DYNAMICS AND MORPHODYNAMICS IN SANDY COASTAL ENVIRONMENTS, APPLICATION TO THE AQUITANIAN COAST

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ABSTRACT

The Aquitanian coast (France) is representative of sandy coastal environments with long linear beaches boarding a large continental shelf and interrupted by the Gironde estuary and the Arcachon inlet. It is a mixed-energy environment with meso-tidal and long swell influences. In order to monitor the hydro and morphodynamics of this environment, several techniques including optical and radar remote sensing are used.

Firstly, SPOT optical images are used to analyse rhythmic sub-tidal and inter-tidal bar morphology and dynamics. The method is based on the semi-empirical inversion of shallow water reflectance in terms of bathymetry. The results obtained at medium spatial scale based on a set of about 20 images are summarised: the bar morphology, their time of response and preliminary analysis of physical forcing based on waverider recording.

Secondly, synthetic aperture radar (SAR) is used for different dynamic aspects mainly for inlets. The PYLA 2001 campaign allowed the deployment of the polarimetric RAMSES P-band SAR (with a frequency of 448 MHz), developed by ONERA. The oceanic part of this campaign aimed both to study the capability of observing ocean surface salinity variability in the Gironde estuary and to obtain the surface currents in the Arcachon inlet. In this study, we focus on the ability of the radar images to retrieve surface currents in the Arcachon Inlet as compared with results of a two-dimensional (2D) hydrodynamic model forced by tidal effects.

Keywords: Morphodynamics, bathymetry, currents, SPOT, SAR

INTRODUCTION

Hydrodynamics and morphodynamics in the coastal zone include a very large range of non-linear and coupled processes that are often difficult to integrate in large-scale numerical models. The hydrodynamics may be governed by tidal currents and/or wave transformation.

The Aquitanian coast is a good example of rhythmic morphology along sandy coasts. Indeed, these relatively undisturbed and low sandy coasts, extending 100 km between the Gironde estuary and the Arcachon lagoon (Figure 1), and bordered by aeolian foredunes, exhibit at least two rhythmic systems. The understanding of this bar evolution in a context dominated by wave energy is important because they usually act as coastal protection. Unfortunately, *in situ* bathymetry of this energetic zone (0 to 10 m water depth) is very sparse and does not often cover the whole coastal area. Therefore, remote sensing is a powerful tool for studying morphological systems whose wavelength is greater than 500 m over a length scale of 100 km, although the repeat cycle of remote sensing platforms is often a limitation. In this study we show a synthesis of the use of high spatial resolution optical imagery to monitor rhythmic sand bar distribution and evolution.

The rather unperturbed sandy coasts are interrupted by estuaries that introduce drastic gradients in a variety of parameters, such as salinity as well as currents, and imply specific dynamics. These areas have an important economic impact related to ecology, navigation, fisheries, building timeliness and others. In the second part of this study, we focus on the applications of synthetic aperture radars (SAR) to estuary and delta dynamics. The data were obtained from the RAMSES P-band SAR (1) which flew in April and May 2001 during the PYLA 2001 campaign.

There are very few SAR data available for such a long wavelength as the P-band, none of them on a satellite. Compared to shorter wavelengths, like C- or X-band, this wavelength is interesting because it is less sensitive to wind gustiness since the roughness it is sensible to the wind flowing over a longer fetch. Also at these frequencies, a radar backscatter dependence on salinity is attempted in addition to surface roughness effects. The salinity, which is a major parameter controlling ocean density, is not yet obtained accurately enough from remote sensing techniques although radiometers are being developed (2). The aim of the PYLA 2001 experiment was to demonstrate the capability of SAR to display salinity gradients, taking advantage of the Gironde plume. Indeed, the imaginary part of the dielectric constant is known to be dependent on sea surface salinity for long radar wavelength such as the P-band (3). Results obtained from PYLA 2001 on the salinity dependence of the radar backscattering can be found in (4). In this study, we will focus on the capability of SAR to provide surface current fields in shallow water (mainly the tidal current evolution related to the bathymetry) at the Arcachon inlet. Indeed, previous studies have shown that, due to the effect of currents on sea surface short waves, SAR images provide current fields (or indirectly the bathymetry) (5). Therefore it was interesting to test the potential of the P-band radar for surface currents in an environment such as the Arcachon inlet. This inlet is rather large (7 km x 15 km) and composed of several channels whose migration, associated with the littoral drift and a mesotidal context, is of several tens of metres each year.

We will first present the study area, then the methods applied to optical and to SAR images before we show the results.

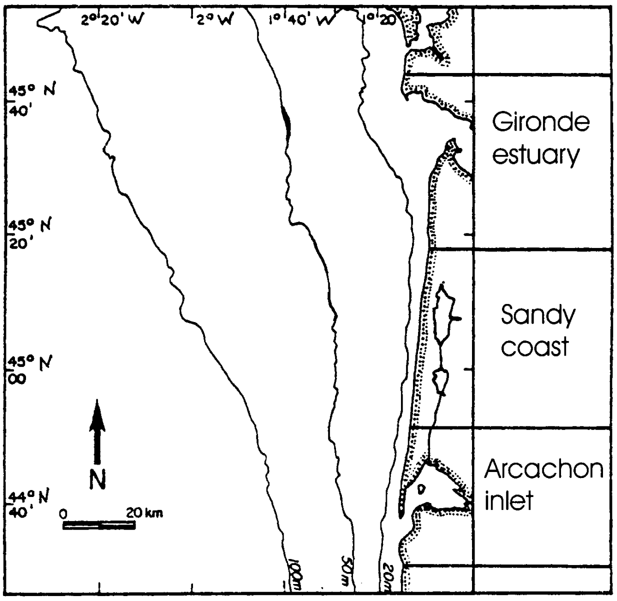


Figure 1: Location of the study area.

STUDY AREA

The study area is situated at the southern part of the French Atlantic coastline, see Figure 1. It is composed of long sandy beaches (mainly undisturbed), interrupted by the Gironde estuary to the north and the Arcachon lagoon to the south (see Figure 1). This is a meso to macro tidal area. Apart from the mouths of Gironde and Arcachon, tidal currents are very low (O 10 cm s^{-1}) and the tidal effect is limited to the tidal range varying between about 3 to 5 metres. The associated intertidal zone is relatively broad (about 200 m), composed of medium-grained quartz sand (6). The wave climate is oceanic with almost continuous long swells (7), whose mean significant wave height (H_s) is of the order of 1.12 m mainly propagating from West-South-West (WSW). Wintry conditions are more energetic and H_s of the order of 6 m are statistically observed every year. The beach morphology exhibits a ridge and runnel system in the lower intertidal zone (as an example, the signature of runnel systems can be seen in Figure 2b). Off the beach, rhythmic subtidal bars are present whose morphology is mostly creshentic with the crest of a few metres depth at low tide.

The Arcachon inlet (Figure 1) is composed of several channels and sand-banks emerging at low tide. In a mesotidal and energetic oceanic wave context, the strong littoral drift implies significant dynamics (channels and sand banks move by several tens of metres each year). The RAMSES P-band SAR image was recorded on 24 April 2001, 12:05 UTC, during flood, with maximum tidal currents greater than 1 m s^{-1} and a tidal water elevation of 1.08m. The wind speed ranged from 1 to 5 m s^{-1} on 24 April 2001 (1.8 m s^{-1} from 310° at the time of the image).

The Gironde estuary is one of the largest estuaries of the European Atlantic coast (8). The mean freshwater flow discharge is of 1000 m^3 s^{-1}. At the time of the RAMSES flight on 18 May 2001, it was one hour after ebb slack at neap tide (tidal coefficient of 44, current magnitude of the order of 10 cm s^{-1}) and under low wind conditions of 3-5 m s^{-1}. Moreover the radar image was taken during a high river flow discharge (around 1500 m^3 s^{-1}) in a fall period implying a very well developed southern low salinity plume, associated with a spatially smaller suspended matter concentration plume.

METHODS

Optical images

The methodology for analysing optical images for coastal morphology is described in detail by (9,10), the main steps are summarized:

- the optical images are re-sampled to the Lambert 3 French geographic system (a conical projection used by "Institut Geographique National", in metres) with an accuracy in the pixel location of about 1.5 pixel.
- the atmospheric correction of the optical images has been performed to transform Numerical counts into ground level equivalent reflectances.
- water depths are obtained by calibrating a radiative transfer model (Hydrolight code (11)).

Concerning the coastal morphology, the vertical information is used only to determine the top of the sub-tidal bars and the lowest astronomical tide levels that are good indicators for the ridge and runnel morphology. Concerning the Arcachon inlet, the bathymetry used to analyse the SAR image is obtained as described in (10) and the validity of the satellite depths has been checked in the range of 0 to 6 m depth, providing mean relative errors of 20%, and root mean square errors of 40 cm.

Modelling the SAR images from current fields

Our modelling approach is based on the simple theory of (12) concerning the modulation of short-scale water surface roughness by currents. In this application the wind speed is supposed to be constant (over a domain of 3 x 3 km^2), but the use of P-band with a Bragg wavelength of about 1 m ensures the horizontal homogeneity of the radar backscatter over the domain. The current-wave interactions are described by weak hydrodynamic interaction theory in the relaxation time approximation (one free parameter: the relaxation time, τ, or relaxation rate $\mu = \tau^{-1}$). A review of the uncertainty on this key parameter can be found in (13). Then, the relative variation of radar cross section, or image intensity *I*, varying in the radial or cross-track (*x*) and azimuthal (*y*) directions is found to be mostly dependent on the radial shear of the surface current velocity $\partial U_x/\partial x$ (first term on the right hand side of Eq. (1)). A second order term is added for velocity bunching modulation which is a particular SAR artefact.

$$\frac{\delta I(x,y)}{I_o} = -\frac{\alpha+\gamma}{\mu}\frac{\partial U_x(x,y)}{\partial x} + \frac{R}{V}\frac{\partial U_x(x,y)}{\partial y} \quad (1)$$

The specification of our application is that current fields are provided by a hydrodynamic 2D model, the MARS 2D, developed at IFREMER and calibrated for the Arcachon Lagoon with a horizontal resolution of 65 m. Thus, the 1D hypothesis of the continuity equation (which would not be valid in our case) is not necessary to take into account of current-bottom topography interaction. Because we are working here with P-band SAR, i.e. longer waves than in previous studies, one may question the validity of the constant relaxation rate parameter of 40 s^{-1} which was used for this preliminary study. However, it is in the range of variation of published parameterisations as a function of radar frequency and wind speed (12 to 130 s^{-1}) for the P-Band (13). Surprisingly, recent measurements in (13) indicate that the uncertainty in μ could be higher for higher radar frequencies than P-Band.

RESULTS

Optical images for near-shore morphology

The analysis of several maps obtained from high resolution optical imagery has provided spatial statistics of the ridge and runnel and crescent morphology. Concerning the horizontal shape of ridge and runnel systems, this analysis confirms what can be easily observed at low tide (Figures 2a,b): the regular patterns show elongated ridges oriented NNE while the irregular ones are shorter with more randomly distributed orientations. Their size distribution is described in (14), with an average ranging between 370 and 463 m. Three couples of images obtained at a few months' interval in the summer period with low wave energy allowed to recognize the ridges and to derive the long-shore system migration rate over the period and to relate it to wave forcing (15). These very shallow water systems respond very rapidly to wave forcing. Thus, for high spatial resolution sensors, the satellite repeat cycle is not sufficient to monitor their temporal evolution except in summer. The sub-tidal bar shapes were found to vary from crescentic (most of the cases, Figure 2c) to lunatic (1989, Figure 2b), with the presence of double systems since 2000. The rhythmic sub-tidal bar wavelength statistics are given in Table 1 (including 2 new images of 2002). One can see that the mean wavelength is found to vary between 579 and 818 m, which implies a ratio of 1.3 to about 1.8 with the ridge and runnel system mean length. Figure 2a shows an example of an optical image in 2002 to illustrate the spatial variability of sub-tidal bars (see Table 1).

Table 1: Statistics of the sub-tidal bar wavelength over a coastal line of a few tens of km (extension of up to year 2002 compared to (14)).

Date	Mean (m)	Std Dev (m)	Std Err (m)	Median (m)	Min (m)	Max (m)
16/07/1986	804	200		804	399	1155
29/07/1989	777	211		793	380	1428
27/05/1991	818	214		767	440	1569
08/09/1991	706	169		688	441	1122
18/05/1992	726	193		700	361	1050
24/06/1998	579	200		539	362	1353
16/07/1999	633	236		568	248	1313
20/04/2000	692	246		614	401	1379
01/08/2000	692	246		614	401	1379
14/08/2002	603	209	34.36	560	330	1317
22/09/2002	595	177	24.55	566	340	1322

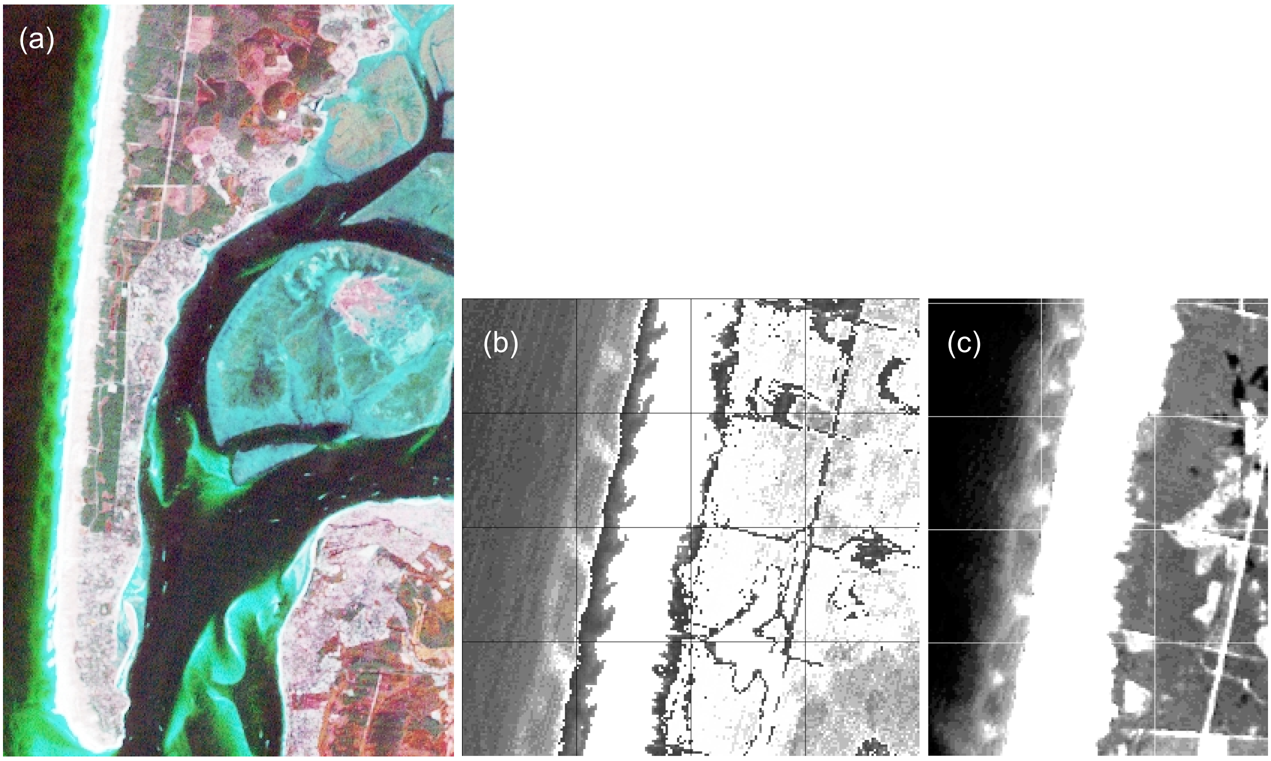


Figure 2: (a) Landsat image (acquisition date: 09/22/2002) using channels 20, 30 and 40 respectively showing the sub-tidal bar along the sandy coast of Aquitaine. (b) and (c) are respectively examples of lunatic (disymmetric) and creshentic (symmetric) bars.

This description of the morphology of sub-tidal bars is very useful because no other data are provided at this spatial scale. Preliminary statistical analysis of the temporal evolution of mean sub-tidal bars such as in Table 1 indicates that system size is decreased as wave energy is increased at scales of several months, mostly in wintry conditions (15). Another approach to understand the evolution of this area is based on a two-dimensional numerical model (16) including wave transformation, wave induced currents and sediment transport which allows to describe the circulation and coupling between the hydrodynamics and the underlying rhythmic systems. In this approach, the initial bathymetry is based on different sources of data including bathymetry from optical images for the 0 to 10 m water depths.

SAR images

Waves

Since relatively monochromatic long swells dominate on the Aquitanian Coast, the fields of wavelengths, directions and heights can be easily obtained from SAR images (17). This allows describing the wave refraction on the continental shelf (18). We will show hereafter that the signature of these long waves is significant as well as their breaking associated with shallow water.

Wave-current interaction to provide current fields

To compare with the experimental image, a simulation based on MARS-2D surface currents is processed. As shown by Figure 3b, during the flood, the highest tidal currents are of the order of 1 m s^{-1} and are mostly aligned with the channel.

Figure 4 shows the evolution of the bathymetry of the Arcachon inlet between 1996-1998 (a), used for simulations with MARS-2D, and 2001 (b) corresponding to the PYLA 2001 experiment and therefore to radar data. On the last panel the difference between the two bathymetries is shown. Comparison of the 1996-1998 and 2001 morphology of the inlet shows that the northern channel has moved to the south (small arrow) and that new small channels have developed in the sand bank between the split of Ferret and the northern channel. The emerged part of this sand bank has moved to the south (large arrow). Figure 4c also emphasizes the limitation of the optical technique that significantly underestimates water depths greater than 10 m (i.e. in the channels and offshore).

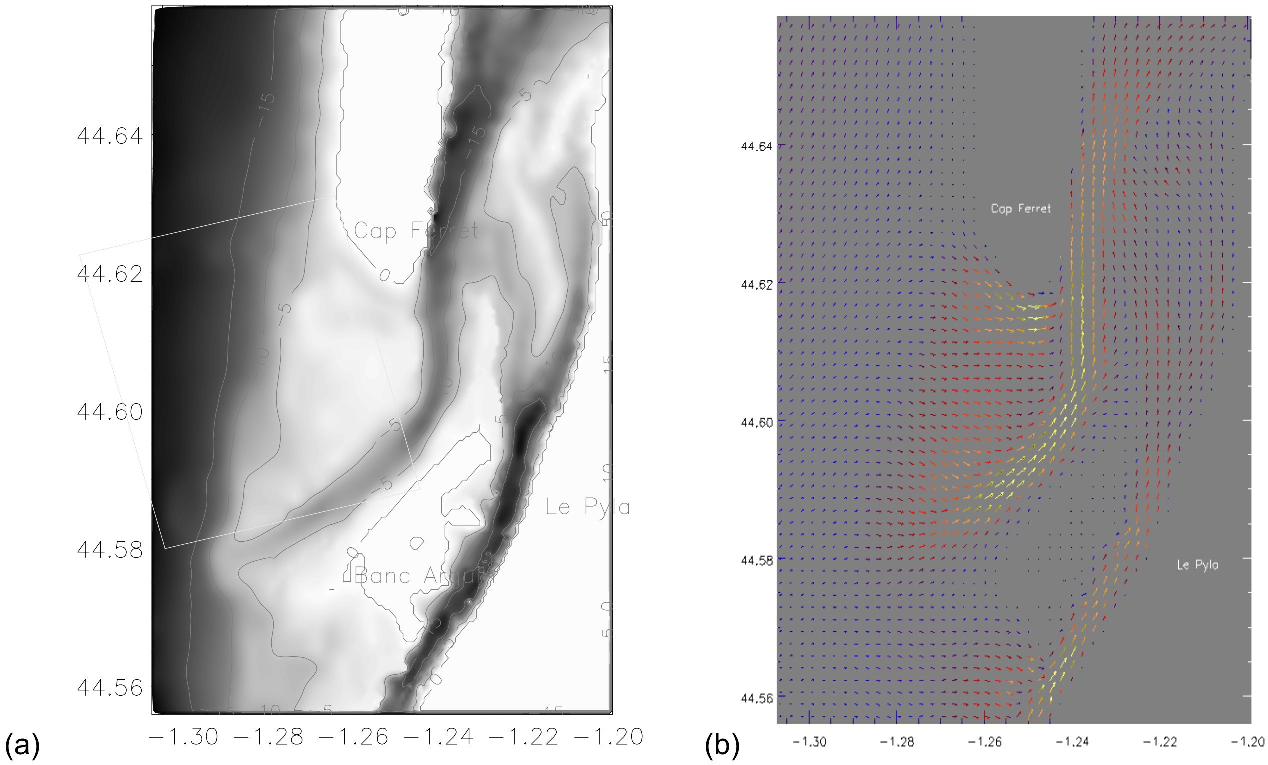


Figure 3: Mars-2D bathymetry (a) mainly based on 1996-1998 soundings (the white rectangle indicates the location of the airborne radar image). Vertically averaged current map (b) as obtained from the MARS-2D numerical model developed at IFREMER for tidal currents corresponding to RAMSES P-Band SAR image (04/24/2001 at 12:05 UTC). The length and the colour of the arrows indicate the magnitude of the current velocities (yellow is of the order of 1 m s^{-1}).

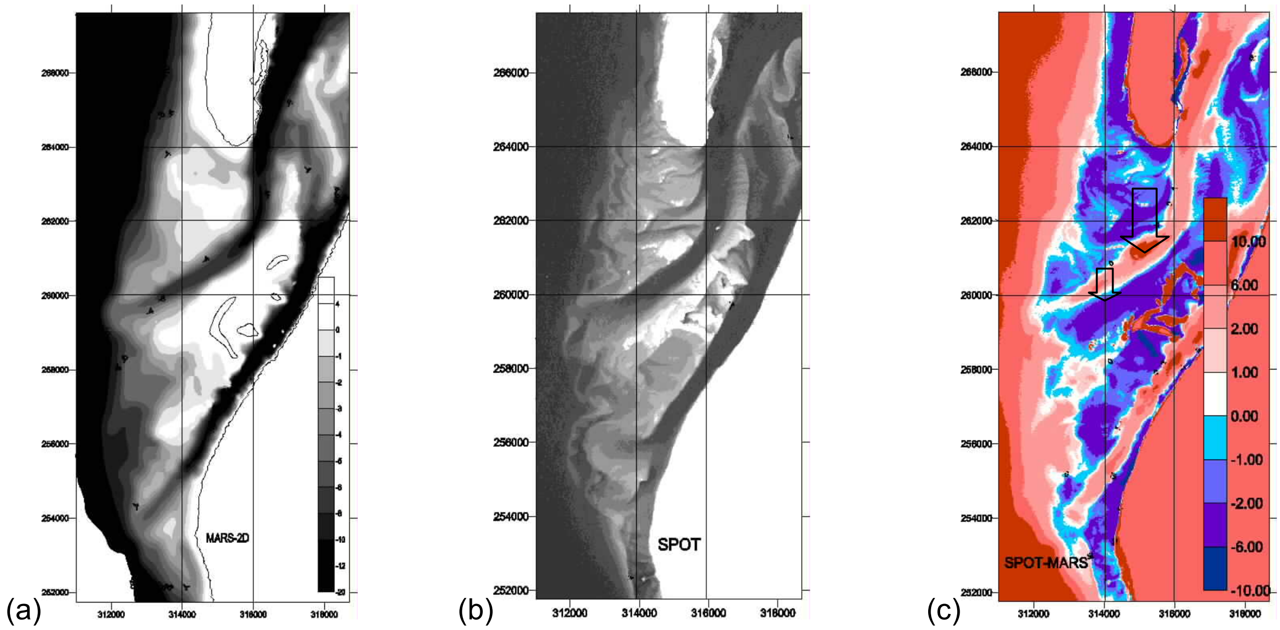
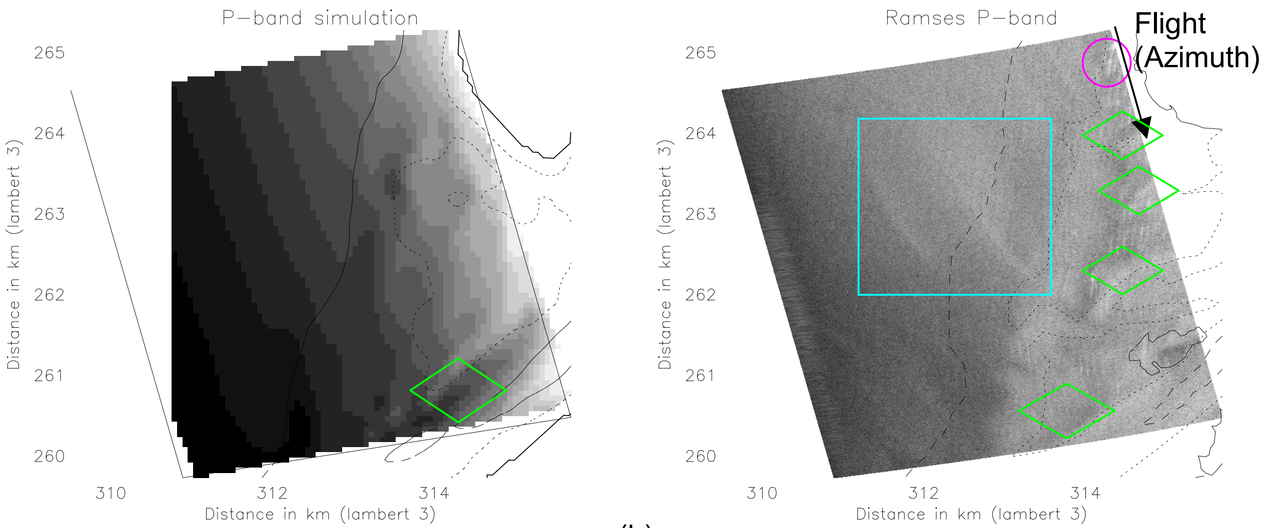


Figure 4: Bathymetries of (a) Mars-2D, 1996-1998, and (b) by the XS1 channel of the SPOT image (CNES 05/15/2001), less than one month after the PYLA 2001 campaign. They are both displayed with the same colour scale. Panel (c) shows the difference between the satellite and the model bathymetry to quantify the system evolution within 3 to 5 years.

This time delay of 3 to 5 years between the simulation and the data acquisition is the most important limitation of the direct validation of current obtained from P-band SAR, but it stresses the necessity of getting reliable data in this area at a high temporal resolution.

Figure 5 shows the radar images, on the left the simulation (see the Method Section) and, on the right, from the RAMSES P-band SAR. The simulation shows the signature of the main morphologic structure, the northern channel (see the intensity gradient in the green diamond). Indeed, this channel has an impact on the current (Figure 3b) and, therefore, on the surface wave roughness as seen by the radar. The RAMSES P-band image displays a similar feature at the northern channel (lowest green diamond), in addition to duplications of this feature associated with three other small channels (green diamonds). As usually observed (12), there is a spatial lag between the bathymetric structure and the radar intensity (gradients are observed on the northern part of the channel whose location is displayed by isolines in depth both for the simulation and the data).



(a) (b)

Figure 5: (a) and (b) displays respectively simulated and RAMSES P-band SAR images. Three isolines (0, 2 and -10 m) of the respective bathymetries are superimposed on the radar images for the dates of the simulation (1996-1998) and Ramses images (2001).

It should be noted that sea swell (as well as its breaking displayed by very bright areas, (see for example the pink circle in Figure 5b) can be observed by the radar, which is not simulated in the left panel. Also, the large rows observed in the blue rectangle in Figure 5b may be associated with wind field structures because they seem aligned with the wind direction (310°). This point should be further analysed to check that the hypothesis of wind effects on the P-band image is valid. Indeed, these effects are usually neglected for sea surface waves of about 1 metre which integrate wind forcing over a longer fetch that shorter waves.

CONCLUSIONS

Remote sensing is a very powerful tool for understanding coastal dynamics and morphodynamics. In this study, several examples have been given either based on optical or SAR images which offer similar spatial resolution (10 m). For the study of shallow water rhythmic bars over sandy coasts of Aquitaine, the optical imagery has been processed to provide morphology and statistics over tens of km. It aims to provide understanding and case studies for forecasting coastline evolution in an oceanic wave dominated, mesotidal area. We intend to extend this methodology at smaller timescales of extreme events with series of images obtained in wintry conditions.

RAMSES P-band SAR images processed by ONERA have been analysed to evaluate the ability of long radar wavelengths to observe inlet surface current fields.

The simulations (according to 12) of the radar backscatter based on 2D surface currents provided by a numerical hydrodynamic model based on a 1996-1998 bathymetry leads to promising results compared to a RAMSES image recorded in 2001. Indeed, the structure of the channels can be recognized. Further developments should be undertaken such as improvement in the current-wave interaction (19) and inversion techniques to provide the surface current field from the SAR images (20).

Further analyses of the radar signal over the ocean including the effect of wave breaking and the full polarisations are also being undertaken.

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