WILLIAM G. BATH

TERRIER/TARTAR: INTEGRATION AND AUTOMATION OF NAVY SHIPBOARD SURVEILLANCE SENSORS

The projected threats to Naval surface forces include massive assaults by aircraft, ships, and submarines carrying antiship cruise missiles and employing electronic countermeasures and other means of delaying detection of the attack as long as possible. Systems must be developed that will help existing shipboard radars to detect and identify attackers promptly and accurately as well as to direct the engagement of large numbers of attacking targets simultaneously. The human operator of surveillance equipment must be assisted by automatic equipment that can combine and correlate the detections of all shipboard surveillance systems and maintain track on a large number of airborne vehicles.

INTRODUCTION

Radar surveillance is an essential part of Fleet defense. Cruisers and destroyers rely primarily on their long-range surveillance radars to detect incoming hostile air targets. These radar systems (or sensors) must detect hostile targets soon enough and measure the positions and velocities of the targets accurately enough for the ships to defend themselves with guided missiles, electronic countermeasures, or guns. The AN/SYS-1 Integrated Automatic Detection and Tracking System is a computer-based radar data processor that enables a ship's radars to perform this surveillance function reliably. SYS-1 is integrated because it combines data from all shipboard surveillance radars to produce a single picture of the surrounding airspace. SYS-1 is automatic because the detection and tracking functions necessary to produce the single picture are performed by a combination of special-purpose electronic hardware and computers rather than by human operators, which is the method currently used.

During the 1960's and early 1970's, APL instrumented Navy ships at sea for the purpose of evaluating the air surveillance pictures produced by these ships' radars using existing manual tracking operations. Data were collected in the Gulf of Tonkin during spring 1967 and during a Pacific Fleet Readiness Evaluation in spring 1970. A detailed comparison of the air surveillance pictures produced on the ships by manual tracking with recorded radar video signals showed that manual methods did not result in a complete and accurate air surveillance picture even when video recordings showed the targets were, in principle, detectable. These experiences led APL to begin development of an automatic detection and tracking system for Navy shipboard radars.

Automation of Navy radars was seen to require development of both special purpose electronics which would adaptively threshold radar video, and digital computer programs to form and update target tracks. An advanced development model automating a single air surveillance radar was built and tested on a Navy guided missile destroyer, the USS SOMERS, in spring 1973. These at-sea tests demonstrated the feasibility of the automation approach. However, the SOMERS tests also demonstrated the need to integrate data from all the ships' surveillance radars and the need for more sophisticated methods of false alarm control. APL then began to design and build the AN/SYS-1 integrated automatic detection and tracking system described in this article.

As demonstrated during at-sea testing in 1978, SYS-1 dramatically increases the percentage of targets a ship detects and the consistency and accuracy with which detected targets are tracked. SYS-1 also reduces the reaction time of the ship's weapon systems. Increases in detection and accuracy are provided by hardware and software that enable SYS-1 to produce a coherent picture of the surrounding airspace and to adapt its detection and tracking decisions to a wide variety of local environments.

SYS-1 technology currently is being applied to the integration of radar information and information from Identification, Friend or Foe equipment, which identifies friendly aircraft through their coded responses to interrogation signals. Other SYS-1 applications discussed in this issue are the AN/SYS-2 system in the New Threat Upgrade Combat System for the TERRIER guided missile cruiser and a system of combining radar tracking data from different ships for the Battle Group Antiair Warfare Coordination Program. The techniques reported in this article are
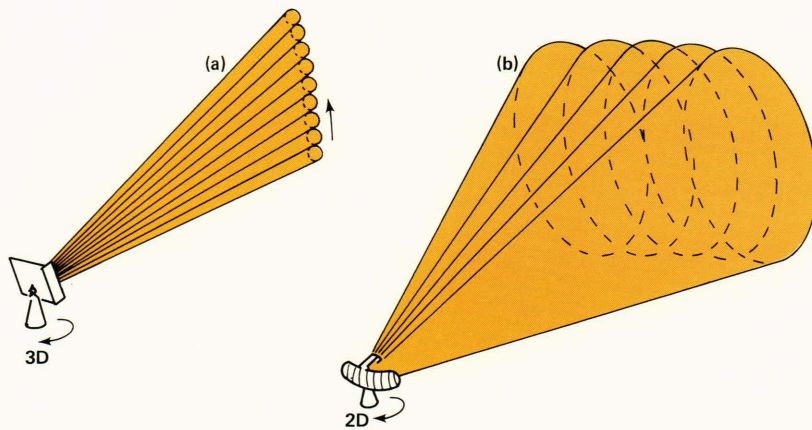
Figure 1 — Existing Navy radars fall into two categories: (a) three-dimensional radars, which form thin pencil beams sequentially with one or two pulses reflected back from a target; and (b) two-dimensional radars, which form wide fan beams with many pulses reflected back from a target. Because each radar has its own advantages in specific clutter and electronic countermeasures environments, an integrated system that combines data from both radars performs beyond the capability of either radar.

unique and have been developed at APL. References 1 and 2 are the patents granted on these techniques.

INTEGRATION AND AUTOMATION OF SURVEILLANCE RADARS: AN/SYS-1

A typical guided missile cruiser or destroyer has a suite of surveillance radars with diverse characteristics. Different radars are installed on the same ship because each radar has its own advantages in a particular natural or electronic countermeasures environment and because, to a limited extent, they provide redundancy, which enhances reliability.

Conventional shipboard surveillance radars fall into two categories: three-dimensional radar, which projects one or more simultaneous pencil beams of microwave radiation (Fig. 1a), and two-dimensional radar, which projects a much broader fan beam (Fig. 1b). Most surveillance radars are pulsed; i.e., the radars transmit very short bursts of energy and wait for returns from potential targets before transmitting again. Both types of radar antenna are rotated to provide 360° azimuth coverage excluding that blocked by superstructure. SYS-1 is designed to integrate improved versions of the radars currently installed on the DDG-2/15 class of guided missile destroyers. SYS-2, a similar system currently under development, is designed to integrate improved versions of the radars currently installed on the guided missile cruisers. In each case, the goal is to capitalize on the strengths of each component radar in order to perform more timely and accurate air surveillance than could be performed by any one of the radars operating independently.

Another goal of SYS-1 is to automate radar detection and tracking. Although Navy radars have become more sophisticated, the actual process of using the radar to detect and track targets is, on most ships, similar to that employed in the 1940's. A radar operator examines a display called a Plan Position Indicator (Fig. 2). When the operator detects a target, he tracks it by watching for the target each time the radar's beam rotates past the target's last indicated position. These manual operations are currently aided by consoles that allow the operator to indicate quickly where the detection occurred and by computers
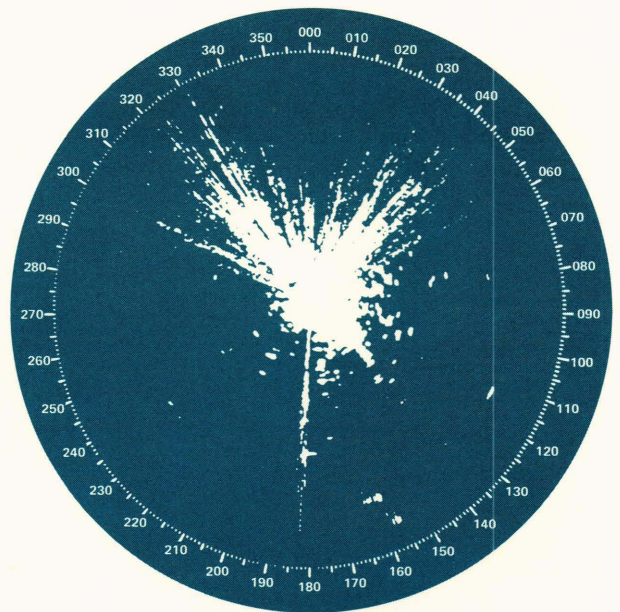
Figure 2 — An unprocessed radar video display is currently used on Navy ships to detect and track targets. As shown here, clutter and electronic countermeasures signals frequently obscure targets. Even when the targets are visible, an operator is usually unable to track more than six targets simultaneously.

that calculate target velocity from the changes in indicated detection positions over time.

BENEFITS OF RADAR INTEGRATION AND AUTOMATION

Because it integrates and automates existing shipboard surveillance radars, SYS-1 provides both a solution to many current surveillance problems and an alternative to the considerable time and expense of designing, constructing, and deploying entirely new surveillance radars. Four major benefits result from radar integration and automation:

- An increase in the number of aircraft detected
- Improvement in the quality of tracking for targets that are detected
- Reduction in system reaction time

- Improvement in the resistance of the surveillance system to electronic countermeaeasures

The increase in the number of aircraft detected is the result of the complementary detection performance of the three-dimensional and two-dimensional radars that are carried on guided missile cruisers and destroyers. The three-dimensional radar, because of the narrow width of its beam, may separate target reflections and "clutter" (reflections from the ocean, from weather phenomena such as clouds or rain, and from land masses), which are unavoidably mixed together by the wider two-dimensional beam. Navy three-dimensional radars typically operate at much higher frequencies than two-dimensional radars. The three-dimensional radar thus has shorter periods of "multipath fade" (situations where the energy reaching the target directly and the energy reaching the target after reflection off the sea surface arrive nearly 180° out of phase, cancel out, and make the target undetectable).

On the other hand, the two-dimensional radar (for a given rotation rate) typically receives many more pulses reflected from a target. This larger amount of received data makes it possible to apply signal processing techniques that discriminate better between target reflections and clutter on the basis of Doppler shift (the change in the frequency of the reflected radar pulse caused by the relative motion of the target and ship). Another advantage of the two-dimensional radar over the three-dimensional radar is that spurious signals from other radars operating at nearly the same frequencies are more easily rejected by filtering techniques. The reflectivity of the sea surface and weather is less severe at the lower two-dimensional radar frequencies; thus, targets may be more easily detected. Another complementary feature of surveillance radars is that they are usually installed so that the ship's mast obstructs them in different directions. Thus, an integrated radar system will detect targets under a much wider variety of conditions than any single, component radar.

Quality of Tracking

Despite the differences between radars, there will certainly be many instances where two or more radars detect the same target. An integrated radar system combines information from all the radars detecting a given target to produce a high-quality, continuous track. (The term "track" refers to the information a surveillance system has determined about a given target, such as position, velocity, and identification.) In an adverse environment, including clutter and jamming, the statistical probabilities of radar detection are degraded. Clearly, as more sensors are integrated, the number of times a target is detected increases. This lessens the probability that the track will be lost. The increased data rate provided by radar integration also improves track accuracy, particularly for maneuvering targets.

Surveillance radars are usually complementary in their measurement capabilities. Three-dimensional radars tend to be more accurate in angle measurements because their higher frequencies allow a smaller beam for a given antenna size. Typically, two-dimensional radars, with their shorter pulse width, tend to be more accurate in range measurements. An integrated system filters measurements from all radars to produce tracks with position and velocity accuracies better than those achievable with the individual radars.[3]

Reaction Time

Although surveillance radars have long detection ranges under ideal conditions, targets are often not detected until they are only a few miles away from the ship. One way targets can escape detection is by flying very low to stay below the radar horizon. These "pop-up" targets appear suddenly and must be engaged immediately. Unfortunately, a single detection by a single radar is insufficient evidence that a target is present; three or four detections describing a target-like trajectory are usually necessary to confirm that a target exists. Thus, a single radar system must wait for two or more rotations of the antenna. The radars used with SYS-1 have selectable rotation periods. This translates into a delay that may be critical when a pop-up target is being engaged. An integrated system can react more quickly to pop-up targets because a collection of radars can produce multiple detections within a single scan of a component radar.

Resistance to Electronic Countermeasures

Hostile electronic countermeasures can consist of noise jamming and deceptive jamming. A noise jammer transmits a high-powered signal in the radar's frequency band in an attempt to mask the radar reflections from targets. A deceptive jammer transmits a waveform similar to that transmitted by the radar in an attempt to make the radar detect targets where none exists. Unintentional deceptive jamming, termed radio-frequency interference, can occur when two ships with similar radars operate in the same task group.

An integrated radar system is less susceptible to electronic countermeasures for two reasons. First, the enemy jammer must simultaneously put energy into the operating frequency bands of all the radars being jammed. For an airborne jammer with limited power, this lowers the jamming energy in each band. Second, as in the case of clutter, the radars are complementary in resisting jamming. Three-dimensional radars tend to have better noise jamming resistance than two-dimensional radars because their narrow beams and low sidelobes limit the angular extent of the region where jamming power can enter the receiver directly (i.e., the region covered by the jammer). Conversely, two-dimensional radars can be more difficult to jam deceptively than existing three-dimensional radars because of the large number of pulses received back from the target because of the beam width.
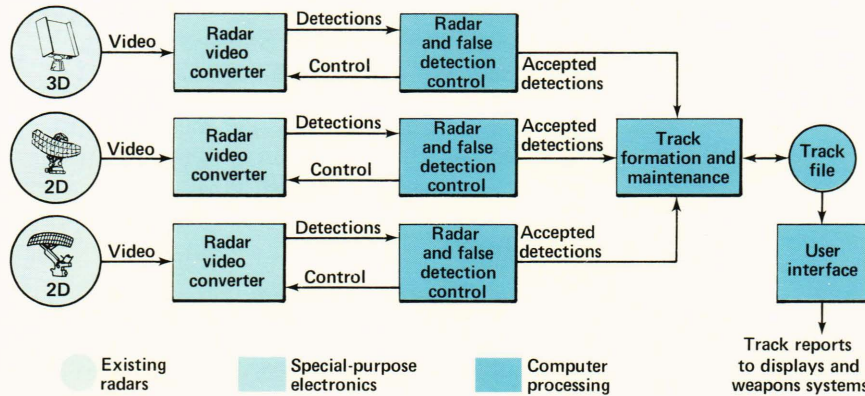
Figure 3 — This figure shows a functional overview of the AN/SYS-1 Integrated Automatic Detection and Tracking System and its associated Radar Video Converters. A combination of special-purpose electronics and computer processing transforms the raw video from three radars into a single picture of the surrounding airspace.

The automation of detection and tracking can by itself improve radar performance under electronic countermeasures conditions. An operator may be unable to detect a target in a jamming environment even when the signal-to-noise ratio is adequate for detection. This can happen when both noise and deceptive jamming put so much information on the display that the operator is unable to pick out the targets. Because of its ability to sort large amounts of information quickly, the automated system will more nearly achieve the radars' theoretical resistance to electronic countermeasures.

FUNCTIONAL OVERVIEW OF AN/SYS-1 INTEGRATED AUTOMATIC DETECTION AND TRACKING

An overview of the SYS-1 approach to radar automation and integration (Fig. 3) illustrates that both special-purpose electronic hardware and computer processing are employed. Special electronics process the video signals coming from the radars to identify detections, thereby reducing the data rate to a level that can be processed by tracking computers. Finally, computer processing classifies radar detections by comparing the characteristics of the processed signals with those expected from aircraft in the particular environment in which the radars are operating. These functions will be explained in greater detail in the following paragraphs.

Special-Purpose Electronics: Radar Video Converter

A surveillance radar has about a million detection opportunities per second. To obtain maximum sensitivity, each resolution cell (a volume equal to one pulse width transformed into distance times the beam cross section) must be examined individually for a target reflection. Resolution cells are currently examined by the radar operator using a video display such as the one shown in Fig. 2. In SYS-1, cells are examined via high-speed processing by special-purpose electronic hardware called Radar Video Converters (Fig. 4) installed in each of the component radars. The target detections and false detections produced by the Radar Video Converters are then processed by
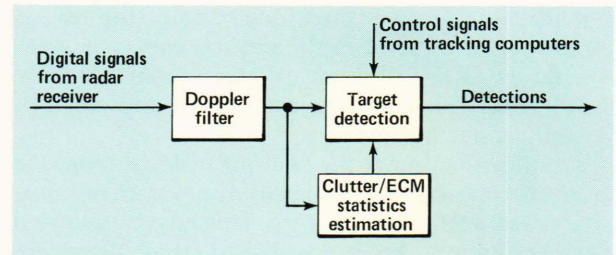

Figure 4 — A Radar Video Converter is a digital signal processor designed to adapt to a wide variety of clutter and electronic countermeasures (ECM) environments. The Radar Video Converter reduces the volume of data to a level that can be processed by the tracking computers. The converter accepts the outputs of high-speed analog-to-digital converters, which transform the radar video to digital signals. These signals are then processed by arithmetic and logic circuits possessing a wide dynamic range and using high-speed random access memories.

the tracking computers to produce a display of tracks that describes the surrounding airspace and that has a low false-alarm rate (Fig. 5). Simultaneously, the tracking computers feed control signals back to the Radar Video Converters. These signals alter the electronic processing in high false-alarm regions and increase sensitivity in the vicinity of targets detected by any of the radars.[1]

In the absence of clutter and electronic countermeasures, the main obstacle to detecting targets and the main source of false detections is the thermal noise in the radar amplifiers. This noise is Gaussian and well understood, and the optimum detection device (matched filter) is well known.[4]

More important than thermal noise is the detection of targets and avoidance of false detections in the presence of clutter and electronic countermeasures. The Radar Video Converter attempts to remove the clutter signal by filtering out frequencies that are not subject to the Doppler shift effect created by relative motion of the reflecting object. As the result of instabilities in the transmitted frequency, motion of the clutter relative to the antenna, and limitations in the receiver circuitry, the clutter signal is usually only partially removed. The remaining clutter and electronic countermeasures are not Gaussian and change radically with time and location.
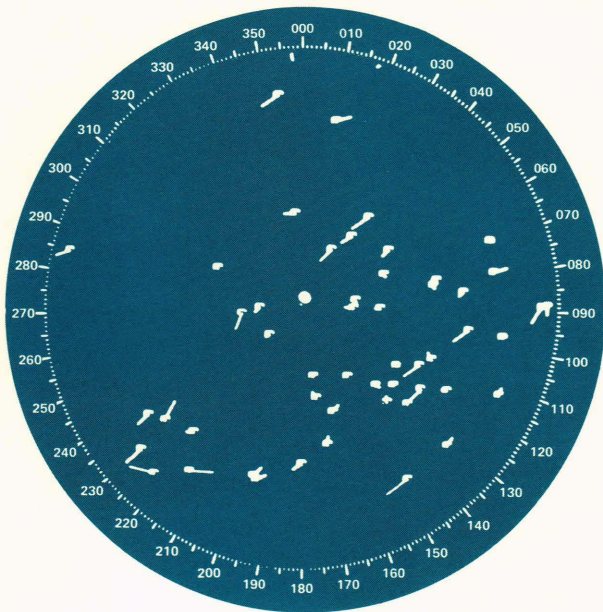
Figure 5 — A display of AN/SYS-1 tracks is used for making command decisions and weapon assignments. Comparison with Fig. 2 shows that the confusing clutter and electronic countermeasures signals have been largely removed. Detailed, precise information about any particular track may be obtained through an auxiliary display.

The detection device must therefore adapt to the local environment by utilizing the Radar Video Converters to estimate the statistics of the radar video near the resolution cell.[2,5] These estimates are used to set the detection criteria. The techniques used to estimate radar video statistics are unique to each component radar. In all cases, however, estimates are made of the magnitude of the combined clutter and electronic countermeasures signal, and a first-order approximation is made of the shape of a signal's probability distribution function. It can be shown mathematically that this procedure ensures a constant probability of false detection for many types of clutter and electronic countermeasures regardless of the instantaneous accuracy of the estimates.

The adaptive features of the Radar Video Converter will maintain a very low false-detection probability for each detection opportunity under the conditions for which it was designed. Corresponding to each time the antenna rotates 360°, a few false detections are expected to occur within the surveillance volume. In practice, although the Radar Video Converters reduce the number of false detections dramatically, they do not achieve the theoretical false-detection rates in all environments. Experiments with the SYS-1 radar suite in an environment of severe clutter and radio-frequency interference indicate that many false detections can be expected per rotation from the three-dimensional surveillance radars used in SYS-1 and a smaller number of false detections from the two-dimensional surveillance radars. Without redesigning the radar waveforms for better Doppler and range resolution, it seems unlikely that these

false-detection rates can be reduced to levels that allow the conclusive determination that a target is present based on a single antenna rotation.

Computer Processing

The solution to the high false-detection rate is to base detection decisions on several antenna rotations (or one or two rotations of antennas from several different radars) by using computer processing. In fact, this is what an operator does when tracking manually. The operator examines the consecutive locations of both real and false detections, matching them mentally with the patterns typical of real targets. The operator also forms a mental map of the radar surveillance volume by observing the clutter and electronic countermeasures. By forming this map, the operator learns what types of clutter and electronic countermeasures returns to expect in various parts of the surveillance volume and to adjust his detection decisions accordingly.

The goal of an integrated automatic detection and tracking system is to duplicate functions currently performed by the operator, but to apply them simultaneously throughout the entire surveillance volume of all the component radars, thus achieving a degree of vigilance and a tracking capacity that a human cannot. Once the returns corresponding to a given target have been identified, a computer can accurately filter positions to produce estimates of current target speed and heading to predict future target positions.

The SYS-1 computer processing may be divided into the following three parts (as shown in Fig. 3):

- False-detection management
- Track formation and maintenance
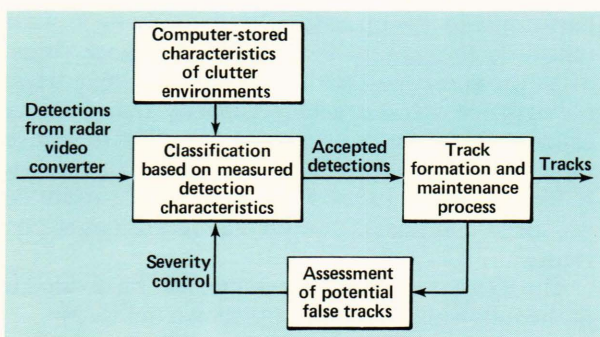- User interfacing

The first two aspects of computer processing will be discussed in detail below.

False-Detection Management — False-detection management is a crucial issue in any automatic system because false tracks can cause time and resources to be wasted in the attempt to engage nonexistent targets and can eventually destroy the user's confidence in the system. SYS-1 is the first successful attempt to produce an air surveillance picture with a low false-track rate while using conventional long-range Navy surveillance radars. The primary reason for this success is that detection and tracking decisions are tailored to the local radar environment in a manner analogous to the way a human operator makes his decisions (Fig. 6).

The SYS-1 computer examines detections from each Radar Video Converter in detail. The amplitude and angular extent of each detection plus the average amplitude of the background signals are used to classify the detection as a real target or as clutter or electronic countermeasures (Fig. 7). For example, in the relatively homogeneous background of sea clutter or
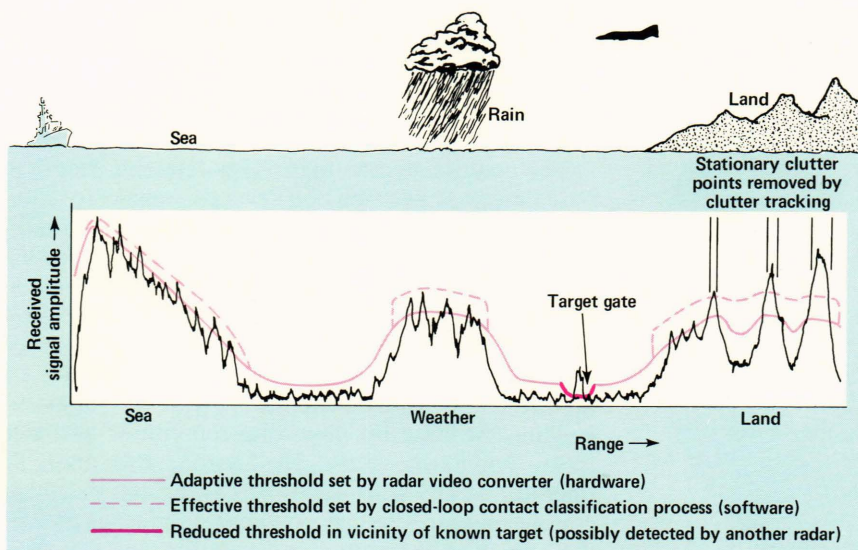
Figure 6 — Examples of SYS-1 control of false alarms in clutter are shown. The Radar Video Converter sets an adaptive threshold electronically; this threshold, combined with an effective threshold set by computer processing of radar returns, allows SYS-1 to adapt target detection and tracking to the local environment. Radar tracking of targets is thus possible against a background of sea, weather, and land interference.

Received signal amplitude

Sea — Weather — Land

Range →

Stationary clutter points removed by clutter tracking

Target gate

— Adaptive threshold set by radar video converter (hardware)
--- Effective threshold set by closed-loop contact classification process (software)
━━ Reduced threshold in vicinity of known target (possibly detected by another radar)

Figure 7 — Closed-loop classification is one technique used by SYS-1 to control false detections. It is based on matching the measured target characteristics with those expected in the local clutter or electronic countermeasures environment.

noise jamming, a very high amplitude signal (relative to the background) is a good indication of a real target. In the presence of either land reflections or radio-frequency interference, more reliable discriminants would be the magnitude of the background level or the angular extent of the detection, respectively.

The computer algorithm in the automated system learns from its mistakes by looking forward into the track-formation process to see the effect of its classification decisions. Classification criteria gradually become more severe until the number of potential new track formations in each local region drops to a reasonable level. Because the environment is continually changing, the classification criteria are continually adapted to the severity of the environment.[6]

Track Formation and Maintenance—There are several ways to group detections from several antenna rotations of two or more radars to form tracks. SYS-1 uses a "contact-to-track" approach in which a single track is formed for each target by grouping together all the detections of that target from all the

surveillance radars.[6] This approach was selected over more conventional approaches such as dividing the surveillance volume into sectors with only one radar's detections used in each sector or merging tracks formed from each radar's detections. The sectoring and track-merging approaches are more reasonably applied to the integration of different types of sensors such as the active/passive sensor integration (to be described later) or to the integration of sensors located at different sites where there is a bandwidth limitation on site-to-site communications.

Two major technical problems arise in track formation and maintenance. The first is the problem of grouping together the radar detections corresponding to each target. In commercial air traffic control systems, this problem is solved by equipping airplanes with transponders that send back to the radar site a unique code identifying the airplane. This is obviously not practical for a military system tracking hostile targets. Instead, the grouping decisions must be based almost entirely on the relative positions and times of the detections. An optimum system would examine all possible groupings of the received detections and would select those most likely to correspond to real target trajectories and known radar measurement accuracies. Since the amount of computing power required to do this is prohibitively large, the SYS-1 system uses a suboptimal algorithm that emphasizes recursive decisions and efficient file-searching procedures. Once the detections have been grouped into tracks, the final decision about whether the track is real or false is based on a sequential probability ratio test that considers the number of detections, the likelihood that detections with these characteristics could be generated in the prevailing clutter and electronic countermeasures environment, and the likelihood that the trajectory implied by the detections could correspond to a real target.

The second problem in track formation and maintenance occurs in trying to combine the measured de-

tection positions to produce accurate estimates of target position and velocity and to predict future target positions. This filtering problem can be regarded from the following three aspects:

1. It is basically a mathematically nonlinear problem. The differential equations of motion, even of a constant-velocity target, are nonlinear when expressed in the polar coordinate system in which the radars make measurements.
2. Estimates must account for intersensor biases, the variable data rate produced by asynchronously rotating radars, and the different measurement accuracies of the individual radars.
3. Sudden target maneuvers require a rapid increase in filter bandwidth to prevent loss of track.

SYS-1 uses an approximation to a nonlinear adaptive Kalman filter to solve these problems.[1]

CONCLUSION

Integration and automation of shipboard surveillance sensors can increase the number of targets detected and ensure continuous, accurate tracking and identification of targets that are detected. These advantages, predicted in theory, have been verified by land-based testing and by at-sea testing of the radar integration and automation concept. SYS-1 was successfully tested at sea on a guided missile destroyer in 1978. A description of the system installed, results of the testing, and examples of improvements in detecting and tracking test aircraft can be found in E. A. Frekko's article in this issue.

A fully integrated and automated shipboard electromagnetic surveillance system has not yet been developed. However, each component technique of integration and automation is being designed and tested. In addition to radar/radar integration, SYS-1 technology is currently being applied to the integration of radars and Identification, Friend or Foe equipment. SYS-1 technology is also being applied to automatic integration of all the surveillance radars in a task group. Although each of these integration tasks requires different electronic hardware and computer processing algorithms, each combines complementary sensors to produce a high-quality surveillance picture that no single sensor is able to produce.

REFERENCES

[1] A. Kossiakoff and J. R. Austin, "Automated Radar Data Processing System," U.S. Patent 4,005,415 (25 Jan 1977).

[2] A. Kossiakoff and J. R. Austin, "Search Radar Adaptive Video Processor," U.S. Patent 3,946,382 (23 Mar 1976).

[3] S. F. Haase, F. R. Castella, and W. G. Bath, "Techniques for Filtering Range and Angle Measurements from Colocated Surveillance Radars," in *Proc. IEEE International Radar Conf.*, Washington, pp. 355-360 (1980).

[4] J. I. Marcum and P. Swerling, "Studies of Target Detection by a Pulsed Radar," *IRE Trans.* IT-6, 59-308 (Apr 1960).

[5] J. Phipps and R. E. Thurber, "Radar Video Converter," patent application, Navy Case No. 61,298.

[6] P. G. Casner and R. J. Prengaman, "Integration and Automation of Multiple Colocated Radars," *Proc. IEE International Radar Conf.*, London, p. 145 (1977).