Spectral Kurtosis–Based Method for Weak Target Detection in Sea Clutter by Microwave Coherent Radar

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ABSTRACT

A new method is proposed to detect small targets embedded in sea clutter for land-based microwave coherent radar using spectral kurtosis as a signature from radar data. It is executed according to the following procedures. First, the echoes of radar from each range gate are processed by the technique of short-time Fourier transform. Then, the kurtosis of each Doppler channel is estimated from the time–Doppler spectra. Last, the spectral kurtosis is compared to a threshold to determine whether a target exists. The proposed method is applied to measured datasets of different sea conditions from slight to moderate. The signal from a small boat is detected successfully. Furthermore, the detection performance of the proposed method is analyzed by the way of Monte Carlo simulation. It demonstrates that the spectral kurtosis–based detector works well for weak target detection when the target’s Doppler frequency is beyond the strong clutter region.

1. Introduction

Microwave coherent radar has long been developed and applied in ocean environment monitoring and sea surface target detection. Microwave Ocean Remote Sensor (MORSE) was recently developed by Wuhan University for marine environmental monitoring (Chen et al. 2012; Fan et al. 2012). It is mainly utilized for ocean parameter extraction, such as wave height and wave period. There are usually many noncooperative targets (e.g., fishing boats and driftwood) near the sea shore. If the targets are in the radar footprint, then the measurement may be inaccurate. It is necessary to detect these targets and to mark them before eliminating their effects on ocean parameter extraction. However, robust radar target detection in sea clutter background is hard to recognize, especially when the target signal is weak compared with the strong and spiky sea clutter.

Recently, much effort has been made to improve the capability of target detection in sea clutter. These methods are mainly classified into four categories: statistical model–based detectors (Guida et al. 1992, 1993; Dong 2012), chaos-based means (Haykin and Li 1995), fractal-based methods (Hu et al. 2006; Guan et al. 2010), and time–frequency analysis approaches (Davidson and Griffiths 2002; Guan et al. 2012). Conventional constant false alarm rate (CFAR) detectors are applied by modeling the envelope of sea clutter as non-Gaussian models, such as Weibull distribution (Guida et al. 1992), lognormal distribution (Guida et al. 1993), and K distribution (Dong 2012). These theories are relatively mature, and more complicated models are developed for various ocean environment and radar parameters. Some researchers demonstrate that the sea clutter exhibits a chaotic characteristic. Making use of the short-time predictability of the chaotic system, a neural network is applied to detect small targets (Haykin and Li 1995). However, this is also queried by some others (McDonald and Damini 2004), and the results are still inconclusive. Fractal-based approaches, such as multifractal analysis (Hu et al. 2006) and multifractal correlation (Guan et al. 2010), utilize the fractal characteristic of the sea surface to distinguish it from targets. However, information of the moving state cannot be obtained by this class of approaches. The time–frequency analysis is utilized in target detection by revealing the variation of frequency spectra with time. New techniques, such as wavelet
transformation (Davidson and Griffiths 2002) and fractional Fourier transform (Guan et al. 2012), are making progress in this field.

This manuscript introduces a new and simple method to solve the target detection problem for microwave coherent radar: the spectral kurtosis (SK)-based detector. Spectral kurtosis is expected to be very sensitive to the nonstationary patterns in the signals, and it is able to indicate at which frequencies those patterns occur (Antoni 2006). For high-resolution microwave radar, the moving targets stay in one range gate for a short time, so they are assumed to be nonstationary patterns. The sea clutter is assumed to be stationary for an appropriate processing interval. Therefore, the spectral kurtosis is expected to detect the transient target signal within sea clutter.

The rest of the manuscript is arranged as follows: in section 2, we introduce the concept of spectral kurtosis and propose the procedures of the adaptive SK detector; in section 3, the measured datasets are briefly described and used to verify our algorithm; in section 4, the detection performance of the proposed method is analyzed by the way of the Monte Carlo method; and finally, conclusions for the present work are given.

### 2. Spectral kurtosis–based detector

#### a. Spectral kurtosis

SK is a statistical tool that gives a measure of the peakiness of the probability density function of the process at a certain frequency. Dwyer (1984) originally introduced the theory of spectral kurtosis (also known as frequency domain kurtosis). His basic idea is to calculate the kurtosis at each frequency of the signal after bandpass filtering. It makes the spectral kurtosis a statistical tool that can indicate not only non-Gaussian components in a signal but also their locations in the frequency domain. Further study of this theory (Antoni 2006) proposes

<table>
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<th>Number/parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
<td>Significant wave height (m)</td>
<td>1.03</td>
<td>1.40</td>
<td>1.68</td>
<td>2.03</td>
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<tr>
<td>Max wave height (m)</td>
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<td>2.01</td>
<td>2.79</td>
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<td>Mean wave period (s)</td>
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<td>5</td>
<td>6</td>
<td>6</td>
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<tr>
<td>Averaged wave direction (°)</td>
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<td>22</td>
<td>90</td>
<td>67</td>
</tr>
<tr>
<td>Averaged wind speed (10 min, m s⁻¹)</td>
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<td>6.1</td>
<td>6.4</td>
<td>13.3</td>
</tr>
<tr>
<td>Averaged wind direction (10 min, °)</td>
<td>47</td>
<td>31</td>
<td>71</td>
<td>95</td>
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</table>

![Fig. 1. Intensity distribution of radar echoes (dBm²) for datasets 1–4. Radar echoes of sea surface show bright and dark stripes alternating with each other. The intensity of boat echoes is too small and is covered by sea clutter.](image)
a formalization of the spectral kurtosis of nonstationary processes by the means of the Wold–Cramer decomposition of ‘conditionally nonstationary’ processes.

For target detection in sea clutter, we assume that the sea clutter is stationary or quasi stationary in the residence time \(t_R\), and the target’s signal is transient and stays in one range gate for time \(t_T\). The radar returns are modeled as

\[
s(t) = c(t) + x(t) + n(t),
\]

where \(c(t)\) denotes sea clutter, \(x(t)\) denotes the target signal, and \(n(t)\) denotes the added Gaussian noise. The proposed method can be applied to small-boat detection as long as \(t_R \gg t_T\).

Through short-time Fourier transformation (STFT), the returned signal obtains the following expression in the frequency domain:

\[
S_i(f) = C_i(f) + X_i(f) + N_i(f) \quad i = 1, \ldots, M,
\]

where \(M\) is the number of time cells. Then, we get the following expression of SK based on STFT:

\[
\text{SK}(f) = \frac{1}{M} \sum_{i=1}^{M} |S_i(f)|^4 - 2. \tag{3}
\]

For high-resolution ocean remote sensing radar, the distance of one range gate is small. The moving boat stays in one range gate for only a few seconds in most occasions. Thus, the signal of the target is assumed to be transient in each range gate. SK is sensitive to the presence of targets.

b. Target detection method

On the basis of the above-mentioned analysis, a new target detection method is proposed for land-based microwave coherent radar. The procedure of the algorithm is as follows:

1) Radar returns of the residence time \(t_R\) are preprocessed to decompose the range gates. Then, a two-dimensional matrix is obtained for further processing. Its rows are range gates, and its columns are time series sampled from the pulses.
2) The time–Doppler spectra of each range gate are estimated through the technique of STFT, which is applied by sliding a rectangular window on the time series of each range gate.
3) The spectral kurtosis is extracted from time–Doppler spectra by estimating the kurtosis of each Doppler channel. \(\text{SK}\) is an array that varies with Doppler frequency, and it indicates the peakiness of the signal in certain Doppler channels.
4) A judgment is made by comparing SK with a threshold. If the kurtosis value in a certain Doppler channel is larger than the threshold, then the target is considered to exist. Else, no target exists. The values exceeding the threshold are recorded for velocity estimation.

The marked values concentrate around the Doppler channels where the boat signal is located. The location depends on the radial velocity of the target. According to the Doppler effect, the relation of the values follows the expression below:

\[
u_r = \frac{\lambda_0}{2 \cos \theta} f_i, \tag{4}
\]

where \(\nu_r\) denotes the radial velocity of the boat, \(f_i\) denotes the center frequency where the larger kurtosis values are located, \(\lambda_0\) denotes the wavelength of the microwave emitted by the radar, and \(\theta\) denotes the grazing angle.

In addition, the center of energy in the Doppler domain is used to estimate the velocity when the target’s signal spreads in several Doppler channels.

3. Measured data processing

a. Dataset introduction

The MORSE system is applied in a 1-month experiment at the end of 2012 on a small island located in the South China Sea. The antennas are located at a height of 20 m MSL and illuminate the sea surface at low grazing angles. The beamwidth of the antenna is about 30°. Six horn antennas are equipped to cover a region of 180°. They operate by turns under a desired time and order. The system transmits S-band electromagnetic waves and covers a detectable range from 200 to 2000 m. The range resolution is 7.5 m.
FIG. 2. Time–Doppler spectra (dB) and the corresponding SK of different range gates: (a) RG 50, value of SK increases quickly when the signal from a boat occurs; (b) RG 65, value of SK may also rise at the edge of the clutter region if the edge line changes sharply; and (c) RG 80, there is no target signal and the value of SK slightly increases at the edge of the clutter region.
Four datasets are selected to validate the proposed method, marked as dataset 1, dataset 2, dataset 3, and dataset 4. The datasets are collected at the same site at different times. Each dataset contains radar echoes from 41 range gates, and the duration is 100 s. The targets are small boats of about 5 m long and 2 m wide. Some available environment parameters are listed in Table 1. Information about the sea waves comes from a buoy, and the data are averaged over 1 h. Information about the wind is taken from an anemometer near the radar system.

The intensity of radar echoes in a time–range plane is plotted in Fig. 1. The four datasets are obtained at different sea conditions but show similar characteristics. The radar echoes of the sea surface show bright and dark stripes alternating with each other. The intensity of boat echoes is small and partly hidden in the sea clutter.

**b. Detection results**

The proposed method is applied to the four datasets. In the processing, the coherent processing interval (CPI) of STFT is set to be 0.5 s as a compromise between energy concentration and time resolution. Other detection parameters and the results are listed in Table 2. The false alarm and detection probability are obtained by the following formulas:

\[
P_{fa} = \frac{N_{fa}}{N_{\text{range}}N_{\text{Doppler}}},
\]

\[
P_{d} = \frac{N_{d}}{N_{\text{target}}},
\]

where, \(N_{fa}\) is the number of false alarms, \(N_{d}\) is the number of range gates that the target detects, \(N_{\text{range}}\) is the number of range gates, \(N_{\text{Doppler}}\) is the number of Doppler channels, and \(N_{\text{target}}\) is the number of range gates (RGs) in which the target really appears during the residence time.

Next, dataset 3 is taken as an example to show details about the application of the SK detector. The time–Doppler spectra at RG 50, RG 65, and RG 80, and the estimated SK based on them are showed in Fig. 2. The Doppler channels containing the boat’s signal correspond to larger values of SK. At the same time, the Doppler channels where sea clutter and Gaussian noise are located have low SK values. However, the kurtosis may also rise at the edge of the clutter region, especially when the spectrum width of sea clutter suddenly increases as a result of wave breaking (Lee et al. 1998).

The threshold is chosen to be 20 in order to avoid too many false alarms. The values of SK that are larger than the threshold are marked, as shown in Fig. 3a. Then, some isolated points are excluded. Last, the radial velocities of the detected boat are estimated and shown in Fig. 3b. The result shows that this boat is moving away from our radar site from RG 40 to RG 74 with a radial speed around 2.75 m s\(^{-1}\).

The detection results of the four datasets provide practical sense about the performance of the proposed method in real-world application. According to the results in Table 2, the SK detector attains detection probabilities above 95% in cases when the false alarm probabilities are less than 1%, and when the significant wave height is between 1 and 2 m. In addition, the probability of false alarm increases with the growth of the wave height. When the sea surface becomes rougher, the nonstationarity of sea clutter may raise the value of SK at the edge of the clutter region. This leads to high false alarm probability. It demonstrates that severe sea condition may worsen the detection performance.

4. Detection performance analysis

In this section, the method of Monte Carlo simulation is utilized to further analyze the performance of the SK-based detector. To obtain data of different signal-to-clutter
ratios (SCR), a simulated target signal is added to measured sea clutter. The Monte Carlo method is applied to estimate the detection probabilities in different conditions, and the program runs for 1000 times for each result.

The sea clutter data come from dataset 3. It is a time series of 100 s from one range gate without targets. The time–Doppler spectra, the SK, and the maximum amplitude in each Doppler channel are plotted in Fig. 4. As shown in the figure, the sea clutter mainly spreads within the Doppler velocity of $-0.5$ to $2.5 \text{ m s}^{-1}$. It is called the clutter region. Other Doppler channels are called the noise region. The amplitude of the target signal is assumed to be Rayleigh distributed and it varies between radar pulses. Here, SCR is defined as the ratio of the target’s energy to the averaged energy of sea clutter and noise in Doppler channels:

$$\text{SCR} = 10 \log \frac{P_{\text{target}}}{P_{\text{noise}} + P_{\text{clutter}}} \text{(dB)},$$  \hspace{1cm} (7)

where $P_{\text{target}}$ is the energy of the target signal, which is assumed to be concentrated in one Doppler channel in the simulation; and $P_{\text{noise}}$ and $P_{\text{clutter}}$ are the energy of noise and sea clutter averaged in the Doppler channels, respectively.

At the same time, the amplitude-based detector is applied as a comparison to the proposed method. The amplitude-based detector makes the maximum amplitude in each Doppler channel the test statistics. To control the false alarm probability, the threshold of the following analysis is chosen as the greatest value of the maximum amplitudes. Accordingly, the threshold of the SK-based detector is chosen as the largest value of the SK in the following analysis.

The detection probabilities of the two methods are shown in Fig. 5. The target signal is outside the clutter region with a velocity of $-2 \text{ m s}^{-1}$ in Fig. 5a and inside the clutter region with a velocity of $1 \text{ m s}^{-1}$ in Fig. 5b. In the noise region, the proposed method shows good detection performance even when the SCR is below 0 dB. And the detection probability is larger than the amplitude-based method. In the clutter region, the detection probability descends quickly, even lower than the amplitude-based method. The detection performance of the amplitude-based method improves slightly in the clutter region due to the utilization of the additive model in our simulation.

To further discuss the factors affecting the performance of the SK-based detector, the detection probabilities for different target velocities are analyzed. As shown in Fig. 6, the detection probability is much lower
in the clutter region than in the noise region. The interference of sea clutter worsens the detection performance, but the increase of SCR improves it. When the SCR increases to 25 dB, the detection probability improves up to 80%, even when the target signal is located in the clutter region. However, the detector does not work when the velocity is near zero, in which case the target stays at the same range gate for a long time.

5. Conclusions

The SK method is first introduced into the field of target detection in sea clutter background. The SK detector is applied to the measured datasets in a recent seaboard experiment. The proposed method works well as long as the sea clutter is stationary or quasi stationary during the processing time. However, the performance of the detector reduces when the target signal is in the clutter region or when the sea condition becomes more severe. In view of the limitation of the SK detector, an improvement of the algorithm is necessary by considering more robust digital signal processing (DSP) techniques like wavelet transform.

About the choice of threshold, it is a problem in the application of the SK detector. The thresholds used in the manuscript come from a compromising choice based on the samples of pure sea clutter data in the same measurement. The SCR of the measured data is not easy to extract because the energy of the target is hard to distinguish from sea clutter in the radar returned signal. Moreover, sea clutter is a complex and dynamic process whose characteristic is determined by a combination of factors. This made it more difficult to summarize an effective approach to determine the threshold automatically. So, reference data are used in the choice of threshold instead of a trade-off between SCR and the threshold. But the analysis of the trade-off between the threshold and the main factors affecting sea clutter is necessary and needs further research.

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