

## **High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields**

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### **LONG-TERM GOAL**

Given remote and direct physical measurements of a realistic ocean wavefield, obtain a high-resolution description of the wavefield by integrating the measurements with phase-resolved wave prediction model including realistic environmental effects such as wind forcing and wave breaking dissipation. Inform and guide the measurements necessary for achieving this reconstruction and address the validity, accuracy and limitations of such wavefield reconstructions.

### **OBJECTIVES**

The specific scientific and technical objectives are to obtain:

1. Development of a phase-resolved, deterministic prediction capability for nonlinear wavefield reconstruction and evolution at intermediate scale ( $O(1) \sim O(10)$ km per dimension) using ship-mounted radar wave measurements
2. Incorporation and evaluation of physics-based wind-forcing and wave-breaking models that are developed/calibrated/validated based on simulations and measurements
3. Characterization and quantification of uncertainty and incompleteness in wave sensing and sensed data
4. Direct comparison between quantitative (point and area) field measurements and phase-resolved wavefield reconstruction and forecasting

5. Development of a theoretical/computational framework for guiding the deployment of wave sensing systems and data interpretation

## **APPROACH**

We develop and apply a comprehensive deterministic model for intermediate scale (up to  $O(10)$ km per dimension) ocean wave prediction by integrating whole-field and multiple-point measurements of the wave environment with simulation-based wavefield reconstruction. The wave reconstruction is based on phase-resolved simulation of nonlinear ocean wave (SNOW) dynamics, and utilizes hybrid (from different types of sensors) measurements. The simulations also incorporate physics-based wind forcing and wave-breaking dissipation models, which are developed/validated/calibrated based on field/laboratory measurements.

Nonlinear wavefield reconstruction is based on an iterative optimization approach using multilevel phase-resolved wave models of different nonlinearity orders. Specifically, for low-level optimization sufficient for mild waves, the linear and second-order Stokes solutions are used. For high-level optimization required for steep waves, an efficient nonlinear wave simulation model (SNOW) based on a high-order spectral method is employed. Once the wavefield is reconstructed, its future evolution is given by the wave propagation model using the reconstructed wavefield as the initial condition (Wu 2004; Yue 2008). In wave modeling, wind forcing is included through a pressure forcing on the free surface, and wave-breaking dissipation is considered by applying an effective low-pass filter to the wave elevation and surface potential in the spectral space. Other physical effects such as those of current and finite depth are also directly considered in wave modeling.

## **WORK COMPLETED**

We focus on the validation and performance tests of the phase-resolved nonlinear wave reconstruction and forecasting capability using HiRes field measurements of realistic ocean waves. Specifically,

- We use instantaneous and continuous (SPROUL- and FLIP-based) radar data to reconstruct and forecast nonlinear wavefields.
- We cross-validate radar-based forecasted wavefields with independent ATM and buoy measurements inside or outside the radar domains
- We study nonlinear wave statistics and large wave events based on forecasted large wavefields using (hybrid point and whole-area) Hi-Res measurements

## **RESULTS**

To assess the performance of wave measurements and model predictions, direct comparisons between wave model predictions and HiRes 2010 field measurements are obtained. The comparisons indicate that phase-resolved reconstruction and forecasting of realistic ocean wavefields can be achieved by our wave prediction model and non-coherence marine radar sensed wave data. The resolution of the reconstructed and forecasted wavefield depends critically on the accuracy of sensed wave data, which is largely affected by radar-data inversion algorithm and the platform motion. Based on the reconstructed and forecasted large-scale wavefields, our study shows that it is of importance to include

nonlinear effects in wavefield evolution for accurately predicting the temporal-spatial information of rogue waves and nonlinear wave statistics.

### ***(1) Prediction Based on Radar Data verse Datawell Buoy Measurement***

To address the key question of whether a phase-resolved wave prediction can be achieved using radar data, we compare the reconstructed and forecasted wavefield to the independent buoy measurement. For this purpose, we use the HiRes measurements on June 18, 2010, in which radar data, buoy data and ATM data are all available. The positions of radar sensed data, ATM data, and buoy data in the large reconstructed wavefield domain are shown in figure 1.

Based on radar sensed wave data, we reconstruct a phase-resolved nonlinear wavefield and compare it to the independent buoy data in both the time history of the wave elevation and the wave spectrum. The comparisons are shown in figure 2. The comparison shows that for the wave spectrum, the agreement between the radar-data-based prediction and the buoy measurement is very well. The predicted time-variation of the wave elevation has a ~45% correlation with the buoy measurement.

### ***(1) Prediction Based on Radar Data verse ATM Measurement***

Figure 2 shows the direct comparisons between the reconstructed wavefield based on radar-sensed data with the independent ATM measurement. For the wave spectrum, the radar-data-based prediction again agrees very well with the independent ATM measurement. For the phase-resolved sea surface, the nonlinear phase-resolved prediction (based on radar data) achieves a ~55% correlation with the ATM measurement.

Despite these encouraging results, we are continuing to explore additional Hi-Res measurement datasets to (i) study the effective use of hybrid measurements under different sea conditions to achieve phase-resolved forecast of large spatial-temporal domains, (ii) quantify/characterize performance of radar as a function of wave-wind conditions, and (iii) explore ways to (re-)calibrate radar measurements using phase-resolved simulation and optimization.

## **IMPACT/APPLICATIONS**

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wavefields based on direct sensing of the waves. Such a capability will significantly improve ocean-surface sensing measurements and deployment, and data assimilation and interpretation, by providing a comprehensive wave-resolved computational framework. Another important potential application of this is to greatly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

## **RELATED PROJECTS**

The present project is related to the project entitled “Fundamental Research to Support Direct Phase-Resolved Simulation of Nonlinear Ocean Wavefield Evolution” (N00014-10-1-069). The present project focuses on the application of the deterministic wave reconstruction/prediction capability to realistic ocean environment while the related project focuses on the understanding of fundamental

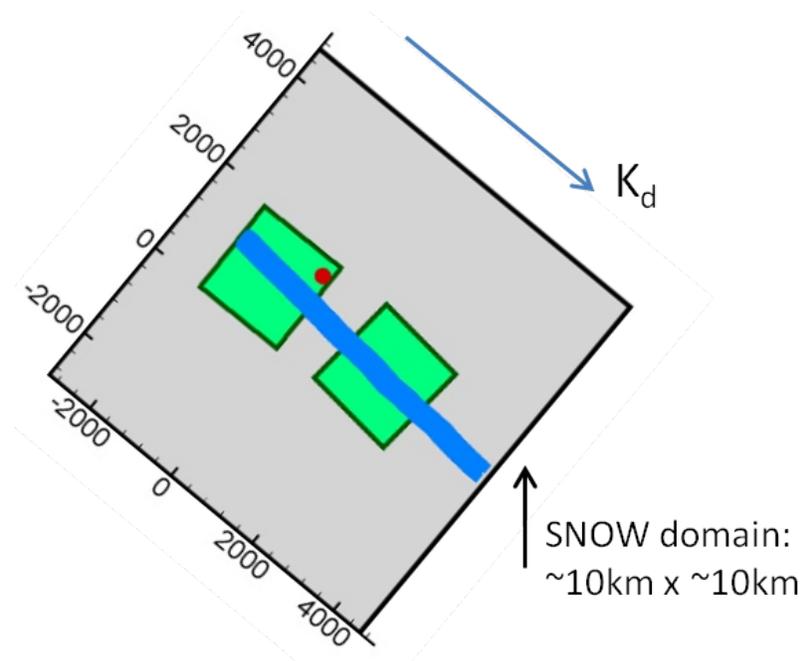
algorithms and accuracies/reliabilities of deterministic wave reconstruction and forecasting based on point and/or whole field wave measurements.

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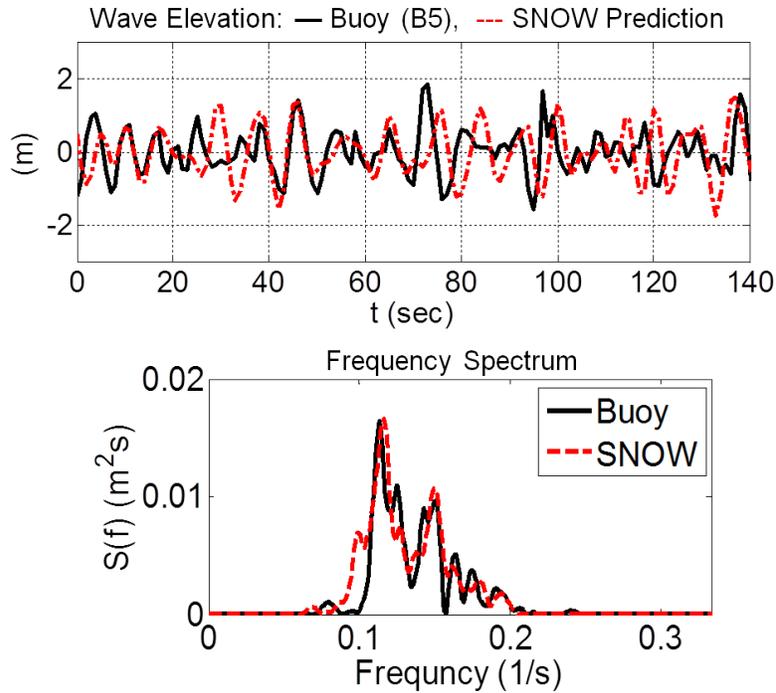
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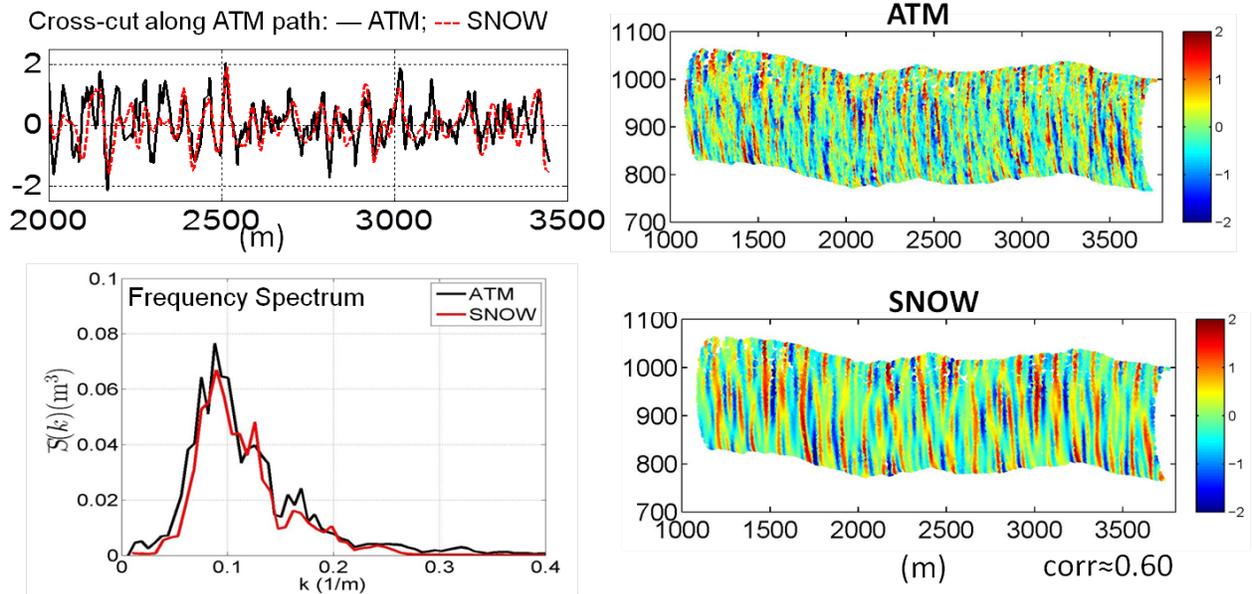
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**Figure 1. Wavefield reconstruction and forecasting in a domain of  $\sim 10 \text{ km} \times 10 \text{ km}$ , using ONR HiRes wave measurements on June 18, 2010. The regions sensed by FLIP-based radars and ATM and the location of the Datawell buoys are indicated: radar data (green regions), ATM data (blue strip), and buoy data (red spot). The dominant wave propagation direction is along the direction of  $K_d$ . The sea state has a significant wave height of  $H_s = \sim 3.3 \text{ m}$ , a peak wave period of  $T_p = \sim 9.5 \text{ s}$ , and a width of directional spreading angle of  $\Theta = \sim 80^\circ$ .**



**Figure 2. Comparison of phased-resolved reconstructed wavefield based on radar data with the independent buoy measurement. Top panel: comparison of the time-variation of the wave elevation; and bottom panel: comparison of the wave spectrum of the sea.**



**Figure 3. Comparison of phased-resolved reconstructed wavefield based on radar data with the independent ATM measurement. Right panels: comparison of the composite wave elevation between ATM measurement and the radar-data-based prediction. Top left panel: comparison of the cross-cut wave elevation along ATM path. Bottom left panel: comparison of the wave spectrum of the sea.**