Monostatic Coherent Radar Sea Clutter Doppler Analysis

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Abstract: Sea clutter is the backscatter returned to a radar system from the sea surface. Maritime radar signal processing compensates for this clutter to achieve effective detection of targets on or near the sea surface. The aim of this work is to develop the modelling and understanding of the variation of sea clutter distribution with Doppler, using monostatic coherent X-band radar data. To evaluate the statistics of the sea clutter the distributions of the probability of false alarm (P_{FA}) from the sea clutter as a function of the detection threshold level have been investigated. The compound k-distribution has been fitted to the P_{FA} of the sea clutter across the Doppler spectrum. The variation of the P_{FA} with Doppler bin has been used to define the relationship between backscattered sea clutter and Doppler. Thus allowing sea clutter to be accounted for effectively, enhancing constant false alarm rate (CFAR) processing.

1. Introduction

Maritime radar operates in a constantly changing environment with the requirement of locating targets on or near an undulating surface. To operate within this complex clutter background a radar system has to be able to evaluate and compensate for it while detecting targets. In order to be able to accurately predict and enhance the performance of radar in a real environment, it is essential to understand the behaviour of this clutter.

Sea clutter has been studied for many years due to its significance for maritime radar systems. The development of understanding of sea clutter returns is critical to the continued enhancement of performance predictions and to the improvements in advanced signal processing algorithms. These developments allow the required CFAR threshold levels to be correctly set, suppressing the clutter and reducing the false alarm rate. If the thresholds are too high, sensitivity is compromised. If they are too low, the radar suffers from excessive false alarms, overloading the system.

Modern radar systems can use coherent processing to reject the bulk of the sea clutter when searching for aircraft or for fast-moving ships, this raises the new problem of understanding the behaviour of the sea clutter in the Doppler domain. Within coherent monostatic data the research into the variation of Doppler with sea clutter distribution has not been fully exploited. This study aims to increase understanding of the relationships between sea clutter distributions and Doppler.

The data used is coherent airborne radar data covering grazing angles from 7° to <1°. The radar operates at X-band (c.a. 9 GHz frequency). In order to have a high enough pulse repetition frequency (PRF) to be able to sample the Doppler, the range measurements are potentially ambiguous. Both the PRF and radio frequency used by the radar system are agile which generates issues when integrating multiple bursts to generate a single sea clutter distribution.

2. Theory

Analysis using electromagnetic scattering theory [1] and empirical analysis [2] of radar data has shown sea clutter as seen by a non-coherent radar to have a compound distribution. This distribution is generated by both Bragg and non-Bragg scattering. Bragg scattering has been noted as returns from the capillary waves, and key non-Bragg scatters noted as the whitecaps on the waves [3, 4]. By representing backscattered sea clutter as a compound distribution modern sea clutter models are able to take into account these multiple scatters and hence generate distributions closer to observed data.

Scattering models can be compared with the P_{FA} curves generated by the sea clutter. Evaluation of these curves makes it possible to define what P_{FA} the radar system will experience for a given threshold level. This defines the radars sensitivity to the sea clutter and is used for CFAR processing.

2.1. Compound K-distribution sea clutter model

The compound K-distribution model is a well established model that was developed by K. Ward [5, 6] and has been found to effectively model sea clutter for higher resolution radar [1]. The compound model takes into account both the long modulation of the gravity waves and the additional non-Bragg scattered speckle component. Using this model it is possible to predict the P_{FA} curves for sea clutter that are vital when developing CFAR algorithms.

Knowledge of the variation of P_{FA} distributions will allow CFAR processing techniques to define the correct threshold levels to produce the required performance level for a radar system. Hence allowing the radar system to effectively detect targets using Doppler filtering taking account of the sea clutter in the Doppler bin the target is located in.

Compound K distribution sea clutter P_{FA} for a square law detector without including noise is

$$\text{Probability } (E > E_T) = \frac{2}{\Gamma(v)} (va)^{v/2} K_v (2(va)^{1/2}), \qquad \textbf{[1]}$$

derived from [1]. Where v is the shape parameter of the distribution, a is the threshold level and K_v is the modified Bessel function of the second kind.

The K-distribution shape parameter is linked to how "spiky" the sea clutter is; it can, in practice, take values between $0.1 \le v \le \infty$. When $v \le 1$ the sea clutter is defined as being very "spiky", and when the shape parameter tends to ∞ the sea clutter become a Rayleigh distribution. The term "spiky" refers to data that has a large number of isolated high level returns from individual range gates. This effect is generally accepted to be caused by Bragg scattering from resonant capillary waves and whitecap scattering.

2.2. Clutter distributions at low P_{FA}

The tail of the P_{FA} distribution is important to radar systems, as to operate effectively they require these low P_{FA} levels. For example, if the radar has a million range/bearing 'cells' a false alarm probability of 10^{-6} corresponds to one false alarm per scan. This is equivalent to probabilities of the order of 10^{-4} to 10^{-3} per range/Doppler cell per burst of pulses, once account is taken of the post-detection processing in the radar.

If the P_{FA} is too high the radar system will be overloaded with false targets and this will hinder processing such as tracking. Hence to achieve low P_{FA} levels, using optimum CFAR threshold values, the tail of the distributions of sea clutter statistics need to be fully understood.

The majority of research into the nature of sea clutter has been with non-coherent data. Limited prior work exists on the analysis of the P_{FA} tail distributions across the Doppler spectrum. By emphasising the fitting at the tail of the P_{FA} distributions the aim is to ensure that the clutter is evaluated in the area that applicable to an operating radar system.

3. Results

3.1. Sea clutter distribution variation with Doppler bin

The Compound K-distribution has been fitted to the P_{FA} curve generated using the distribution of coherent data from each Doppler bin along all the range gates. The variation with Doppler can be characterised by the fitted shape parameter from each Doppler bin. The sea clutter distributions in the outer most, central, and edge of main clutter Doppler locations are of particular interest. A range Doppler plot from single burst is shown in Fig 1.

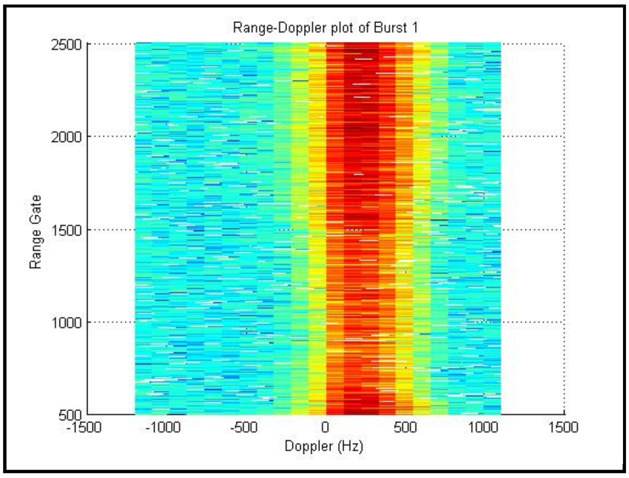

Fig 1 Log Range Doppler plot from a single burst of data

3.2. Range gate limitations

By limiting the range gates selected for signal processing it is possible to use data dominated by sea clutter statistics. This removes the influence of non-sea clutter returns within the processed data, hence giving a better understanding of the sea clutter present.

In Figure 2 the range gates used to produce the P_{FA} plots were limited to 500-2500. This was found to remove the influence of non-sea clutter effects that altered the distributions significantly although only contributed to 1/6 of the data set. A disadvantage of limiting the range gates used for analysing the data is that the amount of data being used to produce the statistics is being reduced. To optimise this process the reduction in data used must be kept to a minimum.

It is important to note that understanding sea clutter dominated sections of the data is vital, but the distributions that are found here can not be used uniformly across all of the data when setting thresholds. As described different sections of the data have different dominating effects and this must be taken into account when designing a CFAR algorithm.

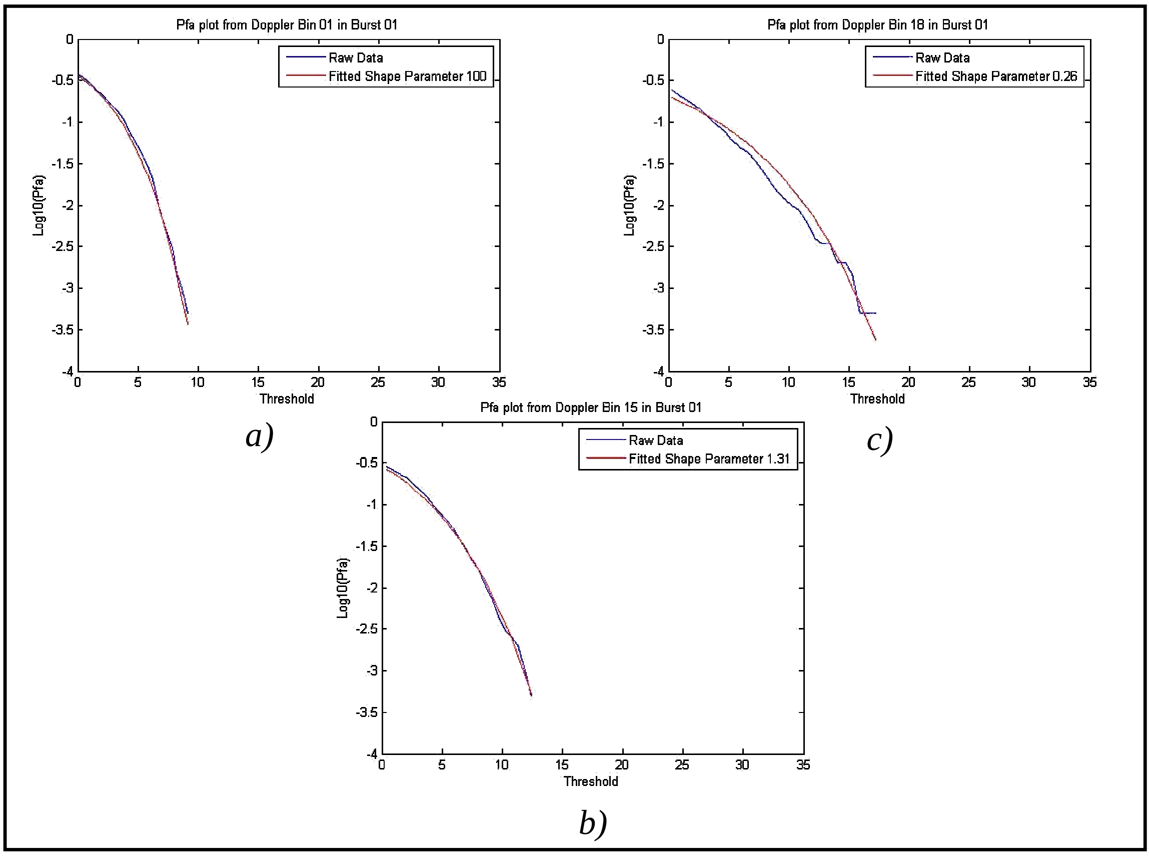

Figure 2 P_{FA} distributions fitted to K-distribution from a) Outer Doppler bin 1 b) Central Doppler Bin 15 c) Edge of Clutter Doppler bin 18

3.3. Amalgamating multiple bursts Doppler distributions

By increasing the amount of data used to produce a P_{FA} distribution the tail of the distribution will be defined at lower P_{FA} levels, which is of particular interest for practical radar operation. A larger data set can be generated by taking data from the same Doppler bin in multiple bursts. To compensate for the PRF agility between bursts the data needs to be re-sampled before combining data from multiple adjacent bursts. As well as allowing the P_{FA} distributions to be defined at lower P_{FA} levels, a direct comparison can now be made between Doppler bins from different bursts.

To re-sample each burst the Doppler range of all the data was limited to that covered by the lowest PRF burst, each burst was then re-sampled at the positions the highest PRF is sampled in the limited Doppler range. The disadvantage of this processing is that the Doppler range is limited by the lowest PRF, and the resolution is limited to the length of the shortest burst, i.e. that with the highest PRF. Down sampling is used instead of up sampling as the generation of artefacts can be reduced in down sampling in comparison to possible generation of artefacts when generating new sampling locations in Doppler.

When combining data the assumption is made that the sea clutter statistics are consistent from bursts to burst. This is a legitimate assumption for a limited number of bursts, but for a larger number of bursts which cover an area of sea that has different sea clutter statistics the assumption is no longer valid.

4. Conclusions

The analysis carried out has provided quantitative confirmation of the previous qualitative observations that the distribution of the sea clutter at Doppler shifts at the edge of the distribution is more 'spiky' clutter than at the centre. The width of the spectrum can be deduced from the observation that the distributions confirm the outermost bins contain only noise, i.e. show a Rayleigh distribution. Spiky clutter requires high thresholds to be set relative to the mean clutter power level. This has a significant impact on the sensitivity that is achievable for targets with Doppler shifts comparable with those of the clutter.

This work uses the distribution of power from a single Doppler bin across all range gates. An issue with this is that it has been shown that sea clutter distributions vary with look angle [1] as well as the reflectivity altering with grazing angle, as modelled in the GIT model [2]. Future work will include analysis of sea clutter from a smaller section of range gates consequently reducing the influence of sea clutter variation with grazing angle. To counteract this reduction data will be taken from the same Doppler bin in additional bursts, to enable effective plots of P_{FA}.

Future work will also look into the variation of Doppler sea clutter distributions with polarisation. The mean levels and the statistical distribution of the sea clutter characteristics are expected to be a function of the polarization, as defined in related work [1].

Acknowledgments

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