SEA STATE CHARACTERIZATION USING NORMALIZED EXPERIMENTAL ONE – DIMENSIONAL RADAR SIGNATURES AND FRACTAL TECHNIQUES

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Abstract

This paper presents a novel method of sea state characterization by using several criteria, which are applied to normalized experimental Synthetic Aperture Radar (SAR) one–dimensional signatures (range profiles), provided to our research group by SET 215 Working Group on "SAR radar techniques". In previous Conference we had provided the "Fractal Dimension" and "Variance σ²" criteria, while here we present the "Fractal Length" and "Power Spectrum Density - Least Squares" criteria. Note that concerning the first criterion ("Fractal Length"), this uses the so – called "Modified Fractal Signature" (MFS) or "blanket" method for calculating the "fractal length" of the radar range profiles. The main idea concerning this proposed technique is the fact that normalized SAR radar range profiles, corresponding to different sea states, produce different values of "Fractal Dimension" and "Fractal Length" for all angles of incidence examined here. As a result, a sea state characterization technique for two different sea states (turbulent and calm sea) is presented in this paper.

1. INTRODUCTION

Fractals can describe an unlimited number of complex patterns that resemble in different scales and are used as a mathematical tool for a variety of applications, such as image analysis and sorting, applied electromagnetism, etc. [1] – [7]. The indistinguishable structure on different scales is a basic feature of fractals. Accordingly, fractals can illustrate a certain very strong form of geometric complexity across multiple data sets, as well as SAR images. Synthetic Aperture Radar (SAR) images can be considered as fractals for a certain range of magnification. In addition, fractal objects have unique properties and features that may be related to their geometric structure.

Previous research in the area of sea clutter investigations by using radar techniques and fractal mathematics methods can be found in [8] – [20]. As opposed to those references, in the present paper, the main objective is to examine the sea state characterization problem by using real SAR backscattered data and fractal techniques (for the latter see, e.g., [21] – [29]). Then, in this paper of ours, we use four different criteria: the 'Fractal Dimension', the "Fractal Length", the "Variance σ^2", and the "Power Spectral Density - Least Squares". The first two criteria are considered here the main ones, following the method by Peleg et al. [21], which has also been applied in the past to real Synthetic Aperture Radar (SAR) images, using the "blanket" technique, to provide useful information about SAR image classification, as reported by Malamou et al. [22].

This paper uses the recorded sea clutter radar data, which were collected during the "NEMO 2014" trials in Taranto, Italy, using FFI (i.e., "Norwegian Institute of Defense", Oslo, Norway) PicoSAR X-band radar as input to a specific SET Working Group. The experiment took place in the Taranto bay in southern Italy on 23 and 24 September 2014. The first day the weather was quite windy, thus creating a rather turbulent sea, in comparison with the second day, during which the sea surface was almost calm.

2. PROBLEM GEOMETRY AND STATEMENT

The geometry of the sea state characterization problem is shown in Fig. 1. Here, a helicopter (with PicoSAR radar inside) rises vertically, whereas maintaining its steady position (latitude and longitude), and transmits electromagnetic (EM) radar pulses towards the sea. In addition, it records the azimuth angle with high sampling density in the grazing angle.

During the experiment performed by FFI in September 2014 (NEMO trials), the helicopter kept low vertical velocity and negligible horizontal velocity (helicopter movement from down to up). The first day (23/9/2014), the wind speed was reported in the range from 10 m/s to 12 m/s (rather high wind speed) and the helicopter pilot kept the direction of the antenna beam up-wind (i.e., the direction of radar pulses - EM wave propagation in the opposite direction of the wind speed) within a 20° window in the horizontal (azimuthal) direction, as grazing angles θ_g (see Fig. 1) scanned from 3° to 37°. The time of the full grazing angle span was approximately 4 minutes.

During the second day (24/9/2014), the wind speed was very low (1 m/s–2 m/s, which sometimes died out locally) and the range of grazing angles was from 4° to 38° with a slight drift in the azimuth pointing angle of the bore sight of no more than 20°.

However, several practical questions arise about the characterization of a signal that embeds noise. To deal with the presence of noise in the signal, a method is presented here, which initially calculates the average of the range profiles (i.e., "range profile averaging"). For avoiding possible noise spikes in the signal, the number of N samples of the range profiles was set to be equal to 65, ensuring that this was sufficient to give the most accurate results.

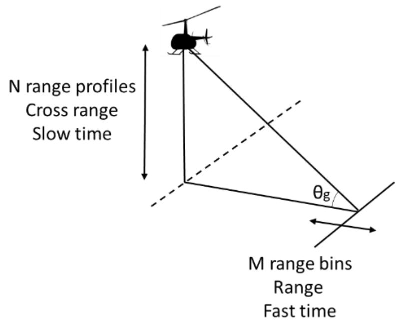

Figure 1. Geometry of the problem

Then the average of the distance profiles was normalized on a scale from 0 to 1 (i.e., "normalized range profiles") and the generated backscattered signal was transformed into the frequency domain (see Fig. 2 and 3 below).

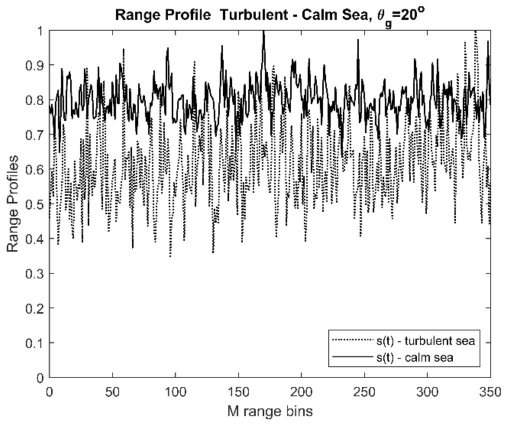

Figure 2. Representative PicoSAR radar range profiles at grazing angle θg = 20° for Day 1 (turbulent sea) and Day 2 (calm sea): time domain

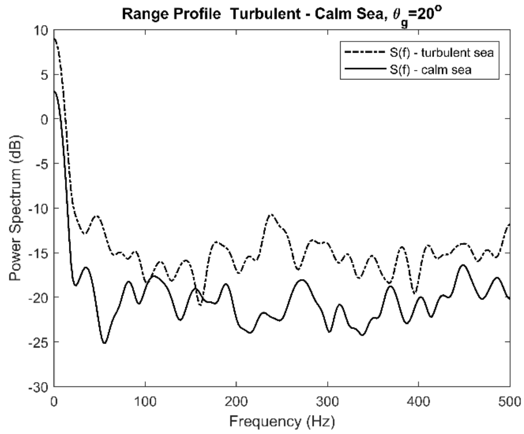

Figure 3. Representative PicoSAR radar range profiles at grazing angle θ_g = 20° for Day 1 (turbulent sea) and Day 2 (calm sea): frequency domain

Observing Fig. 2 and 3, the first day (turbulent sea), the range profiles take values from about 0.3 to 1, whereas during the second day (calm sea), the range profiles take values from 0.6 to 1 (in this case), i.e. smaller variance during the second day. Furthermore, in Fig. 4, the backscattered waves in the frequency domain (i.e., "spectral power") are shown.

3. SEA STATE CHARACTERIZATION RESULTS USING THE "FRACTAL LENGTH" AND "POWER SPECTRUM DENSITY - LEAST SQUARES" CRITERIA : NUMERICAL RESULTS

The sea state characterization criteria that are described in this paper are the "Fractal Length" and the "Power Spectral Density - Least Squares" criteria. Detailed information about all these criteria can be found at Ref. [30].

These criteria use the fractal theory and both fractal criteria use the blanket method, which was introduced by Peleg et. al. [21] and was used to characterize the texture of surfaces.

As mentioned above, the blanket method [3] is used here for the calculation of the fractal length and the fractal dimension of the range profiles in the frequency domain. Initially, in the paper by Peleg et. al. [21], the surfaces are classified based on the change of their properties in terms of the change of image resolution. Subsequently, Malamou et al. [22] and Tang et. al. [23] used the blanket method to characterize SAR images and document images, respectively.

The blanket method was proposed [21] to measure the area of irregular surfaces, which had been studied earlier by Mandelbrot [3] – [5]. The blanket method in one dimension, as applied in this paper, considers that all points, which have a distance δ on both sides of a range profile, create an area of width 2δ, which is called "strip", defined by an upper and a lower blanket. The functions of the "upper" and "lower" curves of the range profile are provided by the following equations [21], [23]. Details on all that can be found at Ref. [30].

3.1. 'Fractal Length' Criterion results

This criterion for sea state characterization is performed by examining the logarithmic fractal length. The "Fractal Length" criterion calculates the logarithm of the fractal length of the normalized average signal for range profiles (averaging with N = 65 range profiles) in the frequency domain, using the blanket method, as briefly described above [30].

The "Fractal Length" criterion examines the difference between the fractal length for the scale δ = 1 and the fractal length logarithm for the scale of δ (the signal for scale δ = 1 is essentially identical to the backscattered signal), see Figures 4 and 5. Then the results for the grazing angles 10° and 25° are shown in Fig. 4 and 5.

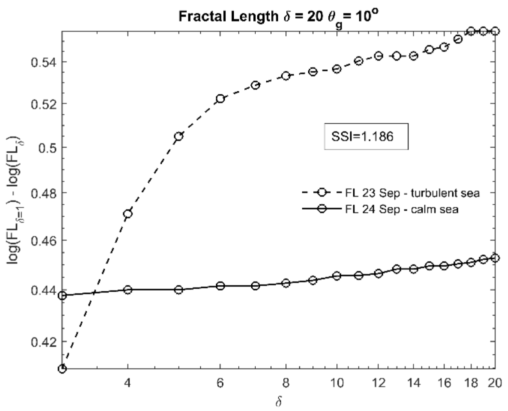

Figure 4. Logarithmic Fractal Length as a function of iteration δ for grazing angle 10°

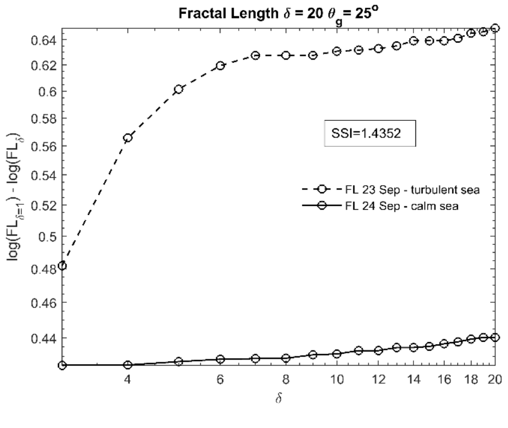

Figure 5. Logarithmic Fractal Length as a function of iteration δ for grazing angle 25°

Furthermore, the Sea State Index (SSI) is calculated for the 'fractal length' criterion. The Sea State Index of this criterion is the ratio of the mean logarithmic fractal length in the case of turbulent sea to the mean logarithmic fractal length for calm sea, in the frequency domain. As shown in Table I, the values of SSI here are higher than 1 for all values of grazing angle (i.e., from 5° to 35°), thus the fractal length criterion examined here is of high confidence.

TABLE I. Sea State Index (SSI) for 'fractal length' criterion for different grazing angles

Angle \ SSI	Fractal Length
5°	1.272
10°	1.186
15°	1.437
20°	1.383
25°	1.435
30°	1.382
35°	1.563

3.2. Power Spectrum Density – Least Squares Approximation Criterion Results

The "Power Spectrum Density - Least Squares" criterion is used here to validate the results of the two main fractal criteria. The least squares approximations of the power spectrum density results, as lines of the form *αx + β,* are shown in Figures 6 and 7 for the grazing angles of 10° and 25°, respectively. These Figures represent the power spectral density (PSD) versus the frequency on a log-log scale for turbulent and calm sea (see also [8], [9]).

Then, in Figures 6 and 7 it can be observed that the slopes of the lines of the least squares approximation (LSA) exhibit an absolute slope for the turbulent sea greater than the absolute slope value for the calm sea, something that is actually used as a criterion for characterizing the sea state. Then the corresponding numerical results are provided in Table II.

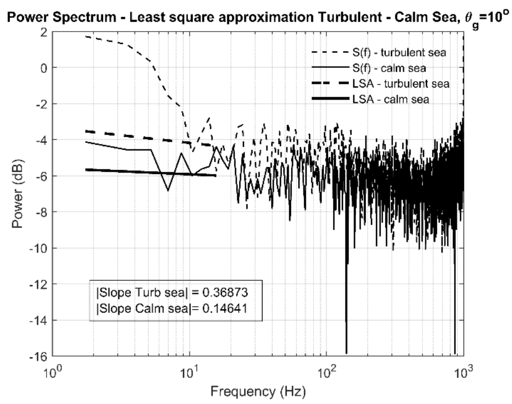

Figure 6. Power Spectrum Density and Least Squares slope for grazing angle 10°

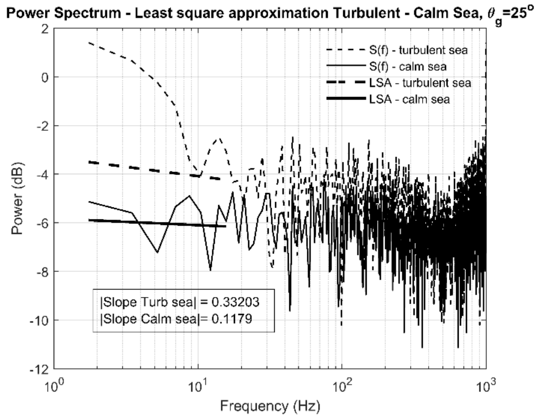

Figure 7. Power Spectrum Density and Least Squares slope for grazing angle 25°.

TABLE II. Absolute slope of least squares approximation results of power spectrum density for turbulent and calm sea

Sea State / Angle	Turbulent	Calm
5°	0.290	0.119
10°	0.368	0.146
15°	0.316	0.166
20°	0.300	0.148
25°	0.332	0.117
30°	0.346	0.115

Concluding, in a manner similar to that described in [8], [9], the "Power Spectrum Density – Least Squares" criterion can be used to characterize the sea state in a satisfactory way.

4. CONCLUSIONS

To summarize, this paper focused on the sea state characterization with the use of the two (2) criteria mentioned above (for further information on these methods, as well as the 'fractal dimension' and 'variance' criteria, the interested reader is referred to Ref. [30]).

These two (2) criteria were applied to the experimental one-dimensional signatures of a synthetic aperture radar (SAR) in the frequency domain (real radar data from sea surface) in two different sea states (turbulent and calm sea). The corresponding recorded sea clutter radar data were collected during the "NEMO 2014" trials in Taranto, Italy, 23–24/9/2014. An X-band PicoSAR airborne radar was used for that purpose by FFI (i.e., "Norwegian Institute of Defense", Oslo, Norway).

The above two (2) criteria were applied to the backscattered radar signals from the sea surface. Namely, to suppress the inherent radar receiver electronic noise, averaging of the radar range profiles was used (here with N = 65 range profiles) and subsequently the data were normalized on a scale from 0 to 1 (i.e., "normalized range profiles"). Finally, the range profiles generated as described above, were transformed to the frequency domain. Finally, the 'Sea State Index' (SSI) was calculated for the above criteria, which were found to be suitable for accurate sea state characterization.

5. FUTURE RESEARCH

In our future related research, we intend to validate the above mentioned criteria [all four (4) of them, see abstract above, as well as Ref. [30]] for sea state characterization for *simulated* backscattered radar data (range profiles) to be produced by a rigorous electromagnetic (EM) code, already developed by our research group. Furthermore, we intend to use fractal methods on the "full set of range profiles" [i.e., *three-dimensional (3D) fractal analysis* on the backscattered radar range profiles], rather than the essentially two-dimensional (2D) analysis of the range profiles, presented in this paper. Finally, the '*uniformity of the spectra'* of the range profiles, for 'calm' and 'turbulent' sea conditions respectively, can be more carefully examined by our research group in the near future.

6. ACKNOWLEDGMENT

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