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

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Abstract

This paper presents a novel method of sea state characterization using the 'Mean Fractal Length (MFL)' criterion which is applied to experimental Synthetic Aperture Radar (SAR) one – dimensional signatures (range profiles), provided to our research group by SET 215 Working Group on 'SAR radar techniques'. The MFL criterion uses the 'blanket' technique to provide sea state characterization from SAR radar range profiles. It is based on the calculation of the area of a 'blanket', corresponding to the range profile under examination, and then on the calculation of the corresponding 'Fractal Length' of the range profile. The main idea concerning this proposed technique is the fact that SAR radar range profiles corresponding to different sea states yield different values of 'Fractal Length, FL', namely 'turbulent sea' yields range profiles with larger FL, because of the more 'anomalous behavior' of the range profiles in that case. 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]. 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 [1]. In addition, fractal objects have unique properties and features that may be related to their geometric structure [2].

The main objective of this paper is to examine the sea state characterization problem using the 'Mean Fractal Length' (MFL). The MFL criterion is a 'product' of the 'Modified Fractal Signature' (MFS) method, which has been applied in the past to real Synthetic Aperture Radar (SAR) images, using the 'blanket' technique, in order to provide useful information about SAR image classification, as reported by Malamou et. al. [1].

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, EXPERIMENTAL 1D RADAR DATA SETS, THE 'STRIP' FRACTAL TECHNIQUE AND PRELIMINARY NUMERICAL RESULTS USING THE 'STRIP' TECHNIQUE

The geometry of the sea state characterization problem is shown in Fig. 1. Here, a helicopter (with PicoSAR radar inside) rises vertically, while 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 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 of 10 to 12 m/s (rather high wind speed) and the helicopter pilot kept the direction of the antenna beam up-wind (i.e. 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 55°. The time of the full grazing angle span was around 5 minutes.

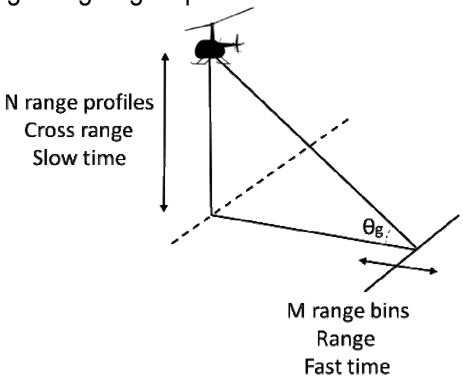

Figure 1. Geometry of sea state characterization problem, where the helicopter rises vertically transmitting PicoSAR radar electromagnetic (EM) pulses towards the sea

During the second day (24/9/2014), the wind speed was very low (1-2 m/s, which sometimes died out locally) and the range of grazing angles was from 4° to 54° with a slight drift in azimuth pointing angle of the bore sight of no more than 20°.

Fig. 2 shows representative radar range profiles (1D radar signatures) from 'Day 1' (23-9-2014, 'turbulent sea') at grazing angles of $\theta_g = 35^0$ (figure on the top), and from 'Day 2' (24-9-2014, 'calm sea'), for $\theta_g = 35^0$ (bottom figure).

As follows from Fig. 2 (i) on 23 September 2014 the grazing angle was chosen, from 35º to 36º (for 'turbulent sea'), with corresponding maximum value of approximately 15,000.

Additionally, as it can be seen from Fig. 2 (ii), during the following day of 24 September 2014, for the same grazing angles of 35º to 36º, but for 'calm sea' in this case, the approximate maximum value of the range profiles was approximately equal to 1,600.

The 'Mean Fractal Length (MFL)' criterion was used for the sea state determination, which computes the mean of the 'Fractal Length' of the range profile, for turbulent and calm sea, and at grazing angles of 35° and 40° as well. The MFL is given by eq. (1):

$$< FL >= \frac{1}{N}\sum_{n=1}^{N}(FL)_n \qquad (1)$$

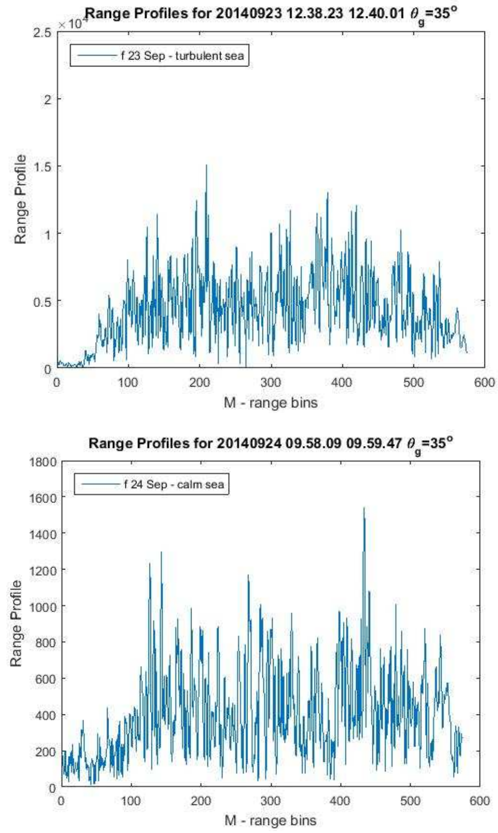

Figure 2. Representative PicoSAR radar range profiles: (i) Day 1, (turbulent sea) grazing angle θg = 35⁰, (ii) Similarly, but for Day 2 (calm sea)

In this Section, it remains to explain how the 'Fractal Length, FL' is calculated. For this reason, the 'blanket technique' will be described briefly [1], [3].

First, for measuring the lengths of irregular curves, S. Peleg et. al. used a 'Mandelbrot method' [3]. In this example, the curve is shown at Fig. 3 (inner curve, out of 3 curves). Considering all points with distances to this curve no more than ε, a strip of width 2ε is formed. This strip creates a 'strip' (2D case examined here, or 'blanket', in the corresponding 3D case), above and below the inner curve, as shown at Fig. 3, which means that all points at distance ε cover the curve within a 'strip' of thickness 2ε. According to S. Peleg et. al. [3], the 'upper' and 'lower' curves of the 'strip' are provided by the following equations:

$$\boldsymbol{u_\varepsilon(i,j) = max\,\{u_{\varepsilon-1}(i,j) + 1, \max_{|(m,n)-(i,j)|\le 1} u_{\varepsilon-1}(m,n)\}} \qquad (2)$$

$$\boldsymbol{b_\varepsilon(i,j) = max\,\{b_{\varepsilon-1}(i,j) - 1, \max_{|(m,n)-(i,j)|\le 1} b_{\varepsilon-1}(m,n)\}} \qquad (3)$$

Eq. (2) ensures that the new upper curve u_ε is higher at least by one than $u_{\varepsilon-1}$, and also at a distance of at least one of $u_{\varepsilon-1}$ in the horizontal and vertical directions [3].

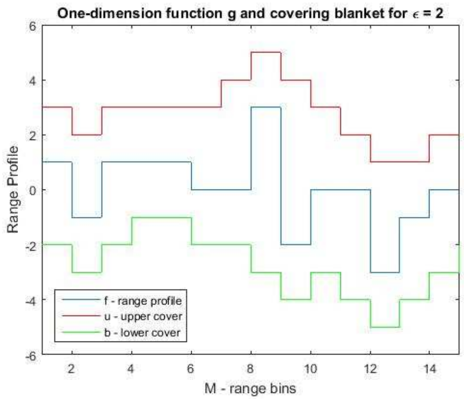

Figure 3. One-dimensional (1D) function g and the 'upper' and 'lower' curves of the strip for iteration number ε=2.

The 'area' υ_ε of the 'strip' is calculated from u_ε and b_ε by :

$$v_\varepsilon = \sum_{i.j} (u_\varepsilon(i,j) - b_\varepsilon(i,j)) \tag{4}$$

The 'fractal length, FL' $L(\varepsilon)$ of the curve is approximately calculated through the subtraction of the strip areas of radii ε and ε-1 divided by 2, or from the area of the 'strip' divided by 2ε, as shown below :

$$L_\varepsilon = \frac{(A_\varepsilon - A_{\varepsilon-1})}{2} \tag{5}$$

$$L_\varepsilon = \frac{A_\varepsilon}{2\varepsilon} \tag{6}$$

The fractal length $L(\varepsilon)$ as a function of the 'resolution' ε ($\varepsilon=1$ corresponds to 'full resolution), for the curve of Fig. 3 [3], is shown at Fig. 4, on a log-log scale (here the plot consists of straight segments, because the curve is ideally fractal. In contrast, the curve would not have to be straight for non - fractal curves [3]).

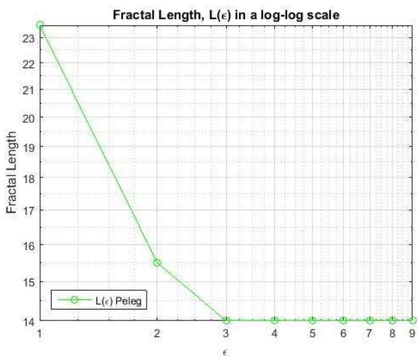

Figure 4. Fractal length L(ε) as a function of resolution ε (ε=1) corresponds to 'full resolution') in log-log scale for one-dimensional (1D) curve g.

In addition, previous research by Malamou et. al. [1], regarding use of the 'Modified Fractal Signature (MFS)' method, which was applied to real Synthetic Aperture Radar (SAR) images, used the 'blanket' technique (in 3D case), to provide useful information for SAR image classification.

The 'Fractal Length technique', as explained above, is now applied to the recorded radar raw data which were provided to us by SET 215 Working Group, as explained above.

The 'upper and lower curves' of the 'radar range profiles' using the Modified Fractal Signature (MFS) method, are indicatively shown at Fig. 5, for different iterations ε = 1 and 20 of the original range profile (here for grazing angle θg = 35°). Note that throughout this Section, ε represents the 'iteration number', or, equivalently, the 'resolution'.

Examining the plots at Fig. 5 it is obvious that as the number of iteration ε increases (i.e. 'resolution' becomes poorer), the covering blankets become more 'extensive'.

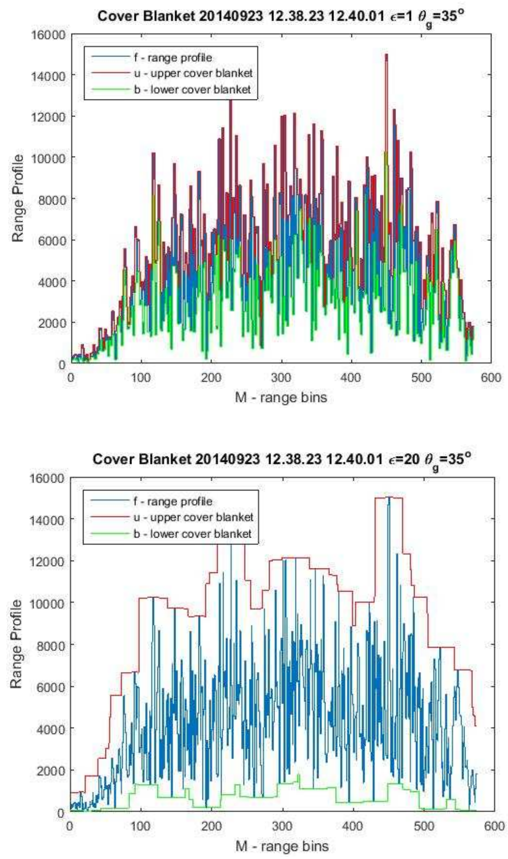

Figure 5. Upper and lower curves for a 'radar range profile' provided to us by FFI, for different scale (iteration) of the MFS method, ε = 1 and 20 respectively (radar range profile used here was for grazing angle θg =35°).

3. SEA STATE CHARACTERIZATION RESULTS USING THE 'MEAN FRACTAL LENGTH (MFL)' CRITERION

The 'Mean Fractal Length (MFL)' criterion is used for characterization of the sea state. The 'Mean Fractal Length (MFL)' Criterion computes the mean of the Fractal Length of the range profile, according to eq. (1).Then, numerical calculations similar to the above were performed, and the results are presented at Fig. 6.

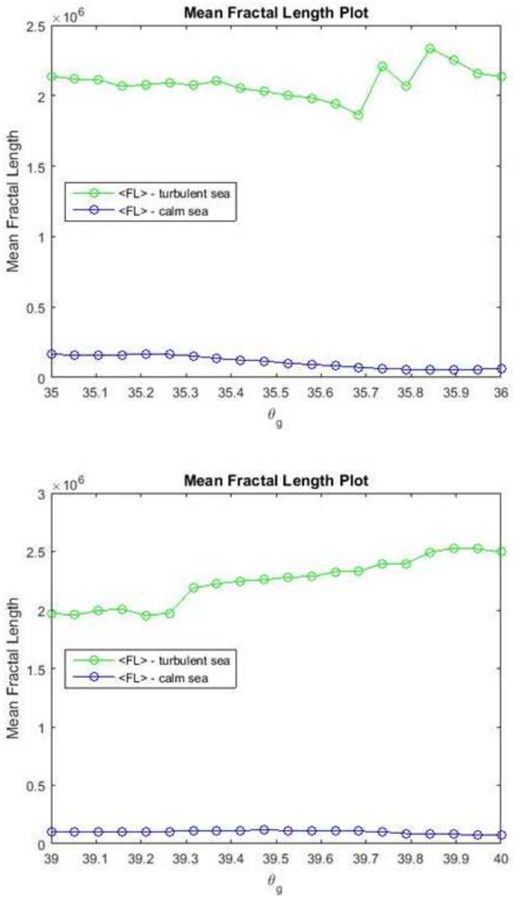

Figure 6. 'Mean Fractal length' (MFL) values of radar range profiles at different sea state [turbulent (green lines) and calm sea (blue lines)], for grazing angles (i) 35° to 36° (upper figure) and (ii) 39° to 40° (lower figure).

The results of Fig. 6 show that the MFL values of radar range profiles during the turbulent sea state are significantly larger than the corresponding values at calm sea, as shown at Table I.

Table I. MFL values results for different sea states

MFL \ Date	**23 Sep 2014 (turbulent sea)**	**24 Sep 2014 (calm sea)**
θg= 35°- 36°	2,090,761	110,631.9
θg= 39°- 40°	2,241,509	100,038.9

Finally, and similarly to above, the sea state index (SSI) is calculated once again for this case. Once again, the 'MFL value' for calm sea was chosen as the reference value. The corresponding results for SSI are shown at Table II, below.

Table II. MFL sea state index (SSI) for different grazing angles

	SSI
θg = 35°- 36°	18.89
θg = 39°- 40°	22.40

Concluding with the above criterion for sea state characterization by using radar range profiles (1D radar signatures), it is evident, from physical intuition that the 'mean fractal length', (MFL) is a reliable criterion for 'real time' sea state characterization, in practical circumstances (because of the presence of additive noise in 'real life' scenarios, etc.).

4. CONCLUSIONS

To summarize, for the characterization of the sea state from experimental 1D radar signatures (range profiles), the 'mean fractal length' (MFL) criterion was used. 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 criterion was found to be suitable and it can be used for sea state characterization. Other criteria for sea state determination, which are, however, of less importance than that described above, will also be presented during our presentation at the Conference.

5. FUTURE RESEARCH

In our future related research, we intend to concentrate on more accurate sea state characterization using a *variety* of sea surface radar range profiles, i.e. in a variety of sea state conditions.

Finally, sea state characterization using fractal characteristics of SAR radar *images* (i.e. 2D SAR radar signatures) may be used, instead of 1D radar signatures, examined here.

6. ACKNOWLEDGMENT

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