Can near-inertial internal waves in the East Sea be observed by synthetic aperture radar?

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[1] Near-inertial (~18 hours) internal waves were observed in the mid-western part of the East Sea on May 18 and 19, 2004 using C-band Synthetic Aperture Radar (SAR) images. Current and temperature measurements obtained during the field experiment from 10 May to 9 June 2004 (IWXES2004, Internal Wave Experiment in the East Sea), were analyzed to investigate the processes by which near-inertial internal waves can be seen in SAR images and how they progress. The spatial distributions of horizontal wavelength and phase speed estimated from two successively acquired SAR images are consistent with those inferred from water temperature and current measurements carried out during the field experiment. Based on these two independent observations (SAR and IWXES2004), we report a strong possibility that the observed wave patterns in the SAR images during IWXES2004 are near-inertial internal waves propagating westward off the east coast of the Korean peninsula with a phase speed of about 0.3 m/s. Citation: Kim, D. J., S. H. Nam, H. R. Kim, W. M. Moon, and K. Kim (2005), Can near-inertial internal waves in the East Sea be observed by synthetic aperture radar?, Geophys. Res. Lett., 32, L02606, doi:10.1029/2004GL021532.

1. Introduction

[2] It is well known that Synthetic Aperture Radar (SAR) is a versatile all weather instrument for measuring sea surface roughness that can be modulated by surface current variations. These surface current variations can be generated by oceanic phenomena such as internal waves or submarine topography. SAR images are often used to improve our understanding of internal wave generation and evolution because they cover such a large area of the ocean’s surface, several hundreds of kilometers on the side. Short period internal solitary waves have already been extensively observed from satellite images. Near-inertial internal waves have been often recorded from moored current measurements and water temperature sensors in the East Sea [Lie, 1988; Kim et al., 2001; Navrotsky et al., 2004]. However, the spatial characteristics of near-inertial internal waves had not been investigated until now, mainly due to lack of measurements.

[3] In this paper, we demonstrate that the near-inertial internal waves could be effectively observed in space-borne SAR images. Using both two successive SAR images and in situ measurement data, the progressing near-inertial internal waves were interpreted.

2. SAR Observations and in Situ Measurements

[5] Currently there are several operational SAR satellites, including ERS-2, RADARSAT and ENVISAT, which are all C-band (5.3 GHz frequency) and operate in sun-synchronous orbit. In order to observe the evolution of internal waves generated in the East Sea, off Korean peninsula, the SAR image acquisition was focused on the western part of the East Sea during the IWXES2004 (Internal Wave Experiment in the East Sea) carried out from May 10 to June 9, 2004. More than fifteen scenes of SAR data, including ENVISAT ASAR [Advanced Synthetic Aperture Radar] and RADARSAT were acquired over the study area during the field campaign. Simultaneous in situ measurements were also carried out on the continental shelf and the shelf slope off the mid-east coast of Korean peninsula, using the East Sea Real-time Ocean Buoy (ESROB) (Figure 1). The ESROB collected both meteorological data and oceanographic data such as water temperature, salinity and current over a whole water column every minute. A conductivity-temperature-depth (CTD) survey was conducted twice during the experiment to obtain the hydrographic sectional structure over the shelf and the slope. Two ENVISAT ASAR images acquired at 13:15 UTC on 18 May (UTC +9 = local time) and 01:28 UTC on 19 May, 2004, during the experiment, show distinct wave patterns off the eastern coast of Korea (Figure 2). These SAR data were absolutely calibrated and geo-coded to extract quantitative information of the wave signatures [European Space Agency, 2004].

3. Observation Results

[6] Three distinct alternating bright and dark wave patterns off Donghae City on the east coast of Korea, which are obliquely aligned to the coastline with an angle of approximately 30 degrees, are clearly visible (Figure 2). The solid lines in Figure 2c and (d) were depicted along the maximum...
The gradient of $\frac{\partial I}{\partial I_0}$ progressing from the brighter to darker areas, which is defined as

$$\frac{\partial I}{\partial I_0} = \frac{(I - I_0)}{I_0}$$  \hspace{1cm} (1)

where $I$ is the intensity of the SAR image and $I_0$ is the intensity of the background SAR image. The distance between solid lines observed near the shore ranges from 13 km to 20 km and its mean distance is approximately 16 km. We interpret the solid lines may represent the trough of near-inertial internal waves for following reasons.

Near-inertial internal waves can induce the spatially varying current field at the surface. The current field interacts with the surface waves and thus causes a spatial modulation of the Bragg scattering waves. The change in SAR intensity is proportional to the modulation of the surface wave height spectrum at the Bragg waves, which are also hydrodynamically affected by the slope of the longer waves [Thompson, 1988]. A schematic diagram was proposed to describe the resulting SAR intensity variations caused by the interaction of near-inertial internal waves, current fields, stratification, and the spectrum of surface capillary waves, as shown in Figure 3. We calculated SAR intensity variations, which account for the contributions of the weak current-gradient generated by the near-inertial internal wave with a 16 km-wavelength. For this calculation we used a wave-current interaction model and composite surface model developed by Romeiser et al. [1997], which includes the effect of hydrodynamic modulation of the Bragg waves by longer waves. The model calculations demonstrated that the current-gradient of $O(10^{-5} \text{ s}^{-1})$ can produce the difference of about 1 dB, where wind is set to the values recorded at the ESROB during the SAR image acquisition. We were able to estimate the phase speed of the waves from the two successively acquired SAR images with about a 12 hour interval during the experiment. The wave stripes labeled as A, B, and C on Figure 2c were propagated shoreward and moved into A’, B’, and C’, respectively (Figure 2d). The mean distance between A-A’, B-B’, and C-C’ is about 12 km, which means that the phase speed of the waves is about 0.3 m/s. The spectral analyses of the current and temperature obtained during the experiment near the Donghae City on the east coast of Korea (Figure 1) show a peak at 18 hours in the energy spectral density distributions (Figure 4) where the
local inertial period in this area is about 19.5 hours. The estimated wavelength of the waves with calculated phase speed is about 18 km. The distance between solid lines observed in each SAR image ranges from 13 km to 20 km. This result enables us to interpret that the wave patterns observed in the SAR images are the sea surface manifestations of “near-inertial internal waves.”

[8] Figure 5 shows a (near-inertial) band-passed time series (local time) of the east-west currents measured at the ESROB at a depth of 5 m for 10 days, from 16 May to 26 May, 2004 (upper) and a time-depth contour of the band-passed currents in the east-west direction (lower). Near-inertial oscillation reaches its maximum at 02:10 (local time) on May 21, about 53 hours after the first SAR image was taken. Since the estimated phase speed of the near-inertial internal wave is 0.3 m/s and the distance between the buoy and the first wave stripe, where the maximum gradient of SAR relative intensity detected is 60 km, the time interval of 53 hours is reasonable. Though no vertical phase shift is significant at a depth below 15 m, there is clear upward phase propagation (downward energy propagation) near the surface, implying that there are surface intensified near-inertial internal motions induced by the wind. This is also consistent with the situations shown in the Figure 3.

[9] The CTD measurements done in May 18, 2004 showed that the pycnocline sloped up toward the coast as outlined in Figure 3. From the WKB solution of the linear inertial-internal wave theory with a slowly varying Brunt-Väisälä frequency $N \left( N = \sqrt{\frac{\frac{d \rho}{\rho} \Omega^2 \sin \varphi}{f^2}} \right)$, is slightly higher near the shore region than the open sea in the upper depth levels. The higher $N$ in the upper ocean, the larger $\theta$, results in the widening of the surface manifestations of near-inertial internal waves. In Figure 3, we can recognize the wavelengths become longer near the shore region than the open sea, as the linear inertial-internal wave theory suggests.

4. Summary and Discussions

[10] Distinct wave patterns moving towards the Donghae City on the east coast of Korean peninsula were observed in SAR images. A dominant peak in the spectra of observed surface currents indicates strong near-inertial (18 hours) motions at the time of observation. The spatial distribution of horizontal wavelengths and the phase speed estimated from two successively acquired SAR images are consistent with those inferred from water temperature and current measurements made during the field experiment carried out from 10 May to 9 June, 2004 (IWXES2004). Based on these two independent observations (ENVISAT ASAR images and IWXES2004), we interpreted the wave patterns observed in SAR images as near-inertial internal waves propagating towards the coast of Korea with a speed of approximately 0.3 m/s. Increase in the horizontal wavelength is recognizable as they approach the coast, probably due to the surfacing of isopycnals near the coast.

[11] We cannot however exclude the possibility that the observed three alternating brighter and darker wave patterns in the SAR images may indicate the presence of atmospheric Lee waves rather than near-inertial internal waves. However, it should first be noticed that the wave patterns in the SAR images are oriented about 30 degree anticlockwise from mountain ridges which align very close to the coastline and there is little indication of any organized waves off Donghae City in two successive images. Secondly, the
prevailing wind during the observation period was westerly wind of 3–4 m/s, which is consistent with the estimated wind speed range from the SAR data [Kim and Moon, 2002]. We estimate the wavelength of Lee waves for the atmospheric buoyancy profile obtained from the radiosonde data, based upon the method by Foldvic [1962], resulting in the wavelength of approximately 5 km at the most, which is significantly shorter than wavelengths of 13–20 km observed in the SAR images. The spatial characteristics of wave patterns in the SAR images and the physical dynamic considerations are not consistent with typical atmospheric Lee waves, and we may rule out the possibility of atmospheric Lee waves.


References


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