SEA STATE DETERMINATION USING NORMALIZED EXPERIMENTAL ONE – DIMENSIONAL RADAR SIGNATURES AT X – BAND AND FRACTAL TECHNIQUES

G. Pouraimis[1], A. Kotopoulis[1], N. Ampilova[2], I. Soloviev[2],

E. Kallitsis[1] and P. Frangos[1]

[1]School of Electrical and Computing Engineering, National Technical University of Athens,
9, Iroon Polytechniou Str., 157 73 Zografou, Athens, Greece

Tel.: +30 210 772 3694; FAX: +30 210 772 2281; e-mail: pfrangos@central.ntua.gr

[2] St. Petersburg State University, Computer Science Department,

e-mail : n.ampilova@spbu.ru, i.soloviev@spbu.ru

Abstract

This paper presents a novel method of sea state characterization using the 'Variance σ²' and 'Fractal Dimension - FD' criteria which are applied to experimental Synthetic Aperture Radar (SAR) one – dimensional signatures (range profiles) in frequency domain. The above approaches are applicable to normalized mean of backscattered signal from sea surface. This analysis is performed by using real recorded sea clutter radar data which provided to our research group by SET 215 Working Group on 'SAR radar techniques'. The Fractal Dimension criterion uses the 'blanket' technique providing sea state characterization from SAR radar range profiles. This method is based on the calculation of the area of a 'blanket', of normalized mean of range profile spectrum. The main idea concerning both 'Variance' and 'Fractal Dimension' proposed techniques is the fact that SAR radar range profiles corresponding to different sea states yield different values of variance and fractal dimension, namely 'turbulent sea' yields range profiles with larger variance in time and frequency domain and larger fractal dimension of signal spectrum because of the more 'anomalous behavior' of the range profiles in those cases. As a result, two sea state characterization techniques for two different sea states (turbulent and calm sea) are presented in this paper.

1. INTRODUCTION

Fractal geometry was introduced by Mandelbrot [1] and has been gaining importance in recent years as a mathematical model for different applications, such as image analysis and classification [2], applied electromagnetism etc. [3] - [7]. Fractals is a very effective method for describing physical objects with a high degree of geometrical complexity which have fine structures (details on arbitrarily small scales) and they are too irregular to be described by Euclidean geometry, appearing self-similarity at different scales [5].The main characteristic of fractals is the self-similar structure at many different scales. Consequently, fractals can descrybe a variety of geometrical complexity of data and also finds applications in characterizing scattering from fractal surfaces [5].

Previous studies indicate that the fractal surfaces permit form expressions for the scattering coefficients under the Kirchhoff approximation [9] and using a fractal function a rough surface scattering can be modelled [7], [8]. For several years great effort has been devoted to the study of clutter analysis based on the fractal characterization of the signal [5], [6] and [9] - [11].

The main objective of this paper is to examine the sea state characterization problem using an analysis of real radar backscattered signals from the sea surface (sea clutter), aiming to estimate the sea state. This paper presents two methods for sea state characterization by using: first, the variance of the mean spectrum of the range profiles and, second, the calculation of the fractal dimension of the range profiles [11]. These methods have been applied in this paper to real experimental Synthetic Aperture Radar (SAR) data [11].

Previous studies used the same experimental one – dimensional radar signatures to provide useful information about sea state characterization [12]. The objective was to use the fractal dimension of the experimental radar signatures as an additional tool for sea surface characterization.

The sea clutter radar data that were used collected during the 'NEMO 2014' trials in Taranto, Italy, using an FFI (i.e. 'Norwegian Institute of Defense', Oslo, Norway) PicoSAR X-band radar as input to a specific SET Working Group. The trial took place in the Taranto bay in southern Italy on 23 and 24 September 2014 where the first day the weather was quite windy, creating a turbulent sea, correlated to the second day, during which the sea surface was almost calm.

2. PROBLEM GEOMETRY AND STATEMENT

The geometry of sea state characterization problem is shown in Fig. 1. The helicopter flying vertically while maintaining its position on latitude and longitude fixed, used a PicoSAR radar transmitting to the sea, radar pulses and receiving data measurements. The experiment focused on up-wind direction towards the sea which means that the azimuth angle of the radar was with high sampling density in grazing angle.

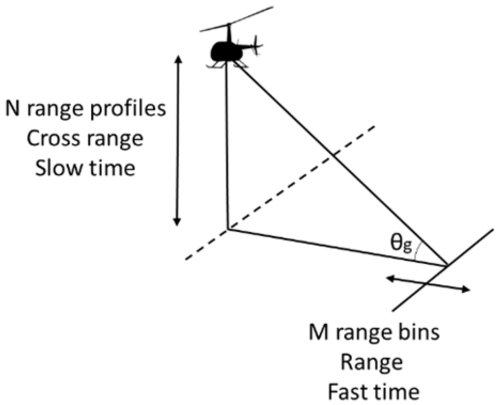


Figure 1. Geometry of the problem

The first day (23/9/2014) of the trial the wind speed was 10-12m/s. The radar azimuth (antenna beam) kept on the direction of the wind (upwind) within a 20° window in the horizontal (azimuthal) direction. The grazing angles as the helicopter was rising vertically ranged from 3° to 55° and the measurement time of the recorded grazing angle was approximately 5 minutes. For this reason it was assumed that the wind and sea conditions were almost constant during this short period.

The second day (24/9/2014) of the experiment, the wind speed was very low (1-2 m/s) and sometimes without wind. The sea clutter data was recorded for grazing angles from 4° to 54° with a slight drift in azimuth pointing angle of the bore sight of no more than 20 degrees.

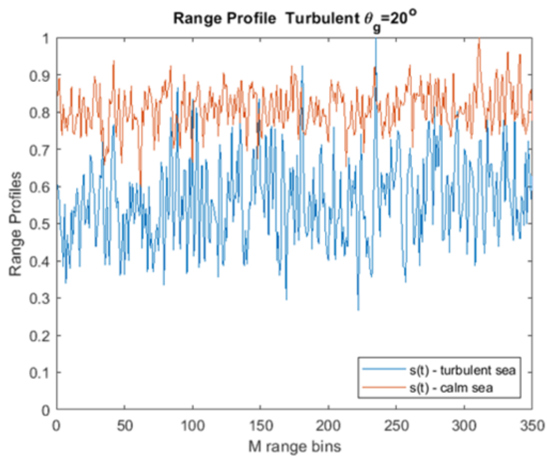
For the data used in our analysis the PicoSAR radar have the following characteristics: pulse width 12μs, bandwidth 150 MHz, PRF 1 kHz and operating frequency fs = 9.4GHz (X Band). The range to the scene center of the trial was 1850m for all grazing angles.

In our previous study of sea state characterization [12] we indicated a novel method of characterizing the sea surface using the 'Mean Fractal Length (MFL)' criterion which was applied to the same experimental Synthetic Aperture Radar (SAR) one – dimensional range profiles that we used in this research, applied on time domain.

However, several practical questions arise when dealing with our analysis to characterize a backscattered signal embedded in noise. To deal with this issue, we present an approach which initially implement averaging of the range profiles for avoiding noise. Determining how many samples of range profiles are required to derive a reasonably accurate estimate of the signal and after running simulations we chose N to be 50 range profiles to ensure that was quite enough to give an accurate result. Then, we normalized the mean signal range profile in range from 0 to 1 and transformed the backscattered signal in frequency domain.

In order to verify the validity of the sea state characterization method, we carried out several experiments in plenty of grazing angle from 5° to 32° as for angle greater than 32° it is noticed a strange behaviour of the signal, that may be caused by complicated physical phenomena and actual antenna beamwidth considerations.

Fig. 2 shows representative normalized mean radar backscattered radar signals for N=50 range profiles (1D radar signatures) in time domain as shown in figure on the top and frequency domain (power spectra) at bottom figure, for 'Day 1' (23-9-2014, 'turbulent sea') and 'Day 2' (24-9-2014, 'calm sea'), at grazing angle of θ_g = 20°.



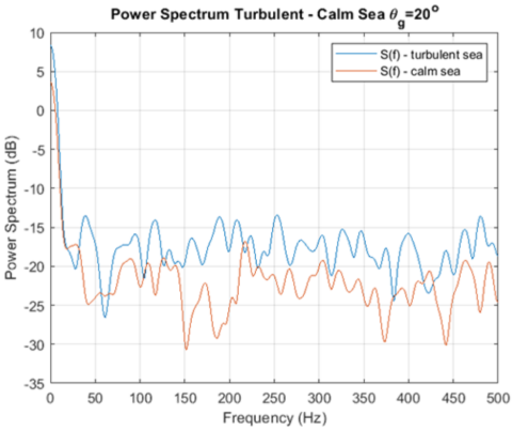


Figure 2. Representative PicoSAR radar range profiles at grazing angle θ_g = 20° for Day 1 (turbulent sea) and Day 2 (calm sea): (i) time domain (ii) frequency domain

As follows from Fig. 2(i), on 23 September 2014 the range of the corresponding values is approximately from 0.3 to 1. The power spectrum of these signals was estimated to determine the power indices.

Moreover during the following day of 24 September 2014, for the same grazing angles of 20°, but for 'calm sea' in this case, the range of values of the range profiles is approximately from 0.6 to 1.

The 'Variance (σ^2)' criterion is used for the sea state determination, which computes the variance of the normalized mean signal in time and frequency domain, for turbulent and calm sea, and at grazing angles from 5° to 30° (increasing every 5°). The Variance (σ^2) is given by eq. (1):

$$\sigma^2 = \frac{1}{fmax} \int_{f=0}^{fmax} (S(f) - S_m)^2 df \quad (1)$$

The 'Fractal Dimension' criterion is the second method that used for the sea state estimation which computes the fractal dimension of the normalized mean range profile in frequency domain, for turbulent and calm sea, and at grazing angle from 5° to 30° as well. The 'Fractal Dimension' is calculated using the 'blanket technique' that has been described briefly in previous study [12].

This criterion was chosen as fractal dimension is a measure of how much space a geometrical set fills [5]. Fractal dimension is a characteristic for fractals description and classification [13] as it makes meaningful the measurement of metric parts of fractal curves, which one of them is their length. The 'blanket' technique provides useful information for SAR image classification [2] and sea state characterization [12].

The 'upper and lower curves' of the 'radar range profiles' are indicatively shown at Fig. 3, for iterations δ=20 of the normalized mean of the backscattered signal on frequency domain (here for grazing angle θg=20°). To be noticed that, δ represents the 'iteration number', or, equivalently, the 'resolution'.

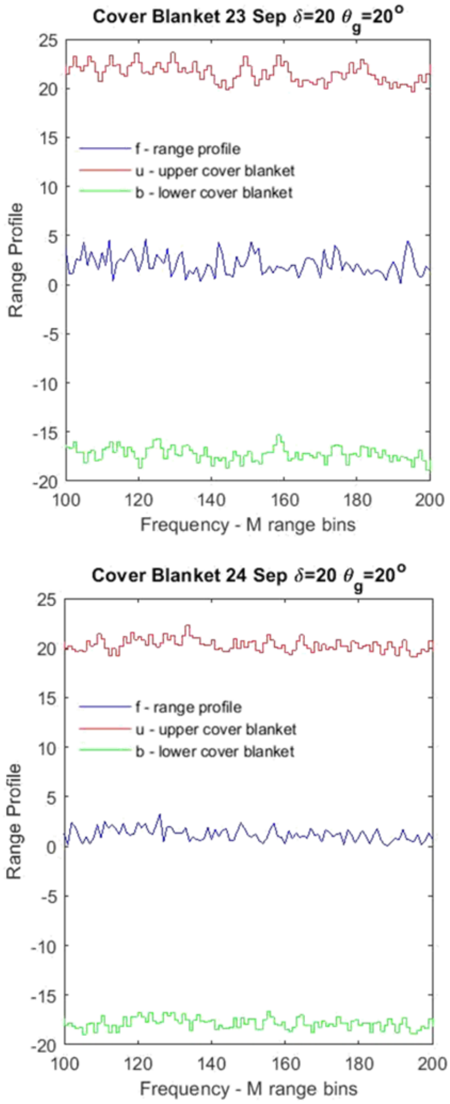


Figure 3. One-dimensional (1D) sea clutter signal and the 'upper' and 'lower' curves of the strip for iteration number δ=20.

3. SEA STATE CHARACTERIZATION RESULTS

The 'Variance (σ^2)' and 'Fractal Dimension' criteria are used for characterization of the sea state. The 'Variance (σ^2)' criterion computes the variance of normalized mean signal in time and frequency domain of N=50 range profiles, according to eq. (1). Then, numerical calculations similar to the above were performed, and the results are presented at Table I.

TABLE I. Variance (σ^2) values results for different sea states and grazing angles

Day / Angle	Frequency Domain		Time Domain	
	Turb	Calm	Turb	Calm
5°	0.288	0.043	0.010	0.003
10°	0.455	0.061	0.015	0.003
15°	0.591	0.055	0.016	0.004
20°	0.386	0.044	0.014	0.003
25°	0.404	0.015	0.014	0.002
30°	0.362	0.023	0.013	0.002

The results of Table I show that the 'variance' values of the radar normalized mean of N=50 range profile in time and frequency domain spectra during the turbulent sea state are significantly larger than the corresponding values at calm sea.

The 'Fractal Dimension' criterion computes the fractal dimension of the normalized mean for N=50 range profiles in frequency domain, using 'blanket' technique as briefly described in our previous research [12].The numerical calculations were performed, and the results are presented at Fig. 4 for grazing angles of 10° and 25°. Similar results measured for the grazing angles from 5° to 30°.

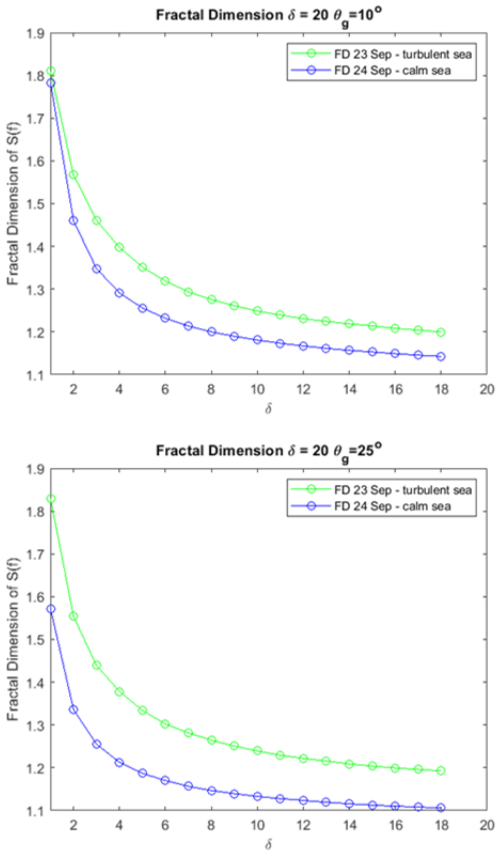


Figure 4. Fractal Dimension $F_D(\delta)$ as a function of resolution δ for grazing angles (i) 10° (upper figure) and (ii) 25° (lower figure).

The results of Fig. 4 show that the fractal dimension values of radar normalized mean of N=50 range profile spectra during the turbulent sea state are significantly larger than the corresponding values at calm sea.

Finally, the Sea State Index (SSI) is calculated for both 'Variance' and 'Fractal Dimension' criteria. The sea state indexes (SSI) use the values for calm sea as reference. The corresponding results for SSI are shown at Table II, below.

TABLE II. Sea State Index (SSI) for 'Variance' and 'Fractal Dimension' criteria for different grazing angles

SSI / Angle	Frequency Domain		Time Domain
	Variance	Fractal Dimension	Variance
5°	6.604	1.033	2.965
10°	8.894	1.058	4.686
15°	10.645	1.034	3.813
20°	8.670	1.056	4.216
25°	25.508	1.111	6.590
30°	15.297	1.073	5.042

From the above numerical results we conclude that the 'variance' and 'fractal dimension' criteria are suitable for 'radar range profile data' in the frequency domain, while the 'variance' criterion only is suitable for sea state determination in the time domain.

4. CONCLUSIONS

This paper proposes the use of two criteria for the characterization of the sea state using *normalized* experimental 1D radar signatures (range profiles). 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)

Concerning the 'Fractal Dimension' criterion, described above, the fractal geometry theory and, especially, the 'blanket' method was applied to the analysis of the sea clutter radar data that had been recorded from sea surfaces. The experiment measured backscattered signals from sea surface for turbulent and calm sea. The sea clutter radar data initially implemented averaging for avoiding noise and then normalized and transformed in frequency domain.

The use of 'Variance σ^2' and 'Fractal Dimension' criteria described above were found to be suitable criteria for sea state determination, as described above.

5. FUTURE RESEARCH

In our future related research, we intend to establish the above criteria in a more accurate fashion. Furthermore, we intend to further establish more accurate sea state characterization techniques in a variety of sea state conditions, if possible.

6. ACKNOWLEDGMENT

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