

# WAVE FIELD ANALYSIS FROM SAR IMAGES OF ENCLOSED SEAS

Fabio Dentale<sup>(1)</sup>, Eugenio Pugliese Carratelli<sup>(1,2)</sup>, Karim Rakha<sup>(3)</sup>, Ferdinando Reale<sup>(1)</sup>

<sup>(1)</sup>Department of Civil Engineering, University of Salerno, Via Ponte Don Melillo, 84084 Fisciano, Salerno, Italy  
phone: +39 089 964088; fax: +39 089 964099; e-mail: fdentale@unisa.it; freale@unisa.it

<sup>(2)</sup>C.U.G.R.I., Piazza Vittorio Emanuele, 84080 Penta di Fisciano, Salerno, Italy  
phone: +39 089 968957, fax: +39 089 968900, e-mail: [epc@unisa.it](mailto:epc@unisa.it)

<sup>(3)</sup>K.I.S.R., Kuwait Institute for Scientific Research. Coastal and Air Pollution Dept., Environment and Urban Development Division, e-mail: [krakha@safat.kisr.edu.kw](mailto:krakha@safat.kisr.edu.kw)

## ABSTRACT

While Synthetic Aperture Radar (SAR) satellite wave data are routinely applied over the oceans to extract spectral shapes, their application over enclosed seas is limited by their low resolution. No spectral information can presently be gathered about wavelengths of less than about 100 meters, thus limiting their usefulness to a restricted number of situations in enclosed or semi-enclosed seas where fetch lengths are necessarily limited.

Yet another important SAR application, i.e. the study and the evaluation of bathymetry effects, can be particularly difficult in enclosed seas because of the sharp variations of the sea surface conditions due to winds and coastal topography that can be very hard to interpret.

The paper presents some examples of SAR data which highlight the possibility of extracting useful information even in such difficult circumstances, as long as satellite images are integrated with other data and with numerical wave simulation.

Two examples are given: the first provides wave field analysis during a heavy storm in the Tyrrhenian sea during which two ESA ERS satellite passes are available; the second example deals with a storm in the Persian Gulf during which two passes at a day's distance (ERS-1 and ERS-2) clearly show shallow bottom effects.

*Keywords:* SAR, wave spectrum, satellite bathymetry, enclosed sea.

## 1 INTRODUCTION

Synthetic Aperture Radar (SAR) data have been used for many years now in order to supply large scale information on the spectral characteristics of the wave fields over the oceans.

The theory beside it is now well developed, and it is based mainly on the fundamental work carried out in the nineties (see for instance Hasselmann K. and Hasselmann S., 1991; Hasselman S. et al., 1996; Romeiser and Alpers, 1997; general review Monaldo et al., 2003); wave spectrum extraction from SAR data has therefore become a routine procedure for ESA satellites (ERS-1, ERS-2 and ENVISAT), and as a result, a large amount of statistical information about the spectral characteristics of wave storms over the oceans has been collected and analysed.

Research work in this field however is far from being settled, as new results and techniques become available. For instance, the interaction between gravity waves, wind and Bragg-backscatter generating capillary waves has only recently being studied and clarified (Kudryavtsev et al., 1999; Kudryavtsev and Makin, 2002). The role of whitecaps in image formation might also be better understood by making use of results in this field (Kudryavtsev et al., 2003).

Alternative semi-empirical approaches to extract wave spectra have been tested over the years (Wang and Jensen, 1998; Yi-Yu Kuo, 1999; Schulz-Stellenfleth and Lehner, 2004 and 2006), and a revival of the random simulation techniques by Brüning et al., (1990) might offer a better understanding of the SAR sea image formation (Pugliese Carratelli et al., 2006).

Bathymetry effects on the wave field image are also the object of extensive research starting from Romeiser and Alpers, (1997) through Grilli and Skourup (1998), to more recent applications by Hesselms et al. (2000), by Giarrusso et al. (2004) and by Pugliese Carratelli (2005a), where the use of standard wave generation models is proposed and tested in order to simulate and clarify such effects.

The use of SAR satellite wave data, and in particular of spectral data, over enclosed or semi-enclosed seas is however much more complex and therefore its applications have so far been very limited in scope. The resolution of satellite SAR is presently of about 30 meters, thus preventing any possibility of detecting wave components shorter than about 60 meters, and practically restricting their applicability to peak wave lengths of 100 meters or more, a rare occurrence under short fetch and fast changing wind conditions such as are to be expected around a complex topography; to the best of the Authors' knowledge, only De Carolis et al. (2004) managed to get significant spectral information in the Mediterranean.

Finally, even if no spectral information is required and the only parameter to be considered is the change in reflectance, the complex bathymetry of enclosed seas may cause sharp variations of the sea surface conditions which can be very hard to read. All this may account for the relative lack of applications in this field and points to the need of further research.

In the following paragraphs some examples of SAR imagery are presented to highlight the possibility of extracting useful information during heavy sea storms, even in enclosed sea such as the Tyrrhenian and the Persian Gulf. In order to do so, however, a strict integration is needed between satellite data and other sources such as wave meters, meteorological data and wave field modelling.

### 1.1 26 TO 29 DECEMBER 1999 STORM – TYRRHENIAN SEA

The area (fig. 1a) considered is a part of the Tyrrhenian sea, and the storm time behaviour is synthetically outlined by the two wave buoy measurement time series (“Ponza” and “Cetraro”, from the Italian National Wave Measurement Network RON) reported in fig. 1b, which also shows the ECMWF (European Centre for Medium Term Weather Forecast) simulated wave data at the nearest grid points to the buoy location. The storm is the strongest ever recorded since wave recording began 17 – odd years ago in Ponza, and as such has been the object intensive studies and analyses (see for instance Pugliese Carratelli et al., 2005b).

Also shown are the exact timing of two ESA ERS–2 satellite passages, during which a number of SAR images are available.

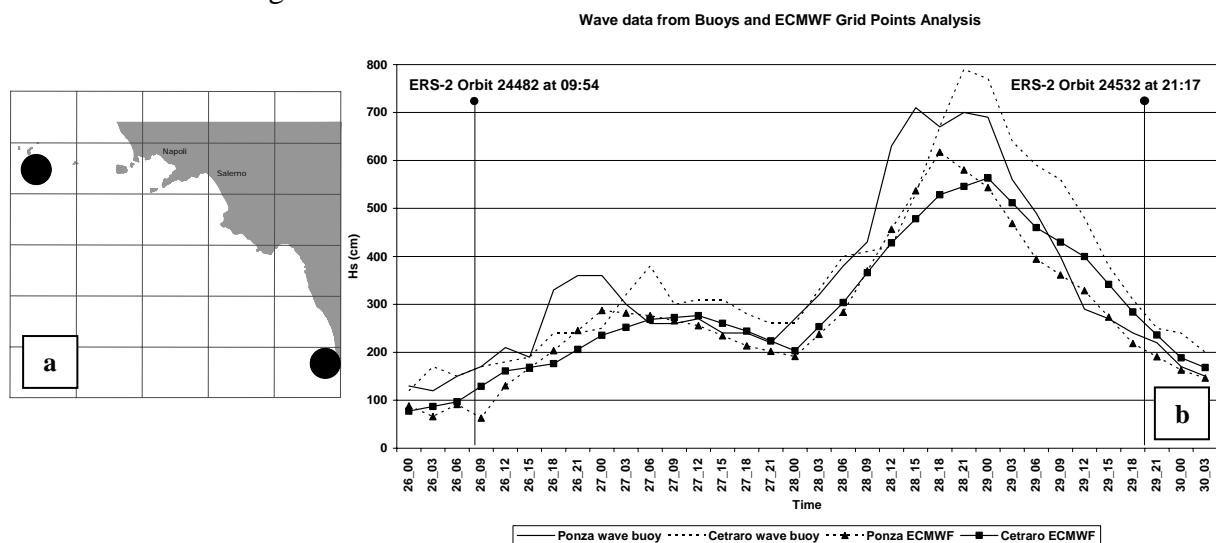


Fig. 1: Storm event from 26 to 29 December 1999 – ECMWF, wave buoy data and ERS–2 satellite passes.

## 1.2 THYRRENIAN SEA – FIRST PASSAGE 26 DECEMBER 1999 AT 09:54

The SAR image reported in fig. 2 gives an outline of the general situation in the area around the northern (Ponza) buoy. Wave parameters measured at 09:00 the Ponza buoy (about 1 km south of the islands) are:  $H_s = 1.70$  m,  $T_m = 5.3$  s,  $T_p = 6.7$  s, propagation direction =  $66^\circ$ . Wind direction, as measured from the local anemometer in the Ponza island itself is  $250^\circ$  and its 10 meter velocity  $V_{10}$  is  $6.5 \text{ ms}^{-1}$  while the same value at the nearest ECMWF grid point is about  $4 \text{ ms}^{-1}$ .

Figures 3 and 4 give an enlarged view of areas 1 and 2 respectively. The image texture is clear enough to detect the wave fronts, and to evaluate the wave direction, both for location 1 and 2.

Power spectra of the pixel intensity values were also calculated (figures 3a and 4a). The only information that can be gathered from such an elaboration is an estimate of the wave direction – or at least of the direction of those components whose length is greater than about 60 meters.

The correspondence between reflectance spectrum and actual wave is a classical research subject, and some new elements are produced in Pugliese Carratelli et al. (2007). It is interesting to consider, however, that according to the results by De Carolis et al. (2004) in similar circumstances, there seems to be no substantial advantage in making use of Hasselmann's method.

In both cases, it is well evident that the average direction as obtained from the spectrum roughly coincides with the direction estimated from the image: nearly exactly along x axis for area 1, i.e. about from about  $281.5^\circ$  since satellite descending orbit direction is about  $8.5^\circ$  to the west.; and about  $300^\circ$  or area 2.

As for the average wavelength, the spectrum centre seems to be located at about  $1/L = 0,010$  which yields an average wavelength of 100 meters; there seems to be no visible component beyond  $1/L = 0,015$  i.e.  $L = 65$ , as it was to be expected according to the resolution limit mentioned above.

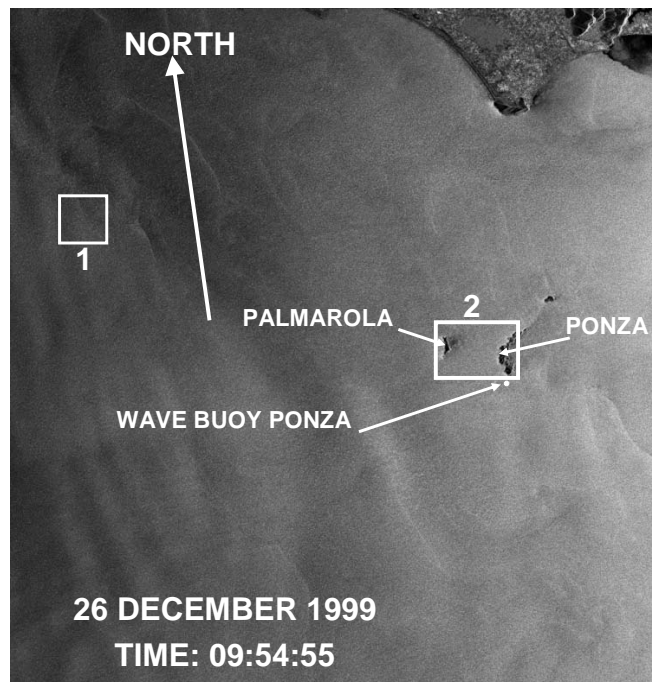


Fig. 2: SAR image of ERS – 2 satellite obtained on 26 December 1999 at 09:54. Absolute orbit 24482, track 79, frame 2781, pass direction descending.

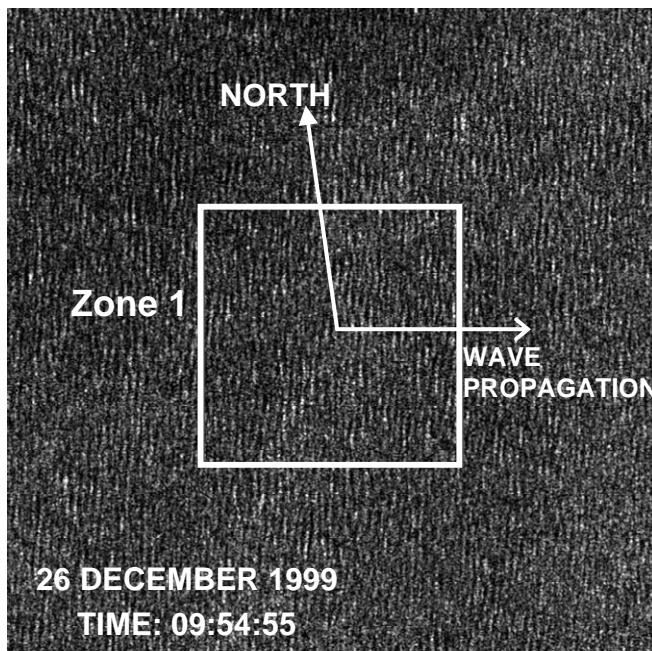
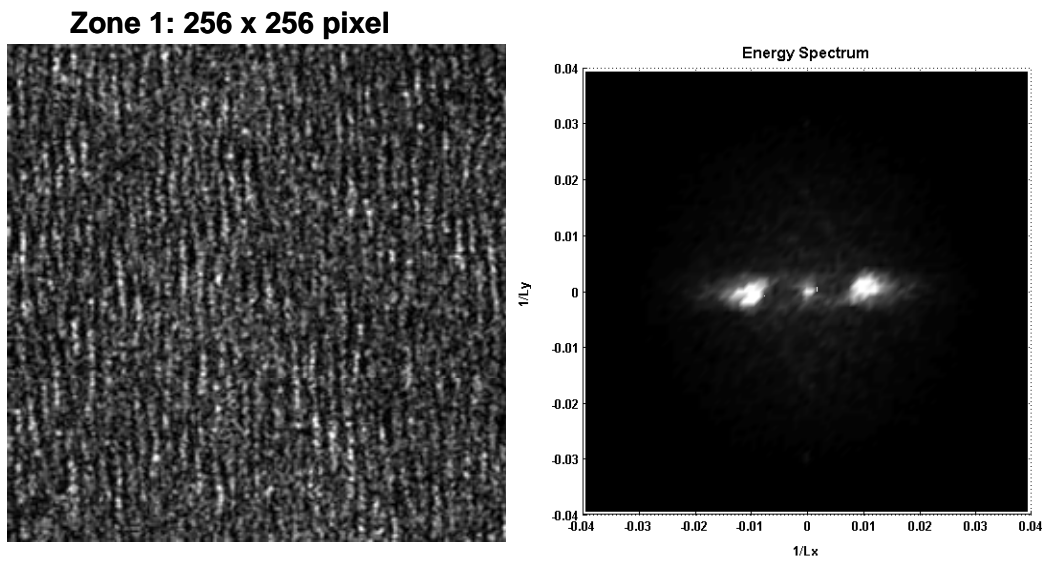
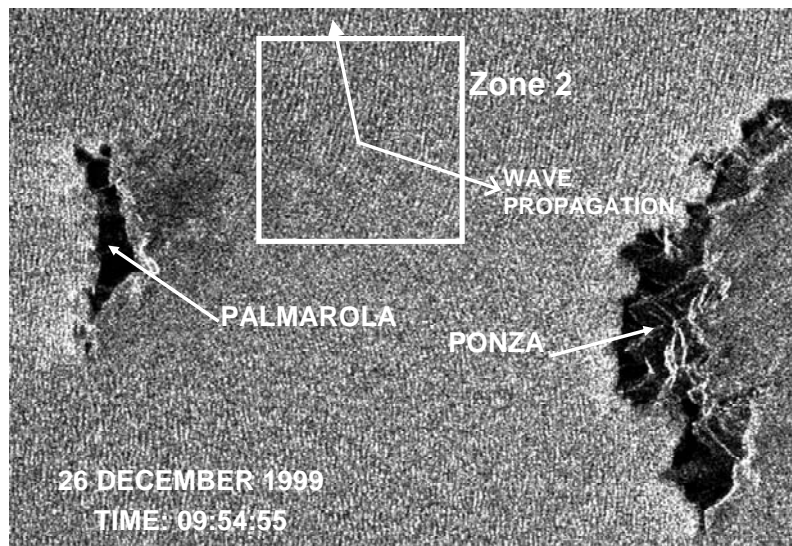


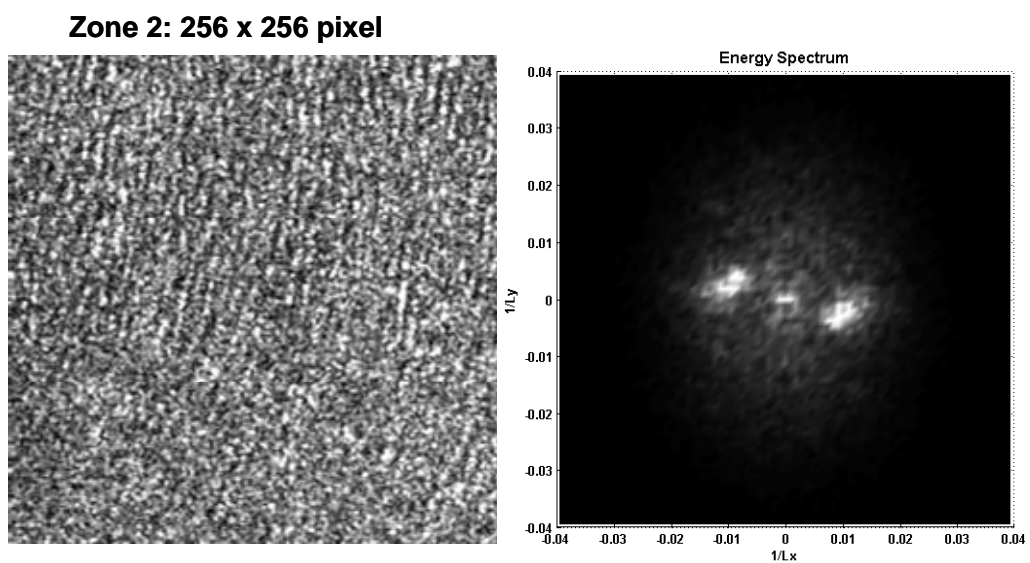
Fig. 3: enlarged area 1, estimated wave direction



**Fig. 3a: enlarged area texture and pixel intensity values energy spectrum.**



**Fig. 4: enlarged area 2, estimated wave direction**



**Fig. 4a: enlarged area 2 texture and pixel intensity values energy spectrum.**

### 1.3 TYRRHENIAN SEA – SECOND PASSAGE 29 DECEMBER 1999 AT 21:17

Unfortunately, there is no image available on or around the peak of the storm at around midnight between the 28<sup>th</sup> and the 29<sup>th</sup>. Three and a half days later the storm was subsiding but still strong, with  $H_s = 2.20$  m,  $T_m = 6.4$  s,  $T_p = 7.7$  s, propagation direction =  $89^\circ$  and wind  $V_{10} = 7$   $\text{ms}^{-1}$ , direction =  $330^\circ$  at 21:00 in Ponza. The image in fig. 5 reveals a number of interesting details about atmospheric processes, while the texture of the enlargements highlights some details about the wave behaviour.

In particular, area 3 (figures 6, 7 to 8) again clearly show the presence and directions of waves, a change of direction of the fronts – or at least of the visible long wave components – is also obvious around the island of Capri.

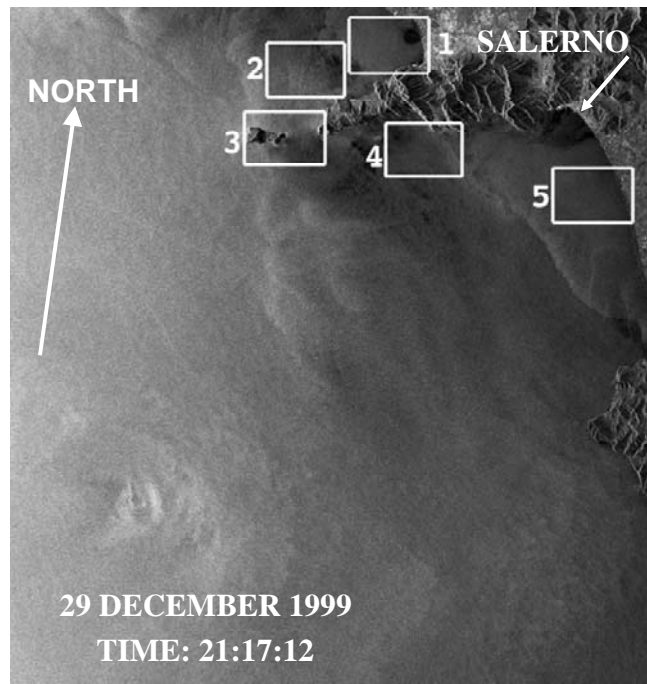


Fig. 5: SAR image of ERS – 2 satellite obtained on 29 December 1999 at 21:17. Absolute orbit 24532, track 129, frame 801, pass direction ascending.

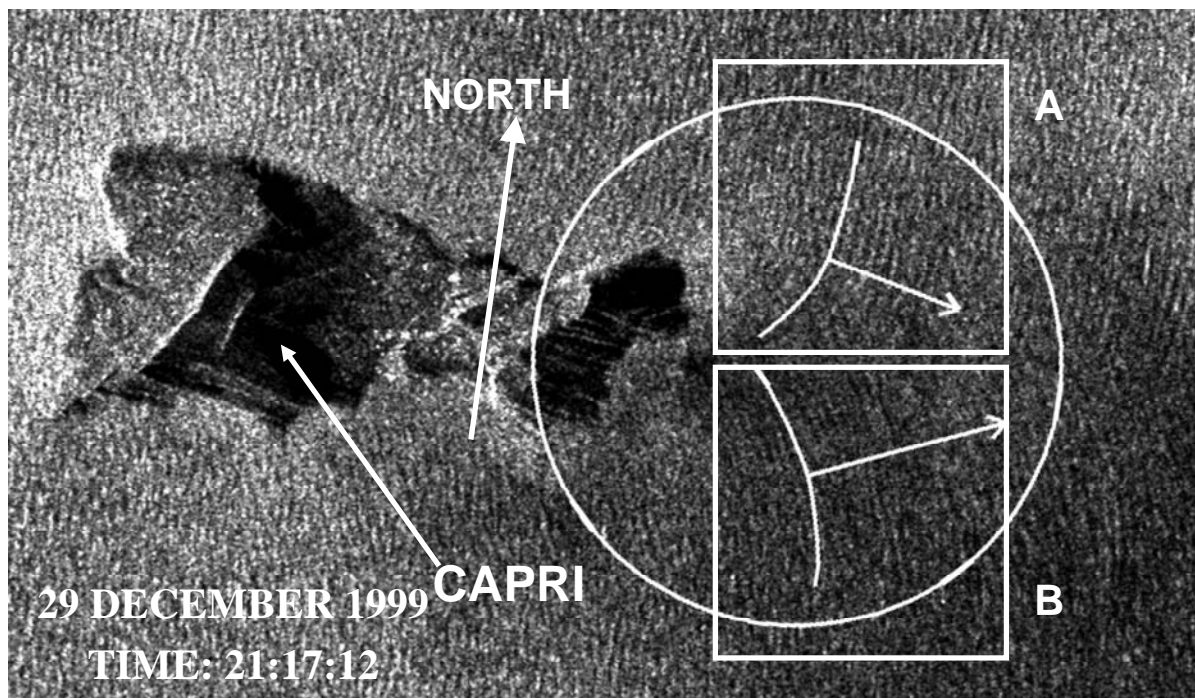
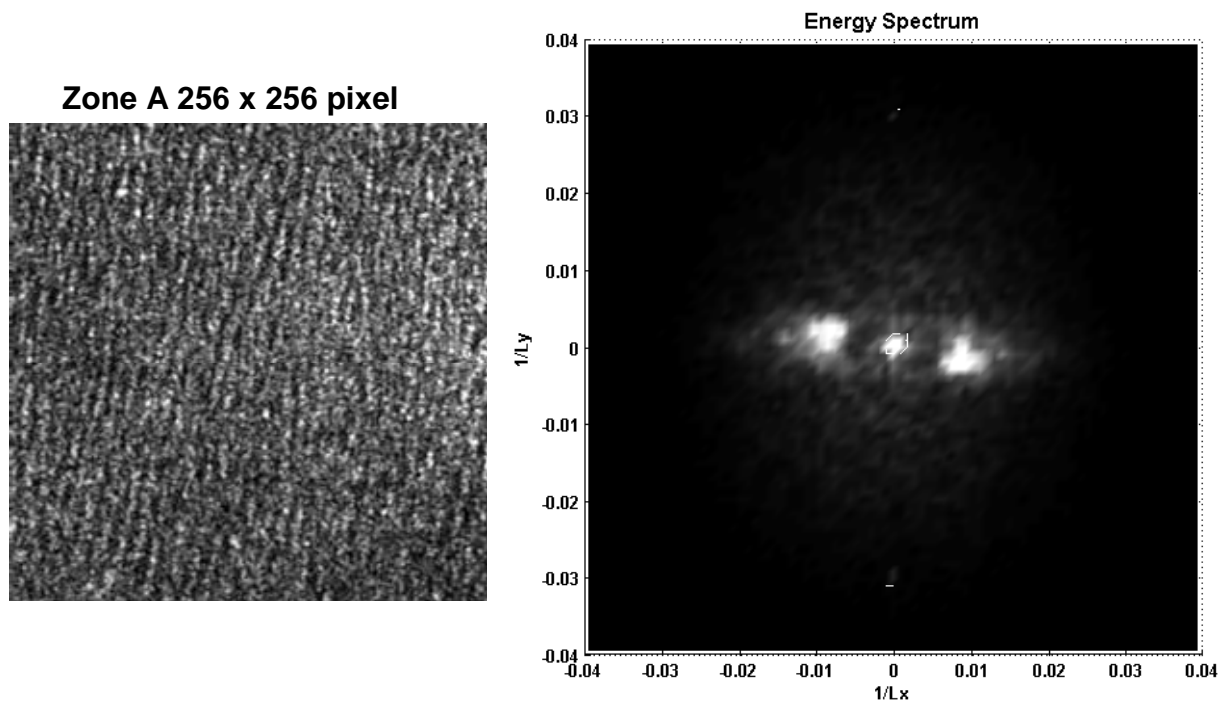
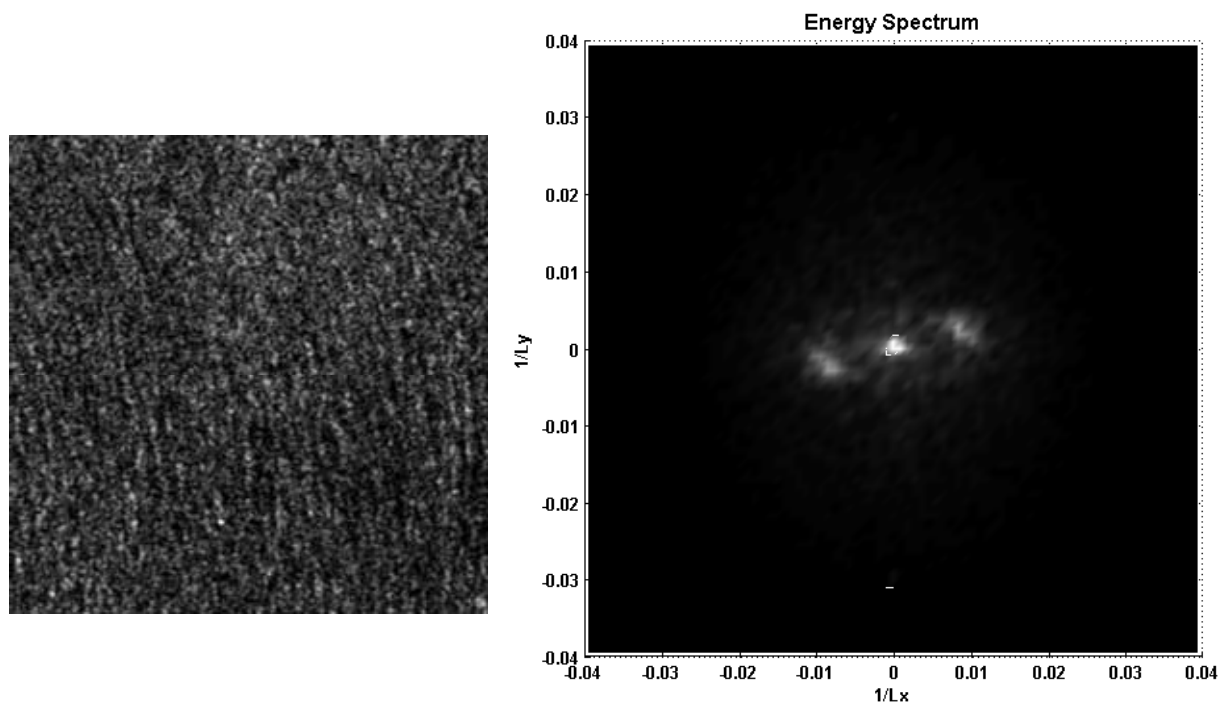


Fig. 6: enlarged area 3, estimated wave direction.



**Fig. 7: Energy spectrum for area 3A.**



**Fig. 8: Energy spectrum for area 3B.**

Power spectra confirm the qualitative estimate of the direction and again show a peak at around  $1/L = 0.01$ . Frequency distributions of pixel intensity values (fig. 9) show a lower average values for area A, which point to a lower wind intensity due to the sheltering effect of the islands, but also indicate a wider spread of the intensity, which remains to be explained.

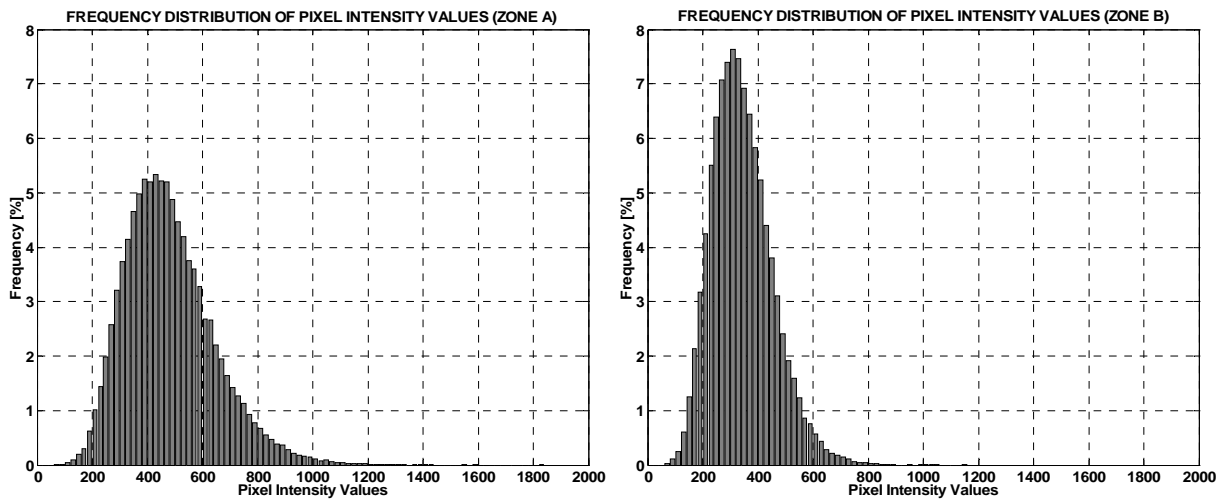


Fig. 9: Pixel intensity value frequency distributions for areas 3A and 3B.

#### 1.4 PERSIAN GULF 29 – 30 SEPTEMBER 1997

SAR images of wave fields have been often used to analyze bottom shape effects on wave fields in shallow water; an example of such an application in enclosed seas is the Malacca Straits study presented in Giarrusso et al. (2004) and Pugliese Carratelli et al. (2005), whereby shallow water wave field was used to reconstruct by making use of the standard model SWAN, and the results compared with a ERS – 2 image.

In a complex SAR image of the sea, however, it is often difficult to separate signatures generated by atmospheric effects from those originating from oceanic processes (see for instance in a different context, Romeiser et al., 2004). The availability of two successive images, at a short delay from each other, as it was sometimes possible when ERS – 1 and ERS – 2 were both working.

An interesting example on the Persian Gulf is reported in the following.

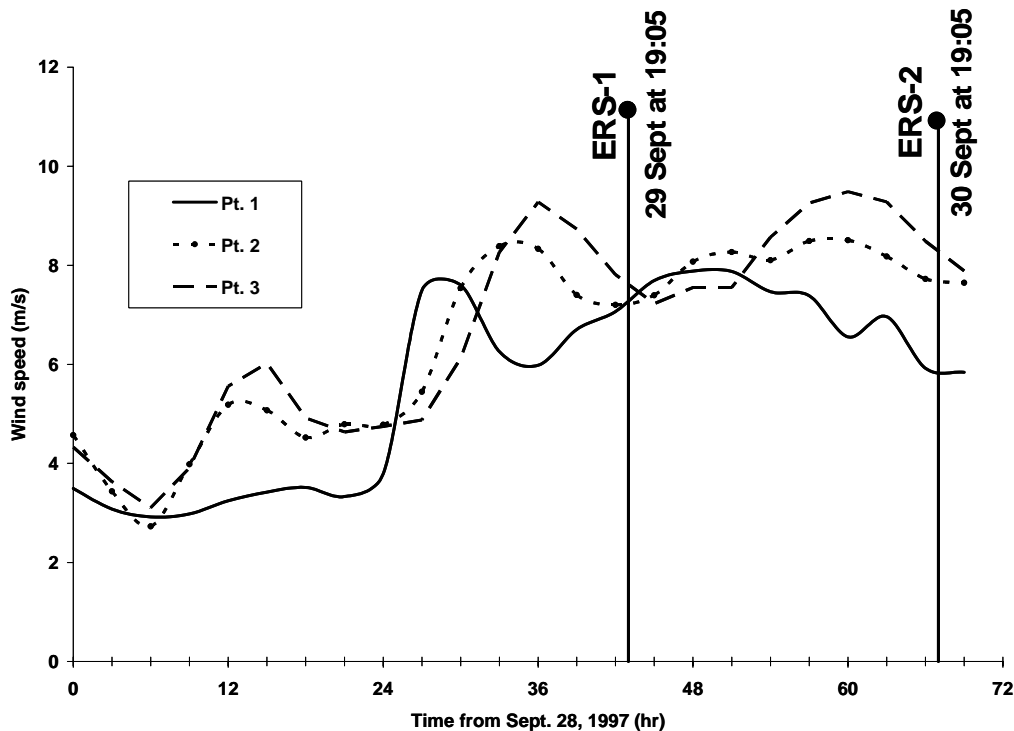
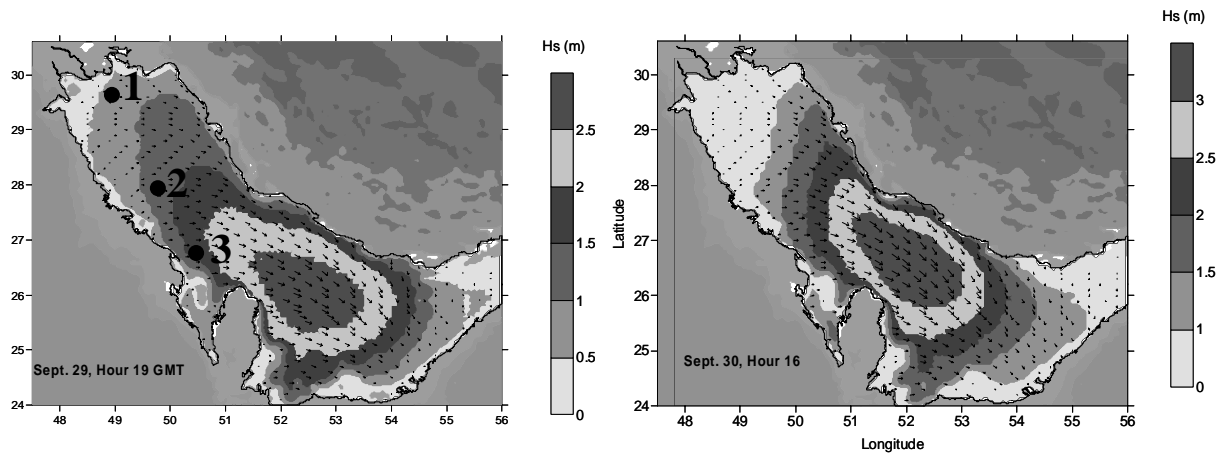


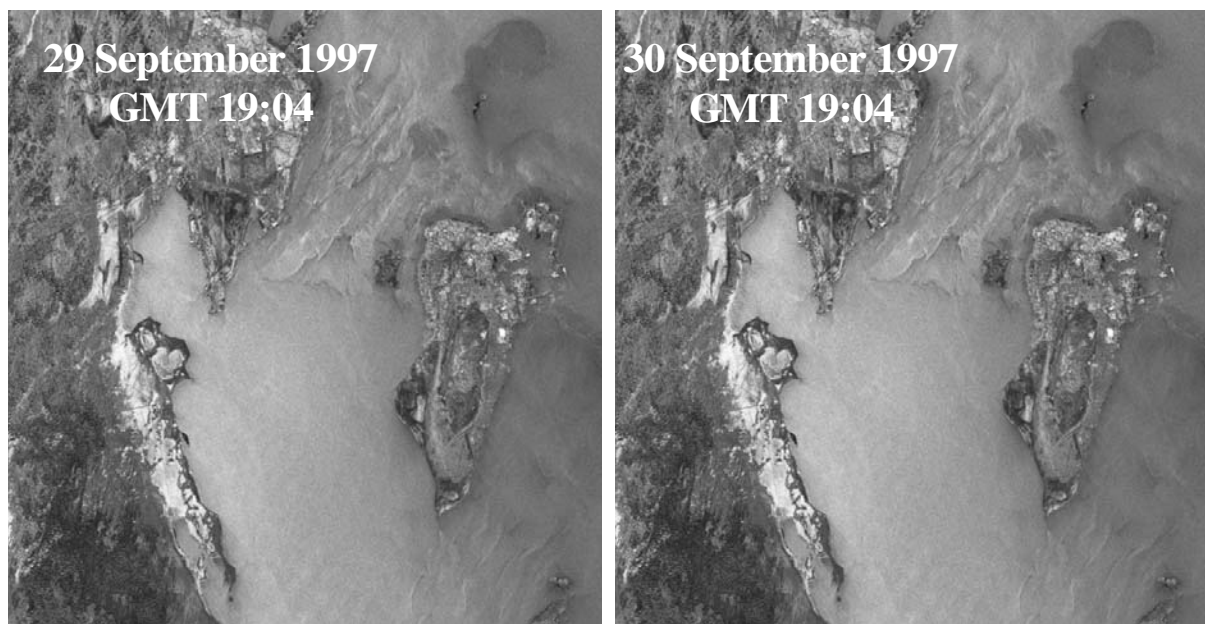
Fig. 10: Storm event 28-30 September 1997- Wind velocity at selected points.

The storm time evolution is reported in fig 10, and the wave fields shortly before the satellite passes are shown in fig 11, both taken from the WAM model results described in Rakha et al. (2007a, 2007b).



**Fig. 11: Storm event 28-30 September 1997- Reconstruction with WAM wave model Rakha et al 2005**

The area of greatest interest is the channel between the isle of Bahrain and the Arabian mainland, two SAR images are available, both at 19:04 GMT, on the 29<sup>th</sup> and on the 30<sup>th</sup> (Fig 12).



**Fig. 12: SAR images from ERS – 1 (29 September) and ERS – 2 (30 September) satellites. Absolute orbits 32466 (ERS – 1) and 12793 (ERS – 2), track 414, frame 513, pass direction ascending.**

Wave significant height as computed by the WAM model taking into account the general wind field is hardly detectable (Fig 11), but it is most likely that the wind would have generated a local wave strong enough to make the bottom features visible in both images. The similarity between the two images is remarkable, suggesting that all the visible signatures are generated by bottom induced processes. A possibility therefore arises of using SAR as monitoring system for shallow sand bottom monitoring.



## 2 CONCLUSIONS

An example was presented of SAR image wave spectral analysis in the Mediterranean; under present spatial resolution, such an occurrence is rare, and can be seen as a test of the possibility of making use of SAR data in order to improve the understanding of extreme events, together with data from different sources.

A second test, based on two passes at a short time distance from ERS – 1 and ERS – 2 a narrow and shallow stretch of sea in the Persian Gulf highlights the consistency of bottom shape signatures in such conditions.

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