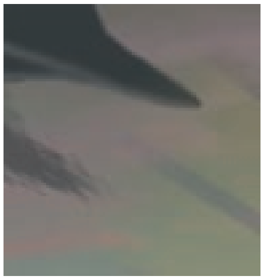


Coherent Data Collection and Analysis Capability for the AN/SPS-48E Radar

Jay F. Roulette and Kenneth A. Skrivseth

The Applied Physics Laboratory, in its role as technical advisor to the Navy for the AN/SPS-48E radar, designed and operates a coherent data collector to analyze radar system performance. This article presents examples of how coherent data analysis has helped the program development efforts and provided insights into the performance of the AN/SPS-48E radar. The topics discussed include beam-to-beam interference, wideband limiting, beam sequence effects, and characterization of land clutter.
(Keywords: AN/SPS-48E, Coherent, Radar, Signal processing.)

INTRODUCTION

Designers of shipboard radar systems have for decades used coherent signal processing to separate moving target echoes from unwanted clutter signals, taking advantage of the Doppler effect. This enables detection of targets even when their associated echoes are weaker than the echoes from strong clutter. As targets have become smaller and fly lower, and as ships operate more often in a strong clutter environment (e.g., adjacent to land clutter), the need for high-quality coherent processing has increased. For modern radar systems, coherent processing is implemented in sophisticated digital signal processors using methods that were impractical until recent advances in speed, memory, and architecture were made. These sophisticated processors allow radar systems to achieve high levels of detection performance with clutter present, consistent with other design factors affecting system coherency.

Coherent processing is a method by which signals are transformed to the frequency domain and are operated on by frequency-selective filters tuned to different Doppler frequencies. Moving targets will exhibit a Doppler frequency shift in their echoes, whereas clutter signals will show little or no Doppler shift. Detection of a weak, Doppler-shifted target signal in the presence of strong zero-Doppler clutter is possible under three conditions:

1. The Doppler filter with good target signal response has very low sidelobe response at the zero (i.e., clutter) Doppler frequency.
2. The target signal is stronger than internal receiver noise.
3. The stability of the radar system is sufficient to avoid other problems.

The ability to collect (record) and process coherent data from radar systems is essential if these advanced systems are to achieve their performance potential. To properly develop such systems, measurement and analysis tools are needed to accurately assess performance, characterize the actual received-signal environment, and identify and diagnose system deficiencies or design shortcomings. The data collected can also provide the basis for defining upgrades to radar systems. Without appropriate measurement and evaluation tools, there is substantial risk that unknown performance shortcomings will exist in a radar system owing to design oversights, small implementation errors, or incorrect assumptions about the signal environment.

APL has developed a coherent data extraction capability for the AN/SPS-48E (hereafter, SPS-48E) radar[1] in parallel with the radar design agent's development of a digital moving target indicator (DMTI) upgrade. (The radar design agent for the SPS-48E is ITT Gilfillan.) The capability to extract coherent data proved invaluable in this radar upgrade process, as well as in follow-on testing of the first-article DMTI at sea. Using field-collected clutter samples from a radar, we can now characterize that radar's clutter performance at the systems level via stability plots and other methods, as described in this article.

Data provided by the coherent data collector (CDC) have been indispensable in supporting further advances in the radar system, including the auxiliary data processor (ADP) field change. In addition, the collection of high-fidelity coherent and noncoherent samples of land and sea clutter has facilitated radar processing modifications and clutter performance evaluations.

RADAR DESCRIPTION

The SPS-48E radar is a shipboard long-range three-dimensional S-band air search radar operating on multiple pencil beams with a rotating phased-array antenna. It is used in air surveillance and provides target detection data to an external automatic tracker.

The system has been operational in the Fleet since 1987 and evolved from a family of SPS-48 radars used on Navy surface combatants since the 1960s. Its output data have been employed to support long-range Standard Missile 2 engagements through a launch-on-search process and through the more common detect, track, and designation process.

The SPS-48E radar is mechanically scanned in azimuth at a 4-s rate and is frequency scanned in elevation. Frequency steering permits the use of multiple simultaneous elevation beams. Each elevation beam has a different frequency, and each frequency uses a separate receiver channel. This feature allows the radar to cover the entire search volume with narrow pencil beams in a short time.

During noncoherent dwells, the SPS-48E transmits nine simultaneous elevation beams, each at a different frequency. Each nine-beam group covers about 6° of elevation. Transmissions of these beam groups are sequenced at different base elevation angles to cover the full specified volume (0–30° or 0–48° elevation, depending on mode). By utilizing nine simultaneous beams in a beam group with a separate receiver for each, the radar can illuminate the entire long-range/high-elevation angle coverage volume required, achieve good azimuth and elevation accuracy with multiple pencil beams, and maintain the 4-s antenna rotation rate.

The SPS-48E DMTI

In recent years the SPS-48E has been upgraded with the DMTI and other processing modifications to enable the reliable detection of small low-flying targets over water. The need for such a coherent capability grew in response to the Navy's increased emphasis on this challenging threat class.

The DMTI is available in low-elevation (Low-E) mode in three simultaneous elevation beams, covering 0 to 2° above the horizon, with a clutter improvement factor of about 35 dB. The range of the Low-E coherent mode is 150 nmi. In this mode, noncoherent volume coverage is simultaneously maintained with a sequence of five stacked beam groups of nine beams each, giving 30° of noncoherent coverage in elevation and a range of 155 nmi. The noncoherent elevation coverage in either Low-E or equal-angle coverage mode for a target in track is up to 65°; elevation steering of the upper beam group is controlled externally by an automatic tracker.

A recent ADP upgrade to the SPS-48E DMTI incorporates several modern signal processing features using commercial off-the-shelf electronics. ADP processing includes coherent velocity estimation, advanced clutter processing, and multiple interval target contact processing. The velocity estimation technique is similar to one developed at the Naval Research Laboratory for the AN/SPS-49A(V)1 and other radars.

The SPS-48E performs well for targets over sea clutter, but the system's stability limit prevents significant Low-E target detection performance for low flyers in land clutter. If a target is physically located above the land clutter by several degrees, however, it is usually detectable since, in this case, the narrow antenna beams are not illuminating the land clutter.

The DMTI Waveform

The baseline SPS-48E waveform sequence includes both coherent transmissions (for DMTI waveforms) and noncoherent transmissions (for non-DMTI waveforms). About one-third of the surveillance time is spent in the DMTI portion; the remaining two-thirds is spent in non-DMTI portions. The DMTI transmissions are at low elevation, where the radar must counter sea clutter; non-DMTI transmissions cover a sequence of elevations to provide volume coverage.

The DMTI portion of the waveform consists of short bursts of six pulses near the horizon at a constant pulse repetition frequency for processing. Each pulse of the six-pulse burst contains three subpulses. Each subpulse forms a separate elevation beam by a shift in frequency, since the antenna is frequency scanned in elevation. Elevation coverage spans the horizon to about 2° in the DMTI portion of this mode. The DMTI operation represents three DMTI radars running simultaneously, each with a beam at a slightly different elevation angle. Here, three independent receivers are used, one for each beam. Beam-to-beam interference, described later in this article, was a particular concern that was examined by gathering relevant data using the CDC.

Overview of Radar DMTI Processing

The SPS-48E radar (Fig. 1) uses a triple conversion receiver. The system is wideband until the second intermediate frequency (IF) conversion, where the individual beams are bandpass filtered and separated. Since three beams are used in the DMTI, there are three coherent oscillator frequencies (one for each beam) in the final conversion of the receiver (final IF is about 1.5 MHz). A single analog-to-digital (A/D) converter is used for each beam. In-phase and quadrature (I/Q) data are developed based on samples that are spaced at multiples of 90° at the IF frequency. The interpolation filter develops the I/Q estimates from A/D samples (see the boxed insert, Intermediate-Frequency Sampling Technique). The I/Q data preserve the amplitude and phase of the IF radar return. The amplitude of the radar return is computed as $\sqrt{(I^2+Q^2)}$. The phase of the return is computed as $\tan^{-1}(Q/I)$. From pulse to pulse, a phase progression will be seen on moving targets due to Doppler, and no phase progression will be seen on stationary reflectors. It is this phase progression on moving targets that allows such targets to be separated from stationary reflectors (clutter).

To remove clutter and pass targets, DMTI filters are employed in each beam independently. A bank of digital filters is used to cover the region between low velocity (small phase shift per pulse) and higher velocity (near 360° phase shift per pulse). Targets moving at speeds such that they present more than a 360° phase progression per pulse are said to be velocity ambiguous, since the radar pulse repetition interval causes aliasing. For example, a phase progression of 400° per pulse appears exactly as a phase progression of 40° per pulse. To avoid velocity blinds (i.e., targets moving at speeds such that their phase progression is 360° per pulse, thus appearing as 0° per pulse), the pulse repetition frequency is jittered on a burst-to-burst basis. This ensures that the phase progression presented by the target will vary on a burst-to-burst basis, and thus the target will not be velocity blinded on all bursts.

At the output of each DMTI filter is a digital constant false alarm rate filter, which makes estimates from the DMTI filter output level and provides a threshold offset to detect targets and regulate false alarms. Detections can occur in any filter in the filter bank. Filter selection logic is used to determine which filter is

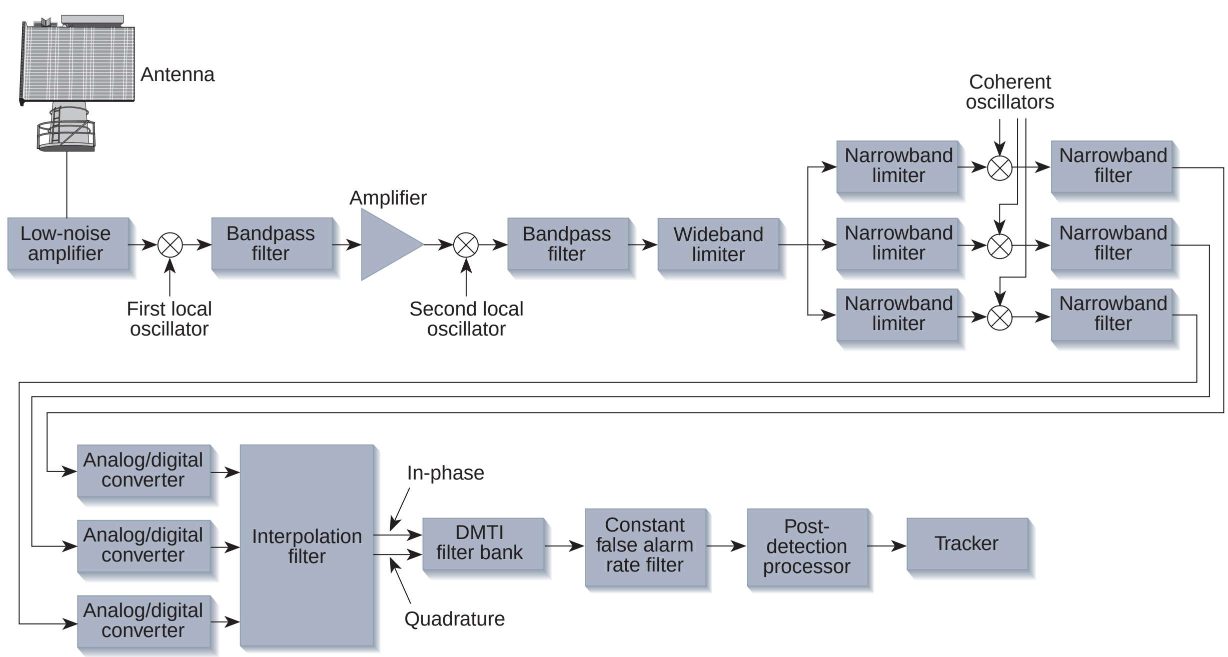
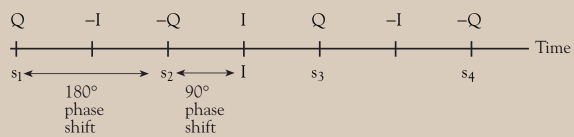


Figure 1. Functional block diagram of the AN/SPS-48E receiver and signal processor.

INTERMEDIATE-FREQUENCY SAMPLING TECHNIQUE

To develop in-phase (I) and quadrature (Q) data, the SPS-48E radar uses an intermediate-frequency (IF) sampling technique with an IF bandwidth of approximately 400 kHz, IF center frequency of about 1.5 MHz, and analog-to-digital (A/D) sampling frequency of 6 MHz. There is a precise 4:1 relation between the IF sample frequency and the IF center frequency. If modulation effects across the received pulsewidth are ignored, the echo may be thought of as several cycles of a sine wave. The sine wave is sampled at four times its rate, i.e., every 90°. Therefore, alternate samples will be in quadrature with each other. To account for modulation effects across the pulse, one sample is defined to be "I"; two leading and two trailing samples are combined by the following equation to create the "Q" sample (s):

$$Q = -\frac{1}{16}s_1 - \frac{9}{16}s_2 + \frac{9}{16}s_3 + \frac{1}{16}s_4$$



This technique provides accuracy acceptable for the clutter cancellation requirements of the SPS-48E low-elevation-mode DMTI. If higher clutter cancellation is required, a more elaborate finite impulse response filter for both the I and the Q channel is required. The advantage of the current technique is that I/Q data are developed with only a single A/D converter. The two baseband analog channels in a conventional receiver are not required, and aliasing due to channel gain mismatch is avoided. Amplitude modulation effects across the received pulse do, however, cause some degradation.

chosen for subsequent processing, and it selects the appropriate DMTI filter based on signal-to-background ratio and the absolute background level.

The detections in each burst of six pulses are post-processed on a burst-to-burst comparison basis to form target contacts. Those contacts are then merged with noncoherent contacts and passed on to the system automatic tracker.

Fundamental to the filtering process is the assumption that the phases of the target and clutter echoes are well behaved. The background clutter shows little or no change in phase from pulse to pulse, whereas the target will exhibit a steady phase progression from pulse to pulse. Instabilities in the radar transmitter and receiver can add "noise" to the received echo, thereby degrading phase progression and limiting the system's sensitivity.

Measuring system performance in clutter requires special instrumentation and analysis techniques such as stability plots. The following section describes such a technique.

INITIAL DATA COLLECTION

To assist in the development of the DMTI upgrade, APL collected data from the prototype SPS-48E onboard the USS *Kidd* in May 1990. Data collection was made possible by adapting the original Mark (MK) 92 radar CDC. An interface unit was built to reformat the output from the SPS-48E so that these radar signals would be compatible with the existing MK 92 CDC. Data analysis programs also had to be modified specifically to handle recorded SPS-48E data.

This interim CDC was limited to a small data collection sector since the design was optimized for another radar. Data could be written to tape at about 100 KB/s. This translates into a recording capability of approximately 12° by 24 nmi, which was adequate to get a first impression of system performance.

One performance measure of prime interest from this data collection effort was radar system stability. The ability of any radar system to cancel clutter depends on the purity (stability) of the transmitted waveform. To quantify the stability of the SPS-48E DMTI waveform, live radar-collected data were processed offline to generate a new data product called a "stability plot." The stability measurement technique is illustrated in Fig. 2. Recorded radar data are applied to the

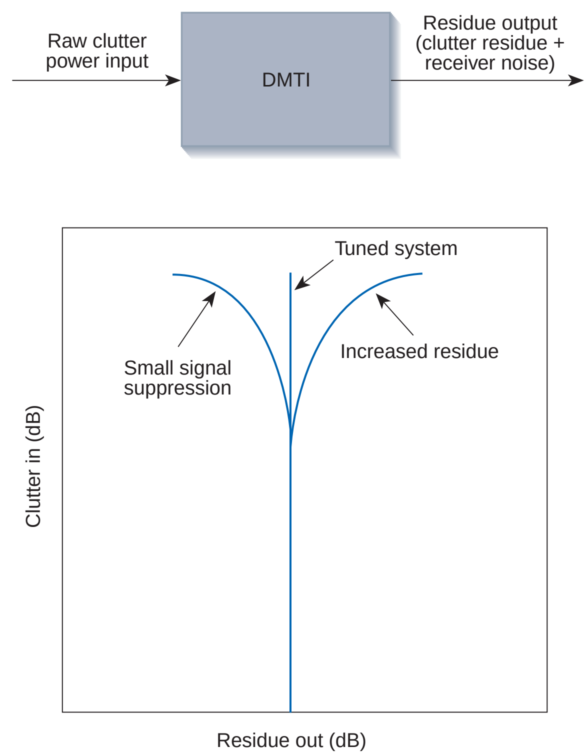


Figure 2. System stability measurement technique. Recorded radar data are processed by an off-line coherent processor. A histogram showing clutter cancellation capability (indicative of stability) is then generated by plotting raw clutter power into the DMTI on the *y* axis and the residue out of the DMTI on the *x* axis. The small signal suppression shown is due to insufficient dynamic range, and the increased residue is due to system instability.

input of an off-line DMTI processor. The input clutter signal and the residue out of the modeled DMTI can then be used to quantify system stability. The stability plot is generated by plotting raw clutter power on the *y* axis and the clutter residue on the *x* axis. The plot is then smoothed by finding the average residue for all occurrences of a given input clutter power.

In an ideal system, the shape of the stability plot should be nearly vertical, indicating that the filter residue is constant, independent of input clutter level. The filter residue would then be at a value determined by receiver noise. When the system is exposed to clutter that exceeds its stability limit, the plot will bend to the right, indicating that the filter residue is increasing as the input clutter level is increasing. If the system has less dynamic range than clutter cancellation capability, the plot will bend to the left, indicating suppression of receiver noise in areas of high clutter.

Initial inspection of the SPS-48E prototype DMTI data showed the expected cancellation in sea clutter but poor cancellation in land clutter. Sea clutter primarily resides in beam 1, whereas land clutter is clearly visible in all three beams. This finding led to the supposition that some sort of beam-to-beam interference might be occurring and degrading the land clutter cancellation. Beam-to-beam interference was investigated extensively during later exercises onboard the USS *California*.

An oscillator drift problem also occurred intermittently in the receiver, which degraded cancellation on the *Kidd*. Figure 3 shows the phase difference or delta phase between two consecutive pulses as a function of range. Note that for stationary clutter the delta phase should be constant at a value related to the ship's speed. Problems such as oscillator drift would be difficult to isolate and correct without the detailed examination of recorded coherent I/Q data.

The demonstrated usefulness of the data collected with the interim CDC led to the development of a dedicated CDC for the SPS-48E. The interim CDC proved the potential of the radar to cancel sea clutter and detect targets in clutter, but it also raised questions about the effects of using multiple, simultaneous beams at different frequencies.

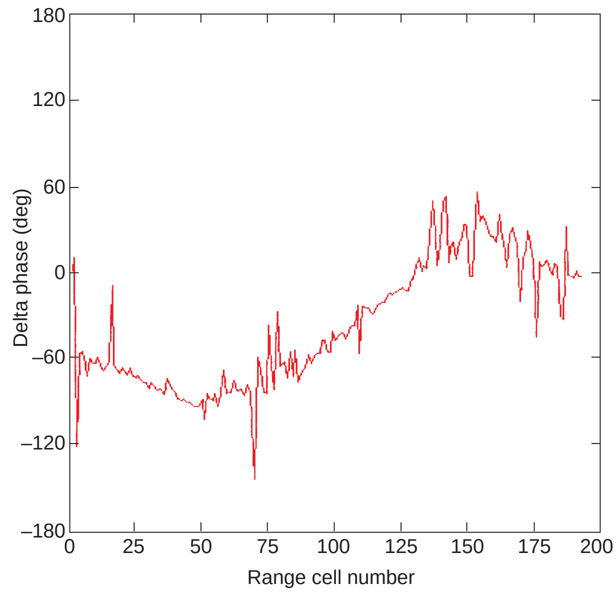


Figure 3. The oscillator drift problem. The phase difference between echoes from two consecutive pulses is shown as a function of range (1 range cell = 0.125 nmi). This plot indicates that the receiver is not maintaining phase stability, thereby degrading the clutter cancellation capability. Note that for stationary clutter the phase difference should be a constant derived from the ship's speed.

DEVELOPMENT OF A DEDICATED SPS-48E CDC

On the basis of the success of the interim CDC, APL designed a dedicated collector in 1992 for the SPS-48E with much greater capability. The dedicated collector is based on a mass storage parallel disk array that can hold 2.6 GB of data.

The CDC for the SPS-48E accepts 16-bit data from the radar, which includes I/Q data and appropriate data tags (run identification, azimuth, latitude and longitude, etc.) to make the data meaningful upon analysis. The input burst data rate is 8 MB/s. Data are recorded during DMTI transmissions and may be recorded optionally during the noncoherent transmissions on the horizon. This limits the average data rate to approximately 4 MB/s. The data are placed into buffer memory and later read out to the parallel disk array, which can accept data at an 8-MB/s input rate. The data may be azimuth sectored prior to storage on the disk to conserve recording time. At a 4-MB/s rate the disk array will fill up in about 11 min. After recording, the data are archived to magnetic tape for permanent storage at a slower data rate (500 KB/s). It takes 1.5 h to archive the entire disk to tape.

A large amount of data can be collected very quickly with a CDC, a capability that is required for some tests. The operator must be selective about what is recorded so as not to completely fill the disk too early. The use of azimuth sectoring and small multiple files has proven beneficial in this respect.

ANALYSIS OF THE SPS-48E COHERENT DATA

Besides its role in assessing system stability as previously discussed, data collected by the CDC have also been used to investigate beam-to-beam interference, wideband limiting, beam sequence effects, and characterization of land clutter amplitude.

Beam-to-Beam Interference

The CDC has been a valuable tool in proving the existence and extent of beam-to-beam interference. Before testing with the CDC, the presence of such interference was difficult to demonstrate.

Extensive investigation into beam-to-beam interference was performed during the SPS-48E DMTI development phase. This type of interference results essentially from running three DMTIs (i.e., one for each beam) at slightly different frequencies simultaneously. Once received, the beams are bandpass filtered to separate them. However, the transmissions are time-limited, not band-limited. Some coherent spectral components from beam 1 can appear in beams 2 and 3. In addition, broadband noise components from beam 1 are transmitted at the frequency of beam 2 and thus will appear directly in the passband of beam 2 at some level. These effects were first postulated based on CDC data from the *Kidd*.

Figure 4 shows two stability plots generated from CDC data recorded at a land-based test site in Van Nuys, California. The data in Fig. 4a are from beam 1 when the radar was radiating only on beam 1. Note that the stability plot is basically vertical, indicating good cancellation. The vertical nature of the plot shows that the DMTI filter residue is approximately constant, independent of the amplitude of the clutter. Figure 4b shows the same data set but from beam 2. Remember that there was no beam 2 transmission; however, energy from beam 1 appears in the receiver at the frequency of beam 2 because of the time-limited nature of the transmission and also because some broadband noise is included with any transmitted waveform. Obviously, the energy in beam 2 has a large noncoherent component evidenced by the plot bending to the right. Therefore, beam-to-beam interference can detrimentally affect clutter cancellation performance since a noncoherent component appears.

Wideband Limiting

After proof of the existence of beam-to-beam interference (Fig. 4b) was obtained, we investigated a technique to mitigate it. The technique uses a linear amplifier with a soft limiter in the wideband portion of the second IF. The limiter provides linear amplification until the limit level is reached. Once the limit level is reached, the amplitude is limited but the phase of the IF is preserved. The limit level is set so that the amount of interference from one beam to another is controlled at an acceptable level, i.e., the level at which false alarms due to beam-to-beam interference are substantially suppressed. Nearly vertical stability plots (Figs. 5a and 5b) generated from land clutter data collected on the *California* show mitigation of the effects of beam-to-beam interference.

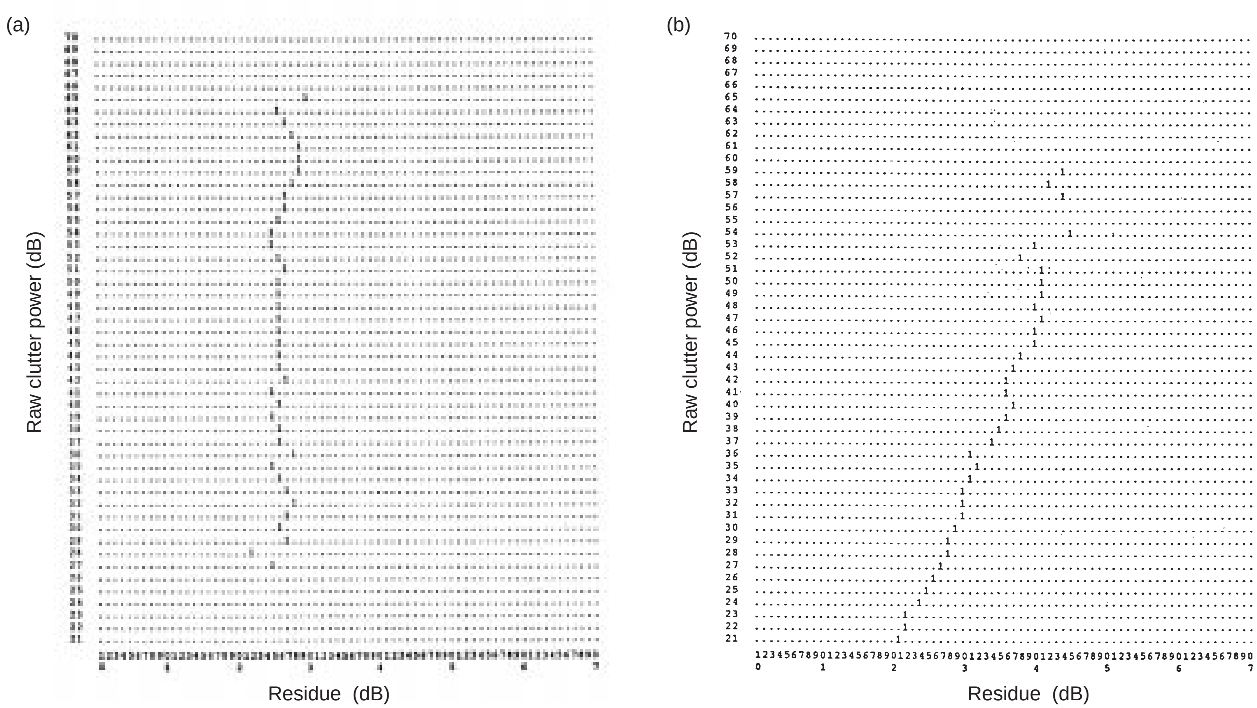


Figure 4. Stability plots generated from data collected at a land-based test site in Van Nuys, California. The radar was only radiating on beam 1. (a) Response in beam 1 (without wideband limiter). The plot is approximately vertical, indicating good cancellation. (b) Response in beam 2 (without wideband limiter). The plot bends to the right at the top, indicating degraded cancellation. This proves that beam-to-beam interference has a noncoherent component since a degraded response occurred in beam 2 when the radar only radiated on beam 1.

Beam Sequence Effects

Since the wideband limiter does not completely control the effects of beam-to-beam interference, some clutter breakthroughs or potential false alarms will occur in certain clutter geometries. To investigate the nature of such breakthroughs, land clutter data were collected with the wideband limiter bypassed. Figure 6a shows raw clutter data recorded under this condition. The ship was operating about 12 nmi off the coast of San Clemente Island, California. The close-in sea clutter is visible, and the island appears beginning at about 12 nmi. The data were recorded using the standard beam transmit sequence of 3-1-2 (i.e., beam 3 is transmitted first, followed by beam 1 and then beam 2).

Figure 6b shows the data of Fig. 6a after DMTI filtering. Note that the edges of the island are apparent. After further investigation, the following reasoning was developed to explain why the edges showed poor cancellation. Beam 3 will strike the land first since its frequency is transmitted first. Noncoherent noise associated with beam 3 transmission has components at the frequency of beam 1. This noncoherent noise in the beam 1 frequency will reach the land clutter simultaneously with the coherent energy of beam 3. So the clutter reflection observed in the beam 1 receiver will include noncoherent noise at the leading edge of the island, appearing in the receiver a few microseconds before the coherent beam 1 reflection is received. Similarly, on the back edge of the island, beam 1 will have passed the island while beam 2 is still striking the island and thus reflecting noise at the frequency of beam 1. Therefore, beam 1 can be expected to experience problems at both the leading and trailing edges of the island owing to corruption from other beams when the wideband limiter is bypassed. Since noncoherent noise cannot be canceled with DMTI or Doppler filters, its presence can degrade detection performance substantially by producing false detections and masking real targets.

Figure 6c shows similar data after DMTI filtering when the radar was transmitting in the 1-2-3 beam sequence with the wideband limiter bypassed. Although no problem occurs at the leading edge of the clutter, corruption is evident at the back edge. This result is due to the following: Since beam 1 strikes the clutter first (using sequence 1-2-3), it will be the offender beam at the leading edge and thus will not be corrupted by the other beams. At the trailing edge, however, beams 2 and 3 can both cause beam-to-beam interference to beam 1.

Land Clutter Amplitude

Data were collected to determine the amplitude of land clutter seen by the SPS-48E radar. The data of Fig. 7 were collected when the ship was operating approximately 14 nmi off of the coast of Point Loma,

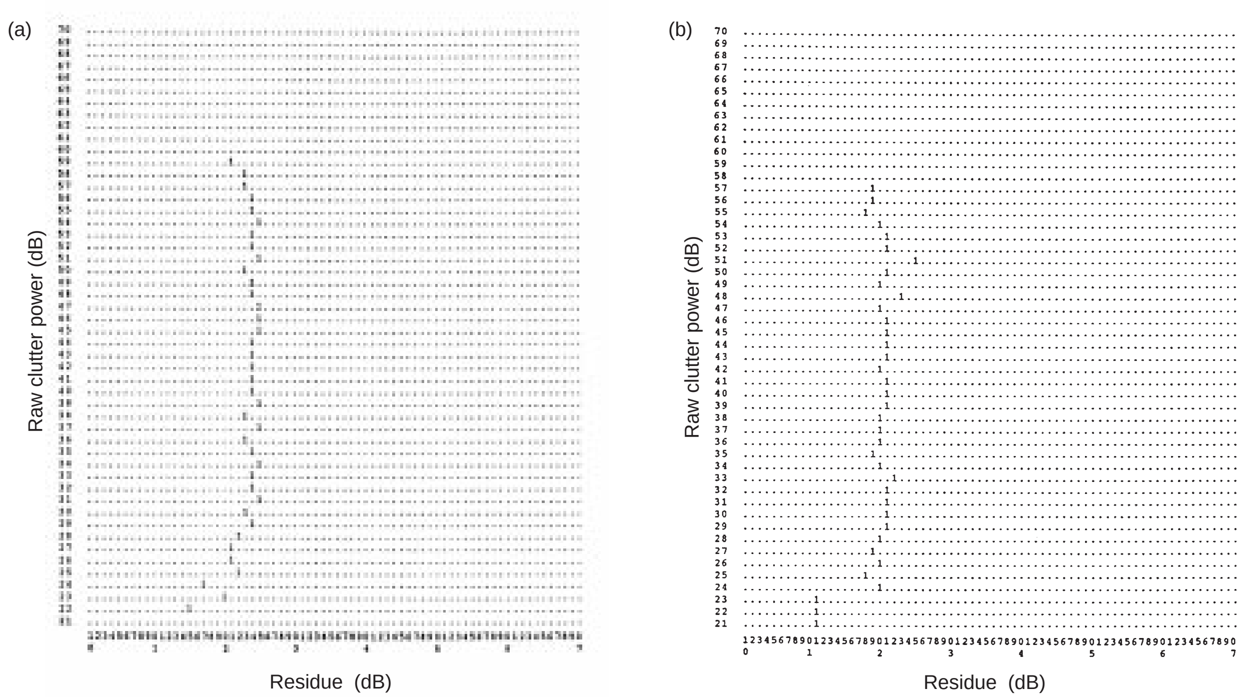


Figure 5. Stability plots generated from data collected on the USS *California*. The system was radiating all three beams with the wideband limiter installed in the receiver. (a) Response in beam 1. (b) Response in beam 2. Note that the wideband limiter effectively controls interference as evidenced by the nearly vertical plots.

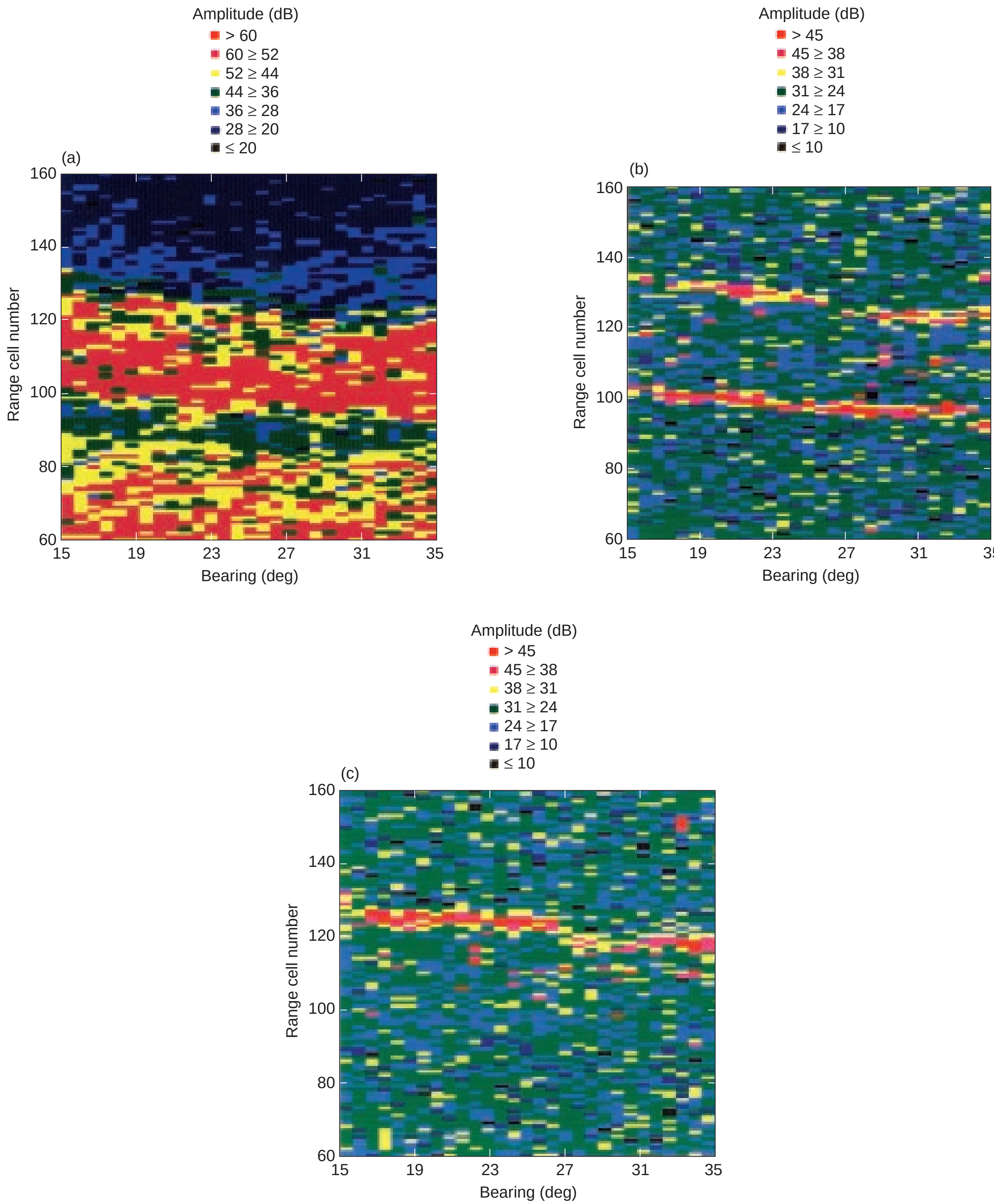


Figure 6. Data collected on the USS *California* while operating approximately 12 nmi off the coast of San Clemente Island with the wideband limiter bypassed. Each range cell represents 0.125 nmi. (a) Raw data using the 3-1-2 beam transmit sequence. (b) Same as Fig. 6a, except after DMTI filtering. Note the appearance of poor cancellation at the edges of the island. (c) Data collected using the 1-2-3 beam transmit sequence shown after DMTI filtering. The area of poor cancellation has moved to the back edge of the clutter, thus demonstrating the effect of beam transmit sequence on the appearance of clutter edges.

California. As seen in Fig. 7a, clutter signals from multiple range intervals essentially fill the area between the ship and the coast. Figure 7b was recorded while the radar was using 30 dB of RF attenuation. Note that the land is still quite strong. Figures 7c and 7d were recorded with 50 and 70 dB of attenuation, respectively; land clutter is still very visible even with 70 dB of attenuation. The clutter-to-noise ratio presented to the radar by this land has peaks on the order of 100 dB, thus confirming that land clutter can definitely present very large clutter echoes, an enormous challenge for radar systems.

CONCLUSIONS

The analysis of coherent data provides insights into radar operation that cannot be readily achieved by other means. For example, the proof of the existence

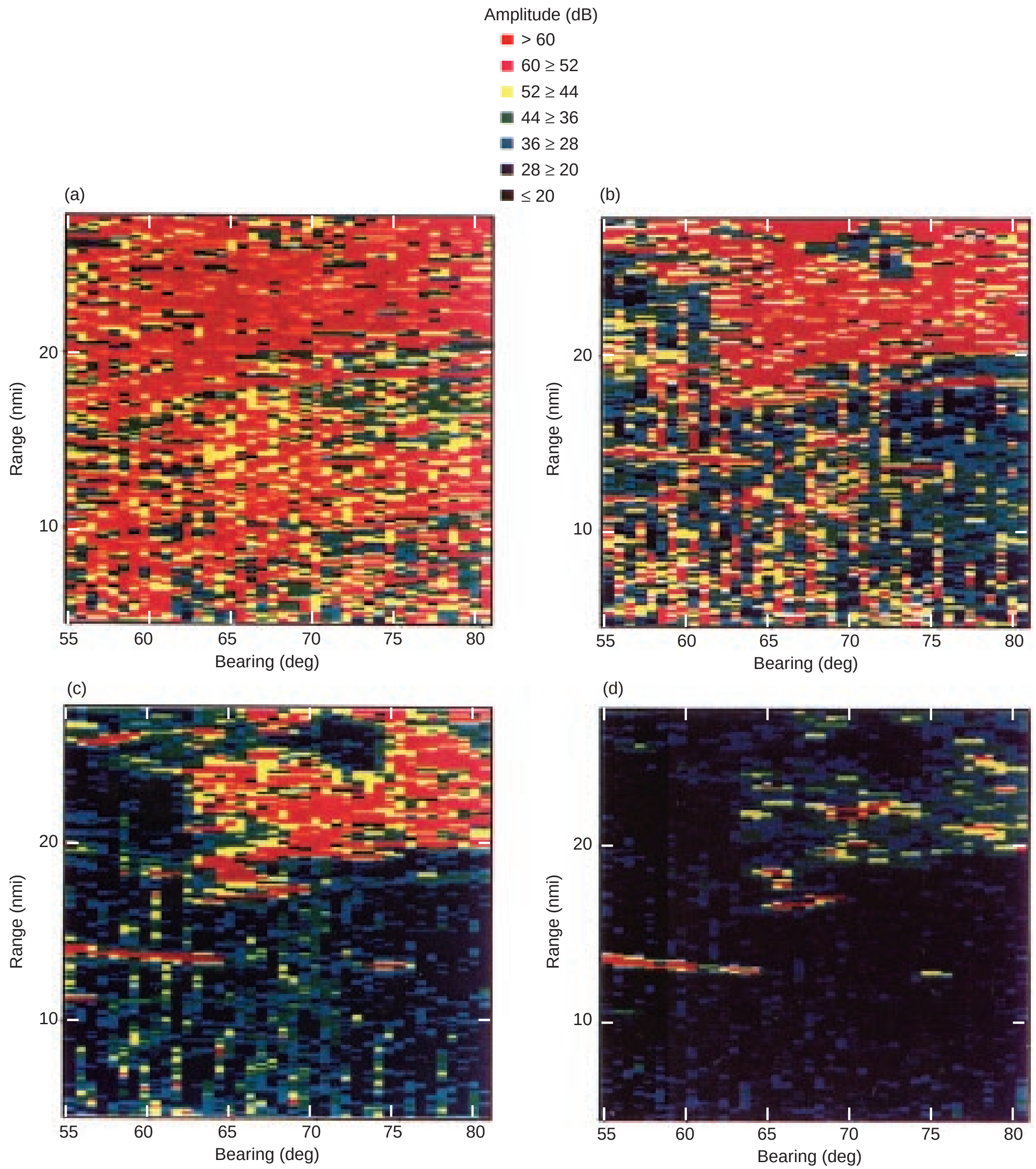


Figure 7. Beam 1 land clutter data collected approximately 14 nmi off the coast of Point Loma, California, using the normal 3-1-2 beam transmit sequence with a wideband limiter at 36 dB: (a) normal sensitivity time control, (b) constant 30-dB attenuation, (c) constant 50-dB attenuation, (d) constant 70-dB attenuation. Noise level is approximately 24 dB. Clutter-to-noise ratios on the order of 100 dB are seen.

of beam-to-beam interference and the need for wide-band limiting were greatly facilitated by the use of CDC data. Analysis of CDC data also spawned follow-on tests to determine the effects on clutter cancellation by altering the beam transmit sequence. Since land clutter caused saturation in the CDC data, tests were devised to characterize the amplitude of the land clutter echoes using attenuators in the radar receiver.

The land clutter data collected with various amounts of attenuation provided input data for a clutter study at APL that compared actual clutter data with clutter predictions made using high-fidelity maps. The I/Q data from targets also provided input data for preliminary studies that proved the viability of velocity estimation techniques using SPS-48E data. These velocity estimation techniques were eventually incorporated into the SPS-48E auxiliary data processor.

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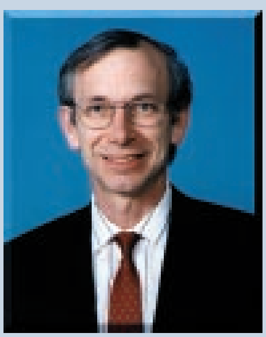

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