RADAR DETECTION OF TARGET SIGNALS IN NON GAUSSIAN CLUTTER: THEORY AND APPLICATIONS

A. Farina, A. Russo and F. Scannapieco
Selenia S.p.A. Radar Department - Via Tiburtina Km. 12,400
00131 - Rome Italy

ABSTRACT

The present paper pursues, extends and concludes the theory and the presentation of results initiated with the papers /1/, /2/ and /3/ prepared by the same authors. The purpose of the present paper is manifold. First, a brief revision is provided of the mathematical background to derive radar detection algorithms for any type of probability density and autocorrelation functions of target and clutter. A relevant requirement concerning this theory is the derivation of adequate mathematical models for the target and clutter processes. This is done with particular reference to the Lognormal and Weibull cases. A remarkable result refers to the derivation of models for the coherent echoes train case. The leading concept of "Whitening and Gaussianing" filter is then introduced as a fundamental block to derive radar detection schematics. The aforementioned theory is applied to the derivation of completely new detection schemes and to the evaluation of the corresponding detection performance when the amplitude probability density of the clutter is Lognormal or Weibull. Another novelty of this paper refers to the presentation of detection schemes having adaptive features. More in detail, methods are suggested for the on-line estimation of the "whitening-Gaussianing" filter weights. Results are presented concerning the detection loss versus the number of range cells along which the average of weights estimate is performed. Detection loss are evaluated for different number of processed pulses and for different parameters of clutter and target signals. Another adaptive feature explored refers to the on line evaluation of a CFAR detection threshold. Even in this case, an evaluation of the corresponding detection loss is enclosed.

1. INTRODUCTION

This paper affords the problem of detecting target echoes modelled as a Gaussian distributed and time correlated coherent sequence (Swerling cases belong to this model). The clutter, in which the target is buried in addition to white Gaussian noise (WGN), has non-Gaussian probability density for its in-phase and quadrature components. This problem is particular relevant for detection and tracking of aircraft flying at low elevation over the ground or sea. It is also of practical interest when the radar has high resolution in range and/or angle. The theory of optimum detection of target embedded in clutter is well established when the probability density of clutter amplitude is Rayleigh or, in other words, the in-phase and quadrature components are jointly Gaussian distributed processes; the clutter autocorrelation function may have any shape. The optimum processor is a coherent linear filter, for the suppression of clutter and enhancement of target echo, cascaded with a modulus extractor and a comparison with a suitable threshold. The optimum processor for non-Rayleigh clutter is no longer a linear filter. The detection performance of conventional processors in non-Rayleigh clutter generally deteriorates from that in Rayleigh clutter. This is due to the long tail of the distribution which results in a problematic setting of the detection threshold. In fact, an increase of false alarm rate should be expected or, alternatively, a reduction of detection probability should occur to maintain proper CFAR characteristics. The paper is organized as follows. The ensuing Section 2 outlines the background theory of radar detection in a non-Gaussian frame. Section 3 derives mathematical models of a coherent echoes sequence having an assigned time autocorrelation function and a Lognormal or Weibull probability density for the amplitude. These two preliminary Sections set the scene for deriving detection schemes to deal with Lognormal and Weibull clutter. Detection performance are evaluated by resorting to a Monte Carlo simulation on a digital computer (Section 4). The conceived processors are then equipped with adaptive features which are described in Section 5.

2. OPTIMUM RADAR DETECTION IN NON-GAUSSIAN FRAME

This Section affords the problem of optimum radar detection when the clutter, the target or both are time correlated and have a non Gaussian probability density for their in-phase and quadrature components. The optimum detection schemes are based on the recursive evaluation of the log-likelihood ratio for the two alternative bypotheses, followed by a comparison with a suitable threshold. In the two alternative hypotheses, the target and clutter signals are represented as the output of two dynamic nonlinear systems driven by white Gaussian noise. Roughly speaking, the optimum detector scheme is built around to two nonlinear optimum (in the minimum-mean-square-error sense) estimators of the signal in the two alternative hypotheses. The rationale of the approach is to transform the non Gaussian time correlated incoming radar echoes in two white Gaussian noises ("Whitening-Gaussianing approach"); this is achieved by making the difference of the two estimated signals with the actual radar echo. At this point the detection problem is reduced to the classical case of a Gaussian signal in Gaussian noise. The corresponding detection scheme is shown in Fig. 1. The received echo z_k is processed through two nonlinear filters. The upper filter is matched to the condition that the signal to be detected is the sum of target plus clutter, while the bottom filter is built around the condition that the signal to be detected is just the clutter source. By making a difference of the two estimates $\hat{z}_1$ (k/k-1) and $\hat{z}_0$ (k/k-1) with the incoming echo z(k), two residulas of estimates V_1 and V_0 are obtained. Detection is now achieved by integrating (over N echoes) the difference between two quadratic forms in the residuals. It should be noted that the processor operates on the correlated radar echo z(k) by providing two WGNs V_1 and V_0 over which detection is accomplished. In other words. the two nonlinear filters operate as whitening filters; whitening filter is a well known concept in the classic radar detection theory. Four mayor problems are related to this scheme. The first one is due to the difficulty of finding explicit equations for the two recursive nonlinear filters. The second problem refers to the inability of evaluating the corresponding detection performance of the conceived processor. The general way to proceed is to derive suboptimal nonlinear estimators and to assess detection performance by means of Monte Carlo simulation techniques. The third problem refers to the on-line evaluation of the nonlinear filter parameters (Sect. 5.1). The last problem concerns with the threshold setting which depends on the parameters of the processor and of the signal and clutter sources. A simple way to avoid these dependencies is to resort to a cell averaging CFAR threshold (Sect. 5.2) which evaluates in an automatic fashion the threshold value. In Section 4 the theory so far presented is applied to the case of clutter having Lognormal or Weibull probability density for the amplitude.

3. MODELS OF COHERENT ECHOES TRAIN FROM LOGNORMAL AND WEIBULL CLUTTER

The purpose of this Section is to illustrate the mathematical procedure of generating a sequence of complex valued samples having an assigned covariance matrix and a Lognormal or Weibull probability density of the amplitudes. Briefly speaking a coherent sequence of WGN samples feeds the cascade of a linear dynamic filter and a nonlinear memoryless device. The poles of the linear filter introduces a first shaping in the autocorrelation of the process. The nonlinearity modifies further on the autocorrelation shape and in addition, changes the shape of the probability density of the in-phase and quadrature components. The output sequence is non Gaussian distributed and time correlated at will. Two major problems are related with this model. The first concerns with the conception of the nonlinearity shape to achieve the desired probability density. The second problem refers to the derivation of a mathematical relationship between the covariance matrices of the input and output sequences of the nonlinearity. The first problem is generally solved in two steps. At first, a real valued variable (A, see Fig. 2) having the desired probability density (i.e. Lognormal, Weibull) is generated. Then, by multiplying the real valued variable by exp $(j\varphi)$, where φ is an evenly distributed random phase, the complex valued random variable is obtained. Figure 2 shows the nonlinearities for the Lognormal and Weibull cases, respectively. The derivation of a mathematical relationship between the covariance matrices of the input and the output of the nonlinearities of Figure 2 is hardly successful. Nevertheless, solutions have been obtained for the Lognormal and Weibull cases. Figs. 3-a and 3-b show the relationship between the one lag autocorrelation coefficient "q" (y-axis) of the Lognormal and Weibull variables and the autocorrelation "p"(x-axis) of the input Gaussian variables, respectively. The parameters of the curves are related to the skewness of the random variables. For the Lognormal case, the skewness increases with the parameter σ. For the Weibull case, the skewness increases as the parameter "a" goes to zero.

4. NEW DETECTION SCHEMES AND PERFORMANCE EVALUATION

In accordance with the theory developed in the previous Sections, new detection schemes are derived to deal with Lognormal and Weibull clutter. For convenience, the analysis has been limited to the cases of Rayleigh target amplitude. The main problem, common to the Lognormal and Weibull cases, is to find a suitable architecture for the nonlinear prediction filters of Figure 1. Indicating with f(.) the nonlinear memoryless device of Figure 2, the inverse function $f^{-1}(.)$ transforms the received echoes in Gaussian samples. For large clutter-to-noise ratio values, it is possible to show that a suboptimum nonlinear clutter prediction is the cascade of the nonlinearity $f^{-1}(.)$, a linear prediction filter and again a nonlinearity f(.). The Gaussian samples are processed by a linear filter which makes the prediction in the Gaussian frame. The predicted variable is transformed in the non Gaussian world by the nonlinearity f(.). This is exactly true in H0 hypothesis and for high clutter-to-noise ratio (CNR) values. The H1 hypothesis is equivalent to H0, if the target signal is subtracted by the incoming echoes. In the Lognormal clutter case the target signal has been assumed a-priori known. The detection performance have been evaluated in a number of operational situations of interest. Figure 4 is a sample of the performance. The clutter spectrum has been assumed Gaussian shaped with mean Doppler frequency $F_c = 0$ and one step autocorrelation function q taken as a parameter. The Doppler frequency of the target has been assumed $F_s = 0.5$ PRF, where PRF is the pulse-repetition-frequency. In the Weibull clutter case the target signal has been assumed a coherent correlated Gaussian process, the one-step correlation coefficient being ρ_s. Figure 5 compares the detection performance of the a-priori known target, with the Swerling 0, and partially fluctuating target cases.

5. ADAPTIVE FEATURES FOR ON-LINE PROCESSING

In this Section results concerning the adaptive implementation of the proposed processors are outlined. The problems of on-line estimation of the weights of nonlinear predictors and CFAR threshold have been considered. Three relevant results have been obtained, namely: (i) the evaluation of the number of independent range cells to estimate the weights, (ii) the evaluation of a CFAR threshold for different P_{FA} values and the number of range cells along which the log-likelihood ratio is averaged, and (iii) the evaluation of the corresponding loss for adaptation and CFAR processing.

The adaptivity can be confined to the on-line evaluation of the weights of the linear prediction filter. This is achieved through the estimation of the clutter covariance matrix as seen after the transformation induced by $f^{-1}(.)$. The clutter covariance matrix

M_c is on-line evaluated by averaging along m contiguous range cells around that under test. Detection loss due to the limited number "m" of range cells have been evaluated by means of Monte Carlo simulation technique. Fig. 6 shows preliminary detection loss for different values of correlation coefficient q for the Weibull clutter case.

One of the major limitation of the proposed processors refers to the great amount of parameters from which the detection threshold depend. In addition to the P_{FA} and the number of processed echoes N, the threshold depends on the clutter correlation coefficient, the clutter-to-noise and the signal-to-noise values. A method to overcome this problem is to implement a CFAR threshold. The value of the CFAR threshold is found in two steps: (i) the mean value of the log-likelihood ratio is estimated by averaging along a number of range cells surrounding that under test; (ii) this mean value is multiplied with a suitable constant "γ" dependent on the desired P_{FA} value. Fig. 7 shows the parameter γ versus the P_{FA} value. By means of Monte Carlo simulation, it has been shown that the parameter γ does not change even if the receiver parameters are varied. Exception is made for the SNR value (the detector is matched to that a-priori known target amplitude). This is fairly true if the number of range cells along which the likelihood ratio is averaged is around ten. It is noted that a loss of less than 1 dB is experienced with ten range cells.

6. REFERENCES

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/2/ A. FARINA, A. RUSSO and F.A. STUDER, "Coherent Radar Detection in Lognormal Clutter", IEE Proc., Pt. F, CRSP, Vol. 133, No. 1, February 1986, pp. 39- 54.

/3/ A. FARINA and A. RUSSO, "Radar Detection of Correlated Targets in Clutter", to be published IEEE Trans. on AES, 1986.

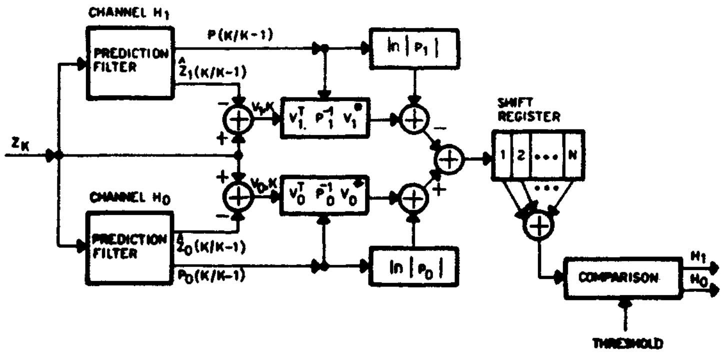

FIG. 1 - OPTIMUM RADAR DETECTOR FOR TARGET AND/OR CLUTTER HAVING ANY TYPE OF PROBABILITY DENSITY AND TIME AUTOCORRELATION FUNCTIONS (THE PREDICTION FILTERS ARE OF THE KALMAN TYPE WHEN THE PROBABILITY DENSITIES ARE GAUSSIAN, OTHERWISE ARE NONLINEAR)

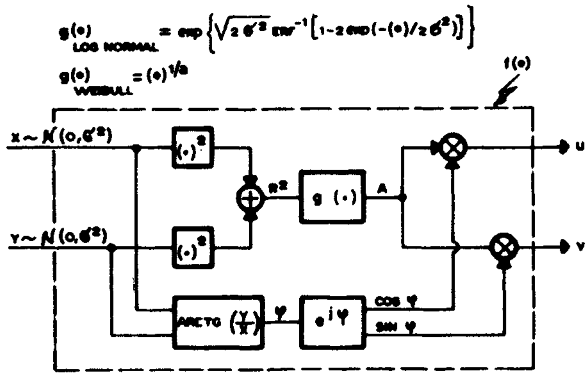

FIG. 2 - NONLINEAR MEMORYLESS DEVICE TO GENERATE A COHERENT LOGNORMAL AND WEIBULL CLUTTER

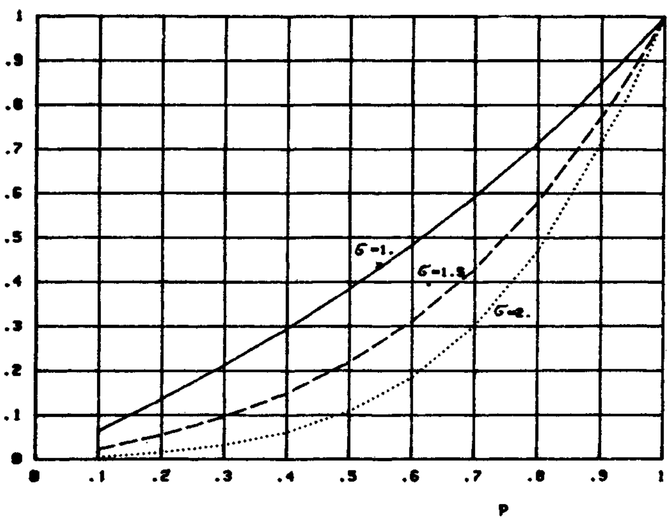

FIG. 3a - RELATIONSHIP BETWEEN THE CORRELATION COEFFICIENT q OF THE LOGNORMAL SEQUENCE AND THE CORRELATION COEFFICIENT p OF THE GAUSSIAN SEQUENCE.

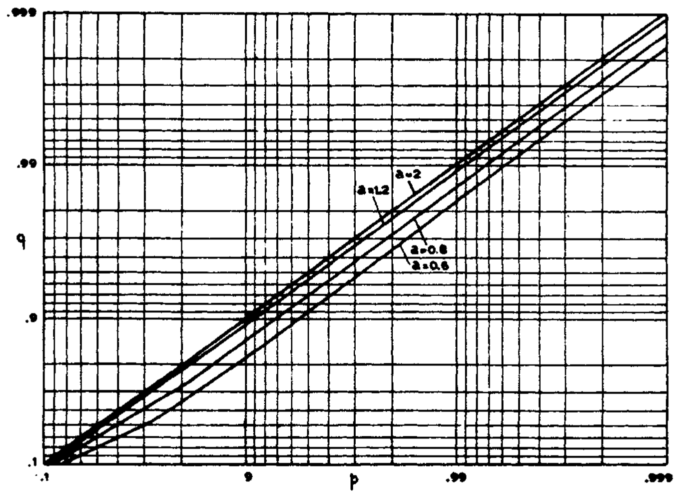

FIG. 3b - RELATIONSHIP BETWEEN THE CORRELATION COEFFICIENT q OF THE WEIBULL SEQUENCE AND THE CORRELATION COEFFICIENT "P" OF THE GAUSSIAN SEQUENCE.

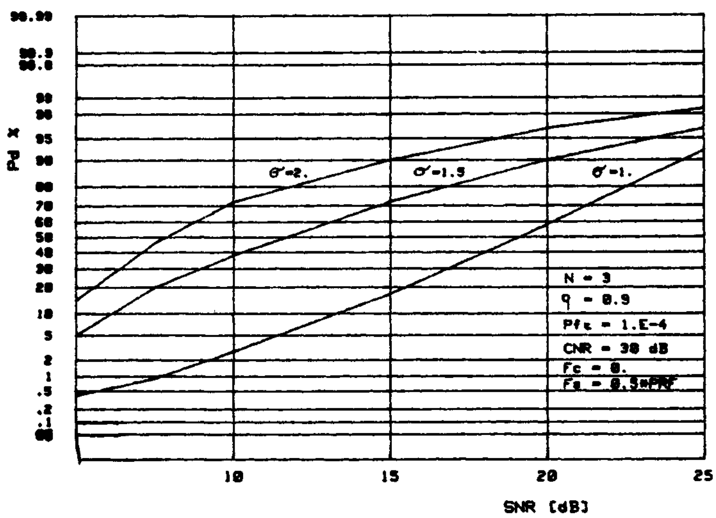

FIG. 4 - DETECTION PERFORMANCE FOR A-PRIORI KNOWN TARGET IN COHERENT LOG-NORMAL CLUTTER.

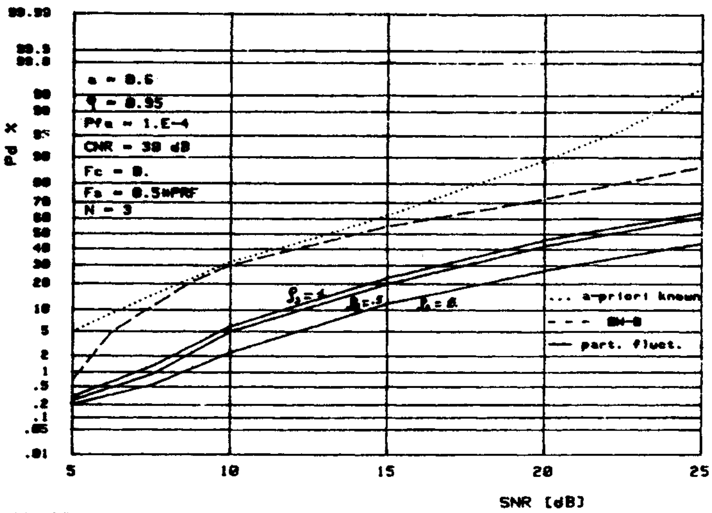

FIG. 5 - DETECTION PERFORMANCE FOR FLUCTUATING TARGET IN WEIBULL CLUTTER.

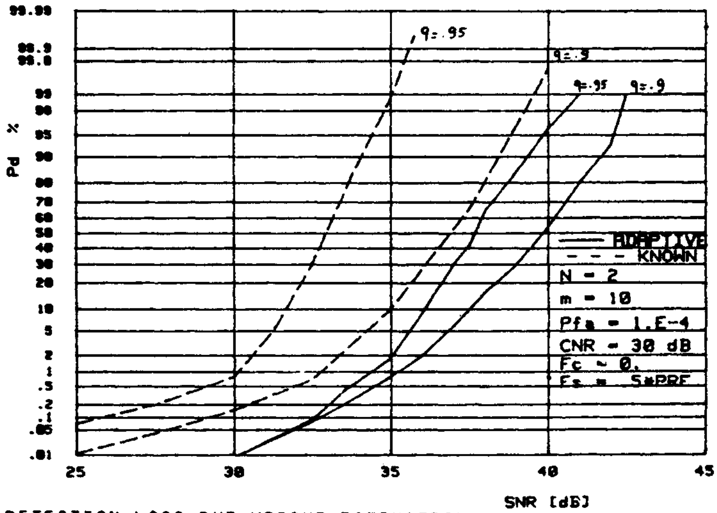

FIG. 6 - DETECTION LOSS DUE WEIGHT ESTIMATION

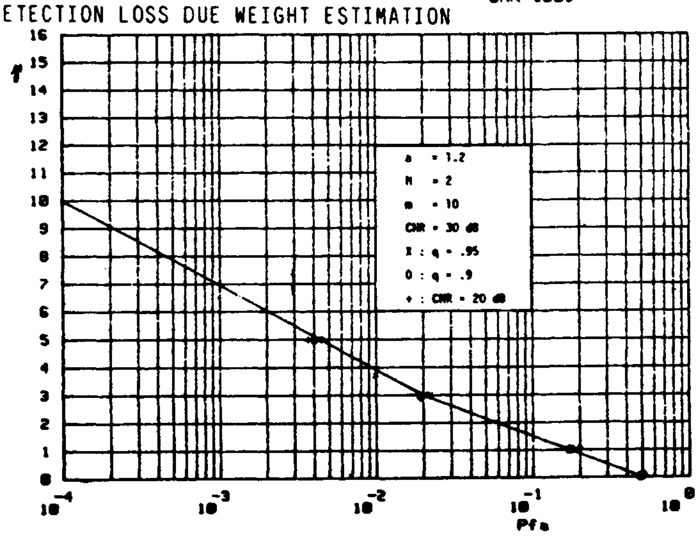

FIG. 7 - PARAMETER γ OF CFAR THRESHOLD