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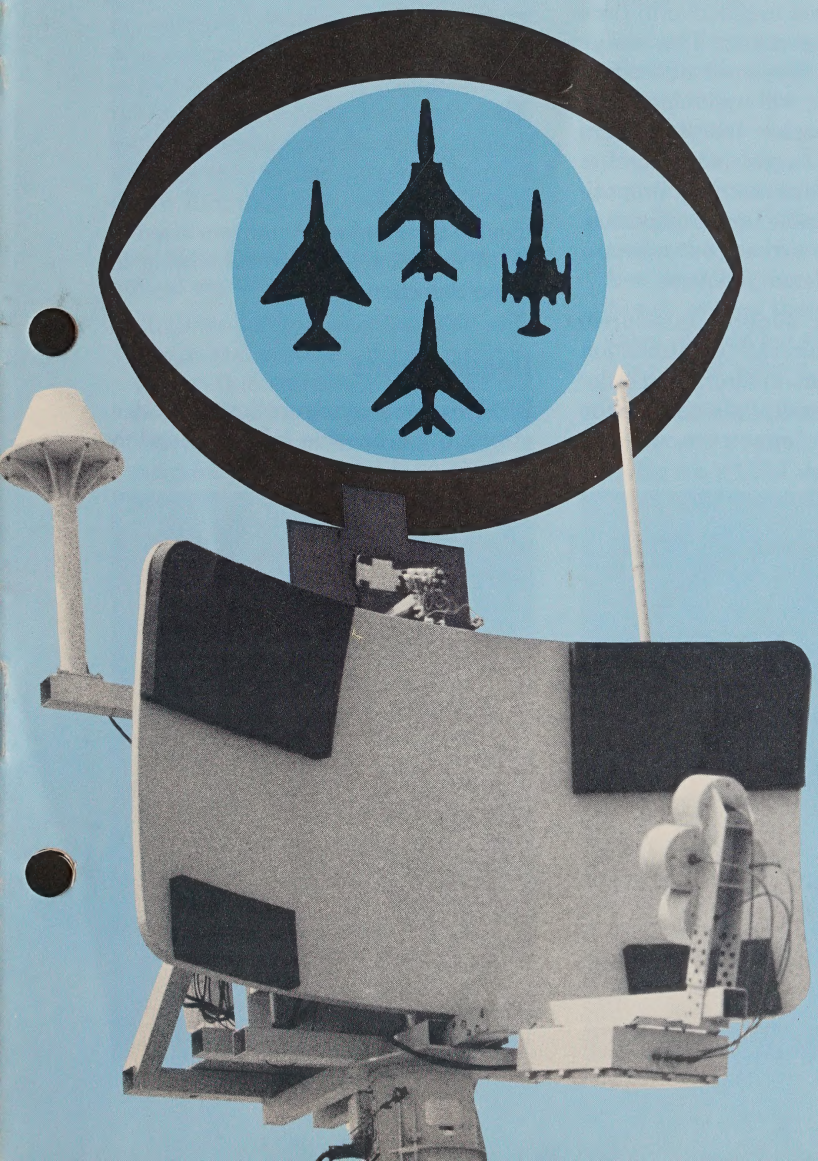
Aircraft Detection and Identification Using Passive Electronic Support Measures



WATKINS-JOHNSON COMPANY
Tech-notes

Modern radars excel in their ability to detect and track an airborne aluminum reflector, i.e., an aircraft. However, since one reflection is pretty much like another, the radar by itself is ineffective at distinguishing the identity of a target, as depicted in Figure 1. This shortcoming is normally corrected by using an active IFF (Identification Friend or Foe) interrogator mounted on the radar to trigger coded responses from a transponder aboard each aircraft. The concern is that existing IFF techniques may be spoofed, jammed, or otherwise rendered ineffective in time of hostile engagement. The radar community has developed additional techniques which will undoubtedly be of some effectiveness, but it appears that conclusive target identification through radar alone is a risky proposition. Without reliable target identification, the most advanced weapon systems are rendered impotent.

ESM (electronic support measures) techniques for aircraft identification utilize the fact that an aircraft, in order to do its job, is literally "glowing" in the electromagnetic spectrum. Unlike radar reflections which simply mirror the characteristics of the radar transmitter, the ESM emissions are highly characteristic of the particular on-board emitters carried by the aircraft. These characteristic emissions can be detected and identified by a properly designed and integrated passive ESM system, as depicted in Figure 2. The radar provides azimuth and range, while the ESM provides azimuth and ID (identification). The fusion of these sensors provides all three, as diagrammed in Figure 3.

The fusion of radar and ESM detection and identification techniques is particularly potent in a wartime scenario. Aircraft which seek to evade radar detection through jamming techniques become powerful beacons, as seen by the ESM receiver, while aircraft which disable their on-board emitters to avoid ESM detection remain vulnerable to radar detection.

Requirements

ESM receiver configurations that are effective for passive emitter location

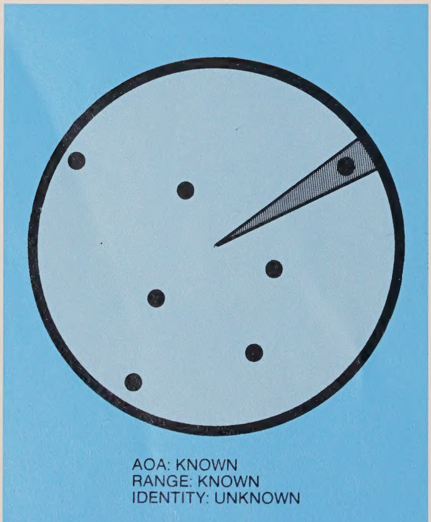


Figure 1. Radar display (without IFF).

Figure 2. Passive ESM display.

Figure 3. Radar display augmented by ESM sensor.

and identification must meet the following requirements:

1. High sensitivity to achieve 200+ mile range and provide sidelobe penetration so that emitters which may not be illuminating the sensor can still be detected. For most scenarios, this requires a sensitivity of -90 dBm or better.
2. Restricted instantaneous field-of-view to filter the dense environment. Even a 10° field-of-view often encompasses millions of pulses per second.
3. Accurate DF (direction finding) capability over a moderate look-angle to match the search radar characteristics and permit track correlation by AOA (angle-of-arrival). Effective track correlation has been shown to require accuracies on the order of one degree or better.
4. Broad coverage in frequency, elevation and polarization (while still maintaining DF accuracy!). Emitters of interest range from 500 MHz to 18 GHz and beyond. Elevation typically extends from 0 to 30 degrees. Polarization cannot be predicted, especially when intercepting emitter sidelobes.
5. Jamming can be expected in a wartime environment. Complete immunity is not possible, but degradation should be confined to only the frequency and azimuth associated with the jammer.
6. Relatively short (several seconds) acquisition time to match radar performance envelope and operational needs.
7. Automatic emitter sorting and identification with very low false-alarm rate, even in dense environments with overlapping signals and high data rates. This is a form of pattern recognition or AI (artificial intelligence). False ID rate must be under extremely low (0.1%, or even as low as 0.001% in threat configurations), or else there will be several false alarms per second, rendering the system useless.
8. Automatic command and data interface to a central processor where radar and ESM data can be correlated in a fusion process.
9. Effective real-world emitter and platform data is required for correct ID. Many existing data bases are incomplete and not sufficiently precise, and an upgraded data base must be developed. Also, the data base and platform-mapping algorithms must allow for considerable overlaps in emitter characteristics. Critical signals must be templated to accomplish correct ID.

Configuration Tradeoffs

At first glance, a high-gain parabolic rotating DF antenna coupled with a conventional superheterodyne receiving system would appear to meet the target identification requirements. The large antenna aperture and narrow receiver bandwidth provide high sensitivity, while simultaneously narrowing the field-of-view to provide filtering of the environment. Such a system is illustrated conceptually in Figure 4. However, such a system does not provide monopulse DF, but relies instead on interpreting an amplitude response pattern over several 360° rotations of the antenna. The time required to do this is excessive, the pattern analysis is insufficiently accurate, and the result is vulnerable to error as a result of the emitter's own modulation pattern and signals received through the sidelobes of the receiving antenna. Also, the reflector size required to provide accuracy of a degree or so at 500 MHz is approximately 150 feet. Since this system must scan in both angle and frequency, it would typically require several tens of seconds to intercept an emitter — much too long to meet most operational requirements.

An alternate approach would be to use the quick reaction and broad AOA coverage system which is normally employed for threat warning applications. This type of coverage is illustrated conceptually in Figure 5. It utilizes a broadband or an IFM receiver and a quadrant DF concept. Unfortunately, the gain of such systems is considerably less than is required to achieve operation at the required target tracking ranges. Threat reaction systems are designed for close-in threats which are radiating directly toward the sensor, not for distant targets which are not illuminating the sensor. Also, the angular accuracy, assuming a cost-effective number of receiver channels, is not sufficient to provide the high accuracy which is necessary to achieve unambiguous track association in the dense European scenario.

One could propose an improved threat reaction system using channelized superheterodyne receivers and multiple-beam antennas to provide high sensitivity and high angular accuracy over a broad range of frequency, azimuth, and elevation. This is illustrated in Figure 6. However, the cost of such a system is high, and the data processing to handle the thou-

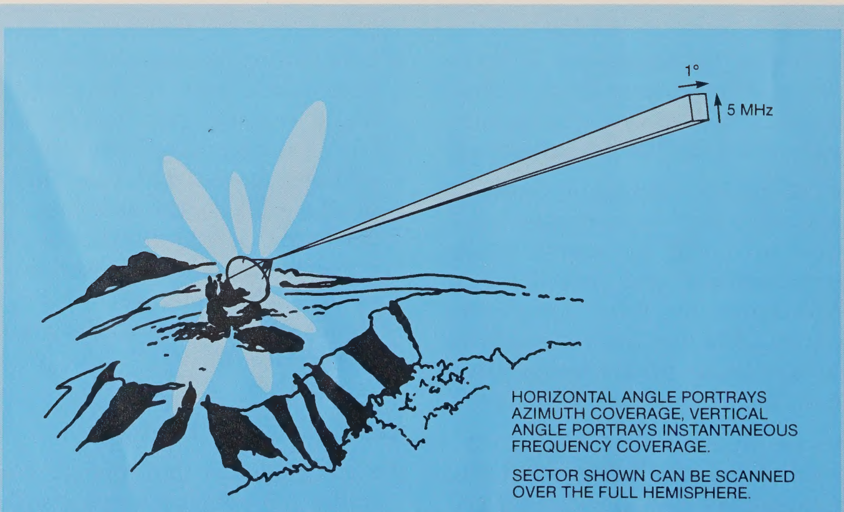


Figure 4. Conventional ELINT receiving system.

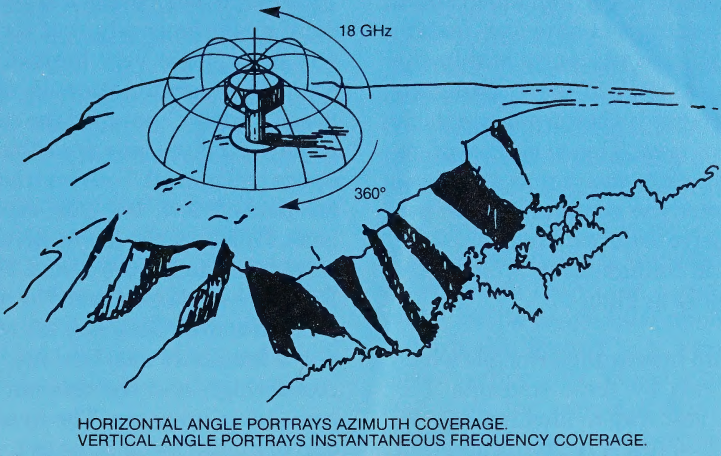


Figure 5. Threat warning receiver.

sands of emitters in the field-of-view is quite ambitious.

An effective hybrid approach which meets the passive ID requirement with relatively low cost and risk can be achieved by utilizing a three-channel superheterodyne receiver coupled to a sum-difference monopulse antenna system with sidelobe blanking. The monopulse AOA interpolation permits reducing the reflector size by about a factor of 10 over the classical rotating DF, while still maintaining angular

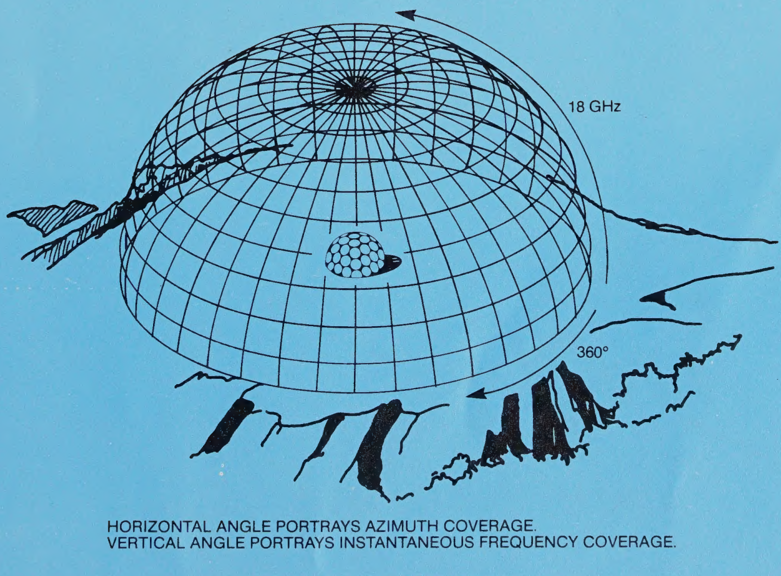
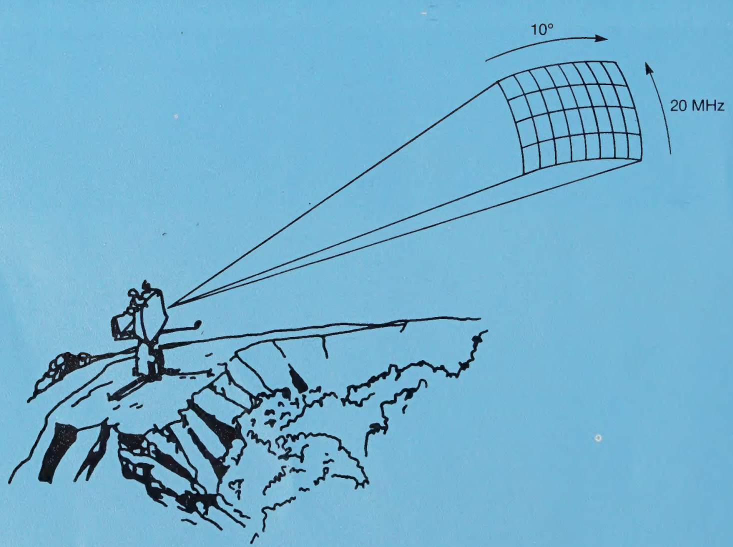


Figure 6. Ideal ESM sensor.

accuracy. Monopulse processing eliminates the need to scan and integrate an angular sector, and provides instantaneous DF for any pulse within the monopulse field-of-view. Sidelobe blanking is used to blank pulses outside the field-of-view. This system configuration is close enough to the basic superheterodyne configuration to permit extensive use of existing hardware. The hybrid configuration is illustrated conceptually in Figure 7.

There is an interesting principle which is illustrated by these tradeoffs. Perhaps the best way to illustrate it is by analogy to optics. A receiving antenna, like a camera, can have its characteristics tailored to a given requirement by selecting an appropriate focal length. If the requirement is for high sensitivity, a telephoto lens is used. It can provide superb range, but it must be scanned to cover a wider field of view, and this is a slow process. On the other hand, a wide-angle lens covers a wide field-of-view instantaneously, but its sensitivity or range is very limited, and its angular discrimination is crude. It doesn't matter how good the camera is or how good the lens is — the laws of optics still prevail. You can trade range for field-of-view, but you cannot get both. Those are the alternatives which correspond to Figure 4 and Figure 5. Figure 6 would be achieved by arraying a few hundred cameras, all with telephoto lenses. It can be done, but the cost is high and the amount of film processing, immense. The hybrid solution of Figure 7 is analogous to using a 3-D camera with a moderate length lens and taking a series of snapshots while scanning the horizon. The lens is still powerful enough for good sensitivity. The 3-D feature adds one additional lens, which provides the ability to accurately locate objects within the



HORIZONTAL ANGLE PORTRAYS AZIMUTH COVERAGE.
VERTICAL ANGLE PORTRAYS INSTANTANEOUS FREQUENCY COVERAGE.
SECTOR SHOWN CAN BE SCANNED OVER THE FULL HEMISPHERE.

Figure 7. Hybrid AOA/frequency matrix ESM sensor.

field-of-view. The cost, though higher than a single camera, is fairly reasonable. Since funding is generally limited, the important requirement is to optimize performance by carefully tailoring the system performance envelope to the mission requirement.

The remainder of this paper describes an implementation of the hybrid configuration. It is primarily a hardware description, though it should be noted that the signal ID software and data base are of major importance and could easily be the topic of another complete paper.

Hardware Configuration

The hybrid configuration described above has been implemented in the WJ-1780 AOA/Frequency Matrix Surveillance and Identification System. A block diagram of this configuration is given in Figure 8. Excellent accuracy and sensitivity are achieved by using a moderate field-of-view, typically between 5 and 20 degrees in azimuth, by about 20 MHz in frequency. This field-of-view can be moved mechanically over the full 360 degrees in azimuth and scanned electronically over the full 0.5 to 18 GHz in frequency. The frequency is step-scanned, with dwell time configured to match threat characteristics. The field-of-view is then subdivided by monopulse AOA processing and by a frequency discriminator into a frequency/AOA matrix to provide high angular and frequency accuracy.

The antenna design is more complex than one might think. Amplitude monopulse is well known as a radar technique, but its use in radar applications is normally limited to a narrow frequency range. Also, in radar, the polarization of the signal is known, and sidelobe blanking is not required. For passive ESM, a wide frequency coverage is required. Incident polarization is not known, so antenna gain must vary very little as a function of polarization. Sidelobe blanking must be accomplished for all off-axis azimuths, elevations and polarizations. Unequal horizontal and vertical beamwidths are necessary to achieve azimuth accuracy while providing broad elevation coverage.

The required optimization, then, must preserve extremely tight DF accuracy over a broad frequency range, unknown polarization, and unknown

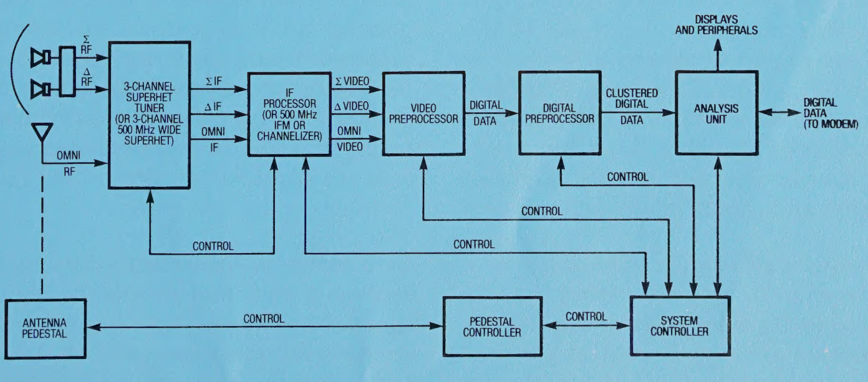


Figure 8. ESM sensor block diagram.

elevation. Simultaneously, high gain must be provided for sufficient system sensitivity, while maintaining low sidelobes to permit sidelobe blanking over all off-axis azimuths, elevations and frequencies. Such a simultaneous optimization poses a serious challenge to the antenna designer, and extensive surveys found no existing designs to meet the requirement. Watkins-Johnson has developed a suitable design as described below.

The ESM antenna which has been developed uses a parabolic section reflector with height equal to half the width to provide increased elevation beamwidth. The feed structure employs cavity-backed spirals in the low band and horn antennas in the high band. Polarization is right-hand circular to permit reception of both horizontally and vertically polarized signals. The normal monopulse configuration would use two feeds mounted side-by-side to produce squinted-beam patterns, with a hybrid to generate the sum and difference patterns. However, the feed diameter required at the low end of the band imposes a physical limit on how closely the feeds can be spaced and the resultant spacing becomes excessive at the high end of the range. This problem is solved by arraying two additional feeds above and below the left and right feeds, such that the spacing of the phase centers is reduced to one-half of the separation of the feeds. The high-band reflector is mounted atop the low-band reflector, while the rf equipment shelter is mounted in a weatherproof enclosure behind the low-band antenna.

Frequency coverage is provided by a three-channel superheterodyne to process the sum, difference and omnidirectional channels from the antenna. The instantaneous bandwidth can range from 5 to 40 MHz to achieve the best compromise between sensitivity, time-to-scan, and processing bandwidth.

A self-calibration system utilizing an external signal generator and antenna is used to derive calibration curves for both AOA and frequency correction. These correction values are stored by the processing unit and are used to correct measurement data before sending it to the ID Processor, or displaying it to the operator. This calibration scheme also provides an excellent self-test capability. It also allows simulation of threat emitter characteristics, permitting front-to-back verification of the complete intercept and ID function.

A critical design feature was the development of a digital preprocessor unit, which incorporates a hardware algorithm to "cluster" or "deinterleave" received pulses on the basis of their fine frequency and angle-of-arrival. The problem is that during a given receiver dwell, several signals may be within the instantaneous frequency/AOA coverage of the receiver. Since the pulse repetition intervals may vary significantly, the minimum dwell period must be sufficient to insure that at least 5 to 10 pulses of a long PRI train will be admitted. Thousands of pulses from a short PRI train will be received during such a dwell period. Digitizing and passing all this data to the microprocessor would result in a prohibitive processing requirement. In addition, sorting all these pulses into individual trains in software is time consuming, and adequate time is simply not available.

As a result, a cluster algorithm was developed and implemented in high-speed hardware. This algorithm screens each incoming pulse by AOA and frequency against a 16 x 32 cell matrix. Pulses falling in the same cell of the matrix are sent to a 32-pulse buffer for transmission to the processor unit. All pulses after the first 32 are disregarded, thus limiting the number of pulses from high-speed trains. A total of eight buffers are available during each dwell, so up to 8 trains can be collected simultaneously. In addition, a threshold level of three pulses is required to open a given channel, thus screening out spurious noise hits.

The processing includes an adaptive feature to cluster pulses whose parameters vary slightly from pulse-to-pulse and, therefore, scatter into adjacent cells of the AOA/frequency matrix. The clustering is performed in a manner wherein pulses which are evenly smeared over a moderate region are coalesced into a single signal, whereas two tightly grouped sets of pulses will be listed as two separate trains, even if their spacing is small compared to the more "smeared" set of pulses. This is illustrated in Figure 9.

The hardware which does this processing can handle input pulse data rates of 500,000 pulses per second.

Signal processing, operator display and automatic interface to the fusion processor are accomplished through an Intel microprocessor chassis incorporating an 8086 and an 80286 processor. The 8086 handles most processing functions, while the high-speed 80286 is used to effect the required high-speed, real-time sorting of received pulse data. Additional 80286 processors can be added to increase signal throughput. A separate Intel microprocessor provides receiver control, and implements the calibration and priority-scan routines. A modem provides communication from the ESM sensor to the fusion processor, while standard alphanumeric displays, keyboard, printer and disc storage provide data display and diagnostic interface for the ESM test operator.

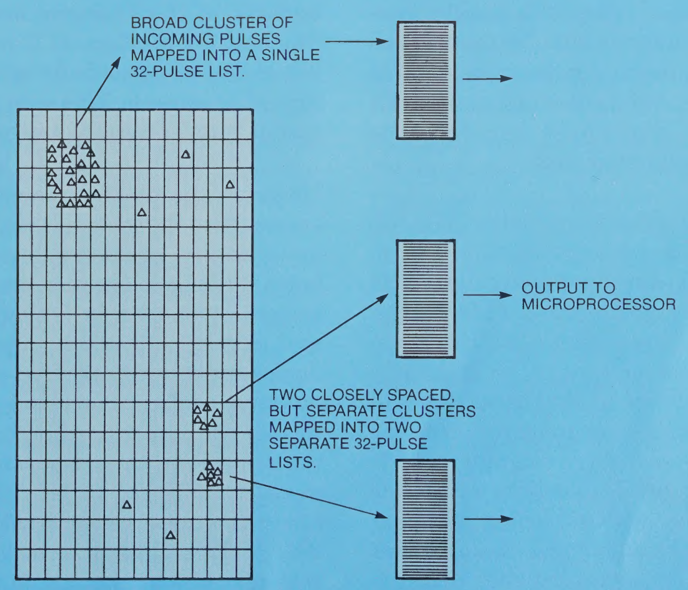


Figure 9. Adaptive cluster AOA/frequency processing.

This discussion has concentrated on the hardware configuration. However, note that the pulse processing software and data base to perform the ID function are crucial to system success. Processing algorithms must handle hundreds of thousands of pulses per second while tolerating distortions such as dropouts, noise hits, and multipath, while recognizing complex patterns, and while separating or "deinterleaving" multiple signals. Most data bases are both imprecise and incomplete, and often incorrectly reflect the fine-grain waveform characteristics. WJ-1780 software is based on a long sequence of W-J receivers and has been extensively tested, improved and validated in the field. Extensive work has also been done to develop the data base, but space and security considerations preclude a further discussion of these areas.

Acquisition Time

A key characteristic of a passive location and identification system is the time required to acquire a target. This differs, depending on whether the ESM system is directed by a radar or is scanning autonomously.

In a radar-guided application, it is not necessary to scan the angular field-of-view, but simply to position it to encompass and track a radar target which has been selected to ID. Five to ten-degree coverage is typically adequate to insure that the target is in the beam, despite tracking errors or data-channel delays. Signals outside the sector are blanked via amplitude comparison with an omnidirectional antenna. This provides a significant reduction in signal density, which is vital when utilizing a high-gain system in dense environments, and also provides significant immunity to jammers outside the main beam of the receiving antenna. Monopulse DF processing, then, offers high AOA accuracy on a pulse-by-pulse basis.

How much time is required to scan for an emitter in this configuration? Since the emitter is already known to be within the azimuth coverage (in the radar-guided application), only frequency scanning is required. An effective scan philosophy is to dwell on each frequency sector for at least the maximum PRI expected at that frequency to check for an intercept. If we assume an average maximum PRI of 5 msec, a 20-MHz frequency sector, and a total range of threat frequencies spanning 8 GHz, then a complete acquisition scan would require 0.005 seconds times 8 GHz/20 MHz, which equals two seconds. In addition to this time, whenever a pulse is intercepted in a frequency sector, the system must dwell for at least 5 to 10 times the maximum PRI in order to collect sufficient pulses for PRI analysis. Assuming 40 active emitters in the 10-degree sector, and dwelling for 8 pulses at 5 msec PRI, would add 1.6 seconds, for a total scan time of 3.6 seconds. This is an adequate update rate for most requirements.

However, the problem becomes more severe when the system is not operated under control of a surveillance radar, but is used in a self-scan mode. Now the system must scan in both frequency and azimuth. Assuming that a 180-degree sector is to be covered with a 10° antenna configuration, and that 200 signals are encountered in that sector, the acquisition time calculated above must be multiplied by 180/10 and the analysis time must be multiplied by 200/40. This yields a scan time of 44 seconds which, though not absurd (especially considering the sensitivity range of the ESM system), is longer than is desirable.

This scan time can be shortened in several ways. First, the frequency bandwidth can be increased, say by a factor of two, simply by going to tuners with 40-MHz bandwidth. The angular scan time can also be reduced by a factor of two by going to a broader antenna beam with 20° coverage. These modifications would still provide reasonable accuracy, but they would reduce the scan time to 11 seconds.

A more pronounced improvement can be achieved by utilizing a wideband superheterodyne receiver such as the W-J TN-122, which provides 500-MHz instantaneous bandwidth over a full 0.5 to 18 GHz tuning range. If environmental density is not extreme, this can simply be used in conjunction with a wideband discriminator. If sensitivity and pulse overlap are significant problems, an IF channelizer can be employed to process the output of the tuner. This yields an increase in scan rate by a factor of 25 or, in the previous example, cuts the scan time to under two seconds.

Summary

ESM hardware for passive emitter location and identification requires special characteristics not normally encountered in elint or threat warning systems. A hybrid ESM system has been developed to meet this requirement. The system offers the high sensitivity and accuracy normally associated with superheterodyne systems, while utilizing matrix processing over a moderate AOA/frequency sector to permit signal deinterleaving and rapid scanning over the entire frequency range. The system has been deployed and tested with extremely encouraging results.

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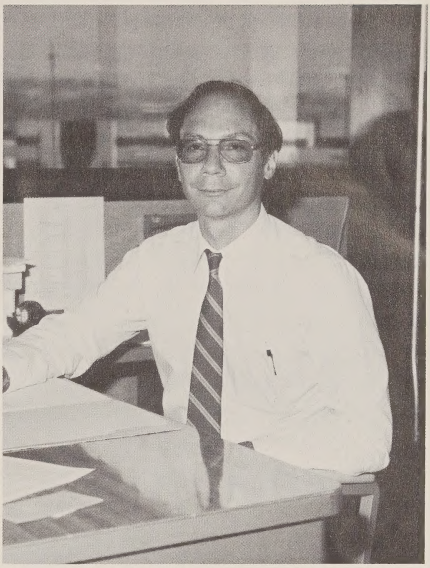

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Dr. Schindall is Manager of the ESM Department in the Watkins-Johnson Recon Division. The ESM Department designs and produces digitally controlled microwave receiving equipment, and defines, develops, produces and delivers complete receiving and analysis systems to meet a wide variety of customer requirements.

In earlier work in the Recon Division, Dr. Schindall devised an innovative PRI spectrum analyzer which has introduced a new capability in signal processing and provided new markets for the division. He also played a strong role in identifying and capturing the market for standardized digitally controlled microwave receiving systems, and for expansion of this technology to include computer control and automatic signal identification. Previous developments by Dr. Schindall at Watkins-Johnson Company include the invention and design of the digital controllers used in the QRC-259 (T), WJ-1240 and WJ-940 receivers.

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