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A New Stochastic Model for Oil Spill Observation by Means of Single-Look SAR Data

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In this paper sensitivity of generalized K-distribution of three parameters as descriptors of dark features over marine single-look SAR images is investigated. The working hypothesis is that the generalized K-distribution, a three parameters probability density function (pdf), is a suitable speckle model for marine SAR images ensuring a continuous and physically consistent transition among different scattering scenarios. This speckle model can embody the Rayleigh case (a descriptor of land areas e.g. islands), the Rice case (a descriptor of the areas in which dominant scatter e.g. ships are present) and the K distribution (a descriptor of oil free areas).The reference data set is provided by the ESA under the CAT-1 Project C1P-2769.

Key words: *Synthetic Aperture Radar (SAR), sea remote sensing, microwave, generalized K-distribution.*

1. Introduction

Synthetic Aperture Radar (SAR) is a key sensor in a great number of environmental applications. An enormous quantity of SAR image data to be analyzed calls for automated and skillful geophysical feature extraction procedures. In this, the stochastic nature of a SAR image is investigated as an additional source of the information to be exploited to learn more about the underlying physics to be observed.

A classical Rayleigh distribution model for the amplitude of a backscattered signal well fits homogeneous land scenes and serves as a reference since it is associated with the so-called fully-developed speckle (Jakeman, Pusey, 1976.). Several other distributions have been used to model speckle statistic, namely: the β (Maffett, Wackerman, 1991), lognormal (Ulaby, Dobson , 1989), and Weibull (Maffett, Wackerman, 1991) distributions. The K distribution has been found to be a particularly useful model for sea amplitude statistics [1]. The K-distribution model has a reasonable justification in terms of physical scattering processes, and it reduces to the Rayleigh distribution model under appropriate circumstances (Jakeman, Pusey, 1976.), (Oliver,1984; Oliver, 1986; Jakeman, Tough, 1987). Moreover, the K distribution model has been generalized to model the amplitude of backscattered signals with a non-uniform distribution of the phase by a fluctuating population of objects (Jakeman, Tough, 1987; Barakat, 1986).

The proposed model is based on the generalized-K probability density function (pdf) (Barakat, 1986), which ensures a continuous and physically consistent transition among different scattering scenarios (Jakeman, Tough, 1987). This speckle model can embody the Rayleigh case, the Rice case and the K case (Jakeman, Tough, 1987; Barakat, 1986; Corona et al., 2004).

In this study sensitivity of three generalized K-distribution parameters as descriptors of marine features over SAR images is investigated. In practice, instead of suppressing the speckle by means of appropriate averagings which make the SAR image spatial resolution coarser, we look for the speckle statistics under the unitary generalized K distribution formulation to assist the geophysical image analysis.

In particular, the study is focused on the use of a statistical model to improve oil-spill detection.

The basic idea is to estimate the electromagnetic return of selected regions of interest (ROI) over single-look SAR images by means of three characteristic parameters of the generalized K-distribution: α, η, and ν. The working hypothesis is that these three parameters assume the values within characteristic intervals depending on the different analyzed marine scenes. The physical interpretation has been carried out considering typical aspects associated with such analysis i.e. the influence of the wind and the incorrect time/spatial co-location between SAR and wind data. The reference data set has been provided by the European Space Agency (ESA) under the CAT-1 Project C1P-2769 and the SeaWinds/QuikSCAT wind data have been provided by NASA (PODAAC).

2. Generalized K Model

In this section, the speckle model employed in this study is briefly summarized. The basic assumption is that the backscattered field received at a linearly polarized receiving antenna can be written as the sum of *N* elementary fields

$$E(\mathbf{r},t) = \sum_{i=1}^{N} a_i(\mathbf{r},t) e^{-j\Phi_i(\mathbf{r},t)} \tag{1}$$

where:

- $a_i(\mathbf{r},t)$ - real form factor governing the *i*th elementary scattering field,
- $\Phi_i(\mathbf{r},t)$ - *i*th elementary field phase factor depending on the propagation path and *N* is the number of elementary scattering field contributions.

Amplitudes $a_i(\cdot)$ and phases $\Phi_i(\cdot)$ are real random variables with corresponding continuous pdfs, and *N* is a discrete random variable.

Mathematically, (1) can be seen as a random walk in a complex plane in which the number of steps is ruled by *N,* and the *i*th step is ruled by a_i and Φ_i (Corona et al., 2004).

Since the physical processes governing a_i, Φ_i and *N* are essentially independent, it is possible to consider them consequently (Barakat, 1986; Corona et al., 2004). Further, since the physical process governing the elementary fields is the same, all a_i are characterized by the same pdf $f'(a)$, and all Φ_i are characterized by the same pdf $f''(\Phi)$ (Barakat, 1986).

Moreover, the excess of propagation path lengths is larger than the electromagnetic wavelength *λ*, and hence, all Φ_i are uniformly distributed over the radians (rectangular pdf). This is a characteristic of a strong-backscattering regime (Jakeman, Tough, 1987; Barakat, 1986).

An effective and physical pdf for *N* is the negative binomial pdf (Barakat, 1986). Say *α is* a real and non-negative parameter associated with such a pdf, it is possible to note that for *α* approaching large values the limiting Poisson pdf is found (Barakat, 1986).

If the latter assumption is considered, the popular Rayleigh field model is recovered (Barakat, 1986). In general, if it is relaxed by manipulating (1) the intensity total field pdf characterized by a K-pdf [1] is obtained, (Barakat, 1986). The actual shape of the K-pdf is dictated by *α*. In other words, the field model generalization of the exponential pdf is obtained which is relevant to the intensity distribution in a case of the Rayleigh field model (Corona et al., 2004).

It is actually possible to generalize such a model to the weak-backscattering regime i.e. to the case of nonuniformly distributed phases. Mathematically it corresponds to a directional bias in the random walk and is modeled in (Barakat, 1986) in terms of the von Mises pdf. The von Mises pdf measures the departure from the uniform phase distribution by parameter *ν*, which reduces to a uniform case when set to zero.

In (Barakat, 1986), after some mathematical manipulations it is shown that the pdf of the square magnitude of the total linear field is given by the following analytical expression which, unfortunately, is not directly valuable:

$$f(h) = \frac{1}{2} I_o\left(\frac{\nu\sqrt{h}}{\alpha}\right) \int_0^{\infty} \Psi(s) J_o(\sqrt{h}s) s ds \tag{2}$$

where:

- $J_o(\cdot)$ - Bessel function of the first kind of the zeroth-order,
- I_0 - modified Bessel function of the first kind of the zeroth-order,
- $\Psi(\cdot)$ - function depending on the mean number of elementary field scattering contributions, *α* and *ν* (Barakat, 1986).

Equation (2) can be greatly simplified when the mean number of elementary field scattering contributions tend to infinity (but *α* and *ν* are left arbitrary) (Barakat, 1986). Hence, we have

$$f(h) = \frac{2\cdot\alpha}{\Gamma(\alpha)\cdot\eta^{\alpha+1}} \cdot \left(\frac{\alpha}{1+\frac{\nu^2}{4\cdot\alpha}}\right)^{\frac{(\alpha-1)}{2}} \cdot h^{\frac{(\alpha-1)}{2}} \cdot I_0\left(\frac{\nu}{\eta}\cdot\sqrt{h}\right) \cdot K_{\alpha-1}\left\{\frac{2}{\eta}\cdot\left[\left(1+\frac{\nu^2}{4\cdot\alpha}\right)\cdot\alpha\cdot h\right]^{\frac{1}{2}}\right\} \tag{3}$$

where:

$\Gamma(\cdot)$ - Eulerian gamma function,
$K_{\alpha-1}(\cdot)$ - modified Bessel function of the second kind of order α-1 and η is needed to a dominant scatterer.

It is also important to note that proper estimation of the K-generalized three parameters is required for a complete characterization of the model. This is actually a delicate matter which must be carefully considered. In fact, the assumption of the underlying statistical model is not fully satisfied when the real SAR data are considered. In this study, a simple estimation procedure of three parameters developed in [8] and based on the χ_2 test has been accomplished.

3. Experimental results

In this section sensitivity of three generalized K-distribution parameters as descriptors of dark features over marine single-look complex (SLC) SAR images is investigated. SAR images were acquired by the AMI sensor mounted on board of the ERS-2 satellite operated by the ESA.

Specifically, three SAR images have been considered. The first SAR image is relevant to the acquisition of 21 January 2002, 10:01 (ERS-2, SLCI, orbit 35318, frame 2763, center lat. 41.763N, center lon 10.678E, descending pass) off the coast of Orbetello, Tuscany, Italy. The image is completely over the sea. A meteorological front is present together with an elongated multiple oil spill aligned to the wake of a ship (see Fig. 1). This image shows the typical features associated with an illegal oil spill.

The second SAR image is relevant to the acquisition of 02 June 2003, 21:02 (ERS-2, SLCI, orbit 42439, frame 1089, center lat. 54.409N, center lon 14.161E, ascending pass) over the Baltic Sea south of Sweden near the border between Germany and Poland. On left side it is possible to see the land with lagoon, in the center an oil spill is present while the rest of the image shows a large free sea area (see Fig. 2).

The third and last SAR image is relevant to the acquisition of 1 February 2003, 11:25 (ERS-2, SLCI, orbit 40701, frame 2745, center lat. 42.718N, center lon 9.912W, descending pass) off the Galicia coasts after sinking of the Prestige oil tanker (see Fig. 3). It is a more complex scene compared to the previous ones. A meteorological front (high wind on the right side), a small portion of land (top-right), several oil patches and ships are recognizable in the image.

Table 1. Estimated values of K-generalized three parameters relevant to the colored areas shown in Fig. 1

	η	α	υ
Sea 1	8.232E-3	27.00	6.93
Sea 2	8.464E-3	25.00	7.45
Oil 1	4.578E-3	13.00	6.41
Oil 2	6.561E-3	18.00	7.03

Table 2. Estimated values of K-generalized three parameters relevant to the colored areas shown in Fig.2

	η	α	υ
Sea	1.100E-2	22.00	7.69
Land	1.121E-2	13.00	6.09
Oil	9.764E-3	16.00	6.38

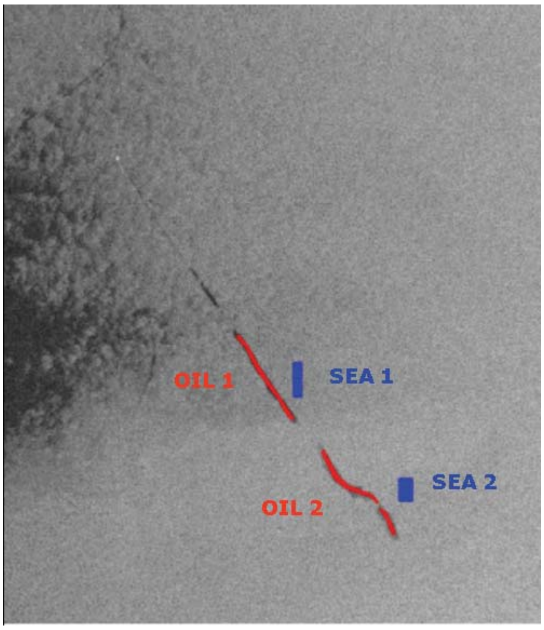

Fig. 1. Zoom of the area of interest relevant to quicklook of the SAR acquisition of 21 January 2002, 10:01. The stained areas are relevant to the selected sub-scenes for the sensitivity study.

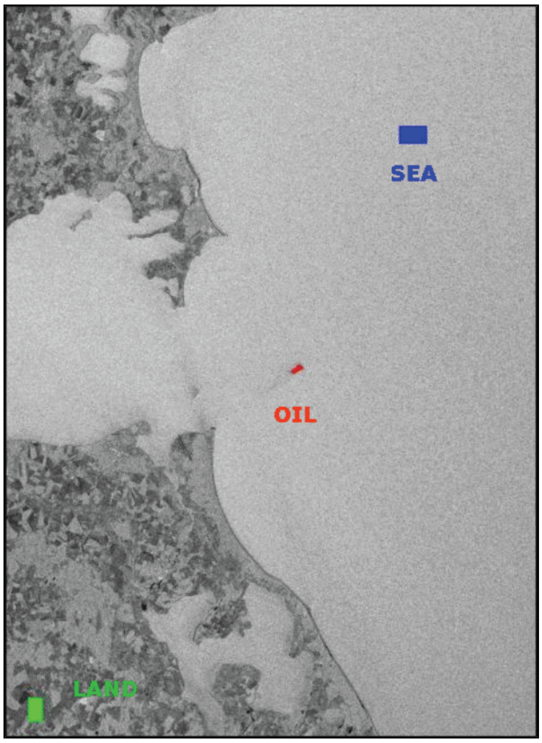

Fig. 2. Zoom of the area of interest relevant to quicklook of the SAR acquisition of 02 June 2003, 21:02. The stained areas are relevant to the selected sub-scenes.

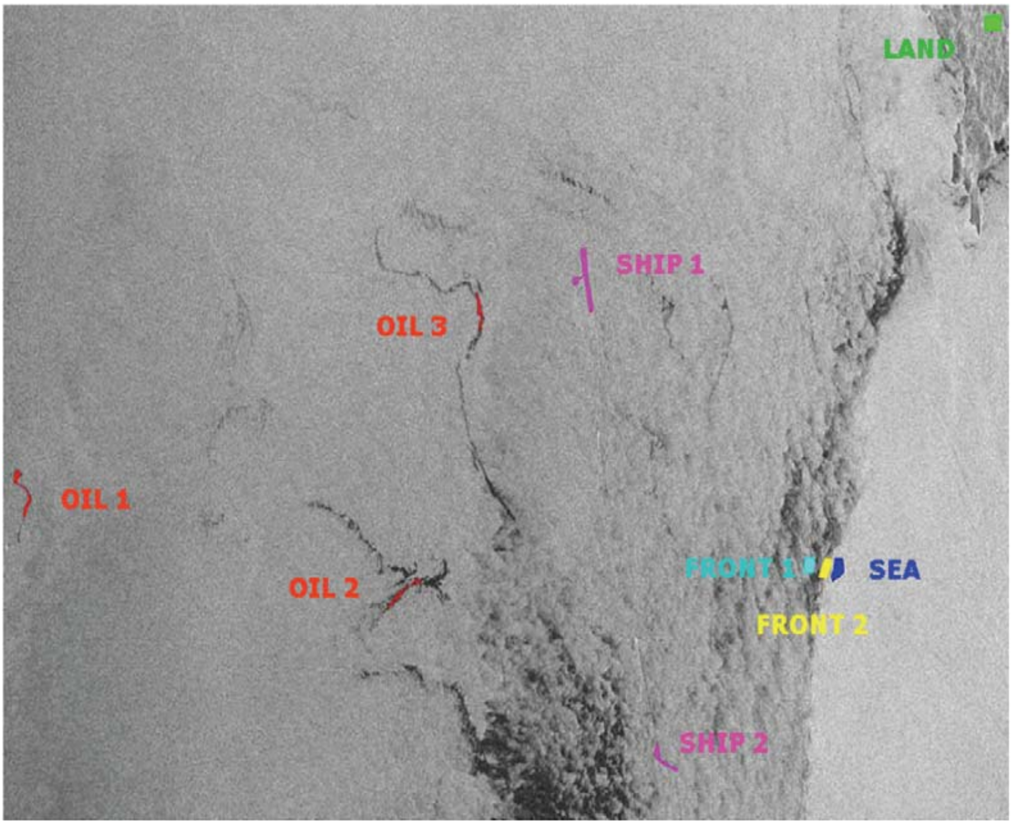

Fig. 3. Zoom of the area of interest relevant to quicklook of the SAR acquisition of 1 February 2003, 11:25. The stained areas are relevant to the selected sub-scenes for the sensitivity study.

The sensitivity study is conducted estimating three generalized K-distribution parameters relevant to the specific areas, highlighted by colours, manually selected in the SAR images.

In each image the free sea surface area is first selected for reference (blue area) and an oil covered surface (red area). Land and ships are indicated with green and pink, respectively. In the third image two sea areas in correspondence to a meteorological front are considered, (light blue and yellow areas). The amplitude data set relevant to each specific area is analyzed and the corresponding generalized three K-distribution parameters are evaluated.

To perform the physical interpretation, the wind information is taken into account. However, the different time/spatial co-location between SAR and wind data provides only rough information on meteo-marine conditions.

On a quantitative basis it is interesting to proceed systematically among the three cases which represent an increasing level of difficulty for the physical interpretation process. The list of the three estimated parameters making use of the generalized K model is presented in Tables 1 to 3.

Table 1 deals with the generalized K-distribution parameters relevant to the selected areas belonging to the first image.

Table 1 shows that the free sea areas are comparable, especially for the α and η values. In fact, the difference between the α values is approximately 7.4% ($\Delta\alpha$) and it is approximately 2.7 %($\Delta\eta$) for the η values. As far as the areas relevant to the oil are considered, it is found that α and η decrease with respect to the free sea areas while v value is unchanged. Let us compare now each oil areas with the corresponding sea areas. α varies of about 50% for the areas nearby the ship and of about 28% for the areas selected far from the ship. Generally, the difference of the α variations is expected to be affected by the type of the spilled oil, its age and the meteo-marine conditions. In this case, since the oil is spilled by the same ship in different phases, it is mostly likely that the α variations are due to weathering processes which have been affecting the areas far from the ship for a longer time.

The parameter estimation results relevant to the second SAR image confirm all that experienced in the first case (see Table 2). With reference to the sea and oil areas, there is a difference of approximately 13% for η and 27% for α. With reference to the land, η is comparable with the sea value ($\Delta\eta$=2%) while α decreases in about 41%.

The parameter estimation results relevant to the third SAR image show that, as expected, the presence of the oil decreases the value of α. The differences between the free sea areas and the oil covered ones are $\Delta\alpha$=38% a $\Delta\alpha$=23% a $\Delta\alpha$=15% for the oil patches 1,2 and 3, respectively. In this case, since the deploying mechanism is linked to a ship sinking, the values variation is mainly due to the meteo-marine conditions rather than the emulsification processes.

In the areas corresponding to the meteorological front, since the wind low producing a look-alike, a decrease in α and η values is obtained. The values corresponding to the land are similar as regards η ($\Delta\eta$=10%) and low with respect to α ($\Delta\alpha$=31%). The values corresponding to the ships are low as regards η and high with respect to α. In all cases v values are comparable.

Table 3. Estimated values of the K-generalized three parameters relevant to the colored areas shown in Fig. 3.

	η	α	υ
Sea	1.138E-3	26.00	6.93
Met. Front 1	7.531E-3	19.00	6.23
Met. Front 2	1.200E-2	10.00	5.31
Land	7.351E-2	18.00	6.35
Oil 1	6.701E-3	16.00	6.47
Oil 2	4.489E-3	20.00	6.97
Oil 3	5.329E-3	22.00	7.12
Ship 1	9.574E-3	23.00	6.97
Ship 2	9.421E-3	20.00	6.32

Table 4. Summarizing the scheme of the η and α parameter values for different marine scattering scenarios

	η	α
Sea	High	High
Land	Low	Low
Oil	Low	Low
Look-alike	Low	Low
Ship	Low	High

In conclusion it is possible to state:

– α, η and v parameters of the generalized K pdf show a different sensitivity with regard to the hydrocarbon presence on the sea surface;
– the most sensible parameters are α and η;
– the values of these parameters are influenced by: the kind of the oil, age (weathering processes) of hydrocarbon and meteo-marine conditions.

To emphasize these results a summary Table is reported, see Table 4.

4. Conclusions

The generalized K-distribution is a three parameters probability density function (pdf) and is here considered to provide a statistical speckle model which is able to characterize different scattering scenarios over marine SAR images.

Hence, by means of a differential analysis, first a free sea area has been selected for deducing the reference parameters, and then the variations relevant to hydrocarbon, rather than looking-alike, have been estimated.

Since it has not been possible to achieve wind fields perfectly, space/time co-located with respect to the SAR images, only rough information on meteo-marine conditions have been considered for carrying out physical interpretation.

The preliminary analysis has shown that:

– the presence of oil-spill causes a decrease in α and η parameters;
– the look-alike due to low wind speed areas, wind front areas and areas sheltered by land introduce a decrease in α and η parameters comparable to those caused by the presence of an oil-spill. Therefore, the discrimination between oil spill and look-alike is possible if the wind field is perfectly known;
– the land surfaces are characterized by high values of η (like for the sea) and by relatively low values of α;
– the presence of ships causes low values of η and high values of α.

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Naujas stochastinis modelis naftos išsiliejimo žvalgymui naudojant vienetinio SAR atvaizdo duomenis

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Šiame straipsnyje nagrinėjamas trijų apibendrinančio K-pasiskirstymo parametrų, kaip taškelių (tamsių dėmelių), pastebimų vienetiniame jūros SAR (sintezuotos apertūros radaro) atvaizde deskriptorių, jautrumas. Priimta darbinė hipotezė, kuria remiantis apibendrintas K-pasiskirstymas, kaip trijų parametrų tikimybės tankio funkcija (pdf), yra laikomas tinkamu taškelių modeliu dešifruojant jūros paviršiaus SAR atvaizdus, ir atitinka tolydų ir fizikiniu požiūriu nuoseklų perėjimą tarp skirtingų atspindžių sklaidos scenarijų. Šis taškelių modelis gali įkūnyti Relėjaus (žemyninių plotų, pvz., šalių, deskriptorius), Rais (plotų, kuriuose yra dominuojantys sklaidos faktoriai, pvz., laivai) ir K-pasiskirstymo (neužterštų nafta plotų) atvejus. Panaudoti duomenys yra gauti iš ESA pagal CAT-1 projektą CIP-2769.