A MODEL FOR WIND SPEED AND WAVE HEIGHT RETRIEVAL FROM RADAR ALTIMETER MEASUREMENTS

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ABSTRACT

A numerical algorithm is here proposed to simulate the measurement of ocean wave height and wind speed by radar altimeter. The algorithm takes into account a realistic ocean wave spectrum and employs a parametric sub-model to simulate the electromagnetic waves scattering from the surface, thus providing greater flexibility and realism than the analytical models currently used. The model is shown to be consistent even when different backscatter models are employed, and numerical results prove that the measured value of the significant wave height does not depend upon the wave period while - on the opposite - wind speed measurements are significantly affected by it.
The aim of this work is two-fold: on the one hand to provide a tool to improve the understanding and thus the accurate calibration of altimeter data, and on the other hand to develop a model which could eventually be used to simulate the sea state response as seen by the altimeter and by other microwave instruments.

INTRODUCTION

The measure of the heavy sea by means of altimeter radar is a widely consolidated practice: the technique is based on the emission of a short impulse of radio waves and on the analysis of the temporal behaviour of the reflected signal.
Together with the measurement of the wave motion, wind speed on the surface of the sea is currently evaluated on the basis of the percentage of reflected energy; estimating this latter parameter is much harder task and – as it will be shown in the following - it is also influenced by wave motion itself.
The direct action of wind causes ripples to appear on the sea surface; such ripples are caused by the balance between surface tension and gravity and their height and length are of the order of a few centimetres, thus substantially smaller than the proper sea waves, generated by the balance between gravity and momentum.
Ripples cause the backscattering of electromagnetic waves through the Bragg interference, a very complex problem to simulate. The algorithms for the extraction of wind data to leave from the pulse response (wave form) have been implemented and developed in the early eighties: a classic paper by Brown [1], described the general principles of the model. A new formulation of these procedures is given in [2] and in [3]; the measures of sea state are systematically collected and verified [4],[5].
In order to critically review these algorithms and possibly to improve their performances and to point out possible errors especially in the wind speed evaluation, a numerical model of simulation of the coupled sea surface/radar altimeter system is being developed by the Authors and is here described in its basic form. The same model, after proper testing and calibration, could eventually be developed and employed to simulate the sea surface data provide by other sensors such as the scatterometer and the SAR.

METHODOLOGY

The conceptual simulation model described here has been implemented through two separate computer codes: the first one simulates the sea surface by synthetically generating a space and time succession of sea surface heights, while the second simulates the altimeter response.

The first program is based on widely experienced and now universally accepted techniques [6] [7],[8] It makes use of a JONSWAP sea spectrum (Fig.1), expressed by:

$$S = Ag^2(2\pi)^{-4} f^{-5} \exp\left\{-1.25 * \left(f / f_p\right)^{-4}\right\} * \gamma^{\exp\left[0.5\left(f/f_p-1\right)^2/\varpi^2\right]} * d(\vartheta) \qquad (1)$$

d(ϑ) being the spreading function, where ϑ is the angle measured from the main wave propagation direction.

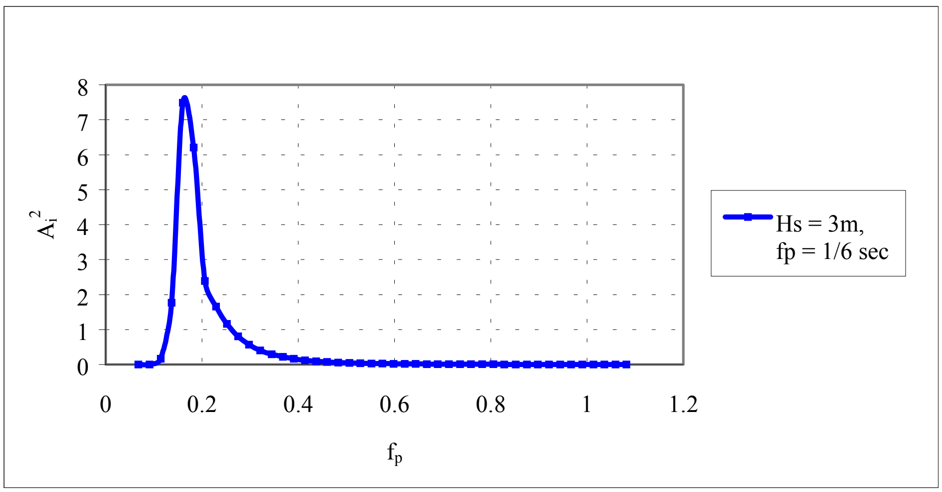

Fig. 1. Wave spectrum

The actual implementation of the procedure presented here is based on the large experience of wave synthesis techniques which have been developed in the past.
In carrying out the numerical experiment shown in this paper, the spreading function has been taken as a constant, thus representing a one –dimensional (and thus long crested) sea The formula used for the simulations is therefore:

$$\eta(x) = \sum_i a_i \cos(\omega_i t + k_i x + \varphi_i) \qquad (2)$$

The a_i terms represents the spectral amplitude values, ; ω_i and k_i represent the terms of angular frequency and wave number which are connected by the linear dispersion relation, while the terms φ_i represent the pseudo-random phase angles through which the pseudo-random realisations of a given of sea state are produced.[9]
The consistency of results to the number of realisations, and the number of spectral components was checked [10] in order to limit the computational effort and also in order to validate the procedure.
In order to evaluate the performance of the data retrieval algorithm for different sea states, tests were performed for various values of the characteristic wave height Hs, which is related to the total spectral energy and therefore to the A value in (1),

and the spectrum peak period T_p ($T_p=1/f_p$). The other parameters such as: ω (shape parameter), γ (amplification parameter), α (function of the parameter of the fetch) have been kept constant.

Given the very short altimeter pulse length (of the order of 3 ns) as compared to even the shortest time periods in the sea spectrum, all the realisations are stationary, i.e. based on a fixed time t. A single realisation is therefore an array of η values at fixed intervals dx, which represents a stretch of sea of length L (Fig. 2).

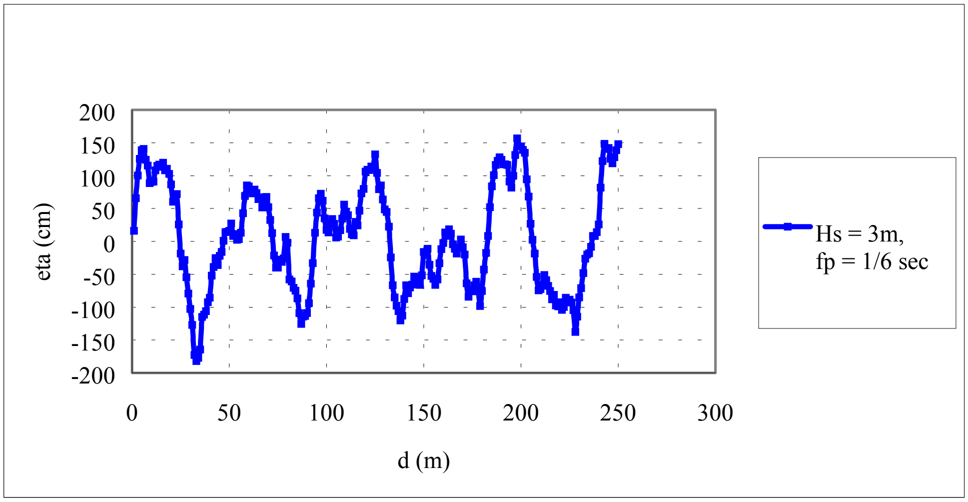

Fig. 2. Instantaneous water height

The second software module simulates the sea surface altimeter response in two steps: first the pulse response $I_r(t)$.is calculated, and then the intensity of the reflected signal I_o (t) (wave form) is obtained by simply convoluting the time history of the signal emitted by the antenna $I_{fs}(t)$ with $I_r(t)$.
The pulse response is calculated by dividing the signal energy I_o into segments of intensity I_o/L x dx, L being the footprint length; for each segment the backscattering coefficient σ_o is then calculated and the reflected signal is delayed it according to the distance from the single element to the altimeter.
In our model the backscattered energy by the elementary surface of length dx is numerically calculated as a function of the incidence angle θ - and therefore of the local sea slope $d\eta/dx$.
On of the main reason for implementing a numerical – rather than an analytical – model is to allow a wide flexibility in the choice of the backscattering sub model; in this paper the following equation is assumed for σ_o :

$$\sigma_o = K \sin\left[\alpha\left(\theta - 90^\circ\right)\right] \tag{3}$$

Varying the alpha (α) parameter (Fig. 3) the shape of the diagram varies so as to represent a large variety of behaviours of the surface.

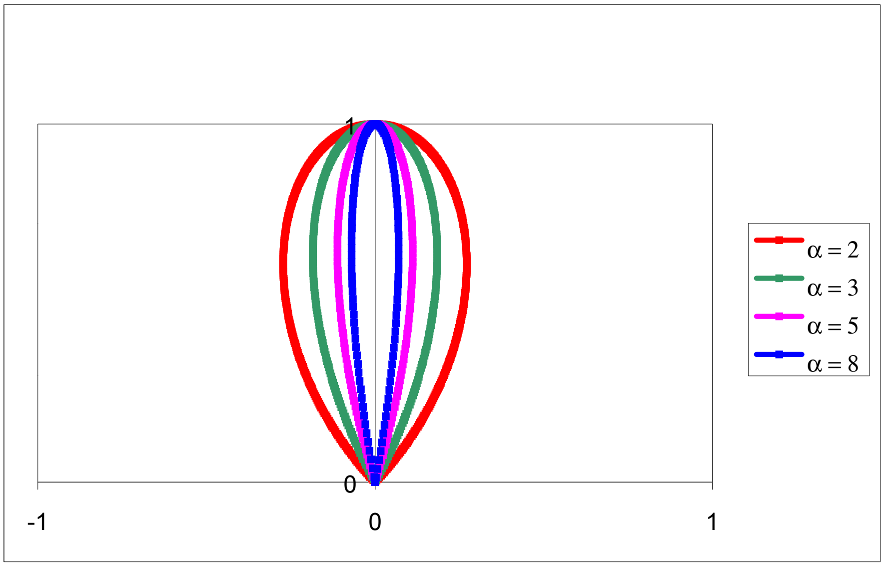

Fig. 3. Backscattering function

RESULTS

The results reported here refer to a backscattering behaviour which goes from the limiting case of fully diffusion, to an α value of 8, which represents a nearly perfect reflection, through the intermediate values 2, 3, 5.
The $I_{fs}(t)$ is a simple step function of height $I_{o,}$ so the response $I_r(t)$ is a S shaped curve asymptotically settling to a constant I_{ra} (Fig. 4).

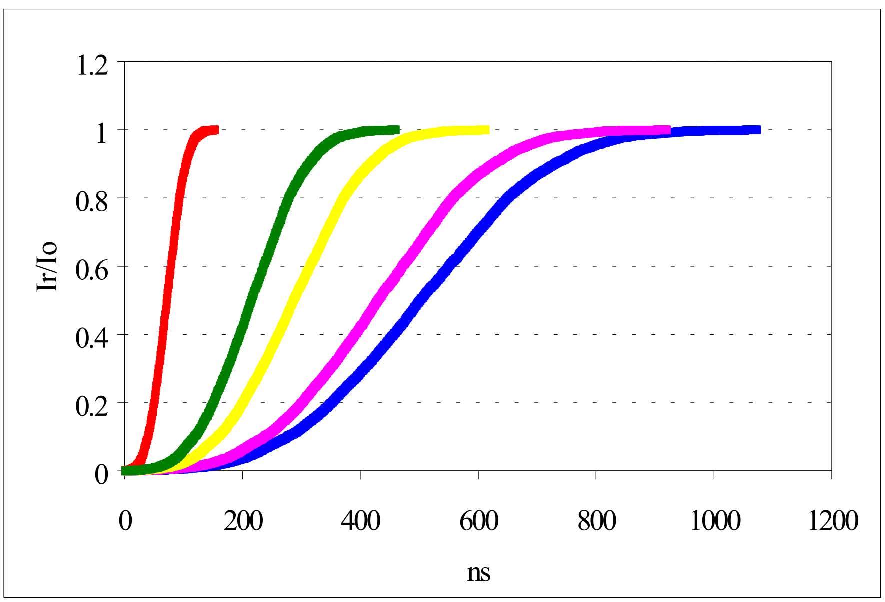

Fig. 4. Wave forms for different α value

Rather than resorting to a complex deconvolution algorithm as it would be needed in a real case, the time T_r where the curve reaches one half of the asymptotic is taken as an estimating parameter for $H_{s.}$

An obvious validation test is the variation of T_r with the parameter α of the model backscattering, or – in other words –with the micro-scale behaviour of the surface (Fig. 5).

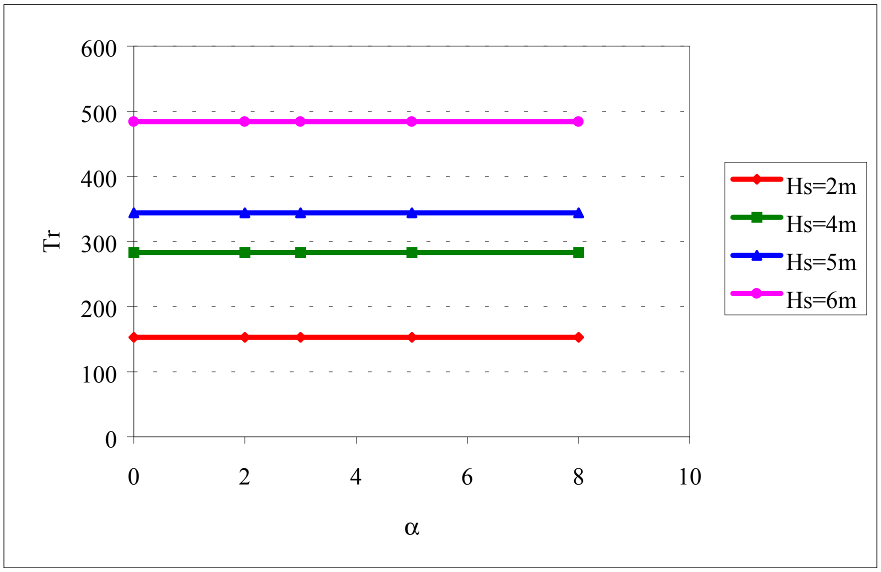

Fig. 5. Influence of α on T_r

The $T_r(\alpha)$ function for a given H_s is constant, thus confirming both the reliability of the model implementation and the accuracy of the real world measures, since it is obviously possible to construct a calibration function Hs(Tr) (Fig. 6) which does not depend on the way the incident beam is scattered an thus on the surface roughness or the wind intensity.

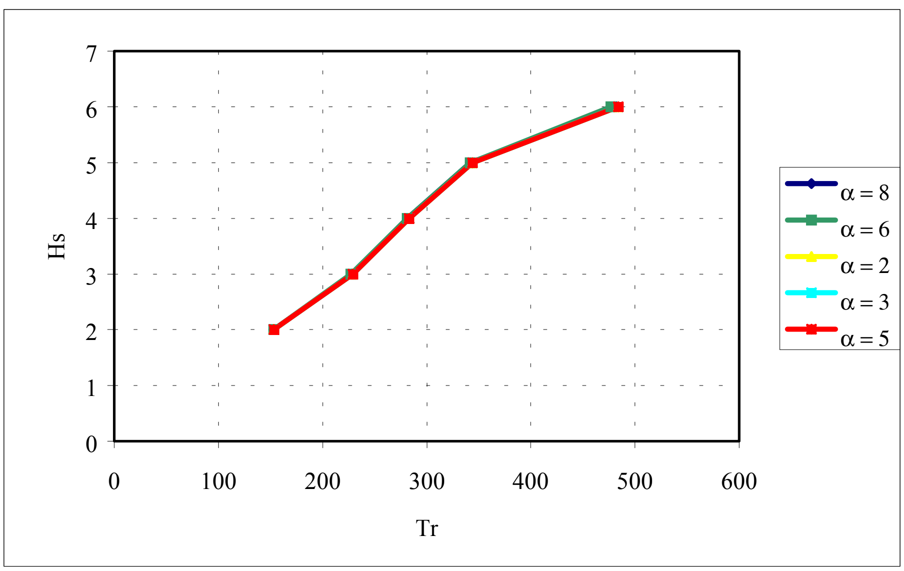

Fig. 6. Calibration function

A further check (Fig. 7) shows that the measure of the sea state is only slightly dependent on the peak period T_p of the spectrum; while it is certainly worth while enquiring onto this dependence, it is still is possible to conclude that the measurement of H_s are only slightly affected by the sea spectrum parameters.

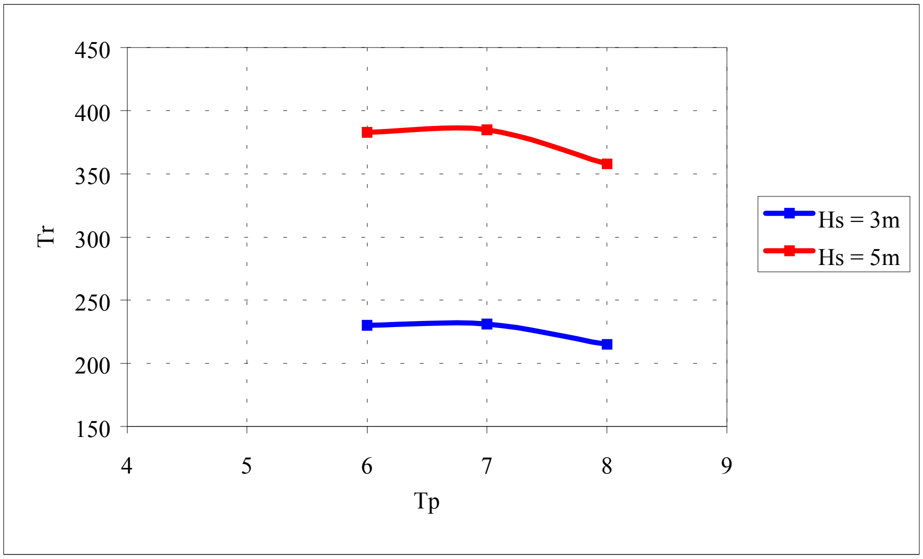

Fig. 7. Influence of H_s and T_p on T_r

The results on the measurement of the wind are less encouraging. A number of numerical experiments were carried out to simulate I_r, by keeping k constant and by varying α with fully developed sea states, i.e. with H_s and peak periods T_p connected to H_p through the classic relation:

$$T_p = 8.5\pi \cdot \sqrt{\frac{H_s}{4g}} \tag{4}$$

Fig. 8 shows that the I_{ra} value does not depend on the wave height, thus encouraging on the possibility to employ such parameter as a measure of k and thus of the surface wind intensity for different sea-states; however the same figure also evidences the dependency of the results on the backscattering sub-model, which - considering the uncertainties which hinder the understanding of the Bragg mechanisms - clearly explains the low reliability of this kind of measurement.

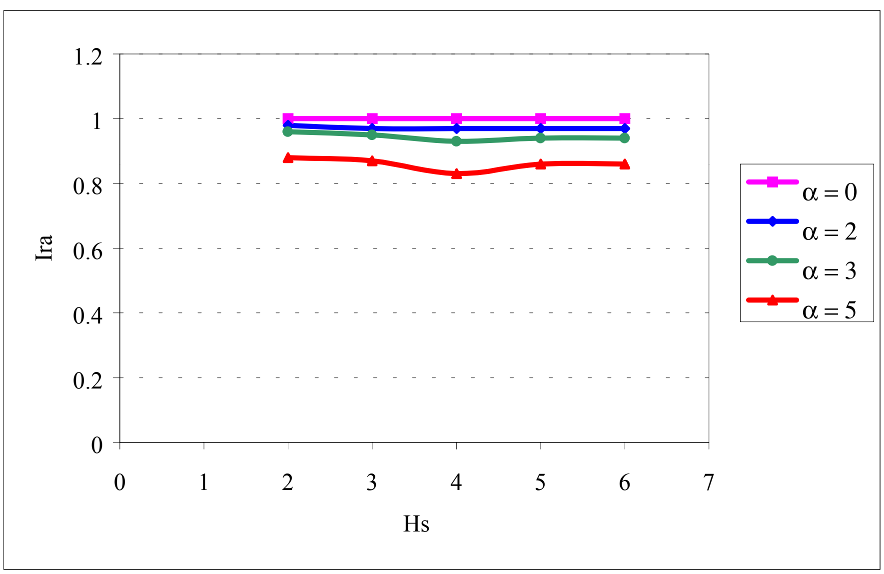

Fig. 8. Influence of α on I_{ra}

The dependence of I_{ra} on the spectrum peak period T_p has been explored much in the same way, with fixed values of K and H_s; "fig. 9" thus shows the obvious importance of the sea wave spectrum on the hypothetical measure of the wind even if the uncertainties of the microscopic behaviour of the were to be overcome.

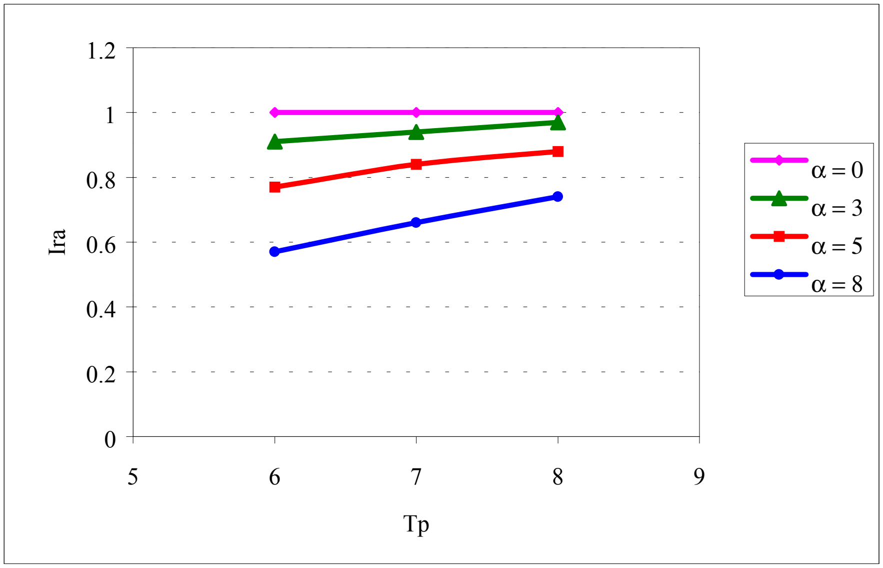

Fig. 9. Influence of α and T_p on I_{ra}

FUTURE PERSPECTIVES

Calibration of wave - and even more so - wind data as obtained from satellite measurement is far from being a trivial task. Sea truth data are usually collected at fixed points in space and supply a local time history (Fig.10).

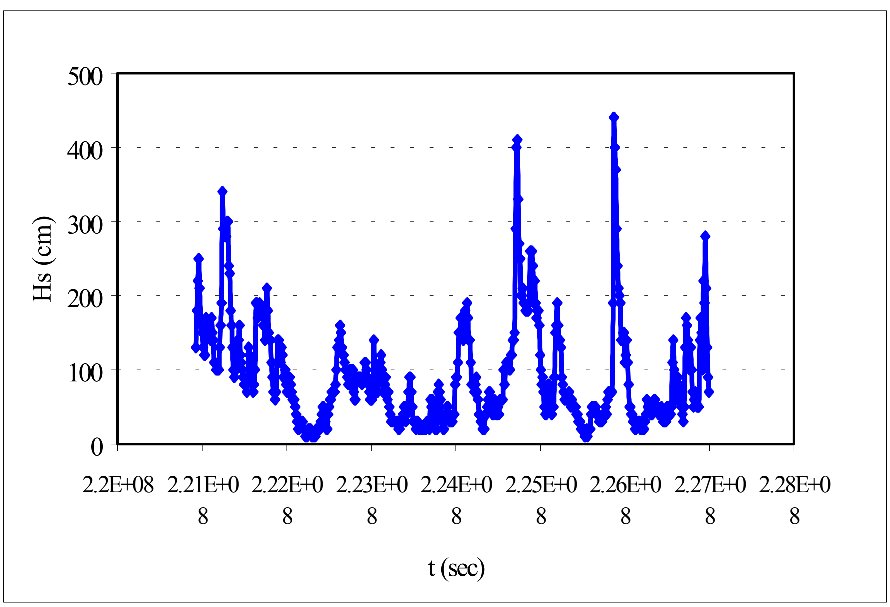

Fig. 10. Wave buoy data

Satellite data – on the opposite - is collected at very short time intervals while the satellite moves at a very high speed thus supplying a nearly instantaneous cross section along the satellite path (Fig. 11).
Correlating the two sets of data is usually carried out by making use of the weather analysis data for the wind and some kind of sea generation model for the wave. The correlation can be further improved by individually analyzing each satellite passage and by making use of the better understanding of the instrument response to both the wind and sea state, as provided by the results shown in the paper.

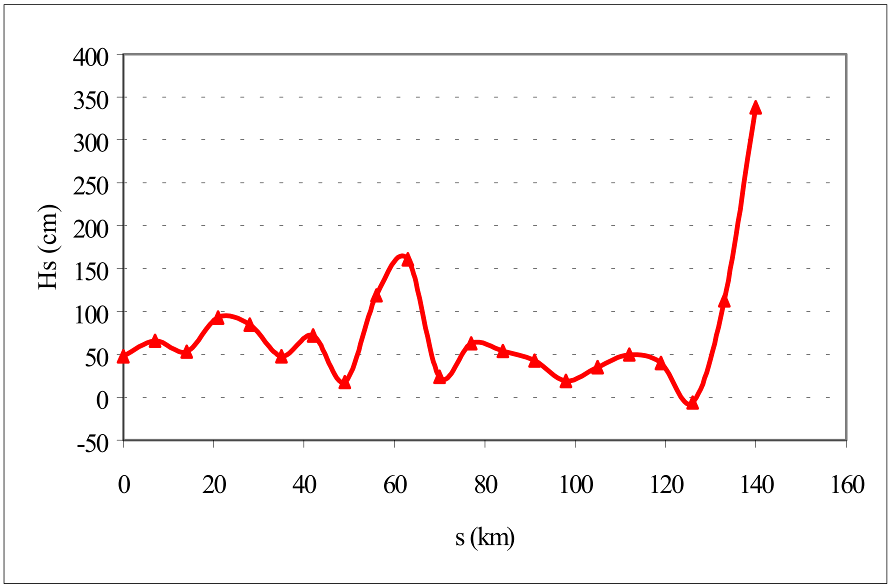

Fig.11. Satellite data

CONCLUSIONS

A numerical model of the satellite altimeter wave form was implemented and tested successfully; such a model, based on simulating the sea surface height through a spectral representation of the wave field allows a greater flexibility than any closed formula. Given the big difference in spatial scale between the electromagnetic wave interaction with the surface ripples and the significant sea wave dimension, it is possible to decouple the model into a sea wave random wavefield generator and a backscatter algorithm.
A sensitivity analysis was carried out on the effect of the physical parameters of the sea state and of the backscattering process on the quality of the measurements; a number of useful conclusions were reached.
The significant wave height can be accurately estimated, despite of any uncertainty on the backscattering process or on it simulation algorithm; when tested with non-fully developed sea spectra, however, a minor influence of. the peak period seems to appear.
On the opposite, the surface wind measurement is strongly affected not only by the backscattering process itself – as it was already known, but also by the sea state spectrum and in particular by its peak frequency. This might lead to a further cause of bias in the extracted wind speed data, since their calibration is normally based on the assumption of a fully developed sea, and especially in an enclosed sea like the Mediterranean, this assumption might be often far from the reality.

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REFERENCES

[1] G. S. Brown, “The average impulse response of a rough surface and its applications,” *IEEE Trans. Antennas Propag.*, vol. AP-25,pp. 67-74, Jan 197

[2] A. Bartolini and C. Celani, “A new algorithm for the reconstruction of the time delay from sea echo data of a radar altimeter,” *Proceedings of IGARSS ’93 Symposium*, 1993.

[3] A. Bartolini., C. Celani and F. Nirchio, “ERS-1 altimeter data processing over the Mediterranean Sea: algorithmical tailoring and validation at I-PAF,” *Proceedings of IGARSS ’93 Symposium,* 1993.

[5] M. H. Calvez, F. Ogor, J. Stum and J.P. Dumont, *ESA/ESRIN Report CLS.OC.NT./96.011*.

[4] P. Gaspar and F. Ogor, “Estimation.” *Report of Task 2 of Ifremer Contract* 96/2.246 002/C, 1996.

[6] M.D. Miles and E. R. Funke, “A Comparison of Methods for Synthesis of Directional Data.” *International Offshore Mechanics and Arctic Symposium*, 1987.

[7] M.D. Miles, “ A Note on Directional Random Wave Synthesis in the Single Summation Method.” *XXIII IAHR Congress*, Ottawa 1989.

[8] Bovolin V., E. Cassese and E. Pugliese Carratelli, “Multidirectional spectral simulation of wave drift induced dispersion”. *IAHR Congress, San Francisco 1997, Seminar on multidirectional Waves and their interaction with structures*

[9] L. Rebaudengo Landò, G. Scarsi and A. C. Taramasso, “Random Waves in Directional Seas.” *Excerpta, Vol 4, 1989.*

[10] C.C. Giarrusso, E. Pugliese Carratelli and G. Spulsi "On the Effects of Wave Drift on the Dispersion of Floating Pollutants". *In press "Ocean Engineering", 2000*