On the Role of SAR for Observing "Local Generation" of Internal Solitary Waves off the Iberian Peninsula

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EXTENDED ABSTRACT

Large waves of internal tidal period (internal tides) are well-known to result from the interaction of the surface or barotropic tide with steep sea-floor or shelf-break topography. On the other hand, large-amplitude internal solitary waves (ISWs, of shorter periods than the tidal waves) have been observed occurring in packets in open ocean areas well away from such topography, such as those in the Bay of Biscay [1]. These waves could be generated by the reflection or scattering of an internal tidal beam from the near surface thermocline [2]. In the Bay of Biscay, the ISWs, instead of having travelled along the thermocline from the shelf break, do indeed appear to be generated locally in the central Bay by the near-surface reflection of beams of internal tidal energy originating from the shelf break in the northern Bay (the Celtic shelf slope) 150km further to the north [3].

It is well known that short-period ISWs are capable of producing sea surface roughness variations that are observable in Synthetic Aperture Radar (SAR) satellite images [4], [5]. The use of SAR is particularly useful for investigation of the above ''local generation'' mechanism because, although other sensors (such as MERIS and MODIS) are capable of observing ISW packets from space, it is necessary to observe simultaneously large cloud-free ocean regions, in order to map out the ISW patterns. SAR modes such as the Wide Swath WS ENVISAT mode are thus particularly suited for this application, since they can observe in a single "snap-shot", 400km x 400km ocean surface areas. Analysis of the ISW SAR signature intensity modulations reveals the character of the generation mechanism, since it is possible to observe the gradually decreasing levels of activity with increased distance from the generation source. Sometimes, as will be shown here, this "source" is located as much as 150 km from the shelf break (or other generating topography), with no internal waves (or lower intensity modulations) being observed closer to the shelf break.

Two main generation "hotspots" have so far been identified in the Bay of Biscay: the northern shelf break from which ISWs travel towards the South-South-West (SSW) [3], and the Cape Finisterre region off North-West Spain, where the ISWs travel towards the East-North-East (ENE) [6]. Both sets of waves appear to result from the "local generation" hypothesis. In the present paper, we investigate available satellite imagery (ERS SAR and ENVISAT ASAR data) to reveal for the first time other prominent local generation "hotspots" and the main propagation directions associated with them. It has recently been demonstrated [6], that the wave-trains from Cape Finisterre, in the Southern Bay of Biscay, travel in two slightly different directions (055°T and 040°T). The generation sites for these wave-trains lie on either side of the Ortegal Promontory (OP), an undersea ''headland'' projecting towards the North-West from the north-western coast of Spain (near 44°N, 8.5°W), and over which the barotropic tides are forced to flow. These generation sites were estimated by calculating the strength of the barotropic tidal forcing in the region, and identifying the likely propagation pathways (rays) of internal tidal (IT) energy. For each generation site, IT rays emanating from ''critical'' topography (where the ray slope is equal to the topographic slope) in regions of strong barotropic forcing, rise to the surface (for one site after a reflection from the sea-floor) and pass through (or "reflect from") the near-surface thermocline close to the earliest occurrences of the ISWs observed in the SAR images. These rays would then produce, through nonlinear processes, the ISWs through the same ''local generation'' mechanism that has been used to explain the occurrence of the ISWs in the northern and central

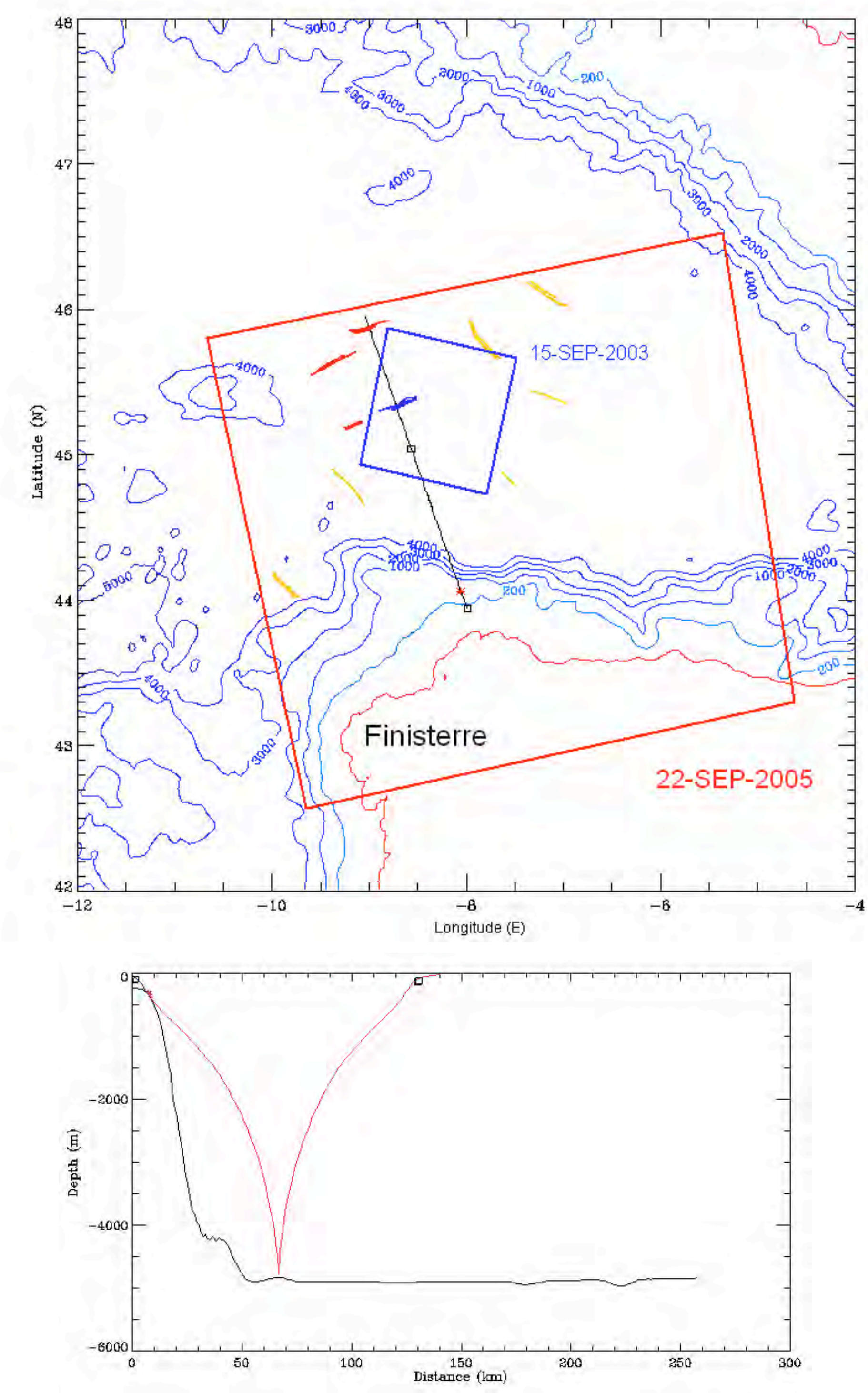

Figure 1. a) Map of the Bay of Biscay with internal wave crests based on two ENVISAT ASAR images dated 22 September 2005 (22:17 UTC) and 15 September 2003 (10:53 UTC). The red and blue squares show the areas covered by each image. Internal wave packets marked in blue and red were identified as travelling towards the North-North-West (NNW), and appear to be generated near OP. b) Ray-tracing diagram showing IT ray paths (emanating from critical topography) along the black line in part (a). The small black squares in part (a) show where the ray path crosses the near-surface thermocline (at a depth of 50m), and are also marked in part (b). The NNW-travelling ISWs in part (a) are therefore consistent with the "local generation" hypothesis, after a reflection of the IT ray from the sea-floor. Red star marks critical slope.

Bay. In addition to these already discovered wave-trains, we have now identified new wave packets travelling towards the North-North-West (NNW) which also appear to be generated from the OP, and are also consistent with the "local generation" hypothesis (i.e. after a reflection of an IT ray from the sea-floor). In the present paper we also provide evidence that a further IT ray that propagates upwards from the OP and towards the West-South-West (WSW), is capable of generating ISWs that propagate towards 235°T, as predicted but not shown in our previous investigations.

In addition to the Ortegal Promontory region, we have also investigated the Estremadura Promontory (EP) region, off the West coast of Portugal, to the West of Lisbon (Cape Roca). This is a much larger feature, extending from the coast to the West for more than 100 km, where the barotropic tidal flow is forced to cross the EP in a nearly perpendicular direction. It is therefore a region likely to produce strong internal tides, since the barotropic tidal flow strongly crosses the bathymetric contours, thus producing a large generating body force [7]. So far we have identified two generation sites: one over the southern slopes of EP, located near 38.6°N, 9.9°W, at a depth between 1000 m and 2000m; and another generation site off the west coast of Portugal, over the western continental slopes, located near 37.4°N, 9.6°W, at a depth between 1000m and 1500m. Both of the IT ray paths originating from these critical slope regions propagate into the deep ocean, and surface after a bottom reflection. The first IT ray path (that generates over the southern slopes of EP and propagates initially downwards) propagates towards the South-South-West (SSW), and the ISWs that were observed near 37.9°N, 10.2°W propagating in the same direction, are probably associated to the near-surface reflection of such IT beam. A further IT ray path seems to emanate from the western continental slopes, and appears to be the source of a packet of ISWs observed near 37.6°N, 10.5°W travelling towards the West-North-West, that is consistent with the "local generation" hypothesis, after a reflection of the IT ray from the sea-floor.

The methods we have used to deduce the generation sites for the SAR observed waves, namely the depth integrated body force developed in [7], and the examination of IT ray paths, are expected to prove equally useful for studies in other areas of the world's oceans. We can thus use SAR to examine whether the ''local generation'' mechanism is more widely applicable than previously thought. We also remark that, in regions where *in situ* measurements are not yet available, and we rely entirely on satellite data for preliminary studies, the methods described here will provide useful information for planning field work and optimising ship time, by revealing the most likely locations of the internal waves and their generation sites.

Keywords: Internal solitary waves, Internal tides, Synthetic Aperture Radar, Iberian Peninsula.

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