VOL. 15 NO. 6 NOVEMBER/DECEMBER 1988

Spinning DF Antenna Systems

WATKINS-JOHNSON COMPANY
Tech-notes

Modern electronic warfare has reached an extremely high level of sophistication. The literature speaks of ESM, ECM, and ECCM. One can imagine this sequence becoming an infinite series. But key to all aspects of electronic warfare is a knowledge of the location of target emitters or, at the very least, the direction of arrival of their emissions. Direction finding systems provide the means whereby this information may be obtained.

Direction finding systems may be divided into two general categories: monopulse and rotating. Monopulse DF systems consist of broad-beam antennas (often an array) coupled to a bank of receivers. These, in turn, feed a complex DF processor, where a direction of arrival is determined for each and every pulse received. This type of DF has the advantage of speed and minimal input requirements (one pulse) for determining the direction of arrival. Its disadvantages include high cost and, often, low sensititivy.

Rotating DF systems consist of a single, narrow-beam antenna coupled to a single receiver which, in turn, feeds a relatively simple DF processor. This processor can be either manually controlled to determine the emitter bearing, or the data can be fed into an automatic DF algorithm. Spinning DF systems have the advantages of simplicity (and, therefore, low cost) and high sensitivity. Their disadvantages include the necessity for integrating data from a number of antenna turns, which implies several seconds to determine a bearing. Also, since the antenna has a narrow beam, the instantaneous field of view is limited, even though the antenna spins at high speed. Table 1 summarizes the characteristics of monopulse and spinning DF systems.

Historically, the controversy between these general types of DF systems has raged, with each technique having its supporters and detractors. The argument boils down to a trade-off between the high probability of intercept, instantaneous DF, and high cost of the monopulse system and the high sensitivity, simplicity, and low cost of the spinning system. Ultimately, however, the basic issue remains the same — determining the direction of arrival of emissions.

Ever since the first wartime use of radar, the need to determine the location of the radar installation (or, at the very least, the direction from which the

PARAMETER	MONOPULSE TECHNIQUE	SPINNING TECHNIQUE
Gain	Low-High	High
Beamwidth	Broad	Narrow
Free-Space Accuracy	High	High
Complexity	Matched Channels	Single Channel
Reaction Time	Instantaneous	Requires Several Pulses for Good Accuracy
System Sensitivity	Low	High
Vehicular Installation Requirements	Minimal, even Flush-Mounted	External to Vehicle
Reliability	Matched Channels Degrade with Age	Drive System and Rotary Joint Failures
Cost	Expensive	Inexpensive
Automatic DF	Automatic	Manual or Automatic

Table 1. Comparison of Monopulse and Spinning DF Techniques.

radar signals emanate) has been the first step in its neutralization. Both the radar signals themselves and the means of detecting them have become more sophisticated over the past 45+ years. In many applications, however, the spinning DF system is still the best choice. This article will consider the characteristics of modern spinning DF systems and suggest future developments from which these systems will benefit.

Typical Spinning DF System Elements

Figure 1 is a simplified block diagram of the typical spinning DF system. Although these systems include receivers and, usually, an omnidirectional antenna, these elements of the system will not be addressed in this article. The other elements are discussed below.

The antenna itself can be any of a number of types. (The performance trade-offs among the various possible antenna types will be discussed below.) The main characteristic of all of these antennas is directivity. For spinning DF purposes, an antenna with high directivity is essential. Depending on the application, this directivity may be only in the azimuth plane, or in both azimuth and elevation. Qualitatively speaking, directivity implies a significant difference in amplitude between the front lobe of the antenna and the back lobe. This is an important definition; actual antenna beamwidth is less significant than simply having a clearly distinct main lobe. That is, one can DF with some degree of confidence as long as the main beam of the antenna is easily distinguishable from any other beam. Figure 2 shows two typical antenna beams: that of a narrow beam directional antenna and that of a wide beam directional antenna.

Being able to determine direction of arrival is only half of the battle. One is also interested in achieving the highest possible accuracy. Generally, DF accu-

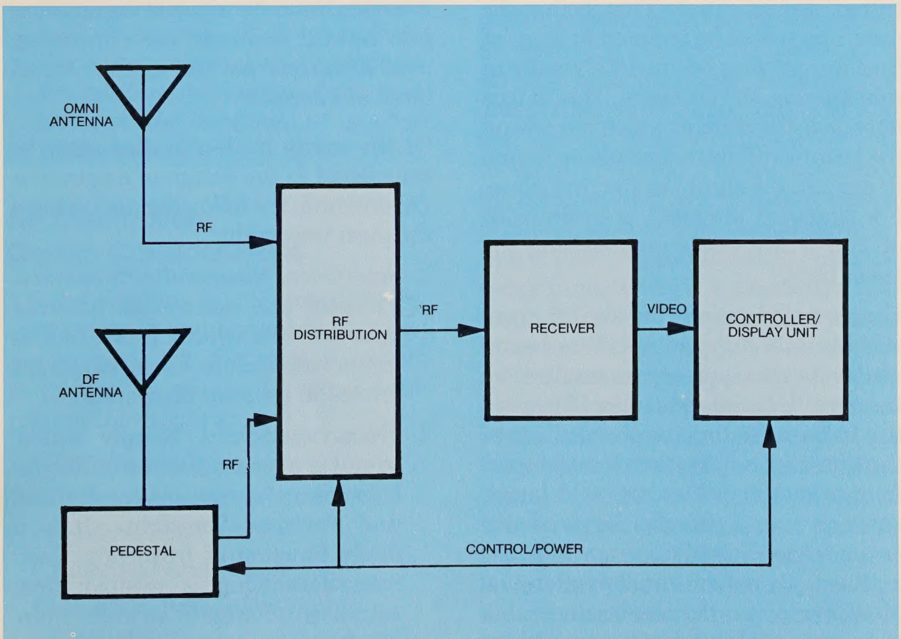

Figure 1. Typical spinning DF system block diagram.

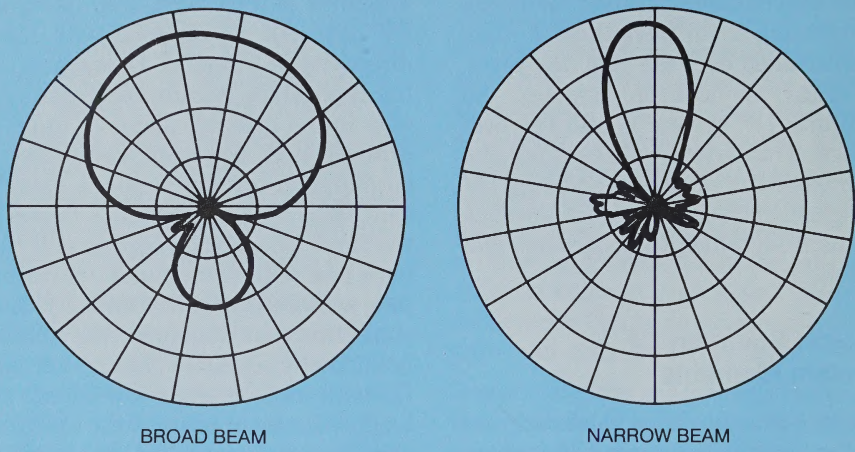

Figure 2. Typical antenna beams.

racies on the order of $\frac{1}{10}$ of a beamwidth can be achieved. It should be clear from Figure 2 that a better fix on the direction of arrival can be obtained from the narrow-beam antenna than from the broad-beam one, all other things being equal. This being the case, one would be tempted to suggest that minimizing beamwidth results in maximizing DF accuracy. This is true only up to the point at which narrowing the beamwidth further results in failure to acquire the signal in the first place. For practical purposes, a beamwidth of 2 or 3 degrees is approaching the lower limit.

For most applications, physical size constraints set the upper limit of the beamwidth. As the size becomes smaller, the beamwidth becomes broader. There are two factors affecting the physical size of the antenna: application/location and frequency range of operation. A larger antenna can generally be used for groundbased installations, while aircraft usually require smaller antennas. Moreover, given the minimum usable limit of 2 or 3 degrees of beamwidth at the upper end of the band, the maximum antenna size is effectively set. This, in turn, determines the beamwidth at the low end of the frequency band. The broader the frequency band of interest, the more pronounced this phenomenon becomes. For this reason, it is often desirable to break the antenna into several elements, each operating over a narrow portion of the overall band of interest.

Of the many trade-offs that must be considered in the design of a spinning DF antenna, the following are perhaps the most important:

1. *Size/Gain/Beamwidth/Sidelobes.* Physical size determines antenna gain and beamwidth. It also has an impact on sidelobe levels, which are related to reflector illumination.

2. *Frequency/Squint.* Simply stated, squint is a measure of the difference between an antenna's mechanical and electrical boresights. It is a direct function of frequency. Their interrelationship is twofold: first, squint can change in an indeterminate fashion as frequency changes; second, the broader the frequency

range, the greater the number of squint correction factors that will have to be considered to determine an accurate angle of arrival.

3. *Size/Low Frequency.* The laws of physics decree that antenna aperture size varies inversely with frequency. So, the lower the desired frequency of operation, the larger the aperture must be. This rule runs precisely counter to the desires of airborne DF antenna designers and users, who would wish such antennas to be as small as possible.
4. *Elevation Performance/Size.* For the same reason as above, achieving good elevation coverage, including uniformity of performance as a function of elevation angle, is another trade-off that must be considered.
5. *Polarization/Frequency Range/Size.* Most emitters of interest are linearly polarized. To improve the response of the DF antenna, the designer selects the polarization that will not null out signals of interest. Since the exact polarization depends on the relative orientation of the emitter and the receiver, it is often indeterminate.

RF Distribution Design Considerations

RF distributions for spinning DF systems tend to be highly specialized — that is, designed for the specific system in which they are used. Factors determining the design are:

- Tuner noise figure
- System sensitivity requirements
- Receiver band breaks
- Antenna band breaks
- Distance from antenna to rf distribution
- Distance from rf distribution to tuner
- Type of cable or waveguide being used
- Switched or multiplexed band breaks

Since each application is different, little can be said of a general nature about rf distribution design. However, most modern applications demand maximum system sensitivity and dynamic range. These can be obtained by locating the rf distribution as close as possible to the antenna, preferably directly at the antenna output. This sets the noise figure of the system before any lengthy cable runs. Minimizing the noise figure maximizes system sensitivity. The correct selection of gain stages can then optimize the overall performance of the system.

Pedestal Design Considerations

Spinning DF pedestals are subjected to severe loads. Spinning at a relatively high speed is not the difficulty. The problem comes in the sector-scan mode of operation, where the pedestal is turning back and forth between predetermined sector limits. The wear and tear on the pedestal caused by this mode of operation can be minimized by commanding the pedestal into a profiled acceleration/deceleration so that it does not run full speed into the sector limit, where it is required to stop instantaneously; nor must it accelerate to top speed instantly after leaving the sector limit in the opposite direction. Nevertheless, the pedestal is the component of the system subjected to the most severe stresses in normal operation. Add to this the fact that it consists of moving parts, and it is clear that the pedestal must be well designed to minimize scheduled maintenance, and at the same time maximize system MTBF.

Moreover, for most applications, the pedestal must be small and lightweight.

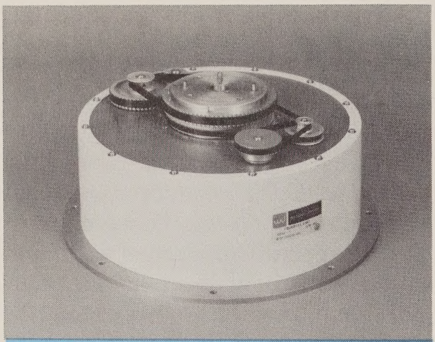

Figure 3. WJ-49726 pedestal.

This is certainly true for airborne and most shipboard applications. Although not nearly as important, it is also true for most groundbased systems, since the pedestal usually either sits on the roof of a shelter, on top of a tower, or on a vehicle of some sort. In all of these cases, it is usually highly desirable to keep the size and weight of the pedestal down. Unfortunately, small, lightweight pedestals are exactly the opposite of what the mechanical engineer would like to see in these applications.

A good compromise solution to these requirements is a belt-driven pedestal such as the one shown in Figure 3. The belt drive is small and lightweight, yet capable of handling the loads imposed by the spinning DF antenna. This is especially true if Kevlar-reinforced belts are used. Kevlar threads add significantly to the lifetime of the belts without the risk of damage to pulleys threatened by steel-reinforced belts. From a maintainability point of view, the belt-driven pedestal is also a good choice. Careful attention to design detail can make it a simple matter to replace belts or other parts as required.

Controller/Display Design Considerations

The spinning DF pedestal is controlled by means of a DF system controller. This unit also usually houses a display, graphically representing the direction of arrival of the received signal. The operator then determines the direction of arrival by placing a cursor over the displayed "feather" and reading the angle of the cursor from a display.

Accomplishing the two goals of directing the motion of the spinning DF pedestal and displaying the angle of arrival of received signals requires two functional parts: the control circuitry and the video processing/display circuitry. For the most part, design considerations affecting either of these functional parts are independent of the type of antenna employed, or of any other element of the system. In both cases, the fundamental questions are the same: how much of the function can be performed digitally and how much can be performed by software, thus minimizing the amount of hardware required.

The earliest DF controller/display units were built entirely around analog technology. The bearing information from the pedestal was in the form of analog voltages from synchros. The video from the receiver was processed through analog circuitry to create a polar display of signal amplitude versus angle of arrival that was then displayed on a CRT.

In order to capture the displayed signal for long enough to allow the operator to determine the angle of arrival, it was necessary to use some type of storage tube. The primary choices were either a variable-persistence or a bi-stable CRT. A variable-persistence CRT performs this time integration of data function by allowing the operator to decay the stored information at a set rate. Theoretically, this decay rate could be made arbitrarily slow; however, after some time the displayed data becomes unreadable. Moreover, permanent damage to the phosphor could occur if the same data is stored for too long a time.

The bi-stable storage tube was a better choice, in that it would store the information until it was "erased" by writing over the entire display. Although the storage retention time of the bi-stable display is somewhat longer than that of the variable-persistence CRT, it too, ultimately suffers the same drawbacks.

A partial solution to these problems was to combine a conventional CRT with digitally refreshed circuits. This was, however, at best a temporary solution and, in fact, most sytems continued to use the storage CRT.

This basic design approach has changed very little for many years. The advent of digital electronics made it possible to perform many of the analog circuit functions digitally, but even today most displays are CRTs. And, since the display is almost invariably a CRT (an analog device), there has been little impetus to do much of the processing digitally. After all, why convert from analog to digital, then back to analog again to display the data?

Today the situation is changing. This is largely owing to the availability of viable alternatives to the traditional CRT display. These include liquid crystal displays, plasma displays, and electroluminescent (EL) displays. All of these have at least one important feature in common: the interface to them is digital. Once a digital display is employed, the use of digital processing begins to make sense.

New Technologies for Spinning DF Antennas

The latest development in spinning DF antenna design is the low-profile antenna, shown in Figure 4. In this design, a cylindrical parabolic surface is used to create the azimuth pattern. A tapered horn is used to produce the elevation pattern. By selecting the horn flare angle and length, one can adjust the elevation beamwidth. Although the elements are inherently vertically polarized, external polarizers positioned at the aperture of each element can create other polarizations. In particular, antennas of this type with slant-linear polarization have been built.

As shown in Figure 4, each antenna element is very thin. This permits the use of several elements to cover a given frequency band. Each element can cover a 2:1 frequency band, with several elements stacked on top of each other as required to cover the desired frequency range.

This design has the following advantages over traditional spinning DF antennas:

1. *Azimuth and elevation beamwidth are independently controllable.* This is because the azimuth and elevation portions of the antenna are really two separate antennas. Having independent control of azimuth and elevation beamwidths gives the antenna designer another degree of freedom for controlling antenna gain.

2. *Squint is eliminated.* The azimuth cylindrical parabola is a machined part that can be held to very tight tolerances, and the alignment of the parabolic boresight with respect to the pedestal boresight can be held to similar tolerances. Equally important, the electrical boresight is invariant with frequency. The net result is a DF antenna with no squint.

3. *The antenna has a very low profile.* Broad frequency ranges can be covered by stacking a number of very thin elements. For example, an antenna covering 0.5 to 18 GHz will fit inside an envelope only nine

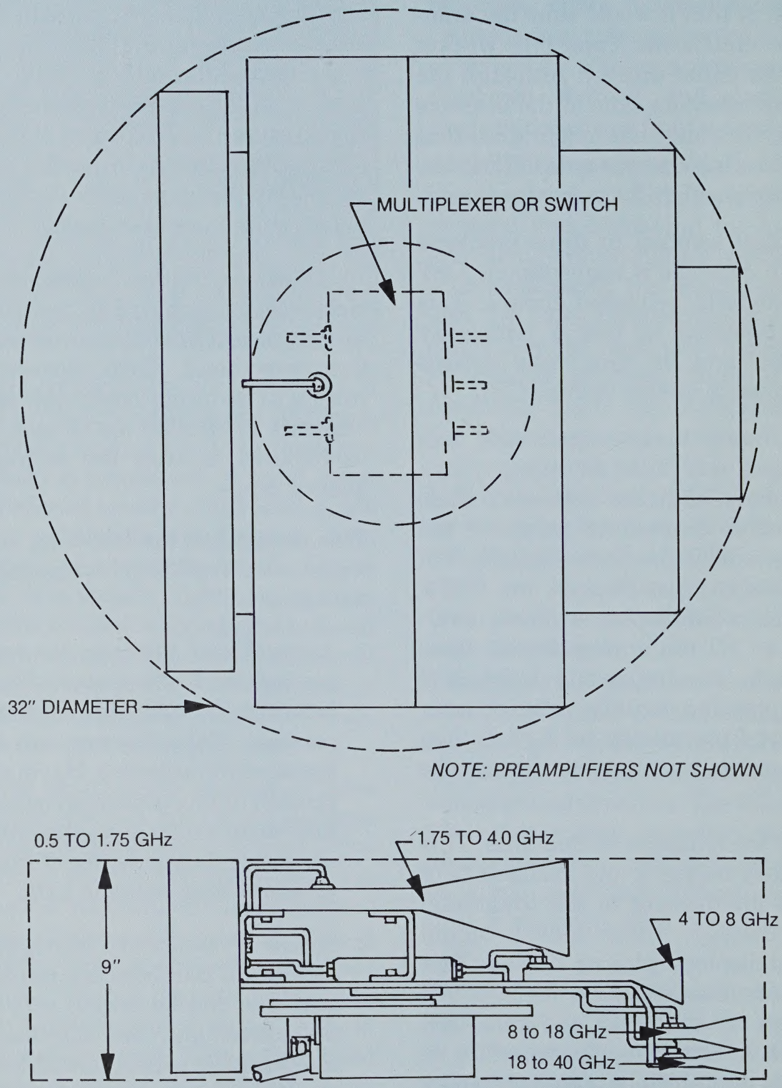

Figure 4. WJ49201 low-profile antenna.

inches high. This profile is ideal for airborne systems, and is advantageous for other applications as well.

4. *Low sidelobe levels.* The azimuthal parabola is deliberately under-illuminated, thus resulting in sidelobes that are typically 20 dB below the peak of the beam. Normally, such under-illumination would result in poor gain; however, being able to control the elevation beamwidth independently makes it possible to have both low sidelobes and high gain.

5. *There is no inherent limit to antenna system frequency coverage.* Additional bandwidth can be obtained by adding more elements to the stack.

6. *Slant-linear polarization* can be achieved over the entire bandwidth of the system. Slant-linear polarization is particularly useful for DF purposes. Although most signals of interest are linearly polarized, the exact polarization with respect to the DF antenna is indeterminate. Under these circumstances, slant-linear polarization is a most appropriate choice.

Taken together, these advantages mean better DF accuracy over broader frequency ranges in a smaller physical package.

New Technologies for Spinning DF RF Distributions

Two recent developments have had an impact on rf distribution packages for spinning DF applications. First, GaAs FET preamplifier bandwidths have increased. Instead of octave-band amplifiers, one can now obtain, without difficulty, preamplifiers that operate over two, or even three octaves. Such amplifiers greatly reduce the complexity and expense of rf distribution packages for spinning DF antenna systems. They also reduce the amount of space required to house the rf distribution components.

Second, GaAs FET preamplifiers to 40 GHz are now available. This extended frequency coverage allows one to field spinning DF systems covering the range from 0.5 to 40 GHz, consisting of a single low-profile antenna assembly, rf distribution, and controller/display unit. Moreover, the performance from 18 to 40 GHz will be comparable to that achieved in the lower frequencies.

The low-profile antenna itself is also a new technology affecting rf distributions, although it does so indirectly. The antenna is designed in such a way as to allow mounting of the preamplifiers directly on the output of the antenna elements. This eliminates all cable loss betweeen antenna and preamplifier and sets the system noise figure right at the output of the antenna. System sensitivity and dynamic range are thus independent of the distance between the antenna and the receiver.

New Technologies for Spinning DF Controllers

New technologies affecting the design and performance of spinning DF controller/display units can be summarized in one word: digitization. As noted above, the availability of displays accepting digital inputs has opened a whole new world in controller/display design and performance.

Figure 5 shows a functional block diagram of the WJ-49861 controller. The first feature of note is that the control and display electronics are completely digital. Digital position information comes to the controller from a digital shaft encoder on the pedestal. The received video is immediately digitized, after which it is further processed for display purposes. By the same token, digital commands are sent to the servo amplifier through the motor control circuitry. The servo amplifier then controls the movement of the pedestal.

The second feature of this unit is the EL display. This display offers the following advantages over a CRT:

1. *Reduced Volume.* The EL display's volume is about 10% of that of a conventional CRT. The implications of this size reduction are significant. A controller/display unit with an EL display can be packaged in a variety of configurations, including a number of shallow box concepts that are totally out of the question for a unit containing a CRT. This

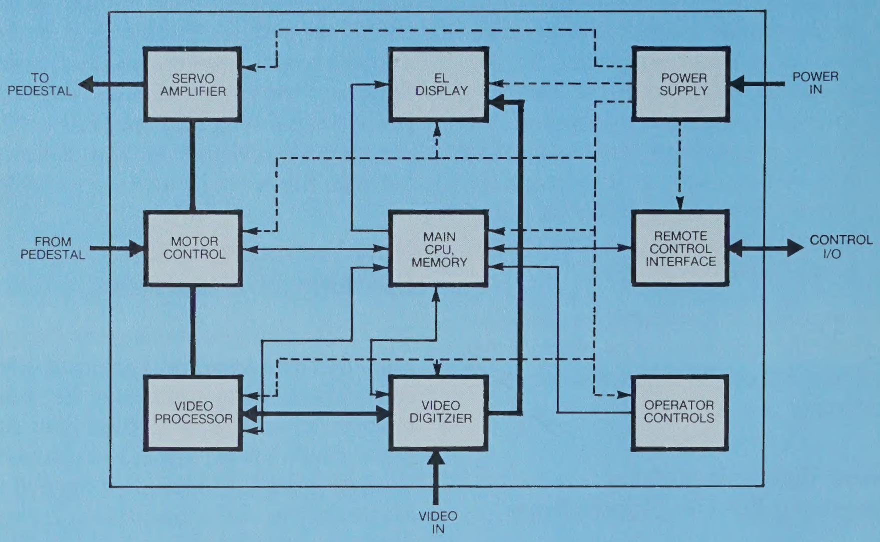

Figure 5. WJ-49861 controller functional block diagram.

provides a degree of design flexibility previously unavailable.

2. *Reliability.* Two factors contribute to the improved reliability of an EL display versus a CRT. First, the unit is completely solid state and is, therefore, inherently more reliable than tube technology. Second, the power requirements for an EL display are extremely benign compared to those for a CRT. The lifetime of the device is inversely proportional to the power being dissipated in it.
3. *Cost.* An EL display costs about 40% of the cost of a CRT graphics display.
4. *Availability of Support Hardware.* Compatible graphics circuit card assemblies (CCAs) are commercially available for EL displays. A number of these CCAs can be economically adapted to the needs of a polar display format.
5. *Compatibility with Night Vision Goggles.* Night vision goggles operate by enhancing the available light between approximately 600 and 900 nanometers. Light sources in this range either blind the operator or cause the goggles to protectively shut down. EL displays are available whose emitted light wavelength falls below the approximately 600-nanometer cutoff. For example, the display used in the WJ-49861 controller emits visible light at a wavelength of 585 nanometers.

The advantages of digital processing coupled with an EL display cannot be underemphasized. Digital video processing opens up new horizons. Where once an operator had to be content with a single display format (usually polar), digital video processing and display technology makes it possible to offer a number of different formats at minimal cost, each of which can enhance the ability of the operator to determine the angle of arrival of target emissions. The cost associated with generating these new displays is limited to nonrecurring software, which can

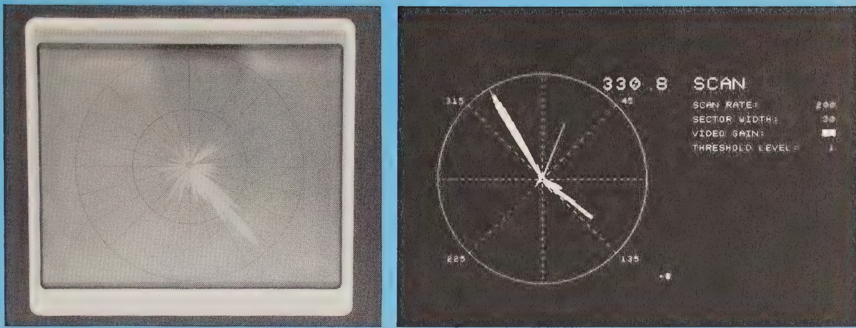

Figure 6. CRT versus electroluminescent display.

be amortized over a large number of units. Figure 6 through 9 illustrate this point.

Figure 6 shows the comparison of an analog CRT polar display and a digital EL polar display. The CRT display is very austere, showing only the received video in polar coordinates along with a bearing cursor. In contrast, the EL display not only shows *that* information, but also has alphanumeric data showing the bearing of the cursor and other system status information. Although this information may be available elsewhere on the front panel of the traditional controller, it is much more convenient to be able to see it without drawing attention completely away from the polar display.

The ability to display more information is a two-edged sword, however. One must ask and answer the question, when is there just enough informaton displayed for the user, and not too much? Fortunately, digital processing and software provide a solution to this dilemma as well. By creating different pages for the display, one can limit the amount of information displayed at any one time, while at the same time provide a greater variety of information than was possible using CRTs and analog techniques. Figure 7 is an example of this. This page of the WJ-49861 display is used for set-up purposes only. Using this display, the

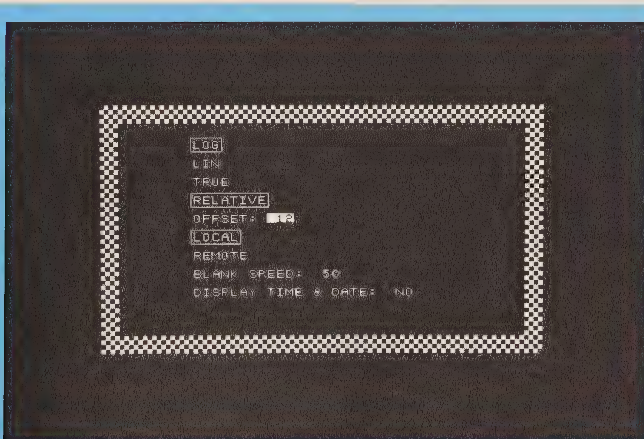

Figure 7. WJ-49861 display set-up page.

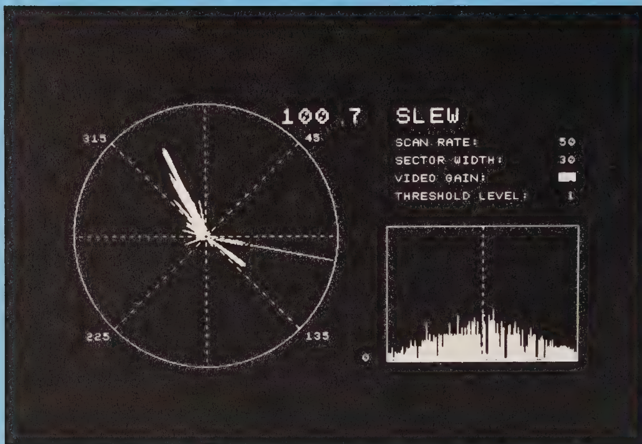

Figure 8. WJ-49861 magnified video display.

operator selects system parameters that are not likely to change often during the course of a mission. Once established, these parameters are stored in battery-backed RAM. The operator can then go to the operational display format, which does not keep this set-up information continually before his eyes.

The WJ-49861 controller also has a magnified video display, shown in Figure 8. This display is a rectilinear display of the video within ±4 degrees of the cursor angle. The display was created to take full advantage of the resolution obtainable from the digital video processing. The ability to generate this type of display is a direct result of being able to digitize and store video information — a capability unavailable in analog CRT systems. Improved resolution translates directly into increased DF accuracy.

DF accuracy can be increased in yet another way by virtue of digital video processing. The WJ-49861 has another display called *inverse video*. The value

Figure 9. WJ-49861 inverse video display.

of this display is in determining emitter bearing for very low-level signals. The traditional polar format, as shown in Figures 6 or 8, shows these signals as very short lines emanating from the center of the circle, where there is the least amount of resolution. Instead, the *inverse video* makes the circumference of the circle the point of zero video amplitude and builds the pattern towards the center, as shown in Figure 9. Now those low-level emissions appear in the area of maximum resolution, making it much easier to determine with accuracy their angle of arrival.

Future Directions for Spinning DF Systems

The advent of digital video processing presents the greatest near-term opportunity for improvements in spinning DF systems. At least three important future developments are worthy of note.

Automatic DF. Having already digitized and stored the video information, it becomes simply a matter of software manipulation to perform the angle of arrival determination automatically. There are already several algorithms for automatic angle of arrival determination. Selecting the best algorithm given the available information is the next challenge facing engineers involved in spinning DF systems. This is essentially the last step required to complete the automation of spinning DF controllers. All other functions performed by the controller, including the drawing of the display, can be handed off to a remote operator on a computer terminal. At the present state of the art, one has two choices: perform the actual DF function manually by moving the bearing cursor over the antenna "feather" as has always been done, or perform automatic DF by processing the controller's digital data elsewhere. A better alternative is to provide that information automatically from within the spinning DF controller.

Color Displays. Although not presently available, multicolor EL displays are not far in the future. Having such a display will open new opportunities for display enhancement, including tracking of multiple emitters, tagging emitters with frequency information, etc. Today's monochromatic solutions to these problems are less than adequate.

Faster Display Update Capability. One of the gating factors determining the quality of the information displayed is the update rate. Today's technology does not allow anything like real-time display update. Hence, the information derived from the display lags somewhat behind the data collection capability. Improvements in this area will undoubtedly take place in the near future.

Conclusion

Spinning DF systems, although a very old DF technique, still have an important place in modern electronic warfare systems. This is especially true where low cost and high accuracy are more important than instantaneous bearing determination and very high probability of intercept. Adding to the attractiveness of spinning DF systems are new technologies in the antennas themselves and in the controller/display units. Antennas with better performance and lower physical profile are now available. Controllers with digital video processing and electroluminescent displays offer many features that improve the accuracy of the system, as well as flexibility in physical configuration previously unobtainable. Continued improvements, particularly in display and digital processing techniques, will make spinning DF systems even more attractive in the future.

AUTHOR'S NOTE: The digital video processing techniques discussed in this article have been developed exclusively by Watkins-Johnson Company and are marketed under the trademark name of SANSCRiT digital video processing. SANSCRiT digital video processing and the displays it generates are protected by copyright.

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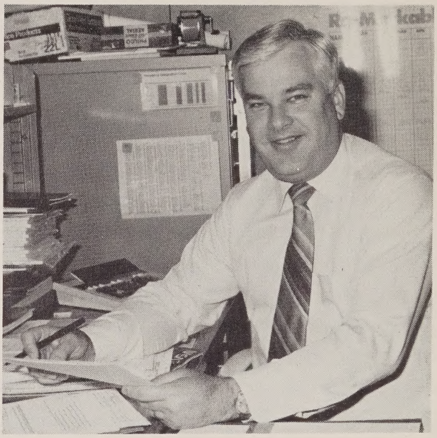

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