

# Communications Research Centre

## LOW DOPPLER TARGET DETECTION IN GROUND CLUTTER

by

John S. Bird

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John S. Bird

*(Radar and Communications Technology Branch)*

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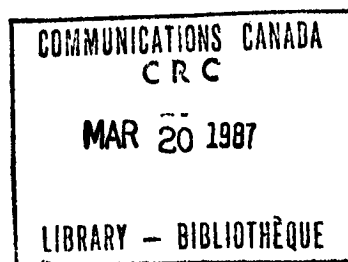
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# Low-Doppler Target Detection in Ground Clutter

by

John S. Bird

## ABSTRACT

This report presents evidence that a significant portion of ground clutter as seen by a stationary step-scan radar possesses a long-term stable coherent component. It is shown that knowledge of this component can be used to provide subclutter visibility of low-Doppler targets, and also to provide some target identification capability. Experimental data from an S-band phased array radar for different terrain types, seasons, and windspeeds are presented showing gains up to 25 dB. Detection-performance curves are presented for both conventional and coherent clutter processing techniques.

## 1.0 INTRODUCTION

A chronic problem for most ground-based surveillance radar systems is the detection of radially stationary targets in the presence of ground clutter. Returns from aircraft flying tangential to the radar or from a hovering helicopter can be buried in the clutter and hence the target lost to the radar. Many schemes for handling ground clutter have been proposed, analysed and implemented (Dax [1], Sutherland [2], Muehe et al [3], O'Donnell et al [4], O'Donnell and Muehe [5]). Generally they fall into two broad classes: adaptive threshold techniques (noncoherent clutter maps and sliding window normalizers) and pulse cancellation. Adaptive thresholding is used when target and clutter cannot be separated by Doppler filtering and pulse cancellation is used when separation is possible. These traditional methods have been developed under constraints imposed by continuous-scan antennas. For step-scan phased array antennas the constraints are removed permitting the use of a coherent threshold, which can significantly improve low-Doppler target detectability.

A typical processing scheme for a step-scan phased array radar consists of a receiver, Doppler filter bank and detector. Pulse cancellers have been used in such systems to reduce dynamic range and the effect of filter leakage from high level ground clutter returns into neighboring Doppler cells [5]. This, however, renders the radar totally blind to targets flying at the so-called blind speeds, which includes the important zero-Doppler region. Adaptive thresholding has been used [5] to combat clutter in the low Doppler regions; however, detection performance is poor even for moderate clutter levels and can decrease as the clutter increases. On the other hand, the performance of a coherent threshold (as will be demonstrated in this report) can be independent of clutter level and there are no blind speeds to deal with.

The key to the utility of coherent thresholding lies in the very nature of the clutter returns. These returns must be coherent over the long term (minutes, hours, days, etc.). It is the purpose of this report to demonstrate that a large portion of ground clutter does possess this long term coherency and to use this characteristic of the clutter to establish the merits of coherent clutter processing. Since we are primarily concerned with detecting low Doppler targets the comparison will be between the adaptive and coherent thresholding techniques.

In addition it will be shown that coherent clutter processing can be used to identify or differentiate certain target and/or clutter types from a background of heavy ground clutter.

Coherent thresholding was first presented in the context of a coherent clutter map in 1982 [6]. Further evidence of the viability of the technique was presented in 1984 [7]. This report combines these results, presented in more detail, with new experimental evidence and an extension to multiple dwells. The theoretical and experimental results are presented in the operational context of an adaptive ground-based phased-array surveillance radar.

This report is divided into 6 sections, the first of which is the introduction. The second section examines the coherent nature of ground clutter and its statistical representation in the phase plane. The third section describes the effect of coherent clutter on various detection schemes and defines the coherent-to-diffuse power ratio, CDR, as a measure for comparison. Experimental evidence to support the suggested model for ground clutter and to describe the extent to which the model holds for different terrain types, seasons, wind speeds and times of day is given in section 4. In section 5 experimental clutter results are used to demonstrate the detectability of low-Doppler targets in real ground clutter and the merits of a coherent clutter map. The final section concludes the discussion by summarizing the main result and suggesting direction for further work.

## 2.0 CLUTTER AND TARGET RETURNS

### 2.1 Receiving System

The receiving system under consideration is shown in Figure 1. It consists of a coherent receiver followed by a base-band zero-Doppler filter. (Other Doppler filters are used to detect targets at higher Doppler frequencies but are not shown.)

The output of the zero-Doppler filter consists of the coherent sum of K returns and may be represented in the phase plane as a single point. The outputs for several groups of K returns plotted in the phase plane is a scatter plot of zero-Doppler clutter returns. This scatter plot characterizes the probability distribution of the interference which the target must compete against for detection. Several assumptions about this clutter distribution will be made and supported by experimental evidence.

## 2.2 Phase Plane Description of Ground Clutter

Ground clutter as seen by a step-scan radar consists of a coherent component and a diffuse component the relative powers of which depend on the nature of the clutter. Figure 2 illustrates this by showing 50 returns, plotted in the phase plane, for a patch of clutter consisting of a small metal research tower and bush. The individual returns were separated by 8 seconds with the complete scatter plot representing 6.67 minutes of data.

These returns are tightly grouped in the phase plane about an average amplitude and phase. The amplitude of the coherent component of the clutter is defined as

$$C \triangleq (u_I^2 + u_Q^2)^{\frac{1}{2}} \quad (1)$$

where

$$u_I = \frac{1}{N} \sum_{n=1}^N I(n) \quad (2)$$

$$u_Q = \frac{1}{N} \sum_{n=1}^N Q(n) \quad (3)$$

where  $I(n)$  and  $Q(n)$  are the in-phase and quadrature components of the  $n^{\text{th}}$  output of the zero-Doppler filter. For Figure 2 each point represents a single return as the length,  $K$ , for the filter was 1. The phase of the coherent component of the clutter is defined as

$$\theta \triangleq \arctan \left( \frac{u_Q}{u_I} \right) \quad (4)$$

The amplitude of the diffuse component is defined from the variation about the mean clutter point as

$$D \triangleq (\sigma_I^2 + \sigma_Q^2)^{\frac{1}{2}} \quad (5)$$

where

$$\sigma_I^2 = \frac{1}{N-1} \sum_{n=1}^N (I(n) - u_I)^2 \quad (6)$$

$$\sigma_Q^2 = \frac{1}{N-1} \sum_{n=1}^N (Q(n) - u_Q)^2 \quad (7)$$

### Phased Array Antenna

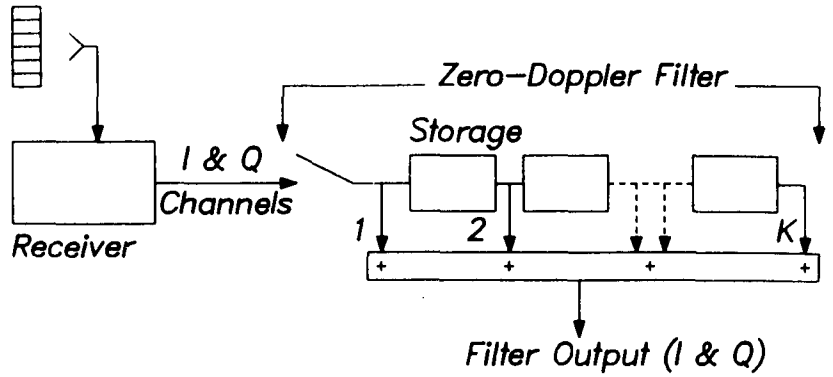


Fig. 1 Radar receiving system.

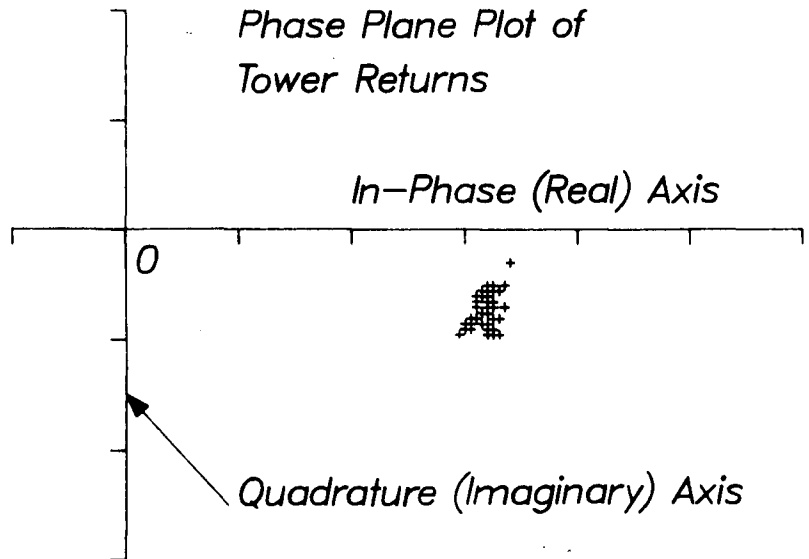


Fig. 2 Phase plane plot of 50 returns from a metal tower and bush.



The diffuse component of the clutter is also assumed to contain a system noise component since the two cannot be separated. Therefore in areas where the clutter returns are very small or almost entirely coherent, a large part of the diffuse component will be system noise. On the other hand, when the diffuse component of the clutter is large, the contribution due to system noise will be negligible.

The coherent-to-diffuse power ratio is defined as

$$\text{CDR} \triangleq \frac{C^2}{D^2} = \frac{u_I^2 + u_Q^2}{\sigma_I^2 + \sigma_I^2} \quad (8)$$

For the data shown in Figure 2 the CDR was 24 dB indicating that the power associated with the coherent component of the clutter was 24 dB larger than that associated with the diffuse component. The CDR is an important measure in determining how effective coherent thresholding techniques will be in combating clutter.

### 3.0 TARGET DETECTION AND IDENTIFICATION

In this section the concept of clutter returns consisting of a coherent as well as a diffuse component is used to develop coherent thresholding techniques that can significantly increase low-Doppler target detectability. Also it is shown how certain targets can be identified by exploiting differences from surrounding clutter.

#### 3.1 Target Detection

In conventional radars it is standard practice to use a measure of the power of clutter returns as a parameter to set detection thresholds. Depending on how close the actual clutter distribution is to the assumed distribution, the results of such a procedure can be good or disastrous. A probability distribution that is often used to describe the amplitude of clutter returns is the Rayleigh distribution. This distribution describes the amplitude of a complex variable whose real and imaginary components are independent identically distributed Gaussian random variables. We will use this distribution to describe the diffuse component of the clutter and show how a coherent component in the clutter drastically affects the performance of detection schemes that make the diffuse assumption for the complete clutter return.

The performance of three thresholding techniques will be compared. The first technique, which is used in many radars, assumes that the entire clutter return is diffuse (Gaussian in-phase and quadrature components) and sets the threshold accordingly. The second technique makes no assumption about the distribution but dynamically adjusts the threshold until the desired probability of false alarm is attained. The third technique recognizes the possibility of a coherent component in the clutter and establishes a threshold around the average clutter vector in the phase plane. This final technique is referred to as a coherent thresholding.

In making the above comparisons it is assumed that the target amplitude distribution is Rayleigh and that the target return is independent from sample to sample. This assumption means that the target return simply augments the diffuse component of the clutter at the output of the zero-Doppler filter. Comparisons will be made on the basis of the probability of detection with CDR and signal-to-clutter ratios being defined at the filter output. Where K returns are combined in the filter the single return coherent-to-diffuse ratio,  $CDR_s$ , is

$$CDR_s = \frac{CDR}{K} \quad (9)$$

where it is assumed that the diffuse components of the returns are independent.

### 3.1.1 Thresholding Schemes

#### 3.1.1.1 Conventional Thresholding

Conventional thresholding assumes that the amplitude of the total clutter return is Rayleigh distributed.

$$p(r) = \frac{2r}{P^2} \exp\left(\frac{-r^2}{P^2}\right) \quad (10)$$

where  $r$  is the amplitude and  $P^2$  is the returned clutter power. Therefore the threshold required to maintain a certain probability of false alarm is

$$T_G = (P^2 \ln\left(\frac{1}{P_F}\right))^{\frac{1}{2}} \quad (11)$$

where  $T_G$  is the threshold (the subscript G signifies that the clutter signal distribution is assumed to be Gaussian) and  $P_F$  is the probability of false alarm. If the clutter return is made up of a coherent and diffuse component the threshold  $T_G$  becomes

$$T_G = ((C^2 + D^2) \ln\left(\frac{1}{P_F}\right))^{\frac{1}{2}} \quad (12)$$

and the true probability of false alarm becomes the integral of a Ricean distribution

$$P_{FG} = \int_{T_G}^{\infty} \frac{2r}{D^2} \exp\left(\frac{-(C^2 + r^2)}{D^2}\right) I_0\left(\frac{2Cr}{D^2}\right) dr \quad (13)$$

where  $I_0(\cdot)$  is the modified Bessel function of order zero and the subscript G indicates that this is not the design  $P_F$ .

Since both the target and the diffuse clutter component are Gaussian distributed in signal space the target power designated as  $S^2$  simply adds to the diffuse component resulting in the following probability of detection

$$P_{DG} = \int_{T_G}^{\infty} \frac{2r}{(S^2 + D^2)} \exp\left(-\frac{(C^2 + r^2)}{(S^2 + D^2)}\right) I_0\left(\frac{2Cr}{(S^2 + D^2)}\right) dr \quad (14)$$

### 3.1.1.2 Adaptive Thresholding

Adaptive thresholding does not make any assumption about the distribution of the clutter but dynamically adjusts the threshold until the desired  $P_F$  is reached. This procedure is difficult in practice since it requires many samples (in the order of  $1/P_F$ ) to establish the threshold. However in real systems the actual probability of false alarm is not of prime interest. What is of interest is whether the data processing system can handle the number of hits declared. Therefore this threshold is of some practical significance.

For the clutter model assumed here the adaptive procedure would continue until a threshold,  $T_A$ , satisfying the following integral of a Ricean distribution is determined.

$$P_{FA} = \int_{T_A}^{\infty} \frac{2r}{D^2} \exp\left(-\frac{(C^2 + r^2)}{D^2}\right) I_0\left(\frac{2Cr}{D^2}\right) dr \quad (15)$$

where  $P_F$  is the desired probability of false alarm. The probability of detection is found by using (14) with  $T_G$  replaced by  $T_A$ . Since  $T_A$  cannot be solved for explicitly from (15) it was determined by an iterative method for the subsequent performance comparisons.

### 3.1.1.3 Coherent Thresholding

Coherent thresholding assumes that there is a coherent component to the clutter and either subtracts this component from the return to centralize the diffuse distribution in the phase plane, or establishes a circular threshold about the average coherent offset. Either way an estimate of the coherent component must be made and stored in a coherent clutter map.

Assuming that this estimate has been made a target need only compete with the diffuse component of the clutter for detection. The threshold and the probability of detection can be determined using the distribution of (10) with  $P^2$  equal to  $D^2$  and  $S^2 + D^2$  respectively. Therefore

$$T_C = (D^2 \ln(\frac{1}{P_F}))^{\frac{1}{2}} \quad (16)$$

and

$$P_{DC} = \exp\left(\frac{-T_C^2}{(S^2 + D^2)}\right) \quad (17)$$

### 3.1.2 Performance Comparisons

#### 3.1.2.1 Single Sample Detection

It is shown in the appendix that the signal-to-interference ratio gain achieved by using one threshold technique over another can be attained by equating the appropriate expressions for probability of detection by scaling the target power. The general expression for this gain is quite complicated and therefore it is difficult to relate it to the clutter parameters C and D. Considerable simplification is achieved under a large signal assumption for which the gain becomes the ratio of the squares of the two thresholds. Although this assumption is not strictly true for our analysis, the gain so obtained is a good estimate of the actual gain for signal-to-diffuse ratios as small as those required for  $P_{DC} = 0.8$ . Therefore the signal-to-interference power gain achieved (this is equivalent to a signal-to-noise ratio gain) by using coherent thresholding over conventional thresholding is

$$SIR_G \approx \frac{T_G^2}{T_C^2} = CDR + 1 \quad (18)$$

where  $SIR_G$  is the signal-to-interference power gain and CDR is the coherent-to-diffuse power ratio defined in (8). The gain for using coherent thresholding rather than adaptive thresholding is not easily determined because there is no explicit expression for  $T_A$ . However, from the detection curves to follow it will be seen that the gain is "approximately" one-half (in decibels) of that shown in (18).

To illustrate the significance of this gain consider again Figure 2. For this resolution cell the CDR is 24 dB and therefore the  $SIR_G$  is approximately 24 dB as well since the linear addition of one is insignificant. A target that is just detectable with the coherent threshold would have to have a 24 dB larger cross section to be detectable using a conventional threshold and 12 dB larger using an adaptive threshold.

How this large detection gain is achieved is illustrated in Figure 3. For a single sample from the zero-Doppler filter the threshold  $T_G$  is equivalent to establishing a circular contour in the phase plane and declaring a target present if the return is outside this contour. Figure

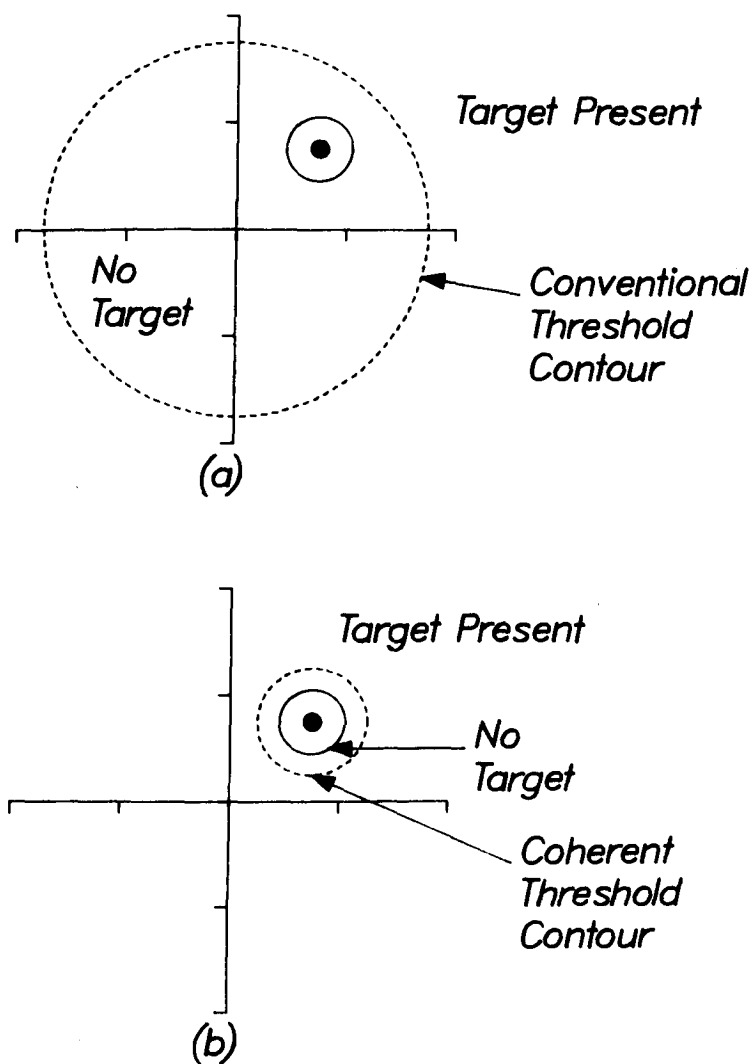


Fig. 3 Conventional and coherent thresholds, for a single sample, in the phase plane.

3a shows the circular contour and corresponding decision regions. If the clutter possesses a coherent and diffuse component as shown by the offset circle, a target which is random in phase is more likely to be detected with the offset coherent threshold shown in 3b than the centred threshold of in Figure 3a. The centred threshold must be large enough to encompass the entire coherent component no matter how small the diffuse component otherwise the false alarm probability will be large. The offset threshold, however, need only encompass the diffuse component.

Probability of detection curves for a design  $P_F$  of  $10^{-4}$  and two values of CDR are shown in Figure 4. The same curve is shown for the coherent threshold because its performance is independent of the size of the coherent clutter component. Coherent thresholding has a gain of CDR+1 over conventional thresholding and approximately one-half that over adaptive thresholding. It should be noted that as the coherent component decreases all three thresholds coincide and their performances are identical.

These curves show the performance for a single sample at the output of the zero Doppler filter. If the filter integrates  $K$  returns, the SCR and CDR must be scaled to get the single return ratios as outlined in equation (9).

#### 3.1.2.2 Multiple Sample Detection

Multiple sample detection involves noncoherently integrating  $M$  samples from the zero-Doppler filter with each sample composed of the coherent sum of  $K$  different returns. A square-law detector is assumed. Coherent thresholding is accomplished by subtracting a coherent estimate of the clutter mean from the sample before it enters the square-law detector. Therefore the performances of the conventional and adaptive thresholds are described using the noncentral chi-squared distribution with  $2M$  degrees of freedom and that of the coherent threshold with the central chi-squared distribution, respectively. Probabilities of false alarm and detection are determined through the use of the generalized  $Q$  function [8].

Figure 5 shows the performance of the three thresholds for  $M=10$  and two values of CDR. The gain for using coherent thresholding over conventional is approximately equal to the CDR+1, as is shown in the Appendix, for a large signal assumption and  $M=1$ . This estimate of the gain was found to be good for all of the cases calculated using different values of  $M$  and signal-to-clutter ratios such that  $P_D = .8$  for the coherent threshold.

### 3.2 Target Identification

The essence of target identification is to observe the returns from a target and those from surrounding clutter objects and be able to tell the difference. If the target is not moving and is immersed in a "sea" of large stationary clutter objects this is indeed a very difficult

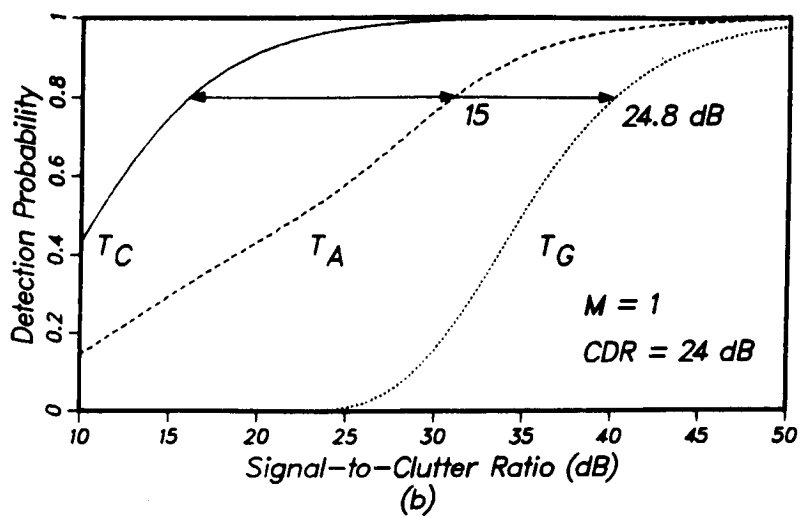
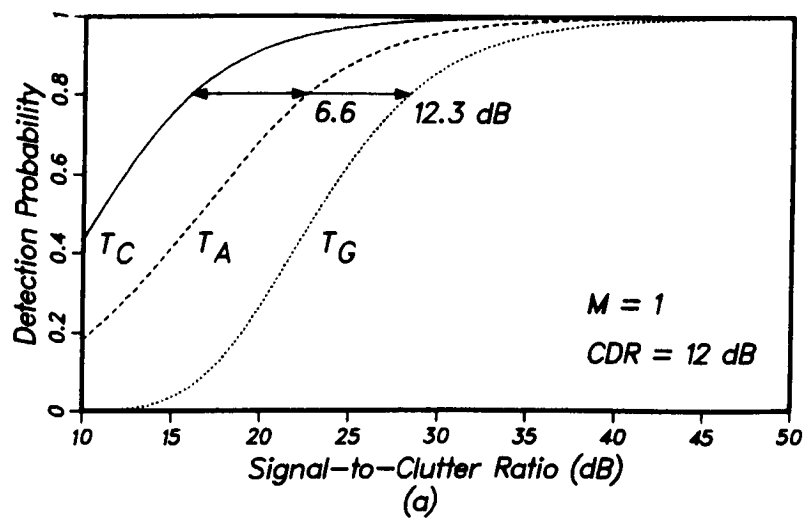


Fig. 4 Single sample probability of detection curves for the three thresholds for CDR's equal to 12 and 24 dB, and  $P_F = 10^{-4}$ .

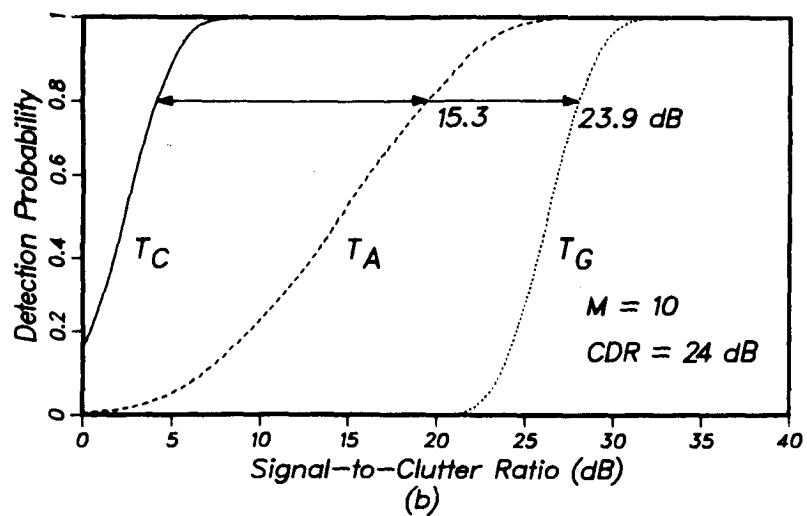
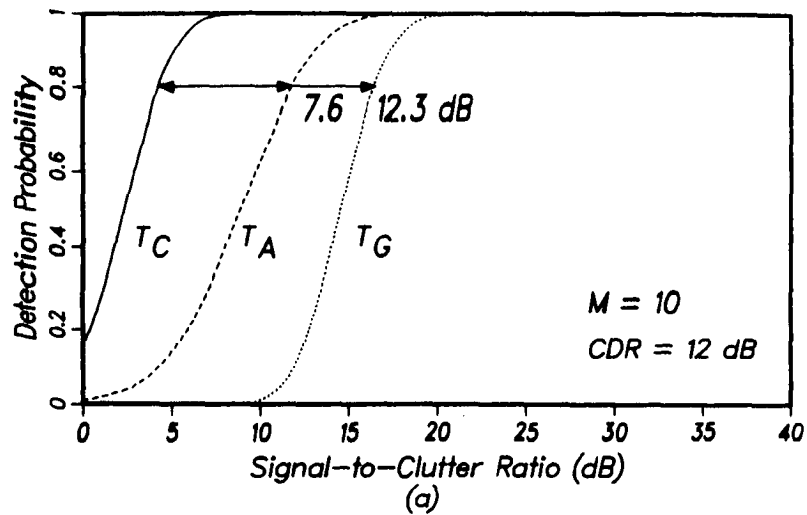


Fig. 5  $M$  sample probability of detection curves for the three thresholds for CDR's equal to 12 and 24 dB and  $P_F=10^{-4}$ .



problem. To illustrate how coherent clutter processing can be used in some situations to solve this problem, consider a stationary man-made structure located in bush type terrain. As was already stated clutter returns from bush tend to be diffuse (how much so will be discussed in the next section), but the returns from the man-made structure tend to be coherent. Therefore by calculating the CDR as described in (8) for each range cell as the radar searches the terrain it is possible to identify the cell with the man-made structure as that with an abnormally large CDR. This is possible even though the total return from the structure is much smaller than the surrounding returns. Similarly, it is possible to detect the presence of new objects in a range cell or changes in a structure by observing shifts in the coherent mean of the returns.

Figure 6 shows an example of radar clutter returns as a function of range. The solid line represents the coherent target cross section and the dotted line the diffuse target cross section. It is clear from the profile that the object causing the return from point "A" is different in nature from the surrounding objects. This object is a metal tower which is surrounded by bush. Although the tower, in terms of total returned power, does not stand out as anything different it is clearly separated from the background clutter when coherent decomposition is used.

#### 4.0 EXPERIMENTAL EVIDENCE OF APPLICABILITY

Since the merits of coherent clutter decomposition for target detection and identification depend on the nature of the clutter being observed, a year-long clutter measurement program with this application in mind was initiated. It was desired to know under what kind of weather conditions and over what kind of terrain type would coherent clutter processing be of value. The measurements were made using a step-scan phased array radar operating at a wavelength of 10 cm. The phased array antenna had a 4° horizontal and a 6° vertical beamwidth and the beam was steered parallel to the ground and swept through an 80° sector in 1° steps. At each pointing angle a single pulse of 1  $\mu$ s duration was transmitted and the clutter returns recorded at a range bin spacing of 50 m. One sweep was made every 8 seconds with the beam step rate within the sweep being 1024 Hz. The peak power for the radar was 500 watts which limited the maximum useful range to 8 km.

A total of 50 sweeps were made each measurement day for a net recording time of 6.67 minutes. The returns were coherently demodulated, digitized at baseband, and recorded on digital magnetic tape. Along with the clutter data a sample of the transmitter pulse and a receiver calibration pulse were recorded to provide calibration information on a pulse-by-pulse basis. The local wind speed was also recorded.

A map of the area viewed by the radar is shown in Figure 7. The terrain to the left of the Ottawa River is mainly bushland and the terrain on the right is mainly urban and suburban. Four areas marked A, B, C and D are of special interest. Area A contains a small metal tower surrounded by bush, area B bush only, area C a combination of bush and rock, and area D an urban centre. Returns from each of these areas are discussed in detail.

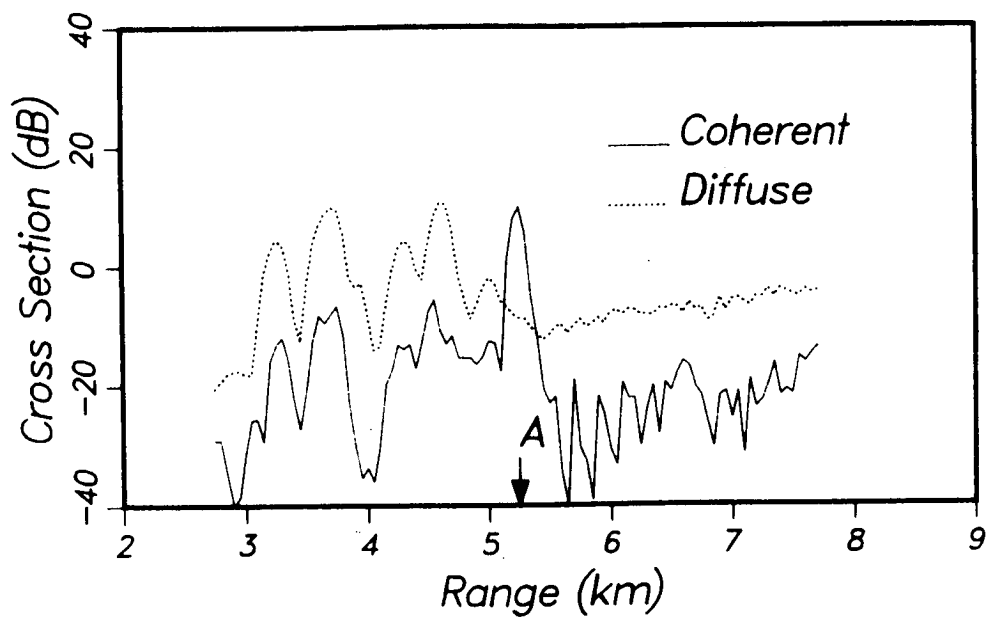


Fig. 6 Diffuse and coherent returns illustrating the identification of the range cell (A) containing a metal tower.

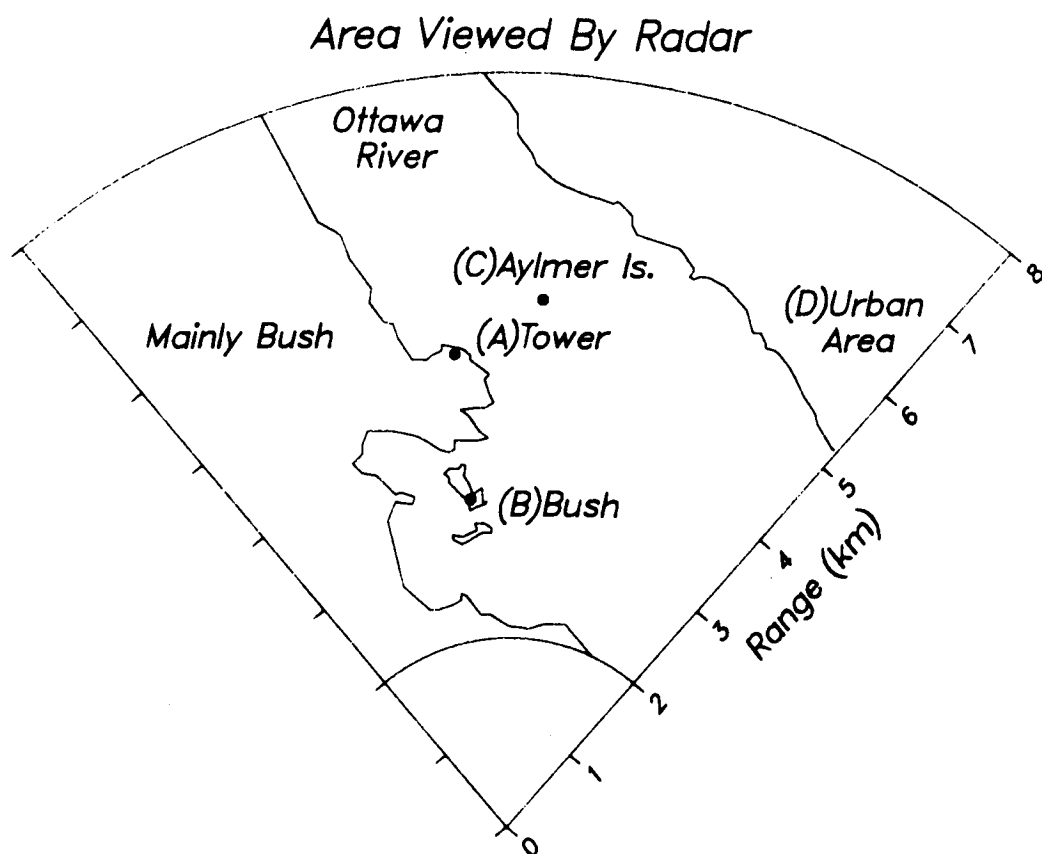


Fig. 7 Map of area view by the radar.

#### 4.1 High and Low Wind Speeds

Since the coherent component of clutter is associated with stationary clutter objects, this component will decrease when the clutter is set in motion by the wind. Conversely, the diffuse component will increase. Therefore, on a windy day the coherent-to-diffuse power ratio will decrease and coherent clutter processing becomes less effective.

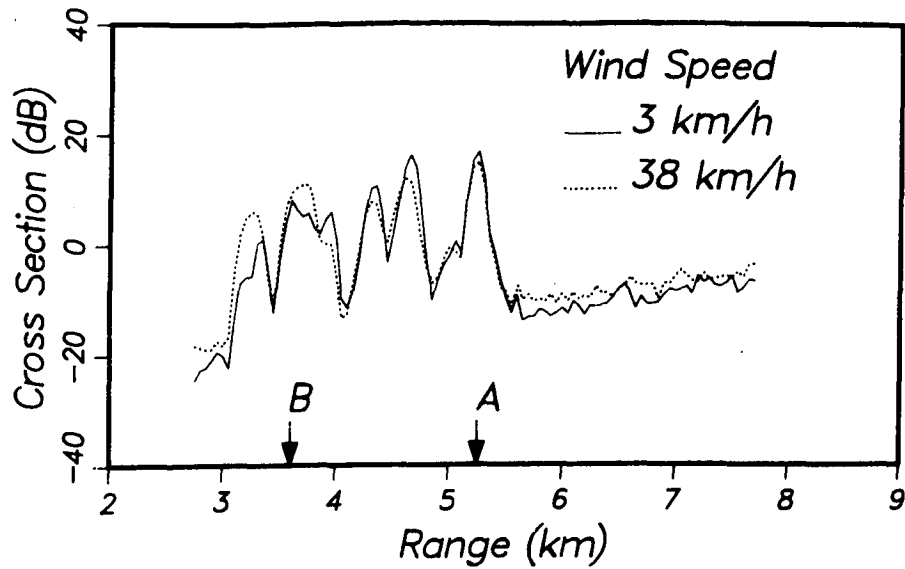
Figure 8 shows a range profile through points A and B in Figure 7. The total power returned (measured in effective target area and illustrated in 8a) and the CDR (illustrated in 8b) are shown as a function of range for a high wind speed (38 km/hr) and a low wind speed (3 km/hr) condition in the month of January 1984. The two total power curves are quite similar different wind speeds however the CDR curves are not. Clutter from ranges less than that of point A shows a large decrease in CDR for an increase in wind speed. The scatterers in the range cells are mainly bush and therefore subject to wind-induced motion. The clutter from point A on the other hand does not exhibit a large decrease in CDR for an increase in wind speed. The corresponding clutter object is a metal tower which is not moved significantly by the wind.

Coherent clutter processing offers an average of about 10 dB of processing gain over the bushland for low wind speeds but at high wind speeds this gain is lost. Therefore, it can be concluded that coherent processing is effective over bushland only if the wind speed is low. The processing gain for the tower is also reduced at the higher wind speeds but to a lesser extent than for bushland (i.e. changes from 25 dB to 20 db).

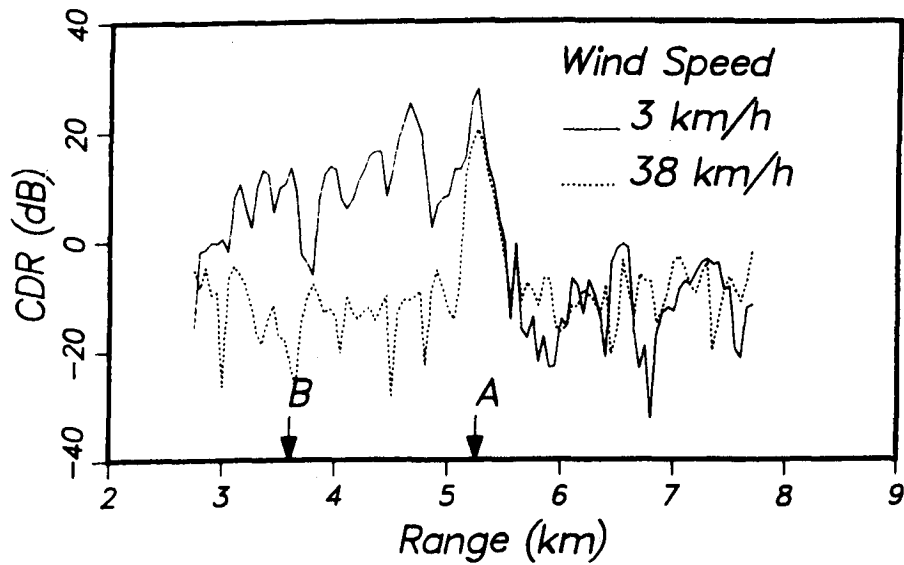
Clutter from urban areas has a significant coherent component that is less affected by wind speed than that for bush. Figure 9 shows the profiles for the high and low wind speeds for an urban centre across the Ottawa River from the radar site. For the low wind speed condition most of the urban area exhibits a CDR near 20 dB. For the high wind speed the CDR is reduced, but there still is a significant area that has a ratio greater than or near 10 dB. This indicates that the coherent processing of clutter has merit over the urban area even when it would be of little value over bushland.

#### 4.2 Relationship with Wind Speed and Season

In the last section it was shown that the coherent-to-diffuse ratio decreased with increasing wind speed. In this section the coherent and diffuse components are investigated separately to determine their individual relationships to the wind speed and therefore their contribution to the coherent-to-diffuse ratio. Also a comparison is made between summer and winter conditions. Figure 10 shows three groups of measurements from different resolution cells corresponding to different terrain types for the month of January 1984 plotted as a function of wind speed. Also plotted is the linear least squares fit to these measurements. The total power returned is plotted with crosses, the coherent power with circles, the

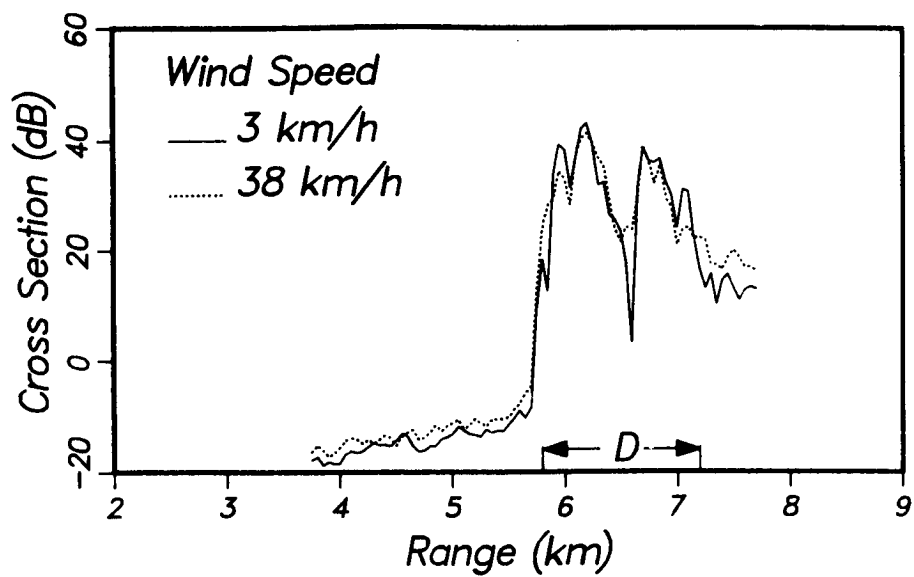


(a)

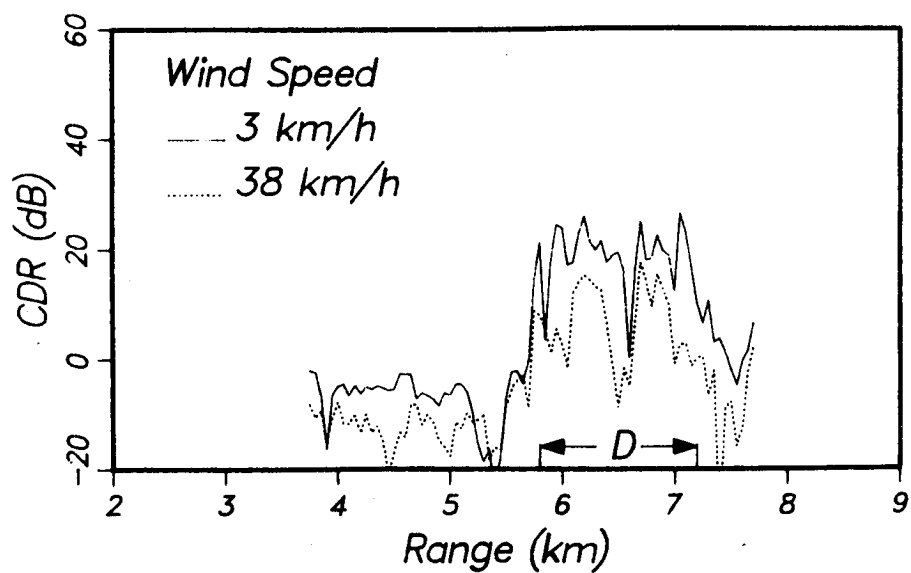


(b)

Fig. 8 Clutter returns from bushland for low and high wind speeds.



(a)



(b)

Fig. 9 Clutter returns from an urban centre for low and high wind speeds.

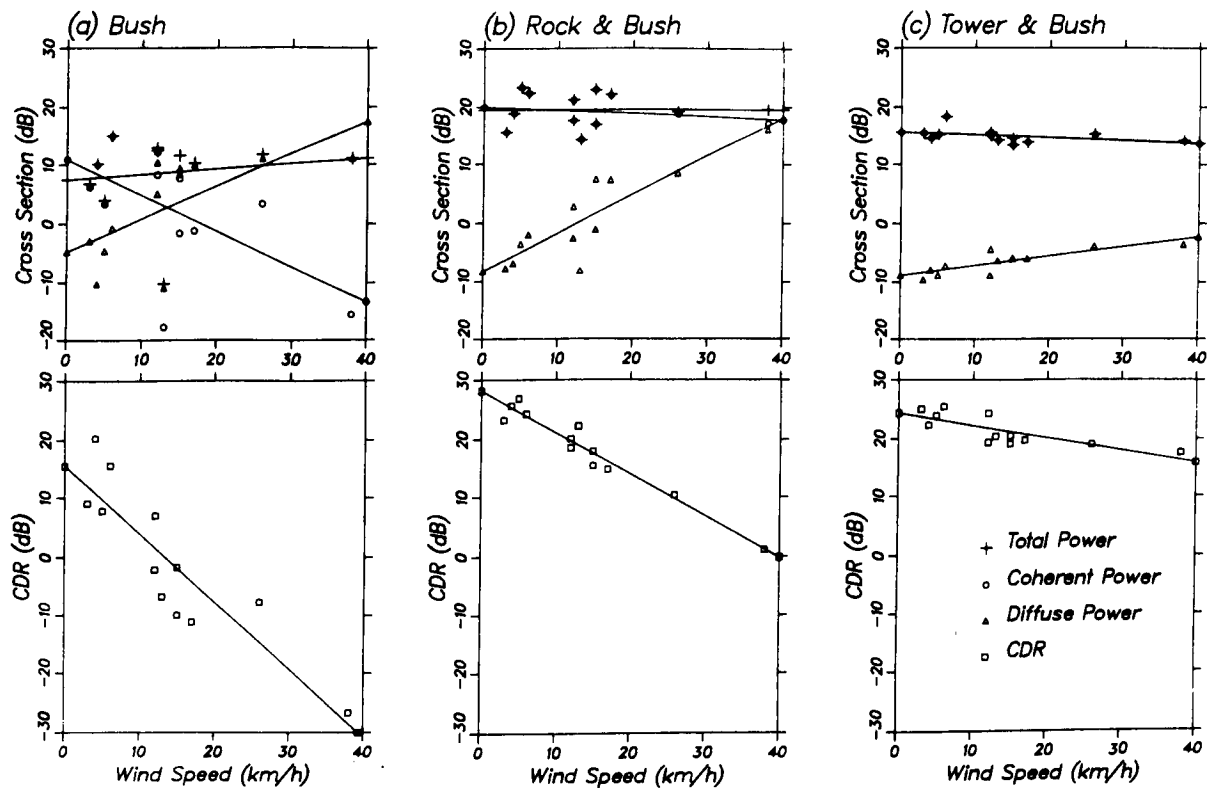


Fig. 10 Variations of returns with windspeed for three types of terrain under winter conditions.

diffuse power with triangles and the CDR with squares. The straight line for each set of data points is marked at both ends with the appropriate symbol.

The first group (Figure 10a) was recorded for resolution cell B in Figure 7 and is typical of what was received for bushland in winter. For this type of terrain (leaveless trees and a snow cover) the CDR decreased for increasing wind speed with a slope of approximately  $-1.2$  dB/km/h. This decrease was due to an increase in the diffuse component which was matched by a corresponding decrease in the coherent component. The total power however remained about the same. There is considerable spread about the straight line approximations for the total, diffuse, and coherent power but the points for the CDR fit reasonably well.

The second group (Figure 10b) was recorded for resolution cell C in Figure 7 and is typical of returns from a combination of rock, ice and trees. When these data were recorded the small rocky island was surrounded by ice and was covered with snow. For this type of terrain the CDR decreased with increasing wind speed with a slope of approximately  $-0.7$  dB/km/h which is considerably less than the slope for cell B. The reason for the decrease is also different. In cell B both the diffuse and coherent components changed with wind speed but for cell C the coherent component remained fairly constant and the diffuse component alone changed. This indicates that a major portion of the clutter return from the island was from rock and ice whereas from the bushland it was from the trees. For this data set the straight lines are good approximations to the relationships with wind speed.

The third group (Figure 10c) was recorded for resolution cell A in Figure 7 and is typical of urban returns. This resolution cell contains a metal tower and some vegetation. Again the CDR decreased for increasing wind speed but the slope is only  $-.2$  dB/km/h. The coherent power received and the total power were almost identical, with the diffuse power being about 25 dB lower for low wind speeds and 14 dB lower for high wind speeds. The decrease in CDR was due almost entirely to an increase in the diffuse component. For this group the data points were very tightly grouped around the straight line approximations.

Looking at the three winter condition groups together it can be seen that for low wind speeds all the terrain types exhibited a large coherent component that could be removed by coherent clutter processing. As the wind speed increased, however, the CDR decreased rapidly for the bushland, moderately for the combination of rock and bush and more slowly for the tower. It can be concluded that at high wind speeds coherent processing is valuable only in areas with little wind-induced motion such as urban centres.

Figure 11 shows measurements taken for the same resolution cells as above but under summer conditions (June 1984). The result for the bush (Figure 11a) is considerably different from that determined for winter (Figure 10a). The coherent component, although slightly smaller, behaves the same, decreasing with increasing wind speed, but the diffuse component



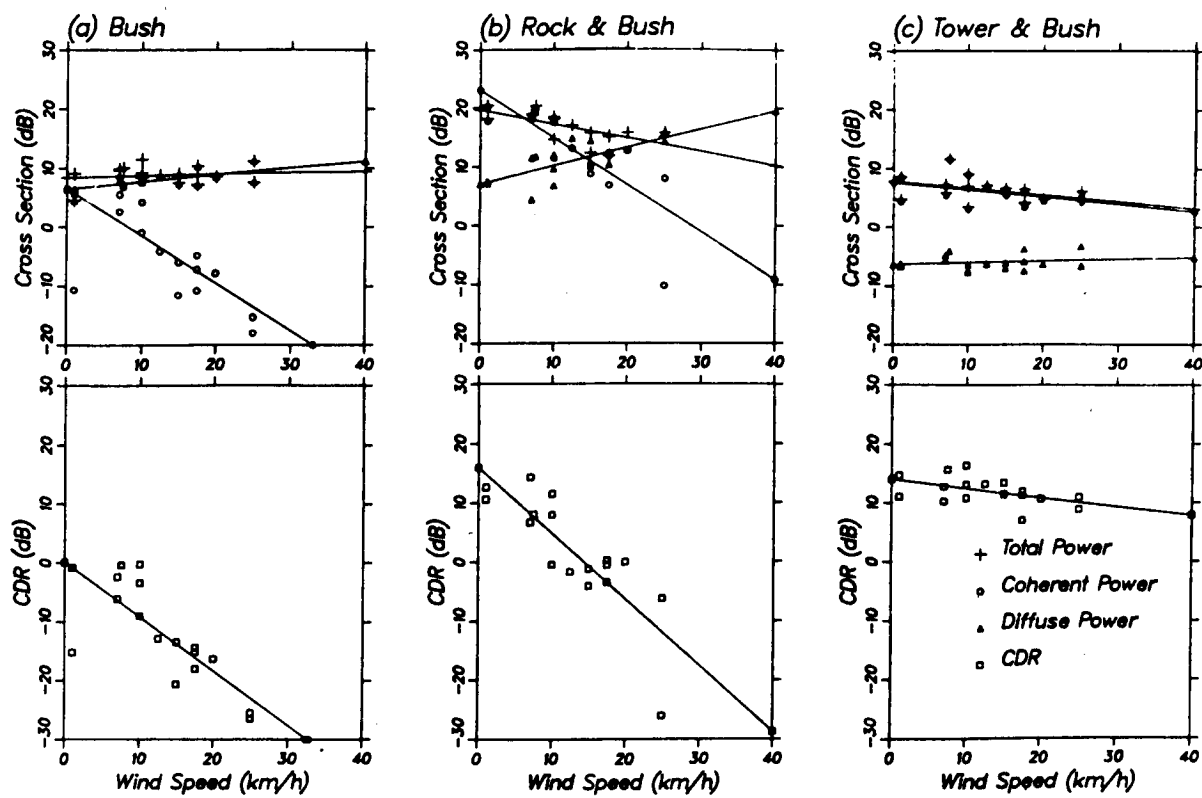


Fig. 11 Variations of returns with windspeed for three types of terrain under summer conditions.

remains relatively unaffected by the wind. Also the total return is almost entirely diffuse even at small wind speeds. The cause for this is that for trees with leaves the clutter returns are mainly diffuse even for the slightest of breeze and therefore an increasing wind speed does not add any additional randomness to the scatters. Coherent processing over summer bushland is therefore not an effective technique for clutter removal; however, for the identification of stationary structures its performance is enhanced because of the increased randomness of the background returns.

For the rock and bushland combination (Figure 11b) there is again a significant difference from the winter condition (Figure 10b). In the summer the complex clutter object behaves like winter bush terrain (Figure 10a). The coherent component decreases with increasing wind speed and the diffuse component increases. At low wind speeds coherent processing promises a gain of approximately 10 to 15 dB but this gain disappears rapidly once the wind speed reaches about 10 km/h.

For the tower and bush combination representing urban terrain the summer returns (Figure 11c) are not much different from the winter returns (Figure 10a) except in absolute level. This drop in level for the summer may be due to a partial shadowing of the tower by the leafy canopy of surrounding bush. The diffuse returns from the cell containing the tower do not increase significantly with wind speed as they did in the winter indicating that this component of the clutter may be saturated as mentioned above for the bush returns. The coherent component from the tower decreases slightly with increasing wind speed but at approximately the same slope as it did in the winter. The resulting CDR also decreases but is large enough (approximately 10 dB) to provide a significant gain with coherent processing.

The main difference between the winter and summer conditions is that the bush clutter in summer tends to be saturated with motion even at low wind speeds whereas in the winter it is not. This result indicates that coherent processing to remove clutter has merit in bush areas only in the winter and then only at low wind speeds. However in the summer it is still effective as a target identification procedure. In urban areas or areas that are similar (lack of vegetation) such as deserts or tundra coherent processing is valuable for both summer and winter and for both small and large wind speeds.

#### 4.3 Daily Variations

It was shown earlier (Figure 2) that the coherent returns from a clutter object were stable in phase and amplitude over a period of about 7 minutes. Any processing scheme designed to take advantage of this stability must be able to adapt to slow variations that take place over larger time spans such as hours or days. To estimate these variations, radar returns from the radar range described by Figure 7 were recorded every 12 minutes for periods of up to 38 hours. Figure 12 shows the scatter plot for one 38 hour set of measurements for the range cell containing the tower, and Figure 13 the time history of the phase of the

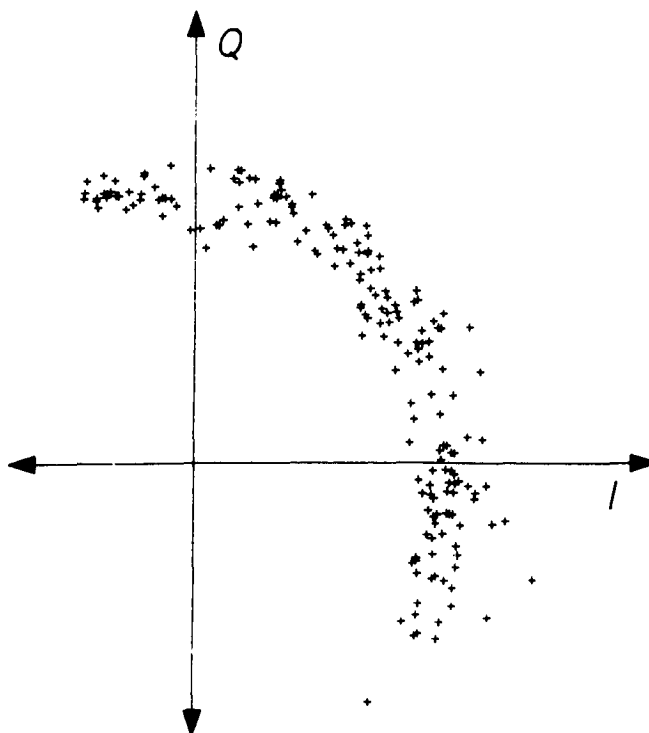


Fig. 12 Scatter plot of returns from the tower over a 38 hour time span.

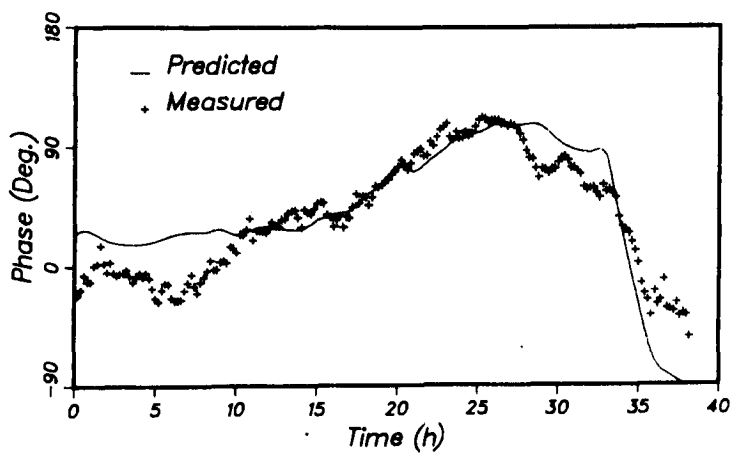


Fig. 13 Phase plot of returns from the tower over a 38 hour time span plus a prediction of the phase variation due to changes in temperature.

returns. The scatter plot shows a large coherent component of constant amplitude rotating slowly with a small diffuse component superimposed. The time history of the phase variations correlates well with predicted variations in the refractive index resulting from temperature changes [9]. This result indicates that a coherent clutter map must be updated at a rate sufficient to track daily variations in the propagation paths that are a result of environmental conditions.

## 5.0 COHERENT THRESHOLDING GAINS AND THE COHERENT CLUTTER MAP

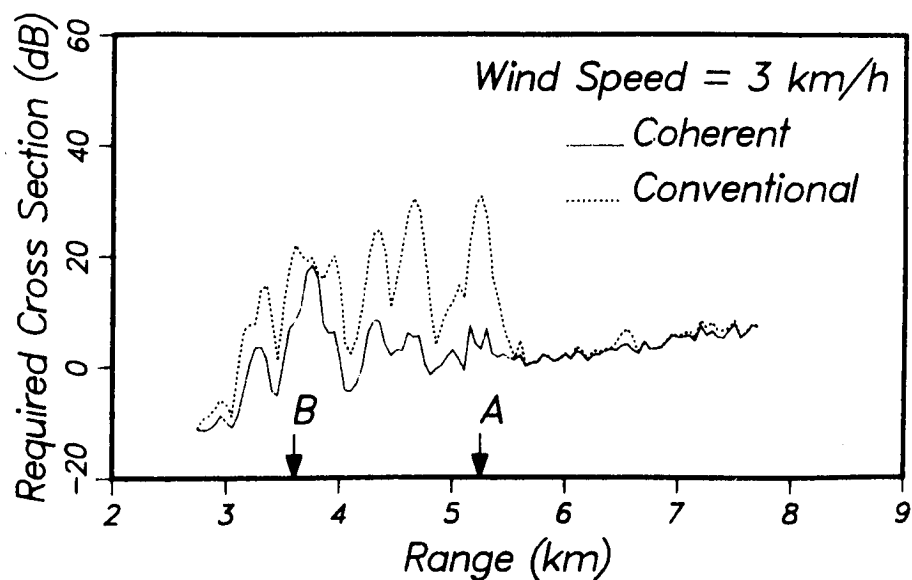
To illustrate quantitatively the effect that a coherent component of the clutter has on target detection the target cross section required to yield an 0.8 probability of detection with a false alarm probability of  $10^{-4}$  was calculated for the data shown in Figures 8 and 9. These calculations were made assuming a single filter sample, a Rayleigh target distribution, and that the diffuse component of the clutter was Rayleigh distributed with parameter D (equation 5) around the coherent offset C (equation 1). Figure 14 shows the results for the low (3 km/h) and high (38 km/h) wind speed conditions for the range profile through points A and B of Figure 7. For the low wind speed condition (Figure 14a) the required target cross section for a  $P_D$  of 0.8 is quite different for the two thresholds except over the river where there was no significant return. Typically over the clutter region the required target cross section for the conventional threshold is 10 to 30 dB higher than that required for the threshold after coherent clutter removal.

For the higher wind speed (Figure 14b) the required target cross section is almost identical for the two thresholding schemes. This is because the coherent component of the clutter has essentially disappeared and therefore the two thresholds are identical. The one exception is at point A where the return from the metal tower, being unaffected by the wind, still has a significant coherent component. For this cell the detection gain over the conventional threshold is approximately 20 dB.

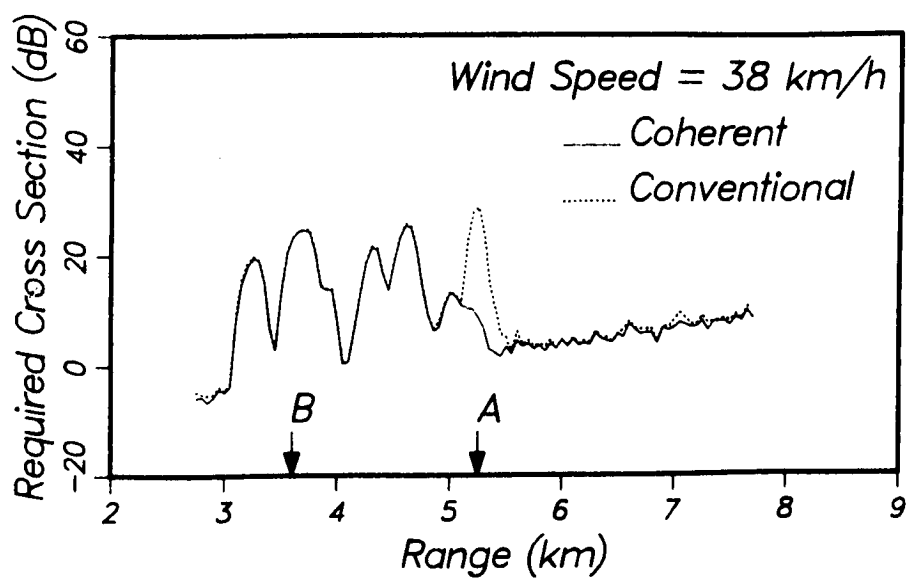
Figure 15 shows the required target cross section for the urban centre (area D in Figure 7) for the two wind speeds. For the low wind speed condition (Figure 15a) the required target cross-section is typically 20 to 30 dB higher for the conventional threshold than for the coherent threshold applied after coherent clutter removal. For the high wind speed condition (Figure 15b) the advantage is reduced to, typically, 10 to 20 dB but is still significant.

For M samples, integrated noncoherently, the required cross section would decrease but the difference in required target cross section between noherent and conventional thresholding would remain the same.

It has been shown that a significant portion of ground clutter has a large stable coherent component and that the knowledge of this component can be used to enhance the detection of low-Doppler targets. With a processor storing an estimate of the coherent part of the clutter and subtracting this estimate from the current return, the target need only compete with the diffuse part of the clutter. Coherent clutter maps,



(a)



(b)

Fig. 14 Target cross section required for a single sample  $P_D$  of 0.8 and a  $P_F$  of  $10^{-4}$  over bushland.

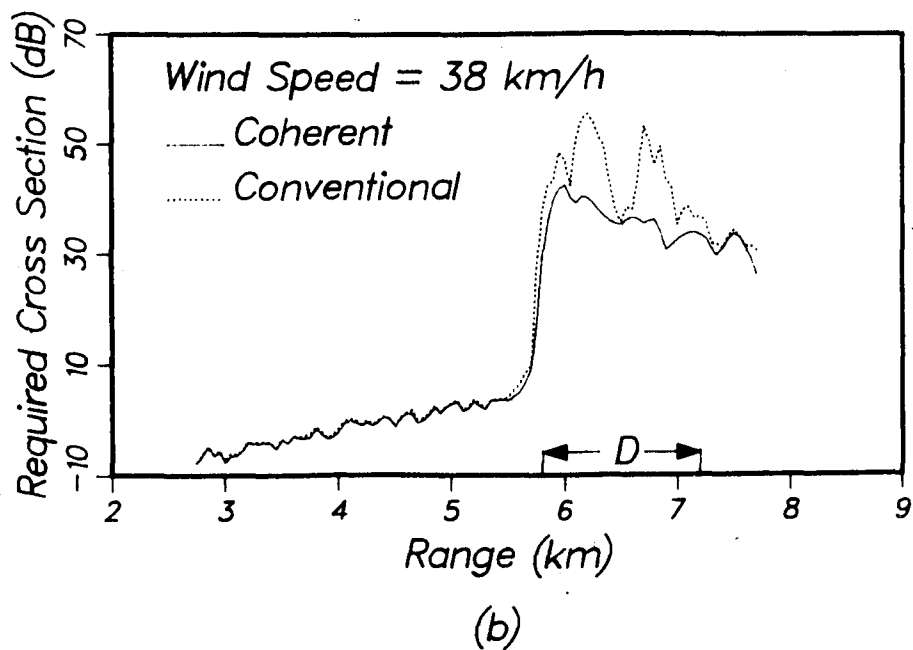
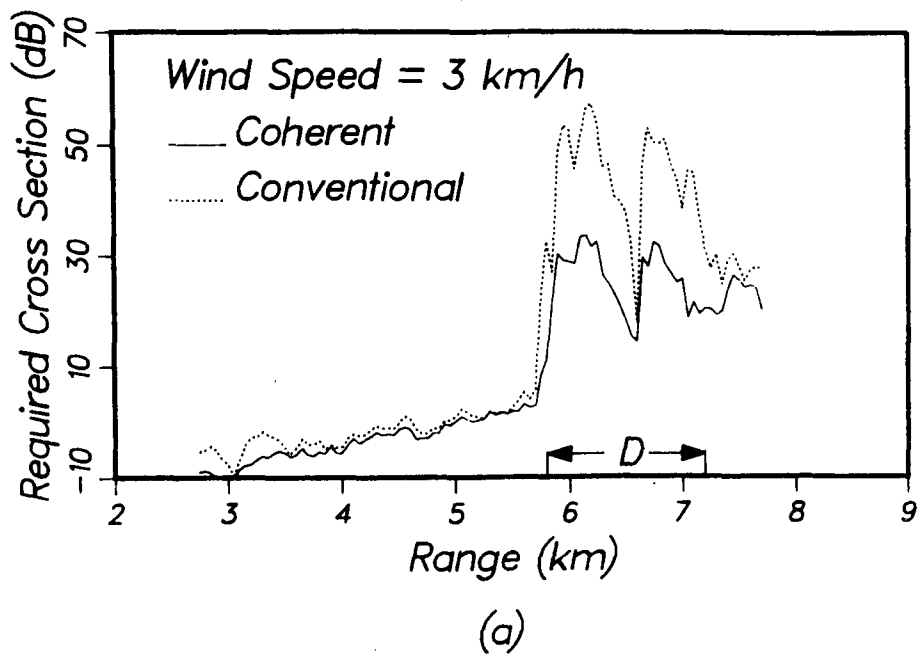


Fig. 15 Target cross section required for a single sample  $P_D$  of 0.8 and a  $P_F$  of  $10^{-4}$  over an urban centre.

built up from coherent clutter estimates and updated according to the needs of the particular resolution cell, could be implemented using semiconductor memory. To cover the entire radar space such a memory would have to be large but not unreasonably so. Smaller memories coupled with some computer intelligence to assign memory locations to cells exhibiting significant CDR's may be more practical.

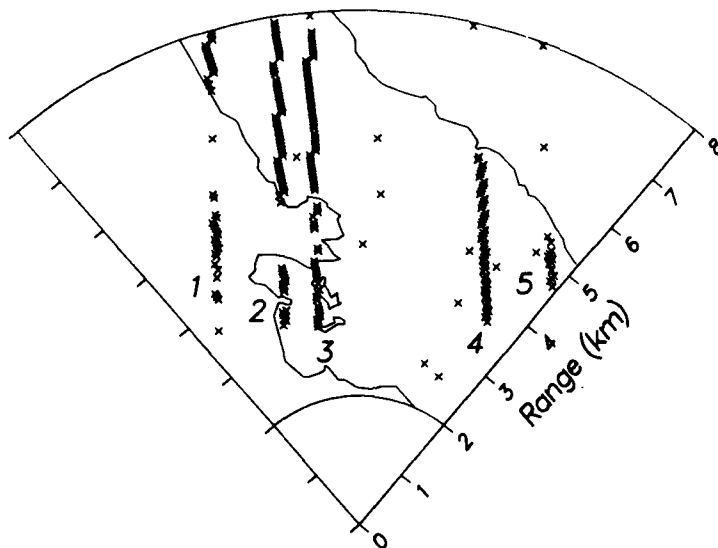
In addition to the above, portions of memory could be assigned to assist the tracking process in the tracking of particular targets through dense clutter regions. The tracker would predict the probable future location of a target and direct that a coherent clutter map be built for that region. When the target enters the high clutter area the coherent part of the clutter would be removed using the map and the target would only have to compete with the diffuse component of the clutter.

To illustrate the ability of a coherent clutter map to enhance low Doppler target detectability five Rayleigh targets were added to the clutter recorded for the low and high wind speed conditions, simulating the condition of targets slowing moving away from the radar. Figures 16 and 17 show the resulting detections for the conventional processor and the coherent clutter map processor. The cross sections of the simulated targets were set relatively large (20 dB) so that the thresholds for the two processing schemes could be high, thereby reducing the number of false alarms which tend to confuse cumulative detection displays. Nevertheless, the essential features of the target tracks remain.

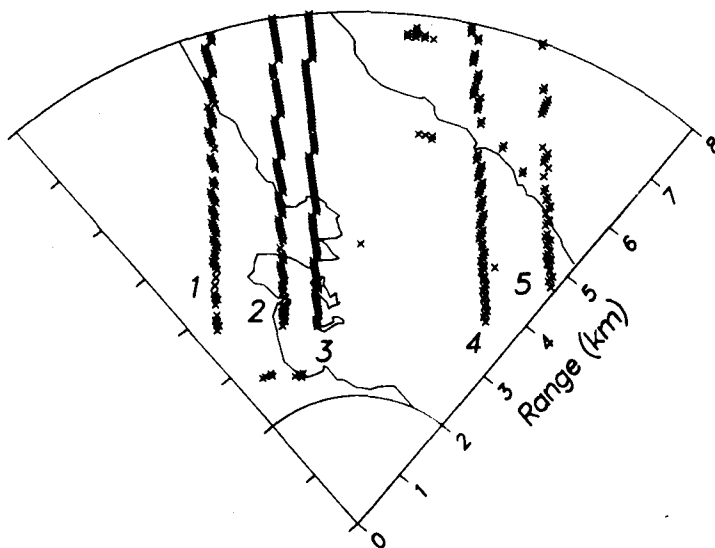
For the low wind speed condition (Figure 16) most of the clutter has a significant coherent component and therefore coherent clutter removal performs well against conventional processing. Over the river both schemes perform identically as can be seen at the start of track 4. Once land is encountered, however, the coherent clutter map processor out-performs the conventional processor as evidenced by the continuation of the tracks in Figure 16b. Track 1, which is mainly in bush has areas for which the conventional processor and coherent clutter map processor perform equally well. These areas are low lying fields with small clutter returns. Track 3, when approaching the metal tower (point A in Figure 7), is followed by both processors but over the tower only the coherent processor follows the track. Tracks 4 and 5 over the urban and suburban area drop out periodically but can be followed with the coherent processor, while the conventional processor loses them entirely.

For the high wind speed condition (Figure 17) the diffuse component of the clutter has increased and the coherent decreased. Therefore both processors perform essentially the same with the coherent processor filling in some points missed by the conventional processor, for example, over the metal tower (point A, Figure 7). Tracks 4 and 5 are lost entirely over the urban and suburban area because the diffuse component of the clutter has increased to such an extent that only a 30 to 40 dB target could be detected consistently (see Figure 15b). The conventional processor however would require a 50 to 60 dB target in the same area.

Wind Speed = 3 km/h



(a) Conventional Thresholding

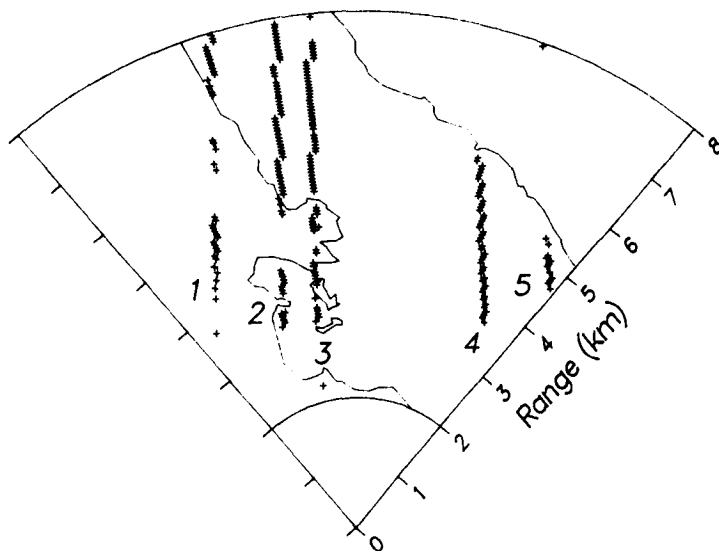


(b) Coherent Thresholding

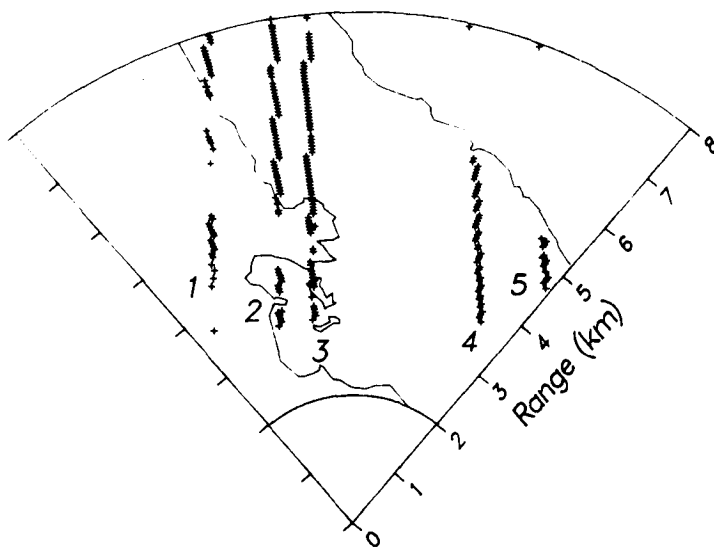
Fig. 16 Single sample tracks of simulated targets through real clutter for a low windspeed.



Wind Speed = 38 km/h



(a) Conventional Thresholding



(b) Coherent Thresholding

Fig. 17 Single sample tracks of simulated targets through real clutter for a high windspeed.

From these tracks it can be seen that coherent clutter processing has merit as a scheme to enhance low-Doppler target detection in high clutter areas.

## 6.0 CONCLUSION

In conclusion, this research into the coherent decomposition of clutter has resulted in some promising techniques that improve the detection and identification of low-Doppler targets. Experimental evidence supporting these techniques has been gathered using an S band phased array radar. Further work must be done to validate these techniques at higher frequencies where the motion induced by the wind is a larger fraction of the wavelength. Radars operating below S band should enjoy even greater gains than those described here.

## APPENDIX

In this appendix it is shown that the gain in signal-to-interference ratio for using a coherent threshold,  $T_C$ , over another threshold,  $T$ , in order to obtain the same  $P_D$  is approximately equal to the ratio  $T^2/T_C^2$  under the assumption of a large target signal.

This gain is determined by equating the two expressions for  $P_D$  and solving for the resulting ratio of signal powers. Substituting  $bS^2 + D^2$  for  $S^2 + D^2$  in equation (14) and equating it to (17) we have

$$\exp\left(\frac{-T_C^2}{S^2 + D^2}\right) = \int_0^\infty \frac{2r}{T(bS^2 + D^2)} \exp\left(\frac{-(C^2 + r^2)}{(bS^2 + D^2)}\right) I_0\left(\frac{2Cr}{(bS^2 + D^2)}\right) dr \quad (A-1)$$

where  $b$  is the ratio in signal powers required to make the equality hold. Since small argument approximations are to be used in the following it is convenient to change the limits of integration to finite limits using the fact that  $1 - P_{DC} = 1 - P_D$ . Therefore

$$1 - \exp\left(\frac{-T_C^2}{S^2 + D^2}\right) = \int_0^T \frac{2r}{(bS^2 + D^2)} \exp\left(\frac{-(C^2 + r^2)}{(bS^2 + D^2)}\right) I_0\left(\frac{2Cr}{(bS^2 + D^2)}\right) dr \quad (A-2)$$

Under the assumption of a large  $S^2$  the following small argument approximations are made

$$\exp(x) \approx 1 + x \quad (A-3)$$

$$I_0(x) \approx 1 \quad (A-4)$$

Therefore (A-2) becomes

$$\frac{T_C^2}{S^2 + D^2} = \int_0^T \frac{2r}{bS^2 + D^2} \left(1 - \frac{C^2}{bS^2 + D^2} - \frac{r^2}{bS^2 + D^2}\right) dr \quad (A-5)$$

Performing the integration and rearranging terms we have

$$\frac{bS^2 + D^2}{S^2 + D^2} = \left(1 - \frac{C^2}{bS^2 + D^2}\right) \frac{T^2}{T_C^2} - \frac{1}{4(bS^2 + D^2)} \frac{T^4}{T_C^4} \quad (A-6)$$

In the limit as  $S^2 \rightarrow \infty$  we have

$$b = \frac{T^2}{T_C^2} \quad (A-7)$$

which is the required result.

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