PERISCOPE DETECTION RADAR

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ABSTRACT

The periscope detection problem is described. An advanced simulation model is developed which allows the performance of advanced periscope detection radars to be determined. An advanced system employing three-dimensional filters and distribution-free CFAR is postulated. Detection curves are developed showing the effects of radar resolution, platform altitude and sea state on system performance. The best detection performance is achieved with high resolution radar operating at low platform altitudes.

PERISCOPE DETECTION RADAR

The periscope detection problem is unique in radar detection theory. A small RCS (1/4 m^2-to-1m^2) fluctuating target, which is exposed for only a very brief period (perhaps only 5 s), must be detected in a field of wide dynamic range non-Gaussian sea clutter. Further, the periscope or snorkel (for diesel submarines) may be stationary or moving at zero speed relative to the local mean surface waves. This generally precludes the use of spectral discrimination techniques employing Doppler processing as a reliable detection mechanization.

Several periscope detection radars have been fielded (e.g., APS-116, APS-119, APS-134, APS-137). These radars all work on the same principle [1]. They transmit a wide bandwidth providing high range resolution matched as closely as possible to the physical dimensions of the periscope or snorkel. A rapid scanning antenna (150-300 r/min) is used to sample target and clutter returns on a scan-to-scan basis. Clutter tends to decorrelate over the exposure time of the periscope while target returns tend to be correlated. The target is extracted from the clutter background using scan-to-scan integration. The scan-to-scan integrator has generally been implemented using analog mechanization which compromises the performance potential of this technique.

Improvements in the performance of current periscope detection radars are needed to meet new requirements related to operation in shallow littoral waters and reduction of periscope RCS signatures.

This paper describes an investigation of several aspects of the periscope detection problem which can lead to improved periscope detection performance. These involve development of 1) an advanced simulation model which allows a parametric prediction of periscope detection radar performance and 2) synthesis and evaluation of advanced signal processing concepts which allow the full performance potential of the current design principle to be realized.

The successful optimization of the detection performance of any surveillance radar operating in a maritime environment depends upon a complete and accurate characterization of the sea clutter return. This is particularly critical for periscope detecting radars where experimental results have shown highly non-Gaussian statistics [2].

In this paper, sea clutter is simulated using a physically derived model which emulates the mechanisms postulated to generate non-Gaussian sea clutter. The resultant K-distributed clutter has been calibrated against experimental data providing a parametric relationship between radar system and environmental factors (i.e., radar resolution and polarization, sea state, grazing angle and wind direction) as they affect the sea clutter characteristics [3, 4]. The simulation approach, which involves using the rejection method for generating random deviates, has been recently described [5].

Use of this simulation model provides a tool which allows the performance of advanced concept versions of periscope detection radars to be predicted. Critical questions such as the effect of radar resolution, platform altitude, and the utility of frequency agility on performance can be addressed. Also, the performance improvement provided by advanced radar concepts such as three-dimensional filtering, non-parametric CFAR and periscope signature recognition techniques can be predicted relative to the performance provided by current designs.

The paper also addresses the use of three-dimensional filtering [6] and non-parametric CFAR [7] as applied to the periscope detection problem. Three-dimensional filters, which are tuned to the velocity trajectories of the target, provide a means for collecting the total energy radiated by the radar over multiple scans before a detection decision is made. The effect is analogous to the improvement provided by Doppler filter processing over that available from conventional radar processing.

False alarm control is a significant problem for radars where clutter backgrounds are significantly larger than target returns. The non-Gaussian character of high resolution sea clutter and its combination with receiver noise results in an uncertain background distribution in which detection decisions must be accomplished. Distribution-free CFAR processors are required to allow formation of detection decisions with a constant false alarm rate. A basic rank-ordering distribution-free CFAR is described which regulates the false alarms into the three-dimensional filter.

Sea Clutter Model

The composite K-distributed model utilized postulates that sea clutter is due to the compound effect of two fluctuating components. The speckle component due to reflections from capillary waves is modeled as classical Rayleigh-distributed clutter. This component has a short correlation time and can be further decorrelated by frequency agility.

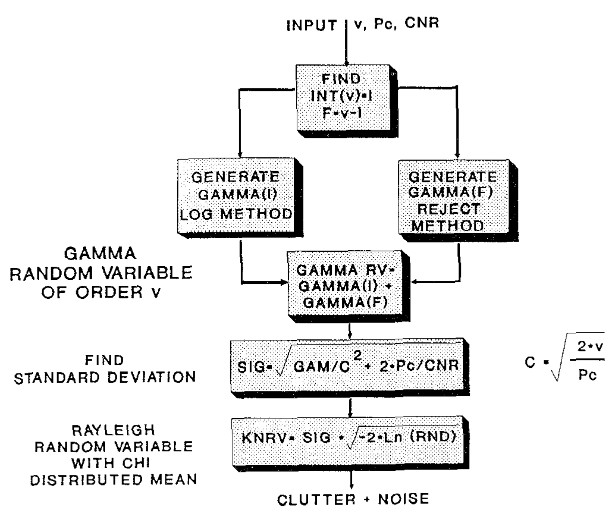

Figure 1: K-Disributed Clutter Simulation

The other component is associated with the sea swell structure, which has a long correlation time and is not affected by frequency agility. This component is modeled with a chi-distribution by using an empirical fit to experimental sea clutter data [3, 4].

In this model, the sea clutter is characterized as a Rayleigh process with a spatially varying mean. A correlated root-Gamma (chi distribution) process is used to characterize the spatially varying mean. Generation of the root-Gamma variable is complicated by the fact that its probability distribution function is not generally available as an analytic function. This difficulty has been circumvented, as depicted in Figure 1, by employing the rejection method for generating a random variable which requires only that the probability density function of the variable be available [5].This method is described in Appendix A.

Detection of small targets such as periscopes are limited by both receiver noise as well as sea clutter. Figure 2 depicts a time series generated by simulating the physically derived sea clutter model with 8 foot radar resolution coherently combined with receiver noise. The spiky nature of the sea clutter is evident as is the apparent difficulty of detecting a small fluctuating periscope target whose magnitude is

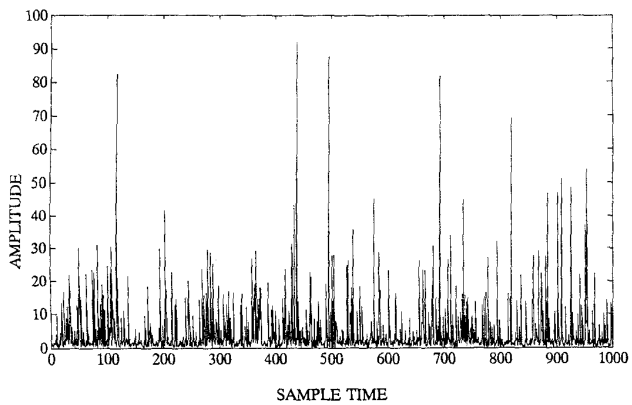

Figure 2: Simulation of Sea Spikes

significantly less than that of the sea spikes.

The empirically derived K-distributed shape factor appropriate for an X-band radar [4] is given by

$$v = 10^{.67\log(\phi_g) + .625\log(\tau r_c/30) + s - k} \quad (1)$$

where

τ = Pulse width (n sec.)

ϕ_g = Grazing angle (degrees)

r_c = Cross range resolution (meters)

s = -1/3 for up-or-down swell; +1/3 for across swell

k = 1 for vertical polarization; 1.7 for horizontal polarization

K-distributed clutter in receiver noise can be generated using the compound formulation as [7]

$$rn = \sigma_{cn} * \sqrt{-2*\ln(RND)} \quad (2)$$

where

$$\sigma_{cn} = \sqrt{G_{am}/C^2 + 2*P_c/CNR} \quad (3)$$

and G_{am} is a gamma random variable, P_c is the clutter power, CNR is the clutter-to-noise power ratio, and $C^2 = 2v/P_c$. Targets can be introduced into the simulation by first resolving rn into quadrature components (x_i and x_q) and then using

$$rns = \sqrt{(v_s - x_i)^2 + x_q^2} \quad (4)$$

where v_s is the signal voltage. Generation of v_s as an appropriate random variable allows any of the Swerling type targets to be simulated [5].

Figure 3 depicts an example of the probability distribution function obtained by simulating a relatively complex situation. In this

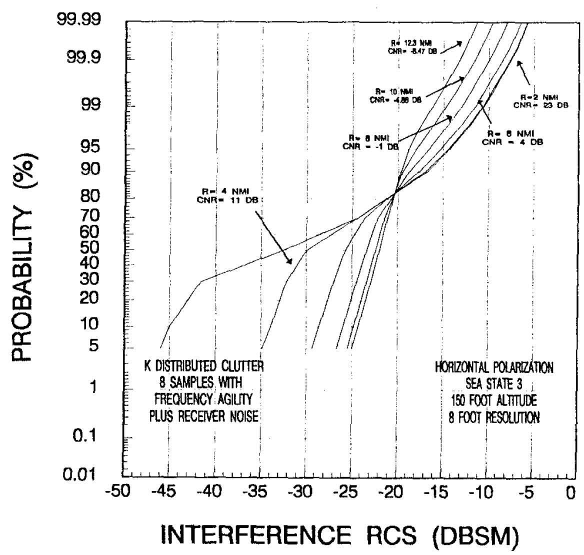

Figure 3: Probability Distribution of K-Distributed Clutter with Noise

example, eight frequency-agile high-resolution (8 foot resolution) K-distributed clutter samples are combined in a receiver noise background with varying clutter-to-noise ratios. The distribution is calibrated in terms of the expected clutter equivalent radar cross section to allow determination of the radar cross section which can be detected for a particular false alarm rate. The distribution varies as a function of clutter-to-noise ratio (CNR) and clutter shape parameter (v), both of which are a function of grazing angle. The varying distributions indicate a need for adaptive false alarm control to maintain a constant false alarm ratio.

System Description

The elements of a postulated detection radar using the standard design principle are depicted in Figure 4. The various design

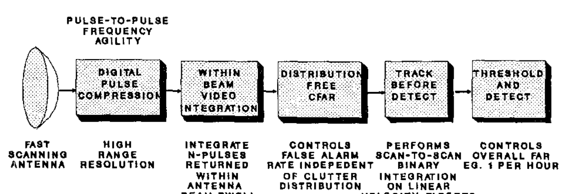

Figure 4: Radar Signal Processing Block Diagram

mechanisms unique to the periscope detection problem are: 1) the fast scanning antenna coupled with high radar range resolution, 2) frequency agility to improve the target signal-to-noise ratio, 3) distribution-free CFAR to regulate false alarms and 4) a track-before-detect filter to examine multiple radar scans for periscope targets.

The principle of track-before-detect (T-B-D) processing is depicted in Figure 5 which illustrates normalized target and sea clutter returns plotted on a scan-to-scan basis. The T-B-D filter is illustrated as a linear velocity template which is matched to a particular target trajectory. One template is required for each realizable target velocity consistent with the radar's range resolution. In the illustation, detection

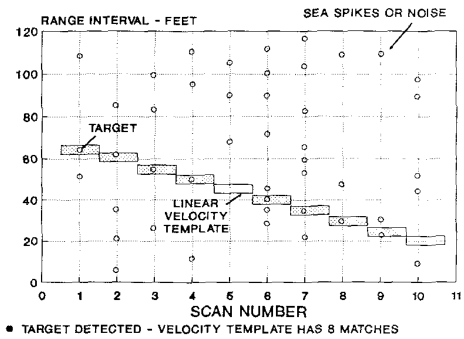

Figure 5: Track Before Detect Scenario

occurs when at least 8 target responses fall within the linear velocity template set for a periscope exposure time of 5 seconds (i.e., 10 scans). False alarms occur when at least 8 random noise or sea spikes fall within the template response.

Collection of the full energy returned from the target before a detection decision is made results in superior detection performance than that achieved by thresholding on a single scan basis before application of scan-to-scan integration. T-B-D processing falls within the general discipline of three-dimensional filters. As with one-dimensional filters, processing can be accomplished in the temporal domain (as is illustrated in Figure 5) or in the transform domain. For three-dimensional filters, the Hough transform is appropriate for detection of either linear velocity or linear accelerating targets [8].

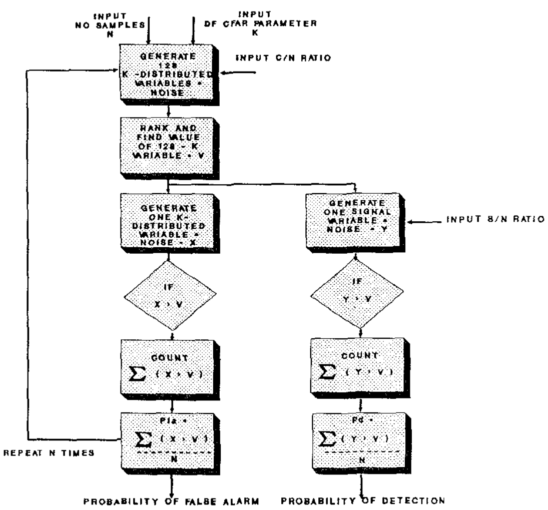

Figure 6: Distribution Free CFAR Simulation

Figure 6 depicts a simulation to evaluate the detection loss of a distribution-free CFAR for the periscope detection problem. The distribution-free CFAR illustrated in Figure 6 uses a rank order approach that provides a constant false alarm rate into the T-B-D filter illustrated in Figure 5.

System Performance

Figures 7 and 8 depict the system performance predicted for an advanced airborne periscope detection radar illustrated in Figure 4. A transmitted average power of 500 watts, an antenna gain of 33 dB, a scan rate of 2 r/sec. and a Swerling 3 target is assumed.

Figure 7 illustrates the effect of radar resolution on the ability to detect small radar targets from an airborne platform at 150 foot altitude. It assumes that the target extent is always less than the radar's

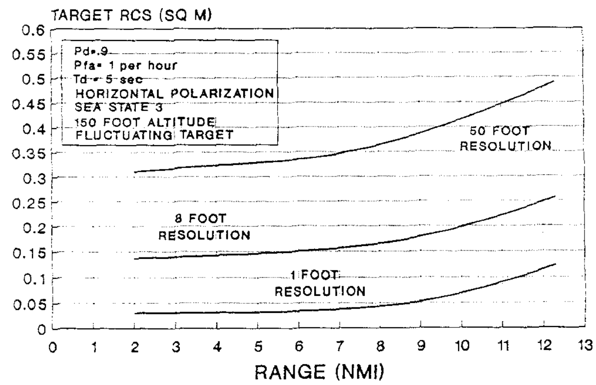

Figure 7: Small Target Detection Performance for Various Resolutions

resolution and that 500 MHz radar bandwidth is transmitted through a combination of pulse compression and frequency agility. Scan-to-scan integration with a 5 s period is employed in the three-dimensional filter to capture the minimum expected target exposure time. The curve illustrates the advantage of increased resolution in detecting small targets whose range extent is less than the target's extent.

Figure 8 illustrates the effect on target detection of various platform altitudes and sea states for an 8 foot resolution. For a given target range, the grazing angle to the clutter increases with platform altitude, thereby increasing the CNR and accentuating the effects of the clutter on target detection. The curve illustrates that minimum size targets can be detected at low altitudes,

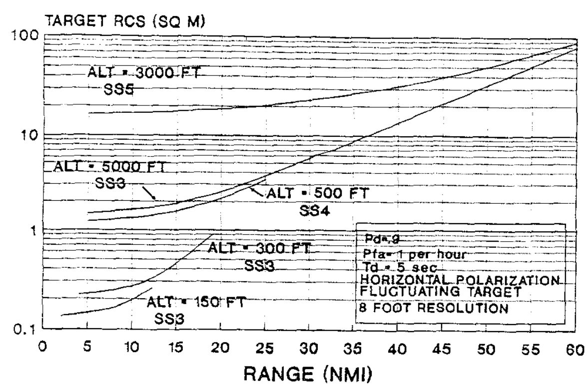

Figure 8: Small Target Detection Performance for Various Altitudes and Sea States

but that the overall detection range is limited by the radar horizon. Also at the horizon (i.e., at low grazing angles), target detection tends to be noise limited, resulting in decreased target detectability at the further ranges due to SNR considerations.

The overall conclusion is that detection of small short exposure targets is possible with high resolution radar which are matched to the target dimensions and operate at low altitudes.

APPENDIX A

SIMULATION OF K-DISTRIBUTED CLUTTER

Most random variables used in radar simulations can be generated by the transformation method [9]. To apply this method, the cumulative probability distribution of the random variable must generally be available in closed form so that its inverse function can be determined. This method can be used to generate a Rayleigh distributed random variable given by

$$v = u \bullet \sqrt{-2 * \ln (RND)} \qquad \text{(A1)}$$

where u is a parameter proportional to the mean of the distribution ($E(v) = (\pi/2)^{1/2} u$) and RND is a uniformly distributed variable, 0-1.

K-distributed clutter is generated when u is a random variable with a chi or root gamma probability distribution. Unfortunately, the chi distribution is not invertible so that it cannot be generated using the transformation method. However, since its probability density function is available, it can be generated using the rejection method [9].

In the rejection method, an invertible comparison function f(t) is selected which everywhere lies above the probability density function p(t) of the variable to be generated. Then a test random variable (t) is generated from the comparison function and the ratio q = f(t)/p(t) is formed. Next, a uniform deviate 0-1 is generated and if less than q, the test random variable is accepted and otherwise rejected.

An algorithm for generation of a gamma random deviate of order v is given in Figure A-1. The algorithm first generates a gamma random variable of integer order k using the logarithmic method and a second gamma random variable of order a = v-k < 1 using the rejection method. The overall gamma deviate is then the sum of the two gamma random variables. The efficiency of the simulation is enhanced by partitioning the comparison function into subregions such that

$$f_1(t) = \frac{t^{a}-1}{\Gamma(a)} \; ; \; 0 \le t \le 1 \qquad \text{(A2)}$$
$$f_2(t) = \frac{e^{-}t}{\Gamma(a)} \; ; \; t \le 1$$

The chi or root gamma random variable u is then obtained using the transform

$$u = \frac{\sqrt{t}}{b} \qquad \text{(A3)}$$

where the clutter power is given by $P_c = 2v/b^2$.

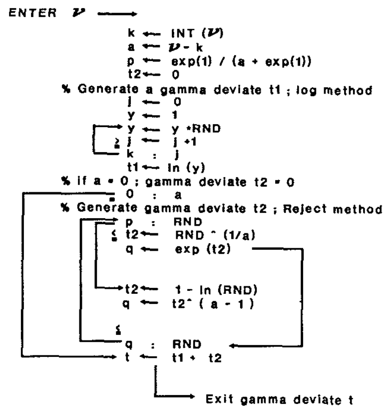

Figure A1: Simulation of a Gamma Random Deviate of Order v

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