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WN-002

Web Note

BASICS OF THE WATSON-WATT RADIO DIRECTION FINDING TECHNIQUE

This Web Note discusses the basics of the Watson-Watt DF technique (the DF technique employed by all RDF Products DF equipment). The material is presented in an easy-to-read format suitable for readers more interested in practical applications rather than a highly technical discussion of purely theoretical issues.

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I HISTORICAL PERSPECTIVE AND OVERVIEW

The Watson-Watt DF technique is named after its inventor Sir R. A. Watson-Watt of Great Britain. Also known as the "twin-channel" DF technique, it was developed shortly after World War I. Although the earliest systems were very primitive by today's standards (largely due to the primitive nature of radio technology in general at that time), today's modern successors stand on the shoulders of the innovation and brilliance of Watson-Watt, Adcock, and the other prominent early 20th century pioneers of radio direction finding technology.

Although the Watson-Watt DF technique was one of the earliest DF techniques, it has stood up well to the tests of time. When considering bearing accuracy, sensitivity, listen-through capability, flexibility, compactness, and economy, it is arguably the best narrow-aperture DF technique available. RDF Products' implementation of the Watson-Watt DF technique using modern technology extends its performance and versatility even further.

II DF TECHNOLOGY OVERVIEW

In the most general sense, all non-rotating radio direction finding systems employ a DF antenna having an array of spatially-displaced aerials (three or more are required for non-ambiguous operation) that are illuminated by the received signal wavefront. The resulting voltages produced by these aerials exhibit characteristics (phase, amplitude, or both) that are then measured. Since these characteristics are unique for every received azimuth in a properly designed DF antenna, the wavefront angle-of-arrival (bearing) can be ascertained by appropriately processing and analyzing the aerial output voltages.

To be somewhat more specific, modern non-rotating DF systems tend to fall into one of two broad categories. In *phase-comparison* DF systems, three or more aerials are configured in such a fashion that the relative *phases* of their output voltages are unique for every wavefront angle-of-arrival. Bearings can then be computed by analyzing the relative phases of these output voltages. Phase-comparison DF systems include Dopplers and interferometers.

In *amplitude-comparison* DF systems, two or more directive antenna arrays are configured in such a fashion that the relative *amplitudes* of their outputs are unique for every wavefront angle-of-arrival. Bearings can then be computed by appropriately analyzing the relative amplitudes of these output voltages. Amplitude-comparison DF systems include Watson-Watts and Wullenwebers.

III OVERVIEW OF THE WATSON-WATT DF TECHNIQUE

As mentioned above, the Watson-Watt DF technique falls into the amplitude-comparison DF technique category. A basic single-channel Watson-Watt DF system is illustrated in block diagram form in Figure 1 below.

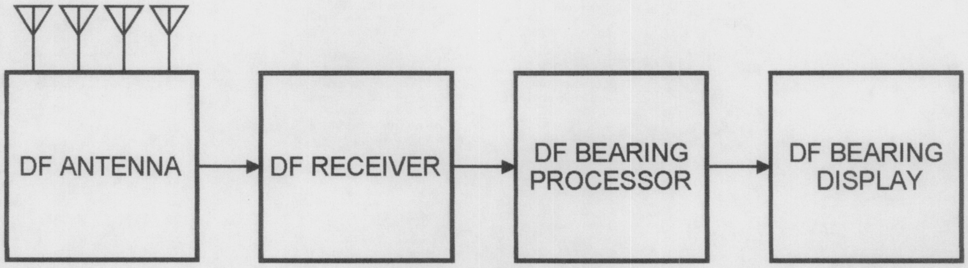


Figure 1 - **Watson-Watt DF System Simplified Functional Block Diagram**

A standard Watson-Watt DF system employs either Adcock or loop DF antennas, with Adcocks usually preferred because of their superior performance. Actually, the DF antenna is really an array of three separate but co-located antennas. Referring to a 4-aerial Adcock configuration, the first of these antennas is the N-S bi-directional array comprising the north and south aerials. As illustrated in Figure 2 below, the resulting figure-of eight azimuthal gain pattern consists of circular lobes with maximum sensitivity to the north and south and nulls to the east and west. This figure-of-eight gain pattern is obtained by applying the N and S aerial voltages to a *differencing* network that vectorially subtracts them (N-S) to produce what will ultimately become the "Y-axis" voltage.

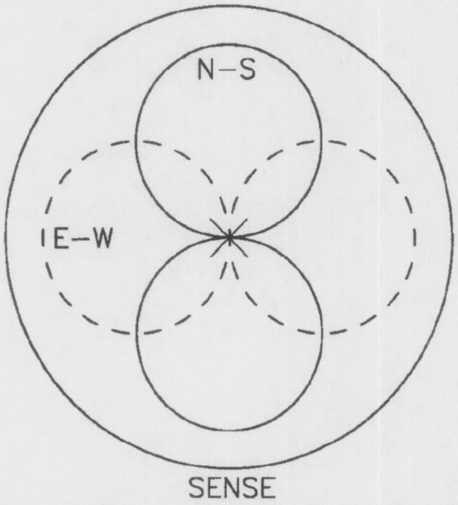


Figure 2 - Adcock DF Antenna Azimuthal Gain Patterns

The second of these antennas is the E-W bi-directional array comprising the east and west aerials. Again as illustrated in Figure 2, its azimuthal gain pattern is identical to that of the N-S bi-directional array, but perpendicularly oriented (as a consequence of the fact that the two arrays are physically at right angles to each other). This pattern is again obtained by applying the E and W aerial voltages to a differencing network that vectorially subtracts them (E-W) to produce what will ultimately become the "X-axis" voltage.

The third of these antennas is the omni-directional sense antenna. This omni-directional sense azimuthal gain pattern is also illustrated in Figure 2. The sense antenna is required to resolve a 180° ambiguity that would otherwise result.

Since the Watson-Watt DF technique falls into the amplitude-comparison category as discussed above, the purpose of the remaining components of the DF system (i.e., the DF receiver, DF bearing processor, and DF bearing display) is simply to measure the X- and Y-axis voltages and then compute and display the bearing. (As the reader will recall from the above discussion regarding amplitude-comparison DF systems, the relative amplitudes of these two voltages are unique for every wavefront angle-of-arrival). They can therefore be "mapped" into a corresponding bearing using an appropriate algorithm that performs a computation based on their ratio.)

Once the DF antenna fundamentals discussed above are understood, the basic principle of the Watson-Watt DF technique is easy to understand. Essentially, the voltages produced by the three co-located antennas discussed above are electronically processed in the DF antenna and then sent to the DF receiver as a single composite signal. The DF receiver then processes this signal in a fashion very similar to that of most any receiver, and then outputs a demodulated version of the composite signal to the DF bearing processor.

The DF bearing processor then further demodulates this composite signal to recover two voltages proportional to the X- and Y-axis voltages produced at the outputs of the bi-directional antennas as discussed above. The recovered X-axis and Y-axis voltages are used to compute the bearing (using an algorithm that examines the ratio of these two voltages). The information obtained as a result of this computation is then sent to the bearing display.

The above-mentioned Watson-Watt DF system components are further discussed below.

IV DF ANTENNAS

A. ADCOCKS

In theory, any antenna array that can produce the gain patterns similar to those illustrated in Figure 1 can serve as the DF antenna for a Watson-Watt DF system. In practice, Adcock and loop antenna arrays are by far the most common, with Adcocks being preferred because of their vastly superior performance.

The underlying principle of the Adcock DF antenna is the fact that if the outputs of two closely-spaced omni-directional antennas (usually monopoles or vertical dipoles) are vectorially subtracted, the resulting gain pattern will have a bi-directional figure-of-eight shape with nearly circular lobes as illustrated in Figure 2 above. This configuration is often referred to in the literature as an *Adcock aerial pair*. An Adcock DF antenna typically comprises two co-located perpendicularly-oriented Adcock aerial pairs. A typical monopole implementation of an Adcock DF antenna is illustrated in Figure 3 below. This particular model is the RDF Products Model DMA-1418B1, which is a 370-1000 MHz mobile DF unit intended to mount on vehicle roof-tops or the undersides of aircraft fuselages. Note that it is very important that monopole Adcock DF antennas be mounted atop large metallic ground-planes for proper operation.

As discussed in Section III above, an omni-directional sense antenna is a necessary component of an Adcock DF antenna so that a 180° ambiguity that would otherwise result can be resolved. Note that the DMA-1418B1 employs a *central sense* aerial for this purpose.

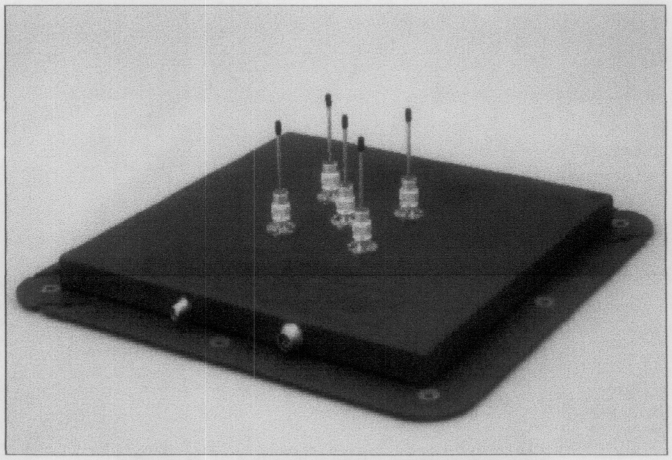


Figure 3 - DMA-1418B1 370-1000 MHz Mobile Adcock DF Antenna

It is also possible to obtain the necessary sense signal by vectorially summing the voltages from the four aerials comprising the two Adcock aerial pairs. This is known as a *derived sense* configuration, and is the technique employed by the majority of RDF Products DF antennas).

As mentioned above, Adcock DF antennas can also be constructed using vertical dipoles. The compelling advantage of dipole Adcocks is that the dipoles (unlike monopoles) do not require ground-planes and are therefore far better suited for mast-mounted applications as would be encountered in fixed-site and shipboard DF installations.

Adcock DF antennas are capable of covering wide frequency ranges. The primary constraint is aerial spacing (sometimes referred to as the DF antenna *aperture*). As mentioned above, the basic Adcock aerial pair requires closely-spaced aerials to generate the desired bi-direction figure-of-eight gain pattern with circular lobes. As the spacing becomes wider, these lobes begin to lose their circularity (i.e., they become elongated) which causes bearing errors. Good Adcock designs therefore limit the maximum spacing to 1/3 wavelength or so (at the high-end frequency) in order to limit this “spacing error”.

On the other hand, it is also undesirable for the spacing to be too narrow. Since a narrow-spaced Adcock DF antenna samples a smaller portion of the illuminating wavefront, sensitivity is reduced. In addition, balancing becomes more difficult with narrow spacing and the resulting phase and amplitude imbalances become a source of bearing error. Good Adcock designs therefore limit the minimum spacing to no less than 1/10 wavelength or so (at the low-end frequency) to limit sensitivity degradation and imbalance errors.

Spacing constraints thus limit frequency coverage to a ratio of 3- or 4-to-1 for good designs. An additional constraint is imposed by the bandwidth of the individual aerials. In principle, they are efficient only at and near their resonant frequency. It is therefore necessary to accept diminished sensitivity over substantial portions of the Adcock’s frequency range when frequency coverage is wide. Although some vendors specify frequency coverages far greater than 4:1 for their Adcock DF antennas, users should be aware that extreme performance compromises have necessarily been made to achieve such wide coverage.

Spacing constraints can be eased by adding more Adcock aerial pairs and using wider spacing. If four (rather than two Adcock) aerial pairs are employed (in a uniform circular array of eight aerials), maximum spacing can be extended from the 1/3 wavelength limit mentioned above up to a full wavelength. This correspondingly extends frequency coverage by a factor of three or so, thus allowing frequency coverage ratios of up to 10- or 12-to-1. Unfortunately, aerial bandwidth limitations become even more acute over such a wide frequency range. Also, the resulting Adcock DF antenna is much larger and more expensive. For this reason, most Adcock DF antennas employ only two Adcock element pairs.

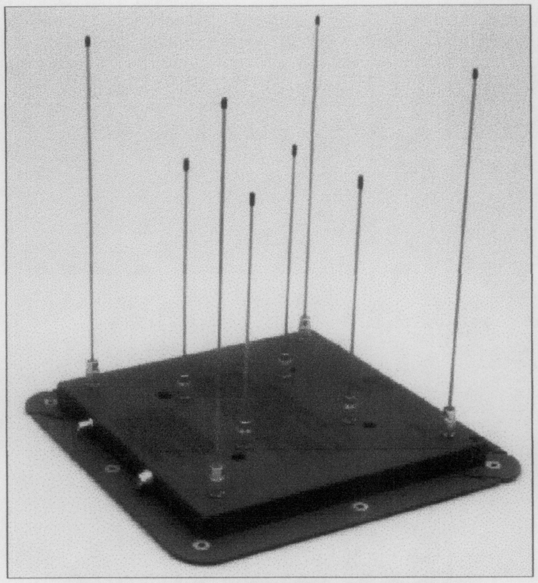


Figure 4 - **DMA-1315B1 80-520 MHz Mobile Adcock DF Antenna**

An alternative approach to extending frequency coverage is to co-locate two (or more) 4-aerial arrays on the same platform (for monopole Adcocks). This approach is superior from the standpoint that the aerial heights (and thus their resonant frequencies) can be better optimized for the band of interest. On the other hand, the design is greatly complicated by possible interaction between the two aerial sets that can cause serious performance degradation. Very careful engineering is required to prevent such interaction. A highly successful implementation of such an antenna is the dual-band 80-520 MHz RDF Products Model DMA-1315B1 illustrated in Figure 4.

For mast-mounted dipole Adcocks, the issue is more straightforward. Since the second array can be stacked higher up the mast (and thus away from the immediate vicinity of the first array), array interaction can be more easily avoided.

B. LOOPS

Since a loop antenna also provides the necessary bi-directional figure-of-eight gain pattern, it too can be used as the fundamental element of a DF antenna compatible with Watson-Watt DF systems (in place of the Adcock element pair). The most common implementation is the cross-loop configuration where two co-located perpendicularly-oriented loop antennas are substituted for the Adcock element pairs. A central vertical rod is usually employed as the sense antenna.

Ferrite loops (loops wound on ferrite rods) can also be employed, although their performance is usually not as good as that of cross-loops. Ferrite loops have the advantage of presenting a much lower physical profile for less visibility (important in covert applications).

Loop antennas should only be considered in cases where compactness is the overriding constraint (as in mobile DF applications under 30 MHz), since their performance is not nearly as good as that of Adcocks.

In comparison to Adcocks, loop performance is poor in two respects. First, their sensitivity is not nearly as good. To obtain even minimally usable sensitivity, loops must be tuned to resonance at the frequency of interest. Since tuned loops exhibit high Q (selectivity), they are inherently narrow-band in nature and cannot be used over a wide frequency range unless complicated variable tuning networks are employed. Although some vendors offer untuned ferrite loops covering the full HF range, their sensitivity is very poor. Ferrite loops are substantially less sensitive than cross loops in most cases.

The second shortcoming of loops is their extremely poor performance when receiving signals with a significant horizontally-polarized component. To explain, recall that the fundamental requirement of a Watson-Watt DF system is that the loop or Adcock aerial pair exhibit a bi-directional figure-of-eight gain pattern with circular lobes. The problem with the loop antenna is that *it meets this condition only when the illuminating wavefront is vertically-polarized.* If the illuminating wavefront is horizontally-polarized, severe pattern distortion results which in turn causes large bearing errors. Even a small horizontally-polarized component on a predominantly vertically-polarized wavefront can cause significant bearing errors. The problem becomes more severe as the elevation of the received wavefront increases.

In the early days of DF (when all DF antennas were loops), this problem was known as the "night-effect". During daylight hours when received signals were primarily vertically-polarized ground waves, these DF systems functioned reasonably well. At night, however, when skywave reception was predominant, DF operators noticed large and violent bearing fluctuations that greatly diminished the usefulness of these DF systems (skywave signals arrive at high elevation angels and contain large horizontally-polarized components). F. Adcock correctly understood what was causing this phenomenon and invented the Adcock DF antenna (patented in 1919 - British Patent No. 130490) as a result. The innovative feature of the Adcock aerial pair is that its inherently vertically-polarized aerials have the ability to almost completely reject horizontally-polarized signal components, and thus do not suffer from pattern distortion when illuminated by wavefronts having significant horizontally-polarized signal components. The invention of the Adcock DF antenna was a major break-through in DF technology.

Users should consider loop antennas only when Adcocks are too large for the application at hand. When loops are employed, users should be prepared to accept serious performance trade-offs in DF sensitivity and bearing accuracy. Users should also be aware that loops work especially poorly when mounted on aircraft.

For more information on loops versus Adcocks, see RDF Products Application Note AN-002 ("A Comparison of Loop and Adcock Antennas for Single-Frequency Fixed-Site DF Applications" - June, 1994). This paper provides a much more detailed analysis of this subject, although in more technical language.

V **DF RECEIVERS**

Fundamentally, the DF receiver accepts the output from the DF antenna (which is a representation of the voltages appearing at the X- and Y-axis bi-directional antenna outputs), provides the standard signal processing features common to all receivers (input preselection, frequency conversion, IF filtering, etc.) and converts these voltages to a baseband or near-baseband (low-frequency) format suitable for subsequent processing in the bearing processor.

The earliest Watson-Watt DF receivers were actually three carefully matched receivers - one for the X-axis bi-directional antenna output, the second for the Y-axis bi-directional antenna output, and the third for the omni-directional sense antenna output. Using one or more common local oscillators, these signals were ultimately converted down to very low IFs (intermediate frequencies) and then applied to the DF bearing processor. These systems were known as *3-channel* Watson-Watt DFs.

Since the requirement for three matched receivers was awkward and uneconomical, a *single-*

channel implementation of the Watson-Watt technique was eventually developed. Although this requires only one receiver, it also requires the use of a modulation scheme in the DF antenna so that all three DF antenna outputs (X-axis, Y-axis, and sense) can be combined into a single composite signal without loss of information.

Very briefly, the X-axis bi-directional output is fed to an amplitude modulator driven by an audio tone frequency to produce an AM (amplitude modulated) output. The Y-axis bi-directional output is similarly fed to an identical amplitude modulator that is driven by a *different* audio tone frequency, also producing an AM output. These two signals are then linearly combined. The composite signal can be shown to be a standard AM signal with simultaneous tone modulation at the two audio tone frequencies, with the modulation percentage of each tone modulation component being proportional to their respective X- and Y-axis bi-directional outputs. Although the details of this process are somewhat involved and beyond the scope of this discussion, the important point to keep in mind is that *the DF antenna sends a composite dual-tone modulated AM signal containing all the information necessary to compute the bearing to a single DF receiver, and that there is no loss of information from the DF antenna as a result of this process.*

The DF receiver must have an AM demodulator that detects this composite AM signal and recovers the two tones. *The relative amplitude of these two recovered tones is identical to the relative amplitude of the DF antenna X- and Y-axis bi-directional output voltages.* These recovered tones are then applied to the DF bearing processor.

Of course, the receiver can also have additional demodulators as well (FM, CW, SSB, etc.) to facilitate audio listen-through as required. Note however that the other demodulators must operate concurrently with the AM demodulator if simultaneous DF and listen-through capability is desired.

Most modern implementations of the Watson-Watt DF technique are single-channel. Although some 3-channel Watson-Watt DF systems are still made, the extremely high price of these systems prohibits their use in all but the most high-end DF applications.

VI DF BEARING PROCESSORS

A single-channel Watson-Watt DF bearing processor accepts the two tones from the DF receiver AM demodulator, separates them, and then rectifies them to convert them into two DC voltages that are proportional to the respective tone amplitudes. These two resulting DC voltages are therefore also proportional in amplitude to the DF antenna X- and Y-axis voltages as discussed above.

These two DC voltages are then passed through integrators to reduce noise. In most DF bearing processors, selectable integration time is employed to best match the duration of received signals. All RDF Products DF bearing processors include hardware-implemented integrators with selectable integration times of 80 milliseconds (Fast), 150 milliseconds (Medium), and 375 milliseconds (Slow). Integration times can be extended in software to as much 10 seconds (using the provided software), although integration times of over one second are rarely useful.

Some DF bearing processors also allow operators to enable a track & hold feature. Track & hold "freezes" the bearing for a specified time interval after the signal has disappeared. Many DF users find track & hold helpful in tracking short-duration pulsed signals. All RDF Products DF bearing processors include this feature.

Following integration and any possible track & hold action, the X- and Y-axis DC voltages are then sent to the bearing display.

VII DF BEARING DISPLAYS

Essentially, the DF bearing display accepts that X- and Y-axis DC voltages, computes the bearing using a 4-quadrant arc-tangent algorithm, and then displays the resulting bearing on whatever display device is employed.

This process is greatly simplified if the bearing display is a two-axis magnetically-controlled mechanical pointer. In this case, the X- and Y-axis DC voltages are simply applied to the deflection coils (after any necessary amplification and level-shifting). With this simple scheme, the bearing computer and display are all combined in a single device. In this context, the mechanical pointer can be thought of as a simple analog bearing computer. Because of this simplicity and the fact that magnetically-controlled mechanical pointers could be constructed with the primitive electro-mechanical technology that existed in the early 20th century, mechanical pointers were widely used in early DF systems.

When cathode ray tubes (CRTs) became available in the 1930s, they began to replace the mechanical pointers because of their faster response and ability to provide magnitude as well as azimuthal information (that is, to provide the bearing information in a *polar* format). This magnitude information is extremely important in mobile DF applications where it serves as a bearing *quality* indicator, thus greatly assisting the operator in discriminating between desired signals and undesired noise and reflections. DF systems employing mechanical pointers as bearing displays cannot make this discrimination and thus perform poorly in the dynamic DF environments encountered in mobile DF applications. With CRTs, it is necessary to first "chop" the X- and Y-axis DC voltages into voltage ramps (to obtain the necessary trace sweep) prior applying them to the CRT vertical and horizontal deflection plates. Otherwise, the concept is very similar in principle to that of the two-axis mechanical pointer discussed above. Again, the CRT serves both as an analog bearing computer as well as a DF bearing display. The original RDF Products DF receivers and bearing processors employed CRTs because of their excellent mobile DF performance. Current RDF Products DF receivers/processors employ modern TFT liquid crystal bearing displays (see Figure 5). The fast response time and brilliance of modern TFT displays makes them excellent successors to the venerable CRTs.

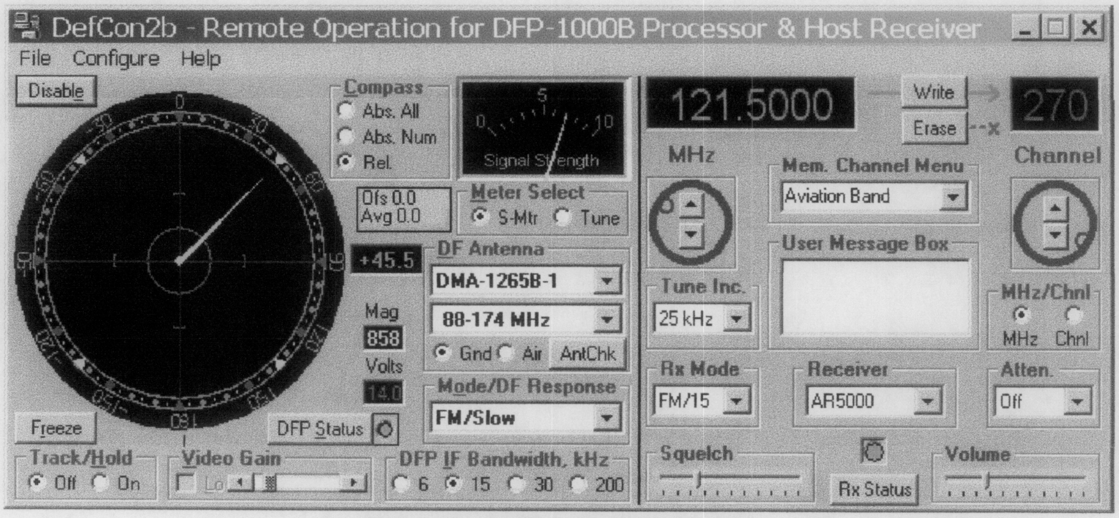
In more recent years, azimuth ring and numeric displays have found their way into DF systems. For these types of displays, the X- and Y-axis DC voltages must first be converted to a digital format using an analog-to-digital converter. The resulting digitized representation of these two voltages is then sent to a microprocessor, which in turn computes the bearing in software using a 4-quadrant arc-tangent algorithm. Once the bearing has been computed, the microprocessor can drive one or more of several different display formats, including azimuth rings and numeric displays.


Figure 5 - DFP-1000B DF Bearing Processor/Display

Azimuth rings comprise a circular array of light emitting diodes (LEDs) or liquid crystal display (LCD) elements, one of which illuminates to indicate azimuth. The azimuth ring display is really little more than a modern implementation of the early mechanical pointer display discussed above, its primary advantages being speed and economy. Note, however, that since ring displays can practically employ only a limited number of display elements, bearing resolution is typically limited to 5 or 10 degrees. Although azimuth ring displays are widely used in many low-end DF systems, their performance is poor in comparison to the real-time polar bearing display discussed above. In fact, the primary rationale for the use of the ring display is manufacturing economy, even though this economy is achieved at the expense of seriously diminished performance. Azimuth ring displays are also used in some higher-end DF systems as well, but typically in conjunction with a numeric bearing display as discussed below.

Numeric bearing displays are typically 3-digit devices allowing azimuthal resolution of 1 degree. Their primary advantage is their improved accuracy and resolution as compared to all of the afore-mentioned bearing displays. Mechanical pointer and polar bearing displays are seldom accurate to better than 2-3 degrees (unless they have been individually calibrated) and are therefore less appropriate for fixed-site DF applications where exceptional bearing accuracy is required. Azimuth rings are accurate, but are typically limited in resolution to 5 degrees or so as discussed above. Although numeric bearing displays are well-suited for many fixed-site DF applications, they are almost useless for mobile DF applications (the operator will not be able to interpret the jumble of numbers that appear when bearings are changing). Professional-quality DF systems therefore supplement the numeric bearing display with a real-time polar bearing display.

Bearing displays can also be software emulated on computers. To facilitate this all current RDF Products DF receivers/processors have RS-232 outputs so that the equipment can be fully computer operated. Figure 6 illustrates the main screen for DefCon2b, which is RDF Products' Windows-based operating software for all of its current DF processors/receivers. Note that both real-time polar as well as numeric bearing displays are presented. For users preferring to write their own software, RDF Products publishes a detailed RS-232 protocol specification.



DefCon2b - Remote Operation for DFP-1000B Processor & Host Receiver

Compass: ● Rel.

Ofs 0.0
Avg 0.0

+45.5

Mag 858

Volts 14.0

Meter Select: ● S-Mtr

DF Antenna: DMA-1265B-1, 88-174 MHz, ● Gnd

Mode/DF Response: FM/Slow

Track/Hold: ● Off

DFP IF Bandwidth, kHz: ● 15

121.5000 MHz

270 Channel

Mem. Channel Menu: Aviation Band

Tune Inc.: 25 kHz

MHz/Chnl: ● MHz

Rx Mode: FM/15

Receiver: AR5000

Atten.: Off

Figure 6 - DefCon2b Main Screen

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