losses for commonly-used coaxial cables, thus avoiding the inconvenience imposed by the more traditional graphical interpolation techniques normally employed. Using this routine, it is necessary only to select the cable type, cable length, and frequency. The routine then computes cable loss (based upon manufacturer's data). The routine also has a "user-defined" cable selection option. With this option, the user specifies cable loss at two frequencies in the range of interest for a specified cable length. The routine can then compute cable loss for other frequencies and cable lengths.

C. TEST TRANSMITTER ANTENNA

1. GENERAL REQUIREMENTS

The test transmitter antenna must generate a vertically- polarized wavefront resulting in a closely predictable field strength at the DF antenna under test. Furthermore, input VSWR should be low so that cable losses are minimized and easily predicted. Unfortunately, the rather simple test transmitter antenna described in AN-003 for bearing accuracy testing is not suitable for the more demanding requirements of DF sensitivity testing. Detailed information regarding a more suitable test transmitter antenna is provided in the paragraphs that follow.

2. CONSTRUCTION

Reference monopole antennas are employed where precise field strength generation is required. Such antennas are commercially available from companies specializing in EMI measurement.

Reference monopole antennas can also be inexpensively constructed with readily available materials by technical users having access to appropriate electronic laboratory test equipment (the FCC has done this for many years, and has long accepted test results from properly constructed and verified user-built reference antennas). The schematic representation of the RDF Products Model DTI-420 Reference Monopole antenna is presented in Figure 4.

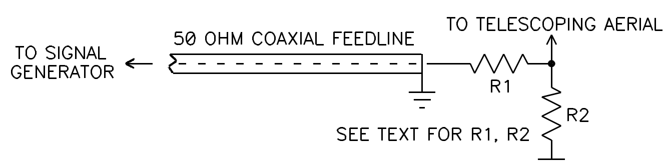

Figure 4 – Test Transmitter Antenna Schematic Diagram

The DTI-420 employs a telescoping aerial that is adjusted in height to approximately 1/4 wavelength at the frequency of interest. The two resistors comprise a minimum-loss resistive matching network that matches the 50 ohm line impedance to the nominal 36.5 ohm antenna

antenna feedpoint impedance so that a low input VSWR is obtained. Although the gain of a 1/4 wavelength monopole transmit antenna is theoretically 5.16 dBi, this gain is offset by the loss of the minimum-loss resistive matching network, conveniently resulting in a net gain of very close to 0 dBi (exclusive of cable losses) for the DTI-420.

Suitable telescoping aerials are available from Mouser Electronics (1-800-346-6873) and other sources. Mouser P/N 43AR105 (variable in length from 5.8 - 33.3") and P/N 43AR103 (variable in length from 3.6 - 19.8") together are suitable for covering the 80-520 MHz range when modified as described below. Since these inexpensive aerials are somewhat fragile and can be easily bent or broken, several spares should be obtained. Although these aerials employ metric threads at the base, they can be easily modified to accommodate a standard 6-32 machine screw by drilling out the threaded base hole with a number 36 drill bit and then tapping the widened hole with a 6-32 tap.

A 3/8" long by 1/4" wide brass hex spacer with a #6 threaded stud at one end is then screwed into each aerial base and soldered to the aerial for improved sturdiness (it is necessary to file off the plating at and around the aerial base to improve solderability). Additional spacers can then be added to the taller aerial as required to extend low frequency coverage (for coverage down to 80 MHz, a total spacer length of 3-3/8" is required for the taller aerial).

The two resistors should be 1/8 watt (for small size). If 5% standard value resistors are employed, 27 and 68 ohms should be used for R1 and R2 respectively. If 1% standard value resistors are employed, 26.1 and 69.8 ohms should be used.

Mechanically, the test transmitter antenna should be built on a square aluminum chassis approximately 12" x 12" and no greater than 1" high as illustrated in Figures 5 and 6. The chassis sidewalls should have bare-metal horizontal base flanges so that a bare-metal baseplate (not illustrated) can be installed that will ensure that good electrical contact is made with the underlying ground screen upon which the unit will ultimately be placed. It is not important whether these flanges protrude inward or outward. The baseplate should then be secured to the flanges with counter-sunk machine screws.

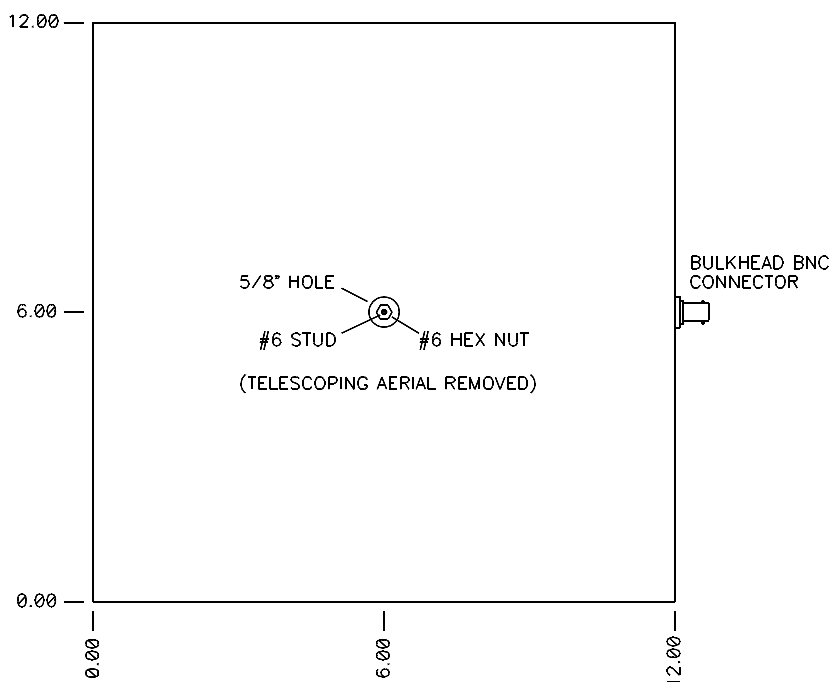

Figure 5 – Test Transmitter Antenna, Top View

A 5/8" hole is punched or drilled at the center of the top surface to accommodate the telescoping aerial. The aerial is actually mounted on a 1" x 3" x 3/32" piece of unclad printed circuit board laminate. A 9/64" hole is drilled in the center of this board so that a 6-32 x 1/2" machine screw (which is used as the mounting stud for the telescoping aerial) can be installed. The hardware stack-up for mounting the 6-32 machine screw is as follows: Screw head, #6 flat washer, printed circuit board laminate, #6 flat washer, #6 tooth washer, #6 hex nut.

Two 11/64" mounting holes are then drilled near each end of the board to accommodate 8-32 mounting screws. The board assembly is then mounted to the chassis from the underside of the top surface positioned so that the 6-32 aerial mounting stud protrudes upward and is centered in the 5/8" hole. The assembly is then secured with the two 8-32 mounting screws (through two additional 11/64" mounting holes drilled in the chassis) and associated mounting hardware.

The resistors should be soldered directly to the flat washer closest to the screw head of the 6-32 machine screw. All lead lengths must be kept extremely short for good high frequency performance. The ground lead of R2 should be soldered directly to the shield of the coaxial cable as close as possible to where the center conductor breaks out.

The shield of the coaxial cable must also be directly grounded to the chassis via the shortest possible path. This can be done with the aid of a solder lug secured to the chassis by a #6 machine screw and hex nut. The solder lug should make contact with the coaxial cable shield as close as possible to where the center conductor breaks out.

Although the coaxial cable can be directly routed out of the box via a hole at the center of either of the four chassis walls, it is best to mount a double-BNC female bulkhead connector at the exit point so that feed cables of various lengths and types can be conveniently accommodated.

Using good construction techniques and exercising special care to maintain very short lead lengths and ground paths, the DTI-420 Reference Monopole antenna can provide excellent results to well over 500 MHz.

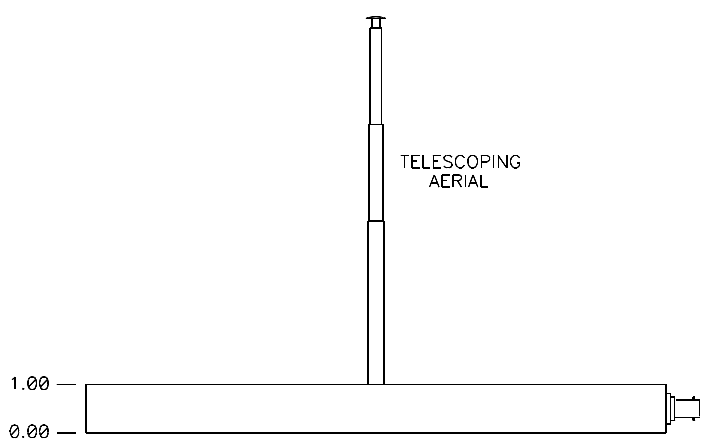

Figure 6 – Test Transmitter Antenna, Profile View

3. TESTING AND VERIFICATION

a. Resonant Frequency And Return Loss Measurement

A good indication of proper antenna performance can be obtained by mounting the unit on a large ground screen, installing the telescoping aerial (extended to an appropriate length) and conducting a swept return loss measurement with a network analyzer through a short length of coaxial feedline. Long cable lengths should be avoided for this test since their losses and other characteristics can obscure the measurement. A pronounced dip in return loss should be observed (typically 20 dB or greater at resonance). At 200 MHz and higher, the dip becomes increasingly broad.

For the benefit of those readers not familiar with the concept of *return loss*, it is a figure-of-merit relating to power reflection from a load back to its source, and is related to VSWR as follows:

$$\text{Return loss} = 20 \times \log((\text{VSWR}+1)/(\text{VSWR}-1)) \qquad (10)$$

where return loss is in dB, the VSWR is greater than unity, and common logarithms are employed. Using Eq. (10), VSWRs of 1.5:1, 2:1, and 3:1 respectively correspond to return losses of 14, 9.5, and 6 dB. A VSWR of 1:1 corresponds to infinite return loss, while a return loss of 0 dB corresponds to infinite VSWR.

Monopoles are nominally resonant for an aerial length of 1/4 wavelength as per the equation

$$L = 75/f \qquad (11)$$

where L is the length in meters and f is in MHz (to convert meters to inches, multiply by 39.37). Eq. (11) is precise, however, only when the aerial diameter approaches zero. Actual resonant length is somewhat shorter due to capacitive loading effects of the non-infinitesimal surface area of a practical aerial having a non-zero diameter. If a network analyzer is available, resonant aerial height can be empirically established by direct measurement at all test frequencies of interest.

For users not having access to a network analyzer or other suitable instrument, resonance must be established solely on the basis of properly estimating required aerial length. In this regard, Schelkunoff has presented the following equation in Ref. (3) to predict the correction factor that must be applied to Eq. (11) in order to achieve resonance:

$$k = 1 - 0.22567/(\ln(\mathbf{8}/d)-1) \qquad (12)$$

where k is the length correction factor, **8** is the wavelength, d is the aerial diameter (same units as **8**), and natural logarithms are employed. To illustrate Eqs. (11) and (12) with an example, suppose that the resonant aerial length for 100 MHz and an aerial thickness of 0.3" is to be computed. First, Eq. (11) is employed to compute 1/4 wavelength at 100 MHz (29.53"). Next, Eq. (12) is employed to compute the correction factor (0.9546). Finally, the results of Eqs. (11) and (12) are multiplied together to compute the resonant aerial length (28.19").

For most self-supporting aerials in the VHF/UHF range, k is typically close to 0.95. In fact, many references simply use 0.95 as a blanket correction factor and avoid the effort required to solve for k using Eq. (12).

Unfortunately, Eqs. (11) and (12) do not accurately predict resonant aerial length for the DTI-420 Reference Monopole. This may be partly due to the fact that Eq. (12) appears to be an approximation intended for dipoles rather than an exact solution for monopoles. It may also be partly due to the fact that Eq. (12) is not applicable to a telescoping aerial with a tapering diameter.

Resonant length is thus best established by direct VSWR measurement or using manufacturer's data. For the reader's convenience, the utility program RDFUTIL1 includes a routine for computing resonant aerial length of the DTI-420. When using the DTI-420, the telescoping aerial should be extended to the computed length in such a fashion that the thickest sections are first exposed.

Regardless of the method by which required aerial length is determined, it is particularly convenient to mark the frequencies corresponding to these lengths directly on a yardstick. It is then necessary only to extend or collapse the aerial to these pre-marked frequency lines on the yardstick, thus saving time and avoiding errors.

b. Site Attenuation Measurement

The best overall test of the precision of the reference antenna is to place two of them on a large ground screen with sufficient separation to ensure proper far-field performance and verify that site attenuation is close to the theoretical value. *Site attenuation is defined as the difference in power between that applied to the input terminals of the transmit antenna and that measured at the output terminals of the receive antenna*. Stated another way, if a certain amount of input power is fed to the transmit antenna, some specific lesser amount of power should be recovered at the receive antenna. This resulting power loss is site attenuation and should be close to the theoretical value. If the measured power loss and the predicted value differ substantially, a problem must exist with either the equipment, the procedures employed, or the site itself.

Site attenuation is given by the equation

$$SA = 20 \times \log(d) + 20 \times \log(f) - 27.56 - g + c \qquad (13)$$

where SA is the site attenuation in dB, d is the distance separating the two antennas in meters, f is in MHz, g is the combined (added) gain of the transmit and receive antennas in dBi, c is the combined transmit and receive antenna cable loss in dB, and common logarithms are employed. When g and c are both equal to zero, SA is equal to the isotropic path loss given in Eq. (2).

The gain of the DTI-420 reference monopole was stated above to be 0 dBi (5.16 dBi minus the loss of the resistive matching network). Although this is true when the antenna is used for transmitting in all cases or for receiving a space wave, this is not the case when receiving a surface wave. In fact, as Ames and Edson demonstrate in Ref. (4), that the gain of a 1/4 wavelength monopole receiving a surface wave is -0.86 dBi, or approximately 6 dB less than that when the same antenna is used for transmitting. For the reference monopole described above then, its gain when used as a receiving antenna is -6 dBi. Combined transmit/receive antenna gain then is -6 + 0 = -6 dBi. -6 is thus entered as g in Eq. (13).

To better illustrate the use of Eq. (13), assume d = 9 meters, f = 100 MHz, g = -6 dbi (using reference monopoles as discussed above), and c = 4 dB (combined cable loss). Theoretical site attenuation is then

$$SA = 20 \times \log(9) + 20 \times \log(100) - 27.56 - (-6) + 4$$
$$= 41.52 \text{ dB}$$

Also, this test confirms the suitability of the ground screen and the site environment. With regard to the ground screen, adequate size, conductivity, and flatness are the most important issues. With regard to the site environment, it is important that there be no reflecting objects in the immediate vicinity.

The site attenuation measurement should be conducted at a number of different frequencies throughout the range of interest. According to FCC Document OET-55, measurements should be conducted at 10 MHz intervals from 30-100 MHz, 25 MHz intervals from 100-300 MHz, and 50 MHz intervals from 300-1000 MHz as discussed in Ref. (5).

In order for the site to meet FCC standards, it is necessary that there be no more than 3 dB difference between measured and theoretical site attenuation at all test frequencies in the band of interest. The newer American National Standards Institute (ANSI) standards C63.4 - C63.7 (Ref. (6-9)) allow 4 dB variation. The additional 1 dB tolerance is granted to allow for the fact that the ANSI standard requires that site attenuation be measured for both vertically- and horizontally-polarized signals (in contrast to FCC Document OET-55, which requires qualification for horizontally-polarized signals only - it has been found that site anomalies are more pronounced with vertically-polarized signals).

The importance of the site attenuation measurement test cannot be overemphasized. This test should be considered as a mandatory pre-requisite for DF sensitivity testing, and any vendor-supplied DF sensitivity test data taken on a site not qualified by a fully documented site attenuation measurement test should be considered suspect and challenged as such.

This is fundamentally no different than the FCC's strict policy of not accepting vendor or certification agency EMI compliance test data unless properly conducted and documented site attenuation measurement test has been conducted. A copy of the documentation for the RDF Products 1-meter test site is presented in the Appendix.

4. MISCELLANEOUS TOPICS

a. Antenna Factor

Antenna factor is a figure-of-merit frequently employed in the EMI industry that quantifies the "efficiency" of test antennas with regard to their ability to convert an electric field into an output voltage. More specifically, antenna factor *is the ratio (expressed in dB) of the electric field strength of the illuminating wavefront to the resulting voltage present at the antenna output terminals*. In its simplest form, antenna factor can be expressed as

$$AF = 20 \times \log(E_{FS}/E_{ANT}) \quad (14)$$

where AF is the antenna factor in dB, E_{FS} is the electric field strength in volts/meter, E_{ANT} is the antenna output voltage in volts, and common logarithms are employed. As an example, if an antenna illuminated by a wavefront having an electric field strength of 1 volt/meter at a particular frequency provides an output of 0.5 volts, the antenna factor (at that frequency) is 6 dB. Antenna factor also applies to transmit antennas by reciprocity.

Note that the *higher* the antenna factor, the *less* the recovered antenna output voltage. In addition, antenna factor is frequency sensitive. Antenna factor is also influenced by the gain of the antenna, as well as any impedance transformations.

A more inclusive expression for antenna factor taking these additional factors into account is

$$AF = 20 \times \log(f) - 20 \times \log(R_L/R_R)^{1/2} - 31.42 - g \qquad (15)$$

where AF is the antenna factor in dB, f is the frequency in MHz, R_R is the antenna radiation resistance in ohms, R_L is the line impedance (normally 50 ohms), g is the antenna gain in dBi, and common logarithms are employed. Eq. (15) is valid for resonant antennas only, disregards cable losses, and assumes a lossless impedance transformation between the antenna feedpoint and the transmission line. If the antenna employs a resistive matching network to transform the radiation resistance to the line impedance (as is the case for the DTI-420 Reference Monopole antenna discussed earlier in this Section), Eq. (15) is still valid provided that the loss imposed by this network (as well as any other losses) is included as an offset to antenna gain (g).

To illustrate Eq. (15) by example, the antenna factor at 100 MHz for an ideal resonant balanced dipole having a gain of 2.15 dB with a 73 ohm radiation resistance driving a 50 ohm line through a lossless impedance transforming balun is 8.07 dB. If a lossy balun is employed, the loss can be measured and directly added to the antenna factor.

Commercially available "calibrated" antennas are usually specified in terms of antenna factor rather than gain. They are supplied with tables or graphs showing antenna factor as a function of frequency. The antenna factor at each test frequency is obtained by direct measurement in a radiated field generated by a precision source.

Since there is a well-defined relationship between antenna factor and gain as shown in Eq. (15), antenna factor can be thought of as an alternative means of expressing antenna gain.

b. Normalized Site Attenuation

Normalized site attenuation (NSA) is an alternative means of expressing site attenuation that is independent of frequency and the gains or antenna factors of the test antennas employed. This is in contrast to measured site attenuation as quantified in Eq. (13), which accounts for antenna gain and operating frequency.

The concept underlying NSA is that quantification of site attenuation should be based strictly upon the characteristics of the site itself, and should therefore be independent of the characteristics of the test antennas employed in the measurement process. Although one might think that path loss as presented in Eq. (2) would be a good figure-of-merit for expressing site attenuation independently of the test antennas, the EMI industry has instead adopted NSA.

NSA is simply measured site attenuation less the combined transmit and receive antenna factors, or

$$NSA = SA - (AF_T + AF_R) \tag{16}$$

Where NSA is normalized site attenuation in dB, SA is measured site attenuation in dB, AF_T is the antenna factor of the transmit antenna in dB, and AF_R is the antenna factor of the receive antenna in dB.

c. Calibrated Versus Reference Antennas

Most calibrated antennas are broadband designs employing conical (rather than telescoping) aerials to facilitate automated swept frequency testing over wide frequency ranges. These broadband antennas are widely used in the EMI industry.

As stated above, calibrated antennas must be calibrated against a precision source. The preferred method of calibration of antennas used for FCC emissions measurements is comparison to the reference antenna. The concept underlying the reference antenna is that it is a relatively simple antenna (i.e., a basic dipole or monopole) that with reasonable care can be physically constructed in such a fashion that it can be relied upon to exhibit precise and repeatable electrical characteristics so that its gain or antenna factor can be assumed to be the same as that predicted by theory. This assumption has been experimentally verified by many sources on many occasions including the FCC and National Institute of Standards and Technology (NIST).

The DTI-420 Reference Monopole antenna discussed earlier in this Section is an example of such a reference antenna. If constructed as described, its accuracy will be superior to that of commercially available broadband calibrated antennas.

D. GROUND SCREEN REQUIREMENTS

It is very important that both the DF and test transmitter antennas be placed on a flat conductive ground screen in order to augment the normally poor and non-uniform conductivity that is characteristic of most soil. An excellent material for this ground screen is so-called "hardware cloth".

Hardware cloth consists of meshed galvanized wire and is available in 3' and 4' wide rolls from most building supply stores. All wire junctions are welded for good conductive continuity. Hardware cloth with a 1/4" mesh is particularly well suited for ground screen applications.

Hardware cloth should not be confused with "chicken wire", which has non-welded junctions and a much coarser mesh. Although other materials may be substituted for hardware cloth, it is important that the selected material have a fine mesh and exhibit good conductive continuity.

The DF antenna ground screen should be laid down in a square configuration centered on the desired location of the DF antenna. Each side of the square should be at least 0.75 wavelengths at the lowest test frequency. A 3' x 3' sheet of galvanized sheet metal should be mounted at the center of the ground screen, soldered to the wire mesh every 9" along its perimeter.

The test transmitter antenna ground screen should be the same size as the DF antenna ground screen, centered on the desired location of the test transmitter. A 3' x 3' sheet of galvanized sheet metal should be mounted at the center of the ground screen, soldered to the mesh every 9" along its perimeter.

If the two ground screens do not overlap, a "runway" should be constructed using a 3' wide length of hardware cloth to join them. This runway should be centered on a line connecting the center points of the two ground screens.

Adjacent strips of hardware cloth should be soldered at 12" intervals to ensure good conductive continuity. The galvanized wire takes solder easily when new, but becomes very difficult to solder after it has oxidized as a result of age or exposure to weather. Solderability can be restored to oxidized wire by scraping it with a knife.

Figure 7 illustrates a ground screen layout suitable for testing mobile Adcock DF antennas in the 80-1000 MHz range.

E. ELEVATED GROUND SCREEN

An elevated ground screen offers the advantage that the operator's console and operating personnel can be located *below* the ground screen (test platform) and thus not be a source of reflections. Similarly, nearby vegetation and other obstacles can also be eliminated as reflection sources provided that they do not extend above the height of the test platform. Finally, the test platform can be made very flat for best antenna site characteristics. For these reasons, elevated test sites are highly desirable.

On the down side, construction of a good quality elevated test site is very expensive and time consuming. Furthermore, elevated test sites need to be quite large, since the ground screen is not augmented by the earth ground (as is the case when the test site is constructed on the ground). Finally, ongoing maintenance is usually necessary to keep the test platform level and for periodic repainting. For these reasons, elevated test sites are impractical for most users (and even for most DF equipment vendors, for that matter).

Despite these difficulties, RDF Products constructed an elevated test site in the Arizona desert. The test platform is 20' x 60', and is mounted approximately 7' off the ground as illustrated in Figures 6 and 7 below. This elevated test site provides outstanding performance for all DF antenna tests and measurements. RDF Products has also constructed a ground level test site in Vancouver, Washington, with equally good results.

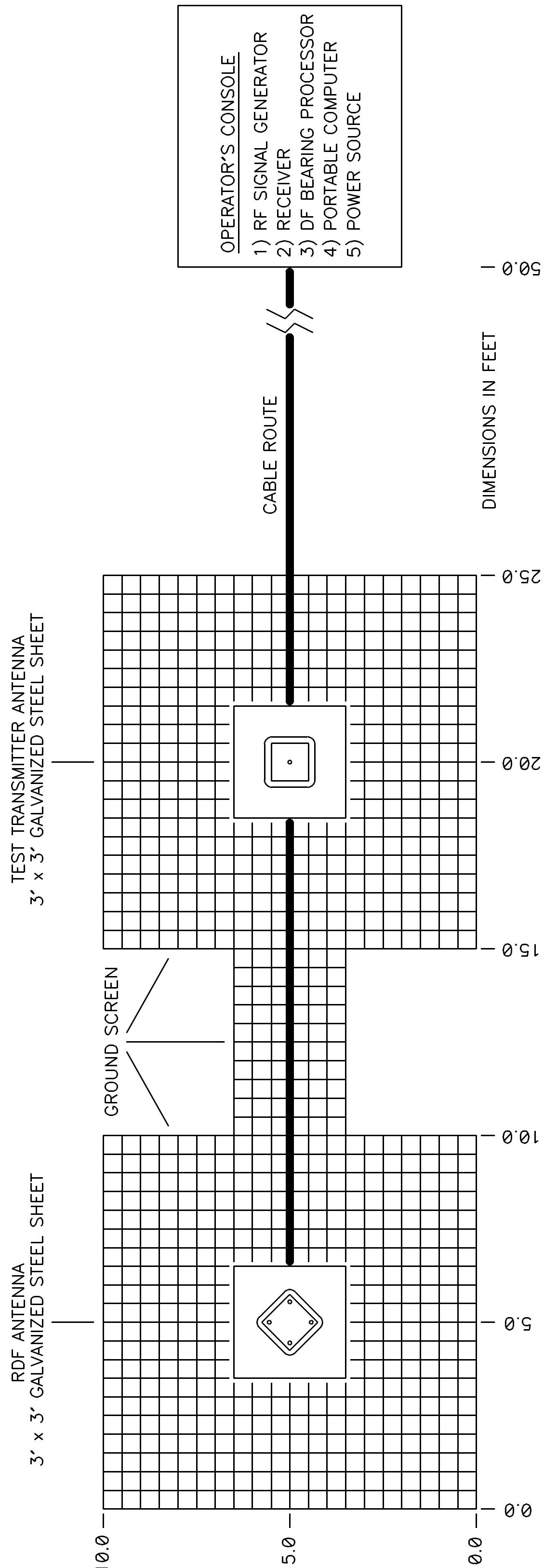

Figure 7 – Recommended 15' RDF Sensitivity Test Site For DTI Model DMA–1315 RDF Antenna

Figure 8 - Elevated DF Antenna Test Site (full view)

Figure 9 - Elevated DF Antenna Test Site (end view)

F. REQUIRED NUMBER OF TEST FREQUENCIES

Although there are no rigid rules dictating any specific number of test frequencies, there are some general guidelines that can be helpful in making this determination. These guidelines are discussed below.

For wide-band DF antennas, eight test frequencies per octave are usually more than adequate. Ideally, these frequencies should be separated by a constant percentage factor (approximately 10.5 % for eight test frequencies per octave). For a DF antenna with a low-end test frequency of 100 MHz for example, the next test frequency would then be 100 x 1.105 = 110.5 MHz, followed by 110.5 x 1.105 = 122.1 MHz, etc. In practice, it is not necessary that they be spaced with such precision (a convenient dispensation that allows selection of specific frequencies of interest, or other frequencies that might somehow be convenient for test purposes). It is important, however, that test frequencies at or very near the specified upper and lower band limits of the DF antenna be included.

For narrow-band DF antennas (those having bandwidths of 20% or less), a minimum of three test frequencies should be employed; one each at or near the upper and lower band limits and the third near the center frequency. One exception to this guideline is for a DF antenna designed to work at a single specific frequency, where testing at the single frequency is sufficient. The other exception is for a wide-band DF antenna that has effectively been converted into a narrow-band DF antenna by the use of a narrow output filter. In this case, testing at only one or two frequencies is acceptable.

With some DF antenna designs, performance can be compromised in specific narrow frequency ranges as a consequence of certain engineering design trade-offs that may have been necessary. One example of this is for a monopole DF antenna that is elevated on a mast or tripod. When the antenna is removed from the ground plane, the mast or tripod effectively becomes part of the DF antenna, with the result that performance can be severely degraded, particularly at frequencies where the mast or tripod is resonant.

Another example of this is in a multi-band DF antenna where monopoles are used to cover one frequency range and loops another. It frequently happens that loop resonances occur that result in compromised performance at certain frequencies covered by the monopoles.

Since the vendor is sometimes reluctant to reveal such design trade-offs to customers, it is important that the customer carefully examine the DF antenna and conduct tests at any specific frequencies where performance might be suspect.

G. MISCELLANEOUS ISSUES

1. REFLECTING OBJECTS

The test site should be free of reflecting objects in its immediate vicinity. According to FCC Document OET-55 as discussed in Ref. (5), the minimum area to be free of such reflecting objects is that contained by an ellipse having an eccentricity e = 0.5 with the locations of the two antennas as the foci. In the general case, the ellipse major and minor diameters would respectively be 2.0 and 1.732 times the antenna separation. For a 4-meter test site, this would correspond to major and minor diameters of 8.0 and 6.9 meters, respectively.

Although such clearance is usually a necessary condition for a successful site attenuation test, it is not usually by itself a sufficient condition. Sizeable reflecting objects outside this ellipse can still cause unacceptable site attenuation behavior.

2. DF ANTENNA RF CABLE LOSSES

In most cases, it is necessary to add extension cables to the DF antenna so that it can be connected to the DF receiver/processor at the operator's console. Since this results in additional net RF cable loss, measured DF sensitivity is somewhat less than true DF sensitivity.

Since most DF antennas employ amplifiers, the effect of up to 3 dB or so of additional RF cable loss is usually negligible and can be ignored. In cases where standard RG-58 extension cables impose excessive loss, however, a lower loss extension cable should be employed. A 50' length of RG-8 with foam dielectric, for example, imposes only 2 dB of matched loss at 500 MHz.

The reader should not confuse this discussion regarding DF antenna RF cable losses with the RF cable losses associated with the test transmit antenna. Since these latter cable losses directly degrade measured DF antenna sensitivity, they must be accurately established (either by direct measurement or referring to manufacturer's data) and factored into DF sensitivity computations.

3. FCC STANDARDS

Although FCC standards and techniques have been discussed at considerable length in this Application Note (particularly with regard to site verification and reference antennas), we are not suggesting that it is necessary to expend the considerable time and effort that would be required to formally qualify the test site to meet FCC requirements. Our purpose has been only to rely upon the FCC's vast experience in the field of radiated emissions measurement over the past 70 years, enhanced by its enormous material resources and highly skilled personnel, and apply it as appropriate to the much narrower requirements of DF sensitivity testing.

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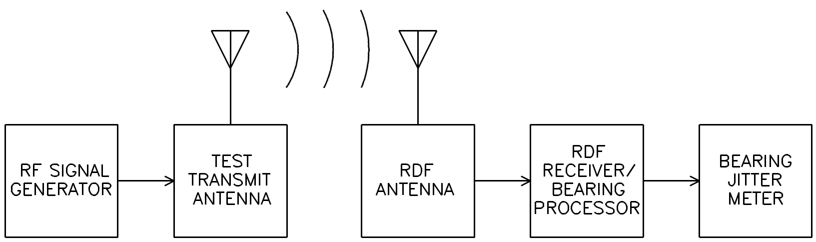
SECTION IV - DF SENSITIVITY TESTING

A. OVERVIEW

Once the necessary equipment has been procured and the test site constructed and verified as discussed in the preceding Sections, the actual test procedure is fundamentally rather straightforward. Essentially, the procedure entails positioning the DF and test transmit antennas at their appropriate locations on the ground screen, connecting the DF antenna to the DF receiver, connecting the test transmit antenna to the signal generator, connecting the bearing-to-noise ratio measurement device to the DF receiver/processor, selecting the desired test frequencies, and then adjusting the signal generator output amplitude at each test frequency in succession until the desired DF receiver/processor bearing-to-noise ratio threshold criterion (i.e., 6 degrees RMS bearing jitter) is obtained. Figure 10 illustrates the basic test setup.



Test Procedure:
1) Mount test transmit and RDF antennas at appropriate locations on qualified test site.
2) Adjust RF signal generator output amplitude at each test frequency for desired RMS bearing jitter threshold (6 degrees RMS jitter for DTI RDF equipment).
3) Enter signal generator output amplitude, test transmit antenna cable loss, test transmit antenna gain, and test transmit/RDF antenna spacing at each test frequency into software program ANTDATA3 to compute RDF sensitivity.
4) Refer to text for details and additional information.

Figure 10 - DF Sensitivity Basic Test Setup And Procedure

The required signal generator output amplitude, test transmit antenna cable loss, test transmit antenna gain, and spacing between the test transmit and DF antennas are then recorded for each test frequency. Finally, this information is used to compute DF sensitivity using the equations presented in the preceding Sections.

These issues, along with certain practical considerations, are discussed in greater detail in the paragraphs that follow. In addition, a test worksheet form is provided that helps the user to conveniently organize data collection, along with test software that performs all the necessary computations and produces a permanent test record.

B. SITE STABILITY

Before conducting a sensitivity test, it is good practice to first conduct a site stability test to verify that no significant bearing jitter is induced by the dynamics of the site itself. Potential dynamic factors that can cause site instability are wind-induced movement of DF/test transmit antenna aerials or nearby vegetation, and normal movement of operator personnel.

To conduct this test, simply obtain a bearing at the selected test frequency and increase the signal generator output amplitude so that a strong signal is received. If the site is stable, bearing jitter or waver (as visually indicated on the bearing display) should be insignificant. Since this test can be conducted quickly and easily, it should be conducted at all test frequencies.

C. INTERFERENCE ISSUES

The single greatest difficulty likely to be encountered in conducting DF sensitivity testing is signal interference on the selected test frequency. This problem is particularly pernicious as a result of the fact that the threshold signal level being detected from the test transmit antenna is so weak, and further militated by the necessary lengthy measurement time (typically 2 minutes), which creates a rather large temporal window of vulnerability.

Such interference falls into three categories. The first category comprises on-the-air transmitters operating at or near the desired test frequency. The remedy for this class of interference is to either wait until the offending transmitter goes off the air or move the test frequency as required to avoid the interference. Tests conducted at frequencies in the TV, FM broadcast, and VHF civil and public safety bands are particularly prone to such interference. In extreme cases, the test site may have to be relocated.

The second interference category comprises man-made interference caused by fluorescent lights, arcing-brush motors, vehicle ignitions, power-line leakage, and computers. This type of interference diminishes in magnitude as the frequency increases, but can still cause trouble even in the VHF range. Such interference can be mitigated to a degree by turning off nearby fluorescent lights, motors, and computers. Special precautions may be necessary to ensure that the computer located in the operator console used to conduct the test not cause interference (slower computers are preferred since they produce less interference).

The third interference category comprises natural causes of noise caused by atmospheric, ionospheric, and galactic phenomena. Atmospheric and ionospheric disturbances (which typically manifest themselves as "static crashes" are normally a problem only well below 30 MHz. Galactic noise is of such low magnitude that it would cause trouble only for DF systems having extremely low noise figures. In those applications where naturally-induced noise is a problem, outdoor field testing may have to be abandoned in favor of TEM cells and anechoic chambers.

The most important aspect of dealing with interference is the ability to detect its occurrence. The best way to detect interference is to audibly monitor the DF receiver output, both prior to and during the test. Another useful technique is to run the test several times at a given frequency and verify that the results are similar. Erratic and inconsistent results are a strong indication of interference.

D. DF SYSTEM SENSITIVITY TEST WORKSHEET

For the user's convenience, a worksheet form is provided in the Appendix that helps facilitate orderly data collection during the course of the DF sensitivity test. When properly filled out, this worksheet contains in concise form all the data necessary for the subsequent sensitivity computations. The form may be reproduced as required.

The two near-field correction factor columns may be ignored for normal far-field testing. These columns are filled in only for cases where near-field correction factors have been computed that offset the errors inherent in near-field testing.

E. DF SYSTEM SENSITIVITY COMPUTATION AND TEST REPORT SOFTWARE

Since it is tedious and time consuming to manually perform the computations necessary to determine DF sensitivity, the DOS program ANTDATA3 has been written to relieve the user of this laborious requirement. For the user's convenience, ANTDATA3 is provided on the RDF Products Publications CD.

ANTDATA3 is very straightforward to use, prompting the user to enter the data already recorded on the worksheet form discussed above. Entries may be conveniently reviewed and edited as required. The program then computes DF sensitivity in uV/m for all entered test frequencies. If desired, the program also provides a complete printed test report (including all input data) that can conveniently serve as a permanent test record.

Copies of this printed report for actual tests performed on the RDF Products Model DMA-1315R2 80-520 MHz Mobile Adcock DF Antenna are provided for illustrative purposes in the Appendix. Note that for far-field tests, the near-field correction factor entries should be zero.

F. INDOOR DF SENSITIVITY TESTING

1. OVERVIEW

Because of the logistical difficulties and effort required to conduct outdoor DF sensitivity tests, indoor techniques are sometimes employed. Fundamentally, there are three indoor DF sensitivity test techniques. First, an indoor test site can be constructed employing anechoic chambers or TEM cells. If successfully implemented, such techniques more conveniently replicate the results of outdoor testing. Second, the aerials can be removed from the DF antenna and signals injected into the aerial connectors through special signal splitters designed to replicate the effects of an incoming wavefront. Finally, special instruments known as bearing synthesizers can be used in conjunction with RF signal generators to measure the DF sensitivity of only the DF receiver/processor exclusive of the DF antenna. These techniques are discussed in more detail in the paragraphs that follow.

2. INDOOR TEST SITES

An ideal indoor test site would allow DF sensitivity testing to be conducted indoors with procedures and results very similar to those associated with outdoor sites. Anechoic chambers (rooms with special material placed on the walls designed to absorb radio waves) are generally used for this sort of testing. Unfortunately, anechoic chambers are large and expensive, and do not provide perfect absorption. When used at all for DF sensitivity testing, they are used primarily at UHF and microwave frequencies.

TEM (transverse electromagnetic) cells and their derivatives are also sometimes employed. These are essentially large transmission lines that are excited at one end with a signal generator and terminated at the other end with a dummy load. When properly constructed, the electric field within the cell itself can be precisely predicted. Ideally, the DF antenna can be placed in the cell and exposed to this known electric field. Unfortunately, the use of such cells is limited to small, inefficient DF antennas, since 1) the cell must be physically small with respect to a wavelength at the operating frequency, and 2) efficient antennas cause field distortion that change the characteristics of the electric field in ways that are difficult to predict. The TEM cell is very useful for testing small, inefficient ferrite loop DF antennas in the HF range. Such antennas are ordinarily compact enough to fit into the TEM cell, and are so inefficient as receiving apertures that the field distortion they impose is sufficiently small to be ignored. In fact, the TEM cell is particularly attractive for testing sensitivity of such HF DF antennas, since it shields the antenna from the normally unavoidable atmospheric and ionospheric noise that is so troublesome in the lower HF band.

In most cases, however, indoor DF sensitivity testing yields poor results compared to outdoor testing. Although the FCC now accepts the results of indoor EMI testing under certain conditions, it has traditionally been reluctant to recognize indoor test sites.

3. SIGNAL SPLITTERS

DF antennas with removable aerials can be sensitivity tested by removing the aerials and injecting the signal generator output into the aerial connectors through a precision signal splitter with cable lengths such that the signal phase at each aerial connector is similar to that which would result from illumination by a far-field wavefront. Although this technique may at first glance appear conceptually elegant, it completely ignores the efficiency of the aerials themselves, as well as the phase and amplitude perturbations induced by aerial mutual coupling. It is thus by itself of very limited use for determining absolute DF antenna sensitivity.

The technique does, nonetheless, have great merit as a method of verifying DF antenna sensitivity, since it does, when properly conducted, confirm proper performance of the DF antenna electronics. It is excellent for production test, and is also useful for users wishing to conduct performance verification tests. RDF Products monopole Adcock DF antennas can readily be tested both for sensitivity and bearing accuracy in this fashion using the Model DTI-410 Precision Signal Splitter.

Note that this technique cannot be applied to DF antennas with non-removable aerials, or those without aerial connectors.

4. DF BEARING SYNTHESIZERS

Bearing synthesizers are precision instruments that accept the antenna encoding tones generated by the DF receiver/processor, combine these tones in a precise ratio appropriate to the azimuth selected on the synthesizer front panel, and then apply these combined tones to the appropriate modulation port of an RF signal generator. This causes the RF signal generator output to effectively simulate the output of a near-ideal DF antenna at the selected azimuth. Precisely controlled bearing accuracy and receiver DF sensitivity measurements can then be made.

Since the DF antenna is completely excluded from this test, measurements can only be conducted on the DF receiver/processor. Such tests are nonetheless very useful for performance verification and system troubleshooting. All RDF Products DF receiver/processors can be checked with the Model DTI-100B DF Bearing Synthesizer (illustrated in Figure 11 below).

<u>Figure 11</u> - DTI-100B DF Bearing Synthesizer

REFERENCES

1. Alex J. Burwasser, "Measuring Bearing Accuracy Of Mobile Adcock DF Antennas", RDF Products Application Note AN-003, October, 1994.

2. John D. Kraus, "Antennas", p. 56, McGraw-Hill, 1950.

3. Harold E. Taggart, "Radiated EMI Instrumentation Errors", p. 34, EMC Technology Magazine, October, 1982.

4. John W. Ames and William A. Edson, "Gain, Capture Area, And Transmission Loss For Grounded Monopoles And Elevated Dipoles", p. 44-55, RF Design Magazine, Cardiff Publishing, November/December 1983.

5. Compliance Engineering Magazine Application Note, "Setting Up Your Open Field Test Site", p. 2, Compliance Engineering, 1990.

6. ANSI C63.4 (1988), American National Standard For Electromagnetic Compatibility -- Radio Noise Emissions From Low Voltage Electrical And Electronic Equipment In The Range 10 kHz To 1 GHz -- Methods Of Measurement.

7. ANSI C63.5 (1988), American National Standard For Electromagnetic Compatibility -- Radiated Emission Measurements In EMI Control -- Calibration of Antennas.

8. ANSI C63.6 (1988), American National Standard For Electromagnetic Compatibility -- Open Area Test Site Measurements -- Guide For The Computation Of Errors.

9. ANSI C63.7 (1988), Guide For Construction Of Open Area Test Sites For Performing Radiated Emissions Measurements.

APPENDIX

This Appendix presents the following documents for the reader's convenient reference:

1. RDF Products Antenna Test Site Qualification Report - This document describes the 1-meter test site employed by RDF Products for DF system sensitivity measurements and provides site attenuation test data.

2. DF System Sensitivity Test Worksheet - This document is provided as a form that facilitates orderly data collection during the course of DF sensitivity testing. The form may be reproduced as required.

3. ANTDATA3 DF System Sensitivity Test Reports - These documents are sample test reports generated by the software program ANTDATA3, a test program that accepts the raw data taken during the course of DF system sensitivity testing, computes sensitivity, and generates a printed test report. The sample reports are for a RDF Products Model DMA-1315R2 Mobile Adcock DF Antenna, and are produced using actual data taken from measurements made at the RDF Products 1-meter test site.

In addition, the following DOS software programs are provided on the RDF Products Publications CD:

1. RDFUTIL1 - DF Miscellaneous Computation And Conversion Program. This program performs various computations and conversions that are useful in RF, DF, and antenna work.

2. ANTDATA3 - DF System Sensitivity Computation Program And Summary Test Report (see description on this page above).

RF Products MEMO

RF Products
6476 Bounty Court
San Diego, CA 92120
(619) 583-2024 (Tel/Fax)

To: File

From: Alex J. Burwasser

Subject: RDF Products 1-Meter Open-Area Antenna Test Site Qualification Report

Date: December 8, 1994

==

A. OVERVIEW

This report documents the qualification of the RF Products 1-meter open-area antenna test site for vertically-polarized signals in the 80-520 MHz range. The report begins with a description of the site, followed by an account of the test methodology employed, which in turn is followed by a comparison of theoretical site attenuation with that actually established by careful measurement. These test results are discussed at the conclusion of this report.

B. SITE DESCRIPTION

The RF Products open-area antenna test site is located atop a flat horizontal roof directly adjacent to the main building. The flat roof measures 11' 3" x 26' 5", and is elevated 8' above ground. It is longitudinally adjacent to the roof of the main building, which slopes upward and away from the flat roof. The roof of the main building is fabricated with wooden shingles covering tar paper. All vent pipes were either removed or replaced with plastic substitutes. A tall metal mast atop the roof and its supporting metal guy wires were removed. Nearby vegetation was either removed or trimmed back.

The flat roof is completely covered with 1/4" mesh galvanized steel "hardware cloth" to provide a large continuous, high-conductivity ground screen. Adjoining strips of hardware cloth are soldered together at 12" intervals to ensure excellent conductive continuity. The hardware cloth is nailed down to the roof for best flatness.

The two designated test antenna locations are positioned 1 meter apart near the center of the flat roof along its central longitudinal axis with underlying 3' wide galvanized steel sheets arranged so that the direct path between the two antenna locations has the benefit of a solid (rather than meshed) ground screen. These steel sheets are in turn soldered along their edges directly to the underlying hardware cloth at 9" intervals, both for mechanical stability and conductive continuity.

Two DTI-420 Reference Monopole Antennas were then carefully positioned at the designated test antenna locations. The 20' feed cables were brought directly away from the DTI-420s in such a fashion that they were kept flat to the ground screen and draped over the exposed long side of the flat roof down to the operator's console. The operator's console is located directly underneath the flat roof and ground screen, both to provide protection from weather and to prevent test equipment and operating personnel from inducing proximity effects that might impact site accuracy.

C. SITE ATTENUATION MEASUREMENT PROCEDURE

Site attenuation measurements were conducted with a Hewlett-Packard Model 4396A Spectrum/Network Analyzer. To offset antenna feed cable losses, the two feed cables were first connected "back-to-back" (using a double BNC female adaptor) and the analyzer calibrated in such a fashion as to normalize subsequent measurements to account for cable losses.

The two feed cables were then reconnected to the DTI-420 Reference Monopole Antennas. The telescoping aerials were adjusted in height for resonance at 80 MHz (the lowest test frequency), and the attenuation measured at 80 MHz was then read from the analyzer. This measured attenuation was then recorded as the site attenuation at 80 MHz. This procedure was then repeated for the remaining test frequencies. The test results are presented in the table below.

D. SITE ATTENUATION THEORETICAL COMPUTATIONS

Since measured site attenuation is meaningful only when compared against theoretical site attenuation under the same conditions, the results of the theoretical computations are also presented in the table below for comparison. Since the separation between the two antennas is not sufficient at many of the test frequencies to permit standard far-field site attenuation equations to be employed, near-field modeling had to be used. This was accomplished using the antenna modeling software package Antenna Optimizer-Professional (Version 6.35) published by Brian Beezley of Vista, California.

E. TEST RESULTS

The test results are as follows:

	Measured Site	Computed Site	
Test Freq., MHz	Atten., dB	Atten., dB	Error, dB
80.0	19.6	19.9	-0.3
90.0	20.6	20.4	+0.2
100.0	20.9	20.9	0.0
110.0	21.4	21.3	+0.1
120.0	21.9	21.8	+0.1
130.0	22.3	22.2	+0.1
140.0	22.9	22.7	+0.2
150.0	23.8	23.1	+0.7
160.0	24.8	23.5	+1.3
170.0	24.8	23.9	+0.9
190.0	24.4	24.8	-0.4
210.0	23.9	25.5	-1.6
230.0	26.3	26.2	+0.1
250.0	27.4	26.8	+0.6
270.0	26.8	27.4	-0.6
295.0	28.6	28.0	+0.6
320.0	28.4	28.7	-0.3
345.0	29.4	29.3	+0.1
370.0	30.6	29.9	+0.7
395.0	30.5	30.4	+0.1
420.0	30.2	30.9	-0.7
445.0	31.1	31.4	-0.3
470.0	31.6	31.9	-0.3
495.0	31.8	32.2	-0.4
520.0	31.8	32.7	-0.9

As can be seen from the above table, site attenuation is well within 1 dB at most test frequencies, with a worst-case error of 1.6 dB at 210 MHz. Even this worst-case error is well with the 3 dB limit specified by FCC Document OET-55 and the 4 dB limit specified by ANSI Standards C63.4 - C63.7. The RDF Products 1-meter open-area antenna test site is thus demonstrated to be well-qualified for vertically-polarized signals in the 80-520 MHz range.

Note: A similar test was subsequently successfully conducted for the RDF Products elevated test site at the Arizona production facility (see discussion in Section III-E and Figures 8 and 9).

DF SYSTEM SENSITIVITY MEASUREMENT WORKSHEET

DF ANTENNA MODEL #: **S/N:**

RECEIVER/PROCESSOR TYPE: **IF BANDWIDTH (kHz):**

INTEGRATOR NOISE BANDWIDTH (Hz): **NOTES:**

SENSITIVITY THRESHOLD CRITERION:

TEST FREQ MHZ	SIG GEN OUTPUT dBm	CABLE LOSS dB	TX ANT GAIN dBi	NEAR-FIELD GAIN CORR FACTOR dB	NEAR-FIELD PHASE CORR FACTOR dB	ANTENNA SPACING METERS	TX ANT AERIAL HT IN	MISC

TEST ENGINEER: ____________________ **TEST DATE:** ___________ **PAGE**___**OF**___

** DF SYSTEM SENSITIVITY SUMMARY TEST REPORT **

DF ANTENNA MODEL:	DMA-1315R2 (DAA-142 VHF AERIALS ONLY)
SERIAL NUMBER:	94EAE167
RECEIVER/PROCESSOR TYPE:	ICOM R7100/DFR-1000 (AUDIO INTERFACE)
IF BANDWIDTH (kHz):	15
INTEGRATOR NOISE BANDWIDTH (Hz):	1.5
SENSITIVITY THRESHOLD CRITERION:	6 DEGS RMS BEARING JITTER (20 dB SNR)
TEST DATE:	12-20-1994
TEST ENGINEER:	A. J. BURWASSER

TEST FREQ MHz	SIG GEN OUTPUT dBm	CABLE LOSS dB	TRANSMIT ANTENNA GAIN dBi	NEAR-FIELD GAIN CORR FACTOR dB	NEAR-FIELD PHASE CORR FACTOR dB	ANTENNA SPACING METERS	** SENS uV/m
80.000	-81.50	0.80	0.00	2.64	1.97	1.00	7.82
90.000	-83.50	0.85	0.00	2.21	1.83	1.00	6.59
110.000	-90.00	0.97	0.00	1.61	1.17	1.00	3.56
120.000	-92.50	1.03	0.00	1.39	0.92	1.00	2.80
130.000	-95.50	1.07	0.00	1.21	0.73	1.00	2.06
140.000	-96.50	1.08	0.00	1.07	0.57	1.00	1.89
160.000	-100.00	1.15	0.00	0.84	0.25	1.00	1.34
170.000	-101.50	1.19	0.00	0.76	0.00	1.00	1.16
190.000	-105.50	1.34	0.00	0.62	0.00	1.00	0.73
210.000	-105.50	1.34	0.00	0.52	0.00	1.00	0.74
230.000	-103.50	1.44	0.00	0.44	0.00	1.00	0.93
250.000	-99.50	1.51	0.00	0.38	0.00	1.00	1.48
270.000	-98.50	1.58	0.00	0.33	0.00	1.00	1.65

```
M    +----+----+----+----+----+----+----+----+----+----+   0.0
I    :                            *    *                :
C    :                       *              *           :
R    :                    *                      *      *
O    :            *  *                                  :
V    +    -    -    -    -    -    -    -    -    -    +   2.5
O    :          *                                       :
L    :       *                                          :
T    :                                                  :
S    :                                                  :
     +    -    -    -    -    -    -    -    -    -    +   5.0
P    :                                                  :
E    :                                                  :
R    :  *                                               :
     :                                                  :
M    +    -    -    -    -    -    -    -    -    -    +   7.5
E    *                                                  :
T    :                                                  :
E    :                                                  :
R    :                                                  :
     +----+----+----+----+----+----+----+----+----+----+  10.0
   80.000   118.000   156.000   194.000   232.000   270.000
                        FREQUENCY (MHz)
```

RF PRODUCTS - SAN DIEGO CA

** DF SYSTEM SENSITIVITY SUMMARY TEST REPORT **

DF ANTENNA MODEL:	DMA-1315R2 (DAA-071 UHF AERIALS ONLY)
SERIAL NUMBER:	94EAE167
RECEIVER/PROCESSOR TYPE:	ICOM R7100/DFR-1000 (AUDIO INTERFACE)
IF BANDWIDTH (kHz):	15
INTEGRATOR NOISE BANDWIDTH (Hz):	1.5
SENSITIVITY THRESHOLD CRITERION:	6 DEGS RMS BEARING JITTER (20 dB SNR)
TEST DATE:	12-20-1994
TEST ENGINEER:	A. J. BURWASSER

TEST FREQ MHz	SIG GEN OUTPUT dBm	CABLE LOSS dB	TRANSMIT ANTENNA GAIN dBi	NEAR-FIELD GAIN CORR FACTOR dB	NEAR-FIELD PHASE CORR FACTOR dB	ANTENNA SPACING METERS	** SENS uV/m
220.000	-85.50	1.27	0.00	0.46	0.00	1.00	7.53
235.000	-87.50	1.35	0.00	0.41	0.00	1.00	5.96
250.000	-88.00	1.41	0.00	0.36	0.00	1.00	5.62
270.000	-90.00	1.47	0.00	0.32	0.00	1.00	4.46
295.000	-93.00	1.52	0.00	0.27	0.00	1.00	3.16
320.000	-95.00	1.67	0.00	0.23	0.00	1.00	2.47
345.000	-94.50	1.67	0.00	0.00	0.00	1.00	2.69
370.000	-95.00	1.93	0.00	0.00	0.00	1.00	2.47
395.000	-96.00	1.88	0.00	0.00	0.00	1.00	2.21
420.000	-95.50	2.03	0.00	0.00	0.00	1.00	2.30
445.000	-93.50	1.95	0.00	0.00	0.00	1.00	2.92
470.000	-93.00	2.04	0.00	0.00	0.00	1.00	3.07
495.000	-93.00	2.08	0.00	0.00	0.00	1.00	3.05
520.000	-92.50	2.29	0.00	0.00	0.00	1.00	3.16

```
     M    +----+----+----+----+----+----+----+----+----+----+   0.0
     I    :                                                 :
     C    :                                                 :
     R    :                                                 :
     O    :                            *                    :
     V    +    -    -    - *  -*   *    -  * -    -    -    +   2.5
     O    :            *                        *   *   *   *
     L    :                                                 :
     T    :                                                 :
     S    :       *                                         :
          +    -    -    -    -    -    -    -    -    -    +   5.0
     P    :    *                                            :
     E    :  *                                              :
     R    :                                                 :
          :                                                 :
     M    *    -    -    -    -    -    -    -    -    -    +   7.5
     E    :                                                 :
     T    :                                                 :
     E    :                                                 :
     R    :                                                 :
          +----+----+----+----+----+----+----+----+----+----+  10.0
       220.000   280.000   340.000   400.000   460.000   520.000
                             FREQUENCY (MHz)
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