PERFORMANCE ASSESSMENT OF BROADBAND IMPULSIVE NOISE JAMMERS

J. Heine, K. Theriault, D. Boseck
BBN Systems and Technologies
70 Fawcett Street
Cambridge, MA 02138

Abstract A noise jammer raises the noise level observed by a threat sonar to degrade the sonar's detection performance. In this paper we assess the potential for a specific noise jammer waveform used to countermeasure low frequency active sonars. This waveform is a long duration train of broadband acoustic impulses, each of which has significant low frequency energy. We describe the performance of the impulsive countermeasure on a typical active system processor implementation by comparing experimentally determined receiver operator characteristic curves for the sonar processor with and without jammer energy present. Performance was also determined as a function of pulse intervals. The pulse sequence time series input was synthesized from measurements of high intensity impulses transmitted from a range of approximately 35 Nm in a nominal half-channel environment. Required density functions were obtained from a Monte Carlo simulation involving 10^5 iterations of signal, jammer pulses and noise input. The time average power required for the pulse waveform to achieve a specified detection system degradation was found to be 9 dB more than that of a continuous gaussian noise waveform.

1. INTRODUCTION

There is a significant probability that a future adversary will develop a low frequency active sonar capability aimed at locating US submarines. The availability to US Navy forces of a suite of active acoustic countermeasures which either confuse or overload threat low frequency active systems could have significant impact in protecting fleet assets. To be effective however, such acoustic countermeasures must provide protection in a wide range of environments, against both monostatic and multistatic systems, and in both surveillance and tactical scenarios.

For purposes of this discussion, the specific scenario of concern, shown in Figure 1, can be a submarine discovering that it is under observation by a proximate threat system (in the case shown a multistatic system) and that the rate of signal transmissions and the tactical situation indicates that an initiation of a tracking solution will cause a weapon launch. Under these circumstances the submarine would consider confirming its presence by launching a countermeasure if such action would provide a higher probability of escaping.

Active acoustic countermeasure alternatives are directly analogous to the canonical electronic warfare radar countermeasures: e.g. noise jammers, active decoys/deception jammers, and passive decoys (chaff). Functionally, these countermeasures degrade active system performance in different ways.

Noise Jammer: increases the perceived ambient noise level of a threat low frequency active sonar sufficiently to significantly reduce its detection range. Jamming is achieved by one or more devices, each of which must radiate sufficient power to impact any threat mono- or multistatic receiver with a state of the art receive sensor system. Tactical use usually involves deployment of the device by the target platform after determination that it is "in extremus." Other options, such as predeployment in a defined operating area, are plausible.

Active Decoy or Deception Jammer: masks a real target by returning suitably modified, false replicas of the threat low frequency active system signal. Masking attempts to insure that the active system does not achieve or maintain a tracking solution. The decoy confuses the information processing system of the threat system by either presenting a more observable target than the real target or by simply presenting a number of alternatives to the real target. Which of the two approaches to confusion is more effective depends on the source level achievable by the decoy and on the number and distribution of decoys deployed. Since low frequency active systems imply relatively large source transducers, achieving a significant source level can be expected to impact size of the countermeasure and hence the number of such devices carried by a submarine. Further, since decoys are expendable, device cost may also be a factor. It is clear that the effectiveness of a strategy to jam the threat sonar information processing system using relatively low power devices will depend on the number of devices deployed and their ability for coordinated action to create false tracks with realistic bearing rates. The implication is that a significant number of devices either must be predeployed or they must be deployed and distributed over a relatively wide area by the target.

Passive Decoys: are the acoustic equivalent of rapid blooming chaff employed by surface ships as a missile defense. That is, passive decoys provide target like returns with appropriate target strengths from many points. Such devices would be seeded over large areas to attempt to confuse the information processing system of the threat sonar. Like the active decoy, such devices must be either predeployed or submarine deployable including some method of distribution.

Low frequency active system issues which dictate the form and the performance of an active acoustic countermeasure are shown in Figure 2. Design factors which must generally be considered in developing both the form and the tactical employment of an active acoustic countermeasure against low frequency active threat sonars are shown in Figure 3. There has been little systematic exploration of the paths identified in these figures. It is possible to say however, that a countermeasure must be able to operate autonomously, it must be expendable to insure minimum constraint on operational assets, it must be deployable from both the submarine and from other cooperating assets and it must provide effective performance over a range of operating conditions (environments, threat systems, scenarios) to maximize its applicability.

In the work described in this paper we focused on the first of these countermeasures. Specifically, we considered the potential effectiveness of alternative jammer configurations and wave forms. One of the wave forms considered was a sequence of impulses such as is shown Figure 4. The spacing of the impulse train is such that at least two impulses overlap the signal wave form. The measure of performance we used for evaluating the wave form was the degradation in achievable detection range by a threat sonar when jammed by the pulse train as compared to that achievable when a more conventional wave form, such as band limited white gaussian noise is used.

To make this comparison, we assessed the increase in signal-to-noise ratio required (or equivalently the decrease in transmission loss required) to achieve the same detection performance with and without the influence of the jammer for both the pulse train and gaussian noise. Referring to the scenario for jammer employment shown in Figure 4, a target-scattered threat low frequency active signal is received by a bistatic receiver along with a jammer wave form. If the jammer wave form is gaussian noise and the threat sonar employs conventional matched filter processing, required detection and false alarm performance determine the system detection index:

$$d = 2Es/No, \qquad (1)$$

where Es is the signal energy required to meet the detection performance requirements and No is the system noise spectrum level. With the jammer present, (1) becomes

$$d = 2Es,j/(No + Nj), \qquad (2)$$

where Nj is the component of system noise power spectrum due to the jammer and Es,j is signal energy required to meet detection performance requirements with jammer interference present. The change in S/N required for a constant source/target/receiver geometry when the jammer is present is therefore:

$$(Es,j/No)/(Es/No) = \Delta S/N, \qquad (3)$$

The relationship between the change in S/N and the jammer noise to ambient noise ratio is therefore:

$$\Delta S/N = (1 + Nj/No) \qquad (4)$$

If the jammer wave form is a pulse train instead gaussian noise, the effect of the interference is to provide a continuous "ringing" of the matched filter. Since the output noise of the filter under the influence of the jammer impulses is not gaussian, the degradation in systems performance would be not given by (4). In fact, we would not expect the variance of the filter output noise process to be a large as that for a gaussian process, so we might expect more impulsive energy would be required. If so, this would manifest itself as a reduced effectiveness for the pulse train wave form relative to that for gaussian noise with the same time averaged power. To assess the magnitude of any loss in effectiveness, we analyzed the achievable performance degradation due to impulsive jamming for a typical set of system characteristics. This analysis is described in the next section. The results obtained are then compared to those for a gaussian jammer in the final section.

2. SIMULATION METHODOLOGY

The objective of the simulation was to estimate the effect of impulsive interference on the detection performance of a typical matched-filter sonar receiver based on the actual jammer impulse signals measured at sea. A simulation was employed so that we could examine the effects of various pulse repetition rates, jammer-to-noise ratios, and signal-to-noise ratios on detection performance for a range of operating points. The simulation employed the actual jammer impulses, together with simulated target echoes and white gaussian background noise. Monte Carlo methods were used to form the performance estimate: the jammer pulses were randomly ordered and spaced, a simple non-fading, random-phase model was used for the target echo, and independent gaussian noise samples represented the ambient background noise.

The simulated receiver, illustrated in Figure 5, consists of matched filtering, magnitude-square, over averaging, and threshold detection. The noise characteristics (both jammer and ambient) were assumed to be perfectly known to the receiver, so that normalization was not required. The transmitted signal was assumed to be an 8-second long, 37 Hz bandwidth hyperbolic FM (linear period FM). The sample rate of the input beam time series were 256 Hz complex (determined by the sample rate of the measured impulse signals); a 16-sample overaverager was used to reduce the sample rate at the input to the threshold test to 16 Hz (real).

The received echo was modeled as a scaled, slightly spread version of the transmitted echo; the spread duration of the echo is 1/16th sec (16 samples at 256 Hz), and hence is matched to the overaverager duration. The echo was assumed to comprise 4 sub-pulses, each 4 samples long; the sub-pulses have identical (fixed) amplitudes, but have independent phases. That is,

$$\tilde{s}(t) = \sum_{n=1}^{4} \sqrt{E} e^{j\phi_n} \tilde{f}(t - t_n) , \qquad (5)$$

where

$\tilde{s}(t) =$ (complex) received echo signal

$\tilde{f}(t) =$ transmitted waveform

$t_n =$ relative delay of nth pulse

$E =$ received energy

$\phi_n =$ random phase, uniformly distributed on $[0, 2\pi]$

We set

$$\int_{-\infty}^{\infty} |\tilde{f}(t)|^2 dt = 1 , \qquad (6)$$

so that the (mean) energy in the received wave form is E. This model corresponds to the case of independent, phase-random pulses considered by Robertson [1].

Ambient noise was represented by white, bandpass gaussian noise with power spectral density No.

The impulsive jammer signals comprise a pulse train with randomized inter-pulse spacing: if the mean interpulse spacing is T sec, then the actual spacing between any two impulses is T + τ_n, where τ_n is uniformly distributed on ±T/4. This randomization prevents pathologies which would result from use of a perfectly periodic pulse train, and represents a strategy which an actual jammer would likely use in practice (to avoid a coherent subtraction CCM). The jammer strength is characterized by the total jammer energy (per pulse) at the matched filter output (in the band of the receiver, B.

The Monte Carlo tests measured the cumulative distribution of the receiver output statistic on both the signal present and signal absent hypotheses; the signal-absent distribution was used to set the threshold to obtain the desired probability of false alarm, and hence determine the probability of detection for various signal to noise and jammer to noise ratio conditions. We decided to operate at a false alarm probability of 10-3; accurate determination of the threshold for this crossing rate requires about 10000 independent trials. Generation of random values for the noise background and for the random echo phase was straightforward, but the jammer signals in the simulation were to be based on actual measured data, and we had available only about 30 measured pulses. We bypassed this difficulty by recognizing that we required independent output values, not different random time series; the required 10000 data points could therefore be generated by randomizing the order of the measured pulses, and by randomly jittering the pulse spacing.

Only 1000 trials were required to generate accurate cumulative distribution functions for the signal present case.

An example of the results of the Monte Carlo tests are shown in Figure 6. This figure shows both the cumulative distribution of the receiver output for the jammer plus ambient noise case, for a jammer-to-noise ratio (JNR) of 28dB and an interpulse spacing of 4 seconds, and the cumulative distribution for the same JNR and mean pulse spacing, and for a SNR of 10 dB. If the threshold is set so that Pfa is 10-3, we see that the resulting Pd for this case is 0.43. This procedure is used to develop ROC curves (Pd versus SNR) for various combinations of JNR and mean pulse spacing. An example of a family of curves developed for an interpulse spacing of 4 seconds is shown in Figure 7.

3. DISCUSSION

The performance of an impulsive jammer, can be compactly represented by plotting the SNR required to achieve a system probability of detection of 0.5 (for a constant PFA = .001) as a function of the average total jammer-to-noise ratio (TJNR) achieved during one integration period. The TJNR is:

$$TJNR = JNR + 10*\log(m), \quad (7)$$

where m is the average number of impulses occurring during an integration period, and where JNR is the jammer to noise ratio for a single impulse. These data are plotted in Figure 8.

To better understand the implications of these data, let us consider the SNR requirements for a gaussian jammer. First we rewrite (2) in the form of the energy Ej incident on the receiver during the integration time T and in the system band B:

$$d = 2Es,j/(No + Ej/BT). \quad (8)$$

Rearranging we obtain:

$$Es,j/No = d/2*(1 + Ej/NoBT). \quad (9)$$

Equation (9) is also plotted in Fig. 8 for the parameters used in the previous section and a value of d of 19.5 as determined by Robertson [1]. Note that this curve is asymptotic to a required SNR of 9.9 dB or 10*log(9.75) for small values of Ej/No or TJNR and is directly proportional to TJNR for large values of Ej/No.

A comparison of all data derived from the simulation to this curve for the gaussian jammer show very similar behavior, except that there is a 9 dB offset. That is, the TJNR required to achieve a specified change in SNR or, equivalently a reduction in transmission loss or detection range, is 9 dB more than would be required for an equivalent gaussian noise jammer. While there appears to be some sensitivity to the number of pulses per integration period, the sensitivity is small.

These results were derived for a specific processor and signal wave form and processor implementation. The details of the numerical values therefore should not be generally applied without additional analysis. However, it is clear that while the acoustic interference produced by an impulsive pulse train can significantly impact performance of a threat low frequency active system, the time average power required for a specified threat low frequency active system performance degradation is likely to be significantly more than that for a continuous wave form. The achievability of sufficiently intense pulse and the potential advantages of an impulsive noise jammer in terms of size and cost and endurance will therefore depend on the technology used to generate the pulses.

Reference

[1] Robertson, G. H., Operating characteristics for a linear detector of CW signals in narrow-band gaussian noise, Bell Syst. Tech. J. 46, No. 4, 755-774 (1967)

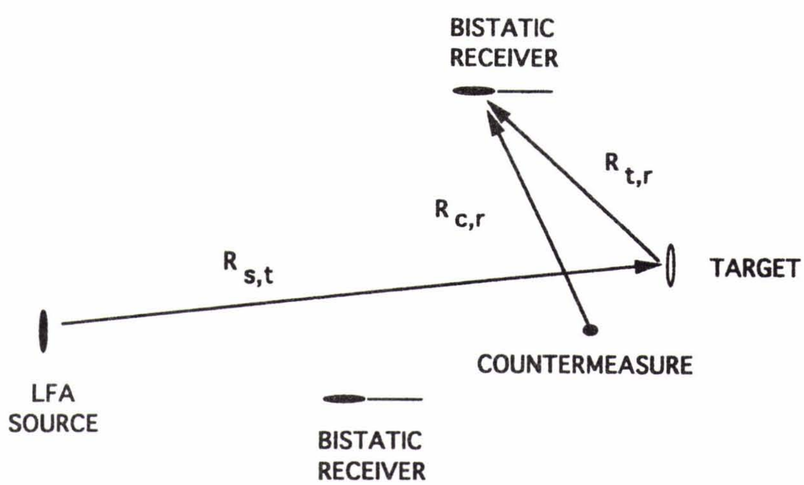

Figure 1. A typical engagement scenario including a jammer countermeasure

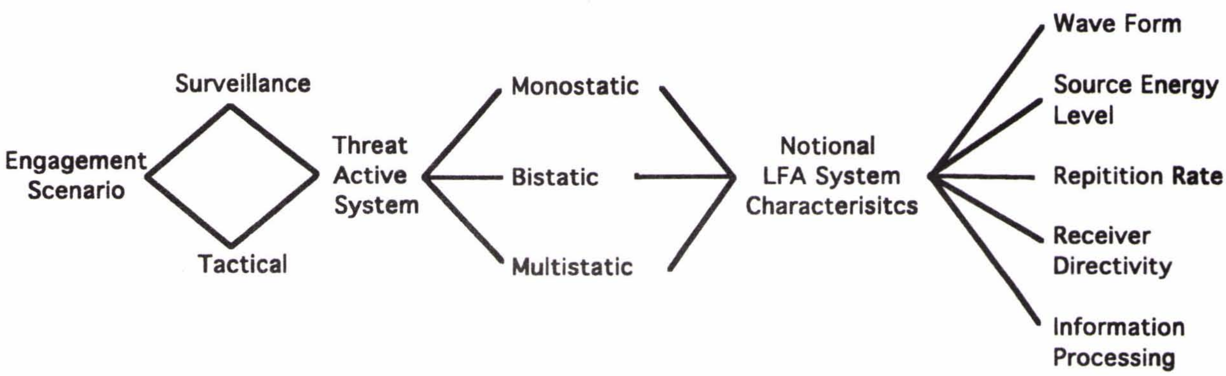

Figure 2. Employment of Low frequency acoustic countermeasures implies a clear understanding of scenario and threat sonar issues.

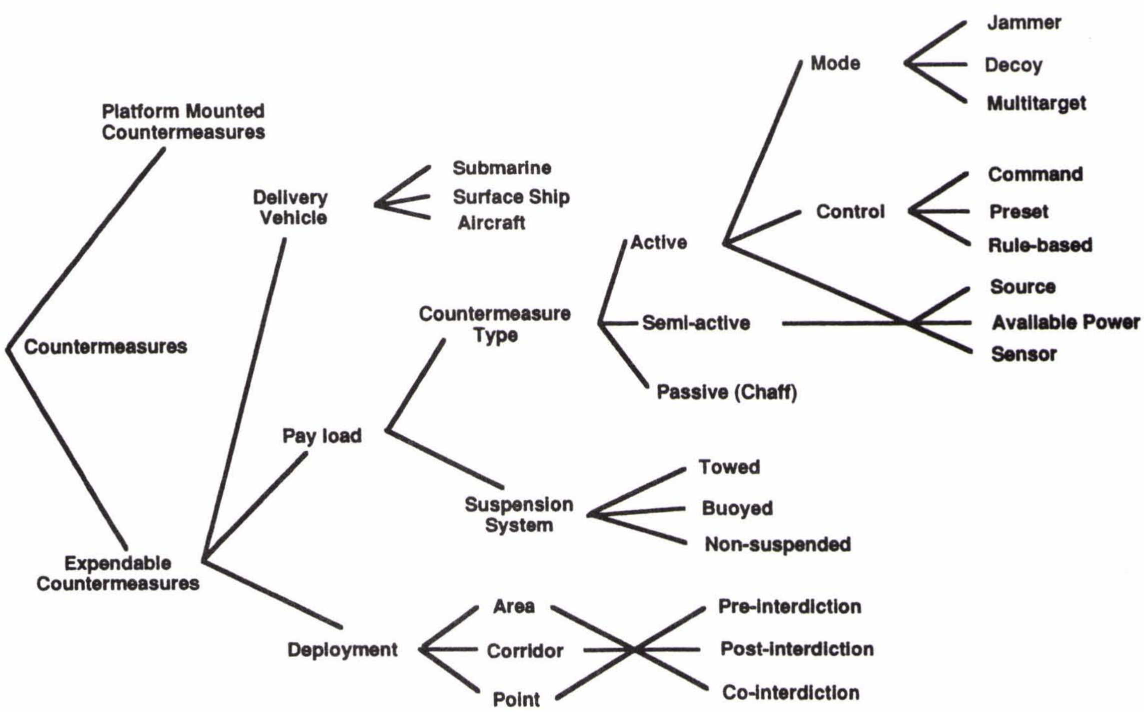

Figure 3. Low frequency active countermeasure design is impacted by system factors and employment scenarios.

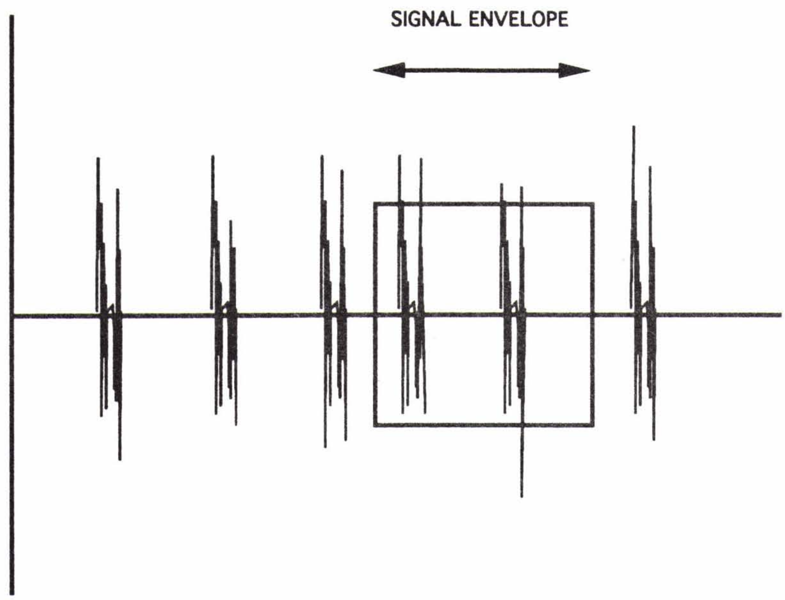

Figure 4. The impulsive jammer wave form is a pulse train wih at least two pulses overlapping each signal wave form.

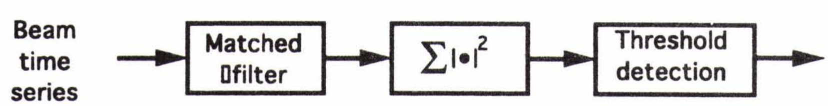

Figure 5. The pulse wave train performance simulation was implemented for a standard active sonar receiver

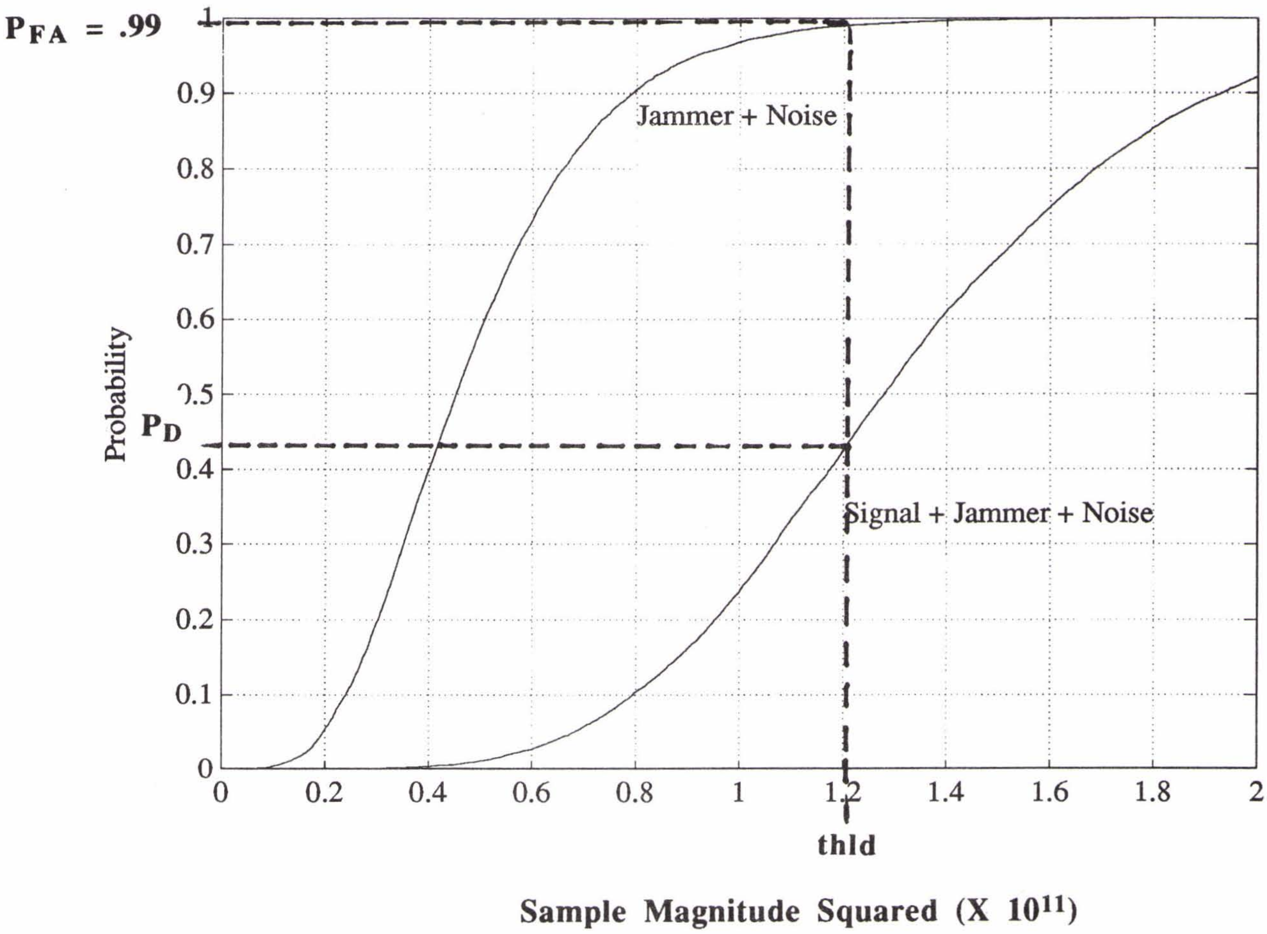

Figure 6: **Cumulative Distribution Functions of an 8 second by 37 Hz Signal for JNR = 28 dB and SNR = 10 dB for an interpulse spacing of 4 seconds.**

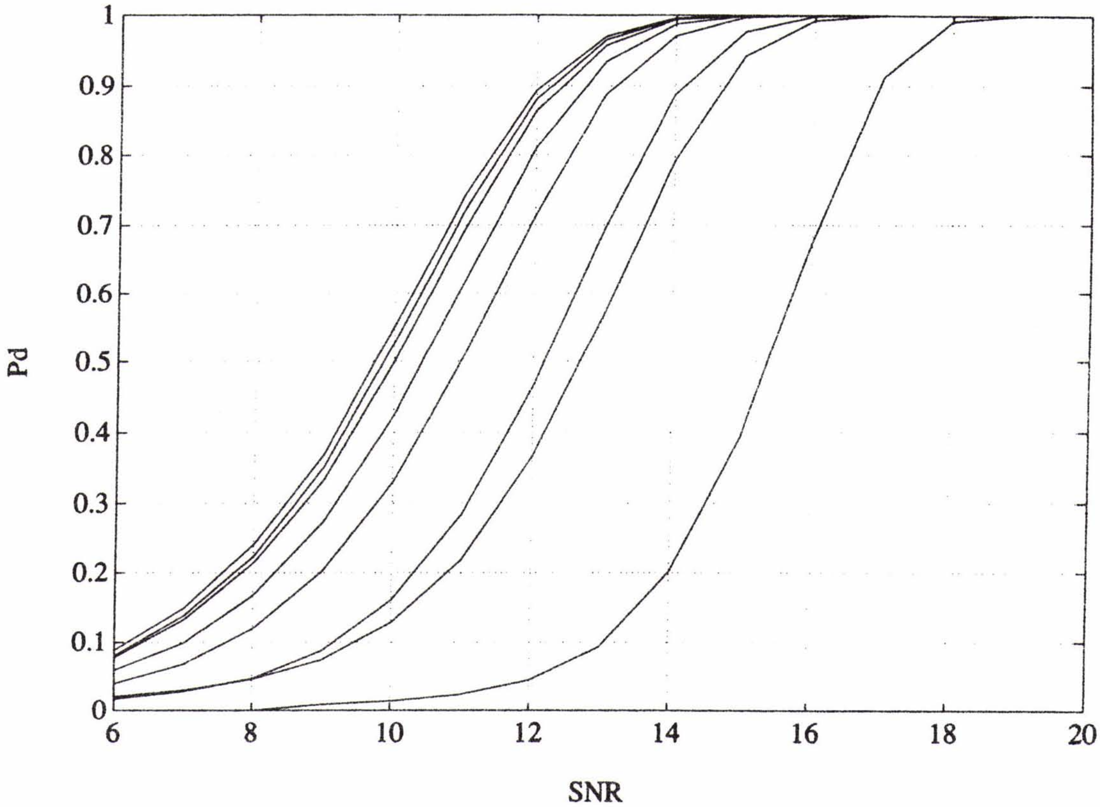

Figure 7: Probability of detection of an 8 second by 37 Hz HFM Signal as a function of SNR and JNR for an interpulse spacing of 4 seconds.

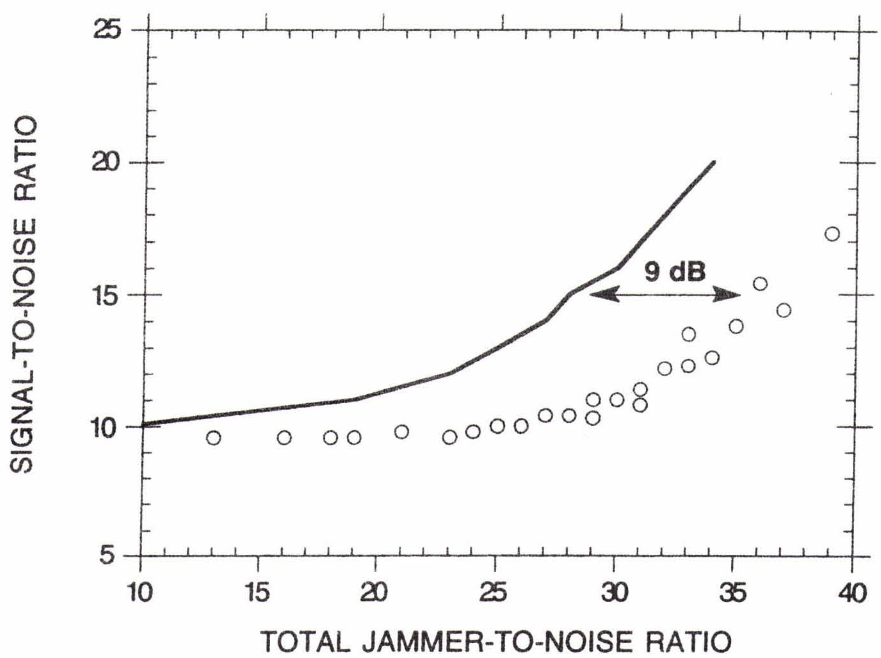

Figure 8: For a given ambient noise background, the signal energy required for a typical active sonar processor to achieve a Pd = 0.5 (Pfa = 10^{-3}) is 9 dB higher for a gaussian jammer than for an impulsive jammer with the same time average power.