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

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Award Number: N00014-08-1-0610
http://www.mit.edu/~vfrl/

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) ~ 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 field/laboratory measurements and nonlinear wavefield reconstruction and prediction
5. Development of a theoretical/computational framework that can guide deployment of wave sensing systems and data interpretation

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Center for Ocean Engineering,Department of Mechanical Engineering,Cambridge,MA,02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

6. Investigation and understanding of key physical factors that dominate the development and nonlinear evolution of rogue wave events

APPROACH

We develop and apply a comprehensive deterministic model for intermediate scale (up to O(10)km per dimension) ocean wave environment prediction by integrating whole-field and multiple-point measurements of the wave and atmospheric environment with simulation-based reconstruction of the wavefield. The wave reconstruction is based on phase-resolved **s**imulation of **n**onlinear **o**cean **w**ave (SNOW) dynamics, and utilizes hybrid (from different types of sensors) measurements that may contain noise, uncertainty and gaps. The simulations also incorporate physics-based wind forcing and wave-breaking dissipation models, which are themselves 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 which is sufficient for mild waves, the theoretical linear and second-order Stokes solutions are used. For high-level optimization which is required for moderately steep waves, an efficient nonlinear wave simulation model (SNOW) based on the high-order spectral method is employed. Once the wavefield is reconstructed, its future evolution is given by wave models using the reconstructed wavefield as an initial condition (Wu 2004; Yue 2008). In wave modeling, wind forcing is included through a pressure distribution on the free surface and wave-breaking dissipation is considered by an effective low-pass filter in spectral space. Other physical effects such as those due to the presence of current and finite depth can also be directly considered in wave modeling.

Large-scale HPC-based SNOW computations are used for phase-resolved prediction of nonlinear ocean surface wave-field evolution. From the directly simulated wave-fields, we investigate the nonlinear statistics of ocean surface waves, particularly the characteristics and occurrence statistics of rogue wave events.

WORK COMPLETED

We focus on validation and performance tests of the nonlinear deterministic wave reconstruction capability using HiRes field measurements of realistic ocean waves. In addition, we investigate the characteristics of rogue wave events in cross sea states. Specifically, the following work is completed:

- **Further development and improvement of high-resolution phase-resolved nonlinear wave reconstruction and forecasting capability:** We extend the reconstruction and forecasting capability for discrete point wave data to the situation with whole-field radar data and ATM data. The effects of current and finite depth are also included. In particular, we develop an effective algorithm with the incorporation of nonlinear phase-resolved wave reconstruction to improve the resolution of radar inversion data.
- **Validation, calibration and direct comparison with HiRes field measurements:** The developed wave reconstruction/forecasting capability is applied to obtain direct comparisons with HiRes 2010 field measurements. The performance of the reconstruction capability is validated and evaluated. Specifically, we complete the following:
    - SNOW reconstruction and forecast based on ATM data measured on June 8th.

  - SNOW reconstruction and forecast based on SPROUL-based radar inversion data on June 5th and 7th. Prediction from the model is compared with on-site buoy data.
  - SNOW reconstruction and forecast based on FLIP-based radar inversion data on June 7th. The effect of sub-domain size on the radar inversion data is studied. The distance dependence error observed in the radar inversion data is recovered using a nonlinear iterative scheme. The effect of time length of record on the radar inversion data is studied.
- **Investigation of rogue wave events in cross seas:** We apply large-scale HPC-based SNOW simulations to study the characteristics of rogue wave events and statistics of rogue wave statistics in cross seas. In particular, we focus on the understanding of the coupling effect of swell and wind waves upon the development of rogue waves.

RESULTS

In the study of rogue wave dynamics using large-scale SNOW computations, it is found that in general, the linear Rayleigh distribution underestimates the occurrence of rogue waves, especially in rough seas with narrow-band spectra. For directional seas, the spreading angle affects the exceeding probability of large waves significantly. As the spreading angle increases, the occurrence of rogue waves tends to become independent of Benjamin-Feir Index (BFI). Moreover, it is found that nonlinear coupling between swell and wind waves in crossing sea states can significantly increase the occurrence of rogue wave events.

In phase-resolved reconstruction and prediction of realistic ocean wave environments, some direct comparisons between wave model prediction and HiRes 2010 field measurements are obtained. Preliminary results indicate that phase-resolved reconstruction and forecasting of the ocean wave-field can be achieved by our wave prediction model and (ship-mounted or FLIP-mounted) Wamos radar sensed data. The resolution of the reconstructed and forecasted wave-field depends critically on the accuracy of sensed wave data, which is controlled by Wamos radar-data inversion and measurements of the platform motion. A sample result on the comparison of the wave model prediction, Wamos data, and independent buoy measurement is described below.

HiRes field measurements (by Sproul-based radar) on June 7th, 2010 are considered. The waves ar realtively strong with a significant wave height of Hs ~ 3.0m. Figure 1 shows a typical surface wave-field measured by Sproul-based radar. The wave-field is short-crested with spreading angle from -45 degrees to 45 degrees. The dominant wave propagation direction is from right to left. The radar measurements of the wave-field at two consecutive time are used to initialize the wave model. The wave model predicts the future time evolution of the wave-field. To cross validate the prediction and radar measurements, the predicted wave-field evolution is compared with the radar measurements of the wave-field, which are not used in the model prediction. Figure 2 shows the comparisons of the wavefields (2km × 2km) at t = 0 and t=3 T (T=6 s) between the wave model prediction and the radar measurements. After the evolution of 3T, as expected, large discrepancy between the prediction and the measurment is seen at the right boundary of the domain as new waves enter into the domain, which are not considered in the wave model. Figure 3 shows the comparison between the model prediction and radar measurement for the time history of wave elevation at three locations (indicated in figure 1). Clearly, as time increases, the agreement between the prediction and the data at point C becomes poor first since point C is the closest to the right boundary of the doamin. Figure 4 shows a sample comparison of time series of wave elevation at a particular location among the model prediction, radar measurement, and (independent) datawell buoy data. The comparison among them is quite encouraging.

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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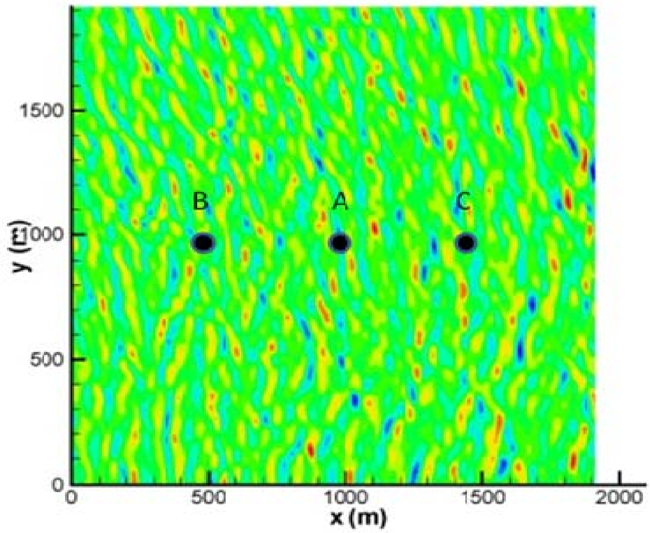

Figure 1: Instantaneous wave-field in a domain of 2 km x 2 km from the Sprould-based radar inversion data. Main wave propagation direction is from right to left.

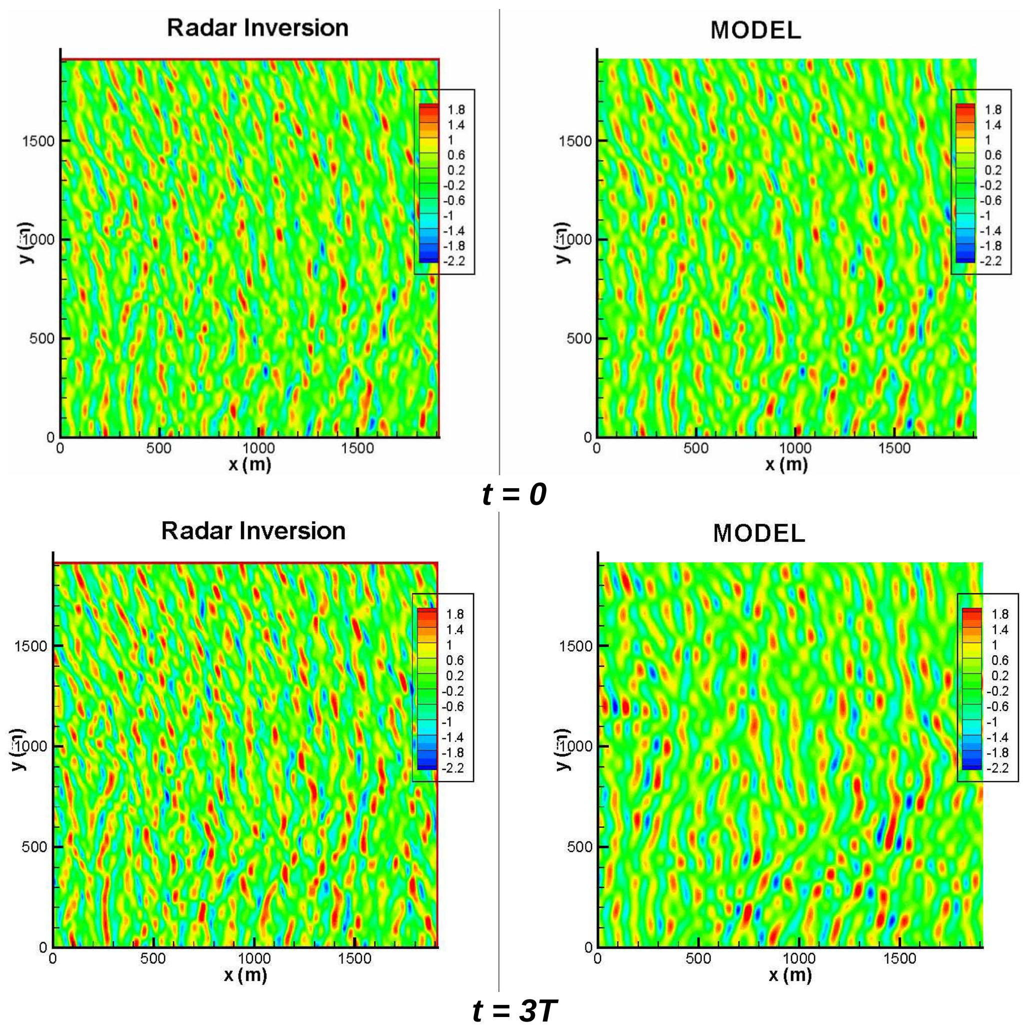

Figure 2: Comparison of the wave-field between the wave model prediction (right panels) and radar inversion data (left panels) at different time. (T = 6 s).

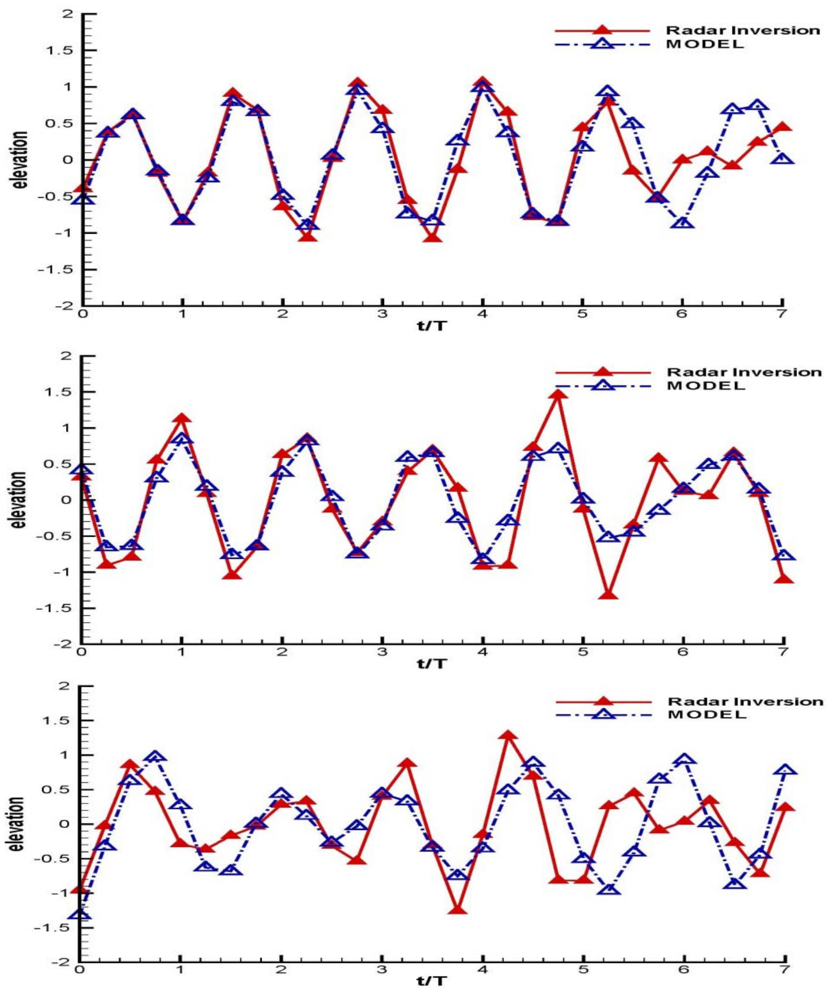

Figure 3: Comaprison of the time series of wave elevation at locates A (top panel), B (middle panel), C (bottom panel) between the model prediction (blue line) and radar inversion data (red line). (T = 6 s).

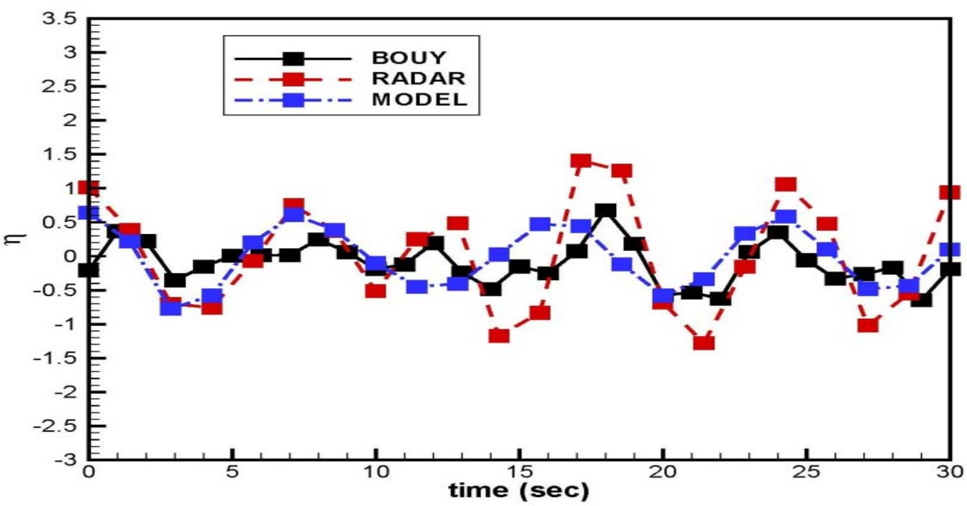

Figure 4: Comparisons of the time series of wave elevation among radar inversion, model prediction and (independent) buoy measurement. Time t=0 corresponds to PDT 17:05:12, June 7, 2010