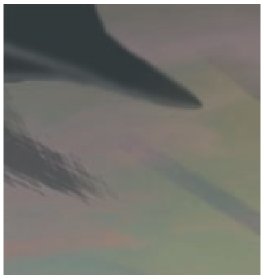

The Mark 92 Modification 6 Fire Control System and APL's Coherent Radar Data Program

Elinor Fong and Stephen W. Kay

The Mark 92 Modification 2 and Modification 6 fire control systems provide horizon search and fire control track functions on FFG 7 class ships. The Applied Physics Laboratory built two coherent radar data collectors to aid in test and evaluation of the Mark 92 Modification 6 system. The first was built in 1984 and the second in 1994. Both of the data collectors use state-of-the-art technology to meet the high-data-rate requirements. The Laboratory also developed a data reduction program to automate data analysis. The data collectors have been used extensively, and the data have been of significant value in evaluating and improving the system.

(Keywords: Clutter, Data collector, Doppler filter, Radar.)

INTRODUCTION

The Mark 92 Modification 6 (MK 92 MOD 6) fire control system (FCS) engineering design model was completed in the fall of 1983. Production versions are currently installed on 12 FFG 7 class ships. The system consists of a horizon search radar known as the combined antenna system (CAS) search, and two fire control radars: (1) CAS track and (2) separate track and illuminator (STIR). The CAS search radar provides horizon search capability, particularly against small radar cross section low-flying targets. The track radars provide track and illumination support for Standard Missile 1. The MOD 6 is an extensive upgrade to the MK 92 MOD 2 FCS. The upgrades include a fully coherent receiver and transmitter, lower antenna sidelobes, advanced electronic counter-countermeasures, and improved reliability and maintainability.

APL designed and built the MK 92 coherent data collector (CDC) to aid in test and evaluation of the MOD 6 FCS. A data reduction capability was developed to automate the analysis process. As the radar program progressed and improvements to the signal processor were proposed, the MK 92 CDC and the data reduction proved to be valuable tools in evaluating proposed radar processor algorithms. The data reduction was expanded to include an emulation of the radar's signal processor so that proposed algorithms could be incorporated and evaluated using previously collected data. This capability enabled analysts to evaluate algorithms without having to implement them into the radar system and conduct tests, which is costly both in terms of time and money.

DESCRIPTION OF THE MK 92 CDC

Russell Rzemien, Jay F. Roulette, and Paul R. Bade designed the original MK 92 MOD 6 CDC in 1985. The CDC records the in-phase and quadrature components of the radar returns, as well as other pertinent radar information. The radar manufacturer built custom radar interface boards that extracted the required radar signals from the FCS. The CDC is able to interface with the CAS search, CAS track, or STIR. The CDC can collect data from only one of the radars at a time.

Originally, the data were stored in a buffer and then transferred to a nine-track tape. Several years later, the original tape drive was replaced with a faster and denser 8-mm tape drive, allowing significantly more data to be recorded. Because the data cannot be transferred to tape as fast as the data are received from the radar, only a portion of the data can be recorded. When collecting search data, the only data recorded are within an operator-specified sector limited in range and bearing. Originally, the sector size could not be much larger than 10° by 15 mi, depending on the radar waveform. When collecting track data, the CDC collects the data continuously for a specified period and then downloads the data to the tape and repeats the cycle. When the CDC is downloading the data to tape, the track data sent by the radar during this time are not recorded.

For many years, the CDC was used in many data collection exercises and test events. Although the sector size for CAS search collection was relatively small and the time during which track data could be collected was relatively short, the data proved to be very useful. One of the problems that plagued the MOD 6 system was difficult to analyze without a large CAS search collection sector. To adequately characterize the problem and evaluate proposed approaches, a sector size of at least 25° by full range was necessary. The larger collection sector required designing and building a new MOD 6 CDC.

Russell Rzemien, Ronald J. Clevering, Brian A. Williamson, and Daryl I. Tewell designed and built the new MOD 6 CDC in 1994. The interface between the radar and the CDC remained unchanged. The new CDC takes advantage of advances in media storage technology to provide significantly larger CAS search collection sectors and essentially continuous collection of track data. The CAS search collection sector can be as large as 270° with no range gating. The data are written to a large disk array that can hold up to 10 gigabytes of data. The data are copied to tape off-line for more permanent storage.

Figure 1 is a functional block diagram of the MK 92 CDC. The input processing card receives the in-phase and quadrature data, waveform information, radar set status, and timing signals. This card also contains a test signal generator that allows CDC operation to be tested without being connected to a radar. After the input processing card performs some data buffering, it passes the data to the data controller and formatter, where header and trailer words are added to the data stream. The data controller and formatter then divides the data into blocks that are multiplexed out to high-speed random access memory boards (buffer A and buffer B) over internal busses. It then notifies the system controller when data are available from the buffers. The system controller selects data from these buffers on the basis of an operator-selected azimuth sector and directs the data to an external hard disk array for temporary storage. At an appropriate time, the operator directs the system controller to access the data stored in the hard disk array and then place the data into permanent storage on magnetic tape.

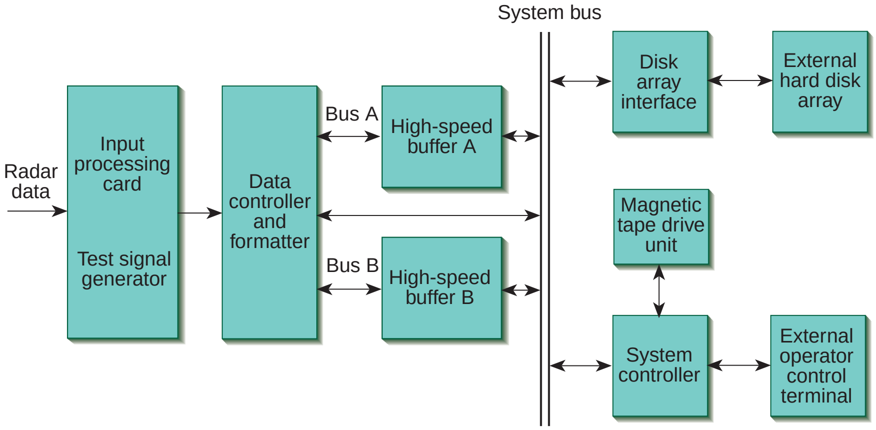

Figure 1. MK 92 CDC functional block diagram.

MK 92 CDC DATA REDUCTION PROGRAM

Each time the MK 92 CDC participates in a test, dozens of data tapes are generated. Objects of interest vary, depending on the objectives of the collection. Aircraft and missiles participating in an exercise, aircraft of opportunity, surface shipping, and clutter have all been recorded and studied. Clutter types include land, sea, atmospheric (such as rain), and man-made objects.

Each MK 92 CDC data tape consists of one or more data files containing data covering up to several hundred radar scans. Each scan consists of the data collected in a 1-s interval, corresponding to the rotation period of the CAS search radar. For the CAS track radar, a time window within the 1-s period provides a convenient sectoring mechanism. Each scan comprises multiple dwells, and each dwell contains one or more pulses having the same RF frequency, pulse repetition frequency, and other operating characteristics. Each pulse consists of thousands of range samples.

In addition to these data tapes, data are also collected from auxiliary sources that help the analyst to interpret the CDC data. These sources include log sheets and notes filled out by the test conductor, data products from the data collector of the SYS-2(V)2 automatic detector and tracker, Global Positioning System data, and radar video collected using the Hawkeye airborne radar video instrumentation collector, which was originally developed for another project and adapted for use on the MK 92.

Figure 2 shows the external interfaces of the MK 92 CDC data reduction program. Typically, a tape summary is produced for each data tape, and then individual files are selected for further analysis. The data products are used for further analysis outside of the data reduction program or for inclusion in reports and presentations.

The objectives of the data reduction program are the following:

- Provide rapid-response graphical and textual data products
- Provide a graphic user interface for ease of use
- Facilitate easy modification and maintenance of software
- Support both in-house and field testing
- Make the best use of commercially available hardware and software

Figure 3 shows the internal components of the data reduction program. Most of the software programs were written using a matrix computation and visualization package called Matlab (see http://www.mathworks.com). Matlab provides extensive built-in digital signal processing functions, high-level language facilities, and an easily programmed graphic user interface. Matlab minimized the amount of code that had to be developed and allowed for easy modification and maintenance of the code. C code was written to interface with the tape drive unit and to produce the tape summaries and disk data files.

The data on the tape are stored on disk using an industry-standard format called the Network Common Data Form (NetCDF). NetCDF and a public domain interface program were developed by the University Corporation for Atmospheric Research (see http://www.unidata.ucar.edu). C code was developed to read the data from the tape drive unit and, using the NetCDF C library, save the data to disk. Matlab can access the disk file by calling the NetCDF C library via a C program called MexCDF developed at the U.S. Geological Survey in Woods Hole, Massachusetts (see ftp://crusty.er.usgs.gov/pub/mexcdf).

The software runs on a Unix workstation using the Sun Solaris operating system. The system is used in the field to verify that the CDC is functioning correctly, as well as to provide a "quick-look" capability during testing. It is also used in-house to analyze large amounts of data. Therefore, the software has to run efficiently on everything from a laptop Unix computer to a full-size desktop workstation.

The data reduction program has been used to analyze current radar system performance and to emulate new algorithms. Figure 4 demonstrates the current radar system performance against a target in a heavy-clutter environment. This figure is a bearing collapsed range vs. scan contact plot. Figure 5 is the same data set but with a new processing technique discussed later in this article. The data reduction program allows the analyst to document the improvement in clutter rejection both numerically and graphically.

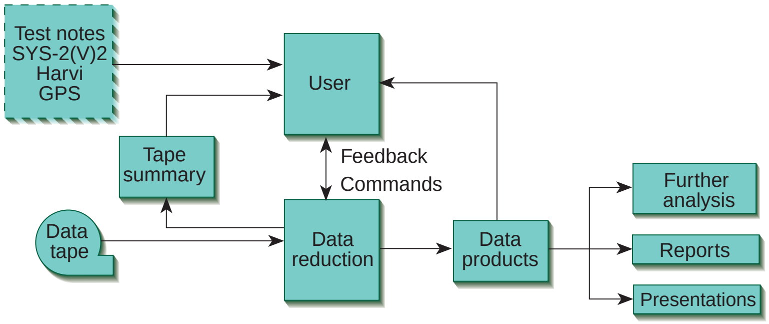

Figure 2. MK 92 CDC data reduction showing external interfaces. (HARVI = Hawkeye airborne radar video instrumentation, GPS = Global Positioning System.)

MK 92 CDC DATA ANALYSIS

False-Alarm Rate Reduction

The CAS search engineering development model demonstrated a high false-alarm rate during land-based testing in 1985. The radar, mounted on a trailer at Wallops Island, Virginia, overlooked the ocean. In that direction, CAS search experienced a much higher false-alarm rate than expected when operating with the coherent waveforms,

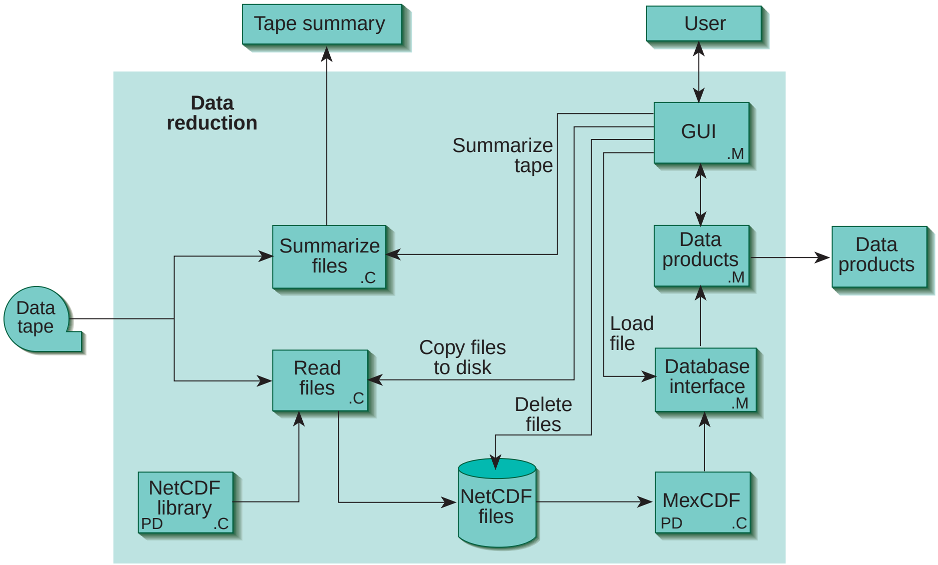

Figure 3. MK 92 CDC data reduction showing internal components. (.C = C code, .M = Matlab, NetCDF = Network Common Data Form, MexCDF = C program developed at the U.S. Geological Survey, PD = public domain.)

even when the ocean appeared to be relatively calm. One of the initial uses for the CDC data was to identify the cause of this problem. Analysis of the data showed that the average sea clutter return had small radar cross section and a low Doppler rate, as expected. The data, however, revealed the presence of sea spikes that had a radar cross section that could be 20 dB greater than the average sea clutter return, and they also had a Doppler rate higher than the average sea clutter return. These spikes were not being filtered out by the radar's low-Doppler-rate filters because their Doppler rate was higher than predicted, and their amplitude was large enough to exceed the constant false-alarm rate discriminator. These filters were designed to reject clutter but allow slowly moving targets through, based on the assumption that the clutter was well behaved (i.e., did not contain these spikes). Having identified the cause of the false alarms, the low-Doppler-rate filters were disabled, and only the high-Doppler-rate filters were used. Since the Doppler rate of spiky sea clutter was not high

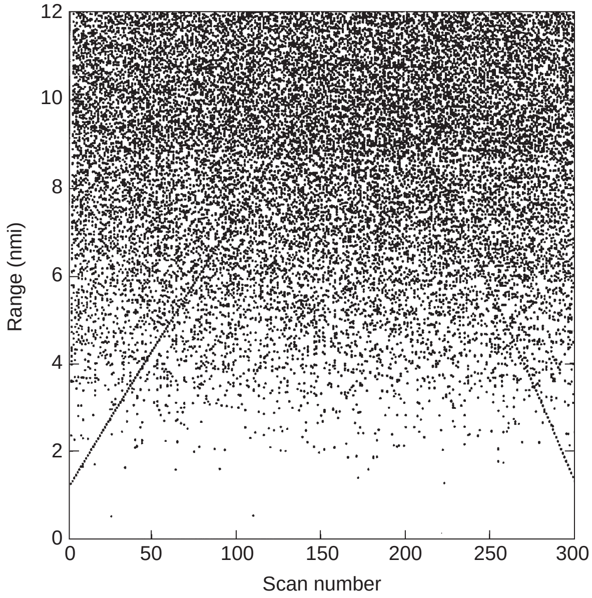

Figure 4. Detections and uncanceled clutter based on current processing. The number of detections is 39,843.

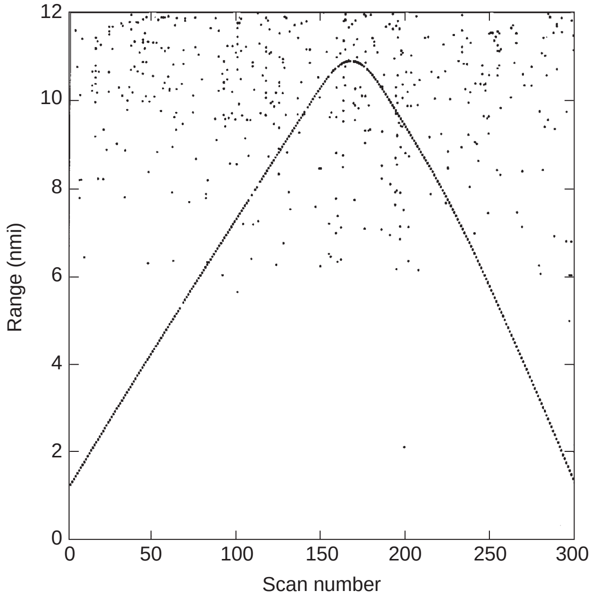

Figure 5. Detections and uncanceled clutter based on the modified front fill/back fill technique. The number of detections is 2394.

enough to pass the high-Doppler-rate filter, the false-alarm rate was greatly reduced.

First-Pulse Anomaly

During an investigation to use MK 92 data for possible imaging applications, Larry T. Younkins of APL analyzed the MK 92 CDC data collected using the first production MK 92 MOD 6 FCS. He noticed that the phase change between the first and second received pulses was different from the phase change between the remaining pulses, and that whenever the system switched its RF frequency, the first transmitted pulse at the new frequency was at a different phase than the other transmitted pulses at the same frequency. This phenomenon is referred to as the first-pulse anomaly. The transmitted pulses must have the same phase or a known phase to measure the pulse-to-pulse phase change of the received pulses. The pulse-to-pulse phase change is a direct measure of the Doppler shift or velocity of the target. Ideally, if the target is not accelerating, the pulse-to-pulse phase change of the received pulses should be constant over the coherent burst of pulses. Because coherent processing depends on well-behaved phase characteristics in the transmitted pulses, the first-pulse anomaly degrades the coherency of the system. The MK 92 radars are medium pulse repetition frequency radars and transmit either five or seven coherent pulses in a burst. The pulse repetition frequency and radar frequency are constant within a burst but are random from burst to burst. The phase difference between the first and second pulses was not consistent from burst to burst. For some bursts the phase difference was quite small; for other bursts the phase difference was as large as 40°.

CAS track data were collected and analyzed during one exercise in which a Learjet was towing a 1-m^2 sphere. Figure 6 is a plot of the pulse-to-pulse phase difference ($\Delta\phi$) across a burst for five different bursts. Since the MK 92 is a medium pulse repetition frequency system, the Doppler is aliased, and the pulse-to-pulse $\Delta\phi$ will not be the same from burst to burst. However, the pulse-to-pulse $\Delta\phi$ should be constant across a single burst. As seen in Fig. 6, $\Delta\phi$ between pulses 1 and 2 is distinctly different than that between the remaining pulses in the burst. Figure 7 presents histograms of the second-order phase difference, which is defined as

$$\begin{aligned}\Delta(\Delta\phi_i) &= \Delta\phi_i - \Delta\phi_{i+1} \\ &= (\phi_i - \phi_{i+1}) - (\phi_{i+1} - \phi_{i+2}) \ .\end{aligned}$$

If no first-pulse anomaly existed, $\Delta(\Delta\phi_i)$ would be approximately zero for all pulses in the burst. As seen in Fig. 7, $\Delta(\Delta\phi_i)$ is approximately zero for all cases except the one that contained the first pulse.

To determine whether this phenomenon originated in the transmitter or the receiver, multiple time-around clutter, sometimes referred to as multiple interval clutter (MIC), was examined. (See the following section for a description of MIC.) CAS search data from land clutter in the second interval was analyzed. For second-interval clutter, no clutter return is contained in the first pulse; rather, it is contained in the remaining pulses in the burst. If the first-pulse anomaly existed when the pulse was transmitted, then the anomaly would now be seen in the second pulse. However, if it did not exist until the pulse was received, then the anomaly would be present in the first pulse, which contains only noise, and the anomaly probably would not be observable. The phase of the second and remaining pulses would not exhibit any signs of corruption. Figure 8 shows the $\Delta\phi$ for pulses 2 through 6 for five representative pulse bursts. Pulse 1 is not shown since it contains only noise and is not of interest. As clearly seen in Fig. 8, $\Delta\phi$ for pulse 2 exhibits the anomalous behavior, indicating that the corruption occurred before or during the transmission of the pulse.

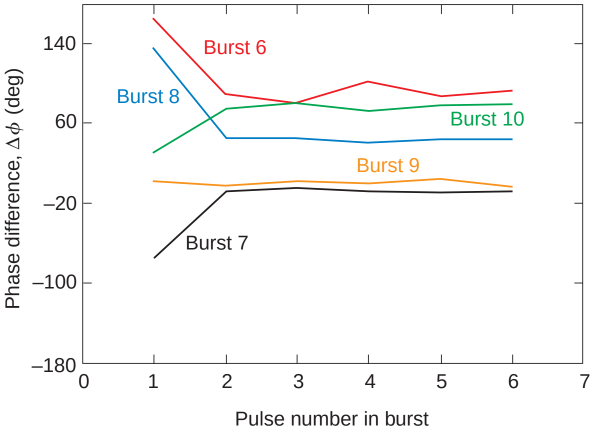

Figure 6. Phase difference ($\Delta\phi$) across a burst for five different bursts of pulses for a towed air target.

This analysis led to an examination and correction of the exciter units for all the remaining MOD 6 systems. Unfortunately, a residual phase difference in the first pulse remained; time and money constraints precluded correcting the problem completely. Nevertheless, the system was able to meet its requirements because the weight of the first pulse in the MK 92 coherent filters was smaller than in the remaining pulses, so the degradation was small. Thus, the system was able to cancel first-interval clutter well enough to detect and track targets representative of the specified threat.

Multiple Interval Clutter

A problem that seemed to plague the MOD 6 system was MIC. The CDC played an important role in helping to ameliorate the effects of MIC. When the MOD

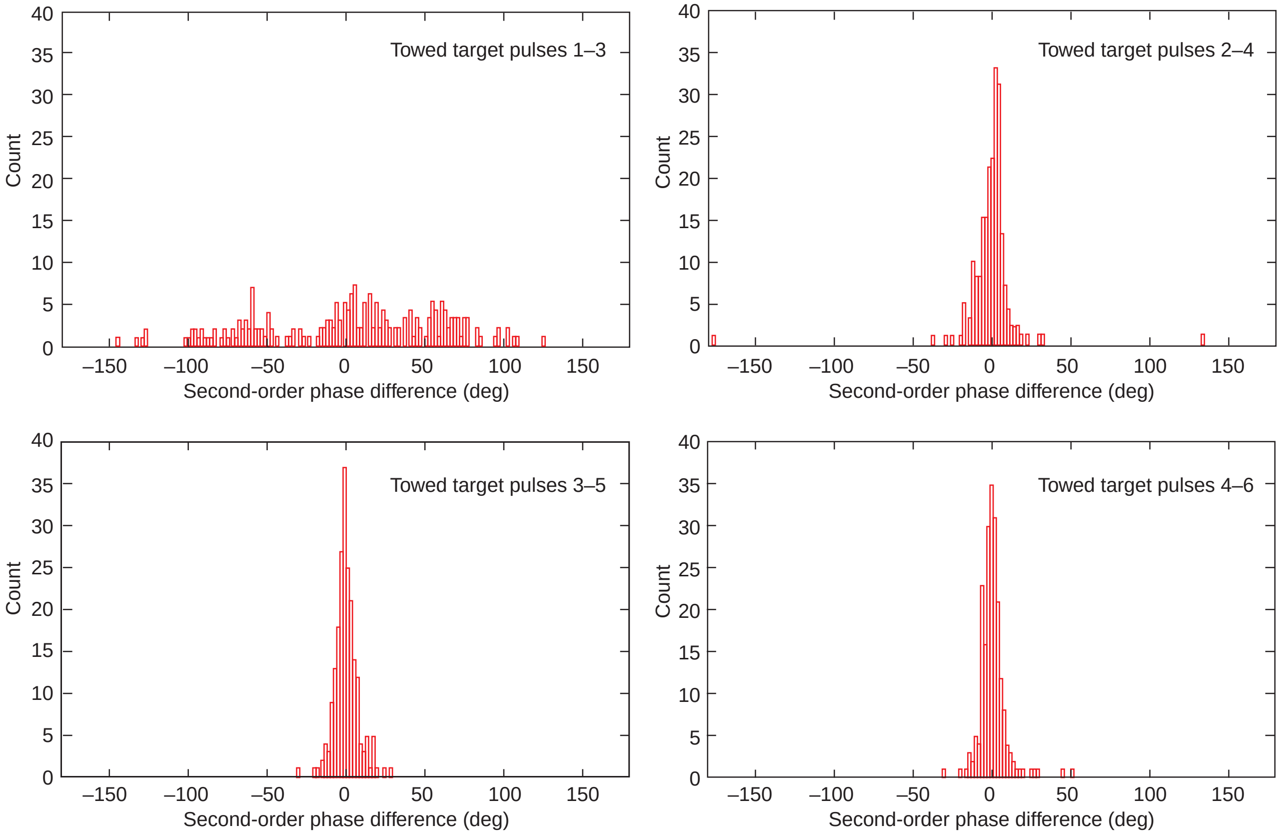

Figure 7. Histograms of the second-order phase difference $(\phi_i - \phi_{i+1}) - (\phi_{i+1} - \phi_{i+2})$ for a towed air target.

6 system was designed, the MIC from beyond the third interval* was not expected. Automatic processing, which detected MIC and processed the data using fill pulses (i.e., pulses that are transmitted but given zero weight in the receiver processor),[1] was implemented in the MOD 6 system. However, testing off the coast of California showed that MIC from beyond the fifth interval could occur when large surface-based ducts trap the radar energy and propagate the energy to far ranges. The fill pulses in the MOD 6 system were not adequate, and extremely large numbers of false alarms were experienced in the presence of MIC. The problem was twofold: The large amplitude of MIC caused some desensitization, and the large number of false alarms caused the automatic detect and track processor to discard many of the detections, including those of the target, to maintain a low false-alarm track rate.

Both of these consequences caused a significant delay in detecting and tracking the threat in the presence of MIC. What makes MIC particularly difficult to process is that it is contained only in a subset of pulses in a burst and it is aliased in range. Also, from burst to burst and scan to scan, the apparent range of the detections jumps around. This phenomenon creates a strobe-like effect on the plan position indicator, and the automatic tracker cannot use traditional clutter map techniques to discard the false alarms. Therefore, both the operator and the automatic tracker have great

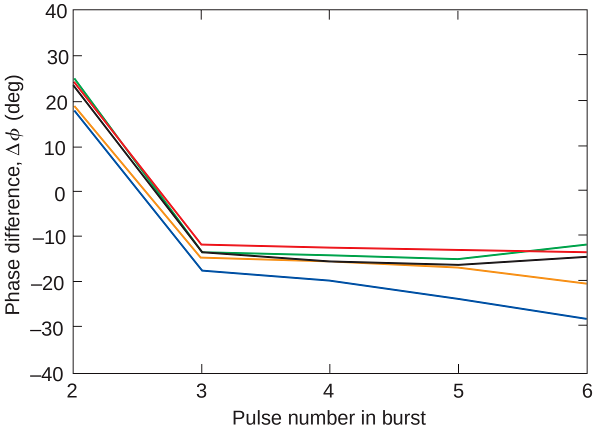

Figure 8. Phase difference ($\Delta\phi$) across a burst for five different bursts of pulses for second-interval land clutter.

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*Note: Intervals are defined as multiples of the fundamental radar pulse interval. For example, a radar that transmits pulses that cover 20 mi in range between transmissions will still receive echoes from beyond this range. The echoes from ranges of 20 to 40 mi are considered second interval, 40 to 60 mi are third interval, and so on.

difficulty in discriminating targets from the false alarms caused by MIC.

Over the years, several solutions have been proposed, such as slowing down the CAS search antenna to increase the time on target. The extra time on target would have allowed for more fill pulses, or burst-to-burst discrimination could be performed. This solution was somewhat costly and unacceptable because of the increased reaction time against the threat. Sidney A. Taylor of APL suggested a technique, described fully in Ref. 2, called "front-fill/back-fill" as an option. This technique was tested using previously collected MIC data from tests off the coast of California and resulted in elimination of 75 to 80% of the false alarms from MIC. This option held much promise because of its effectiveness and relative ease of implementation.

One concern related to this technique is that it cannot cancel the MIC present simultaneously from multiple intervals. If the clutter return at a particular range cell is from two sources in different intervals, then the front-fill/back-fill technique may be ineffective. The data collected off the coast of California indicated that MIC of this type was not a concern. Within a burst, MIC from different intervals may be present, but at a single range cell, MIC was from a single interval. Since the front-fill/back-fill processing varied from range cell to range cell, the technique appeared to be sufficient.

One of the areas of the world where large surface-based ducts are expected is the Arabian Gulf. Anecdotal reports from the Fleet indicated that MIC was experienced for essentially 360° around the ship. These reports were puzzling because the terrain suggested that clutter return from MIC should only be experienced in a bearing sector of about 45–60° in extent in the direction of the coast of Iran. However, no MIC was expected in the direction of Saudi Arabia because of the low terrain profile. No CDC data were ever collected in the Arabian Gulf, so it was difficult to ascertain what was causing the false alarms. APL and Lockheed Martin Tactical Defense Systems, the radar manufacturer, were tasked to collect and analyze data in the Arabian Gulf and determine if the front-fill/back-fill technique would be effective.

Two data collections in the Arabian Gulf were performed. The first occurred in February 1995, and very little MIC was observed. Environmental data taken indicated that no surface-based ducts were evident. The MK 92 MOD 6 CAS search radar did not produce any false alarms from MIC during this data collection. The second occurred in July 1995. In contrast to the first data collection, numerous CAS search false alarms from MIC were observed. A typical height of the surface-based ducts was 500 ft. Test personnel confirmed early reports that MIC was present for essentially 360° around the ship. Figure 9 is a plan position indicator plot representative of what the radar operators must contend with when dense MIC is present. During the data collection, aircraft were flown through areas that contained many false alarms from MIC. Even though the operators knew where the aircraft were flying, the density of the false alarms was such that the operators lost sight of the aircraft.

A quick analysis of the data indicated that the source of MIC was from objects in the middle of the Gulf, not from land clutter. Navigation maps of the area showed the presence of platforms used for oil drilling. These platforms have substantial range and bearing extent. In addition, MIC from oil tankers was common.

The CDC data associated with this test were processed using the front-fill/back-fill technique. Approximately 70% of the false alarms were eliminated. The plan position indicator plot in Fig. 9 shows the detections (including false alarms) for a CDC data file using current radar processing. Figure 10 is a plot of the detections for the same input data using the front-fill/back-fill technique. Although many of the false alarms were eliminated, the number was less than expected. Initially, MIC from multiple sources was thought to have caused the poorer performance. However, analysis of the data indicated that MIC from multiple sources was not present. The cause of the poorer than expected performance was the first-pulse anomaly.

The front-fill/back-fill technique was sensitive to the first-pulse anomaly when MIC was from the fourth interval. The first-pulse anomaly only degraded cancellation of first-interval clutter slightly because seven pulses were processed and because the first pulse was weighted less than the others. However, the front-fill/back-fill

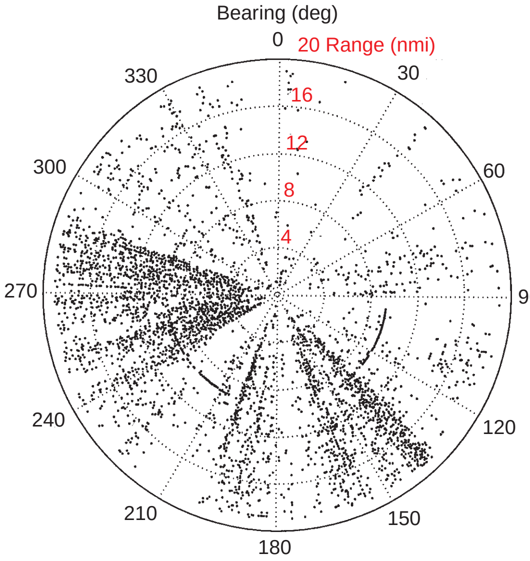

Figure 9. Uncanceled multiple-interval clutter returns using current processing. The number of detections is 6149, and the number of scans is 4.

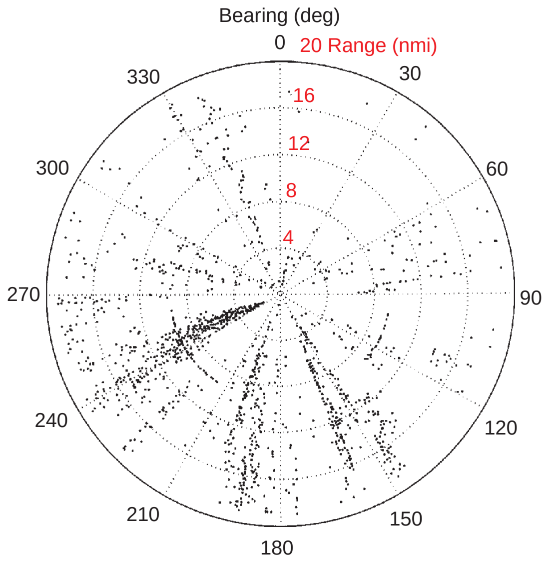

Figure 10. Uncanceled multiple-interval clutter returns using the front-fill/back-fill technique. The number of detections is 1995, and the number of scans is 4.

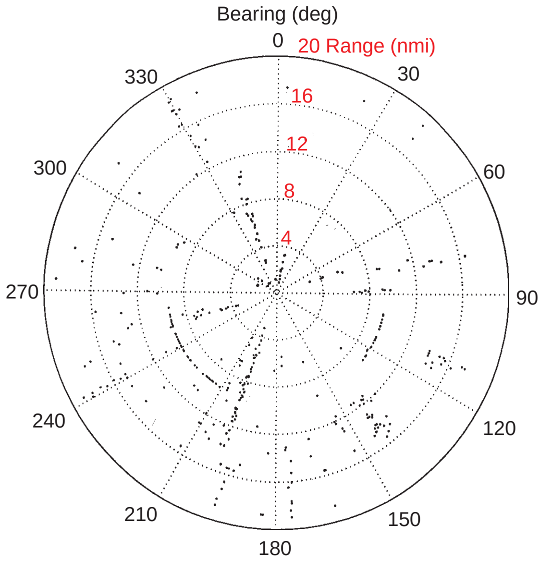

Figure 11. Uncanceled multiple-interval clutter returns using the modified front-fill/back fill technique. The number of detections is 546, and the number of scans is 4.

technique only processes four pulses, making the filters more sensitive to the first-pulse anomaly. Thus, the weights in the front-fill filters were changed, and a significant improvement was realized. This modification will cause a slight degradation in cancellation when both first-interval and fourth-interval clutter are present. Figure 11 is a plot of the detections after the same data in Figs. 9 and 10 were processed by the modified front-fill/back-fill technique. Over 90% of the false alarms were eliminated. The remaining false alarms were caused by very large returns that exceeded the subclutter cancellation and from returns from large ships whose Doppler was outside the clutter notch of the filters.

CONCLUSION

The MK 92 CDC has been used extensively over the past decade to evaluate and improve radar processing. It has allowed the analysts to implement and verify various radar signal processing algorithms off-line and perform a direct comparison with real system performance. Without the CDC, multiple tests would have been necessary to verify the various techniques. In addition, the CDC data enabled analysts to characterize the radar environment, allowing appropriate techniques to be developed.

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