A Wavelet Technique to Extract the Backscatter Signatures from SAR Images of the Sea

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Abstract— SAR images of the sea often show backscatter patterns linked to the horizontal structure of the Marine Atmospheric Boundary Layer (MABL) at the interface with the sea surface. In general, their dimensions are spread over a wide range of length scales, presenting spatial periodicity as well as intermittence. With the aim to isolate such backscatter structures, the two-dimensional Continuous Wavelet Transform (CWT2) analysis has been applied to SAR images of the sea. The CWT2 analysis permits to highlight the backscatter cells associated to the structure of MABL, as well as to evidence the structure of the atmospheric gravity waves occurring at the lee side of islands and coast. The cells detected in the range 0.3 km ÷ 4 km are directly associated to the wind spatial structure deriving, in turns, from the turbulent characteristics of the wind flow. They have an elliptic shape, with the major axis along the (aliased) wind direction. Those with size falling inside the spatial range 4 km ÷ 20 km describe, instead, the atmospheric gravity waves structure (if present) and the structures linked to the wind shading. The technique developed is the background for several applications: it has been used to compute the wind fields without any a priori information, as well as to study the inner structure of the Langmuir atmospheric circulation. Other applications could be on the detection of sea surface oil slicks.

1. INTRODUCTION

The increased availability of satellite Synthetic Aperture Radar images over the sea and coastal areas imposes on scientists the development of methods to extract geophysical information from the detailed maps of the radar backscatter. Scientific literature about SAR images over the ocean has shown a variety of geophysical phenomena detectable by SAR [1, 7–11, 15], including the multiscale structure in the atmospheric turbulence under high winds and the structure of the convective turbulence under low wind. More recently, some effort has been devoted to evaluate the wind direction, using the backscatter signatures produced by the atmospheric wind rolls or those occurring at the lee side of islands [12] as effect of wind shielding, by computing the local gradient of the image backscatter [5, 6] or by using the two dimensional Continuous Wavelet Transform (CWT2) [13, 14].

This paper outlines the possibilities offered by the CWT2 in detecting and quantifying the backscatter structures linked to the spatial structure of the Marine Atmospheric Boundary Layer (MABL), both in the small (0.3 km ÷ 4 km) and in the intermediate (4 km ÷ 20 km) ranges. It summarises the CWT2 methodology applied to SAR images, providing the results obtainable by showing a case study chosen among the hundreds of images analysed.

2. THE METHODOLOGY

The Continuous Wavelet Transform [2, 4] $\tilde{f}$ of a function $f(u)$ is a local transform, dependent on the parameters $s$ and $\tau$, defined as

$$\tilde{f}(s, \tau) = \langle \psi_{s,\tau}, f \rangle = \int_{-\infty}^{+\infty} du \, \psi_{s,\tau}^*(u) f(u)$$

where $\psi_{s,\tau}(u) = |s|^{-1} \psi \left( \frac{u-\tau}{s} \right)$ is the mother wavelet at a given scale (or dilation) $s$ and location $\tau$ (the asterisk denotes complex conjugation). The quantity $|\tilde{f}(s, \tau)|^2$ plays the role of local energy density at given $(s, \tau)$. The Continuous Wavelet Transform in two dimensions (CWT2) is then,

$$\tilde{f}(s_x, \tau_x; s_y, \tau_y) = \int_{-\infty}^{+\infty} du \, \int_{-\infty}^{+\infty} dv \, \psi_{s_x,\tau_x}^*(u) \psi_{s_y,\tau_y}^*(v) \, f(u, v).$$
The CWT2 has been computed using the Mexican Hat as mother wavelet, able to capture the fine scale structure of the data and suitable for the continuous wavelet transform because it is non-orthogonal.

The images must be preprocessed before the CWT2 analysis, to mask the land and to mitigate the effects introduced by the variation in range of the radar incidence angle to avoid that structures on the inner part of the image, where the radar incidence angle is smaller and the radar backscatter higher, prevail on the outer ones.

The choice of the scales range is very important because it defines the geophysical phenomena to investigate: if the wind field retrieval is of interest, the spatial range is set from 300 m to 4 km; if phenomena such as the atmospheric gravity waves are the object of study, the spatial range has to be set from 4 km up to 20 km.

A basic quantity yielded by the CWT2 is the wavelet variance map, derived from the wavelet coefficients. Providing information about the energy distribution as a function of \((s_r, s_c)\), in the same way as the two dimensional Fourier spectrum does as a function of wavenumbers, it is used to select the scales, taken around the maximum of the wavelet variance map, to built a SAR-like map (reconstructed map). This is obtained adding the wavelet coefficient maps at the selected scales: a SAR-like image is thus obtained, representing a spatial pattern due to only the most energetic spatial scales present in the original SAR image.

The reconstructed map undergoes a thresholding process to isolate the structures from the background. The result of this procedure is a map of backscatter cells, then used as a mask on the original SAR image to get the values of the Normalised Radar Cross Section inside the detected cells, as well as to estimate their shape and size. The reconstructed map depends on the range of scales used in the analysis. Thus, the CWT2 methodology shown here acts as a filtering procedure based on energetic considerations.

3. A CASE STUDY

Among the hundreds images processed with the methodology above described, we present an Envisat ASAR Wide Swath \([3]\) image taken in the eastern Mediterranean Sea in the Crete island area (Fig. 1). This image covers about 400 km by 400 km, with a pixel resolution of 75 m by 75 m.

While the fine structure (O(1 km)) of the radar backscatter is not well visible, masked by the tilting effect due to the change of the radar incidence angle — from 16° on the right side to 43° on the left side, larger structures such as the atmospheric gravity waves and wind sheltered areas at the islands lee side (the wind blowed from northwest) are detectable by eye.

The map reconstructed in the range 0.3 km ÷ 4 km, shown in the left panel of Fig. 2, evidences the small scale structure of the radar backscatter, formed by elliptic cells with a major axes orien-
tation falling into two classes, roughly 90° apart, as evidenced in the right panel of Fig. 2, which reports the frequency distribution of the orientation of the cells’ major axis. The existence of these two classes is due to the texture of the SAR images, and does not represent the geophysical pattern of the backscatter cells excited by the turbulent wind. These may be extracted considering those with directions close to the most probable one, in this case $\theta = 300°$. Thus a reconstructed map with only the cells produced by the wind can be obtained. Fig. 3 reports it for the whole image of Fig. 1 (left panel) and for a portion of it. Note the uneven spatial distribution of the cells but also the high spatial resolution of information obtained. From this map, used as a mask over the original one, it is then possible to retrieve the wind field [14] and to produce a statistics of the cell’s size, which may have important implications of the study of the air-sea interaction because it can be linked to the structure of the MABL.

Figure 2: Map reconstruction in the spatial range 0.3 km ÷ 4 km. Left panel: the reconstructed map. Right panel: the frequency distribution of the orientation of cells’ major axis.

Figure 3: Reconstructed map with only the cells produced by the wind. Left panel: whole map, corresponding to Fig. 1. Right panel: a blow up of it.
The map reconstructed in the range $4\,\text{km} \div 20\,\text{km}$, reported in the left panel of Fig. 4, clearly shows the pattern of the atmospheric gravity waves in its upper right part. The two dimensional spectral analysis of this map yields the 2D spectrum shown in the right panel of Fig. 4, where two directions are evidenced: that of the maximum energy, occurring at a peak wavelength of 8350 m and an aliased direction of propagation of $296^\circ$, and a secondary one, due to the presence of different atmospheric gravity wave trains in the image, with a peak wavelength of 16.7 km and a direction of $63^\circ$. This does not really represent a geophysical phenomenon different from that evidenced by the primary peak.

These information may be used, as in [11], to estimate the vertical thickness of the MABL.

![Map reconstruction](image)

Figure 4: Map reconstruction in the spatial range $4\,\text{km} \div 20\,\text{km}$. Left panel: the reconstructed map. Right panel: the 2D power spectrum of the reconstructed map.

4. CONCLUSIONS

The described methodology has been applied over hundreds of SAR images, demonstrating its robustness and its capability to detect the most energetic backscatter signatures over the sea. These are strongly related to the horizontal structure of the MABL, roughly from 0.6 km to 10 km, where micro-scale (convection, thermals, dynamical instabilities) and meso-scale (thunderstorms, atmospheric gravity waves and orographic disturbances) atmospheric phenomena occur.

The case study shown here indicates a common feature of the radar backscatter from the sea surface: its complexity, deriving both from the complexity of the MABL and the possibility of wrong interpretation of the backscatter signatures. For instance, the secondary peak in the 2D power spectrum shown in the right panel of Fig. 4 does not represent any other atmospheric phenomenon but it is only produced by the simultaneous presence of different wave trains. This prevents of extract geophysical quantitative information directly from the SAR images, which must be deeply processed instead.

The ongoing research is aimed to derive a statistics on the performances of the model, especially for the wind speed estimations, since the possibility to compare the results with scatterometer wind fields. Future research will be devoted to derive further quantitative geophysical information from the structure of the MABL evidenced by the CWT2 analysis.

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REFERENCES


