IL NUOVO CIMENTO Vol. 24 C, N. 1 Gennaio-Febbraio 2001

Wavelet analysis applied to SAR images to detect atmospheric structures(*)

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(ricevuto il 2 Novembre 1999; revisionato il 19 Maggio 2000; approvato il 26 Giugno 2000)

Summary. — The aim of this work is to evaluate the possibilities offered by the wavelet analysis in the study of the spatial structure of the radar backscatter, which is linked to the spatial structure of the marine atmospheric boundary layer. Continuous wavelet analysis has been applied to a SAR image of the sea surface, previously analysed by the more classical Conditional Sampling technique. The main problem coped with has been to select, among the large number of wavelet maps produced by the analysis (256), those containing the more energetic backscatter structures. Since the phenomenon imaged by SAR was the convective turbulence, a multiscale and quasi-periodic or intermittent process, a selection of wavelet maps according to their mean energy was unsuccessful. On the contrary, a method based on the calculation of the standard deviation of the less probable highest wavelet amplitudes led to a right selection of the wavelet maps and to a convincing reconstruction of the map of backscatter structures, which resulted similar to that provided through the Conditional Sampling.

PACS 92.60.Fm – Boundary layer structure and processes.
PACS 92.10.Kp – Sea-air energy exchange processes.
PACS 05.45.Tp – Time series analysis.
PACS 47.27.Nz – Boundary layer and shear turbulence.

1. – Introduction

Over the sea, the Synthetic Aperture Radar (SAR) images provide such a wealth of details of the sea surface structure, to make often their interpretation difficult and doubtful. This occurs, for instance, when oceanographic (vortices, current fronts, wave etc.) and meteorological (orographic disturbances, wind rolls, convective turbulence, etc.) signatures are present at the same time in an image. The information obtainable through the visual inspection of the images is not sufficient any more, and the necessity

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(*) Paper presented at the Workshop on Synthetic Aperture Radar (SAR), Florence, 25-26 February, 1998.

to go towards an objective way to detect and to quantify the number and the dimension of the backscatter structures exhibited by the images is felt.

While quantitative information may be actually derived for the waves [1-3] and for the wind field [4-8] it is still a challenge to detect non-periodic structures often occurring in the nature, both in the ocean and in the atmospheric boundary layer.

There are several papers [9-19] dealing with the investigation of the marine atmospheric boundary layer through the SAR images. Among them [19] used a technique of Conditional Sampling to reveal backscatter structures from a SAR image, to estimate their two-dimensional size and to relate them to the convective turbulence in the atmospheric boundary layer.

Owing to the intrinsic difficulties in using the Conditional Sampling, as well as to have further tool in the SAR image analysis, attention has been addressed to the wavelet analysis. It is important to point out the difference between the two techniques cited in this paper: Conditional Sampling is based on the analysis of the local variance, while Continuous Wavelet is a signal decomposition based on a probe function (the mother wavelet).

This work is structured into four more sections. Section **2** is devoted to present the case study and to describe the analysis already done on the SAR image [19], which represents the starting point of this work. Section **3** briefly introduces the wavelet analysis, providing some detail about the method followed to obtain the results, presented in sect. **4**. Discussion follows in sect. **5**. Last section is devoted to the conclusions.

2. – The SAR image and the VISA analysis

A small portion (~ 2.2 km by 2.2 km) of the original SAR image (18 km by 27 km), taken in October 1990 in the northern Adriatic Sea by an airborne SAR at C-band (5.31 GHz), is shown in fig. 1. The area is offshore the Venice coast, around the oceanographic platform “Acqua Alta” of the Italian National Research Council (CNR).

The mean wind speed was low (3.8 m s^{-1}) and the air-sea temperature $\Delta T = -4°\text{C}$. The wind direction (35°) resulted parallel to the image rows, approximatively from left to right in fig. 1.

A sequence of bright and dark patches of the radar backscatter, elongated in the cross-wind direction (and thus anisotropic) is clearly recognizable in the image. The white patches of hundreds meters represent areas of stronger radar return, where the sea surface roughness, excited by the wind, has more energy. Their spatial layout results from the imprint of the atmospheric boundary layer on the sea surface.

The Variable Interval Space Averaging (VISA) analysis has been applied to the image of fig. 1, in order to extract the shape and the dimension of the more energetic backscatter structures. The VISA analysis is a version of a Conditional Sampling technique, first developed by [20].

Given an experimental series of the variable z in the x domain, VISA analysis consists of the computation of its normalised short-interval variance $\sigma^2_{s,z}(x)$,

$$\sigma^2_{s,z}(x) = \frac{\text{var}(z)}{\sigma^2_z} = \frac{1}{\sigma^2_z}\left[\frac{1}{x_a}\int_{x-\frac{x_a}{2}}^{x+\frac{x_a}{2}} z^2 \text{d}x - \left(\frac{1}{x_a}\int_{x-\frac{x_a}{2}}^{x+\frac{x_a}{2}} z \text{d}x\right)^2\right], \tag{1}$$

where x_a is the short interval and σ^2_z the overall variance of the data series (long-term variance). Equation (1) acts as a band pass filter of about $1.3\,x_a$.

Fig. 1. – A portion of 256 by 256 pixel (2150 m by 2150 m) of the original SAR image. Pixel size: 8.4 m.

The image of fig. 1 has been transformed into a map of the variance applying eq. (1) to each row. The result is shown in fig. 2. The areas of high variance (white areas) appear as couple of white filaments elongated crosswind. Fairly complicated considerations concerning the mean shape of the wind stress as well as the shape of the ensemble average of the radar backscatter in the areas of high variance [19] led to consider only the patches on the left of the couples related to the convective turbulence cells.

It is of interest to evaluate if the above results may be obtained also applying the continuous wavelet technique to the SAR image.

3. – The two-dimensional Continuous Wavelet Analysis

There exists a considerable literature concerning the wavelet analysis (for instance [21, 22], to which the reader is addressed. In this section only the quantities used in this work are presented.

Applied to a spatial data series $z(x)$, the wavelet analysis provides the wavelet coefficients $C_x(s_x, X)$

$$C_x(s_x, X) = \frac{1}{\sqrt{s_x}} \int z(x) W^* \left(\frac{x - X}{s_x} \right) \mathrm{d}x \,,$$

where $W(\frac{x-X}{s})$ is the mother wavelet translated by X and scaled by a factor s. The

Fig. 2. – Image of the normalised short-interval variance obtained from eq. (1) applied to the SAR image of fig. 1. The couples of white filaments represent the areas of high variance. Only the left side of the coupled structures is connected with the wind stress. Image size: 256 by 256 pixels (2150 m by 2150 m). Pixel size = 8.4 m.

wavelet used here is the complex Morlet [23], *i.e.*

$$W(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2} e^{ik_0 x} \tag{2}$$

with $k_0 = 5$ to ensure that $\overline{W(x)} \approx 0$.

Using the Morlet wavelet, the scale s is proportional to the wavelet wave number k_{wlt}. The square modulus of $C_x(s_x, X)$, which represents the local energy of the process at the scale s and position X, is the wavelet spectrum.

Examples of using wavelet analysis with the Morlet wavelets for one-dimensional time series may be found in [22].

The analysis has been carried out separately to the image rows and columns, obtaining respectively the wavelet coefficients $C_x(s_x, X)$ and $C_y(s_y, Y)$. Sixteen scales have been analysed, corresponding to wavelengths from 50 to 500 meters. Therefore, 256 maps of wavelet coefficient $C(s_x, s_y, X, Y) = \dfrac{C_x(s_x, X) + C_y(s_y, Y)}{2}$ have been obtained. This large number of wavelet maps has brought the problem to select those representing the more energetic backscatter structures, as well as of presenting the results in a readable form. Next section will show how these problems have been tackled.

Fig. 3. – Reconstruction of the SAR image of fig. 1 obtained adding all the 256 wavelet maps $C(s_x, s_y, X, Y)$.

4. – Results

Figure 3 represents the reconstruction of the original SAR image obtained adding all the wavelet maps $C(s_x, s_y, X, Y)$ together. This image reveals the texture of the sea surface roughness: areas of high radar backscatter, corresponding to areas of stronger wind, have as a zigzag shape. The similarity of this reconstructed image with the original one (fig. 1) assures that the method works properly.

However, the interest is to isolate the more energetic structures present in the SAR image and not to use the wavelet analysis for image reconstruction. To this aim, we have to select, among the wavelet maps produced by the calculation, those containing more energy. The method followed has been to compute the standard deviation of the less probable highest wavelet amplitudes, those exceeding the 70 % probability distribution.

Figure 4 reports the standard deviation of each wavelet map $C(s_x, s_y)$ as a function of the wavelet wavelength. This map provides an indication about the anisotropy of the radar backscatter at all scales, as well as about their horizontal and vertical dimensions. Note that while isotropy is present in the upper left part of the image, corresponding to the smaller wavelengths, this is destroyed at $160 \leq \lambda_x \leq 200$ and $300 \leq \lambda_y \leq 500$ m. Thus, these are the scales we are looking for.

The map of the wavelet standard deviation helps thus to identify the wavelengths where asymmetry occurs (and hence the wavelet maps), in order to build an image with

Fig. 4. – Map of the standard deviation of the less probable highest wavelet amplitudes (value of amplitudes where the probability exceed 70%) as a function of the wavelets wavelength. Abscissae: wavelet wavelength for rows. Ordinate: wavelet wavelength for columns.

only the selected wavelet maps. Figure 5 represents the reconstruction of the SAR image in the wavelength range 160 m $\leq \lambda_x \leq$ 200 m and 300 m $\leq \lambda_y \leq$ 500 m.

The backscatter structures are well isolated, and their spatial arrangement results very similar to that of the normalised short-interval variance (fig. 2). An important result is that the backscatter couples are also reproduced. Some difference exists in the definition of the most elongated structures (for instance, that at $x = 170$ and $30 < y < 130$ in fig. 2 is split in three structures in fig. 5), but this seems rather a problem of imaging than of calculation.

5. – Discussion

There are two aspects of the results which deserve a discussion.

The first concerns the method to select, from the wavelet maps computed, those related to the most energetic backscatter structures. Different methods may bring to different results. While the average quantities, like the mean or the variance of the wavelet maps, are not suitable (only intermittent or isolated structures are of interest), the method which relies on the probability distribution of the wavelet map values seems more promising, as it worked in the present study. Further tests have to be carried out, however.

Fig. 5. – Reconstruction of the SAR image of fig. 1 obtained adding the wavelet maps $C(s_x, s_y, X, Y)$ corresponding to the wavelength $160 \leq \lambda_x \leq 200$ m and $300 \leq \lambda_y \leq 500$ m.

The second aspect concerns the comparison between the results provided by the VISA and the wavelet analysis. These are intrinsically different, since the former provides a map of the local variance of the SAR image, whereas the latter the map of the wavelet local amplitudes or energy, in a range of vertical and horizontal scales or wavelengths. Bearing in mind this difference, the identification of the backscatter structures singled out by VISA and wavelet analysis is acceptable.

6. – Conclusions

The VISA and wavelet techniques yield consistent results when applied to a SAR image. They are, to some extent, complementary and they should be both used in the analysis of intermittent backscatter structures. VISA suffers for the indetermination of the short interval and of the threshold definition, but then it has not any constraints about the scales of the phenomena to detect and runs fast. Wavelet technique, instead, requires a methodology to select from the resulting maps those pertinent to the phenomena of interest, as well as a prior definition of the scales, which may be inconvenient when the phenomenology imaged by SAR in unknown. A too fine resolution of the scales may yield an impracticable computing time.

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This work has been funded by the Italian Space Agency (ASI).

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