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Sea surface slicks measured by SAR(*)(**)

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Summary. — The Synthetic Aperture Radar (SAR) system capability to detect and characterise marine surface slicks was tested during the SAR-580 experiment in the northern Adriatic Sea, offshore the Venice coast, in October 1990. Two small artificial slicks of oleyl alcohol were produced in an area around the oceanographic platform of the Italian National Research Council (CNR). The oleyl alcohol produces a damping of the sea centimetric waves, which has been measured by an airborne two band (C and X) SAR, by a tower based 3 band (L, S and C) scatterometer and by a wave gauge, installed on board the platform, which measures the instantaneous sea surface elevation in the range from gravity up to capillary waves. The good agreement among measures proves that multi-frequency SAR is able to detect and characterise sea surface films. Slicks in SAR images taken during SIR-C/X-SAR mission in 1994 have been analysed on the basis of these results and L-band measurements of spatial attenuation near the borders of the slicks have been done, in order to test the slicks detectability using single-band SAR images.

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1. – Introduction

It is well known that the surfactants are responsible for sea wave damping and reflectivity modulation over a broad range of frequencies from the visible to the microwave regions of the spectrum. Measurements of slick-induced damping of short-gravity ocean waves excited by the wind provide data which can be useful for the investigation and characterisation of ocean microlayers on a thermodynamic basis [1]. Lombardini *et al.* [2]

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proved the feasibility of detecting, charting and characterising sea water films by measuring, with a proper wave gauge [3], spectral depressions of short-gravity wind waves. On the basis of a theoretical model these authors inferred the soluble or insoluble nature of the substance forming the film itself, the rheological parameters and the surface film fragmentation.

In this paper we consider the use of multi-frequency radar and SAR for the detection and characterisation of substances forming sea surface film. This new methodology was suggested and outlined in 1985 [4]. Today airborne and space-borne SAR availability allows the experimentation on artificial or natural slicks [5-7]. The basic mechanism involved is the normalised radar cross-section which, for incidence angles higher than 20 °, is proportional to the spectral energy density of the sea waves having wavelength Λ that obey the Bragg resonance condition

$$\Lambda = \frac{\lambda}{2\sin\vartheta}, \tag{1}$$

where λ is the radar wavelength and ϑ the incidence angle of radar beam. For low incidence angles the backscatter is due to specular reflection [8,9]. The sea waves that are Bragg resonant with microwaves employed by the SAR systems fall in the short gravity wave region. In this same region, the theory of rheology of air-water interface [10-13] predicts a maximum of the ratio between the damping coefficients of waves for water covered by a surface film and pure. The mathematical analysis by Levich [14], based upon the Navier-Stokes equation and developed for the case of small ripples on an interface covered by a surface-active substance, has been extended by Cini *et al.* [15] with a formalism which includes both soluble and insoluble monomolecular films for the two coexisting modal solutions: the Laplace or transversal mode and the Marangoni or longitudinal mode [16].

Spectral measurements carried out both in tanks and in many oceanic sites [2,17-19] on slicked waters clearly show this damping effect. The ratios between spectra measured in pure water and in water covered by film have a maximum in the 3–10 Hz range [1, 20]. From observed ratios and theory we can deduce rheological parameters, such as the relaxation characteristic frequency and the viscoelastic modulus, as well as the film concentration [21] or fragmentation [2].

We tested the ability of multi-frequency SAR to characterise surface films with data obtained during an experiment in October 1990 in the northern Adriatic Sea, when an airborne SAR flew over a research platform, on board of which time series of radar backscatter as well as high-frequency wave spectra were recorded. The experimental results showed that the multi-frequency SAR is an ideal instrument to monitor sea surface substances, since SAR data contain information about the spectral components affected by damping. In the following sections we discuss the results obtained analysing marine slicks imaged by spaceborne SAR on the basis of the above methodology.

2. – The experiment

The experiment, organised and supported by the Italian Space Agency (ASI), took place in October 1990 in the northern Adriatic Sea, offshore the Venice coast in the area around the oceanographic platform "Acqua Alta" of the Italian National Research Council (CNR). It was designed to study the characteristics of the radar backscatter from the sea surface and its attenuation in the presence of films on the sea surface.

Fig. 1. – The two-flight Nadir (oriented lines) of the aeroplane carrying the right-looking SAR, the test site area (a square of 18 km size) off the Venice Lagoon, and the CNR platform (cross) used for sea truth measurements.

2˙1. *Airborne* SAR. – A CONVAIR 580 aircraft, equipped with C and X band, VV polarisation SAR, carried out two orthogonal flights over the platform area (see fig. 1) at a flight altitude of 6093 m and at SAR incidence angles ranging from $45\,^\circ$ to $76\,^\circ$. Consequently, the ground range resolution resulted variable according to ϑ : at $\vartheta = 64\,^\circ$, roughly the middle incidence angle, it was 4.4 m. The azimuthal ground resolution, independent of the geometry of operation, was also 4.4 m. Details about the system and its performance may be found in [22, 23]. The main SAR characteristics are summarised in table I. Four images, two for each band, were obtained.

2˙2. *Platform instrumentation*. – The platform measurements consisted of time series of radar backscatter at L, S, and C bands, of the sea surface elevation at broad frequency band and of the horizontal and vertical components of the wind vector, along with the bulk air and sea temperatures. Technical details of the experiment may be found in [24].

Tower-based scatterometer. The radar scatterometer (ITS 600) is a specially designed pulse Doppler fully coherent radar, that allows to carry out many kinds of measurements on sea surface backscatter and wave spectrum at three bands (L, S and C at, 1.35, 2.7 and 5.4 GHz, respectively). The main characteristics are summarised in table II. The scatterometer was installed at 13 m above the sea level and oriented upwind with incidence angle of $60\,^\circ$. It operates by switching successively the radio-frequency to three

Table I. – *The SAR main characteristics.*

SAR	System
C and X frequencies	5.31 GHz, 9.375 GHz
Polarisation	VV
Height	6093 m
Incidence angle	$45< \theta <75$ deg
Slant range	8616 to 24989 m
Headings	314 and 14 deg
Pixel spacing	4.4 m (azimuth)
Pixel spacing	4.0 m (slant range)

matched antennas illuminating the same target area.

The scatterometer illuminates the sea surface by means of short radio-frequency pulses and the backscattered echoes on two channels in quadrature are recorded. The amplitude signal is proportional to the amplitude of the Bragg resonant liquid wave. Amplitude and phase angles, in the frequency domain give measures of some parameter of the sea surface as significant waveheight, dominant frequency, amplitude of wave orbital motion, surface currents, etc. The phase (I) and quadrature (Q) signal channels are alternately sampled 128 times each at 600 Hz before band switching, then reference temperature and signal noise are sampled and finally the record is stored.

Wave gauge. The interferential microwave probe was mounted upwind and some meters outboard to minimise the tower effects, in order to record the water elevation time series.

The basic element of this probe is a Teflon-coated wire held straight vertical; the lower end of which is dipped in water, while the other end is fed by a microwave source. The microwave energy travels downward confined to a close proximity of the coated wire by surface wave effect [25], generating a reflected wave at the air-water discontinuity. In conditions of good matching in the microwave system, the field in the transmission line has a standing-wave pattern, which uniquely determines the location of the water contact. Changes in height of the water surface correspond to changes in phase angle between propagated and returning microwaves. More details about the system may be found in ref. [2, 6, 20, 21, 26] and the technical implementation and data processing are described in Lombardini *et al.* [3].

In laboratory and clean water conditions the time series of the sea water elevation

Table II. – *The ITS 600 radar scatterometer characteristics.*

Pulse Doppler, all solid state, fully coherent radar
L, S, C bands operation frequencies at 1.35, 2.7 and 5.4 GHz
50 ns transmitted pulsewidth
100 mW transmitted power
11 degrees antenna beam width
10 to 600 m acquisition range
Internal calibrator
Filtered complex video signal
220 V/I 00W power requirement
50 kg weight

are affected by instrumental errors of few micrometers and frequency spectra can be obtained without distortion up to 20 Hz, near the theoretical 26 Hz cut-off value imposed by capillary phenomena on the Teflon coated copper wire 0.5 mm thick. At this frequency a flat spectral noise at level of $10^{-13}\,\mathrm{m}^2/\mathrm{Hz}$ is reached. In open sea frequency spectra can be obtained up to 15 Hz.

The spectral density for slicked water $S_\mathrm{s}(f)$ in the 2–18 Hz band is used to deduce the damping ratio

$$y(f) = \frac{S_0(f)}{S_\mathrm{s}(f)}, \tag{2}$$

where $S_0(f)$ is the spectral density for a clean sea excited by the observed wind [27]. This ratio, plotted *vs.* frequency, shows a peaked curve which may be fitted to a theoretical model [12, 28, 29] binding the frequency of the maximum f_M and maximal damping ratio y_M, with the rheological parameters of the surface, *i.e.* the elastic modulus ε_0 and the characteristic frequency ω_D.

Measurements performed in laboratory and theoretical considerations have shown that for both soluble and insoluble film f_M and y_M reach values depending only on rheological characteristics of substance forming the film in saturated concentration conditions. We point out that films on the sea surface can rarely reach that concentration level connected to theoretical conditions.

For soluble films a relationship between the bulk concentration and the corresponding damping ratio has been inferred [30]. This relation allows us to deduce the value of bulk concentration by measuring the offset of the experimental maximum value reached by the ratio y_e from the saturated theoretical value y_0. For insoluble substances, information on the surface coverage may be obtained by means of the so-called “filling factor” [31] as defined by the formula

$$F = \frac{1 - 1/y_\mathrm{e}}{1 - 1/y_0}. \tag{3}$$

Note that at 4 Hz, for instance, a drop of F as small as one-thousandth can lower the observable damping ratio by 1.5 dB. Consequently, it is very unlikely that an experimental point will fall near the theoretical curve.

Anemometer. The instrument used for wind measurements was a K-Gill twin propeller anemometer (Young Co., Michigan, USA) calibrated in the wind tunnel of the Department of Aerospace Engineering of the Politecnico of Milano. It was installed upwind, 7.5 m out from the platform (about three times the platform radius) and at 7.3 m above mean sea level. This was the most suitable position for the anemometer in order to minimise flow distortion effects.

2·3. *Measurements*. – During the experiment the mean wind speed was of $3.8\,\mathrm{m\,s^{-1}}$, the significant wave height 0.35 m and the wave frequency 0.17 Hz. These conditions were ideal to make artificial spreading slicks and to measure backscatter fluctuations by remote-sensing systems and wave motion by gauge.

Two small spots ($\sim 10^4\,\mathrm{m}^2$ each) were produced on the sea surface upwind the oceanographic platform at approximate distances of 1 km and 100 m, respectively, using in all 3.5 litres of oleyl alcohol. In order to obtain a quasi-monomolecular film, the oil was diluted in liquid hexane before to be poured. Carried by surface current, one of the spots crossed the tower letting us to measure the wave damping by the three-frequency scatterometer and by the wave gauge installed on board. The first SAR flight over the test site occurred about 30 minutes after.

3. – Data analysis

In fig. 2 we show a 4.4 km by 4.4 km portion of the C-band image acquired by SAR during the first passage at 11:57 UT on 24 October 1990. It is the slant range representation of 1024 by 1024 pixels with grey scale whose brightness is proportional to the square root radar cross-section. The tower is visible as a bright spot in the centre; the two artificial slicks are clearly visible as dark areas far from the platform 200 m and 600 m; wind structures appear as elliptic areas that modulate the mean radar cross-section (flight, looking, wind and North directions are also indicated). The mean wind direction was $35\,^{\circ}$, *i.e.* parallel to the image rows approximately, from right to left. The sea waves are not imaged, because their wavelength was lower than the SAR cut-off. The bright horizontal streak, parallel to the SAR looking direction was caused by strong scattering of the electromagnetic waves by the metallic structure of the platform.

3·1. SAR *data.* – The SAR system owned by the Canadian Centre of Remote Sensing operated at two bands, C and X. A total of four slant range images were afterwards available, that cover the ground by a variable length (28 to 56 km) in the flight direction and a fixed width (18.35 km) in the range direction. These images were carefully examined and analysed following different techniques (false colour display, pixel compression, spreading correction, etc.). It was concluded that

1) The slicks were imaged only during the first passage, by both C and X bands, and not in the second passage, occurred 15 min after, probably because the two very thin surface films were dissolved by the sea action and the wind direction was orthogonal to the range.

2) The C-band results more efficient than the X-band both on the land and on the sea.

3) The radar echo damping due to the slicks are stronger at C-band than at X-band.

4) All the images present high signal in the near-range that decreases regularly toward far-range only on the sea surface and not over the land.

The last observation may be explained considering the different SAR incidence angle and antenna pattern throughout the image. The radar backscatter is due, in the first approximation [32, 33], to the presence on the sea surface of small waves of wavelength satisfying the Bragg relationship (1). From to the radar backscatter and by associating to each range position the corresponding incidence angle ϑ (provided that translation from slant range to ground range is made), formula (1) gives the wavelength of the water surface wave component responsible for backscatter. The strength of backscatter depends also on the energy of these sea waves, which increases with the increasing of wavelength. Therefore the image is biased by the change of incidence angle as, for the same wind conditions, the backscatter decreases as ϑ increases.

The incidence angle pertinent to the portion of the image in fig. 2 is $\vartheta = 64\,^{\circ} \pm 4\,^{\circ}$. Because of the limited extent of this image, the SAR incidence angle variation is very

Fig. 2. – A portion of the C-band image acquired during the first SAR flight. There is imaged a sea area of 4.4 km by 4.4 km surrounding the platform, visible as a small bright spot in the middle of the figure. The bright horizontal streak is due to scattering by the platform structure. The two black spots are caused by artificial slicks. Flight, looking, wind and North directions are also indicated.

small ($\approx 8\,^\circ$) and the bias introduced by this angle variation could be neglected in the damping computation, but we have suppressed it using a detrend filter.

3˙2. *Scatterometer data.* – The data collected by this instrument while the oleyl alcohol film approached the platform consist of a time record of 45 minutes. In fig. 3(a) we present the backscatter time history of (I^2+Q^2) recorded during this time in L, S and C bands. The three curves are shifted by 10 dB for clarity sake. The reduction of the backscatter, induced by the oleyl alcohol slick, is present in all three radar bands with different value, stronger at S and C than at L band at $t \approx 1700\,\mathrm{s}$.

3˙3. *Wave gauge data.* – Similarly to the scatterometer it was recorded the time history lasting 45 min and sampled at 78.125 Hz frequency. The wave gauge data series were divided in 512 point segments and passed through a FFT. In fig. 3(b) we plot the sea wave power spectral components whose wavelengths are Bragg resonant with the wavelengths of all radars involved in this experiment. A 2.1 Hz component is added in

Fig. 3. – a) The backscatter time history recorded by our *L*-*S*-*C* band scatterometer, while the slick approached the platform. b) The time history of five spectral components deduced by our wave gauge. The plots are shifted by 10 dB for clarity sake.

order to verify the effect of slick at frequency far from the expected resonant attenuation. The figure clearly shows that the damping is only present at frequencies greater than 2 Hz and it reaches its maximum around 6–8 Hz, corresponding, for Bragg condition, to a value between 5 Hz for *S*-band and 8 Hz for *C*-band.

The slick-damping time delay between scatterometers and wave gauge are due to the different positions of the antenna footprint and the wave gauge.

3˙4. *Discussion.* – The analysis of the SAR images reveals that the slick-induced signal attenuation is stronger at *C*-band than at *X*-band. Similarly the attenuations of the scatterometer indicate that the radar echo damping results stronger at *S* and *C* than at *L*-band. This is in agreement with the gauge measurements, which exhibit the maximum damping at a frequency closer to that of the sea waves responsible of *S*-*C* band backscattering.

Considering the microwave wavelengths and the incidence angles, eq. (1) fixes the Bragg condition in the radar backscattering from sea. Consequently the radar cross-

Fig. 4. – Comparison among damping ratios obtained by the radars and by the wave gauge data: the full line is the display of the ratio of the power spectral components from gauge data between pure and slick-covered water; the three (+) and the two (⊕) points are the plots of $\sigma_0/\sigma_\mathrm{s}$ from multi-frequency scatterometer data and from SAR-580 images, respectively. The three (∗) points are the plots of $\sigma_0/\sigma_\mathrm{s}$ from SIR-C/X-SAR images.

section σ is, in a good approximation, proportional to the square amplitude of Bragg resonant sea waves. According to this condition, the computed ratio $\sigma_0/\sigma_\mathrm{s}$ between the mean radar backscatter signal before and after the damping and the mean of the damped signal for SAR as well as for the three scatterometers, indicate good agreement with the values of attenuation obtained from sea elevation gauge data.

Figure 4 shows the comparison among damping ratios obtained both by the radars and the wave gauge data: the full line is the display of $S_0(f)/S_\mathrm{s}(f)$ ratio of the power spectral components from gauge data; the three (+) and the two (⊕) points are the plots of $\sigma_0/\sigma_\mathrm{s}$ coming from scatterometer and from SAR, respectively. Their abscissae have been calculated using formula (1).

A good agreement is found among these measurements and the differences can be explained considering the different position and different time of the acquisitions of wave damped by oleyl alcohol slick during its spreading and evolution.

In conclusion, for film-covered waters, we obtain a relationship between the damping coefficients ratio $y(f)$ as deduced by theory, the radar backscatter ratios $\sigma_0/\sigma_\mathrm{s}$, and gauge measurements $S_0(f)/S_\mathrm{s}(f)$:

$$y(f) = \sigma_0/\sigma_\mathrm{s} = S_0(f)/S_\mathrm{s}(f). \tag{4}$$

The results obtained in this experiment confirm the first experiment carried out in the Tyrrhenian Sea in 1984 [4] with a two-frequency S and X band radar.

4. – SIR-C/X-SAR **images**

During the first SIR-C/X-SAR mission a German experiment was carried out with the aim to detect and characterise an artificial oleyl alcohol slick produced in the German Bight of the North Sea, west of the Sylt island, on April 18, 1994.

Fig. 5. – L-band SIR-C/X-SAR image of oleyl alcohol. The numbered lines indicate signal levels differing by 1.5 dB.

The space shuttle *Endeavour* mounted three SARs operating at L, C, and X bands (1.25, 5.30, and 9.60 GHz, respectively). The L and C band operated in multi-polarisation mode while X-band at vertical polarisation only. The incidence angle varied between 20 ° and 55 °, and the SAR swath on the ground varied between 15 and 90 km.

As reported by Gade *et al.* [34], during this experiment 120 litres of oleyl alcohol were spread on the water surface generating a slick covering an area of about $0.5\,\mathrm{km}^2$. The wind speed was $5\,\mathrm{ms}^{-1}$. The authors found that the reduction is lowest at L band (-5 dB), whereas it is similar at C and X band (-10 dB). They assume that the measured reductions of the backscattered radar power, particularly at C band, can be affected by instrumental limitations, *i.e.* by the fact that the backscattered radar power reaches the noise floor.

Since wind conditions were similar to that of the SAR-580 experiment on the Adriatic Sea, it is possible to compare the data. In fig. 4 we show the existing agreement between the ratio $S_0(f)/S_\mathrm{s}(f)$ (full line) of the power spectral components measured by the wave gauge in the Adriatic Sea, and the ratios $\sigma_0/\sigma_\mathrm{s}$ of the radar cross-sections ($*$) coming from measured backscatter for the three SAR bands during the German experiment. The abscissae have been calculated according to formula (1). The agreement in the L and X bands is evident. The backscatter ratio for the C-band results lower than the wave gauge spectral ratio according to the mentioned limitation of the signal-to-noise ratio for this radar band.

Now we suggest a new approach able to discriminate between the radar backscatter damping originated by film and the fall of the wind generating short gravity waves.

Since the water waves damp exponentially with a time damping coefficient δ and propagate with their phase speed, the amplitudes must decrease according to the equation

$$e^{-\delta t} = e^{-\alpha x}, \qquad (5)$$

where α is the spatial damping coefficient.

We measured the spatial attenuation existing near the borders of the slick by plotting within the slick itself the contours at signal levels differing by 1.5 dB. In fig. 5 we show as an example the slick seen by the L-band. On the image was previously applied a low-pass filter. By measuring the mean distance of these contours, in the wind direction, we derive the spatial attenuation, finding $\alpha = 0.0016\,\mathrm{m}^{-1}$. This value has to be compared to the spatial damping coefficient α_0 of the associated Bragg resonant wave of pure water:

$$\alpha_0 = \frac{2\eta\kappa^2}{\omega/\kappa}, \tag{6}$$

i.e. the time damping coefficient δ_0 divided by phase speed.

A simple calculation gives $\alpha_0 = 0.0057\,\mathrm{m}^{-1}$ that is lower than the "slicked" ones of 5.5 dB according to the measured ratio of backscatter signals out and inside the slick and with the gauge measurements. In the C and X bands this procedure cannot be applied because the pixel spacing is too high respect to the path which reduces to $1/e$ the Bragg resonant wave amplitude.

5. – Concluding remarks

During the SAR-580 mission in 1990, a surface film experiment was performed in order to test multi-frequency SAR and radars capability of detecting and characterising surface films, using as a reference instrument the specially designed and built wave gauge. We found that the measured damping ratios, *i.e.* the ratios of the backscattered radar power from a slick-free and a slick-covered water surface, at C and X band for the airborne SAR and at L, S and C band for the ground-based scatterometer, are in agreement with the ratio $S_0(f)/S_\mathrm{s}(f)$ of the power spectral components measured by the gauge. This result seems to be confirmed by the analogous experiment performed in the North Sea during the first SIR-C/X-SAR mission in 1994.

The presented results show that, under low to moderate wind conditions, multi-frequency radar techniques are capable to monitor the surface water quality and to characterise surface films.

The comparison among measurements seems to confirm that the Bragg mechanism in the radar backscattering plays a primary role, at least within the experimental conditions (VV polarisation, low wind, incidence angles greater than $30\,°$). Utilising a large radar footprint of a scatterometer mounted on platform or of an airborne SAR, the large variation of the incidence angle through extended slicks, allows the acquisition of a portion of the frequency spectrum which is wide enough to reveal and characterise the slick itself, as shown in Trivero *et al.* [26].

Finally, the new approach, aimed to detect the film and consisting in the spatial damping analysis through the slick borders using only one radar band, seems to be a promising tool to investigate the nature of surface slicks.

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