ROUGHNESS PARAMETERS ESTIMATION OF SEA SURFACE FROM SAR IMAGES

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ABSTRACT

Some knowledge of sea state and conditions is input in ship detection algorithms based on inversion of scattering models for Synthetic Aperture Radar (SAR) images.

This paper shows a novel technique for the estimation of roughness parameters of the sea surface from SAR images. The estimation procedure is based on the minimization of the absolute error between the Radar Cross Section (RCS) of the sea surface measured on the SAR image and the expected RCS computed using the Kirchhoff approach within the Geometrical Optics (GO) solution. The technique is tested on three different TerraSAR-X images acquired in November 2012 over the Portsmouth harbour in the UK.

Index Terms— Synthetic Aperture Radar (SAR), scattering models, roughness parameters estimation, maritime surveillance, ship-detection.

1. INTRODUCTION

Maritime surveillance is a topic of growing interest during the recent years and the requests for monitoring the ocean pollution and tracking the movement of illegal cargos have increased. In particular, ship-detection represents one of the main applications in this field and the Synthetic Aperture Radar (SAR) is regarded as a useful technology to support the coastal monitoring and ships tracking thanks to its capability to acquire images independently from daylight and meteorological conditions [1].

Traditional ship-detection algorithms are based on CFAR (Constant False Alarm Rate) methods [2] where the sea clutter is modeled according to a suitable statistical distribution. The sea background is characterized statistically and then the detector looks for individual pixels (or small group of pixels) whose brightness values are statistically unusual. At this stage, only the ocean clutter is taken into account while the modeling (statistical or analytical) of ship targets is generally neglected to keep the overall model simple. As a consequence, the detector may result in a higher false-alarm rate [3]. In [4], the overall ship-detection performances are improved with an algorithm including a simplified model of a canonical ship through a proper scattering evaluation block. The canonical ship can be considered as a complex metallic object, which can be decomposed by using a series of rectangular facets (parallelepiped representation) and, consequently, the total component field can be obtained with a vectorial summation on each facet [5]. In addition, the computation of the Radar Cross Section (RCS) of large and complex targets involve different scattering mechanisms, such as specular reflection, diffraction by edge and tips, multiple scattering and shadowing effects [6]. In [4] only the electromagnetic field backscattered from a canonical ship is considered: single and multiple scattering contributions are isolated and located on a real SAR image and, finally, non-parallelepiped like targets are rejected to improve the detection performances. Each scattering contribution depends on different parameters: the dielectric constant of the water and the ship, the radar parameters, the orientation angle between the radar and the ship and the average roughness parameters of the sea surface. The estimation of these roughness parameters is then required for the evaluation of the multiple scattering contributions, whose analysis may lead to an improvement of the performances of the ship-detection algorithm introduced in [4]. In general, the field scattered from the sea surface depends both on its electromagnetic and geometrical aspects; but, while the evaluation of the dielectric constants of the sea is known in literature [7], the estimation of average roughness parameters of the sea surface with SAR is poorly addressed. In [8], for example, the roughness parameters of several bare fields are estimated by using a radar scatterometer in dual polarization. The main objective of this paper is to fill this gap by introducing a method to estimate these roughness parameters from the RCS evaluation of the sea surface and, as anticipated, use this knowledge to improve the ship-detection performance.

The paper is organized as follows: in section 2 the electromagnetic model for the backscattering from the sea surface is presented; in section 3 the inversion of the model to retrieve the roughness parameters is explained; in section 4 the datasets employed and the ground truth available are shown; in section 5 the results are reported and discussed and, finally, some future perspectives are considered.

2. ELECTROMAGNETIC MODEL

In this paper, building on [9], the sea surface is modeled as a Gaussian stochastic process with a Gaussian autocorrelation function, whose standard deviation and correlation length are represented by the parameters σ and *L* respectively. The correlation length represents the max distance between two points, at which the heights of the two points can be considered correlated. The standard deviation, instead, is a measure of how much the different heights of the Gaussian surface spread out; the higher the standard deviation is, the greater the probability to find a point at a height different form the average height is. It is clear from these definitions that the greater the ratio σ/L is the rougher the sea surface results; viceversa the lower $\sigma/L \rightarrow 0$ the sea surface is considered completely smooth.

In high frequency regime, where the dimensions of reflecting objects are much larger than the electromagnetic wavelength, the backscattered electromagnetic field is evaluable in the phasor domain in closed form by using the Kirchhoff approach (KA) within the Physical Optics (PO) or Geometrical Optics (GO) solutions according to the sea surface roughness. In particular, the PO approximation is applied if $k\sigma \ll 1$ where k is the radar wavenumber; viceversa the GO approximation is adopted if $k\sigma \gg 1$, [10]. Due to the wind, the sea surface is never completely smooth and presents several capillary waves [7]; for this reason the GO approximation has been chosen and it is the unique solution being analyzed in the following.

For the sake of simplicity, the analytical expression provided in [9] for the single backscattering from a rough surface is reported for the GO approximation:

$$\sigma^{0} = \frac{\left|S_{pq}\right|^{2}ab}{64\pi^{2}\cos^{2}\theta\sigma^{2}/L^{2}}exp\left(-\frac{tg^{2}\theta}{4\sigma^{2}/L^{2}}\right)$$
(1)

where σ^0 is the RCS of the sea surface; S_{pq} is the generic element of the scattering matrix with *p* and *q* standing for horizontal, *h*, or vertical, *v*, polarization, respectively; *a* and *b* are the dimensions of the rectangular portion of sea where the RCS is evaluated and θ is the radar look angle.

Equation (1) does not depend on the roughness parameters σ and L separately, but σ^0 is a function of the ratio σ/L ; however, given the nature of equation (1), it is not possible to invert it and retrieve a closed-form expression for the ratio σ/L . At this aim, numerical calculations are employed to estimate the ratio σ/L and the estimation technique is shown in the following section.

3. ROUGHNESS PARAMETERS ESTIMATION

In order to estimate the ratio σ/L , the absolute error (*E*) is considered in the following equation:

$$E = \left| \widehat{\sigma^0} - \sigma^0 \right| \tag{2}$$

where σ^0 is the RCS of the sea surface as measured on the SAR images and σ^0 is the RCS computed according to equation (1). Equation (2) can be rewritten as follows:

$$E = \left| \widehat{\sigma^{0}} - \frac{A(\varepsilon'_{sw}, \varepsilon''_{sw}, a, b, \theta)}{\sigma^{2}/L^{2}} exp\left(-\frac{B(\theta)}{\sigma^{2}/L^{2}}\right) \right|$$

$$A = \frac{\left|S_{pq}\right|^{2} ab}{64\pi^{2} \cos^{2} \theta} \quad \text{and} \quad B = \frac{tg^{2}\theta}{4}$$
(3)

where ε'_{sw} and ε''_{sw} are, respectively, the real and the imaginary part of the relative dielectric constant of the saline water; while *a* and *b* are the dimensions of the sea water area set equal to the pixel area. The parameters involved in the expression of *A* and *B* can be retrieved from the literature and from the ancillary data of the sensor. In particular, ε'_{sw} and ε''_{sw} are needed to compute the element of the scattering matrix S_{pq} ; while *a*, *b* and θ can be retrieved from the ancillary data of the sensor. In this way, the expression of *E* is only function of the roughness parameters and σ/L can be estimated as the ratio which minimizes the absolute error *E*:

$$\frac{\widehat{\sigma}}{L} : E\left(\frac{\widehat{\sigma}}{L}\right)$$
 is minimum (4)

In the next section the estimation procedure is applied to three different datasets and their outcomes are compared.

4. DATASETS AND GROUND TRUTH

The estimation procedure of the roughness parameters is tested on three different TerraSAR-X images acquired over the Solent area (the channel between the Isle of Wight and Portsmouth) in November 2012. In fig.1 the amplitude of the SAR images is shown; while in tab.1 the acquisition parameters are reported for the different images.

Before processing the image, the absolute calibration has been performed on the three SAR images; in this way the differences in the images radiometry are minimized and the three images can be compared [10]. The pixels intensity has been scaled according to the following formula [10]:

$$\sigma^{0} = k_{s} \left| DN \right|^{2} \sin \theta - NESZ \tag{5}$$

where k_s is the absolute calibration factor, |DN| is the amplitude of each pixel and *NESZ* is the noise equivalent sigma zero of the SAR system. Both k_s and *NESZ* are provided with the ancillary data of the images.

The ground truth (wind speed and direction) has been retrieved from the archives of the Bramblemet



Figure 1: HH amplitude image of the Solent area in slant range (r axis)/azimuth (x axis) plane acquired by the TerraSAR-X sensor on 7th November 2012 (a), on 9th November 2012 (b) and 12th November 2012 (c).

Parameter	07/11	09/11	12/11
Acquisition Time	06:09	17:52	06:17
Azimuth Resolution [m]	1.10	3.30	3.30
Slant Range Resolution [m]	1.18	1.77	1.77
Orbit	Desc. Right	Asce. Right	Desc. Right
Radar look angle [deg]	52°	41°	43°
Working frequency [GHz]	9.65	9.65	9.65
Polarization	HH	HH	HH

Table 1: SAR images acquisition parameters.

weather information system [11], which records the weather conditions in the Central Solent area. The sea state for each image is reported in tab.2.

A Region of Interest (ROI) of 400x400 pixels including the Bramblemet weather station has been isolated for each image and used for the roughness parameters estimation, whose results are shown in the next section.

5. RESULTS

First of all the RCS for each range line of the ROI of each image is computed as average of the pixel intensity along the azimuth direction. In formula:

$$\widehat{\sigma_{j}^{0}} = \sum_{i=1}^{400} \widehat{\sigma_{ij}^{0}} \quad j = 1, 2, ..., 400$$
(6)

where $\widehat{\sigma_j^0}$ is the RCS of the j-th range line and $\widehat{\sigma_{ij}^0}$ is the RCS of the pixel which coordinates are (i,j). The RCS for each range line of the three ROIs are shown in fig. 2(*a*). The RCS of the first two images (acquired on 07/11 and 09/11) is very similar, but since the first one is acquired with a greater look angle it should represent a rougher sea surface;

Parameter	07/11	09/11	12/11
Acquisition Time	06:10	17:55	06:15
Wind speed [kn]	11.2	9.3	5.4
Wind direction [deg]	267°	203°	192°

Table 2: Sea state (wind speed and direction) relative to each dataset, where the North direction corresponds to 0° , the West to 270°, the South to 180° and the East to 90°.

the RCS of the third image (acquired on 12/11), instead, is much lower due to a weaker wind, see tab.2.

In order to minimize equation (3), the radar look angle, the azimuth and the slant range resolution are required and retrieved from the ancillary data of the images (these parameters are shown in tab.1); then the relative dielectric constant of the saline water (ε_{sw}) has been computed according to the model presented in [7]:

$$\mathcal{E}_{sw} = \mathcal{E}'_{sw} (f, s, T) + j \mathcal{E}''_{sw} (f, s, T, \sigma_c)$$
(7)

where *f* is the working frequency of the sensor, *s* and *T* the salinity and the temperature of the sea and σ_c the conductivity of water depending on its salinity. The average information about the salinity and the temperature of the sea in the Solent area has been retrieved from [12] and ε_{sw} has been computed at the X-band:

$$\varepsilon_{sw} = 71.82 + j37.78$$
 (8)

From the knowledge of the relative dielectric constant of the saline water, the element of the scattering matrix has been computed and it results $|S_{HH}|=1.6111$.

Once all these parameters have been estimated, equation (3) can be minimized and the ratio σ/L estimated. The estimations of σ/L are shown in fig. 2(*b*) where the scattering plots of the ROI of each image are reported. The green crosses of each scattering plot represent the mean values of the estimated ratio σ/L . In tab.3, instead, the mean and the standard deviation of the estimated values of



Figure 2: RCS of the *j*-th range lines for each ROI of the three SAR images (a). Scattering plot of the ratio σ/L relative to the ROIs of the three SAR images where the mean value of each ROI is represented by a green cross (b).

	07/11	09/11	12/11
$E\left[\widehat{\sigma/L}\right]$	0.4729	0.2033	0.1970
$s\left[\widehat{\sigma/L}\right]$	0.0191	0.0020	0.0016

Table 3: Mean value, $E\left[\widehat{\sigma/L}\right]$, and relative standard deviation,

 $s\left[\overline{\sigma/L}\right]$, of the estimated roughness ratio ratio σ/L relative to the

ROIs of the three SAR images.

each ROI are reported.

As expected from the RCS plot, the roughest surface corresponds to the image acquired on 07/11, while the smoothest to the image acquired on 12/11 where, due to the really weak wind, most of the incidence radiation is reflected in the specular direction and only a small amount is backscattered to the sensor. Furthermore, the ratio σ/L relative to the image acquired on 09/11 is greater than that one of the image acquired on 12/11 because of the stronger wind speed; but it is lower of the ratio σ/L relative to the image acquired on the 07/11 because the radar look angle is larger while the sea state conditions and the measured RCS are similar.

CONCLUSIONS

A roughness parameters estimation procedure has been introduced and evaluated against different sea states and radar look angles. The preliminary results (see tab.3) are consistent with the geometrical optic theory and with the ground truth retrieved (see tab.2). The authors are currently working on images acquired from sensors working at multiple frequencies to retrieve the ratio σ/L against different sea conditions, radar look angles and working bands.

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