Determination Of Nearshore Wave Conditions And Bathymetry From X-Band Radar Systems

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LONG-TERM GOALS

The long-term goal of this research project is to improve our capability to use X-band marine radars to routinely measure waves, currents and bathymetry in coastal regions.

OBJECTIVES

The scientific objectives of this study are:

1. investigate the imaging mechanisms of X-band radar systems in shallow coastal waters where nonlinear wave steepening, infragravity waves, wave breaking and breaking-induced currents can affect the radar backscatter signal

2. apply high-resolution spectral analysis techniques to the estimation of directional wave spectra from X-band radar images.

3. develop improved techniques for estimating the bottom topography from X-band radar images of the sea surface in shallow water regions with highly nonlinear waves and/or strong currents.

APPROACH

Proudman Oceanographic Laboratory (POL) deployed an X-band (9.8GHz, 3cm wavelength) marine radar during the European COAST3D field experiments in Teignmouth, UK. The study site is a complex three-dimensional tidal inlet. A sequence of 64 radar images was collected at time interval of 2.25s every hour. Although realistic-looking wave patterns are observed in the radar images, it is still unclear how the radar image intensities are related to the sea surface elevation. Marine radars rely upon the scattering of incident electromagnetic waves by the ocean surface to detect ocean waves. Since the 3-cm wavelength of the X-band radar is much smaller than the typical wavelength of gravity waves, it

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14. ABSTRACT
The long-term goal of this research project is to improve our capability to use X-band marine radars to routinely measure waves, currents and bathymetry in coastal regions.

15. SUBJECT TERMS

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is actually the modulation of the radar backscatter by longer gravity waves that governs the appearance of ocean wave patterns in radar images. In shallow coastal waters, the imaging process is further complicated by several factors including nonlinear wave steepening/shadowing, wave breaking, low frequency fluctuations of the mean water level (infragravity waves), and wave-induced currents.

Our approach is to use a time-dependent nonlinear wave propagation model to elucidate the nature of the imaging mechanism of X-band radar systems in nearshore regions. The numerical model is based on a finite difference solution of a fully nonlinear set of Boussinesq-type equations (Nwogu, 1993; Nwogu and Demirbilek, 2001). The governing equations are uniformly valid from deep to shallow water and can simulate most of the phenomena of interest in the nearshore zone including shoaling, refraction, diffraction, reflection, bottom friction, nonlinear wave-wave interactions, wave breaking, wave-induced currents and wave-current interaction. The Boussinesq model is used to simulate the wave conditions that were observed during the COAST3D experiments. Numerical model predictions are compared to data from *in-situ* gauges. Cross-spectral analysis techniques are used to determine the transfer function and coherence between the predicted wave field and the radar backscatter intensities. We then investigate the variation of the transfer function with factors such as wind speed, wave propagation direction, wave height, distance from antenna, etc.

3-D FFT techniques are commonly used to estimate the normalized directional wave spectra from X-band radars (e.g. Young et al., 1985). The 3-D FFT analysis technique implicitly assumes that the wave conditions are stationary and homogenous over the analysis area. This assumption is typically valid in radar image domain sizes of the order of 2km x 2km in deep water. However, we are primarily interested in shallow water where the effects of refraction, diffraction, nonlinear wave-wave interaction, wave breaking, and wave–current interaction lead to a non-spatially homogenous wave field. To estimate the directional wave spectra, we need to select subregions of the image with locally spatially homogenous conditions. This might involve subdomain sizes of the order of 2-5 wavelengths. Applying standard 3-D FFT techniques to such domain sizes will lead to the smearing of the wave energy in wavenumber space. Spectral analysis methods such as the Maximum Entropy Method (MEM) have been shown to provide high-resolution spectral estimates for short non-cyclic records. Hence, we propose to conduct maximum entropy spectral analysis of subregions of the radar image to compare with the standard FFT analysis method. Directional wave spectra determined from the X-band radar data at the *in-situ* gauge locations will be compared with the measured directional spectra.

Data from X-band marine radars have been used to infer the bathymetry in coastal waters. Since the radars provide a time-varying sequence of images of the sea surface, Bell (1999) used a motion-tracking algorithm to determine the wave propagation speeds, wavelengths and directions. A depth inversion algorithm based on linear wave theory was used to estimate the water depths from the phase speeds and wavelengths. Good agreement was generally observed between the inferred and surveyed depths except in regions with strong currents and very shallow water where linear theory breaks down. An improved depth inversion algorithm is being developed that utilizes a nonlinear dispersion relation based on Boussinesq wave theory.

WORK COMPLETED

To allow direct time-domain comparisons of numerical model predictions with *in-situ* gauges, as well as direct comparisons of numerically simulated wave fields with X-band radar images, we modified the Boussinesq model to synthesize multi-directional sea states from the time series of the surface elevation and two components of the horizontal velocity at a gauge location close to the incident wave boundary. The phases of the different frequency components are no longer selected at random and the directions are uniquely determined from the amplitudes of the velocity components.

We have run the Boussinesq model for several incident wave conditions that occurred during the COAST3D Teignmouth experiments. The predicted directional wave spectra at several gauge locations have been compared to the measured data. We have also implemented a 3-D FFT analysis algorithm to estimate directional wave spectra from X-band radar data. For the depth inversion algorithm, we have derived a simplified expression of the nonlinear dispersion relation from the Boussinesq equations. The phase speed, C, is related to the water depth, h, wavenumber, k, and wave height, H, by:

$$C^2 = gh\left(1+\frac{H}{2h}\right)\left[\frac{1-(\alpha+1/3)[k(h+H/2)]^2}{1-\alpha[k(h+H/2)]^2}\right] \tag{1}$$

where $\alpha = -0.392$.

RESULTS

We initially present results of the Boussinesq model simulations for the COAST3D Teignmouth experiments. A 2-D map of the bathymetry and gauge locations where time series data were available is shown in Figure 1. Numerical simulations were carried out for a storm event that occurred on 11/12/99 at 06:00GMT. The incident wave climate at Gauge #3a had significant wave height H_s = 1.6m, and peak period T_p = 7.5s. The boundary conditions for the numerical model were synthesized to match the surface elevation and two components of the horizontal velocity at Gauge #3a. Figure 2 shows a three-dimensional view of waves propagating near the inlet. The measured and predicted surface elevation and velocities at Gauge #3a are shown in Figure 3. It can be seen the newly implemented boundary condition is able to reasonably reproduce the observed time histories at Gauge #3a.

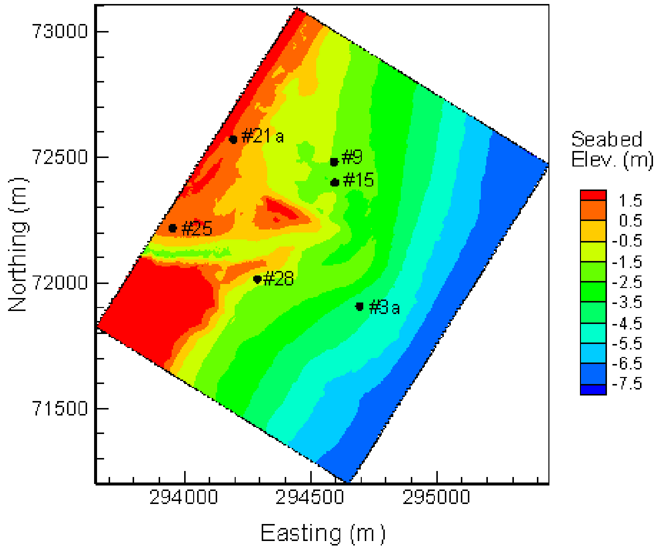

Figure 1. Bathymetry of Teignmouth Tidal Inlet and Gauge Locations.

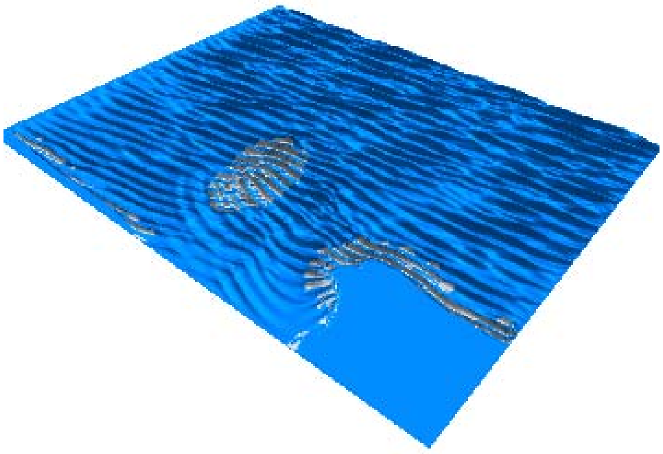

Figure 2. Three Dimensional View of Simulated Waves.

The measured and predicted wave spectra at Gauges #9 and #25 are compared in Figures 4 and 5 respectively. The Boussinesq model slightly underestimates the wave energy at the higher frequencies.

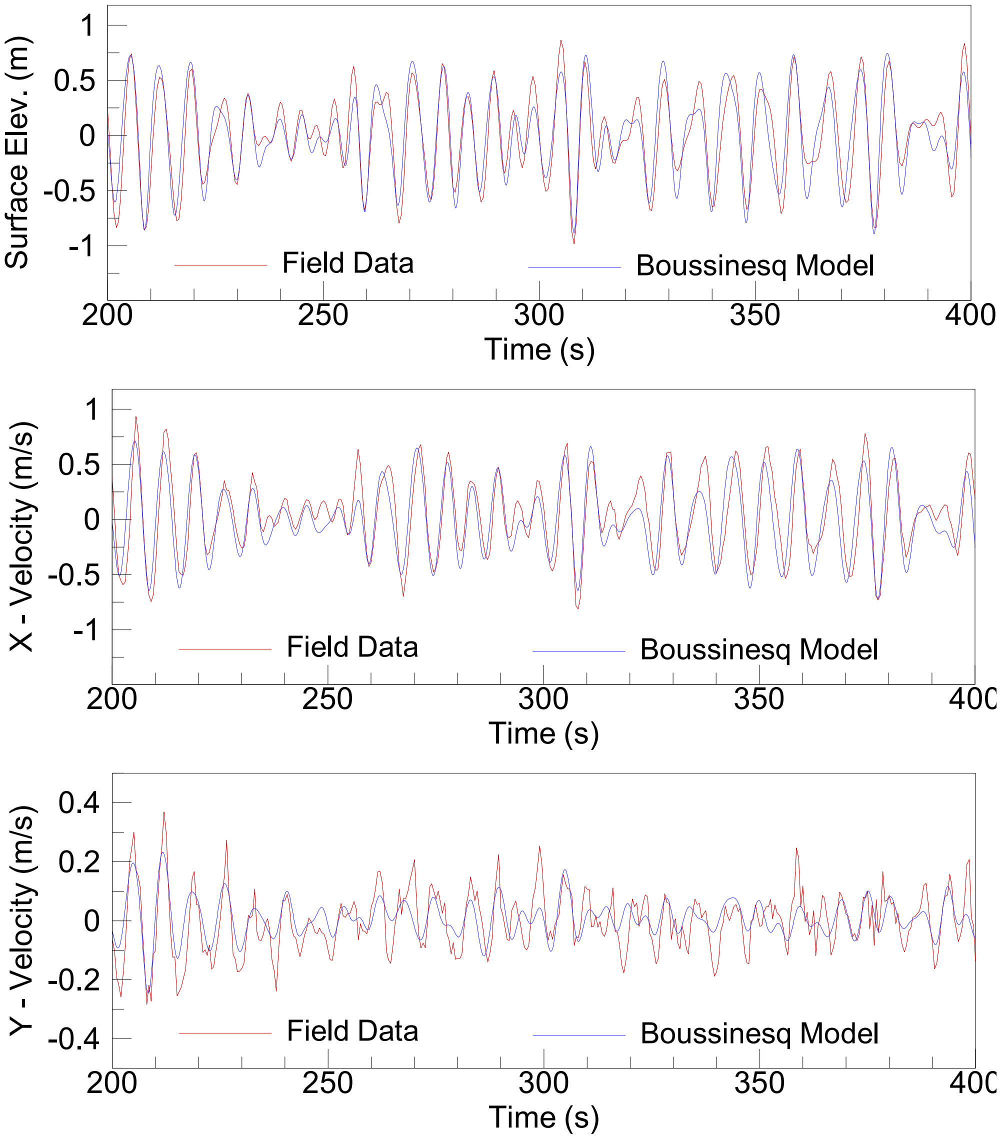

Figure 3. Comparison of Measured and Predicted Sea Surface Elevation and Velocities at Gauge #3a.

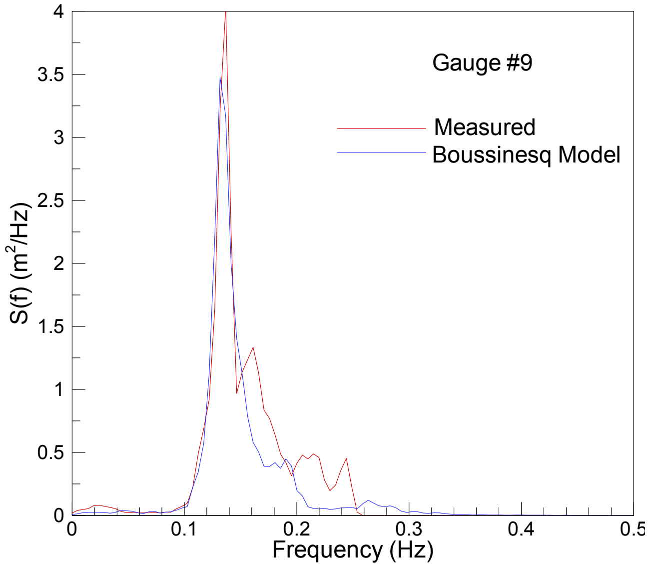

Figure 4. Measured and Predicted Wave Spectra at Gauge#9.

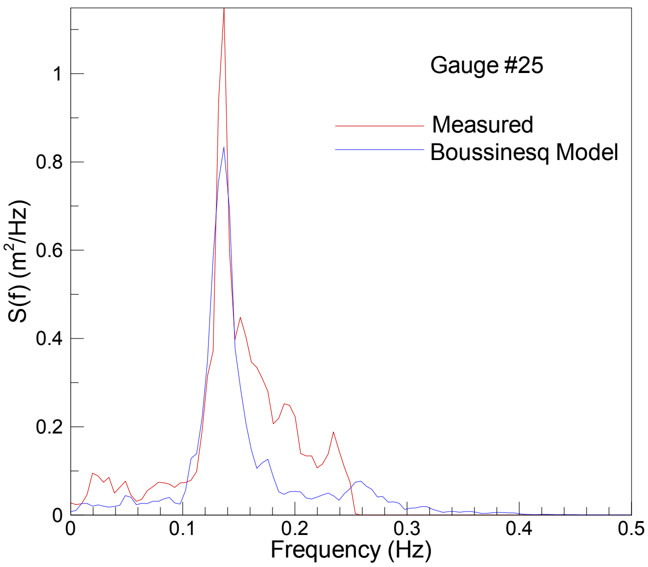

Figure 5. Measured and Predicted Wave Spectra at Gauge#25.

We compared the nonlinear phase speed predictions from Eqn. 1 with the fully nonlinear method of Reinecker and Fenton (1981) in Figure 6. While the simplified Boussinesq expression gives the correct amplitude dispersion trend, we are currently exploring including additional higher-order correction terms to improve the fit.

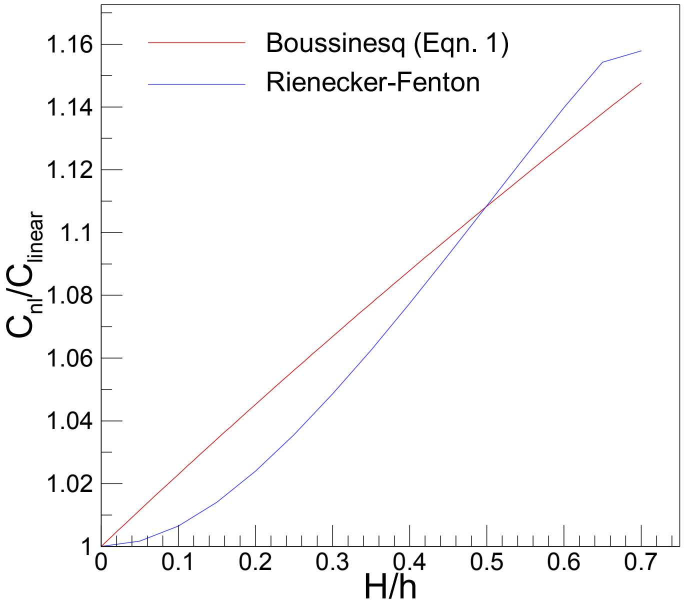

Figure 5. Comparison of Nonlinear Phase Speed Predictions.

IMPACTS/APPLICATIONS

The X-band radar represents a unique and economically affordable tool for the remote observation of coastal regions. It can be used to measure directional wave spectra and circulation patterns in complex three-dimensional coastal inlets and map the underwater topography in areas that are too hazardous for traditional hydrographic survey methods. It is anticipated that this project will lead to the development of several robust algorithms for analyzing the wave field and inferring bottom topography X-band radar images.

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PUBLICATIONS

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