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A MODEL OF COHERENT RADAR LAND BACKSCATTER

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Summary: The detection of targets in a land clutter background is a problem for most ground-based and airborne pulse-Doppler radars. Understanding how land clutter behaves can lead to modified clutter suppression techniques for improving radar target detection performance. This paper presents a model of land clutter which has been validated against a number of different land types observed at different frequencies. The characteristics of the clutter which limit target detection are discussed.

1 INTRODUCTION

The modelling of the clutter environment is of critical importance to the radar designer who has to ensure that the detection capabilities of the radar system designed are maintained in all foreseeable scenarios. A coherent pulse-Doppler radar, which uses Doppler processing to extract target radial velocity and to suppress clutter, requires knowledge of the statistics of the clutter fluctuations in each Doppler channel. By anticipating the behaviour of the clutter background, thresholds may be set at the outputs of these Doppler channels so that design false-alarm rates can be achieved.

Backscatter from the ground presents problems to ground-based or look-down airborne radar systems that attempt to detect targets of interest submerged in such a background.

Models of the clutter environment allow investigation of signal processing architectures and algorithms for determining their clutter suppression capabilities and, hence, detection performance. Improvements to current suppression techniques can then be suggested.

This paper outlines a statistical model of land backscatter as applied to a coherent pulse-Doppler radar. The model has been based on recorded data provided by Lincoln Labs. of MIT. The recordings, acquired at numerous sites in North America, were collected as part of a study undertaken by Lincoln Labs. to characterise land backscatter measurements at low grazing angles. The recordings covered a number of distinct landcover and landform types. Also, certain radar operational parameters, such as carrier frequency range

resolution and polarisation, were varied from recording to recording to determine how these affected the clutter characteristics.

The clutter model, presented in the next section, regards individually the statistical behaviour of the temporal and spatial fluctuations of the clutter, as was the approach taken by [4] for sea clutter. This approach has led to a compound model for sea clutter from which detection probabilities can be readily calculated. A compound model of ground clutter is given here. The implications of this model on target detection is then discussed.

2 CLUTTER MODEL

The clutter model presented in this paper has been developed based on low-grazing angle clutter measurements taken at a number of sites in Canada. The sites analysed in the study are tabulated below in Table 1:

Site	Landcover	Landform
Beiseker	Cropland	Undulating to Hummocky
Big Grass Marsh	Wetland	Level
Brazeau	Forest	Undulating to Ridged
Picture Butte	Cropland	Undulating
Wainwright	Forest	Undulating

Table 1



The measurements were calibrated to give absolute values of RCS. Measurements were acquired at sites over a number of range-azimuth cells. They were recorded using a number of transmitter wavelengths, ranging from VHF (170 MHz) to S-band (3.24 GHz) and X-band (10 GHz), as well as either vertical or horizontal polarisation. In addition, the pulse duration varied so that range resolutions of 15 m, 36 m and 150 m were available.

Marked differences in the clutter characteristics resulting from the use of VHF frequencies as opposed to S or X-band frequencies were observed and these are discussed in the following sections.

In the measurements used for the temporal and spatial analysis of the clutter the number of pulses recorded per range gate, available for processing, was of the order of 1000, with an effective PRF of 15.625 Hz. This gives high quality information on the temporal behaviour of the clutter in each of a small number of range gates.

For the validation of the model via Doppler processing (section 2.4), measurements with 32 pulses transmitted in each of a larger number of range gates were made, with PRFs varying from 62.5 Hz to 93.75 Hz. This gives good spatial description of the clutter, together with realistic Doppler resolution.

For both analysis and validation, range cells from a single azimuth direction were chosen.

The temporal and spatial characteristics of land clutter have been separately modelled using the clutter measurements. They are separately discussed below.

2.1 Temporal Behaviour

Various sources, e.g. [1], have attempted to describe the contributions of scattering energy from a typical resolution cell illuminating a patch of land as coming from two distinct sources: energy being received from a large number of small moving scatterers with dimensions of the order of a wavelength (i.e. those that fall in the Resonance region) and energy from a number of larger, relatively stationary, scatterers with dimensions greater than a wavelength. These two components shall be called the random component and the steady component respectively.

The energy from the random component fluctuates within a train of pulses (dwell) as the scatterers are displaced, by turbulence for example. There is usually pulse-to-pulse correlation of the returns relating to the internal motion of the clutter, the degree of which, as received by the radar, is dependent on the radar wavelength and the PRF.

A proportion of the scatterers observed in a resolution cell will, generally, be stationary over the dwell duration (in fact over several dwell durations). The returns are specular, that is the radar waveform is reflected back from these scatterers with a random phase which remains constant over the dwell. The amplitude of the scatterers within the dwell is assumed to be completely correlated from pulse-to-pulse.

Statistically, the random component behaves in the classical fashion of a Gaussian process where there are a large number of independently fluctuating scatterers within a resolution cell. This comes from the Central Limit Theorem [6]. This constraint may be broken if the number of scatterers in a cell becomes small, as may be the case when small resolution cell sizes are used. For the resolution sizes used in the clutter recordings, this constraint is not expected to be broken. For a coherent pulse-Doppler radar the statistics of the random component received in each of the Inphase and Quadrature channels are Gaussian.

Supplementary to the returns from these two clutter components is uncorrelated complex-Gaussian system noise.

Mathematically, the total interference return from a resolution cell may be given by:

$$z = z_r + z_s + z_n \quad \dots(1)$$

where z_r , z_s and z_n are the complex returns from the random component, steady component and system noise respectively

Each of these terms may be individually defined:

$$\text{random: } z_r = \frac{\alpha_r}{\sqrt{2}} v_I^{(c)} + j \cdot \frac{\alpha_r}{\sqrt{2}} v_Q^{(c)} \quad \dots(2)$$

$$\text{steady: } z_s = \alpha_s e^{j\phi} \quad \dots(3)$$

$$\text{noise: } z_n = \frac{\alpha_n}{\sqrt{2}} v_I^{(n)} + j \cdot \frac{\alpha_n}{\sqrt{2}} v_Q^{(n)} \quad \dots(4)$$

where $v_I^{(c)}$, $v_Q^{(c)}$ are Gaussian random variables describing the random component in the I and Q channels, respectively

$v_I^{(n)}$, $v_Q^{(n)}$ are Gaussian random variables describing the system noise in the I and Q channels, respectively

α_r and α_s are the mean amplitudes of the random and steady component scattered energy in a pulse, respectively

α_n is the mean system noise amplitude

ϕ is the phase of the steady scatterers, constant over a dwell

The mean amplitudes of the scattering components and the phase of the steady component each vary spatially, from range gate to range gate. The characteristics of this, and other, spatial behaviour will be discussed in detail in the next section.

The temporal correlation in the random component may be exhibited by examining its Power Spectral Density (PSD). The amount of correlation is reflected in the width of the PSD as measured at some defined level below the peak. Commonly held theory states that the PSD of ground clutter best fits a Gaussian function [7]. From the clutter recordings analysed this has not been found to be generally true. It has been found to obey consistently a double-sided exponential function:

$$S(f) = \frac{1}{2w} e^{-\frac{|f|}{w}} \quad \dots(5)$$

where f is frequency

w is the (power) spectrum width

The wavelength affects not only the RCS of the scatterers and, hence, the total scattered energy, but also the spectral spread w of the scattered energy. Moving scatterers impart phase modulation on the reflected RF carrier. With large displacements relative to the wavelength, this produces a broad Doppler spectrum of the form described by equation (5). For displacements less than a wavelength the spectrum width and amplitude decreases in proportion to the displacement to wavelength ratio. The RCS of steady scatterers, on the other hand, is generally independent of wavelength.

The RCS of typical moving scatterers, such as leaves and crops, is wavelength dependent. For wavelengths greater than the scatterer dimensions the scatterers are in the Rayleigh region and their RCS diminishes in proportion to the wavelength. At microwave frequencies (e.g. S and X-band) both the dimensions and the displacements of moving scatterers are comparable to a wavelength and, hence, broad Doppler spectra with significant energy are expected. Conversely, at VHF, where dimensions and displacements are less than a wavelength, narrow, low energy spectra are expected.

Figure 1 presents examples of forest clutter PSDs evaluated for a number of data-sets acquired at Wainwright at four different radar frequencies: VHF, L, S and X-bands. The PSD of returns in each of a number of range gates were estimated using a 70 dB weighted 256-pulse FFT and then averaged spatially. The frequency (horizontal) axis is normalised to the PRF whilst the power (vertical) axis is in dBW.

Clutter at the short wavelengths display broad Doppler spreading as expected. As the wavelength increases the spread and energy decreases, so that at VHF there is purely a spike at zero relative Doppler. The PSD of the random component is found to be of the double-sided exponential form (5). The contribution from the steady component is observable from the spike at zero Doppler. Thermal noise is present in varying levels in each recording.

The total single-pulse statistics of the interference power, where the complex return is given by (1), can be shown to be described by a squared-Rice distribution:

$$f_x(x) = \frac{1}{\alpha_r^2 + \alpha_n^2} e^{-\frac{x + \alpha_s^2}{\alpha_r^2 + \alpha_n^2}} I_0\left(\frac{2\alpha_s}{\alpha_r^2 + \alpha_n^2} \sqrt{x}\right) \quad \dots(6)$$

where $x = |z|^2$ is a random variable describing the interference power statistics.

I_0 is a modified Bessel function

Strictly speaking, this pdf (6) is conditional on the mean clutter power which, as discussed later, is spatially varying.

As the radar beam illuminates clutter in different range-azimuth cells the statistics will change from cell to cell since the contribution of each scattering type to the total backscatter will vary. The change in the distribution (6) can be shown by plotting the moments of the distribution from each range gate and observing the variation. The two simplest moments that can be estimated are the mean and standard deviation. The standard deviation, however, is highly dependent on the scale, so a more sensible measure is the normalised standard deviation, called by [6] the "coefficient of variation" and in this paper the "shape parameter", V :

$$V = \frac{S_x}{\mu_1(x)} \quad \dots(7)$$

where S_x is the Standard Deviation of the sample set $\{x\}$

$\mu_1(x)$ is the mean value of $\{x\}$

The statistical distribution described by (6) has the property that as the steady power diminishes (i.e. as $\alpha_r^2 \approx 0$) the shape parameter tends to a value of 1, denoting an exponential-power distribution, i.e. a Rayleigh-amplitude distribution. On the other hand, as the random component disappears (i.e. as α_r^2 and $\alpha_s^2 \approx 0$) the shape parameter tends to a value of 0.

Figure 2 plots the shape parameter for each range cell of a VHF and S-band forest clutter data-set acquired at Brazeau. By observing the variation in shape parameter values with range we can deduce that the contribution of each component of the clutter to the total, or equally the ratio of the two, changes. This implies that the statistics of the clutter in each range cell are changing, so emphasising the spatial variation of the clutter which is discussed in the next section.

The squared-Rice distribution (6), which is a general model of the temporal statistics of the clutter power, has been found to be violated in some experimental data. This may occur when few scatterers are illuminated in a resolution cell, although this has not been fully investigated.

2.2 Spatial Behaviour

Although Figure 2 depicts the spatial behaviour of the clutter power it conceals the spatial variation in each of the random and steady components which are not immediately available from the shape parameters plotted.

Clutter power varies within a dwell, from pulse to pulse, because of the internal motion of the clutter. To investigate the spatial behaviour of the clutter this temporal variation may be ignored by observing the mean power in each dwell. Naturally, the physical distribution and the number of scatterers in a range cell varies from range cell to range cell so that adjacent cells have different mean power. This is particularly accentuated if the dimensions of the range resolution cells are small in relation to the scatterers.

Empirical observations of the spatial variation in mean clutter power has been observed in sea clutter ([2],[3]), both in coherent and non-coherent radars. Statistical modelling of the spatial behaviour in sea clutter has resulted in a compound model of the overall clutter statistics involving both temporal and spatial behaviour, giving the well-known K-distribution model. From this, thresholds for maintaining a design

false-alarm rate and the related detection loss as compared to using Rayleigh-amplitude thresholds have been determined.

In ground clutter there is a spatial variation in the returns due to the natural variation in the physical form of the terrain as well as due to the distribution of scatterers in the radar coverage. Even analysing clutter data taken at the long 150 m range resolution some spatial variation has been observed. This variation has been observed in the Lincoln Labs. clutter data-sets studied as well as in other land clutter measurements, e.g. [5].

The spatial variation in the mean power of each component of land clutter can be seen for each data-set by examining range profiles which show the estimated mean powers for each of a number of range gates. This has been performed on a number of data-sets as shown in Figures 3a and 3b. Range profiles of the mean steady and random power are shown for two X-band data-sets, one from Big Grass Marsh (marshland) and one from Wainwright (forest).

Several observations can be made. The power in each component is seen to vary significantly from range cell to range cell as the landcover and landform varies. The extent of this variation is different for each data-set. In addition to this there is a well-defined empirical relationship between the mean power in the steady component and the mean power in the random component in each range cell:

$$A_r = k A_s \quad \dots(8)$$

This coupling may be better visualised by scatter plots of steady power vs random power, as shown in Figures 3c and 3d, for the profiles of Figures 3a and 3b. Each point signifies a particular range cell. Linear relationships may be ascertained from the scatter plots. These illustrate that the ratio of steady power to random power remains roughly constant over all range gates considered.

This is somewhat predictable since, in nature, the distribution of slowly-moving or stationary scatterers and rapid moving scatterers are generally related. This is because the smaller moving scatterers are likely to be anchored to the stationary scatterers. An example is a forest where the number of leaves illuminated depends on the number of tree trunks present. The argument can equally be applied to other landcover types as implied by Figure 3. Indeed it also applies at different radar frequencies as observed in the measurements. In fact, the linear coupling has been observed qualitatively in most of the clutter data-sets analysed. This phenomenon obviously fails at VHF frequencies

where the RCS of the random component is negligible, so that system noise, alone, is present with the steady component.

In Figures 3a and 3b range profiles of the mean power in the steady and random components were plotted and shown to vary with range. The spectrum width, which depicts the degree of temporal correlation of the random component within a dwell, can also be estimated from returns in each range cell. Range profiles of spectrum width can, hence, be plotted and its spatial behaviour observed in the same way as with the mean clutter power. Figures 3e and 3f display range profiles of spectrum width for the data-sets of Figures 3a and 3b. The range variation is evident in these examples, as well as in others studied (except at VHF where spectrum width is indeterminable).

Modelling of the spatial statistics of these three clutter parameters - mean random power, mean steady power and spectrum width - requires insight into the distribution of values that may be observed. Sample histograms facilitate this by providing a picture of the distribution of values observed in a collection of data-points. These are also called sample probability density functions (sample pdfs). The data-points in this context are the parameter values estimated for each range cell.

Figure 4 plots the sample distribution of the three clutter parameters for the forest clutter data-set of Figure 3. Qualitatively the distribution of random and steady powers show a similar statistical law whilst that of the spectrum width is markedly different.

These curves suggest a generic statistical model which can encompass the spatial statistics of the mean power and spectrum width, namely the Gamma distribution:

$$f_p(p) = \frac{p^{\nu-1} e^{-\frac{p}{\gamma}}}{\gamma^\nu \Gamma(\nu)} \quad \dots (9)$$

$$f_w(w) = \frac{w^{\alpha-1} e^{-\frac{w}{\lambda}}}{\lambda^\alpha \Gamma(\alpha)} \quad \dots (10)$$

where $f_p(p)$ is the pdf of the random or steady power

$f_w(w)$ is the pdf of the spectrum width

ν and α are order parameters

γ and λ are scale parameters

The sample pdfs of the mean random and steady powers suggest that a Gamma Distribution with order parameter $\nu < 1$ is an appropriate model for the spatial statistics of these parameters. In fact, because of the coupled nature of these parameters as previously discussed, the order parameter for both should be identical, whilst the scale parameters will generally differ. In practice, as shown by the spread of points in the scatter plots of steady power vs random power, the estimated steady and random shape parameters will not, in general, be the same.

The sample pdfs of the spectrum width suggest that a Gamma Distribution with order parameter $\alpha > 1$ is more appropriate to describe its spatial statistics.

Supplementary to the stochastic processes which describe the spatial variation of the clutter there are underlying correlation processes which affect these statistics. As shown by the range profiles in Figure 3 the clutter varies with range. However the profiles are not range independent. There is a degree of correlation between contiguous range cells. This is because local clutter scatterers have similar behaviour, especially when high radar range resolution is used.

This aspect of the clutter can affect the performance of spatial non-coherent integration processes, such as CFAR processing, which requires the range samples being integrated to be independent over the extent of the processing interval.

The degree of correlation observed in most of the ground clutter data-sets analysed is small enough to be largely ignored. This is obviously qualified by the statement that other clutter types and resolution cell sizes may alter this fact.

2.3 Detection performance

The implications of the Non-Rayleigh models of sea clutter on target detection is well documented. The spatial variation is such that, to maintain design false-alarm rates, thresholds need to be set higher than is necessary for classical Rayleigh-amplitude clutter. This implies that there is a detection loss imposed by the higher thresholds.

Non-Rayleigh models can be applied to coherent radars that employ Doppler processing for clutter suppression and target separation. In ground clutter, the spatial variation of spectrum width implies that the clutter statistics are not the same in each Doppler channel because different Doppler channels will exhibit different degrees of clutter power variation.

The effect of the spatial variations in the clutter on the statistics of each Doppler channel may be shown by the "shape spectrum". The shape spectrum is similar in concept to a mean power spectrum which displays estimates of the power in a number of Doppler channels, averaged in range. A shape spectrum displays the estimate of the shape parameter in each Doppler channel, where the shape parameter is evaluated from the channel outputs in range. The shape spectrum provides a simple and succinct means of determining which channels have greater spatial variation in power output and, hence, which require greater thresholds to maintain an overall design false-alarm rate.

The form of the shape spectrum is dependent on the characteristics of the clutter. Before discussing this it is necessary to understand how the shape spectrum attains its form. The coupling of the mean power of the steady and random component causes the clutter shape parameters, as due to mean power variation, to be the same in each Doppler channel (i.e. the statistical distributions are the same, notwithstanding the differences in scale). The spectrum width variation, on the other hand, has a more complex effect on the variation in each channel. This is best shown by an idealised picture which depicts what happens to the outputs of Doppler channels when the spectrum width varies spatially.

Figure 5 shows that, as the spectrum width varies, the power levels in the Doppler channels in which the tails of the PSDs are located display greater variation than do those in channels closer to dc. Shape parameters can clearly be seen to be greatest in the channels where the tails of the individual PSDs dominate. Unquestionably the degree of spatial variation of the spectrum width plays an important role in this as too does the level of the noise floor since this determines where the tails of the clutter PSD in each range cell are defined. Both the magnitude of the channel shape parameter values and the location of the maximum shape parameters are determined by these, and other, factors.

2.4 Validation with Recorded Clutter Data

The model described in this paper has been encapsulated in software which allows complex land backscatter returns to be simulated. By performing identical coherent Doppler processing it is possible to validate the model against recorded clutter data.

The stochastic nature of the clutter means that only ensemble behaviour can be observed for comparisons. In the previous section the mean power spectrum and shape spectrum obtainable from a clutter data-set proved to give a concrete

picture of the understanding of the problem of setting thresholds in a ground clutter environment to maintain desired false alarm rate.

Consequently these have been used extensively to provide means of comparisons of the model with recorded data and, hence, to provide the necessary validation. The measurements used for this purpose are different in nature to those hitherto analysed. These have been recorded with 32 pulses per dwell over a large number of range gates. This gives more accurate estimation of the spectra. Moreover, they reflect the realistic Doppler resolutions that most operational pulse-Doppler radars employ.

Numerous clutter measurements have been Doppler-processed, using a 50 dB Dolph-Chebyshev weighted 32-pulse FFT. From this, mean power spectra and shape spectra have been evaluated. For each such data-set a number of parameters characterising the clutter, as required by the model, have been estimated, via numerous techniques. Consequently, simulated clutter returns have been generated which have been processed identically to the associated recorded data.

Figure 6 displays comparisons of mean power and shape spectra for some X-band forest and cropland clutter. Discussing initially the forms of the spectra, the mean power spectra can clearly be seen to accord with (5). The shape spectra exhibit the characteristic form as described in the previous section with higher power level variations in those channels dominated by the tails of the clutter PSDs.

Comparing the spectra of recorded and simulated returns one can see that qualitatively as well as quantitatively the power spectra and the shape spectra match well so implying that these characteristics of the clutter, which affect detection performance, are effectively modelled.

3 CONCLUSIONS

A general statistical model of land backscatter, which models the temporal and spatial fluctuations of the clutter, has been developed, and has been shown to accommodate different clutter types acquired by radars employing different operational parameters. By comparisons of the mean power spectra and shape spectra of recorded data and simulated data the model has been shown to emulate the characteristics of ground clutter that limit pulse-Doppler radar detection performance.

In addition to the effect of the spatial variation of the mean power of the clutter, spatial variation of the spectrum width has been observed. It may play an important part in limiting target detection, especially in those Doppler channels where there is

little clutter-to-noise. Compensation for this, in terms of setting thresholds higher than the classical Rayleigh-amplitude thresholds required to maintain the same overall false-alarm rate, therefore signifies that some detection loss must be accepted.

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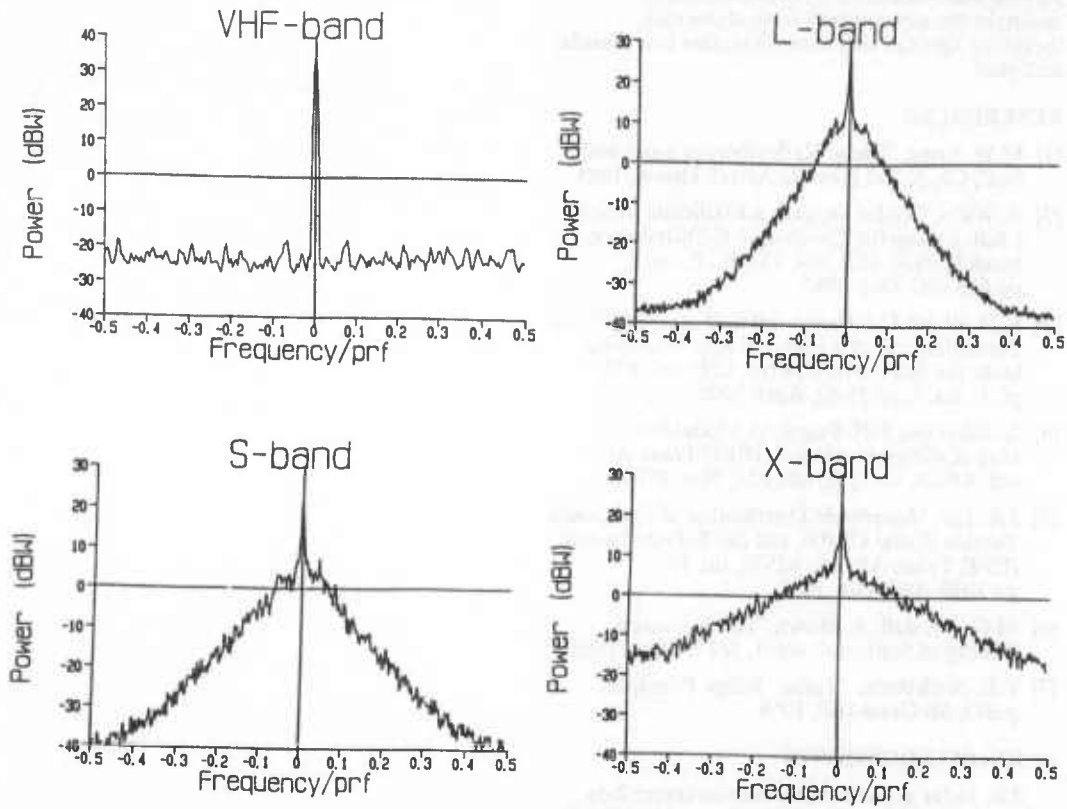


Figure 1 Mean power spectral density for forest clutter at four different radar frequencies, as a function of normalised frequency.

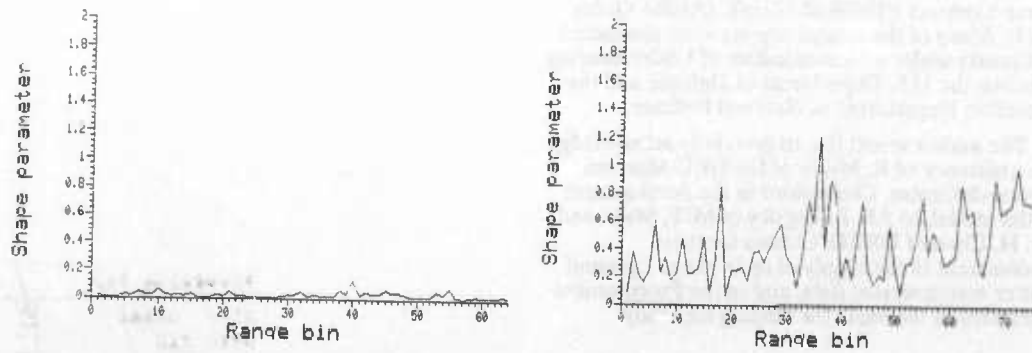


Figure 2 Shape parameter for forest clutter at two different radar frequencies, as a function of range.

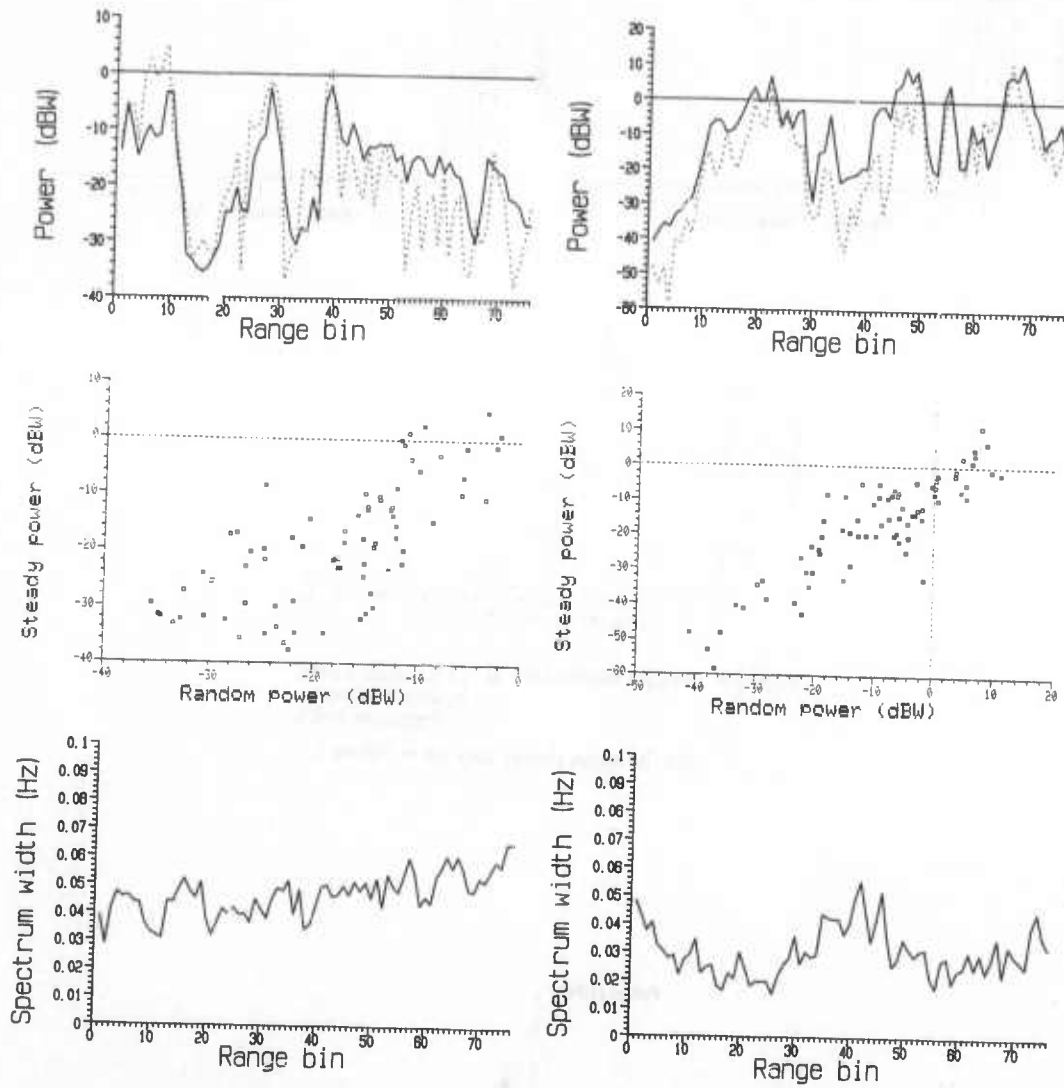


Figure 3 Random (solid line) and steady (dotted line) power for a) Wetland and b) Forest clutter at X-band, as a function of range. c) and d) are scatter plots of steady power vs random power for a) and b) respectively. e) and f) are plots of spectrum width as a function of range for the wetland and forest clutter of a) and b) respectively.

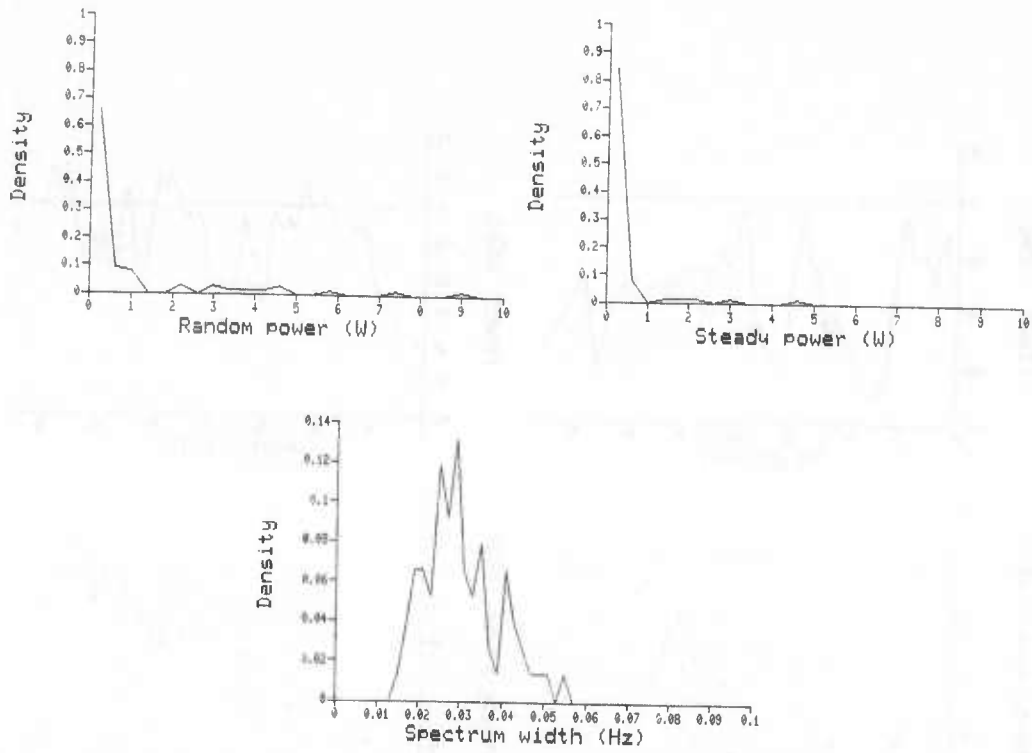


Figure 4 Sample distribution of a) Random power
 b) Steady power
 c) Spectrum width
 for the forest clutter data-set in Figure 3.

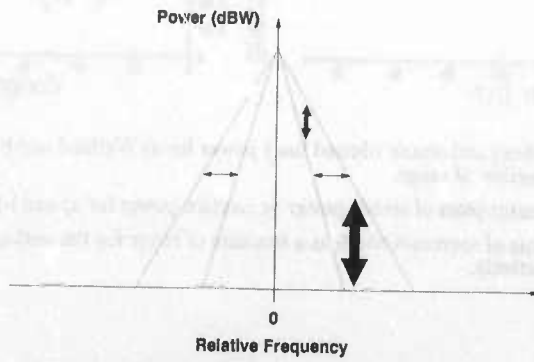


Figure 5 Idealised diagram showing the effect of spectrum width variation on Doppler channel power levels.

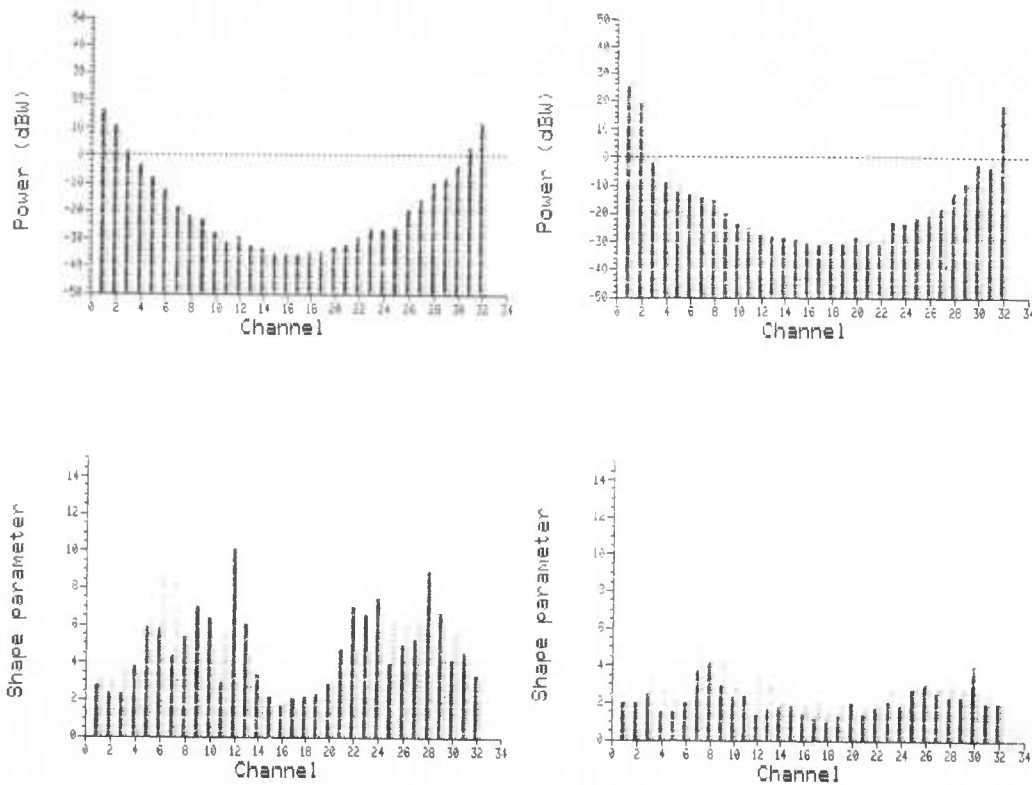


Figure 6 Comparison of mean power spectral density of recorded data (dark bars) with simulated data (light bars) for a) Forest and b) Cropland clutter at X-band. c) and d) give comparison of shape spectra for the forest and cropland clutter of a) and b) respectively.

DISCUSSION

H. Chan (CA) :

What insights led you to choose the Gamma distribution to represent the variation of mean power and the spectral width ?

Author's reply :

I chose the gamma distribution for three reasons. One, it is a mathematically tractable model to use. Secondly, it suitably models non-negative random variables which is necessary for modelling near powers and spectral widths. Thirdly, it offers a tie-in with the K-distribution model of sea clutter, of which much work has been done relating to radar detection performance.

