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# Non-linear internal waves generated at Nazaré canyon: observations over the W Portuguese inner shelf

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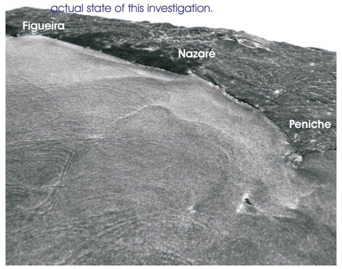
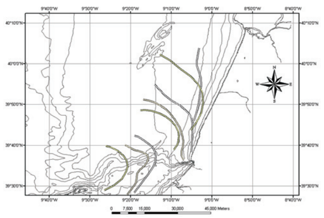
## INTRODUCTION

This work is a contribution to the European project EUROSTRATAFORM, whose objectives include the study of some of the most important canyon systems indenting the European margin and the evaluation of their impacts on the sedimentary dynamics of those regions.

Previous studies based on synthetic aperture radar (SAR) images and some in-situ measurements, show strong non-linear internal wave (NIW) activity over the Western Portuguese shelf, especially during the summer. These studies suggest a tidal/shelf-edge generation of NIW packets that propagate shoreward and reach the inner shelf as dissipated thermocline perturbations. The analysis of recent SAR images from the Nazaré Canyon region, show a near shore generation of NIW at the submarine canyon, as well as their propagation over the inner shelf. This unusual characteristics (inner shelf generation and shallow water propagation), motivated an observation program conducted during the summer 2004, focusing on the measurement of this high frequency processes, as well as the study of its dynamics and local impact in the bottom sediment cover. This work reports the results already achieved and the guidelines of the actual state of this investigation.



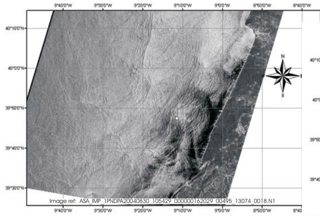


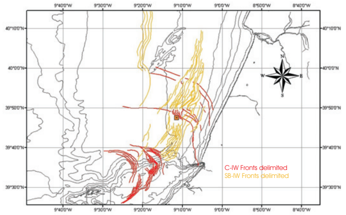
Rigth: ERS2_1999_JUL14_2799
Left: Historical observations of C-IW Fronts

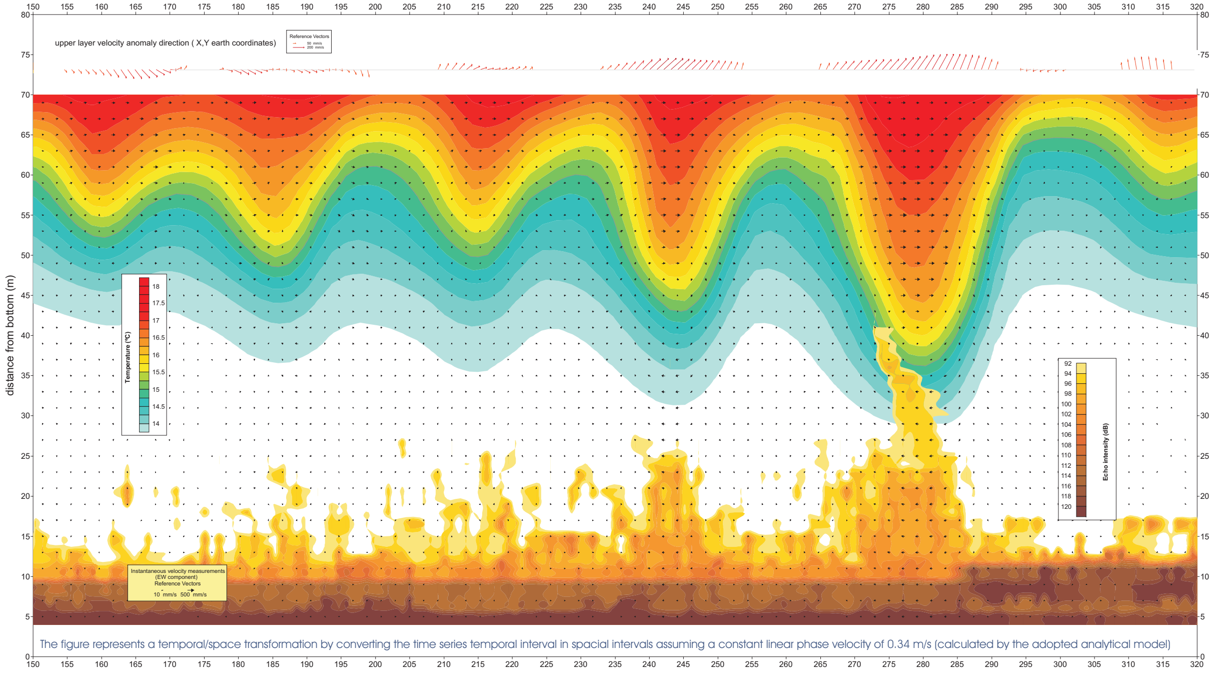
## SAR Observations

A pack of 10 chosen ERS1 and ERS2 SAR images taken over the Nazaré coastal region (from 1994 to 2002) were used to observe the spatial evolution of NIW packets generated at the canyon and to select the in situ measurement spots for the 2004 summer program of observations.
The surface signatures of this phenomenon appear frequently over the canyon axis in a region where the canyon valley suffers a strong constraint (39° 37'N / 009° 23'W). In this area the NIW front shows a very small curvature radius, suggesting a close generation spot. The generated NIW's reveal a radial shoreward propagation. The changing topography of the canyon head region seems to force a deformation of the NIW front due to refraction processes. As a result it is possible to identify tree different fronts from the same packet, with different wave numbers and phase speed. The most persistent is the poleward front that propagates almost parallel to the shore line. In most cases, it was possible to identify in the same set of SAR image 3 different packets along the poleward track, showing the result of 3 successive periodic events of NIW generation. Refraction processes along the propagation path lead to a re-orientation of the wave fronts, which become aligned almost parallel to the shore. The propagation is then almost directed onshore and the wave's dissipation is observed when they reach water depths of approximately 20 m. This process limits the region under the NIW influence to about 40°05'N.

ENVISAT ASAR Image taken during the observations set - 30AUG04 10h54







The figure represents a temporal/space transformation by converting the time series temporal interval in spacial intervals assuming a constant linear phase velocity of 0.34 m/s (calculated by the adopted analytical model)

## Field observations

A program of observations of the NIW activity in the Nazaré Canyon region was conducted onboard the Portuguese Navy hydrographic/oceanographic ship "AURIGA", from August 28th to September 1st 2004. The observations were conducted during spring tide and in a typical summer upwelling condition. Two moorings with thermistor chains and current-meters were deployed at two different positions along this NIW track, previously identified in SAR imagery. In addition, a bottom lander (equipped with an up-looking and a down-looking ADCP) was deployed near the northern mooring. A total of 20 CTD/nephelometer stations, at locations covering the global area of interest, provided the characterization of the hydrographic conditions during the period of observations. In addition, 3 yo-yo CTD/Nephelometer stations were conducted for a period of about 2 hours, at 3 different shelf locations where NIW packets were identified from previous SAR images. These allowed a clear characterization of the 3 NIW packets as they propagated along the shelf from the generation area. To complement the field data, a ASAR ENVISAT image was available for the 30th August at 10:54 UTM.

## Data Processing

The SAR image available for the survey period reveals a complex internal wave activity at the northern observation spot, with both shelf-break (SB-NIW) and canyon (C-NIW) generated NIW packets crossing through each other. These interactions result in the degradation of both wave fronts (as we can see in figure n°X) and render very complex time series measured at this location.

For the C-NIW's (the central interest in this study), it is essential to isolate each individual poleward NIW (with upper layer velocity anomaly direction in the NE quadrant) from the measured time series. Following the two-layer NIW theory, each thermocline depression (identified in the thermistor chain measurements) has bidimensional orbital velocity field associated to it, with currents in the direction of the wave propagation in the upper layer and directly opposed in the lower layer. These high frequency orbital velocities are over impressed in a current signal that results from the contribution of low frequency currents and the tidal current.
Several approaches were followed to isolate the high frequency anomaly velocity associated with NIW's from the current time series. Since the anomalies are in the form of a KDV soliton function (non-sinusoidal), approaches such as digital filtering or wavelets analysis were not very successful. For this reason a new approach, based on the two-layer model non-linear internal wave theory, was used. This approach comprised: the removal of velocity components time series segments which correspond to rapid variations of the velocity (identified from the signal derivative); and a spline adjustment to the remaining signal, which corresponds to the low-frequency tidal and residual current contribution. By subtracting from the original series this low frequency variability, the individual non-linear pulses were isolated. At this time, it became possible to calculate the NIW propagation direction, from the upper layer velocity anomalies components. The representation of these anomalies on a rose diagram allowed the identification of the two main propagation directions of the NIW packets:

1. from E to SE with the higher upper layer velocity anomaly near the SE direction, corresponding to the shelf-break generated NIW's packets;
2. NE, corresponding to the canyon generated NIW's packets.

It is interesting to find that the corresponding bottom layer velocity anomaly presents the maximum energy over the opposite direction of the canyon generated NIW's packets propagation, revealing that this is an energetical process capable of promoting a sediment dynamics impact.

## The analytical model

To analyze the structure and the temporal/spatial evolution of these solitary wave packets, a study of internal wave analytical models is being conducted to verify which one better adjusts to the observed oscillations. From a set of additional equations and new solutions derived from 1897 Korteweg and De Vries soliton equation, the combined KDV was found to be the one that give the best correlated solitary wave solution.

Following the Apel (2002) formulation, when the wave amplitude exceeds the upper layer depth, the comb-KDV relationship becomes:

$$\frac{\partial A}{\partial t}+c_0\left[\left(1+\alpha A+\alpha_3 A^2\right)\frac{\partial A}{\partial x}+\gamma\frac{\partial^3 A}{\partial x^3}\right]=0$$

where $A(x,t)$ is the traveling wave amplitude, and $\alpha$, $\gamma$ and $c_0$ are so-called environmental coefficients representing nonlinearity, dispersion and long-wavelength phase speed respectively. The $\alpha_3$ coefficient introduces a higher order nonlinearity term given, for a two-layer fluid system, by:

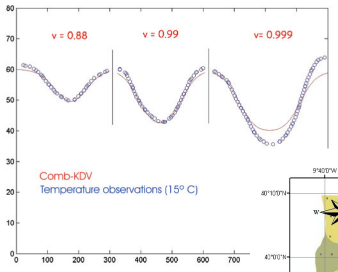
$$\alpha_3=\frac{3}{h_1^2h_2^2}\left[\frac{7}{8}\left(h_2-h_1\right)^2-\left(\frac{h_2^3+h_1^3}{h_1+h_{21}}\right)\right]$$

In this case the Comb-KDV equation is fully integrable, resulting as wave amplitude solution:

$$A(x,t)=-\frac{\alpha}{\alpha_3}\frac{\nu}{2}\left[\tanh\left(\frac{x-V_3t}{\Delta_3}+\delta\right)-\tanh\left(\frac{x-V_3t}{\Delta_3}-\delta\right)\right]$$

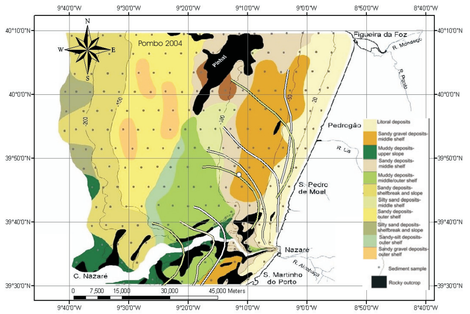
where $\nu$ is a free parameter measuring the degree of nonlinearity and ranges over (0,1). The coefficients $v_3$ and $\Delta_3$ represent respectively the nonlinear speed and the characteristic width.
Forcing the Comb-KDV equation with the water column structure parameters $(\Delta\rho,h_1,h_2)$ we arrive to single internal wave solutions, with amplitude and characteristic width depending on the free parameter value $\nu$.

The figure shows an example of the model adjustment to each individual wave observed in the main scheme, as well the respective free parameter value adopted. It is interesting to verify that the highest wave exceeds the maximum amplitude solution predicted by this equation for the real water column structure parameters, showing that this very strongly nonlinear wave require a high order nonlinearity approach. These results will be integrated, as a next step of the present study, in a Dnoidal Evolution Mode in order to interpret these oscillations as part of solitary wave packets.

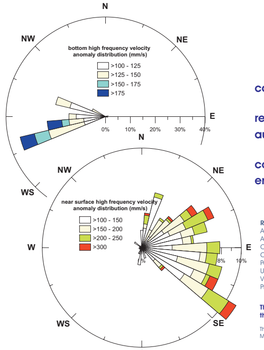


## Sediment dynamics impact

The near spatial coincidence of The C-NIW's activity region with the sandy-gravel deposit is quite obvious. Similarly to the surface gravity waves, NIW orbital velocities also decrease with depth, especially when the lower layer is thick. Therefore C-NIW induced remobilization conditions will be depth controlled. In the inner shelf, shoaling depths will affect C-NIW propagation speeds and degree of nonlinearity.



The waves will arrive at their breaking point in the region where the pycnocline depth is roughly one-half the total depth (Apel 2002). In the study area this depth will be near 20-30m, close to the inner border of the sandy gravel deposit. Finally, it is evident that both deposit and C-IW's activity region have the same northern limitation.



## FINAL CONSIDERATIONS

**The presented results show evidence of high energetic NIW's, generated over the upper canyon rim, which transport significant baroclinic energy to the inner shelf.**

**These NIW's induce high bottom boundary layer orbital velocities capable of sediment remobilization. These periodic semidiurnal pulses persist from late spring time to mid-autumn, following the seasonal rising of the upper thermocline.**

**As a final conclusion it is possible to expect that this non-linear internal activity can compensate the winter storm energetic waves in the maintenance of a highly energetic environment in the mid/inner shelf, during the calm summer.**

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