Detection of air target based on multi-fractal analysis in a laser radar

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A novel approach for detecting laser radar target based on multi-fraction dimension (MFD) of laser clutters has been proposed. The fractal dimension (FD) of laser clutter and the echoes from the plan are estimated using box-counting dimension algorithm. The intrinsic difference in the spectrum of FD D_q between them is extracted and used to detect targets. Experimental results show that the method based on MFD is more reliable than that on FD and can improve the accuracy of detection.

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Clutter is one of the main reasons which degrade the radar detection performance. It is very difficult to detect radar small target in the strong clutter background. All along time, researchers have devoted to find effective algorithm to resolve the problem. Recently, much effort has been devoted to the analysis of radar signals by fractal geometry. Fractal characteristic of sea-scattered signals is studied and fraction dimension (FD) is used for the detection of sea-surface targets in Refs. [1,2]. Multi-fractal feature is used to detect a sea surface target in Ref. [3]. All analyses mentioned above are for sea surface target. In this paper, we apply fractal analysis to detect an air target in the field of the laser radar.

Fractals are self-similar objects. They can be described by non-integer dimension, called FD, which strictly exceeds the corresponding topological dimension. FD is first defined as Hausdorff-Besicovitch (HB) dimension by Felix hausdorff. Considering a bounded set S in Euclidean n-space covers the set S by a countable collection of subsets of diameter d_i (the diameter of S is the greatest distance between any two points in S), the measure of the set S can be defined as

$$H_\varepsilon^D = \inf \sum_{d_i} d_i^D, \tag{1}$$

where $D > 0$ is a real quantity. The limit of H_ε^D, when ε tends to zero, is the HB measure of the set S. The value of D where H^D jumps from ∞ to 0 is called later HB dimension $D_{\rm H}$.

It is not trivial to calculate $D_{\rm H}$ for even simple sets, several algorithms and methods were developed over the past years to compute FD. One of the most popular algorithms for computing FD of signals and images is the box-counting method[4]. Box counting involves covering a fractal with a grid of n dimensional boxes with side length ε and counting the number of no empty boxes $N(\varepsilon)$. The boxes of recursively different sizes are used to cover the fractal. The limiting value of $N(\varepsilon)$ when ε tends to zero is proportional to $\varepsilon^{-D_{\rm B}}$, where the box counting dimension of given fractal is

$$D_{\rm B} = -\lim_{\varepsilon\to 0} \frac{\log N(\varepsilon)}{\log \varepsilon}, \tag{2}$$

here, $D_{\rm B}$ is counted in the following manner[4].

Considering the signal S of length of M hits has been scaled to a length of ε, where, $M = 2^n$, $\varepsilon = \frac{M}{2^q}$ $(q = 1, 2, \cdots, n-1)$. Now, considering signal as a two-dimensional space with x denoting position and y denoting amplitude level. Then, the signal is partied into sects of size ε in x, on each sect, there is a column of squares with size of $\varepsilon \times \varepsilon$, in the ith column, the number of square is counted using

$$n_q(i) = y_{\max}(i) - y_{\min}(i) + 1, \tag{3}$$

where $y_{\max}(i)$ and $y_{\min}(i)$ are the maximum and minimum of the signals in the ith sect, then

$$N_q = \sum_i n_q(i). \tag{4}$$

Give q different values, we can get different N_q, then using Eq. (2), estimate the fractal dimension $D_{\rm B}$ from the least square linear fit of $\log(N_q)$ against $\log(2^q)$. Normally, there exists p, when $q \geq p$, and

$$D_{\rm B} = \frac{\log(N_q)}{\log(2^q)}. \tag{5}$$

To analyze the box dimension of the laser radar echoes, experiments are performed with a great deal real-life data. Owing to the limit of space, here only some of the experiment results are given. Figure 1 shows three

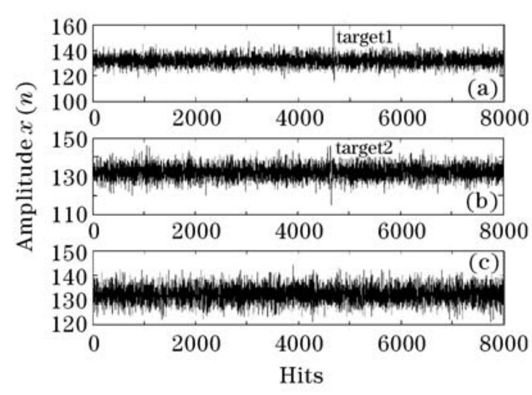

Fig. 1. Examples of the laser clutter amplitude data (a) with big target1, (b) small target2, and (c) without target.

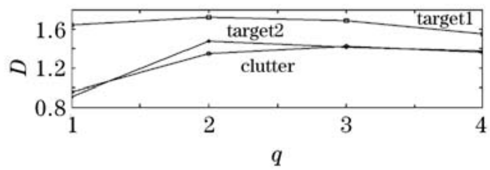

Fig. 2. Fractal dimension D of the clutter and plan targets versus scale q.

examples of laser clutter amplitude data with target1, target2, and without target. Target1 is a big signal with signal to noise ratio (SNR) about 4.75 and target 2 is comparatively a small signal with SNR about 2.82.

Now, we extract two sect data including targets 1 and 2 separately from Figs. 1(a) and (b), and any sect data from Fig. 1(c). Then the box dimension is counted using the algorithm mentioned above. Results are shown in Fig. 2. From it we find that FD of the target1 is about 1.6, while FDs of the target2 and the clutter are both about 1.4. It is easy to extract the strong target from the clutter based on their difference FD, but it is not the case for the small target. When the target signal is weak, its FD is so close to that of the clutter, we cannot extract the target easily. So the FD cannot provide sufficient information to detect target and clutter correctly, especially when the SNR is small. To detect the small target, we consider using the multi-fraction analysis.

Generally, FD is the complete characterization of self similarity of an image only in simple cases. For a self similar distribution showing no isotropic and inhomogeneous scaling properties, the concept of multi-fractals is a better approach. The basic concept of multi-fractal is a spectrum of the FD[5], the spectrum D_q is defined as

$$D_q = \begin{cases} \frac{1}{q-1} \lim\limits_{\varepsilon \to 0} \frac{\log N(q,\varepsilon)}{\log \varepsilon} & q \neq 1 \\ \lim\limits_{\varepsilon \to 0} \frac{\sum_i u_i \log u_i}{\log \varepsilon} & q = 1 \end{cases}, \tag{6}$$

where q is any number in the range from $-\infty$ to $+\infty$, $N(q,\varepsilon) = \sum_i u_i$ is the weighted number of boxes and $u_i = \frac{n_q(i)}{N_q}$, $n_q(i)$ and N_q derived from Eqs. (3) and (4), is the normalized mass in the box-counting method.

The spectra of the fractal dimension D_q give a complete statistical description of a fractal set. Spectra of the fractal dimension D_q of the laser clutter and targets mentioned above in the Fig. 1 are shown in Fig. 3.

It can be seen that the spectra of the fractal dimension D_q of the echoes from the target are different from that of the clutter, and they vary at different SNRs. We carried lots of experiments, the results are coincident. Based on

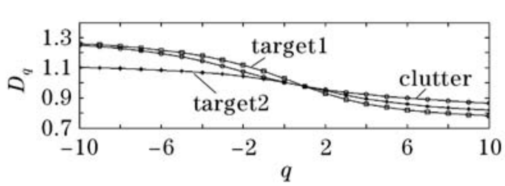

Fig. 3. Spectra of fractal dimensions D_q of the clutter and plan targets.

this, we proposed a new method in the following for the laser radar target detection.

The multi-fractal implies a continuous spectrum of exponents for the characterization of the system, we can extract one feature to different targets from the clutter. Here, we select an exponent of the six. That is to say the value of q is 6. For a set of data, we estimate the D_q of each hit using its neighbor hits, here, q is 6. The dynamic range of D_q is so small that we cannot be easy to extract the target. So, we make a linear transform to the D_q as

$$D(6) = a \times (b - D_6), \tag{7}$$

where a, b are constant and D_6 can be derived from Eq. (6). Using the same method, we can also get the FD of each hit.

Experiments are carried out using the data set in Figs. 1(a) and (b). The results are shown in Fig. 4. From it, we can easily find that the multi-fractal dimension (MFD) method is superior to the FD method. Even for the small target, after processing with MFD method, SNR improves greatly about 3 multiples. While using the FD method, the SNR is not changed remarkably.

The MFD processing is actually a filter processing. After filter, we can extract the target with a threshold. The threshold formula is given by

$$\mathrm{Th} = k \times \sigma, \tag{8}$$

where k is the constant, σ is the variance of $D(6)$. Figure 5 is the detection result of the Fig. 4(d). The signal with the biggest value is the true target, the others are false target, they can be winkled with the correlation

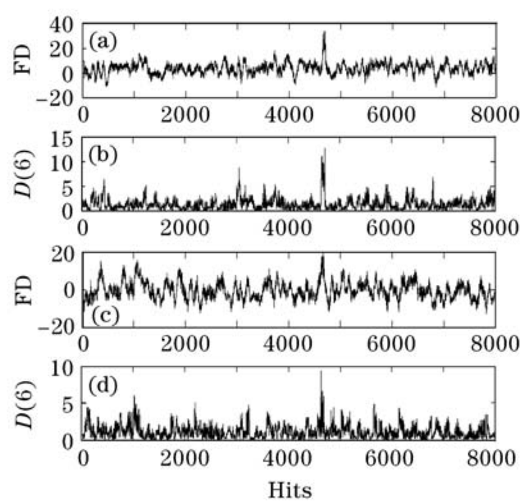

Fig. 4. (a) and (b) are results of Fig. 1(a) with big target1 based on the FD and MFD respectively, (c) and (d) are results of Fig. 1(b) with small target2 based on the FD and MFD respectively.

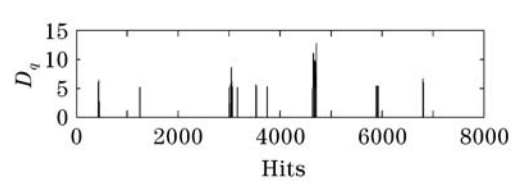

Fig. 5. Detection result.

detection[6].

By applying the concept of the fractal concept, we proposed a new method for air laser radar target detection. Results show that the method using the multi-fractal analysis is excellent than that using the fractal analysis. The MFD is a good method for target detection in radar filed, but its real time detection needs farther research.

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