Abstract: Sea clutter refers to the radar returns from a patch of ocean surface. When a radar detects targets on or above the sea surface, it has to overcome the interference from sea echo itself. Sea clutter presents obviously non-Gaussian, non-stationary for many diverse factors, such as radar polarization mode, working frequency, antenna visual angle, sea state and wind direction, which limit the detection capability of radar. In this paper, we elaborate the production mechanism of sea clutter in detail and propose a new $\alpha$-$\beta$-$\gamma$ filter to suppress sea clutter and detect targets. In addition, the performance analysis and parameter choosing standard are given and the algorithm is proved to be effective with real data.

Key words: $\alpha$-$\beta$-$\gamma$ filter, large-scale structure, sea clutter suppression, target detection

I. Introductions

Sea clutter or sea echo refers to the backscattered returns from a patch of the sea surface illuminated by a transmitted radar signal. Robust detection of low observable targets within sea clutter has not only theoretical but also practical importance to our coastal and national security, since objects within sea clutter may include submarine periscopes, low-flying aircrafts, missiles, small marine vessels and small pieces of ice, etc. Furthermore, sea clutter may vary with radar polarization mode, working frequency, antenna visual angle, sea state and wind direction, so it limits the detection capability of radar severely.

Traditionally, sea clutter has been modeled as a stochastic process, with the observable received signal from a radar resolution cell representing a sample function of that process. For high grazing angles and low-resolution radars, there exist a lot of scattered cells in the range resolution cell to satisfy the central limit theorem, so sea clutter amplitude distribution is often assumed to be Rayleigh distribution. However, for low grazing angles and high-resolution radars, the scattered cells in a resolution cell is much fewer, which causes the empirical distribution calculated from experimental data exhibits significant deviations and trailing from Rayleigh statistics. At such condition, sea clutter has often been observed as highly non-Gaussian and even spiky. That is why Weibull, log-normal and K-distribution have received the most attention to describe sea clutter amplitude during these last years. But all of the distributions mentioned above do not help one gain much analytical or physical understanding. Thus, to gain deeper understanding of the characteristic of sea clutter, the concept of fractal has been employed for the description and modeling of the roughness of sea surface [1-3]. Possible chaotic behavior of sea clutter has also been studied [4, 5].

Since the ultimate goal of sea clutter study is to improve the detection of targets embedded within sea clutter, a lot of effort has been made to design innovative filters for target detection, which include extinction-pulse techniques, time-frequency analysis techniques, wavelet based approaches, neural network based approaches, as well as utilizing the concept of fractal dimension and boxing-counting based multifractal analysis [6]. So as to improve detection accuracy, some researchers also resort to more powerful millimeter wave radars with higher resolution.

In this paper, in view of various sea and weather conditions, we do not strive to design a model to describe sea clutter adaptable for every situation, but propose a new $\alpha$-$\beta$-$\gamma$ filter, based on the Kalman filter, to separate sea clutter and targets from frequency domain. In section II, we briefly introduce the production mechanism and characteristic of sea surface and targets, as well as analyze the difference between them. In section III, we elaborate the theory and method of $\alpha$-$\beta$-$\gamma$ filter to suppress sea clutter. The performance analysis of the filter is given in section IV, and we illustrate how to design a few readily and optimal computable parameters that can accurately and easily detect targets within sea clutter. Experimental results with many frames of real data are presented in section V. Finally, we conclude with summary in section VI.

II. Characteristic of sea surface and targets

From qualitative analysis, the basic characteristic of sea surface is well known to all of us: superimposing ripple, foam and splashing spray to large-scale, approximately periodic wave. Usually, we call the wave 'large-scale structure', while the splashing ripple and spray 'small-scale structure'. The former is generated by wind from distance, and constituted by waves with long wavelength and shape similar to sinusoid. While, the latter is generated due to interfere between different kinds of swell and wind waves. They both lead to the especially irregular pattern of sea surface.

Sea clutter data to be analyzed here has been recorded on the East China Sea from a noncoherent radar operating in X-band. This radar is a two dimensional (azimuth and range) surveillance radar and the observations have been recorded for every direction with respect to the propagation direction of the swell. If radar emits pulses along the radial direction, we can take the radial direction as the time axis, and sea clutter can be regarded as an in-time signal. Fig.1 shows the amplitude data of sea clutter with a target along the radial distance at a certain direction. Fig.2 shows the frequency spectrum of the in-time signal.

![Image 1: Sea clutter amplitude data at a certain direction](image1.png)
must be less than 1. Moreover, it is always so large that it brings us a lot of difficulty to analyze the predicted slope, changing small-scale structure with irregular variation, the frequency spectrum and power. A good method to separate sea clutter and target, just from their structure of sea clutter, and the power of target is much larger is much steeper and holds higher frequency than large-scale structure of sea clutter, and the power of target is much larger than small-scale structure. These two features both indicate us a good method to separate sea clutter and target, just from their frequency spectrum and power.

III. Designing of \( \alpha-\beta-\gamma \) filter

From the analysis above, it can be seen that we need a high-pass filter to suppress the low frequency component of sea clutter. In other words, a low-pass filter to release the large-scale component of sea clutter, which is then subtracted from the original signal received, can also realize clutter suppression and target detection. We will model the sea clutter dynamics process as a discrete-time Markov form and plot the large-scale component as shown in Fig.3.

![Fig.3 Large-scale structure of sea clutter](image)

where, \( Y_0 \) denotes the estimated amplitude of sea clutter, \( Y_a\_p \) denotes the estimated slope of sea clutter amplitude, \( Y_a\_p\_n \) denotes the predicted amplitude, \( Y_s\_p \) denotes the predicted slope, \( M \) denotes the measurement amplitude of sea clutter and \( T \) denotes the sample interval.

Due to the slow change of large-scale structure of sea clutter, we can consider that the slope of the sea clutter amplitude curve keeps constant during a tiny sample interval as follows. Eq. (1) is called slope predicting equation.

\[
Y_s\_p(n) = Y_s(n-1)
\]

Based on this assumption, it becomes easy to predict the amplitude of sea clutter. However, the sea clutter amplitude curve is convex as shown in Fig.3 and the second derivative is always negative. Considering the diminishing slope, we multiply the slope by a proportional divisor \( \alpha \) (less than 1) to solve the problem approximately as follows. Eq. (2) is called amplitude predicting equation.

\[
Y_a\_p(n) = Y_a(n-1) + \alpha \cdot Y_s(n-1) \cdot T
\]

Eq. (2) seems on the surface to be not accurate, but it is practically feasible aiming at the large-scale structure, and we will prove its feasibility with real data in section V.

From the discussion above, it can be seen that we have modeled the dynamics process of sea clutter as a linear model with proper hypothesis. As we all know, Kalman filter is the optimal filter which will minimize the mean squared error within the class of linear estimator. Here, we can get the estimated amplitude and slope by Kalman filter as follows, referring to [8]. Eq. (3) is called amplitude estimating equation and Eq. (4) is called slope estimating equation.

\[
Y_a(n) = Y_a\_p(n) + B \cdot (M(n) - Y_a\_p(n))
\]

\[
Y_s(n) = Y_s\_p(n) + \gamma \cdot (M(n) - Y_a\_p(n))
\]

From Fig.3, we can find that the estimated amplitude \( Y_a \) must fall between \( Y_a\_p(n) \) and \( M(n) \), and be closer to the one owning higher reliability, so parameter \( \beta \) must be less than 1. Moreover, for the uncertainty of \( T \), we just replace \( Y_a\_p(n) \cdot T \) and \( Y_a\_p(n) \cdot T \) by \( Y_a(n) \) and \( Y_a\_p(n) \) to neglect \( T \). However, we have found that \( \gamma \) is always so large that it brings us a lot of difficulty to analyze the influence of three parameters on the filter performance uniformly. As a solution, we modify Eq. (4) to Eq. (5) with the same parameter but different meaning and up to now, the parameter \( \gamma \) is limited between 0 and 1, the same as \( \alpha \) and \( \beta \).

\[
Y_s(n) = Y_s\_p(n) + \gamma \cdot (M(n) - Y_a\_p(n) - Y_s\_p(n))
\]

From Eq. (1) to Eq. (5), we can generalize the whole filter algorithm as follows with three adjustable parameters, called \( \alpha-\beta-\gamma \) filter.

\[
\begin{align*}
Y_a\_p(n) &= Y_a(n-1) + \alpha \cdot Y_s(n-1) \\
Y_a(n) &= Y_a\_p(n) + \beta \cdot (M(n) - Y_a\_p(n)) \\
Y_s(n) &= Y_s\_p(n) + \gamma \cdot (M(n) - Y_a\_p(n) - Y_s\_p(n))
\end{align*}
\]

IV. Performance analysis and parameter choice

The main function of the \( \alpha-\beta-\gamma \) filter is to extract the low frequency component of sea clutter, so it should be a low-pass filter in theory. Supposing that the input signal is \( M \) and the output is \( Y_a \), we can obtain the system function \( H \) by Z-transform as follows.

\[
H = \frac{\beta + (\alpha \cdot \gamma - \beta + \beta \cdot \gamma)Z^{-1} + \beta}{1 + (\alpha \cdot \gamma + \beta + \gamma - 2\beta)Z^{-1} + (1 - \beta - \gamma + \beta \cdot \gamma)Z^{-2}}
\]

And the frequency response of this filter is shown as Fig.7, with the parameters \( \alpha = 0.01, \beta = 0.0033, \gamma = 0.6 \).

Next, we will have a discussion on two criterions to determine the optimal combination of three parameters: filter bandwidth and signal-to-clutter-ratio (SCR) improvement.
A. Influence of three parameters on filter bandwidth

Through increasing one of the three parameters gradually from 0 to 1 with the other two unchangeable, we can analyze the sensibility of every parameter. Firstly, keep $\beta = 0.0033$, $\gamma = 0.6$ invariable, and 3dB bandwidth is changing along with $\alpha$ as Fig.8. Secondly, keep $\alpha = 0.01$, $\gamma = 0.6$ invariable, and 3dB bandwidth is changing along with $\beta$ as Fig.9. Thirdly, keep $\alpha = 0.01$, $\beta = 0.0033$ invariable, and 3dB bandwidth is changing along with $\gamma$ as Fig.10.

To sum up, we have found that the filter bandwidth is gradually increasing along with $\alpha$ and $\beta$, but nearly remaining the same with $\gamma$.

B. Influence of three parameters on SCR improvement

SCR improvement is the most important factor to evaluate the effect of clutter suppression and target detection, since we can just differentiate clutter and targets through a threshold if we have reduced the power of clutter much lower than targets. With the same method as A, keep $\alpha = 0.01$, $\beta = 0.0033$ and $\gamma = 0.6$ invariable respectively, the improvement of SCR is shown as Fig.11 to Fig.13.
From Fig.8 and Fig.9 we can see that $\alpha$ and $\beta$ both make the bandwidth increase. But if the bandwidth is too wide, some high frequency targets will still go through the filter and be suppressed along with clutter; else if the bandwidth is too narrow, some part of low frequency clutter may still remain after the filter with targets. So there must be an optimal filter bandwidth to realize the largest SCR improvement. From Fig.11-Fig.13, we can see that this largest SCR improvement appears at $\alpha = 0.01$, $\beta = 0.0033$ and $\gamma$ has little influence on it.

V. Experimental results

Our work is to apply the $\alpha-\beta-\gamma$ filter to real data to evaluate the correctness of sea clutter suppression and target detection. Fig.14 shows the results of experiments in Fig.2 with the optimal parameters ($\alpha = 0.01$, $\beta = 0.0033$, $\gamma = 0.6$). It can be seen that the low frequency large-scale structure of sea clutter is almost eliminated, with the high frequency component and target remaining. Even so, we can still extract target from clutter clearly with an appropriate threshold, since the power of them differs greatly. However, we can see that both the power of target and sea clutter have reduced, and some of the data after filter is even negative, which may cause some small targets submerged within sea clutter. This is a flaw to be amended.

![Fig.14 Target and sea clutter after filter](image)

Fig.15 and Fig.16 show the grayscale images from a whole round scanning before and after the filter respectively. Fig.15 shows the real situation of sea surface, with a huge patch of strong reflection points, mixed by targets and sea clutter. While, Fig.16 shows that we have suppressed most of the sea clutter with strong reflection, with only some weak points left. We can roughly estimate that there are four targets at current moment and we still need more frames of scanning at every moment to observe the dynamic state of targets to give a judgment.

![Fig.15 Grayscale image before suppression of sea clutter](image)

VI. Conclusions

In this paper, we first introduce the characteristic and difference of sea clutter and sea target, and then a $\alpha-\beta-\gamma$ filter for eliminating sea clutter is presented. It is based on the Kalman filter to suppress the low frequency large-scale structure of sea clutter, which dominates the most part of sea echo, and then leaves the high frequency small-scale component and target to be easily separated by amplitude threshold. Following, we evaluate the system function of the filter, analyze how three parameters affect the filter bandwidth and SCR improvement and give out the optimal parameter combination. At last, the real experiments of one-way and round scanning are made, the results of which show that we have suppressed most of the sea clutter with large power and provided apparent distinction between targets and weak clutter left. All in all, this paper discards the conditional method of sea clutter modeling, but resorts to the distinction of frequency response and power between targets and clutter, and presents a special Kalman filter to realize clutter suppression and target detection. Experiments have shown good results to prove the feasibility and advantage of the filter.

References