Coherent Radar—Opportunities and Demands

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The Applied Physics Laboratory, in its role as Technical Direction Agent for several Navy radar development programs, applies a coherent data collection and analysis methodology when evaluating system performance. Programs that have benefited from this approach include the Mark 92 Modification 6 (MK 92 MOD 6) fire control system, the Phalanx close-in weapon system, and the AN/SPS-48E surveillance radar. Examples from these and other programs, highlighting specific cases where this approach has proved successful, are presented. Programs using Laboratory-designed processors that also collect and play back coherent data at real-time rates are described. An example of the use of the coherent database in the development and verification of a land clutter model is presented. Ongoing and future efforts are described.

INTRODUCTION

Radar systems detect targets by examining reflected energy, or returns, from objects.[1,2] Along with target echoes, however, come returns from the sea surface, land masses, buildings, rainstorms, and other sources. Much of this clutter is far stronger than signals received from the targets of interest. The main challenge to radar systems is discriminating these weaker target echoes from the clutter. Coherent signal processing techniques (see the boxed insert on page 393) are frequently used to this end.[3] These techniques will only work if sufficient waveform stability is provided. Thus, the main demand on the system designer is to ensure that radar system stability and signal processing are sufficient to detect the targets.

The designer, when estimating radar performance, will often use simplified models. Statistical methods are employed since the environment and the target are usually far too complex to be treated by exact mathematical methods. Aircraft echoes, for example, fluctuate tens of decibels in power when changing aspect angle, with respect to the radar, by only a few degrees. Clutter returns, particularly from land, are equally difficult to estimate. Thus, radar performance can only be approximated in many situations.

APL is frequently tasked to evaluate the performance of either existing or proposed radar systems. A methodology frequently used by the Laboratory involves collecting and analyzing the coherent data seen by the radar system prior to any digital signal processing. This approach provides the actual radar view of the environment and gives the designer a powerful tool for assessing system performance in the real world. The data are invaluable for developing accurate radar environment models.

In modern coherent radar receivers, input data rates to the signal processor can easily exceed the capabilities of commercially available storage devices. To meet system analysis requirements, APL builds and operates a number of specialized recording devices (see the boxed insert on the generic coherent data collector). The following sections describe how several Navy programs have benefited from the Laboratory's coherent data collection and analysis methodology.

MK 92 MOD 6 FIRE CONTROL SYSTEM

The Mark 92 Modification 6 (MK 92 MOD 6) fire control system provides radar air and surface surveillance, acquisition, and tracking in support of gun and missile engagements against threats to ownship. In the early 1980s, a letter from the Chief of Naval Operations directed that a comprehensive program be initiated to improve performance of the fire control systems on frigates of the FFG-7 class. The program involved major modifications to the existing version of the radars (designated MOD 2), including development of a coherent transmitter and digital signal processor. As Technical Direction Agent, APL initiated coherent data collection and analysis efforts in support of system test and evaluation.[4] Since the MK 92 MOD 6 fire control system has both search and track radars, the coherent data collector developed to support this effort was designed to collect data from either type of radar.

One of the earliest results of the effort was the discovery of a limitation in the stability of the transmitted pulse. By examining the radar return from stationary targets and clutter, it was apparent that the first pulse transmitted by the radar was not locked in phase properly with respect to subsequent pulses. The result was a reduction in the ability to cancel clutter, since cancellation techniques depend on, among other things, phase stability in the transmitted pulse. Although the program could not afford to replace the electronics responsible for the instability, signal processing changes were implemented to mitigate the problem.

Study of the collected data led to a greater appreciation of the effect of multiple-interval clutter on system performance. Multiple-interval clutter occurs when echoes come from objects so far away that the time required for the echo to return is greater than the time between transmitted pulses. In this case, the first echo will be received during the listening time associated with the second or later transmitted pulse. In its coherent modes, these late-arriving returns perturb the signal processor and may generate false detections.

A common technique used to lessen the effects of multiple-interval clutter is to process only the later pulses in the processing interval, that is, some number of pulses are transmitted before search processing begins. The earlier transmitted pulses are thereby given time to return, and the clutter seen by the processor is stable. This approach does not work well for the MK 92 MOD 6 because it has a limited number of pulses available for processing. Eliminating several pulses results in a significant reduction in system sensitivity and, consequently, a sizable loss in the system's ability to detect targets. An innovative technique was developed at APL in collaboration with Loral Defense Systems, using the collected coherent data. The new approach allowed the radar to automatically select between either those pulses that were not corrupted by distant clutter or pulses consisting only of close-in, and consequently stable, clutter.

In 1995, APL supported radar propagation tests conducted in the Arabian Gulf. The environment frequently produces ducting or trapping of radar signals, resulting in abnormally large returns from objects that would otherwise not be seen by the radar. This phenomenon, combined with the heavy ship traffic and large number of oil platforms in the Gulf, can severely affect system performance. The tests were an opportunity to directly measure the effectiveness of MK 92 MOD 6 coherent processing in a challenging environment.

Figure 1a is a planned position indicator plot produced using the coherent data collected during the exercise. The plot was created by entering the data into a software emulation of the MK 92 MOD 6 radar processor. This is a good representation of what an operator actually sees on the MK 92 MOD 6 planned position indicator display. As a result of data analysis, APL proposed a new approach to multiple-interval clutter processing. This approach typically eliminates over 80%, and in some cases over 90%, of the false detections. Figure 1b illustrates the improvement using the same data in Fig. 1a but incorporating the recommended modifications to the radar's signal processor.

MK 92 MOD 2 RADAR PROCESSOR

The MOD 6 version of the MK 92 fire control system provided significant improvement over the MOD 2 radar. However, the cost of upgrading all frigates with the newer radar is prohibitive, especially in an era of declining defense spending. APL and the Naval Research Laboratory proposed an upgrade to the MOD 2 system that would result in improved performance while costing considerably less than a MOD 6 system. This upgrade was named the MK 92 Commercial-off-the-shelf Affordable Near-term Deficiency-correcting ORDALT (CANDO). (ORDALT stands for ordinance alteration.) The program was initiated primarily to provide MOD 2 ships with reliable detection and tracking capability against low-flying missile threats with small radar cross sections. Program constraints included low system cost, no major changes to the radar, and a rapid development schedule of 2 years.

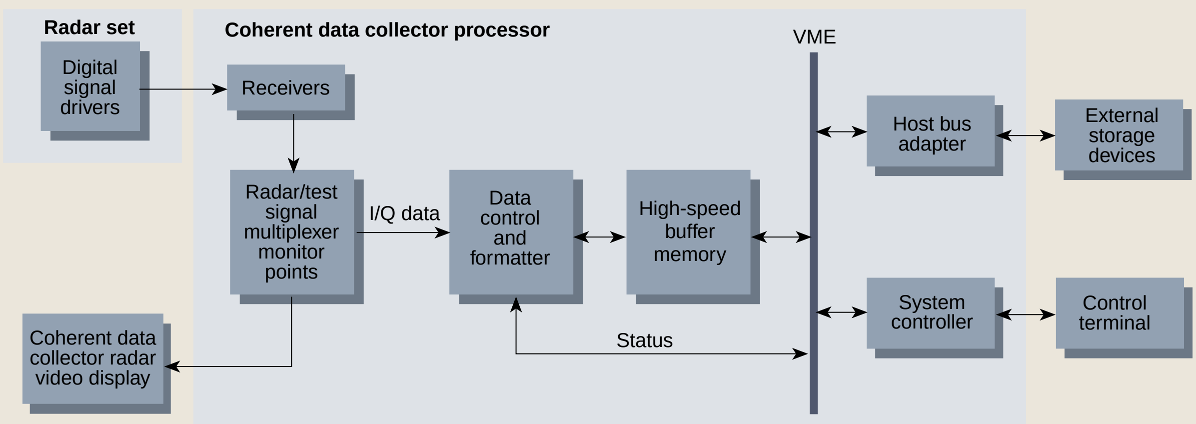
Reliable detection of low-flying threats would require the addition of an automatic detect and track (ADT) capability. Low-flying threats are of particular concern since they are below the horizon and not visible to ship sensors until shortly before they reach the ship, thereby leaving little time for defensive action. Standard ADT techniques would result in too many false tracks, since the MOD 2 system generates a large number of false detections in clutter. The required ADT performance would be achieved using an

THE GENERIC COHERENT DATA COLLECTOR

The block diagram shows the essential elements of a generic coherent data collector. Conceptually, the device is quite simple. It consists of a high-speed digital interface to the radar system, test signal generation capability and signal multiplexing, data control and formatting, high-speed buffer memory, a system controller, a host bus adapter, and peripheral devices. Although some of these functions can be implemented using commercially available circuit cards, the more demanding tasks require custom hardware.

The high-speed digital interface, for example, is usually custom designed, since radar sets seldom make provision for external instrumentation that taps into the high-speed digital signal processor. The interface will frequently provide important radar system information such as triggers for each transmitted pulse, antenna pointing information, and radar mode data. In some cases radar data are available only in analog form, in which case analog-to-digital converters are provided as part of the coherent data collector.

There is usually internally generated test circuitry to simulate radar signals. This capability aids in debugging the coherent data collector during development and provides a means to test system performance when the device is operated in the field. Either radar data or test data can be selected for further processing. (Usually an external planned position indicator



A generic coherent data collector. The actual interface to the radar may require picking up signals from several locations in the radar. In some cases special boards are built for use in the radar to provide signal driving capability to the data collector. The collector itself is typically a combination of custom-built boards and commercially available circuit cards. Peripheral devices, such as the external storage devices, are frequently housed in separate enclosures. I/Q, in-phase channel/quadrature channel.

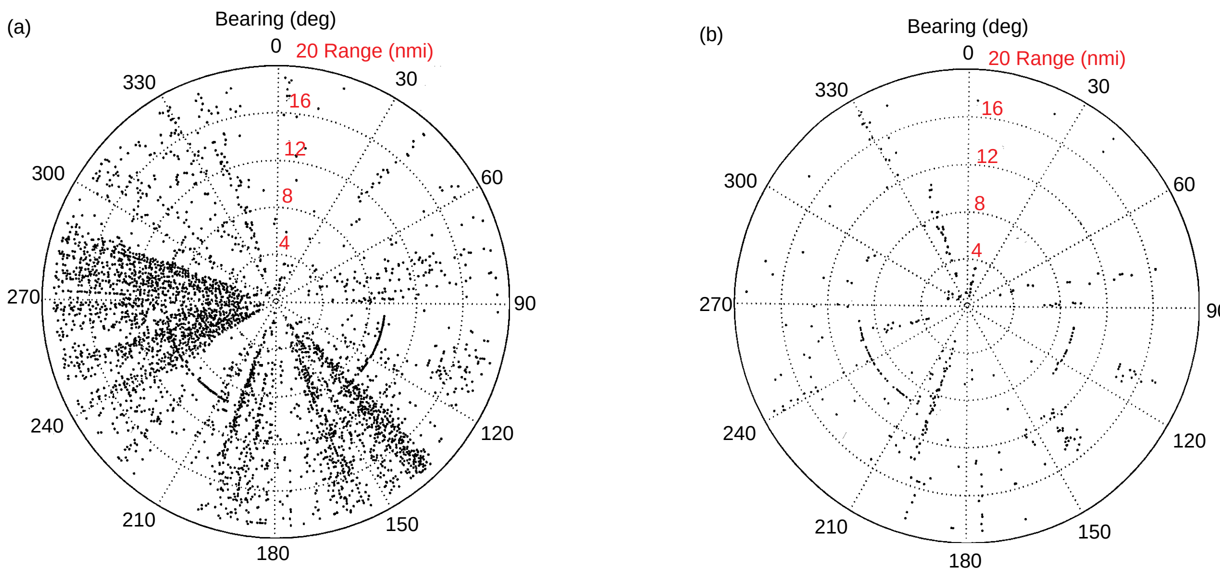


Figure 1. MK 92 multiple-interval clutter false detections. (a) With current clutter processing. The range scale is from 0 to 20 nmi and corresponds to the unambiguous range of the radar, i.e., the maximum range at which an echo can return from a transmitted pulse before a following pulse is transmitted. The false detections, apparent as "bars" of detections radiating out from the center of the planned-position indicator plot, are caused by land and other objects located more than 20 mi from the radar. Four scans; 6149 detections. (b) With the APL modification to clutter processing. Note the almost complete absence of false detection "bars" compared with Fig. 1a. Four scans; 546 detections.

monitor is driven by this circuitry. It acts as an aid to the collector operator.) The data controlling and formatting circuitry group data as needed to optimize throughput by cutting down on overhead or "spare" bits. Test or data synchronization patterns are often inserted into the data at this point.

A high-speed random access memory buffer is frequently used to temporarily store data until some or all of it is sent to permanent storage devices. Even the high-speed storage devices available today are inadequate when faced with data rates that can reach 90 MB/s. In such cases some type of data gating is required to reduce this input rate to a lower sustainable collection rate. The reduction is accomplished by gating the data in range, azimuth, elevation angle, or some combination of these. The rate reduction comes with a loss of coverage. In many cases, however, this loss is not significant. For targets, the position in space may be known well enough to allow gating. Environmental samples may also cover only a fraction of the total surveillance volume.

Permanent storage is frequently provided by external peripheral units. As technology improves, sufficient speed and density will be available to allow these devices to be part of the collector enclosure. Typically, a parallel disk array, consisting of several hard disk drive units operating simultaneously, is used to temporarily hold the data. These devices have the needed storage rate and density to support most test requirements, but they will eventually fill. At a convenient time, the array is downloaded to magnetic tape for permanent storage. These tapes are later used in data reduction and analysis. Given the very high data rates of modern digital radar receivers, this two-tiered approach will likely be used for many years to come.

Occasionally, a tape drive system is used alone, but that usually severely limits the amount of data that can be taken. Permanent storage writing to a medium must keep up with the average data rate from the system. On a per-scan basis, this rate can amount to several megabytes of data per second, which exceeds the capabilities of most affordable tape drive units. (Very-high-speed tape drive units in the 10- to 30-MB/s storage rate range are available but cost from $70,000 to $250,000 per unit.)

An imbedded monoboard computer is used as the system controller. The controller allows the operator to select collector modes, such as internal test, collect data, download data, etc. The operator enters commands to the collector via an external control terminal. The terminal provides status and error messages to the operator. An internal bus is always used for communication between the different devices in the processor. The diagram shows a VME bus because this is the one most frequently used in these applications. (The acronym VME comes from VERSAmodule Eurocard, where VERSAbus is an old Motorola backplane bus and the Eurocard is a circuit board standard.) A host bus adapter provides the interface between the external storage devices and the coherent data collector processor. In some cases, such as data transfers to tape drive units, the interface may exist on the system controller itself.

A collection normally proceeds as follows: First, the operator initializes the collector, entering time of day and date. Next, the collect sector is set and the command is given to start collection. The time at the start of the collection is stored along with data from the collect sector. Collection continues until either the operator stops the collector or the system's permanent storage device fills up. Multiple collect files may be made before the parallel disk array is downloaded to magnetic tape.

Although most coherent data collectors have been built to perform these tasks alone, some have been incorporated into radar processors. In this configuration, the collector not only provides its traditional role but also has been designed to play back the data into the processor at real-time speeds. In this way, collected test data can be replayed through the processor, and the effectiveness of the processing can be studied in detail. In some cases the collector function is available well before the processor design and debug are completed. The collector now takes the place of the radar, allowing the processor circuitry and algorithms to be tested at greatly reduced cost and with far greater efficiency.

innovative track initiation algorithm that receives target velocity information via a new velocity estimation algorithm.

To minimize program cost and risk, a proof-of-concept phase, which included data collection and analysis, was first completed. Data analysis showed that in most environments fast, reliable promotion on the targets of interest was possible. The data also demonstrated that the system was susceptible to multiple-interval clutter. The MOD 6 search radar improvements that ameliorated the effects of multiple-interval clutter are not applicable to MOD 2 because its waveform is different. Unfortunately, the ambitious development schedule did not allow a potential solution proposed by the Naval Research Laboratory to be implemented.

The processor electronics, housed in a unit called the MK 92 radar processor (MRP), consisted of state-of-the-art digital signal processing boards, general-purpose processors, commercial interface boards, and custom-designed boards. Figure 2 shows the board and bus architecture. Custom boards, designed and built at APL, were needed to support unique interface requirements between the MRP and the radar. The commercial interface cards provided standardized interfaces to peripherals or computers. The general-purpose processors provided system control capability and general-purpose calculation ability. The digital signal processing boards provided the high speed needed for radar signal processing of the raw in-phase channel/quadrature channel (I/Q) data received from either live radar data or parallel disk array archived data.

The MRP is designed to act as a data collector, a signal processor, and an automatic tracker. Playback capability, achieved by reloading archived data tapes to

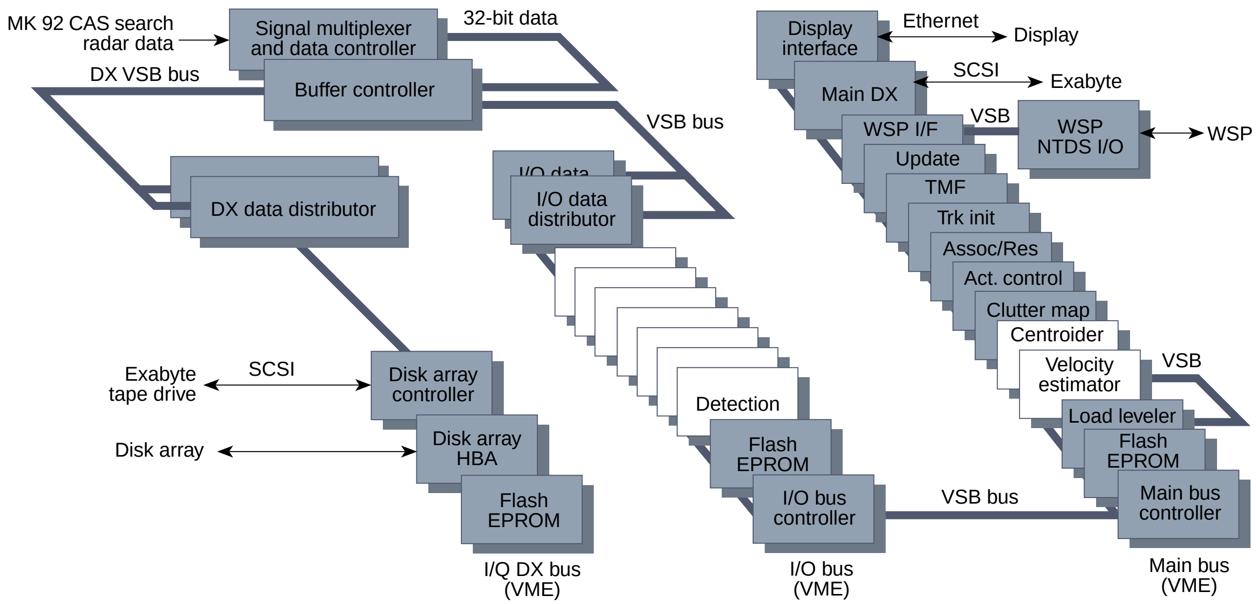


Figure 2. Board architecture for the MK 92 radar processor. Each block represents a circuit board. The white blocks are i860-based boards. Not shown is the parallel disk array that is part of the data collection and playback capability. DX, data extraction; VME, VERSAmodule Eurocard; VSB, VME sub-bus; SCSI, Small Computer System Interface; WSP, Weapons Support Processor; I/F, interface; NTDS, Naval Tactical Data System; I/O, input/output; TMF, Track Management Function; Trk init, track initiation; Assoc/Res, association/resolution; Act. control, activity control; HBA, host bus adapter; I/Q, in-phase channel/quadrature; EPROM, erasable programmable read-only memory; CAS, Combined Antenna System.

the disk array, is implemented to allow stored I/Q data from previous collections to be reprocessed through the system in real time. This capability allowed the program to be successfully completed within the short development schedule. It makes it possible to check processing algorithms under realistic conditions, significantly reducing the amount of expensive at-sea or land-based testing.

The most significant improvement in system performance came from the new automatic tracker. In trackers, spatially correlated detections that meet criteria such as a minimum number of detections are assumed to originate from a real target. Correlation is required to minimize the number of false tracks generated by a system. Trackers maintain several confidence levels for tracks, such as tentative tracks and assumed tracks. The highest confidence track level is called “firm.” Only firm tracks are reported to the combat system and, consequently, to ship personnel responsible for assigning weapons to counter threats. This approach keeps a ship’s resources from being unnecessarily diverted to false tracks generated by clutter. In the process of reducing false tracks, one must be careful not to severely desensitize the system.

The new tracker decreased the number of detections needed to declare a firm track by checking velocity estimates associated with each detection. If the spatially determined range rate corresponded to the velocity estimation, a track would reach firm status sooner. In defending against low-flying threats, every second is important. The new ADT with its quicker firm track promotion logic identifies threats at greater range, thereby increasing the time available for defensive action.

The MRP was used to collect data in at-sea testing involving low-flying missiles with small cross sections. The data were returned to APL for analysis. Figure 3 shows detections from two targets approaching the ship. The arrows show where the detections would form firm tracks using the MRP tracker and where the same detections would have formed firm tracks without the velocity estimator. In both cases, the new tracker provided firm tracks earlier than the older tracker.

As the system matured, further tests and demonstrations of the MRP were conducted at land-based sites. As a result of the successful demonstrations, the system was installed aboard a frigate for live firing tests at the Pacific Missile Range Facility. The tests, involving small, sea-skimming targets, were a complete success; the MRP-equipped ship consistently outperformed two other ships equipped with MK 92 MOD 2. These tests highlight the importance of a properly functioning ADT capability. The CANDO program’s implementation of the combined coherent collection and playback capability demonstrated the value of such an approach to system development.

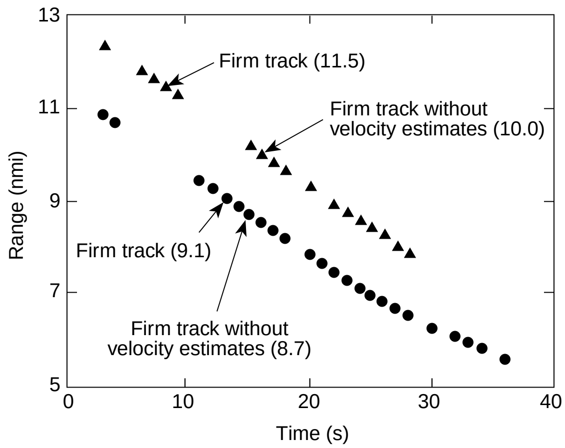


Figure 3. Comparison of MRP tracker performance with and without the use of velocity estimates. Detection/track updates of two low-flying missiles with small radar cross section are shown. The numbers in parentheses are the ranges at which the indicated events occurred, e.g., firm track occurred at 11.5 nmi with velocity estimation.

PHALANX CLOSE-IN WEAPON SYSTEM

Naval combatant ships, such as cruisers, destroyers, and frigates, have several weapon systems for defense against attacking aircraft and missiles. One of these is the Phalanx close-in weapon system. It uses short-range surveillance and tracking radars and a 20-mm gun to engage those threats that have penetrated the outer layers of defense (i.e., those ship's systems used to engage threats farther out from the ship). Because of its close-in defense role, little time is available for Phalanx to detect and engage attackers. Phalanx must cope with large levels of close-in sea clutter, as well as with strong radar returns from land and rain that may appear as multiple-interval clutter. The challenge to the radar designer is to maintain high sensitivity (to detect small, fast-moving targets) while keeping the false-alarm rate (caused by clutter) low.

USS *Coral Sea* (CV 43) received the first afloat Block 0 in 1980. This version had analog processors for both search and track radars. At about the same time, an upgraded system was proposed to meet new threats. Designated Block 1 (first deployed aboard USS *Wisconsin* [BB 64] in 1988), it had an increased search surveillance volume coverage, the ability to acquire and engage faster targets, an increased fire rate, and a larger magazine. As part of the upgrade, a new digital search radar processor and search waveforms were proposed. APL, providing technical direction for the program, proposed and built a coherent data collector to support test and evaluation.[5]

The Laboratory's efforts focused on the search radar. One of the first areas of concern had to do with the large number of false alarms generated when the radar was close to large land masses. Data collection and analysis showed that these false alarms were caused by dynamic range limitations in the receiver. Electronic systems can process signals only over a limited range of amplitudes before becoming saturated. Saturation results in, among other things, the suppression of system noise. In the presence of saturating levels of clutter, the processor will respond to the suppressed noise by lowering its detection threshold (see the boxed insert on coherent radar signal processing) to keep the false-alarm rate constant, while maintaining detection sensitivity. Once the radar is no longer pointing at the large clutter, the receiver noise may rise faster than the detection threshold, resulting in a flood of false alarms.

If receiver gain is reduced to keep the system from becoming saturated, a second problem can develop. The transmit pulse will, at some level, contain noise of its own that appears on the echo signal from either the target or the clutter background. If the echo signal is from the target, this is not as serious a problem, because it does not affect target detectability. (It can cause other limitations, but these are beyond the scope of this article.) However, the radar must cancel or reduce the very large echoes returned from the environment in order to see the small target return. For transmitted noise reflected off a large land mass or other object, the reflected noise will not cancel, resulting in what is called clutter breakthrough. This additional noise raises the overall system noise and can mask the returns from small targets.

These two conflicting processes, noise suppression by receiver saturation and noise enhancement via noise on the transmitted pulse, must be balanced in a well-designed receiver. Radars are not the instruments to measure these effects. For Phalanx, designers were aware of the noise characteristics of the radar but were handicapped by a clutter model that greatly underestimated the size of echoes from land clutter. System tests in the presence of large land masses provided the first indication of problems. However, the actual cause, as described earlier, was not found until the coherent data were collected and analyzed.

These efforts had two results. First, the gain chain of the radar was optimally adjusted to balance receiver noise suppression against clutter breakthrough. The result is a constant noise floor regardless of the level of the clutter. This condition, in turn, keeps the false-alarm rate under control. Second, a change was made in the land clutter model used in the Phalanx program. Figure 4 is a plot of predicted clutter-to-noise ratio at the receiver analog-to-digital converter as a function of range from the radar. Predictions inside 2 nmi are not given, since system performance is not defined that close to land. The orange line indicates the level of land clutter returns based on the original Phalanx weapon specification model. The points are from land clutter

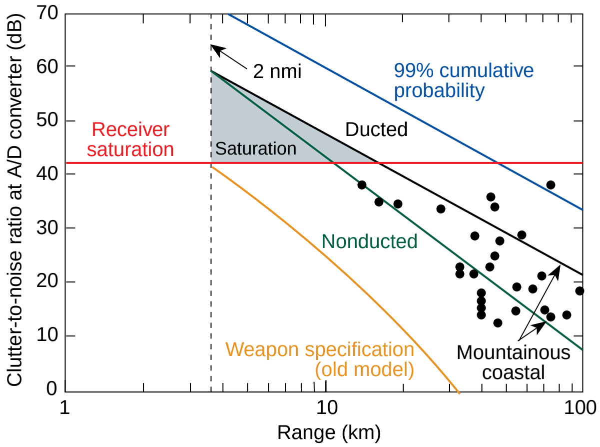


Figure 4. Comparison of Phalanx land clutter models with coherent data collector land clutter data. Ranges inside 2 nmi (3.7 km) are not plotted since land clutter performance at those ranges is undefined. Plotted lines, with the exception of the 99% cumulative probability, are calculated using wide-area mean reflectivity. A/D, analog-to-digital.

measurements. The large discrepancy between the model and land clutter data led to the adoption of a new land clutter model for the Phalanx program. The model, adapted from earlier APL efforts in support of the NATO anti-air warfare program, provides a better fit to the data and greater fidelity in terms of the temporal, spatial, and Doppler statistics of the clutter.

In 1993, APL designed and built a new collector for Phalanx that has considerably greater sustained throughput and storage capacity, which made it possible to collect more data for longer periods of time, characteristics needed to support electromagnetic interference testing and surface craft detection studies. Two years later, this device was installed aboard USS *Lake Erie* (CG 72), an Aegis cruiser, deployed in the Arabian Gulf. USS *Lake Erie* has two Phalanx mounts installed midship facing port and starboard. During the test we observed an interesting phenomenon, illustrated in Fig. 5. Figure 5a shows the distribution of detections over approximately 4 minutes of data collection. Note the large number of false detections near the edge of the data collection sector, which was set from 190 to 350°. Occasionally, the system would attempt to lock on (false assign) to these false detections as if they were caused by a real target. The false detections were seen in all but the quietest of sea states. The false assigns would occur in moderate to heavy seas.

Analysis of the data, illustrated in Fig. 5b, showed a symbiotic relationship between Phalanx mount-to-mount interference and sea clutter. The interference modulates, i.e., suppresses, the sea clutter and causes the false detections. This situation is shown in Fig. 5b as dips in the otherwise slowly changing amplitude and phase of the sea-clutter echo. The bottom plot shows the effect of these dips on coherent processing. Analysis

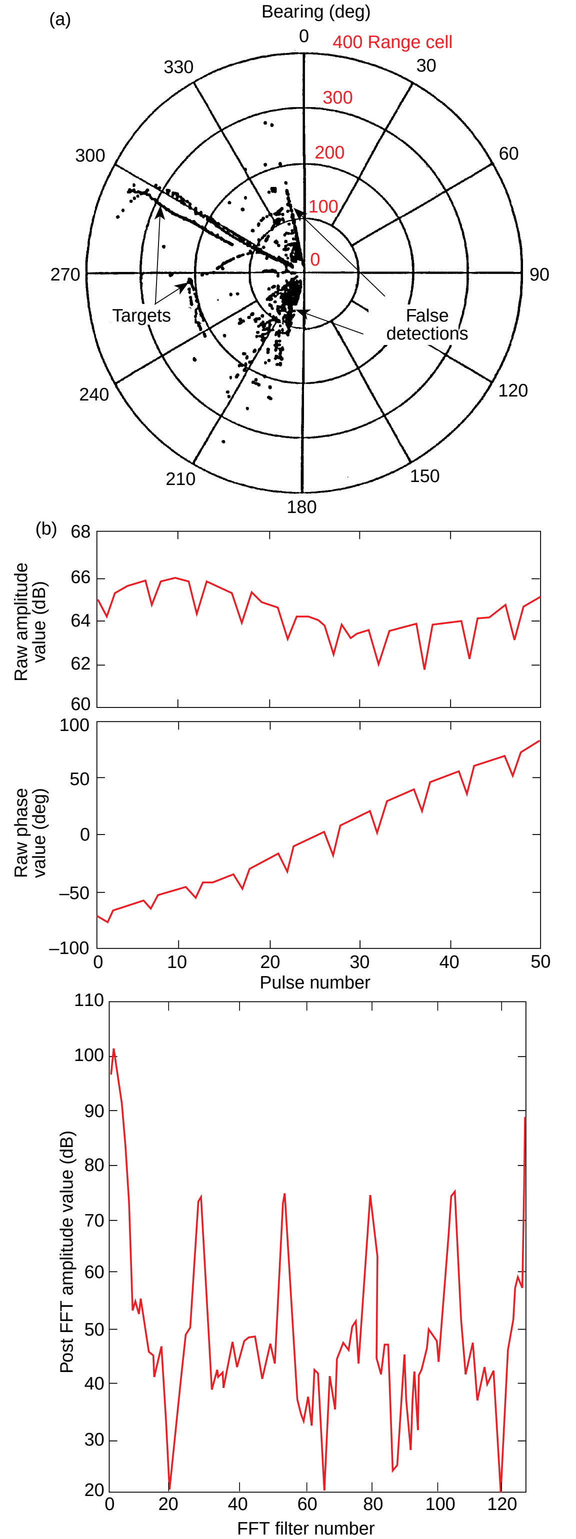


Figure 5. Phalanx mount-to-mount interference resulting in false detections in the presence of sea clutter. (a) A planned position indicator plot showing targets and false detections. (b) The top two plots show the effect of clutter modulation caused by interference on the amplitude (upper plot) and phase (lower plot) at a fixed range. Pulse number refers to consecutive samples, once per radar transmission, at that range. The bottom plot shows the effect on a coherent process of the small amplitude and phase perturbations caused by the modulation. It shows the output of fast Fourier transform (FFT) filters operating on this type of data. The large peaks in the middle would cause detections in a coherent processor.

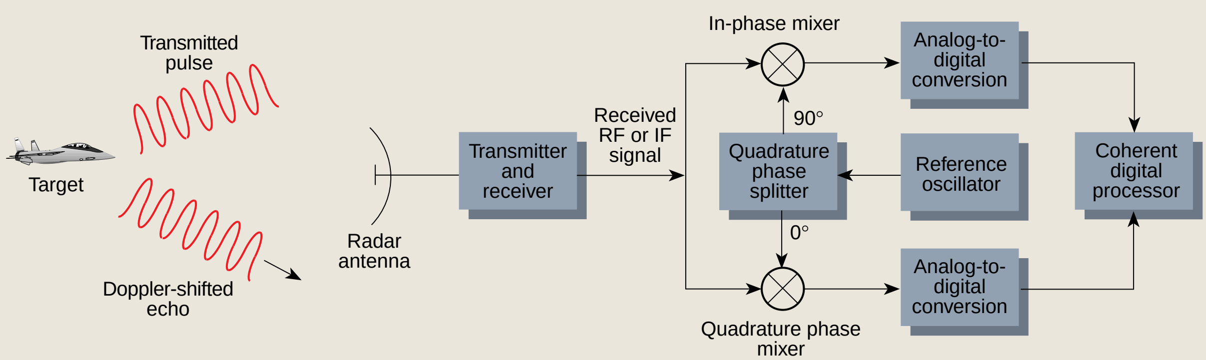
COHERENT RADAR SIGNAL PROCESSING

The Institute of Electrical and Electronics Engineers Standard Radar Definitions (Std 686-1990) defines coherent signal processing as echo integration, filtering, or detection using the amplitude of the received signal and its phase referred to that of a reference oscillator or to the transmitted signal. The key part of this definition is the use of phase information in the signal processing. There are many ways for a processor to use this information. In some cases, echo phase is compared to the phase of a reference oscillator in the receiver. Differences in phase are attributed to relative motion between the radar and the reflector. If the phase is the same, the echo may be treated as "clutter" in a moving target indicator filter and rejected or suppressed from further processing. As is frequently the case in detection and estimation theory, signals may be corrupted by noise, so even in the case of clutter some residue may remain after cancellation.

In some cases phase differences are detected by comparing the phase shift of returns from pulse to pulse. In a modern digital coherent processor, the phase and amplitude information is preserved by digitizing two quadrature video channels. Viewing the echo as a phasor, with phase and amplitude information, this quadrature processing allows the return signal to be transformed into two digital data channels, designated the I (in-phase) channel and the Q (quadrature) channel. The figure illustrates how these digitized channels are derived from either the radio-frequency (RF) or intermediate-frequency (IF) signals. A reference oscillator signal is split into two components, one in phase with the reference and the other 90° out of phase. Each split signal is sent to a mixer to combine with the received signal. The mixer output (a video, or baseband, signal) is digitized, forming the I and Q channels.

The digitized channels are typically processed by moving target indicator filters or a Doppler filter bank. The moving target indicator uses the phase information to enhance target detection and display by suppressing fixed targets and clutter. Doppler filtering enhances radar response to targets at selected Doppler frequencies. Both techniques have advantages and disadvantages. The moving target indicator is somewhat easier to implement, but does not provide velocity (Doppler) information about the target. The Doppler filter bank is more hardware intensive, but provides velocity information with the detections. Because both techniques rely on phase information to distinguish targets from background returns, the coherent radar must be designed with sufficient stability to allow the processor to discriminate the weaker target signal from the strong clutter.

A target detection is declared if the filter output exceeds a threshold. The threshold is usually adjustable, with its value depending on the strength of other radar returns in the neighborhood of the target. Threshold adaptability is used as a means of limiting the number of detections, since excessive detections may overload subsequent processing, result in the generation of false targets (targets formed by correlating noise detections that appear target-like). One of the most demanding requirements for a radar is to maintain its ability to detect small, fast-moving targets while avoiding the generation of these "false alarms."



A coherent radar transmitting a radio-frequency pulse at a target. The reflected pulse is Doppler shifted, received by the radar, and processed into two quadrature receiver channels. Although not shown, the reference oscillator may be used in the radar transmitter to determine the phase of the transmitted pulse. The in-phase and quadrature mixers provide two channels that together contain the phase [arctan(I/Q)] and amplitude [square root of $(I^2 + Q^2)$] information of the received signal. Once digitized, the nature of the coherent processing will depend on system requirements. Detection processing, which typically occurs after envelope detection (i.e., its digital equivalent), is not shown.

showed that the phenomenon was directly tied to the synchronous relationship of the pulse repetition intervals used by the radar.[6] APL proposed a slight modification in the timing of the pulses, which resulted in removing the synchronization. The modification was tried aboard a ship of the same class, and the false alarm problem disappeared.

The effects of the coherent data collection and analysis efforts have been positive for the Phalanx program. In addition to the previous examples, other APL efforts include determining the effectiveness of alternative designs for use in pulse interference detection and mitigation, examining the Doppler characteristics of various targets, and assessing the ability of Phalanx to detect small boats in heavy seas. The Laboratory also provides the data to the radar manufacturer, who in turn uses it to evaluate the effectiveness of possible changes to the system.

AN/SPS-48E AIR SURVEILLANCE RADAR

The AN/SPS-48E radars provide long-range air surveillance capability for aircraft carriers, amphibious assault ships, destroyers, and cruisers. Currently, more than 40 of these radars are deployed. The need for improved clutter performance, especially in view of the increased importance of littoral warfighting capability, led the Naval Sea Systems Command Surveillance Radar Office to fund development of a new Digital Moving Target Indicator (DMTI) mode field change for the AN/SPS-48E air surveillance radar. To support this effort, APL, in its role of providing technical guidance and support, developed a coherent data collection and analysis capability to permit an in-depth performance assessment of the radar system in an operating environment.

USS *Kidd* (DDG 993) was the first ship to be instrumented with a DMTI prototype field change modification. Testing using coherent data consisted of analog/digital performance checks (e.g., search for irregularities in the noise statistics, missing bits, etc.) and overall radar waveform stability measurements. Problems were found in the ability of the radar set to cancel clutter. Figure 6 shows the difference in phase between two consecutive pulses as a function of range. Ideally, the clutter should have a constant phase at each range cell; hence, the delta phase should be approximately zero. The ramp indicates a drift in the stable local oscillator during the radar receive time. The ramping stops when there is no more clutter and the cells being compared are dominated by noise; hence, phase information is uncorrelated. APL informed the radar manufacturer of this situation, and they were able to identify cabling problems that caused corruption of the stable local oscillator. Data were also taken on missiles and drone targets. Analysis of the data was used to verify system performance against important classes of targets.

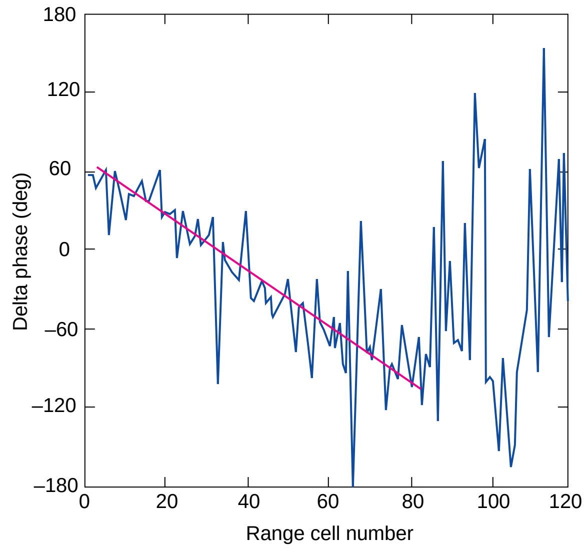


Figure 6. Phase ramping of clutter echoes. The plot shows the change in phase, as a function of range, between two consecutive pulses. The ramping ends at approximately range cell number 80, at which point the clutter is below receiver noise. In noise, consecutive pulses are uncorrelated in phase (and amplitude).

The AN/SPS-48E radar directs its beam in azimuth by mechanically rotating the antenna. Elevation pointing is performed by changing the frequency of the transmitted pulse. The antenna responds to frequency differences by forming beams at different elevations. Problems arise because the transmitted noise associated with the different elevation beams is so wide in frequency that some of it falls into the frequency passband (and elevation) of adjacent beams. The interference is most noticeable when the radar is illuminating large objects, such as land clutter. Coherent data were collected and analyzed to clearly demonstrate the existence and extent of this type of clutter breakthrough.

The clutter breakthrough effects of broadband noise can be mitigated by use of a wideband limiter,[7] although some sensitivity loss occurs in areas affected by the interference. Performance can also be improved by the judicious selection of the sequence of transmitted beams. To demonstrate the effectiveness of these techniques, tests were performed aboard USS *California* (CGN 36) in 1993 with a production DMTI field change kit. Data were collected and analyzed with and without the wideband limiter and with various beam sequencing combinations. The results verified the usefulness of both approaches in mitigating the beam-to-beam interference problem. Figure 7 shows the raw amplitude data from San Clemente Island. Figures 8a and 8b show the effectiveness of a six-pulse DMTI canceller without the wideband limiter but for different transmitted beam sequences. Note the clutter breakthrough, particularly at the leading edge of Fig. 8b. Finally, Fig. 9 shows the cancellation obtained with the wideband limiter. Note the lack of clutter breakthrough at the edges and the "hole" where the island is located. The hole is a result of saturation of the receiver, and consequently suppression of receiver noise, by the large amplitude of the clutter return.

The collected data were also used to gather important information on the amplitude and spatial characteristics of land clutter. This important topic will be covered in detail in a following section.

AN/SPS-48E AUXILIARY DETECTION PROCESSOR

The Cooperative Engagement Capability allows ships and other platforms to share unfiltered sensor measurement data associated with tracks.[8] The approach takes advantage of the different views of the battle environment that are provided by each participant's different location and suite of sensors. The

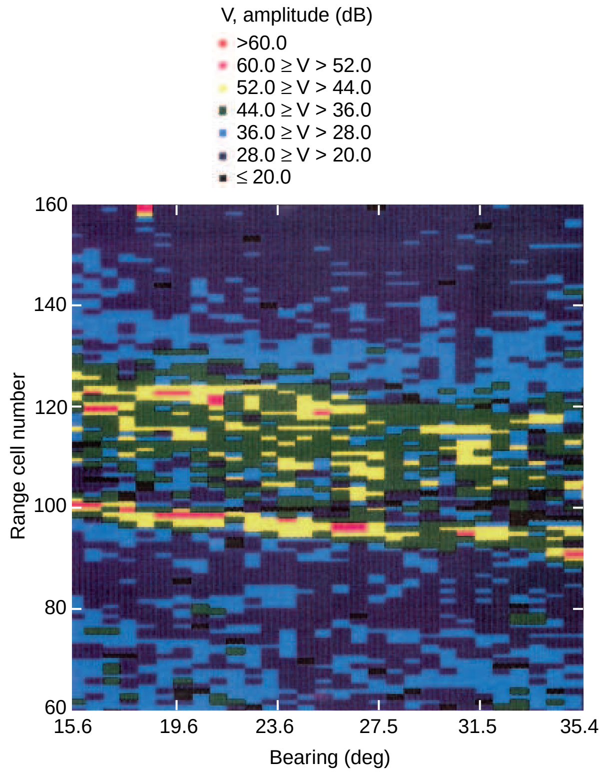


Figure 7. Raw amplitude echoes from San Clemente Island (three beams). Colors are dependent on the amplitude of the return.

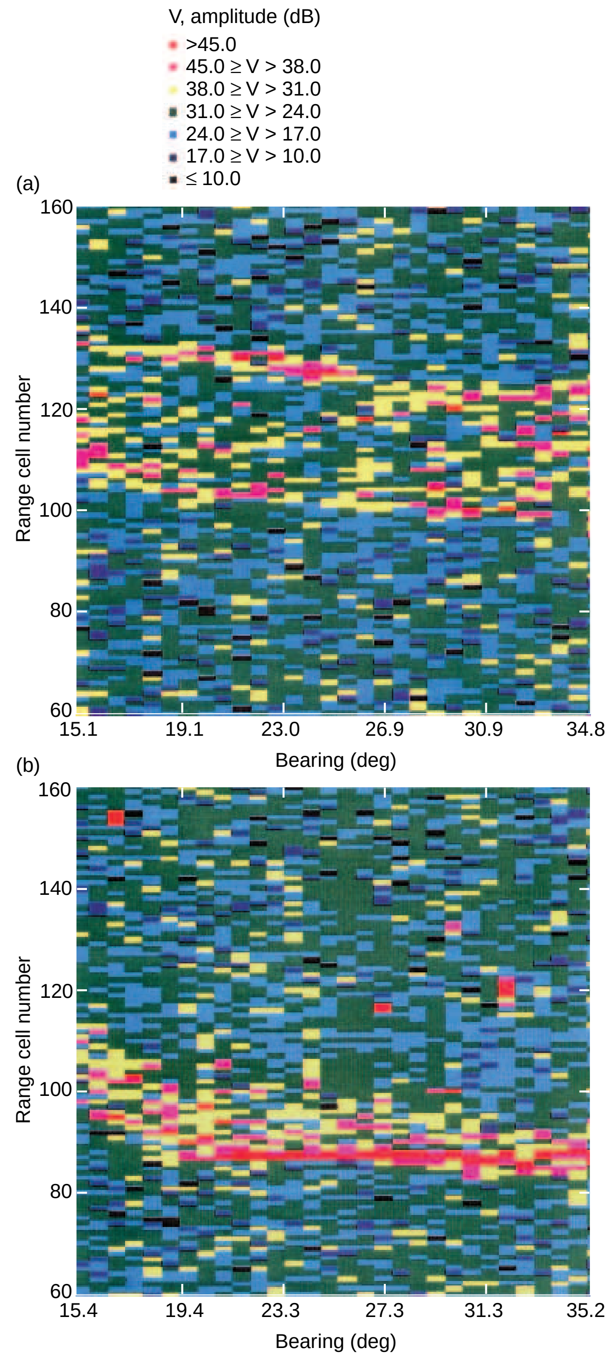


Figure 8. Moving target indicator output of San Clemente Island without the wideband limiter (three beams). (a) A beam transmit sequence of 3-2-1, i.e., beam 3 (highest in elevation) is transmitted first, beam 2 next, and beam 1 (the lowest in elevation) is transmitted last. (b) The beam sequence is changed to 2-1-3.

composite picture is significantly better than the limited view afforded to each combatant. Each participating unit shares measurements from every sensor, including unfiltered range, bearing, elevation, and, if available, Doppler updates. Each participant also maintains sufficient processing capability, provided by the cooperative engagement processor, to allow it to independently process received data into composite tracks (formed by appropriate statistical combinations of inputs from all sensors).

To optimally contribute to the Cooperative Engagement Capability picture, it was decided to provide additional processing capability to the AN/SPS-48E radar in the form of an auxiliary detection processor (ADP). This unit would improve tracker performance by using Doppler information associated with radar detections. The engineering development models were designed and produced by APL. In addition to the improved quality of detection data, the unit provided unambiguous range information for radar contacts.

The ADP interfaces to the radar set, the cooperative engagement processor, and the radar tracking computer. The most important input data to the ADP are the raw I/Q data from the radar's coherent bursts and processed information such as amplitude of best channel, signal-to-noise ratio, background mean level estimation, and constant false-alarm rate threshold. The best channel is the radar velocity filter, on a per-beam and per-range cell basis, which appears to have the best detection information. This determination is made by examining the velocity filters' signal-to-filter residue ratio and the level of filter residue.

Figure 10 shows the board architecture for the ADP. As with the MRP, custom boards were designed and fabricated by APL. These cards provide the I/Q inter-

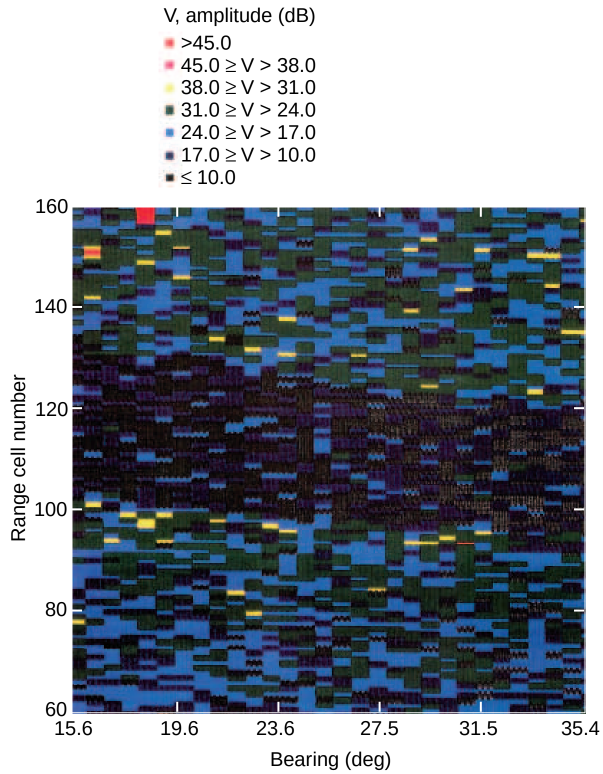


Figure 9. Moving target indicator output of San Clemente Island with the wideband limiter (three beams). Note the absence of clutter breakthrough at the edges of the island. Note too the "hole" in the center of the island, which is an indication of clutter saturating the receiver and thereby suppressing system noise.

face to the radar and perform the formatting and buffering needed to support processing of the data, coherent data collection capability, and real-time playback. The primary function of the moving target indicator detection cards is to provide ambiguous velocity estimates. Processing is limited to those range cells that pass a number of detection and filtering criteria. For example, the threshold value is determined on the basis of the value provided by the best channel and is modified by an activity monitor (number of contacts) in the ADP.

If a detection is declared, or if a track gate (from the radar) is associated with a group of I/Q data, further processing is performed. The "coherency" of the data is checked across the pulses in the burst by comparing the change in phase between two pulses. For valid targets, this change should be reasonably constant. Radio-frequency interference, or multiple-interval clutter, would cause large discontinuities across the burst. Detections that pass these checks are range centroided, and the ambiguous range and velocity estimates are sent to the range unfold and velocity unfold processors. Further processing is performed until the contacts are sent to the tracker, along with the velocity estimation.

The difference between the AN/SPS-48E ADP and the MK 92 MOD 2 MRP shows how rapidly technology developed in the area of commercial off-the-shelf processors. The ADP was developed in 1991, 3 years before

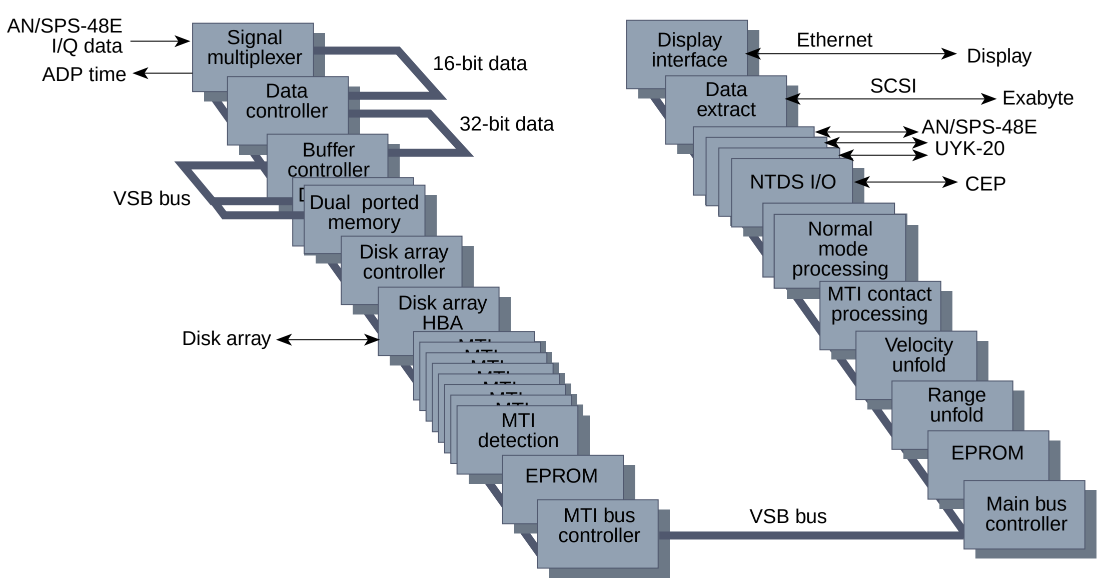


Figure 10. Architecture for the AN/SPS-48E auxiliary detection processor. ADP, auxiliary data processor; VSB, VME sub-bus; HBA, host bus adaptor; MTI, moving target indicator; NTDS, Naval Tactical Data System; I/O, input/output; I/Q, in-phase channel/quadrature; SCSI, Small Computer System Interface; CEP, cooperative engagement processor; EPROM, erasable programmable read-only memory.

the MRP. Moving target indicator processing in the ADP had to be gated by an adjustable threshold, since the amount of processing needed to perform the mean level estimation, constant false-alarm rate, and velocity filter functions could not be accomplished with the available commercial off-the-shelf processors. Three years later, the MRP was able to perform the needed processing.

Like the MRP, the ADP contains coherent data collection and playback capability used during development. The collection capability provides the raw data needed for off-line proof-of-concept work performed at APL. The playback capability has proved valuable for testing electronic countermeasures improvements that were later added to the system. It was also used in the development of the integration and display processor.

The ADP was moved to production by the radar set manufacturer. There are two basic configurations. In the multisensor integration and tracking system, the ADP centroids are sent to the AN/SYS-2A(V)6 Integrated Automatic Detection and Track System. In another version, the tracking function is performed internally. Currently, four production units are deployed, with additional units to be built.

RADAR LAND CLUTTER MODELING AND VERIFICATION USING COHERENT DATA COLLECTOR DATA

Land provides the most challenging natural clutter environment. Land echoes have, for a single scan, a very broad dynamic range, a potential wide-area coverage, and a highly nonhomogeneous spatial characteristic. Existing theoretical models are approximations at best. They provide important dynamic range information but are of little aid to the radar system designer trying to balance detection sensitivity with subclutter visibility while simultaneously maintaining a constant and well-behaved false-alarm rate. This section describes an ongoing effort at APL that uses the large land clutter database accumulated by the various programs described here. The high quality of the data in terms of range resolution and amplitude dynamic range allows it to be especially useful in developing improved clutter models.

In the last decade, testing radar performance in coastal environments has become increasingly important, largely because of the Navy's shift in emphasis from a "blue water" warfare scenario to fighting in littoral waters. Much effort is now going into evaluating the performance of systems near land. Such testing is expensive and, of course, not possible with new radar systems until they are at an advanced stage in the design effort. In this environment, it has become even more important to have appropriate modeling of land clutter to meet the needs of the system designer.

One approach is to provide accurate modeling of specific areas, as opposed to more generic models. For example, instead of having a model for a "mountainous coastal environment," one would have a high-fidelity model of, say, the Island of Hawaii as seen by a ship located 30 mi offshore. Such a model would provide radar cross-sectional estimates, furnishing the details of the land down to at least the resolution of the radar, i.e., range cell length by azimuth beam width. The model would include relevant radar parameters (pulse width, beamwidth, transmitted power, antenna gain, etc.) and account for propagation conditions and terrain characteristics. In Ref. 9, a model developed at APL is described that provides this capability. The model uses Defense Mapping Agency digital terrain elevation data to determine terrain contours. An optical ray method is used to determine incidence angle. Propagation factors are estimated using the tropospheric electromagnetic parabolic equation routine (TEMPER), developed at APL.[10,11]

As with any such effort, verification is an important element in gaining acceptance of the model. One early attempt at verification occurred in 1993, using clutter measurements collected aboard USS *California*. The ship was in transit from Washington State to Southern California. The AN/SPS-48E coherent data collector provided the collection capability. In this case, the key feature of the collector was not the coherency of the data (phase information does not play a role in determining land backscatter cross section) but the large area coverage of the collected data coupled with the high dynamic range of the amplitude data. The radar itself limited instantaneous dynamic range to approximately 40 dB. However, measurements using various levels of attenuation in the receiver allowed the total range to be extended to 120 dB. Propagation conditions were estimated from data collected by an instrumented helicopter.

Figures 11a and 11b compare the terrain visibility map calculated from the model with a similar map using the collected data.[12] As can be seen, correspondence is quite good for illuminated and shadowed areas. A more detailed comparison is obtained by observing the cumulative distributions of the clutter reflectivity (adjusted for two-way propagation factor) for both model and measured data (Fig. 11c). Figure 11c also shows that the correspondence is relatively good for strong clutter. As the strength of the clutter falls off, however, the model predictions deviate on the low side, reaching up to 35 dB for the smallest clutter. Several possible sources for this discrepancy are being investigated, such as antenna sidelobe contributions, positional smearing as a result of ship movement during the data collection, multiple scattering, two- and three-dimensional diffraction, and

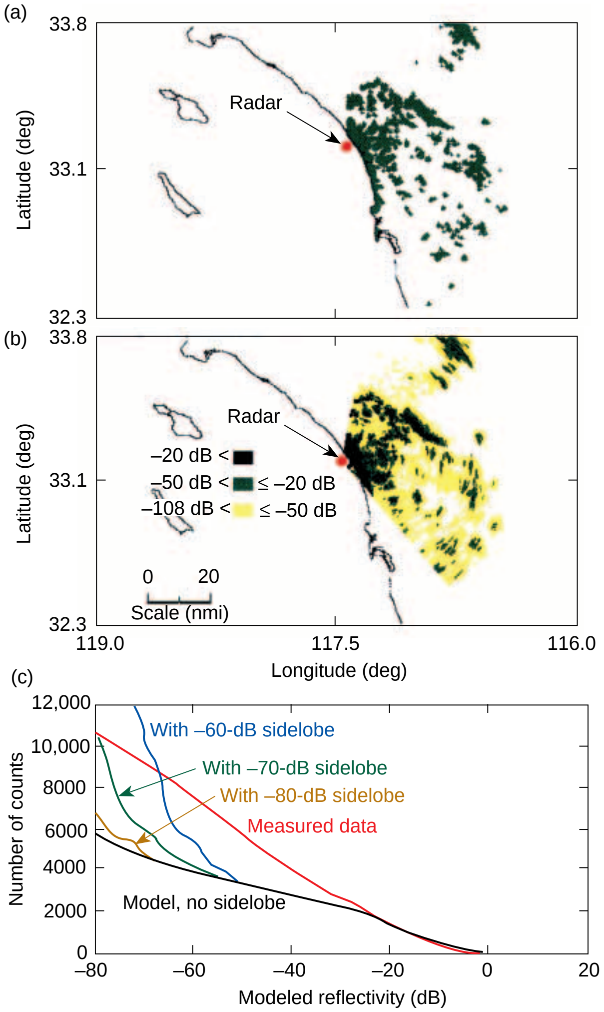


Figure 11. Comparison of coherent data collector land clutter data with theoretical cross-sectional estimates. (a) Predicted clutter return. (b) Actual return using coherent data collector data. (c) Comparison of the cumulative distribution of the radar data with the theoretical prediction. The effects of different levels of antenna sidelobes are shown.

even nonlinearities in the radar receiver/measuring dynamics. Methods for resolving the discrepancies are being studied but will require appropriate measurements for verification.

OTHER EFFORTS

The preceding examples by no means describe all the systems affected by coherent data collection and analysis. Following the success of the AN/SPS-48E work, the target acquisition system (TAS) Mark 23 radar was similarly instrumented using a special interface adapter. TAS is an automatic two-dimensional radar with an associated self-defense command-control system for countering antiship missiles and aircraft threats. Performance in clutter environments against small radar cross-sectional threats is of great importance. TAS rejects the clutter while retaining moving target data by performing moving target indicator and Doppler processing on the digitized radar video.

APL provided a coherent data collection capability to aid in evaluating system performance and capability. In 1991, data were collected from the TAS radar onboard USS *Kitty Hawk* (CV 63) during its transit from Norfolk, Virginia, to Puerto Rico. Analysis of these data demonstrated that the radar estimation of velocity by calculation of phase progression was highly accurate, as validated using low-altitude drone data collected at sea. The data also verified the strong performance of TAS in difficult clutter environments. The effort provided an excellent basis for future performance extensions.

Another highly successful effort involved the Tartar MK 74 MOD 15 radar set.[13] The Naval Sea Systems Command asked APL to design, fabricate, and test a coherent data collector for this radar set. Possible desensitization of the radar in the presence of a missile warhead blast was a concern. At the time, the effect was not accounted for in the radar system analysis because of lack of an appropriate model. Parametric analysis of coherent radar data collected during missile tests would result in the needed model. The device, pictured in Fig. 12, interfaces with the continuous wave illuminator and the pulse radars of the MK 74. It was tested by APL aboard USS *California* and then delivered to the sponsor.

For all these examples building the hardware is only the first step. The collected data must be properly analyzed, keeping in mind the needs of the program and the peculiarities of the radar systems from which the data are collected. A window to the environment as seen by the radar itself is a tremendous asset in evaluating performance. Models and approximations are essential for much of the work, but in the end the system must be tested. With the rising cost of testing and the limited availability of assets, a way must be found that allows system testing, and especially development, to be performed somewhere else than aboard ship. As seen in the MK 92 CANDO and the AN/SPS-48E ADP, a coherent collection and playback capability can provide the needed environment.

Current efforts include the design, fabrication, and test of a prototype TAS auxiliary processor by APL. Three units are planned, each with a range of capabilities similar to those of the MRP and the ADP. One unit will support land-based testing in the summer of 1996. The other two units will be installed aboard ships and participate in the Cooperative Engagement Capability/Initial Operational Capability testing in the fall of 1996. Figure 13 is a block diagram of the hardware architecture of the prototype TAS auxiliary processor. The coherent data extraction capability will provide the important real-time playback capability.

Figure 12. The Tartar coherent data collector processor unit with the front cover removed. The custom boards and other commercial cards are shown in the card cage.

Future efforts include the continuing support of existing radar systems, such as Phalanx, AN/SPS-48E, and possibly the AN/SPS-48E pulse Doppler upgrade. In this last program, the new waveform will require much higher subclutter visibility than the existing radar supports. Coherent data will be used to measure overall system stability. Analysis will allow designers to better determine target detectability, given the more demanding clutter environment presented by the new pulse Doppler upgrade waveform.

Finally, in support of the Aegis Program, APL continues to pursue development of a coherent data collection capability for SPY-1. Design requirements are an order of magnitude higher than that needed for other radar systems,[14] primarily because of the large number of simultaneous high-speed radar data channels that must be instrumented. Each channel's data rate is approximately equivalent to the total data rate of the most capable collectors previously built. Recent advances in storage devices and bus architectures, however, make it feasible to develop a suitable SPY-1 collector. One needs to properly balance risk, potential for growth, cost, and overall capability of the device.

CONCLUSION

Modern radars rely on coherent signal processing techniques to meet the challenges of operations in littoral regions. Programs developing and evaluating radar systems reap significant benefits by applying a methodology of data collection and analysis. The approach provides insight into the performance of these complex systems and gives the designer and system

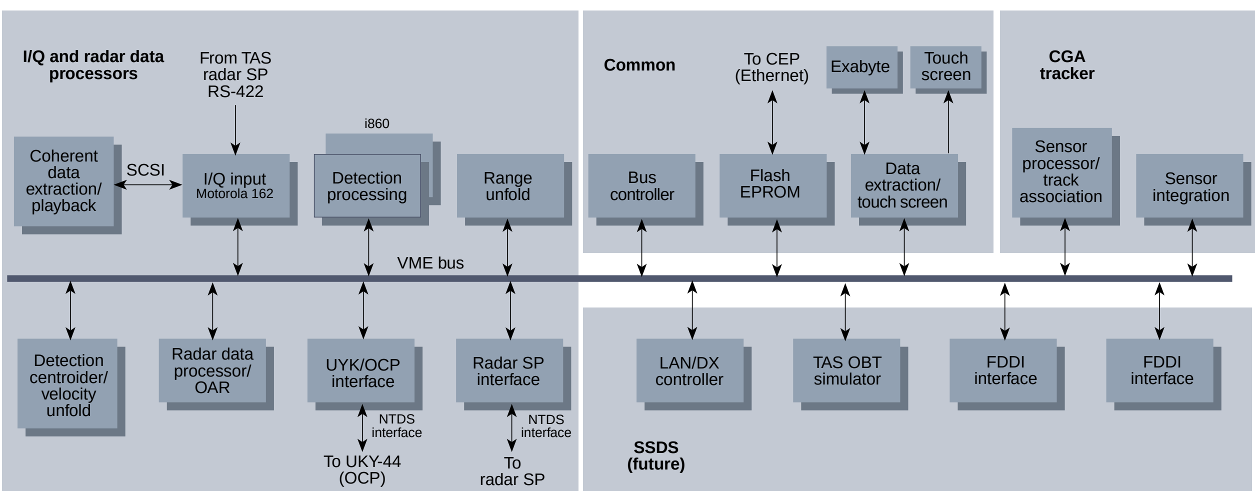


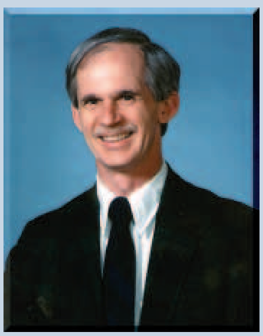
Figure 13. Hardware architecture of the prototype target acquisition system (TAS) auxiliary processor. The detection processing slot is CSPI 1860; all other slots are Motorola 167 (17 slots total). SP, signal processor; SCSI, Small Computer System Interface; I/Q, in-phase channel/quadrature; VME, VERSAmodule Eurocard; NTDS, Naval Tactical Data System; CEP, cooperative engagement processor; EPROM, erasable programmable read-only memory; LAN/DX, local-area network/data extraction; CGA, Common Genealogy Architecture; OAR, output and regulation; OCP, Operational Control Program; SSDS, Ship Self-Defense System; OBT, On Board Training; FDDI, fiber distributed data interface.

analyst a much-needed radar perspective of the environment. Signal processor testing can be done using realistic data at real-time data rates. Design evaluation and system development benefit from realistically complex tests performed in the laboratory prior to the start of expensive at-sea testing. Future developmental efforts likewise benefit from both the technical expertise gained by applying these techniques and the availability of the database accrued during system development.

REFERENCES

1. Barton, D. K., *Modern Radar Systems Analysis*, Artech House, Norwood, MA, pp. 1–8 (1988).
2. Nathanson, F. E., Reilly, J. P., and Cohen, M. N., *Radar Design Principles*, 2nd Ed., McGraw-Hill, New York, pp. 1–41 (1990).
3. Schleher, D. C., *MTI and Pulsed Doppler Radar*, Artech House, Norwood, MA, pp. 1–15 (1991).
4. Rzemien, R., Bade, P. R., and Roulette, J. F., *Functional Description—MK 92 Coherent Data Collector*, JHU/APL FS-85-261, Laurel, MD (1985).
5. Rzemien, R., Bade, P. R., Roulette, J. F., and Thomson, B. A., *Functional Description of Phalanx Coherent Data Collector*, JHU/APL FS-86-146, Laurel, MD (1986).
6. Taylor, S. A., *Presentation of CIWS Intraship EMI Data from USS Lake Erie*, JHU/APL F20-95U-099, Laurel, MD (1995).
7. Roulette, J. F., *Beam Sequence Tests for Mitigation of Beam to Beam Interference in AN/SPS-48E MTI Radar*, JHU/APL F2E-93-6-673, Laurel, MD (1993).
8. "The Cooperative Engagement Capability," *Johns Hopkins APL Tech. Dig.* **16**(4), 377–396 (1995).
9. Lin, C. C., *Development of Land Clutter Model with Digital Terrain Elevation Data*, JHU/APL F2A-92-1-022, Laurel, MD (1992).
10. Dockery, G. D., "Modeling Electromagnetic Wave Propagation in Troposphere Using the Parabolic Equation," *IEEE Trans. Ant. Prop.*, **36**, 1464–1470 (Oct 1988).
11. Dockery, G. D., *Status of Tropospheric Electromagnetic Parabolic Equation Routine (TEMPER) Development*, JHU/APL F2B-89-U-8-012, Laurel, MD (1989).
12. Reilly, J. P., and Lin, C. C., *Radar Terrain Effects Modeling for Shipboard Radar Applications*, JHU/APL FS-95-060, Laurel, MD (1995).
13. Rzemien, R., *Proposed Coherent Data Collector for the TARTAR MK 74 MOD 15 Radar Set*, JHU/APL F2E-92-3-417, Laurel, MD (1992).
14. Rzemien, R., *Design Alternatives for a SPY-1 Coherent Data Collector*, JHU/APL F2E-94-3-443, Laurel, MD (1994).

THE AUTHOR



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