DETECTION OF MESO-SCALE EDDIES AND FRONTAL STRUCTURES BY SYNTHETIC APERTURE RADAR IMAGERY IN THE WESTERN MEDITERRANEAN SEA

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Final report of contract:
MAS3-CT97-5051

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August 29, 2000

Abstract
The report contains the results obtained by Stéphan Rousseau during his post-doctoral position at the ICM under contract EU MAS3-CT97-5051. The work is dealing with SAR imaging of the Western Alboran gyre in the Mediterranean Sea. The work takes place mainly in the framework of the OMEGA-1 campaign in the Alboran sea in October 1996 but also referred to a previous campaign in the same area in 1992 (FE92). Comparisons between in situ data, remote sensing data, wind model and wind estimation retrieved from ERS2 SAR images are done. Results show that influence of the marine atmospheric boundary layer stratification can explained the higher backscatter values obtained inside the WAG. Hydrodynamical interactions between resonants waves and frontal currents also participate locally in the outlining of the WAG boundaries. The occurrence of surface films enhances in some areas the contrast in the frontal zone. No slicks are observed in the inner part of the gyre even if wind conditions allow their presence.
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1 Introduction

Synthetic Aperture Radar (SAR) imaging ability of ocean structures has been reviewed by a large amount of work in both the open ocean and coastal zones (Espedal et al., 1998, Marmorino et al., 1997, Johannessen et al., 1996, Nilsson and Tildesley, 1995). As well as visual observations from space shuttle, SAR images offered in the 80's a unique first look of the sea surface showing submesoscale features outlined by surface films (Munk et al., 2000). In the case of the Mediterranean Sea only few studies have been done using SAR imagery to explore the submesoscale or mesoscale circulation (Font et al., 1993, Martinez et al., 1992) even if the area is one of most relevant areas for submesoscale circulation outlined by surface films and particularly during the fall period (Munk et al., 2000). During the last decade, two majors oceanographic cruises were performed in the Western Mediterranean Sea (OMEGA in 1996 and FE92 in 1992). Their respective in situ data and remote sensing images collections offer an opportunity to relate the oceanic features observed on SAR images to the local circulation deduced from in situ data and concomitant SST images.

For the OMEGA project (MAS-CT95-0001), ERS-2 SAR were acquired by ESA to explore in deeper the imaging of Mediterranean meso-scale features such as the anticyclonic western gyre of the Alboran Sea (ERS A02.E102 PT Jordi Font). Few years before, ERS1 SAR images acquired during FE92 cruise in 1992 (MAS2-CT93-0066) clearly revealed the frontal circulation and submesoscale cyclonic eddy (Font et al., 1996).

In this work we will insist particularly on the OMEGA-1 cruises which offers a larger and more complete in situ data than in the case of FE92 cruise. The main objective in using ERS2 SAR images, in addition to AVHRR image, was to determine in a near real time the mesoscale features in the Algerian Basin and to determine which eddy to observe in the following mission, ALGERS-96, of the R/V Ilesperides (Chic et al., 1997). During the first cruise of the OMEGA-1 campaign one track of ERS-2 satellite allows the imaging of the OMEGA-1 survey zone where in situ measurements were recorded two days before. But, also JERS1 SAR images were obtained for concomitant and near concomitant in situ data during the second OMEGA-1 cruise. Two days after the completion of the first survey (starting from 01/10/96 to 04/10/96), 2 ERS-2 SAR images were obtained. These images, in descending mode, cover partly the western Alboran gyre in the area of 4 surveys legs. In situ data along these 4 legs were recorded between the 03/10/96 at 12h00 UT and the 04/10/96 at 12h00 UT. The various in situ measurements recorded during OMEGA cruise are: ADCP data, CTD data, SEASOAR data and biological data. A mosaic of the ERS2 SAR images of October, 6 1996 is presented in figure 1. Global ERS SAR images mosaics for OMEGA-1 and FE92 cruises are presented in annexes in figures 25 and 26.

2 Description of the data

2.1 SAR data

2.1.1 Principle of SAR imaging

SAR imaging principle is based on interaction between incident radar microwave and small scale sea surface roughness. For ERS-1 and ERS-2 SAR which operate at small incidence angle ($\theta = 23^\circ$), the major contribution to backscattering is the Bragg diffusion. This resonant effect is associated with the occurrence of Bragg resonant wave, whose wavelength
is given by:

$$\lambda_B = \frac{\lambda_0}{2 \sin \theta}$$  (1)

where $\lambda_0$ is the radar microwave and $\theta$ the incident angle. For the C band of ERS SAR the resonant wavelength is about 7-8 cm and appears for light winds blowing higher than 3 m/s (Donelan and Pierson, 1987). If winds are lower there's no Bragg Backscattering contribution and the image is dark.

In this work we used PRI (PRecision Image) products delivered by ESA/ESRIN. The images are in gray scale level coded on 16 bits. The square value of image pixel intensity is proportional to the backscattering coefficient of the surface, which varies with the incidence, radar polarization, frequency and surface roughness. Each ERS SAR PRI product is composed of 8200 * 8000 pixels of 12.5 m resolution. As the orbit is polar, the ERS SAR images of the area of the Alboran Sea are always obtained in ascending mode at 22h30 UT (night vision) and in descending mode at 11h00 UT (day vision). ERS-1/2 satellites revolution in its normal mode is 35 days and the swath of the SAR is 100 km. In this work we also used JERS1 SAR PRI images processed by ESA (AOJ.2) with a similar pixel resolution but for an image size of 80x75 km. JERS1 SAR is working at L band and for HH polarization. A larger wavelength like L band is assumed to be more adequate than C band for imaging sea front (Marmorino et al., 1997). For JERS1 the resonant wavelength is 22 cm. Such a wavelength is less sensitive to viscosity effects than in the case of ERS2 SAR wavelength as when windspeed decreases the shortest wavelengths vanish quicker. For JERS1 characteristics an estimation of the minimal windspeed required is 2 m/s.

2.1.2 Principle of SAR featuring of the sea

As SAR is sensitive to sea surface roughness, each change of surface roughness leads to a different backscattering pattern. In this case, the occurrence of current will lead to a different roughness due to interactions between surface current and short gravity waves. In the same way, atmospheric fronts induce a different roughness on each sides of the front due to variations of the wind stress. Internal waves can also be visible due to their associated current field acting on the small gravity wind waves. In the case of meso-scale current, two major imaging processes are involved: current and small gravity waves interactions and occurrence of natural slicks (Johannessen et al., 1996, Nilsson and Tildesley, 1997). These 2 mechanisms lead to 2 different signatures. The highest signature, in term of contrast, is associated to damping of the sea-surface roughness by natural surface films or anthropogenic slicks. In this case, the damping ratio could reach around 9-10 dB (Gade et al., 1998). When an underlying current occurs, natural slicks are aligned with the local current pattern and reveal an often complicated surface current with meanders, eddies and fronts. Nevertheless, slicks occurrence on ocean is wind dependent. For wind speed higher than 8-10 m/s, natural slicks are destroyed by the wind wave activity. Currents, interacting with small gravity wind waves less than few meters, induce a local modification of the wind waves field and contribute to an enhancement or a decrease of the backscatter of a few dB (Johannessen et al., 1993). Bright or dark lines outline a current shear depending both on the SAR direction relative to local current (Johannessen et al., 1996) and on the convergence. Surface convergence will lead, in a film-free water, to an increased roughness in the vicinity of the convergence region. On the other hand, surface films, that can accumulate in the convergent region, may cause a negative backscatter anomaly due to damping by films and materials (J. Johannessen, personal communication). Atmospheric front can also be visible on SAR images but in this case, the front is usually outlined by a line which separates areas of higher and lower reflectivities. In the case of a current front,
only the shearing zone will have an enhanced backscatter. Finally, a third possible mechanism of imaging of an ocean front is due to the thermal variations that occur across the front. In this case, variations of the stability of the Marine Atmospheric Boundary Layer (MABL) can introduce an additional variation of backscatter coefficient (Wu, 1991, Beal et al., 1997).

2.2 SAR data

Two SAR images (figure 1) covering the 4 last legs of the first survey were acquired by ERS2 on October, 6 1996 at 10H56 UT (Orbit 7649 Frame: 2889 and 2871). Three JERS1 SAR images (figure 2) were also obtained at 11h05 just West of the ERS2 SAR images (JERS1 ORBIT:25565 Frame: 2876,2888 and 2900). For the ERS2 SAR images, four subimages centered along the 4 legs of the survey were extracted from the original PRI SAR images. SAR images were calibrated to obtain backscattering coefficient images \(\sigma_0\) using the method describe in Laur et al., 1998. Backscattering coefficient were obtained using the SAR toolbox routines provided by ESA/ESRIN. ERS2 subimages extraction was done along the 4 following longitudinal legs: -3.8 E, -3.9 E, -4.0 E and -4.1 E. The width of the subimages is of 0.01 degree of longitude. \(\sigma_0\) values were calculated at a 100 m resolution using a mean filter of 8x8 original pixels. Finally, \(\sigma_0\) legs are obtained averaging the pixel in the radial direction and then averaging using a smooth filter of 10 pixels along the longitudinal direction for reducing speckle noise effect.

For clarity, the \(\sigma_0\) tracks as well as the AVHRR and in situ data are presented in figures 13 to 16. The intensity of the calibrated backscatter coefficient is presented in decibel scale.

\[
\sigma_0(dB) = 10. \log(\sigma_0)
\]

In the case of JERS1 SAR images, general examination of Mediterranean Sea images indicate roughly poor sea surface features presence and a low contrast. Nevertheless, some features of hydrodynamical can be found. JERS1 SAR images have been receiving at the end of the post doctoral position so few time could be spend on it. No calibration was performed and strong difference in pixel values from one image to other can’t be corrected (see the 3 images track figure 2 and figure 3). Such a result should imply that a different calibration constant, K (see Laur et al., 1998) is applied for each JERS1 image even on a same track, which is not the case for ERS2 SAR images. Thus, we focused our work on the central image, where a clear frontal structure at the western boundary of the WAG is visible.

Additionally, an azimuthal shift (around 10 km) of the image corners position supplied in the header of the JERS1 SAR file was found. We correct this shift matching the image coastline with a referenced coastline. A larger azimuthal shift to the north is observed when comparing the JERS1 image position to the foreseen position using the ESA DESCW software. Images foreseen to cover the coastal zone are then found inland.

2.3 AVHRR data

An AVHRR image covering the Alboran sea was obtained on October, 6 1996 at 13h38 UT. The time lag with respect to the SAR image is 2h30 hours later. The figure 4 and presents the AVHRR images of the 3d and 6th of October. A previous mapping showed a good spatial correlation between the position of the front in SAR and AVHRR images (Chic et al., 1997). Nevertheless, respecting previous AVHRR images acquired up to 4 days earlier, we can observed a certain variability of the SST inside the western Alboran gyre (see the ICM contribution to the WEB OMEGA atlas: http://radar.ielt.unipi.it). The 6th of October the core of the gyre presents a temperature around 21.5 degree while 3 days
Figure 1: SAR composite image of the 2 ERS-2 SAR images covering the western gyre of the Alboran Sea. October, 6 1996 at 10h56 UT. The ship track is symbolized by cross and ADCP surface current is overplotted.
Figure 2: SAR composite image of the 3 JERS-1 SAR images covering the western gyre of the Alboran Sea. October 6, 1996 at 11h05 UT. Only the frontal feature around 36.5 N 5W is visible.
Figure 3: Example of a longitudinal radial of the 3 georeferenced JERS1 image in the Alboran Sea (October, 6 1996 at 11h05 UT).
ago the temperature was around 1.5 degree higher. Looking deeper, the AVHRR image of the 6th of October shows two features of interest that can be related to SAR features visible in JERS1 and ERS2 SAR images. West of the WAG, a clear pulse of Atlantic water forming a mushroom-like shape is clearly visible on the AVHRR image (Chic et al., 1997). A strong thermal front (3-4 deg C) is visible between the incoming water and the WAG due to cold trapped water of few kilometers width. The frontal feature on JERS1 SAR image fits the boundaries of this local strong frontal structure of around 60 km length. A day later the mushroom structure disappeared on the AVHRR image.

Looking at the north east side of the WAG, a filament shape of cold surface water was coming from the Spanish coast and was trapped and strained towards the central part of the sea following the northern part of the front. Two days later, this filament disappeared and the central part of the sea was filled with cold water. Longitudinal SST radials were extracted from the AVHRR images for 6 OMEGA-1's legs of interest.

2.4 ADCP data

During OMEGA-1, the on board R/V Hesperides ADCP recorded current profiles. The data were processed such that 80 bindepths were obtained from 12 m to 328 m with a vertical resolution of 4 m. Profiles were averaged on a 10 mn base which gives a spatial resolution of 2.5 km.

A common description of a front is to define the jet in term of shear and divergence (Lyzenga, 1991). The shear is related to the relative vorticity, and produces a cyclonic or anticyclonic shear depending on the sign. The divergence can approximated by the two horizontal component of $\text{div}(\vec{U})$, as the vertical term is low referring to the two first ones:

$$\text{div}(\vec{U}) = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

If $\text{div}(\vec{U}) > 0$ divergence

If $\text{div}(\vec{U}) < 0$ convergence

In case of a convergent movement, the minimum of the operator should indicate where the center of the convergence zone is.

As surface films accumulations are often associated with converging movement one goal of this work was to see where slicks, that appear on SAR images, are situated and whether their occurrence is associated with a local frontal convergence and a downwelling process along the isopycnals.

2.5 SEASOAR data: salinity and temperature profiles.

Seasoar data are also available along vessel's cruise and allows us temperature and salinity profiles. Each profile is averaged on 4 km basis with a vertical resolution of 8 m using 51 bindepths from 5 m to 405 m.

2.6 Meteorological data

For obtaining informations on the wind condition in the area of the SAR images, we used outputs from two meteorological mesoscale models. The MASS model from the Department of Astronomy and Meteorology of the University of Barcelona and the HIRLAM model from the Spanish Institute of Meteorology (INM). at a resolution mesh of 0.2 degree. The MASS model wind speed vector's are computed on a stereographic grid of the
Figure 4: AVHRR image of the 03/10/96 at 02h49 UT covering the western gyre of the Alboran Sea (OMEGA Atlas).

Figure 5: AVHRR image of the 06/10/96 at 13h38 UT covering the western gyre of the Alboran Sea (OMEGA Atlas).
Alboran sea with a spatial resolution of 15 km at the center, which can offer an estimation on a regular grid of 0.1 degree. The HIRLAM model offers a regular gridmesh of 0.2 degree resolution. In figures 6 and 7 we present the wind fields of the HIRLAM and MASS models with a respective time lag of two and one hour to the SAR data acquisition. Wind vector for the MASS model where averaged in order to obtain the same resolution as the HIRLAM model. The 2 models present different patterns. First, the MASS model presents a stronger wind speed than the HIRLAM model, mainly in the eastern part where wind speed values reach 25 m/s which seems doubtful referring to in situ data. In the area of the SAR images the MASS model shows two different zones of wind speed condition. The northern part (latitude higher than 36.0 N) is mainly associated with a small wind speed of around 5 m/s while the southern part presents a higher wind speed of around 15 m/s. Near the coast of Spain some weak values and varying direction are found offshore Malaga-Motril. In the area of Gibraltar strait (Ceuta and Algeciras) the values of wind speed and direction are 10-12 m/s and 130-140 degrees for the MASS model. The HIRLAM model shows a calm area in the center of the Alboran sea of wind speed lower than 3 m/s, while wind speed up to 7 m/s are found in the western part. In direction and speed, the HIRLAM model exhibits a good agreement with the in situ measurements.

The local decrease in the center of the Alboran sea as well as local wind front is this area are visible on the SAR images. In situ measurements close to the Gibraltar Strait (Ceuta and Algeciras and ship) at 11h00 UT give an local estimation around 3.0-3.5 m/s with a direction of 30-40 degree. Measurements at the northern coast at Malaga and Almeria gives respectively 5-7 m/s and a wind direction from 300-350 deg. Finally, in order to simulate the wind contribution to $\sigma_0$ we used a constant wind along the 4 legs, blowing at 4 m/s for a wind direction of 340 degree.

From the HIRLAM model, we also obtained the air temperature field at 2 m closest in time to the SAR images (12 h00 UT). The pattern of the marine atmospheric layer shows a clear decrease of the order of 1 deg C from north to south in the area of the western boundary of the eastern Alboran gyre (figure 8). The Western Alboran Gyre is clearly associated with the lowest value (19 C).

2.7 Description of features observed on the SAR images

2.7.1 ERS-2 SAR images

The composite image of the two ERS-2 SAR PRI images of the central part of the Western Alboran Sea has been previously described by Chic et al., 1997 (figure 1). A good agreement between the location of the thermal front observed on the AVHRR image and of the front described by the SAR images has been observed. Dark structures outline the northern-eastern boundary of the western anticyclonic gyre, but slightly more to the North than the pure thermal front. These low backscattering areas are an eastward extension of slicks features observed on SAR images of October 2, 1996 (figure 24). The origin of these dark lines, situated slightly north of the thermal front boundary, is probably due to Atlantic surface water or upwelled waters coming from the north, where few days ago occurred an upwelling. Moreover, the area outlined lies in the doming area of isopycnals at the frontal boundary.

Previous authors reported that in general cooler water is associated with lower backscatter (Martinez Díaz de Leon and Robinson, 1997, Nilsson and Tildesley, 1995) but as these waters are also situated in the shear zone, the influence of hydrodynamical interactions between wave-current should also be explored.

Various others zones of low backscatter are also visible near the Spanish coast and in the middle of the sea. These zones are supposed to be associated with local weak wind speed
Figure 6: Wind field from the HIRLAM Model at 09h00 UT the 06/10/96.

Figure 7: Wind field from the MASS Model at 10h00 UT the 06/10/96.
velocity. For the northern zones, the MASS model, shows a unestablished wind direction at the coast which tend to support this hypothesis. In the central part (south of 36.0 N), the MASS model presents a established wind with a velocity around 15 m/s which is not compatible with the strong decrease of the backscattering coefficient, while the HIRLAM model presents a local value of 3 m/s which can explain the decrease of the backscatter. Nevertheless, along the 4 OMEGA tracks of interest the calibrated backscattering coefficient is of the order of -10 dB. This value is related to small wind speed (around 3 to 4 m/s) with respect to the CMOD-4 model. In the southern part of the image, the increase of the backscatter, which lead to a wind speed of 5 m/s, is not in agreement with the wind speed estimation of approximatelly 15 m/s from the MASS model.

2.7.2 JERS-1 SAR images

The major feature of the JERS-1 images is associated with the detection of a frontal feature at the western boundary of the WAG. A georeferenced subimage in figure 9 shows the area of strong wave-current interaction which should be referred to the convergence area. No slicks features are visible in the area of the SAR frontal structure. The plus symbol line presents the vessel’s track inside the front along which in situ data were recorded. Two tracks are clearly crossing the SAR frontal structure of around 2 km width, the first one along longitude 4.80 W was obtained around 11h00 UT and is purely in time with JERS1 image. The second track along 4.69 W was obtained 11 h later than the JERS1 track. Comparing to the surface ADCP current field (see figure 24) the frontal feature is located in the area of the incoming Atlantic pulse associated with strong current speed (around 2 m/s).
Figure 9: subimage of JERS1 SAR (25565-2888) at 11h05 UT day 06/10/96. The vessel track is overplotted. Two legs clearly cross the front.
3 Data analysis

Continuous subsurface data were collected during the cruise using an on-board water pump at 4.5 m depth which allows a spatial resolution around 250 m. The biological parameters include: temperature, salinity (in psu), fluorescence of the Chlorophyll (in arbitrary units), fluorescence of the dissolved organic matter, gelbstoff (in SFU) and the coefficient of attenuation of light (in m$^{-1}$). For each ERS2 SAR legs of interest we analyzed the relationship between both in situ and remote sensing parameters. The along track variation of the various parameters are presented in figures 13 to 16. We also analyze the two JERS1 SAR legs of interest in light of the in situ data obtained during the second OMEGA-1 survey (figures 10 to 12).

3.1 Leg 4.91 W

The 4.91 W leg was obtained during the second survey on October, 6 1996 (figure 10). Unfortunately a thermostalinometer failure occurred in the area of the boundary of the WAG when JERS1 acquired the SAR image. A clear different pattern between AVHRR SST data and in situ subsurface temperature is found and especially for latitude less than 36.10 N even if the time difference is only few hours. In situ data recorded present roughly cold waters of around 18 deg C, and the decrease of temperature while exiting the WAG does not reach the amplitude observed on the SST image. AVHRR SST value for the WAG is around 21 deg C (which is the right value observed for other leg). As the thermostalinometer stopped crossing the front we argue that the values obtained previously are not so truthful even before the failure. Nevertheless, biological data were correctly acquired. Thus, looking at the gelbstoff fluorescence and the beam attenuation a step increase at 35.88 N from south to north is visible. This first increase indicates the exit of the WAG gyre where biological activity is the lowest in the region. This position corresponds exactly with the position of the frontal structure observed on JERS1 SAR image and induced by wave-current interactions. North of this boundary gelbstoff fluorescence is rather constant, while Chlorophyll fluorescence and beam attenuation increase up to find a maximum at 36.15 N. The location of the SAR frontal structure is found at the edge of the the WAG just where starts the strong thermal decrease. Moreover, the thermal front is enhanced by the presence of trapped colder water between the WAG and the incoming Atlantic water, forming the mushroom like shape which is associated with the lowest salinity values. North of this structure a decrease of temperature is visible and can be associated with the upwelled waters found south of the Spanish coast.

3.2 Leg 4.81 W

The leg 4.81 W was obtained on October 6, by the end of the day. Time difference between SAR image and the crossing of the WAG gyre is of 11h00 later. The figure 11 presents the data obtained. The dashed line locates the position of the SAR frontal structure observed for this leg. In the previous case, the front was situated in the inner part of of the WAG front (high salinity and temperature, low fluorescence and clear water). Looking at the AVHRR image, which only have two hours difference with the SAR data, one can clearly see that SAR frontal structure is also found for this leg, just before the clear decrease of temperature while exiting the WAG. Comparing AVHRR SST and in situ data profiles, values are found similar. The displacement of the front between the location of the SAR frontal structure and the boundary of the WAG is of 7.5 km in 11 hours, which gives a mean displacement of the front to the north of around 20 cm/s. The direction of the displacement is accordance which the anticyclonic circulation of the WAG.
Figure 10: Leg 4.9 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), Gelbstoff Fluorescence (d), density (e), attenuation of light (f), avhrr SST (g). Dashed vertical line locates the front observed on the JERS1 SAR image.
Trapped waters of lowest salinity and lowest density are clearly visible between the WAG gyre and the more variable surface water generally described by low temperature, higher chlorophyll and gelbstoff fluorescence and beam attenuation than in the WAG and a more variable salinity pattern which should indicate higher mixing processes than inside the WAG where the salinity is stable around 36.5 - 36.6 psu.

3.3 Leg 4.69 W

The leg 4.69 was obtained in the morning of October, 7 1996. The leg is outside of the frontal structure observed both in the AVHRR and SAR images of October, 6 (figure 12). The similar general patterns of the WAG gyre in term of temperature, salinity, density, fluorescence and beam attenuation is found. Nevertheless, trapped waters of lowest salinity and temperature are lost. On the contrary just north of the WAG, where temperature decreases, waters of higher salinity (around 37.0 psu) are now found.

3.4 Leg 4.14 W

this leg and the three following are now describing the north-east side of the WAG (figures 13 to 16).

Concerning, the 4.1 W leg, a strong decrease of salinity at 36.45 N separates the Mediterranean surface water, at the north of the front, from the modified Atlantic Water of the WAG, south of the front. Inside the salinity front, mainly between 36.45 and 36.25 (width of around 20 km) the lowest surface salinity values are found (35.75 psu). Inside this water vein of surface Atlantic water, we can see a local increase at the center that could be associated with trapped Mediterranean surface water. This increase at 36.35 N is also found in the temperature profile. The frontal zone is associated with lower values of temperature. The strongest variation of the thermal front is found at the south while the strongest part of the salinity front is found at the northern edge. ADCP surface data reveals that this fresher and cooler vein is found in the shearing zone and not in the core. The current core lies between latitude 36.0 and 36.2 N, where temperature, salinity and backscattering coefficient are roughly constant.

Looking at the SAR radial we see that there's a better agreement between SAR and temperature profile than with salinity profile. SAR data reveals an increase of the backscatter in the area of the thermal front even if it doesn’t cover the whole part of the thermal front. At the beginning of the thermal front where lowest temperature values are found a local decrease of backscatter is found (see the AVHRR image). This decrease reaches 1 dB, but few lines away it can reach -3 dB. This local decrease, which occurs in the area of cold water can be enhanced by the presence of slicks structures which appear as black fine lines on the image. Going south and crossing the thermal front, (of 4 C using in situ data) an increase of 3 dB is found. Then, south of 36.3 N the backscatter is roughly constant even if the thermal front ends at 36.2 N. In general, we found that the increase of backscattering coefficient, is well correlated with an increase of the SST.

AVHRR SST of October 6 and in situ subsurface temperature are well correlated. North of 36.5 N, SST temperature is higher, but can't be verified in the in situ data since it's outside of the leg. Inside the gyre, the increase in temperature up to 21.5 C is found in both data. The AVHRR thermal gradient is slightly lower than the in situ data one's. AVHRR data shows a zone of minimum value of around 18 C between latitude 36.5 and 36.4 N. While, in situ data gives lowest values at 17 C. This phenomena is related to the previous occurrence of an upwelling event that cooled the surface water fews days before. During the time lag of 2 days between in situ data and the AVHRR image the waters
Figure 11: Leg 4.8 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), Gelbstoff Fluorescence (d), density (e), attenuation of light (f), avhrr SST (g). Dashed vertical line locates the front observed on the JERS1 SAR image.
Figure 12: Leg 4.7 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), Gelbstoff Fluorescence (d), density (e), attenuation of light (f), avhrr SST (g).
warmed.

In the vicinity of the lowest temperature values before the salinity front at 36.4 N two peaks of salinity are found in correlation with two peaks of fluorescence which reach up to 0.40. Moreover, the pattern of the attenuation of light coefficient follows a similar pattern with the highest peak reaching 0.18. Then, before, the southern temperature front fluorescence, attenuation coefficient and FCD reach their respective lowest values which are roughly constant inside the Alboran gyre. In SAR data, the strong decrease of the backscattering is obtained close to the salinity front where the highest values and major variations in biological parameters are found.

3.5 Leg 4.03 W

The leg around longitude 4.03 W presents a strongly varying surface salinity north of 36.25 deg. South, we observe the presence of the WAG with stable salinity (around 36.5 psu) and high temperature. Between 36.25 and 36.35 N is found the thermal front with a thermal variation from 21 to 17 C. AVHRR data gives a similar pattern even if the thermal gradient is not so strong due to changes during the time lag that we previously introduced. More in details, two steps increases are visible inside the thermal front in the AVHRR data, that we also found in the SAR data. SAR data presents a 3.5 dB increase when temperature increases between 36.5 N and 36.3 N. The $\sigma_0$ increase is correlated with the doming of temperature observed on the SEASOAR data at 20-25 m. The $\sigma_0$ value is found minimum where lowest temperature values occur. Local decreases up to 4-5 dB can also be found is this area due to slicks in the surrounding area of the front. Increase of the temperature and $\sigma_0$ inside the front occurs in a two steps manner. First, we found that an increase of 1 C provides an increase of near 1 dB. Then, the second step, of 2 C provides an increase of 2 dB. Nevertheless, the first increase of $\sigma_0$ is more around 2 dB if we take into account that the increase starts norther than the thermal increase deduced from the AVHRR data. A common pattern with the previous leg, is that the final increase of the temperature at the end of the front is not clearly associated with an increase of $\sigma_0$.

Concerning the biological data the situation at roughly similar to the previous leg. High values of fluorescence and attenuation coefficient of light are found in the zone of the lowest values of temperature, where salinity fluctuates strongly. The width of the zone is of 0.25 degree of latitude wide. A $\sigma_0$ decrease is observed in vicinity the highest fluorescent zone. Then, increase of backscatter is found in the zone of the highest gradient of temperature of the frontal boundary of the WAG. But due to the time lag of 2 days, that shift slightly to north and smooth the thermal front it is difficult to define precisely, if $\sigma_0$ decrease is clearly associated with high values of fluorescence and attenuation of light coefficient.

3.6 Leg 3.92 W

The 3.92 W leg presents the similar thermal frontal structure but more to the south. The thermal front is situated between 36.15 and 36.3 N in the in situ data, while it's wider in the AVHRR data (between 36.0 and 36.3 N). The main salinity front is found north of the previous thermal front and presents features of trapped Mediterranean surface water of larger salinity (larger than 37.0 psu). More to the North, the salinity decreases and stabilizes to values of modified Atlantic water around 36.5 psu. The lowest values are always found in the area of the coldest water. In the south, after the lowest values, salinity increases intermediate values of 36.5 psu which characterizes modified Atlantic water
Figure 13: Leg 4.14 W: Temperature (a), salinity (b), Chlorophyll fluorescence (arbitrary units) (c), density (d), attenuation of light coefficient (e), backscattering coefficient (f), current velocity from the ADCP (g) and AVHRR SST (h).
Figure 14: Leg 4.03 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), density (d), attenuation of light coefficient (e), backscattering coefficient (f), current velocity from the ADCP (g) and AVHRR (h) radials.
inside the gyre. In details, in situ and AVHRR data shows some discrepancies. In situ data presents in the area of lowest temperature a local peak (associated which the peak of salinity) that could described trapped Mediterranean surface water. This peak is not found two days later in the AVHRR data. Looking at the position of the lowest SST values we found a shift of 0.1 deg of latitude to the North. The position of the minimum is perfectly in accord with the center of the doming of the isotherms in the SEASOAR data. The thermal front in the AVHRR data presents a increase in two steps. Starting from the minimum of temperature at 36.4 N, a first increase of 2.25 C to the south down to 36.25 N producing a local maximum value of temperature. Then, a second increase of 2 C is found down to 36.0 N. Both increases occur before the core of the current. From a general point of view, SAR data along this leg doesn't present a strong different pattern from one edge to the other of the front. Moreover, atmospheric signals around 35.8 N complicate the pattern. Nevertheless, in the area of the first step of the AVHRR thermal front a clear increase of 3 dB is visible. But, the position of the minimum of backscatter is found slightly south of the SST minimum. Globally, it appears that SAR identification of the front decreases as the thermal front intensity decreases (figure 13).

In the 3.92 W leg, the highest values of fluorescence are also found just before the strong increase of temperature, where lowest values of temperature are found (17.5 C) in conjunction with the lowest salinity values (35.80 psu). The highest values of salinity more to the north that reach 37.25 psu are associated with trapped water. This water is not associated with the highest fluorescence values, but with intermediate values describing the northern part of the front. Looking at the local decrease of $\sigma_0$ around 36.35 N, occurring before the increase associated with the southern thermal front, this decrease seems to occurs in the area of the trapped water referring to the in situ data but looking at the AVHRR data this decrease is much more associated with the lowest temperature. Thus, due to the spatial variations that could occur during the 2 days time lag, it seems difficult to go further in the interpretation.

3.7 Leg 3.81 W

The 3.8 N track presents a great difference between AVHRR and in situ temperature, even if similar thermal features are found. The main difference is a less intense thermal front in the AVHRR data than in the in situ data and a shift. Comparing the common zone, we found the local thermal minimum before the thermal front is found more to the north two days later with a shift of near 0.15 degree of latitude. The position of the local maximum value of temperature associated with trapped water of is also similarly shift towards the north. But, the northern edge of the trapped water is similar in both case. This pattern could be explained by the influence of the upwelling that occurs just before the in situ data, and that is visible on AVHRR image of October, 2. For this date, the thermal front was stronger but then smoothed as upwelled surface water warmed during the following days.

The SAR data doesn't reveal a clear thermal front as in the case of the 2 first legs. But, features of trapped water are clearly visible. Thus, we can see that the decrease and increase of near 1.5 C are clearly reproduced by variation of 2 dB. But the area of the main thermal front SAR data doesn't reproduce any frontal structure. In the center of the core an important decrease of $\sigma_0$ at 35.9 N is observed. The decrease is of 2 dB and is not associated with a decrease of the temperature which is roughly constant in this area. Between, 35.6 and 35.8 N $\sigma_0$ reaches its lower values of -10 dB without any correlation with the SST. On the contrary, $\sigma_0$ reaches its lower value when the SST reaches its higher
value. In fact, here the variations of $\sigma_0$ are more influenced by variation of the wind stress as we are in an area of varying wind.

In the 3.81 W leg, the patterns of attenuation of light coefficient and fluorescence are rather similar to the patterns of the three previous legs. The area of highest fluorescence is observed at the cooler zone front before the strong thermal front, but not inside the trapped water of highest temperature. The same pattern is found for the attenuation coefficient of light, but with a secondary peak in the trapped water area. The intensity of the peak of fluorescence is around 25% lower than in the first leg. The strong gradient of attenuation of light coefficient is correlated with the decrease of fluorescence and is found inside the strong thermal front of the WAG. In the SAR data a better correlation is achieved with the AVHRR profile of the day. Nevertheless, the second peak of attenuation of light coefficient found in the trapped water, where highest $\sigma_0$ is found but more probably due to the highest temperature. No $\sigma_0$ decrease is observed in relation with the influence of the fluorescence and no surface films are observed on the SAR image.

3.8 SAR and in situ data: conclusion

In general backscatter variations in the area of the front of the WAG show a good agreement with SST variations. The presence of slicks is encountered in the cool area north of the front, where high values of fluorescence and of the attenuation of light coefficient are found. In the northern part, in the vicinity of the front, local recirculation of Mediterranean surface water can lead to intrusion of trapped water of higher temperature and salinity and lead to local decrease of fluorescence and attenuation of light coefficient. Slicks are only present in the area of high fluorescence in the frontal zone in the outer part of the WAG front. Hydrodynamical frontal features seem to occur at the inner edge of the WAG gyre. No slicks structures are detected inside the gyre.

The crossing of the thermal front of the Alboran gyre, showed by an increase of the temperature is often associated with a increase of the backscattering coefficient but it does not occur in the whole part of the thermal front and its occurrence seems to depend on the intensity of the thermal front. The non concomitant in situ temperature show a stronger thermal gradient than with SST AVHRR concomitant data with SAR images. Moreover, in the AVHRR image a decrease of the thermal front is visible in the leg 3.8 W and 3.9 W which is not visible in the in situ data. The decrease of thermal gradient is maybe one of the reason of the absence of $\sigma_0$ gradient for such legs.

4 Influence of the Atmospheric stability and ocean currents

The two main mechanisms of SAR ocean meso-scale features, like fronts and gyres, are the influence of the variation of the thermal difference between air and sea, and hydrodynamical interactions between Bragg waves and currents.

4.1 Influence of the stability of the Marine Atmospheric Boundary Layer

In order to examine the influence of stability the Marine Atmospheric Boundary Layer (MABL) in the area of an ocean front, we first describe the expected variations of the cross section due to variation of the thermal difference between sea water and the atmospheric boundary layer. We first used the assumption of a constant atmospheric temperature across the thermal ocean front. We describe the theoretical backscatter using the CMOD-4 model and Wu's model (1991).
Figure 15: Leg 3.92 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), density (d), attenuation of light coefficient (e), backscattering coefficient (f), current velocity from the ADCP (g) and AVHRR SST (h).
Figure 16: Leg 3.81 W: Temperature (a) and salinity (b), Chlorophyll fluorescence (c), density (d), attenuation of light coefficient (e), backscattering coefficient (f), current velocity from the ADCP (g) and AVHRR SST (h).
4.1.1 CMOD-4

The CMOD-4 wind retrieval model was developed for the ERS scatterometer but was successfully used for ERS1 and ERS2 SAR images. The CMOD-4 model provides an estimation of \( \sigma \) as function of the wind direction, relative to the radar look angle \( \phi \), and the wind speed at 10 m, \( U_{10} \).

\[
\sigma_0 = B_0[1 + B_1 \cos \phi + B_2 \cos 2\phi] \tag{4}
\]

where \( B_i \) coefficient depend on the local angle of incidence of the radar and the wind speed. The model is tuned for a mean thermal marine atmospheric stratification.

4.1.2 Theoretical model

Influence of non neutral MABL to radar cross section induced by a thermal difference between air and sea surface \( (\Delta T = T_{atm} - T_{sea}) \) has been modeled by Wu (1991). The influence is dependent of the stability of MABL. Variations of the cross-section due the stratification is given by:

1) stable condition case \( (T_{sea} < T_{atm}) \):

\[
\frac{\sigma}{\sigma_0} = \exp \left( -0.3 \frac{\Delta T}{U_{10}} \right) \tag{5}
\]

2) unstable condition case \( (T_{sea} > T_{atm}) \):

\[
\frac{\sigma}{\sigma_0} = \exp \left( -1.55 \frac{\Delta T}{U_{10}} \right) \tag{6}
\]

\( \sigma \) is the global cross-section per unit area and \( \sigma_0 \) is the cross-section associated to the wind-induced cross section that can be modeled by the CMOD-4 model. Using Wu's Model, the influence of the thermal difference induces a higher variation of the cross-section in unstable condition than in the stable case (Beal et al., 1997). In decibel scale:

\[
\sigma(dB) - \sigma_0(dB) = 10 \log \left[ \exp \left( -\alpha \frac{\Delta T}{U_{10}} \right) \right] \tag{7}
\]

where \( \alpha \) depends on the stability condition as previously.

4.1.3 Application to OMEGA-1 cruise

For October, 6 around 10h00 to 12 h00 UT, we assumed a wind speed estimation of 4 m/s and a wind direction of 340 degree in the ocean front area. Measured air temperature is \( T_{atm} \) of 20°C and a sea surface temperature varying from 18°C to 21°C across the front. These values lead to theoretical variations of the cross-section between -1.75 dB to 0.5 dB depending on the position across the front.

We compute the theoretical perturbation due the non neutral stability of the atmospheric boundary layer using sea surface temperature from both in situ and AVHRR images. For the need of the computation we used a windspeed or 4 m/s and a wind direction of 20 degree and supposed in a first step the air temperature constant. These values were used along all the legs to compute the contribution of the wind using the CMOD-4 model. Perturbations were calculated using the model of Wu (1991). The results are shown in figures 17 to 20. The model shows that in most of case the variation of the perturbation in the frontal zone can be explained by the influence of the non neutral stability. Moreover, the best agreement between inferred perturbation using CMOD4 and theoretical using the SST values is found for the AVHRR data. In situ data produce higher perturbations due to the stronger thermal front, that was taking place two days before. Discrepancies along...
the whole track are visible, mainly for the leg 3.92 and 3.81 and are due to the application of constant wind while SAR image and wind model show a non constant wind situation all along the track. Nevertheless, these results show that the main variation in the area of the front can be explained by the influence of the non neutral stability of the atmosphere.

In a second step, we used the air temperature profile obtained by the HIRLAM model at 12h00 UT on October, 6 for improving the model. The new results obtained doesn't provide a clear difference, and the backscatter behavior along the 4 legs is similar than in the previous case. Discrepancies introduced by a varying air temperature (between 19-20 deg C) are negligible comparing to the difference that we relate to wind variations. As a example we present in figure 21, the backscatter perturbation, $\delta \sigma$, simulated with the air temperature profile obtained from HIRLAM model.

### 4.2 Influence of wave and current interaction

In order to examine the hydrodynamical influence of the front we first, present the theoretical model of wave-current interaction in presence of an oceanic front developed by Johannessen et al. (1996) and Lyzenga (1991). Then using the value of the front's parameters obtained during the cruise, we used this model and analyze the results.

#### 4.2.1 Theoretical model

\[
(c_{gx} + u) \frac{\partial f}{\partial x} + \beta_r f = \left( k_x \frac{\partial u}{\partial x} + k_y \frac{\partial v}{\partial x} \right) \frac{1}{N_o} \frac{\partial N_o}{\partial k_x}
\]  \hspace{1cm} (8)

where $N_o$ is the action spectral density, which is the energy spectral density divided by the wave frequency. $k_x$ and $k_y$ are the respective x and y wavenumber components. $f$ represent the net source function for wave action. $\beta_r$ is the relaxation rate.

\[
N_o(k, \phi) = \frac{\rho \omega}{k} S_o(k, \phi)
\]  \hspace{1cm} (9)

where $S_o(k, \phi)$ is the wave height spectrum. The influence of the importance of the contribution of the two first terms can be estimated defining the ratio $(c_{gx} + u)/L$. where $L$ is the characteristic length of the current and $U$ the caracteristical current speed. For Bragg wavelength of few centimeters and using for the caracteristics parameters of the Alboran jet $U= 1$m/s and $L=25$ km, we found that the first term is 4 orders of magnitude less than the second. $\beta_r$ is found between 0.1 and 1.0 s$^{-1}$ for wavelength between 1.0 and 10.0 cm (Lyzenga, 1991). Then, we have:

\[
\beta_r f = \left( k_x \frac{\partial u}{\partial x} + k_y \frac{\partial v}{\partial x} \right) \frac{1}{N_o} \frac{\partial N_o}{\partial k_x}
\]  \hspace{1cm} (10)

We used the following spectral formulation for the decrease of wave spectrum at high frequency:

\[
S_o(k, \phi) = c_o k^{-3} \cos^2 \left( \frac{\phi - \phi_w}{2} \right)
\]  \hspace{1cm} (11)

$\phi_w$ is the wind direction relative to the x axis. Changing the coordinate system from $(k_x, k_y)$ to $(k, \phi)$ we have:

\[
\frac{k}{N_o} \frac{\partial N_o}{\partial k_x} = \frac{k}{N_o} \frac{\partial N_o}{\partial k} \cos \phi - \frac{1}{N_o} \frac{\partial N_o}{\partial \phi} \sin \phi
\]  \hspace{1cm} (12)

The modified wave spectrum in a first approximation is given by:
Figure 17: Leg 4.14 W: $\sigma_0$ perturbation due to the influence of the variation of the SST. Air temperature is assumed constant.

Figure 18: Leg 4.03 W: $\sigma_0$ perturbation due to the influence of the variation of the SST. Air temperature is assumed constant.
Figure 19: Leg 3.92 W: $\sigma_0$ perturbation due to the influence of the variation of the SST. Air temperature is assumed constant.

Figure 20: Leg 3.81 W: $\sigma_0$ perturbation due to the influence of the variation of the SST. Air temperature is assumed constant.
Figure 21: Leg 4.14 W: $\sigma_0$ perturbation due to the influence of the variation of the SST. Air temperature profile is supplied by HIRLAM model’s output.

$$S(k, \phi) = S_o(k, \phi)(1 + f(k, \phi))$$

(13)

Using the Bragg scattering model, the cross-section per unit area, for a radar operating at an incidence angle $\theta$ is given by:

$$\sigma_o(\theta, \phi) = 8\pi k_o^2 G(\theta)(S_o(k_B, \phi) + S_o(k_B, \phi + \pi))$$

(14)

$k_o$ is the radar incident wavenumber and $k_B$ is the resonant Bragg wavenumber. The term $G(\theta)$ is a geometrical term depending on the polarization of the radar.

then, annotating $\sigma$ the perturbed radar cross-section due to the current, the perturbation induced is:

$$\frac{\sigma - \sigma_o}{\sigma_o} = \frac{S_o(k_B, \phi)f(k_B, \phi) + S_o(k_B, \phi + \pi)f(k_B, \phi + \pi)}{S_o(k_B, \phi) + S_o(k_B, \phi + \pi)}$$

(15)

Using that

$$\left( k_x \frac{\partial u}{\partial x} + k_y \frac{\partial v}{\partial x} \right) = \vec{k} \cdot \vec{\partial_x U} = \left| \vec{k} \right| \sqrt{\left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 \cos(\phi - \psi)}$$

(16)

$\psi$ represents the relative intensity between the shear and the convergence patterns of the current and is defined by:

$$\psi = \tan^{-1} \left( \frac{\partial v}{\partial u} \right)$$

(17)

$$S_o(k_B, \phi + \pi) = S_o(k_B, \phi) \tan \gamma \left( \frac{\phi - \phi_w}{2} \right)$$

(18)
After some manipulations Johannessen et al., (1996) found that:

$$\frac{\sigma - \sigma_o}{\sigma_o} = \left[ \frac{\sqrt{\left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2}}{\beta_r} \right] \cos(\phi - \psi) g(\phi, \phi_w)$$  \hspace{1cm} (19)

$$g(\phi, \phi_w) = - \left[ p + 1 - \frac{c_s}{c} \right] \cos \phi + n W \left( \frac{\phi - \phi_w}{2} \right) \sin \phi$$  \hspace{1cm} (20)

$$W(\phi') = \frac{\cos^{2n-1} \sin \phi' - \sin^{2n-1} \phi' \cos \phi'}{\cos^{2n} \phi' + \sin^{2n} \phi'}$$  \hspace{1cm} (21)

The term $W(\phi')$ is independent of the variation of the front direction and for a given image it remains constant, assuming a constant direction of the wind speed over the image area. For ERS SAR $\frac{c_s}{c} \approx 0.5$ and we used $n = 2$ and values of $p$ between 4 and 7. Johannessen et al., shown that the term $g(\phi, \phi_w)$ is always negative for value of $\phi$ between $[-80^\circ, 80^\circ]$. Then, in most of case the sign of the perturbation is the opposite sign of cos($\phi - \psi$). Johannessen et al. (1996) present a graphical method for obtaining easily the sign of the perturbation. But as in our case, the angle is near $80^\circ - 100^\circ$, it is useful to consider the effect of both term.

![Graph](image_url)

**Figure 22:** variations of the global cross-section due to change of the relative radar look direction. The values higher than the wind contribution indicate a front imaged bright and the values lower indicate a front imaged dark.

The figure 22 presents a typical result of the previous model. The calculation of the global cross-section is defined using the additive contribution of wind and hydrodynamical
interactions. We used the CMOD-4 model for a wind speed of 4 m/s and a direction from
the 122 degree referring to the radial axis (wind direction 340 degree). The values of the
shear and divergence are those of Johannessen et al. (1996) and are similar to those can
be found in the western Alboran front. Even if the magnitude of the variations is roughly
low, referring to that observed on SAR images, the model should describes the dark or
bright imaging of ocean front (Johannessen et al., 1996).
We choose two areas to test the model. One is the area of the front described by the in
situ data and the other more the east where such kind of hydrodynamical interactions
seems to occur.

In the first case, the local value of the relative radar look direction is 98 degree. Such
a value lies in the area where no hydrodynamical signature is expected (see figure 22). In
fact, our analysis along the 4 legs shows that most of the $\sigma_0$ variation seems associated
with the atmospheric boundary layer influence.

On the contrary, in the eastern part, the boundary of the gyre appears to to be outlined
by hydrodynamical mechanisms (figure 1). We present in figure 23 a subimage of the area.
Three lines of local higher backscattering are found and followed by dark areas. The order
of variations of backscatter between the increase and decrease is of 5-6 dB. The forward
decrease of backscatter is stronger than the firstly increase. The increase is of the order
of 1 to 2 dB. These lines seems to follow the boundary of the gyre. Unfortunately, the
AVHRR image is cloudy in this area and no in situ data are available for helping us in
understanding these features. We suppose that this phenomena is still links to the presence
of low temperature water that was detected upstream.
The width of the lines of higher backscatter is around few hundreds meters, and darker
areas’ width are of the order of few kilometers. The local value of the relative look angle
direction is of 136 degree. Such a value lies in the area of the maximum enlightenment
effect (see figure 22). In fact, this area is found where the features appear most clearly
even if the modeled perturbation is of the order of 1 dB.
In this area of the gyre, the current shear have to be more intense than in the north
part that previously described. Common visual observations of the Alboran jet show that
the shear/convergent zone is described by a higher sea surface roughness in a fringe of
the order one hundred meters. At the borders of this fringe, surface films and floating
material can be found. The presence of such surface films, should also help to reduce
the backscatter. In the south-east part of the gyre, where some atmospheric features are
visible on the SAR image, we can clearly see, some such slicks inside the frontal boundary.
If we look more closely to the figure 23, and we suppose that each bright line represents
a boundary then we can specify each boundary. The southern one’s should represent the
boundary between the coldest surface water of the gyre-induced upwelling and the western
Alboran gyre. The middle one’s should represent the boundary between the previous one
and the trapped filament shape of recirculating Mediterranean surface water coming from
the coast of Spain. Finally, the northern boundary should represent the boundary between
the previous one and north surface waters which were influenced by the coastal upwelling
that occurred few days before.

4.3 Slicks presence
Visuals observations during the OMEGA and FE92 cruises report that surface films and
accumulation of various floating materials were found in the vicinity of the WAG front.
In SAR images of the Alboran Sea slicks structures are found outside of the Western
and Eastern Alboran Gyre. Slicks are mainly observed between the coast of Spain and
the WAG, where upwellings frequently occur, and between the two gyres where complex submesoscale pattern are visible (see the global mosaic of October, 1996 and the FE92 cruise ERS1 SAR images, figures 25 and 26). The lack of surface films structures inside the two gyres is maybe mainly related with the biological activity that is very low in the two Alboran gyres due to oligotrophic waters. On the contrary, in the northern part of the Alboran Sea, subject to coastal upwelling and gyre-induced upwelling along the boundary of the WAG (Minas et al., 1986), slicks could be more present due a higher biological activity. Concerning the EAG observed during FE92 cruise, slicks are also found in the area of the Almeria-Oran front where offshore upwelling occurs (Font et al., 1996).

5 conclusion

Previous studies on frontal structures by SAR imagery shown that current fronts are often imaged with a perturbation of the backscattering coefficient that can reach up to ±3 dB. The sign of the perturbation depends on the radar look direction relative to the front direction (Johannessen et al., 1996). In the case of the WAG we found that such hydrodynamical imaging process is found in some cases at the western and eastern boundaries of the WAG.

Nevertheless, the imaging of the WAG is often more globally associated with its thermal pattern that induce variations in the Marine Atmospheric Boundary Layer stratification. Variations of the cross section due to this effect are found of the same order than variations due to hydrodynamical interactions process. But here we rather found a global increase of 2-4 dB than a perturbation across the stream line. The minimum value of backscatter is observed in conjunction of slicks structures. The SST variation is around 2 degree and the $\sigma_0$ increase is higher than 2 dB. We emphasize that, the intensity of the SST gradient is directly responsible of the $\sigma_0$ increase. In addition, the concentration of slicks at the boundaries of the WAG should also play a key role in enhancing the contrast between water of low (WAG) and relatively high biological activities. Inside the WAG, where the temperature is around 2 degrees higher, no slicks structures are observed, even if small wind speed allows their presence. We observed that natural slicks structures appears in
the area of lower values of temperature and convergent zone. The occurrence of the slicks leads to an enhancement of the decrease of \( \sigma_0 \) due to cooler water. The area of the northern front of the western Alboran gyre is one of the most productive area in the Mediterranean Sea so that biological activity should play a role in the occurrence of natural slicks at the front that still to be defined.

We found some discrepancy between AVHRR SST and in situ data regarding the thermal intensity of the front and its position. This discrepancy is due to the time lag of two days between in situ data and the AVHRR image of October, 6. Comparison of AVHRR data truly concomitant with in situ data shown a better correlation. When comparing in situ and satellite data, the synchronicity is important, even if it is always possible, in most of case, to correlate SST with in situ data for time lag of few days. In the case of SAR imaging, the synchronicity is more critical, because of the influence of the wind stress. In few hours sea surface roughness can completely change, waves appear, slicks are dispersed and frontal structures disappear. In this case, it’s really important to reduce the time lag between in situ data and SAR-AVHRR images. This is better achieved during the OMEGA-1 cruise in the western part of the WAG, close to the Atlantic water input (figure 24). The images obtained on October 2, are truly concomitant with the first legs of the first OMEGA-1 survey.

As final recommendations for future cruise in the WAG using SAR imaging, it’s seen us important now to emphasize future in situ meshgrid along the boundary of the WAG and the northern part without entering so far in the WAG. In fact, results of OMEGA-1 cruise and FE92 reveal that when WAG is clearly formed, charaterics of its surface waters are strongly stable: high and stable temperature, stable salinity and a low biological activity. Thus, such an along front cruise track should reduce the in situ acquisition time, improve the synopticity of the data and supply a finer zonal resolution than in the case of OMEGA-1 which was around 0.1 deg.

6 Acknowledgments

We are warmly grateful to Jordi Font for giving us the opportunity to realize this work at the ICM. We are grateful to Javier Ruiz from the University of Cadiz (Spain) for providing us the biological surface data and Louis Prieur (CNRS, France) for helpful comments. We also thanks all the OMEGA team for providing this large multidisciplinary dataset (MAS3-CT96-0051). We thanks the Puertos del Estado (SPAIN) for giving us wind in situ measurements that helped us in interpreting SAR images. We are also grateful to Bernat Codina, from the Dpt. of Astronomy of the University of Barcelona for providing us MASS model wind maps. We also thanks the European Space for providing ERS 1 and 2, JERS1 SAR images that were used during this project (AO1.E1, AO2.E102, AOJ.2). This work was supported by the E.U. Marie Curie program under contract MAS3-CT97-5051.
Figure 24: SAR composite image of the 2 ERS-2 SAR images covering the western gyre of the Alboran Sea. October, 2 1996 at 22h36 UT. The ship track is symbolized by crosses and ADCP surface current is overplotted.
References


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7 Communications and Publications

During the post doctoral effort have been made on presentation and writing issues. In annexes papers from published proceedings are supplied.

7.1 Communications


- Detection by ERS2 SAR imagery of the northern front of the western Alboran sea gyre during the OMEGA-1 campaign. In Abstracts of the 4th MAST MTP workshop. p 89-90, Perpignan, France, October 1999.


- Detection of frontal structures in the western Mediterranean by SAR imagery in the framework of the OMEGA project. Rousseau S., third OMEGA meeting workshop, ICM, Barcelona, Spain. November 1998.

7.2 Articles in preparation


Figure 25: Mozaic of the ERS2 SAR images obtained in October, 1996 during OMEGA-1 cruise in the Alboran Sea. Isodepth 400 m is overplotted.
Figure 26: Mozaic of the ERS1 SAR images obtained in September-October, 1992 during FE92 cruise in the Alboran Sea. Isodepth 400 m is overplotted.


DETECTION BY ERS SAR IMAGERY OF THE WESTERN ALBORAN GYRE FRONTAL STRUCTURE (WESTERN MEDITERRANEAN) DURING THE OMEGA–1 AND FE92 CRUISES

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ABSTRACT

We present a comparative description of the SAR imaging of the Western Alboran Gyre (Mediterranean Sea) during the fall season in the light of two in situ cruises (FE92, OMEGA–1). The SAR signature of the frontal boundaries of the gyre is compared to in situ data. Results show that influence of the atmospheric boundary layer stratification variation can explain the main backscatter variation at the front. In both cruises, a clear increase of few dB is found while crossing the front. Features of a cyclonic mesoscale eddy east of WAG are also found both in situ and SAR data. We observed that the northern part of the Alboran Sea can present surface films, while the inner water of the WAG are slick–free. In the light of our results, we suggest that there’s a relation between the amount of slicks and the occurrence of upwelling and advection of Atlantic water.

1.0 INTRODUCTION

Synthetic Aperture Radar (SAR) ability to image ocean structures has been reviewed by a large amount of work in both the open ocean and coastal zones (Espedal et al., 1998, Marmorino et al., 1997, Johannessen et al., 1996, Nilsson and Tildesley, 1995). However, only few studies used SAR imagery in the Mediterranean Sea (Chic et al., 1997, Font et al., 1993, Martínez et al., 1992). In the last decade and during the fall season, two important cruises were carried out while remote sensing data (including ERS SAR, ERS ATSR and AVHRR images) were acquired. In order to evaluate the ability of ERS SAR to detect frontal structures in the Mediterranean Sea, ERS1 SAR images were acquired, during FE92 cruise (September/October 1992), and ERS2 SAR images during OMEGA–1 cruise (October 1996). SAR imagery is sensitive to sea surface roughness and each change of surface roughness leads to a different backscattering pattern. In the case of mesoscale currents, three major imaging processes are involved: current and small gravity waves interactions, occurrence of natural slicks, and variation of the stability of the atmospheric boundary layer (Johannessen et al., 1996, Nilsson and Tildesley, 1997). The strongest signature, in terms of contrast, is associated to damping of the sea–surface roughness by natural or anthropogenic slicks. In this case, the damping ratio could reach around 9–10 dB (Gade et al., 1998). Natural slicks are aligned with the local current pattern and reveal an often complicated surface current structure with meanders, eddies and fronts. Interactions between current and small gravity wind waves (less than few meters) induce a local modification of the wind wave field and contribute to an enhancement or a decrease of the backscatter of few dB. Bright or dark lines will outline a current shear depending on the SAR flight direction relative to local current (Johannessen et al., 1996). The third mechanism is due to variations in the thermal difference between air and sea surface while crossing the front (Wu, 1991). In this work we present a comparative analysis of the SAR imaging of the WAG during both cruises.

2.0 DESCRIPTION OF THE TWO CRUISES

The FE92 cruise occurred in 1992 and covered the whole part of the Alboran Sea from September, 17 to October, 10 with a regular grid of 20' longitude x 10' latitude (Viudez et al., 1996). The second campaign, OMEGA-1, covered the western part of the Alboran Sea in 1996 (from October, 1 to October, 10). During both cruises ERS SAR images were acquired while in situ data (CTD, ADCP) were obtained on board R/V Garcia del Cid (FE92) and R/V Hesperides (OMEGA-1). While during the first cruise the whole dynamic structure of the Alboran was investigated, the second one was focused on the description of the Western Alboran Gyre (WAG) and the associated vertical motions (Allen et al., 1997). Referring to FE92 campaign, ERS1 SAR images lead to a first SAR vision of the dynamic features associated with the frontal circulation of the Alboran Sea (Font et al., 1996, Shirasago, 1996). Frontal structures are outlined by surface films and follow the wavelike front. Mesoscale eddies were also detected. During the OMEGA-1 cruise a larger number of ERS2 SAR PRI images were acquired in order to analyze in detail the frontal pattern. In figures 1 and 2 we present the mosaic images of ERS SAR images acquired during the cruises. ADCP measured current is overplotted for FE92. We focus our study to the SAR imaging of the WAG. Concerning, FE92 campaign, an ERS1 SAR images of September, 15 1992 crossed the WAG, but the time discrepancy between local in situ data is of 10 days. During OMEGA-1, on October, 6 1996 one path of ERS-2 allowed the SAR imaging of the area where 4 cruise legs were done 3 to 2 days before. For this two days, we analyze the variation of the cross-section along longitude 4W where in situ observations are available. Calibrated cross-section coefficient was obtained using the SARTOOLBOX developed by ESA/ESRIN following Laur et al. (1998).

3.0 DESCRIPTION OF THE WAG FRONT

A detailed description of the Alboran Sea hydrodynamics has been obtained during last decades, since various campaigns and remote sensing studies were carried out in order to understand the path of the Atlantic Water (AW) and the mechanisms of the frontal structures (Heburn and La Violette 1990, Viudez et al., 1996). The dynamics of the AW inside the Alboran Sea is associated to modifications of its hydrological characteristics. The incoming Atlantic jet entering through the Strait of Gibraltar, follow a so-called wave like front associated to the presence of two quasi-permanent anticyclonic gyres. The variability of both gyres have been monitored by satellite imagery (Heburn and la Violette, 1990) and their sporadic disappearances time scale is of one or two weeks. Nevertheless, the WAG is a more permanent feature than the EAG. Around the WAG, instability generating mesoscale cyclonic eddies has been observed (Tintore et al, 1991). North of the WAG, the wind (mainly W, NW) induces along the coast of Spain an associated upwelling (Malaga’s upwelling) which lead to a clear thermal gradient between the north upwelled water and the high temperature values of Modified Atlantic Water (MAW) within the WAG. Part of this upwelled water can be advected at the periphery of the anticyclonic system. Another source of upwelled waters is due to subductive motions at the periphery of the WAG (figure 2). The subductive motions are observed along the eastern of the WAG. Frontal upwelled water can clearly outline the eastern boundary of the WAG by a fringe of colder and Chlorophyll-rich water that is clearly visible on satellite images (Arnone, 1995, Garcia–Gorriz and Carr, 1999). This fringe induces a local increase on observed surface density.
Figure 1. Mosaic of the ERS1 SAR images obtained in the Alboran Sea during FE92 cruise.

Figure 2. Mosaic of the ERS2 SAR images obtained in the Alboran Sea during OMEGA cruise.
Figure 3. OMEGA–1 surface data along the 4.0 leg on October, 3 1996 (Allen et al., 1997, Ruiz et al., 1999). AVHRR data is of October, 6 1996.

Figure 4. FE92 surface temperature and density recorded along the 4.0 leg on September, 25 1992 (FE92)
4.0 THE SAR VISION OF THE WAG FRONT

4.1 GENERAL FEATURES

During both cruise periods SAR images present dark structures that track the north boundary of the WAG and a cyclonic circulation along the coast of Spain. We observe more slicks structures North of the thermal front than within the thermal front. We observed that slicks are only present north of the front. No slicks structures are detected inside the WAG even if the wind conditions allow their presence. Cross-section values within the WAG (higher temperature) are found higher than in the northern part (lower temperature). Due to the sampling time difference between in situ data and SAR images a variation of the intensity and the position of the front should be expected (time lag: 2/3 days for OMEGA–1 and 10 days for FE92). SAR images of the OMEGA–1 cruise show a good agreement with sea surface temperature variation in the area of the front even if a decrease of the thermal gradient is observed during the 2/3 days time lag (figures 3, 4). Moreover, the occurrence of the backscatter increase seems to depend on the intensity of the thermal front. In the OMEGA case, the thermal gradient along the legs decreases from west to east. Concerning the FE92 case, the position of the thermal front is observed 0.15 deg south of the frontal SAR features (figures 4, 5).

In some transects for both cruises, trapped waters (with higher temperature and salinity) are entering an area where low temperature and salinity are sampled (figure 4). This intrusion (also observed on leg 4.1 W for OMEGA cruise) is associated with a local decrease of fluorescence and beam attenuation. This phenomenon can be associated with an intrusion of the Mediterranean Surface Water from the North that have recirculated along the Spanish coast as observed on SAR images (September, 15 1992 and October, 2 1996).

Figure 5. Cross-section variations across the WAG along leg 4.0 W (FE92 and OMEGA–1)
4.2 IMPORTANCE OF THE VARIATION OF THE STRATIFICATION

In the case of the OMEGA data, we analyze the influence of the variation of Atmospheric Boundary Layer (ABL) stability in the area of the front using the non neutral stratification model of Wu (1991), arguing that the atmospheric temperature does not change while crossing the thermal ocean front. We used the CMOD-4 model (Stoffelen and Anderson, 1993) to describe the contribution of neutral stratification, while contribution of the perturbation due to non-neutral effect is modeled by Wu (1991). Measured air temperature is 20 deg.C and sea surface temperature varies from 18 deg.C to 21 deg.C across the front. These values lead to theoretical variations of the cross-section between -1.75 dB to 0.5 dB depending on the position across the front. We compute the theoretical perturbation due to the non neutral stability of ABL using sea surface temperature from both in situ and AVHRR images. The model shows that in most cases variations of the perturbation in the frontal zone can be explained by the influence of non neutral stability. Moreover, the best agreement between inferred perturbation using CMOD4 and theoretically computed using SST measurements, is found for the AVHRR data. In situ data produce higher perturbations due to a stronger thermal front, that was taking place two days before. Concerning FE92 campaign, similar results from the image of September, 15 1992 are expected. The thermal front of the WAG is outlined by a increase of around 3 dB along 0.1 deg of latitude. and wind conditions are similar (around 4 m/s and from North West) unfortunately no in situ measurements of SST and air temperature are still unavailable. A future comparison with the position of the front using concomitant ERS1 ATSR data should confirm our expectation.

4.3 MESO-SCALE FEATURING

During the FE92 cruise and east of the WAG, the image of October, 1 presents a cyclonic eddy centered at 35.7 N 3.4W (figure 1). Regarding in situ data this structure (around 20 km diameter) is under the CTD mesh grid resolution. Using continuous thermosalinometer data (data acquisition every minute) along the radial 3.3 W, we observed a peculiar structure inside the frontal zone. The structure has a locally high density (up to 26.7 kg/m**3) while the surrounding surface water are at 25.6 kg/m**3 (figure 6). The cyclonic structure is also in accordance with the ADCP data, even if there's a time lag of 5 days with the SAR image. A clear cyclonic circulation is observed around the eddy and small velocities are found within. The cyclonic path is associated with the so-called wave like frontal structure that links the WAG to the EAG. AVHRR image of September, 28 reveals a roughly complicated SST structure east of the WAG. Presence of vortex inside the intermediate frontal structure is found. Looking at the SAR images, the eddy is partially masked by atmospheric internal waves features. But, for a given range, one can see a clear decrease of the backscatter while crossing the eddy. The minimum is observed in the center of the eddy and reaches a decrease of 4 dB. Meteorological charts of day present a complicated pattern in this area. Several atmospheric fronts are crossing the area. Thus, it’s not possible to obtain an estimation of the contribution of the stratification to cross-section variation. Nevertheless, using CMOD4 model for large range of wind direction, we found that windspeed should lie between 2 and 3 m/s in the surroundings of the eddy. The backscatter decrease inside the gyre is in accordance with a SST decrease and its cyclonic nature.
Figure 6. Surface density variations along leg 3.3 W of the FE92 cruise (September, 26 1992)

5.0 CONCLUSION

We found that the SAR imaging of the WAG is related to higher cross-section values within its inner part. Coldest areas are associated with lower values and presence of surface films. The occurrence of the slicks leads to an enhancement of the backscatter decrease due to cooler water. Such a tendency between cross-section and temperature have been previously observed in other places (Martinez and Robinson, 1997). In the case of the OMEGA cruise, we found that the cross-section frontal increase can mainly be explained by the influence of the atmospheric boundary layer stratification variation. Within the gyre no slicks structures are observed, even if small wind speed allows their presence. We observed that natural slicks structures appear in the area of lowest values of temperature and highest fluorescence values.

The area north of the front of the WAG is the most productive area in the Alboran Sea, and its biological activity should play a role in the occurrence of natural slicks at the front. In our study of the WAG, slicks are found in the northern part, where coastal upwelling occurs with high frequency and are a quasi permanent features on climatologies. In the area between the WAG and the EAG, SAR images can present a large surface of slicks when surface cold water are found in the same area (22/10/96). This kind of situation can be associated with a large zone of high chlorophyll concentration (up to 1 mg/m**3) as observed with SeaWiFS data. Considering our results as preliminary, we believe that a comparative study using synoptic SAR images and SeaWiFS images should clear the relation between the occurrence of slicks structures, the Chlorophyll concentration and the surface temperature field.

6.0 ACKNOWLEDGMENTS

We acknowledge the participants of both cruises on board R/V Hesperides and Garcia del Cid for providing us the in situ data. FE92 SAR data processing was part of the EU MAST EUROMODEL project (MAS2–CT93–0066) and FE92 in situ campaign was founded by the Spanish National Program on Marine Resources. OMEGA–I cruise was part of the OMEGA project by the EU MAST program (MAS3–CT95–0001). We are grateful to ESA for providing ERS1/2 SAR data inside ERS announcement of opportunity projects A0E1 and AO2.E102 (P I. Font). S. Rousseau is supported by the E.U. Marie Curie postdoctoral program under contract MAS3–CT97–5051. E. Garcia–Gorriz is funded by a return grant from the Generalitat de Catalunya. Bernardo Shirazago was supported during in thesis in Barcelona by a scholarship from the Universidad Nacional Autonoma de Mexico.

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Detection of the frontal structure of the Western Alboran Gyre during the OMEGA-1 survey by SAR imagery.

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Abstract - We present last results obtained concerning the SAR imaging of the Western Alboran gyre (Mediterranean Sea). The work takes place in the framework of the OMEGA-1 campaign in the Alboran sea in October 1996. Comparisons between in situ data, remote sensing data, wind model and wind estimation retrieved from ERS2 SAR images are done. Results show that non neutral stratification of the atmospheric boundary layer can explain the main backscatter variation at the front. Additional hydrodynamical features also outline the boundary of the gyre. The influence of slicks enhances in some areas the contrast in the frontal zone. No slicks are observed in the inner part of the gyre even if wind conditions allow their presence.

I. INTRODUCTION

Synthetic Aperture Radar (SAR) ability to image ocean structures has been reviewed by a large amount of work in both the open ocean and coastal zones (Espedal et al., 1998, Marmorino et al., 1997, Johannessen et al., 1996, Nilsson and Tildesley, 1995). However, only few studies have used SAR imagery in the Mediterranean Sea (Chie et al., 1997, Font et al., 1993, Martinez et al., 1992).

During the OMEGA-1 campaign on board the Spanish R/V Hespérides, ERS-2 SAR data were acquired to explore the imaging of Mediterranean meso-scale features such as the anticyclonic western gyre of the Alboran Sea. On October, 6 1996 one track of ERS-2 allowed the SAR imaging of the area where in situ measurements were recorded two days before.

SAR imagery is sensitive to sea surface roughness and each change of surface roughness leads to a different backscattering pattern. In the case of meso-scale currents, three major imaging processes are involved: current and small gravity waves interactions, occurrence of natural slicks, and variation of the stability of the atmospheric boundary layer (Johannessen et al., 1996, Nilsson and Tildesley, 1997). The strongest signature, in terms of contrast, is associated to damping of the sea-surface roughness by natural or anthropogenic slicks. In this case, the damping ratio could reach around 9-10 dB (Gade et al., 1998). Natural slicks are aligned with the local current pattern and reveal an often complicated surface current structure with meanders, eddies and fronts. Interactions between current and small gravity wind waves (less than few meters) induce a local modification of the wind wave field and contribute to an enhancement or a decrease of the backscatter of few dB. Bright or dark lines will outline a current shear depending on the SAR flight direction relative to local current (Johannessen et al., 1996). The third mechanism is due variations in the thermal difference between air and sea surface while crossing the front (Wu, 1991).

II. DESCRIPTION OF THE DATA

ERS-2 SAR images (Figure 1) covering legs of the vessel survey were acquired on October, 6 1996 at 10h56 UT. PRI SAR images were calibrated to obtain the backscattering coefficient, σ0, (Laur et al., 1998). σ0 values were calculated at a 100 m resolution and σ0 tracks were extracted along the cruise legs.

Fig. 1. SAR composite image of the 2 ERS-2 SAR images covering the western gyre of the Alboran Sea on October 6, 1996 at 10h56 UT. Ship track is symbolized by cross and ADCP surface current is overplotted.
AVHRR image covering the Alboran sea was obtained 2 h 30 hours later than SAR data. A large collection of AVHRR data of the period as well as SAR images are found in the OMEGA Atlas of Remote Sensing Data (http://radar.ict.unipi.it/OMEGA).

AVHRR image presents the core of the gyre with a temperature around 21.5 degrees. In the north western part of the front a filament-shaped Mediterranean surface water, coming from the Spanish coast, is trapped and strained toward the centre of the basin. During the cruise an on board ADCP recorded current profiles. The data were processed from 12 m to 332 m with a vertical resolution of 4 m. Profiles were averaged on a 10 mn base leading to an horizontal resolution of around 2.5 km.

Continuous subsurface data were also collected during the cruise using an on-board water pump at 4.5 m depth. Recorded parameters are: temperature, salinity (in psu), fluorescence of the Chlorophyll (in arbitrary units), fluorescence of the dissolved organic matter (in arbitrary units) and the coefficient of light attenuation (in m^{-1}).

We present in situ and remote sensing parameters for the leg along 4.14 W in Figure 2.

Wind conditions were provided both by in situ data and a meteorological mesoscale model (HIRLAM) from the Spanish Institute of Meteorology (INM). In situ data on board or at the coast gives similar estimation of wind condition to those obtained from the model. Local decreases of the wind speed are well reproduced in the area of the decrease of $\sigma_0$ observed on the SAR images. Finally, we simulate the wind contribution to $\sigma_0$ using a constant wind, blowing at 4 m/s for a wind direction of 340 degrees (122 degrees referring to the SAR range axis).

**III. DESCRIPTION OF THE FRONT**

Dark structures outline the north-eastern boundary of the western anticyclonic gyre, but slightly more to the North than the pure thermal front. These low backscattering areas are an eastward prolongation of slicks features observed on SAR images of October 2, 1996. The presence of these two dark patchy lines is probably due to the upwelling that occurs north of the front. Moreover, these patches are found in the area of the domed of isopycnals that takes place at the frontal boundary.

SAR images show a good agreement with sea surface temperature variation in the area of the front. Slicks are encountered in the cool area north of the front, where the highest values of fluorescence and of attenuation of light coefficient are found. Intrusion of trapped water of higher temperature and salinity associated to local decrease of fluorescence and light attenuation coefficient is found as well as local increase of backscatter. Nevertheless, conclusions are limited since in situ and SAR data are non simultaneous. A previously observed result is that slicks are only present north of the front. No slicks structures are detected inside the gyre. The crossing of the thermal front of the Alboran gyre, shown by an increase of the temperature, is often associated with an increase of the backscattering coefficient but it does not occur in the whole thermal front. Its occurrence seems to depend on the intensity of the thermal front.

**IV. INFLUENCE OF ABL STABILITY**

We examine the influence of the Atmospheric Boundary Layer (ABL) stability in the area of the front using the non neutral stratification model of Wu (1991), arguing that the atmospheric temperature does not change while crossing the thermal ocean front. We used the CMOD-4 model (Stoffelen and Anderson, 1993) to describe the contribution of neutral stratification, while contribution of the perturbation due to non-neutral effect is modelled by Wu (1991). Measured air temperature is 20 C and sea surface
temperature varies from 18°C to 21°C across the front. These values lead to theoretical variations of the cross-section between -1.75 dB to 0.5 dB depending on the position across the front.

We compute the theoretical perturbation due to the non-neutral stability of ABL using sea surface temperature from both in situ and AVHRR images. Results are shown in Figure 3. The model shows that in most cases variations of the perturbation in the frontal zone can be explained by the influence of non-neutral stability. Moreover, the best agreement between inferred perturbation using CMOD4 and theoretically computed using SST measurements, is found for the AVHRR data. In situ data produce higher perturbations due to a stronger thermal front, that was taking place two days before.

V. Influence of wave and current interaction

In order to examine the hydrodynamical influence of the front we used the theoretical model of wave-current interaction in presence of an oceanic front (Johannessen et al., 1996). Even if the magnitude of the modeled modulation of $\sigma_0$ is lower than that observed on SAR images, this model should describe the dark or bright imaging of ocean front. We apply the model to two areas. One is the northern part of the front and the other is located at the eastern part. In the first case, the local value of the relative radar look direction is 98 degrees that should not allow hydrodynamical which is in accordance with most of the variation being associated to ABL influence.

On the contrary, in the eastern part, the boundary of the gyre appears to be outlined by hydrodynamical mechanisms (Figure 1). Three lines of local higher backscattering are found and followed by dark areas. The order of variations of backscatter between the increase and decrease is of 5-6 dB. The forward decrease of backscatter is stronger than the increase. The increase is of the order of 1 to 2 dB. These lines seem to follow the boundary of the gyre even if no in situ data is available. The width of the lines of local high $\sigma_0$ values is around few hundred meters, and dark patches width are of the order of one or two kilometers. The local value of the relative look direction is 136 degrees. Such a value lies in the area of the maximum enlight effect. In fact, this area is found to be where the features appear most clearly even if the modelled perturbation is of the order of 1 dB. We suppose that this decrease is related to strained cold surface water observed upstream. Nevertheless, common visual observations of the Alboran gyre front remark that the shearing zone often presents strips of higher sea surface roughness of the order one hundred meters, and strips of surface films or floating material. The presence of such surface films or foam, should also help to reduce the backscatter. In fact such a decrease along a kilometer can't be explained in terms of a regeneration distance of resonant wavelength, downwind the breaking of resonant wave due to current interaction, as for 4 m/s wind speed and C band SAR this distance should only be of the order of 1 m (Marmorino et al., 1997).

![Figure 3. Perturbation due to variations of the thermal stratification along leg 4.14 W.](image)

VI. Conclusion

Previous studies on frontal structures by SAR imagery show that current fronts are often imaged with a perturbation of the backscattering coefficient that can reach up to ±3 dB. The sign of the perturbation depends on the radar look direction relative to the front direction (Johannessen et al., 1996). In our description of the front we found a similar order of variation. But here we rather found a global increase of 2-4 dB than a perturbation across the stream line. The minimum value of backscatter is observed in conjunction of slicks structures. The SST variation is around 2 degrees and the $\sigma_0$ increase is higher than 2 dB. The intensity of the backscatter increase can mostly be interpreted by the influence of non-neutral ABL stratification. Inside the gyre no slicks structures are observed, even if small wind speed allows their presence.

We observed that natural slicks structures appear in the area of lowest values of temperature and highest fluorescence values. The occurrence of the slicks leads to an enhancement of the $\sigma_0$ decrease due to cooler water. The area north of the front of the western Alboran gyre is the most productive area in the Alboran Sea, and its biological activity should play a role in the occurrence of natural slicks at the front that is still to be defined.

Acknowledgments

S. Rousseau is supported by the E.U. Marie Curie program under contract MAS3-CT97-5051. OMEGA-1 cruise was part of the OMEGA project by the EU MAST program (MAS3-CT95-0001). We warmly thank the cruise participants for providing us in situ data and L. Prieur for helpful comments.
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COASTAL MODIFICATIONS OF THE SIGNIFICANT WAVE HEIGHT FIELD
INFERRER FROM ERS-1 SAR PRI IMAGES IN PRESENCE OF SWELL AND
WIND WAVES

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Abstract

We present a method for estimating the Significant Wave Height in coastal zone from
ERS SAR images using the measurement of the width of the spectral azimuthal cutoff
observed on SAR ocean spectrum. It allows the case of an energetic swell propagating
on a wind wave system. It requires the preliminary retrieval of swell properties using
the wave-SAR spectral quasi linear relationship. We applied the proposed method to
two coastal ERS-1 SAR images and explained local discrepancies in SWH and swell
wavenumber as non linear imaging effects.

1 Introduction

Imaging of ocean waves by SAR is strongly influenced by the scatters motions, during the
integration time (Alpers and Brüning, 1986). These motions lead to a constructive imaging
effect when the imaging process is linear, but when the process is non linear these motions
have a destructive effect on ocean waves SAR imagery. This effect manifests itself by a
degradation of the azimuthal resolution in the image plan and resulting in an azimuthal cutoff
in the spectral domain (Alpers and Brüning, 1986, Beal et al., 1983).

Up to nowadays various works were done to estimate either the wind speed or the significant
wave height in off shore zone using the estimation of the azimuthal spectral cutoff (Kerbaol
et al., 1998, Chapron et al., 1995, Høgda et al., 1993, Johnsen et al., 1991). In fact, the
intrinsic width of the spectral azimuthal cutoff is inversely proportional to the rms of wave
radial orbital velocities and thus its estimation can leads, under some assumptions of given
wave spectral models, to an estimation of the wind speed or the significant wave height. In
general, the swell contribution to this rms is generally neglected with respect to the wind
waves contribution (Tucker, 1985, Kerbaol et al., 1998). However, this hypothesis can not
be valid in some sea state cases, e.g., in a coastal area, when a swell of high amplitude
propagates over wind waves of short fetch. In such situations, the spectral azimuthal cutoff
depends both on wind waves and swell. In a previous study, we proposed a method for
estimating the Significant Wave Height in coastal zone in a case of a wind coming from
the coast in bay, that allowed us an precise estimation of the fetch. But when the wind is
blowing from the sea, this method is not precise. We developed here a new method which is
independent on the wind direction. The method is based on the estimation of the azimuthal
spectral cutoff and the discrimination of the respective contributions of swell and wind waves
to this cutoff. Our method is applied to 2 ERS-1 SAR images, one along the French coasts
of the British Channel and the second in the bank of Arguin along the Mauritanian coast.
After a brief recall of the theory of waves imaging by SAR in section 2, we present the SWH
estimation method in section 3. The SAR images and in situ wind and ocean conditions are exposed 4. Results are given in section 5 and conclusions are drawn in section 6.

2 SAR imaging of ocean waves

A complete non linear model of the SAR spectrum of ocean waves was formulated by Hasselmann and Hasselmann (1991). This theory can be reduced to the classical quasi linear approach in the case of long range traveling waves (Monaldo et al., 1993, Rufenach et al., 1991). The relationship between the SAR image intensity spectrum $S_I(k)$ and the wave height variance spectrum $\Psi(k)$ writes:

$$S_I(k) = |T^{SAR}(k)|^2 \Psi(k) \exp(-\left(\frac{R}{V}\right)^2 \sigma_{rv}(\theta_i) k^2) + N(k)$$  \hspace{1cm} (1)

$R/V$ is the range-to-platform velocity ratio, $k_x$ is the azimuthal component of wavenumber $k$, $\theta_i$ is the radar incidence angle, $T^{SAR}(k)$ is the ocean wave SAR modulation transfer function, and $N(k)$ is a noise background. $\sigma_{rv}^2(\theta_i)$ is the rms of the radial orbital velocities imparted by the ocean waves on scatters. It is given by:

$$\sigma_{rv}^2(\theta_i) = \int_0^{2\pi} \int_0^{+\infty} \omega^2 \Psi(\omega, \Phi) G(\theta_i, \Phi) d\Phi d\omega$$  \hspace{1cm} (2)

$\omega$ is the wave angular frequency and $G$ is a geometric factor depending on incidence angle and on wave direction $\Phi$. For small incidence angle such as ERS1 of 23.5 degree, the geometric factor is equal to 1. According to the model, SAR spectral azimuthal cutoff results from the gaussian term in Equation 1, acting as a low-pass filter on the azimuthal components. Note that the spectral width of this filter is inversely proportional to $\sigma_{rv}(\theta_i)$.

When swell and wind-wave are present, their respective influences contribute additively to $\sigma_{rv}^2(\theta_i)$, which can be written as:

$$\sigma_{rv}^2(\theta_i) = \sigma_{rv,s}^2(\theta_i) + \sigma_{rv,w}^2(\theta_i)$$  \hspace{1cm} (3)

3 Significant Wave Height estimation method

3.1 Estimation of the rms of radial orbital velocities

A good estimation of the azimuthal cutoff is obtained when using a gaussian fit of the azimuthal autocorrelation function, defined as the inverse Fourier Transform of the azimuthal SAR spectrum (Kerbaol et al., 1998, Rousseau, 1998).

$$H^*(x, 0) \approx \exp\left(-\frac{V}{R \sigma_{rv}(\theta_i)^2} \frac{x^2}{4}\right)$$  \hspace{1cm} (4)

Moreover, it is well known that the width of the spectral azimuthal cutoff is larger when using the complete SAR spectral theory of ocean waves than when using the quasi linear model (Høgda et al., 1993, Brüning et al., 1990). We need to correct our estimates of $\sigma_{rv}^2(\theta_i)$, $\sigma_{exp}^2$, in order to compensate this effect. For this, we applied the two models (Complete and Quasi
Linear) to Jonswap ocean wave spectra for wind speed varying from 5 to 25 \( m/s^{-1} \). We measured the corresponding spectral widths and, then, the corresponding \( \sigma^2_{\theta_v}(\theta_i) \) terms, \( \sigma^2_C \) and \( \sigma^2_{\theta_L} \), respectively. A polynomial relationship was found between these two last quantities. The same relationship was used to correct our measurements of \( \sigma^2_{\theta_v} \), with the assumption that \( \sigma^2_{\theta_v} \) can be identified to \( \sigma^2_C \).

### 3.2 SAR inferred SWH Estimation

The total significant wave height is defined by:

\[
SWH = 4 \sqrt{m_0}
\]

where \( m_0 = \int \Psi(\mathbf{k}) \, d\mathbf{k} \) is total wave energy. \( SWH \) is expressed in terms of wind waves and swell significant wave heights \( SWH_S \) and \( SWH_W \), respectively, by:

\[
SWH = \sqrt{SWH_S^2 + SWH_W^2}
\]

In a first study (Rousseau and Forget, 1997), the method was using a direct estimation of the fetch as the wind was coming from the land. In sea wind case, the fetch is more difficult to estimate and the previous method is unprecise. Thus, we define here new method which is independent of a preliminary estimation of the fetch and of the wind direction (Rousseau, 1998). The method is based on a preliminary estimation of swell parameters (wavenumber, direction and energy) from the SAR spectrum and the parametrization of the wind wave spectrum by a Jonswap spectrum. The swell wavenumber \( k^*_S \) is estimated from the SAR spectral peak wavenumber and \( \omega_S \) is deduced from \( k^*_S \) by the classical dispersion relationship of gravity waves in shallow water.

Integrating the quasi linear relationship, Forget et al. (1995) found that \( SWH_S \) can be estimated by:

\[
SWH_S = 4. \frac{\sqrt{2} E_S}{\left[T^SAR(k^*_S)\right] \exp\left(-\left(\frac{k^*_S}{\nu}\right)^2 k^2_{z,S} \sigma^2_{\theta_v}(\theta)\right)}
\]

Where, \( E_S \), is the swell adimensional energy integrated around the swell peak (Forget et al, 1995). Then, using the equation 2 for a monochromatic swell we have the rms of swell radial orbital velocities.

\[
\sigma_{\theta_v,S}^2(\theta_i) = \omega_S^2 \left( \sin^2 \theta_i \sin^2 \Phi_S + \cos^2 \theta_i \right) m_0^S
\]

Finally, we obtain \( \sigma_{\theta_v,W} \) using 3. In case of a SAR operating at small incidence angle, like ERS, and using a Jonswap wave spectrum, the \( SWH_W \) is given by:

\[
SWH_W = \left( \frac{\sigma_{\theta_v,W}(\theta_i)}{0.4127 \, U^{0.12}} \right)^{1/0.44}
\]
4 ERS-1 SAR images and in situ conditions

4.1 Methodology

For applying this method, image should present either a roughly radial swell (± 10-15 degree from the radial direction), either a short azimuthal spectral cutoff in order to use the approximation of the quasi linear theory for describing the swell. Each SAR image is decomposed, in imageries of 128x128 pixels sampled with a step of 2 for minimizing inter-pixel correlation effects due to data processing (Forget et al., 1995). The autocorrelation function of each imagerie is then performed and its Fast Fourier Transform leads to the SAR image spectrum after having estimated the azimuthal cutoff parameter, $\sigma_n$. To obtain the wave modulation spectrum, wavelengths larger than 500 m are set to zero and a speckle noise reduction correction is done as well as a final smooth using a 3x3 smoothing window. The peak wavenumber corresponding to the swell peak wavenumber, $k_S$, is then estimated as well as its energy, $E_S$.

4.2 ERS-1 SAR images location

For this study, we used two ERS-1 SAR images in coastal zone. The first one was obtained the 22 of March 1992 at 11h00 UT. The image covers the area of the Cotentin Bay in the British Channel and shows the coast of France (Figure 1 left). A wave buoy was situated is the lower part of the image. The wind condition recorded was between 15-20 m/s for the wind speed and 260-300 degree for the direction. The sea state was rough with a SWH between 3.2-3.5 m. In addition to the wind sea, an energetic swell (T=16 s) is also found in the lee of the wind.

The second image was obtained the 7 of January 1993 at 11h41 UT. The figure 1 right presents the coast of Mauritania and the location of the SAR image and its decomposition in imageries. Unfortunately, no wave buoy data are available. Nevertheless, Wind is blowing between 9-11 m/s from the east north east direction. The sea state conditions obtained from the Vagatla model (Meteofrance), present a energetic northwestern swell (T=14 s, $SWH_S$=1.0 m/s) that propagates over a wind sea of $SWH_W$=1.5 m.

5 Results

5.1 SWH estimation field

The SWH fields are presented in Figures 2 and 3. For each figure, the subplot a presents the deduced $SWH_S$, on which is superimposed the deduced swell wavelength. The subplot b presents the contribution of wind wave, $SWH_W$. The mean values and rms values of SWH are presented in table 1.

Concerning the image of the Cotentin Bay, SWH field seems realistic and in the area of the wave buoy values are similar to in situ data. The map shows a clear increase of the SWH at the western coast of the Island of Jersey, while lowest values are found south in the Bay of Saint Brieux, which is less opened to ocean wind and where swell refraction is clearly visible. Nevertheless, some overestimated values of $SWH_W$ (higher than 6 m/s) are found and seems us unrealistic. These high values are associated with high estimations of $\sigma_{nv}$. This
Figure 1: The Cotentin Bay and its ERS-1 SAR image (left) and the Arguin Bank and its ERS-1 SAR image (right)
effect can be due to either a overestimation in case of an unprecise gaussian fit or the influence of an the increase of the scatters velocities due to the influences of breakers that are not included in the theory.

Concerning the image of the Arguin Bank, which is a case a moderate wind speed and sea-state, the SWH field indicate a roughly decrease of the $SWH_S$ as entering the shallowest area. Values of $SWH_S$ and $SWH_W$ are of the same order of 1. m, which are the order of magnitude of the modelled contributions. Highest values (around 2 m) are found in the southern part, where refraction of swell is clearly visible.

<table>
<thead>
<tr>
<th>Cotentin Bay</th>
<th>$SWH_S$</th>
<th>$SWH_W$</th>
<th>$SWH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean (m)</td>
<td>1.2</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>rms (m)</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Arguin Bank</td>
<td>$SWH_S$</td>
<td>$SWH_W$</td>
<td>SWH</td>
</tr>
<tr>
<td>mean (m)</td>
<td>0.9</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>rms (m)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### 5.2 Coastal discrepancy of the inferred swell wavelength

As the method requires the estimation of the swell wavenumber, deduced from the main peak of the modulation spectrum, we plot the inferred wavenumber as function of the theoretical one applying the dispersion relation in shallow water using a swell period of 14.5 s from the vega model (figure 4. lines on each part of the first bisector, represent a deviation of on standard error of a spectral bin ($\pm \Delta k = 0.002$ rad/m). At the smallest wavenumber, the estimations are similar and deviation of the order of the standard error, but as increase the wavenumber, the estimated wavenumbers start to be underestimated referring to the theoretical ones. This underestimation of the increase of the wavenumber is associated with the increase of the imaging non linealities as wavenumber increase in shallower water. This effect leads to a rotation towards the range axis of the swell vector and then to an underestimation of its azimuthal wavenumber component (Alpers and Bruening, 1986). The theoretical shift introduced by the rotation towards the range axis is found of the same order as the observed shift (Rousseau, 1998).

### 6 Conclusion

We have presented a new method for estimating the significant wave height in coastal zone from ERS SAR images when the sea state consists in two systems, a long wave system (swell) and a short (wind) wave system. The method used a parametrization of the wind wave spectrum by a jonswap model. The method only requires the knowledge of the wind vector. The method is based on the separation of the wind waves and swell contribution.
Figure 2: $SWH$ Estimation in the Cotentin Bay

Figure 3: $SWH$ Estimation in the Bank of Arguin
Figure 4: Variation of the coastal discrepancy of the swell wavelength in the Bank of Arguin to the spectral azimuthal cutoff width and the estimation of the swell energy from the SAR modulation spectrum using the quasi linear relationship. Using ERS SAR data the method allows a description of the variation of SWH at a resolution of 3.6 km. Results shows that a good agreement with in situ buoy or model but locally some high values can be found. This effect is related to unprecise estimation of the azimuthal cutoff width. Moreover, the observed swell wavelength overestimation as depth decrease is explained as an influence of the spectral cutoff, which leads to a rotation of the swell vector due to a combined effect of the true decrease of the wavelength by refraction and non linear imaging processes.

Acknowledgments. We warmly thanks the French maritime services (STNMTE) for providing wave buoy data, the French meteorological services (MeteoFrance) for the wind data and C. Valerio, (CETE) for providing us the SAR image of the Bay of Cotentin.

7 References


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