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14. ABSTRACT

The objectives of the grant were to use a coherent real aperture radar to 1) study the interaction of surface waves with internal wave, the process that is responsible for the synthetic aperture radar (SAR) imagery of internal waves; 2) Determine the extent to which Doppler velocity modulations observed by coherent radars, including along-track interferometric SARs, are faithful representations of surface currents generated by internal waves; and 3) track the temporal and spatial development of internal waves as they are generated, propagate and dissipate.

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Final Report: Measurement of Non-Linear Internal Waves and Their Interaction with Surface Waves using Coherent Real Aperture Radars

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Objectives of the Project

The objectives of our measurements were:

1. To study the interactions of surface waves with internal waves, the process that is responsible for synthetic aperture radar (SAR) imagery of internal waves.

2. To determine the extent to which Doppler velocity modulations observed by coherent radars, including along-track interferometric SARs, are faithful representations of surface currents generated by internal waves.

3. To track the temporal and spatial development of internal waves as they are generated propagate, and dissipate.

Summary of Results

1. Because our cross section measurements were calibrated, we were able to show that at a variety of incidence angles, internal waves produce higher cross sections at HH polarization than VV. This is an indicator of wave breaking and casts doubt on previous theories of internal wave microwave signatures.

2. Cross sections and surface velocities produced by internal waves frequently, but not always, depend on the direction of look of the microwave antenna. Thus Doppler velocity modulations cannot always be faithful representations of the internal wave current.

3. The location of the maximum cross section produced by an internal wave was directly above the maximum surface current, the internal wave crest, produced by the internal wave in deep water. On the shelf, however, the maximum cross section was located on the forward face of the internal wave crest. This provides a potential means of studying internal wave transformations. In no case did our internal wave signatures occur far away from the crest of the internal waves as has been previously reported.

4. Phase speeds of internal waves could be determined in our images. These varied from 0.8 m/s to 3 m/s in our data.

Experiments Conducted

During the Non-Linear Internal Waves Initiative (NLIWI), we deployed our coherent, X-band radar, RiverRad, with fixed antennas on the R/V Melville, and on a Taiwanese vessel, the Ocean Researcher 1, in the South China Sea. We also mounted RiverRad in a scanning mode on the R/V Endeavor off the coast of New Jersey. Finally, we flew another coherent, X-band radar, CORAR, on a Cessna Skymaster aircraft off the coast of New Jersey. Figures 1 and 2 show these installations.

The data collected with these radars documented some very interesting characteristics of the radar surface signatures of non-linear internal waves. We found that these signatures behaved differently depending on the incidence angle of the radar antenna, on the polarization of the radar, and on the nature of the internal waves themselves.

Figure 1. RiverRad installed on the various ships. Left Column – The R/V Melville in 2005 with RiverRad and the PI shown below it. Middle Column – The R/V Endeavor in 2006 with RiverRad shown below it. Right Column - The Taiwanese OR1 with RiverRad and Gene Chatham shown below it.

Figure 2. Left - The Cessna Skymaster and the two pilots, John Ambroult, and John Williams. The white rectangle below the plane houses CORAR's two antennas, one HH and the other VV. Right – Internal waves on the New Jersey Shelf as seen from the Skymaster.

Characteristics of Cross Section and Velocity Modulations

Larger HH than VV Polarized Cross Sections

One feature of these internal wave signatures that has not previously been documented is that internal waves always seem to modulate backscatter cross sections at HH polarization more than at VV polarization. This was a very clear message from our measurements at many incidence angles as illustrated in Figures 3, 4, and 5.
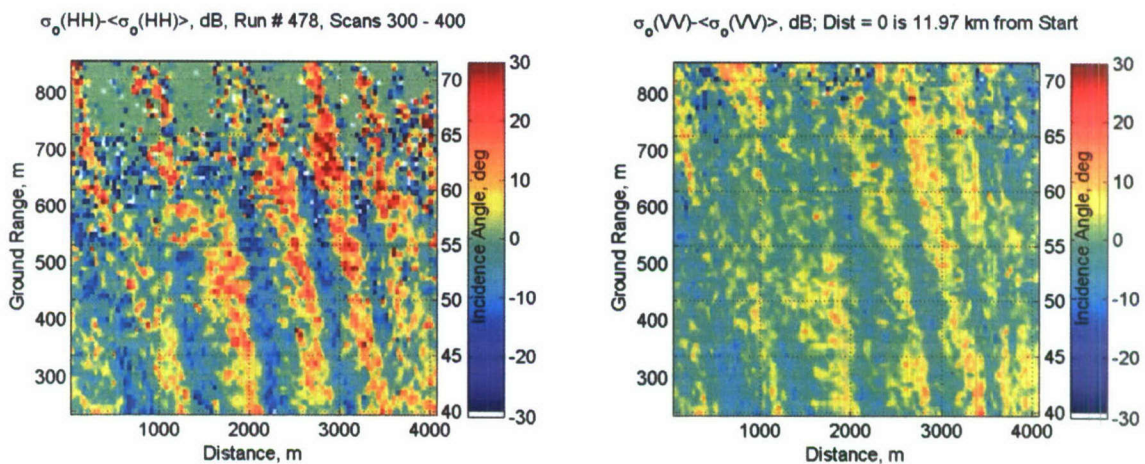

Figure 3. Images of internal waves on the New Jersey shelf obtained with the airborne CORAR. Left: HH polarization, Right: VV polarization.
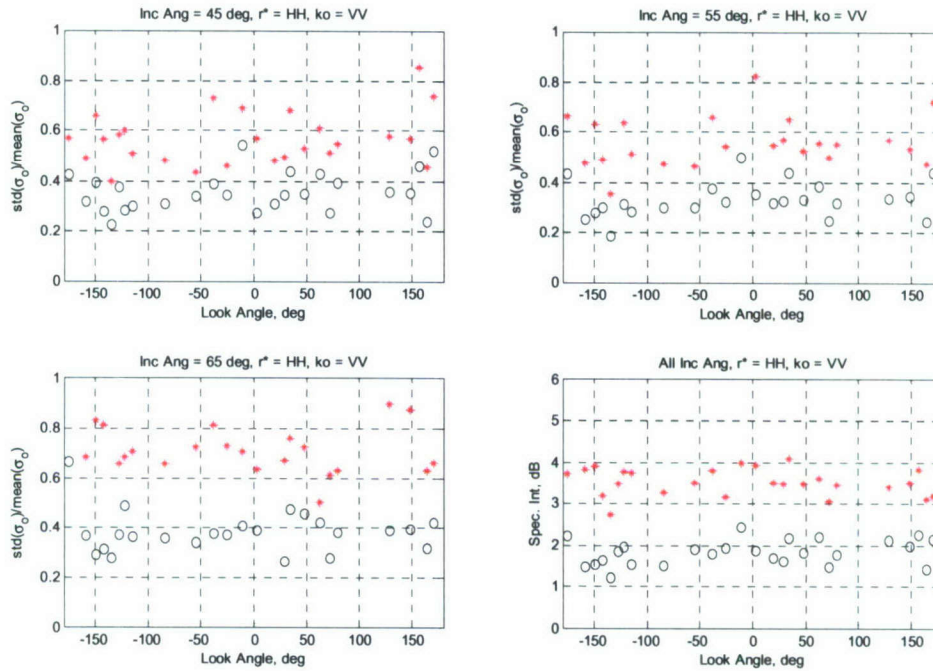
Figure 4. Measures of the visibility of internal waves on the New Jersey shelf by airborne CORAR plotted against antenna look direction. Red asterisks are HH polarization, black circles are VV.
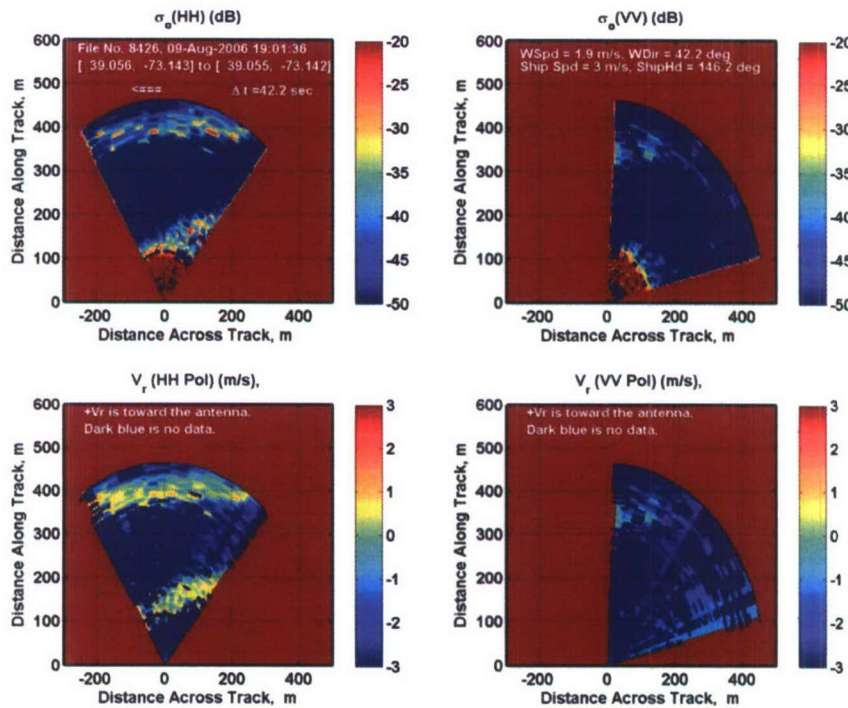

Figure 5. Images of internal waves on the New Jersey shelf obtained with the shipboard RiverRad. Incidence angles were near 88°. Left column: HH polarization, right column: VV; Top row: cross sections, bottom row: velocities.

In all these figures, the internal waves are more visible for HH polarization than for VV. Interestingly, Figure 5 shows that the internal waves are more visible at HH than VV in the velocity images as well as in the cross section images. Note that the greater visibility at HH than VV polarization is consistent across the range of incidence angles from 45° to 88°.

Because our HH and VV cross sections are collected simultaneously and are absolutely calibrated, we were able to document that the maximum values of HH and VV cross sections occur at the same location and that HH cross sections are larger than VV cross sections. This is important because previous models of the surface signatures of internal waves have been based on scattering from freely propagating waves that are modulated by the internal wave surface currents. These theories always predict that HH cross sections will be smaller than VV cross sections. We believe that this is because effects of breaking waves have been ignored. Breaking waves are sometimes known produce larger HH than VV cross sections and we are investigating these possibilities now.
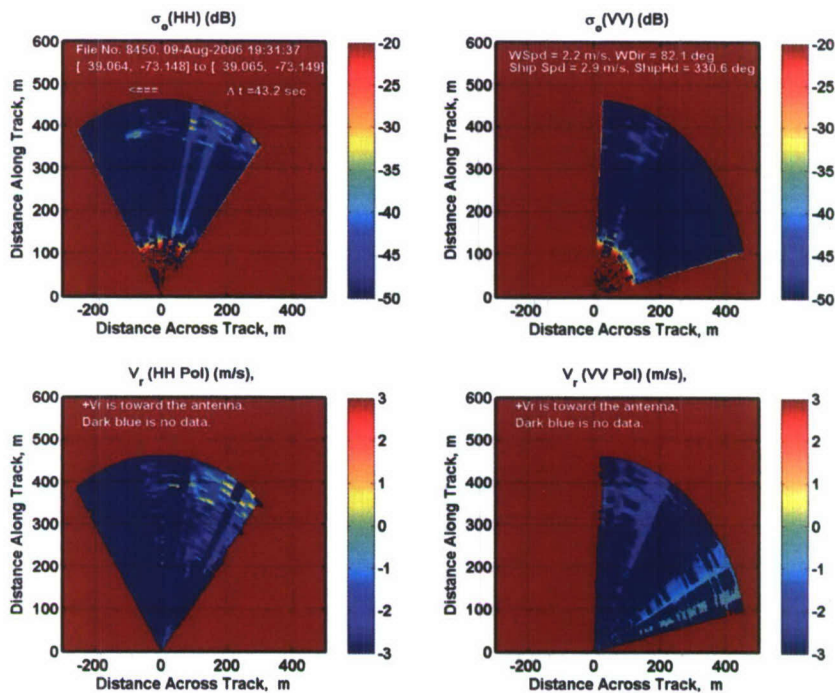
Upwave/Downwave Assymetry

Figure 6. The same internal wave as seen in Figure 5 but viewed from the opposite direction 30 minutes later.

A feature of our data that does not appear to be consistent across a range of incidence angles is the dependence of the visibility of internal waves on the direction from which they are viewed. Figure 4 shows that no dependence on azimuth angle exists for incidence angles between 45° and 65°. Yet Figure 6 is a shipboard image of the same internal wave seen in Figure 5 but observed from the opposite direction. Clearly the

visibility of the internal wave is much less here. The two images were obtained 30 minutes apart.

Figure 7 shows, however, that images obtained on ships do not always show internal waves better when looking into their propagation direction. This figure shows normalized radar cross section observed on several crossings of a train of internal waves traveling west in the deep basin of the South China Sea. Concentrating particularly on wave #2, we see that the cross section looking in the wave propagation direction (second crossing) is as large as or larger than that obtained looking into the internal wave propagation direction (first and third crossings). This is very different than Figures 3 and 4.
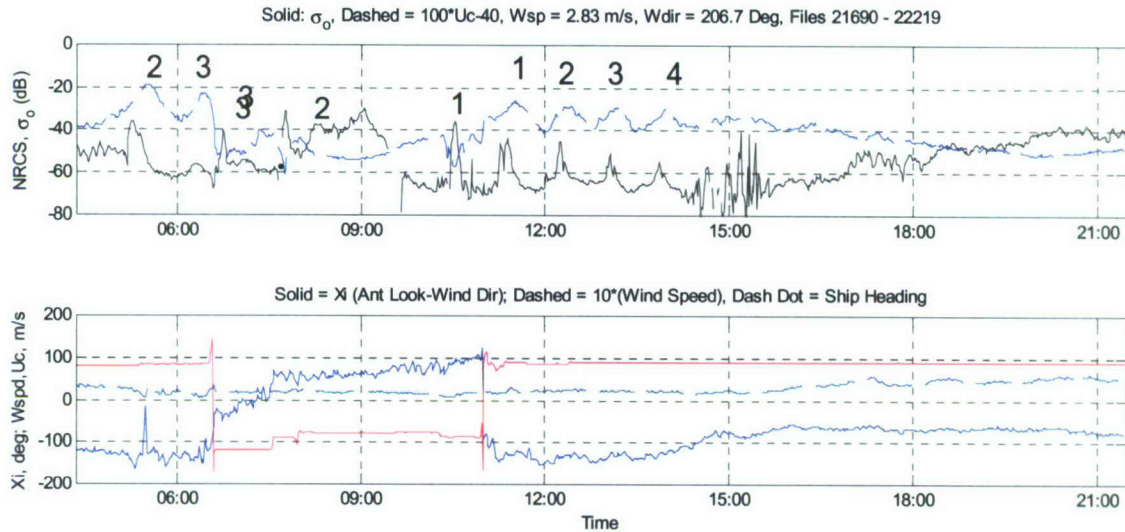

Figure 7. Measurements made on the R/V Melville in 2005. Top: Subsurface velocities (blue) times 10, minus 40 and σ_o(VV) (black). Bottom: Antenna look direction – wind direction (solid blue), wind speed times 10 (dashed blue), and ship heading (red).

Location of Signature Maxima

Previous experiments have had difficulty determining the precise location of the maximum cross section relative to the internal wave crest. This is because the measurement of both locations simultaneously is difficult from aircraft or from the shore. Three out of four of our experiments had the advantage of being carried out onboard ships where other instruments (echo sounders, Doppler sonars) were simultaneously measuring the characteristics of the internal waves. Therefore we were able to determine the relative locations of the maximum surface signature and the crest of the internal wave. Our measurements show that this relative location depends on the type of internal wave. Figures 8 and 9 show space/time plots of the return to RiverRad. The black curves in the figures show the ship's path. The lower panels show the component of subsurface velocity along the ship heading, the ship heading, and the ship speed. They also give wind speed and direction.

We may track the progress of any internal wave in the figures as shown by the sloping black lines in the figures. The slopes of these lines are a measure of the phase

speed of the internal wave if the ship travels perpendicular to its crest. The point where these lines cross the ship's path is the location of the internal wave signature at the time that the velocity measurements in the bottom panel were made. Clearly on the shelf (Figure 8), the maximum cross section occurs on the front face of the internal wave as conventional wisdom dictates. However, in the deep basin (Figure 9), the maximum cross section occurs at the maximum of the subsurface velocity. This is unexpected and unexplained. Furthermore, the maximum of the scatterer velocity appears to follow that of the cross section, which is again unexplained.
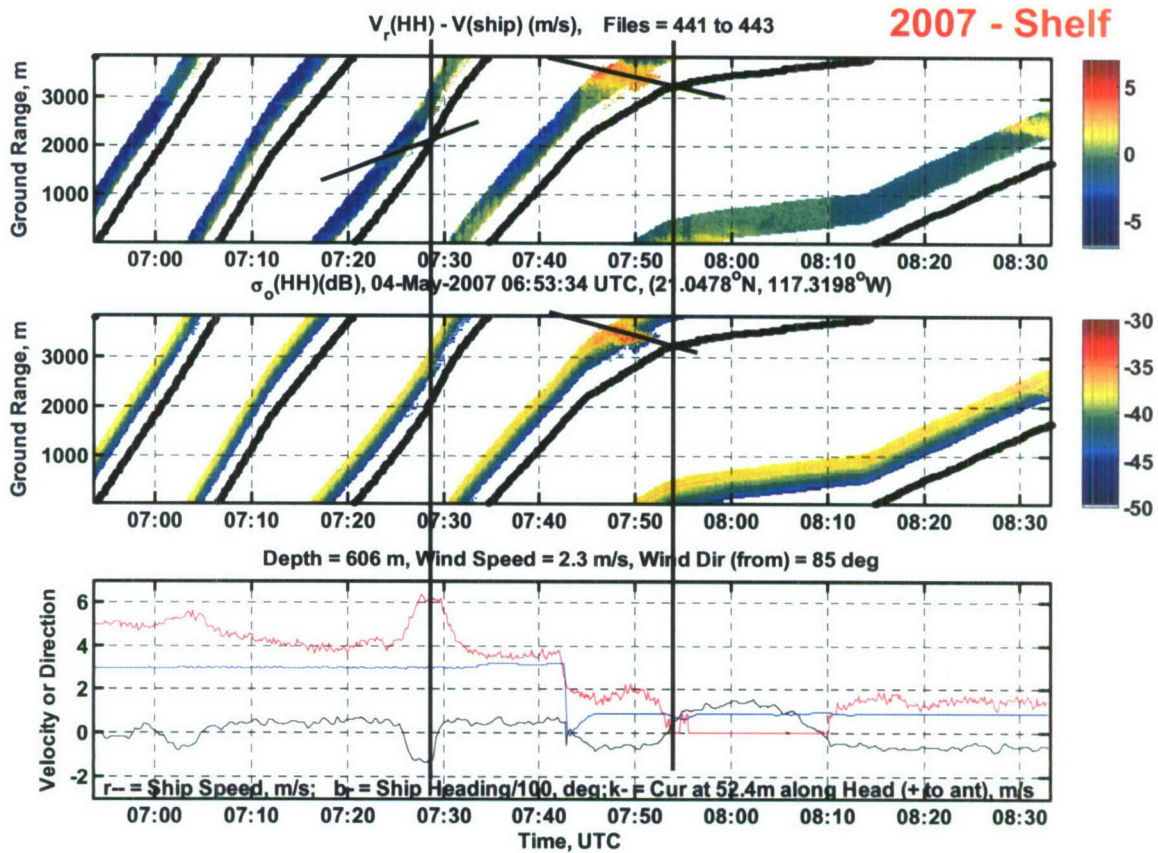

Figure 8. Data taken by RiverRad on the shelf in the South China Sea in 2007 along with data collected by other instruments on the ship, the OR1. Top: space/time plot of scatterer velocities observed by RiverRad; Middle: space/time plot of normalized radar cross sections from RiverRad; Bottom: component of subsurface velocity along the ship heading (black), the ship heading (blue), and the ship speed (red).
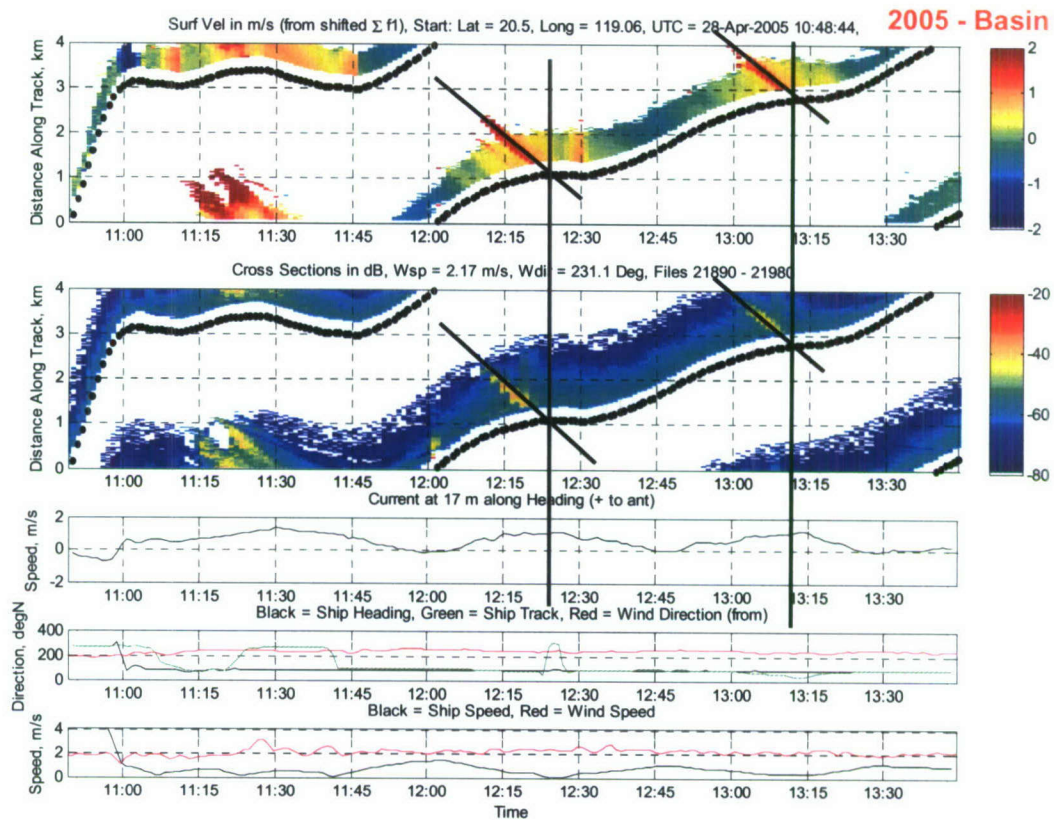
Figure 9. Same as Figure 6 except for data taken in the deep basin of the South China Sea. Here the middle plot shows the subsurface velocity component in the direction of the ship heading (positive is toward the ship's bow).

Conclusion

Data collected in this project have yielded much information about the radar signatures of non-linear internal waves in the ocean. Some of this information contradicts previous theories and experiments, providing incentive for further analysis of the data. Such analysis has been carried out only to a limited extent during these years of data collection. We hope to continue the analysis in the near future. We believe that the data are in hand to understand better the microwave surface signatures of internal waves in the ocean. Eventually such understanding may lead to a determination of the internal wave characteristics from their surface signatures, thus advancing the modeling and prediction of these waves.