A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

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Award Number: N00014-06-1-0027
http://www.mit.edu/~vfrl/

LONG-TERM GOALS

The ultimate goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. The simulation-based model will include and integrate all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transport.

OBJECTIVES

To include and integrate relevant dynamical processes in the upper ocean surface boundary layer (SBL) into a physics-based computational prediction and inverse capability for the time-dependent radiative transport:

- Develop direct simulation of upper ocean hydrodynamic processes and forward prediction of radiative transfer
- Obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment
- Provide guidance for field measurements and obtain cross validations and calibrations with direct simulations and modeling
- Provide a framework for inverse modeling and reconstruction of ocean surface and above water features based on sensed underwater radiance data

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 **A Direct Simulation-Based Study of Radiance in a Dynamic Ocean**		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,77 Massachusetts Ave,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

To reach these objectives, we had and would continue to have a close collaboration with Professor Lian Shen of the Johns Hopkins University (JHU) on the modeling of free surface turbulence roughness.

APPROACH

A simulation approach, based on direct physics-based simulations and modeling, is developed and applied to solve the problem of ocean radiance transport (RT) in a dynamic ocean SBL environment that includes nonlinear capillary-gravity waves (CGW), free-surface turbulence (FST) roughness, wave breaking, and bubble generation and transport. The modeling of these hydrodynamic processes is coupled with the computation of radiative transport.

(1) Radiative Transfer in CGW and FST: Monte Carlo simulation of radiance transfer (RT) (e.g. Walker 1994) is developed with the free surface deformation obtained from direct CGW and FST computations. The effects of absorption and multiple scattering on RT are included.

(2) Nonlinear CGW: An efficient phase-resolved computational approach based on Euler equations is used to compute spatial and temporal nonlinear evolution of capillary and gravity waves. This computational tool builds on an efficient high-order spectral method that we developed for direct simulations of nonlinear gravity wavefield evolution. Nonlinear gravity-gravity and gravity-capillary wave interactions in a broadband wave spectrum are accounted for up to an arbitrary order in the wave steepness.

(3) Steep and Breaking Waves: A Navier-Stokes equations solver for fully coupled air-wave interactions with a level-set method for free surface tracking is employed to compute the details of free surface signature and dissipation due to steep and breaking waves.

(4) FST-Wave Interactions: Navier-Stokes equations based DNS is employed to resolve all eddies in free surface turbulence. LES and LWS are used to compute large eddy and large wave components explicitly, with effects from small-scale motions being represented by subgrid-scale (SGS) models. Fully nonlinear viscous free-surface boundary conditions are imposed. Effects of surfactants are captured through the Plateau-Marangoni-Gibbs effect with surfactant transport directly simulated.

(5) Bubble Transport in CGW and FST: Direct simulation is developed to compute bubble motion in CGW and FST environment. Both Lagrangian and Eulerian approaches are used to trace bubble trajectories. Bubble motion is subject to forces due to added mass, buoyancy, drag, lift, and fluid stress gradients arising from the continuous-phase acceleration. Bubble source is determined based on experimental measurements and/or existing data.

Yue and Liu at MIT are responsible for the study of (1), (2) and (3) as well as integration of (4) and (5) into the simulation capability while Shen at JHU focuses on the study and development of (4) and (5).

WORK COMPLETED

- ***Development and validation of 3D Monte Carlo RT simulation for atmosphere-ocean system***: We developed a three-dimensional coupled atmosphere-ocean Monte Carlo radiative transfer (MIT-RT) simulation capability for both polarized and unpolarized lights. The MIT-RT simulation is time independent, but accounts for the effects of unsteady nonlinear three-dimensional ocean surface. Multiple refractions at ocean surface, total internal reflection, all orders of multiple scattering, and scattering and absorption of both water molecules and marine aerosols are all considered. Various techniques including the use of biased sampling algorithms and parallelization of the code (with MPI) were employed to speed up the program for practical applications.

- ***Application of MIT-RT simulations for investigation the RaDyo forward problem***

  - We calibrated MIT-RT simulations with RaDyO experiments. We reconstructed the ocean wave-field using the wave measurements and compared the MIT-RT simulations with the field measurements of radiance and irradiance.

  - We applied MIT-RT simulation to understand the efects of surface waves on underwater light field. We studied

    - Irregular wave effects on radiance and polarization properties
    - Effects of surface wave steepness/nonlinearity on light field distribution
    - Temporal irradiance fluctuations and “flash” statistics

- ***Preliminary study on the inverse problem of obtaining ocean surface properties from underwater light measurements***

RESULTS

We develop a 3D Monte Carlo (MC) RT simulation capability and Gauss-Poisson (GP) model for predicting unpolarized and polarized radiance and irradiance distribution for the atmosphere-ocean system. The model is systematically validated by direct comparisons with existing theories and numerical model predictions and with direct field measurements. The developed 3D MC RT model is applied to investigate the characteristics of polarization distribution and underwater irradiance in various ocean surface environments. Of particular interest are the distinct features of temporal fluctuation of downwelling irradiance, the theoretical GP model is developed under shallow water assumption and gives a good prediction of probability density distribution of underwater downwelling irradiance.

Cross-calibration of 3D Monte Carlo polarized RT simulations with field experiments: Figure 1 shows a sample comparison of polarized radiance, Stokes vector components (U and Q), degree of polarization and *e*-vector orientation under a wavy ocean surface between MIT-RT prediction and RaDyO field experiments by Voss (2010). The comparison indicates that the key characteristics of radiance observed in the measurements are predicted by MIT-RT. The result also shows the capability of MIT-RT to achieve prediction of underwater polarization with high spatial resolution (down to $O(10^{-2\sim-3})$m) and polar/azimuthal angular resolution (1°).

Effects of ocean surface roughness upon underwater polarization features: To understand the characteristics of underwater polarization in the presence of wind blowing which is the major cause of surface roughness, we perform the 3D MC RT simulations under various incident sun and surface wind conditions. The investigations are taken mainly on maximum value of spatially averaged degree of polarization within Snell's window and maximum value of spatially averaged ellipticity. Figure 2a shows that the maximum degree of polarization is strongly influenced by the surface roughness as well as solar incidence and turbidity of the ocean. Rougher ocean surface leads to lower maximum degree of polarization. Within the Snell's window, higher turbidity causes the larger degree of polarization. Figure 2b gives a dependence of maximum ellipticity on ocean surface roughness and solar incidence. In general, the maximum ellipticity slightly drops in the condition of higher surface roughness. For the same roughness, the ellipticity reaches a peak value when the solar incidence angle is around 60°~70°.

Effects of ocean wave steepness upon underwater irradiance distribution: Figure 3 shows the comparisons between MIT-RT predictions and the RaDyo field measurements of underwater irradiance fluctuation under rough ocean surfaces. A new theoretical model, Gauss-Poisson (GP) model, is also developed to describe the probability density distribution of underwater downwelling irradiance. Figure 3a shows that at the shallow depth, GP model gives predictions which agree well with MIT-RT simulations and field experiments (Stramski, 2009). However, MIT-RT can predict irradiance fluctuations with higher precision at much deeper depth. Figure 3b shows the comparison of probability density distributions at 5 m and 10 m below ocean surface between MIT-RT predictions and the RaDyo field measurement. The agreement between them is quite satisfactory.

IMPACT/APPLICATIONS

The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of structures/objects on or above ocean surface based on sensed underwater irradiance data.

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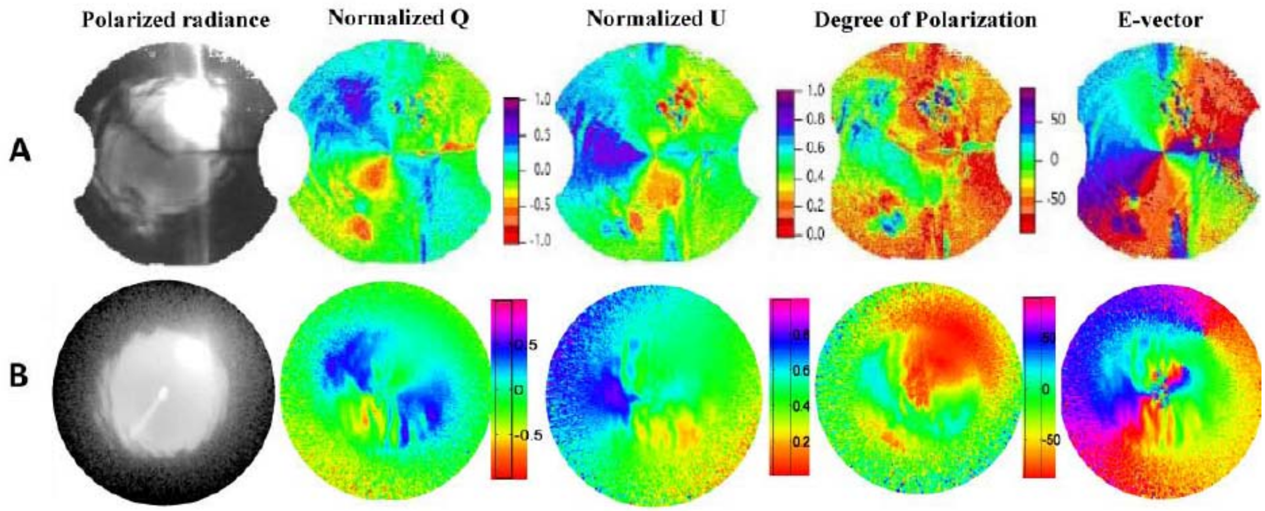

Figure 1: Direct comparisons of underwater polarization field under a dynamic wavy ocean surface between (A) RaDyO field measurement (Voss 2010) and (B) MIT-RT prediction

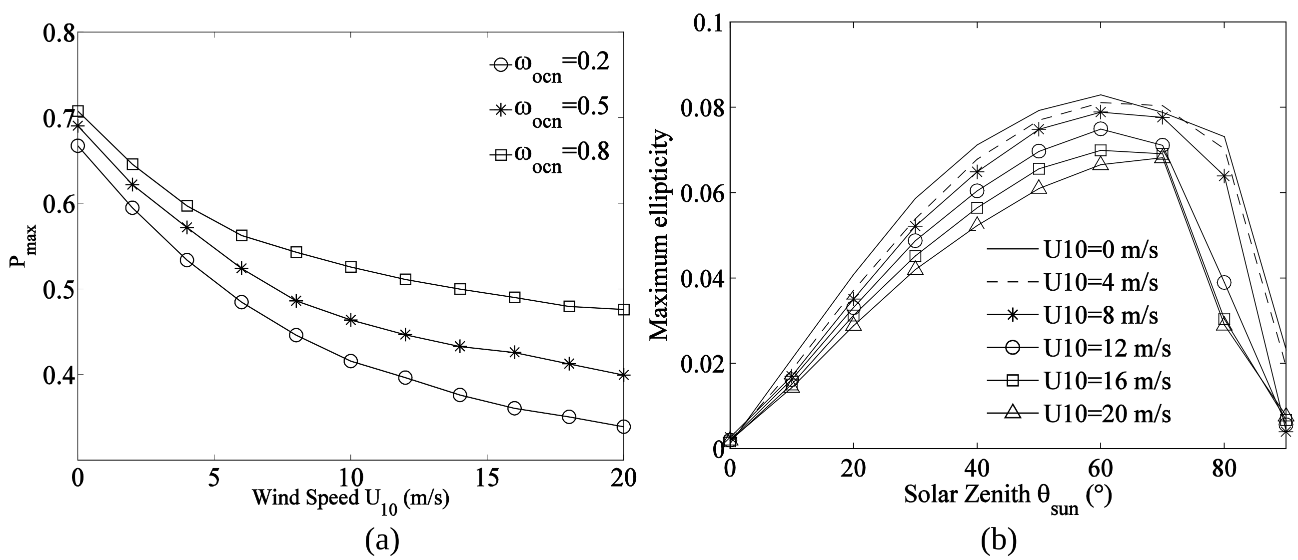

Figure 2. Effects of surface roughness on underwater polarization (a) Maximum degree of polarization within Snell’s window under different surface wind conditions (b) Maximum ellipticity under different solar incidence and different surface wind conditions

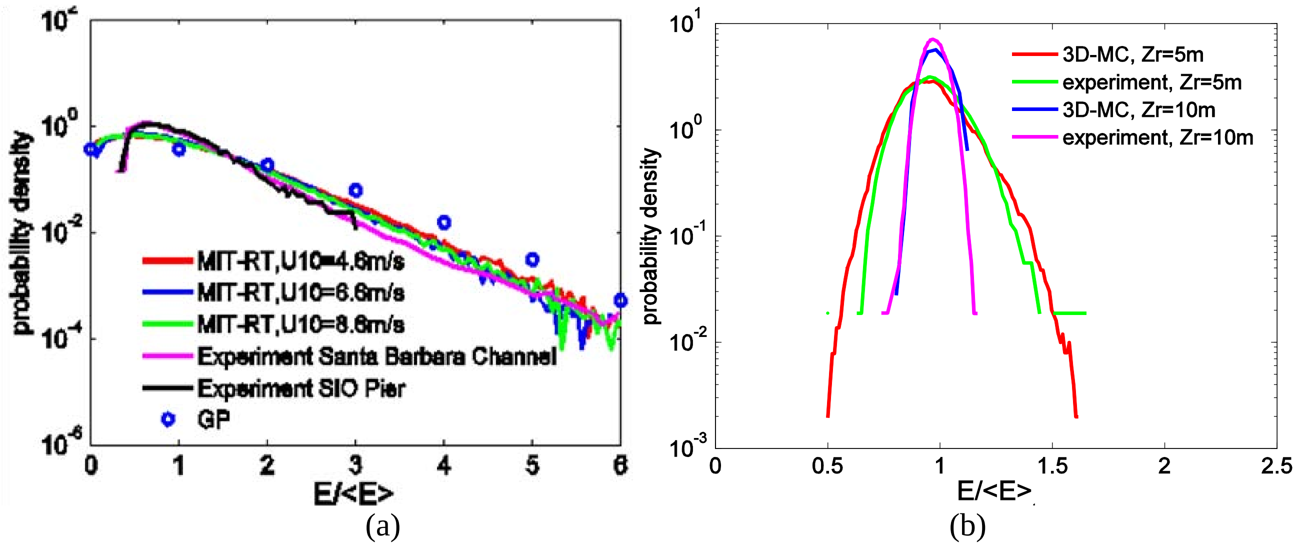

Figure 3. Comparisons of the probability density distribution of irradiance: (a) at depth z = 0.87m below ocean surface between RaDyO measurements (Stramski 2009), GP model, and MIT-RT prediction, and (b) at depth z=5m and 10m between RaDyo measurements and MIT-RT prediction.