# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
10-31-2011

**2. REPORT DATE**
Final

**3. DATES COVERED** *(From - To)*
October 2005 -- September 2011

**4. TITLE AND SUBTITLE**
A Direct Simulation-Based Study of Radiance in a Dynamic Ocean

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
*N00014-06-1-0027*

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Yue, Dick K.P. and Yuming Liu

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Massachusetts Institute of Technoloby
77 Mass Avenue
Cambridge, MA 02139

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
ONR, Code 322OB
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSORING/MONITORING AGENCY REPORT NUMBER**

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

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The objective is to develop direct simulation based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. This direct simulation-based model includes and integrates all of the relevant dynamic processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transport. The direct simulations are applied to obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment and to provide guidance for field measurements and obtain cross validations/calibrations with direct simulations and modeling.

**15. SUBJECT TERMS**
Ocean surface waves, ocean surface turbulence, underwater radiance prediction, Monte Carlo simulation of radiance transfer

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| U | U | U | UU | 8 | Yue, Dick K.P. |
| | | | | | **19b. TELEPONE NUMBER (*Include area code)*** 617-253-6823 |

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

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

Dick K.P. Yue
Center for Ocean Engineering
Massachusetts Institute of Technology
Room 5-321, 77 Massachusetts Ave, Cambridge, MA 02139
phone: (617) 253-6823 fax: (617) 258-9389 email: yue@mit.edu

Yuming Liu
Center for Ocean Engineering
Massachusetts Institute of Technology
Room 5-326A, 77 Massachusetts Ave, Cambridge, MA 02139
phone: (617) 252-1647 fax: (617) 258-9389 email: liu@vfrl.mit.edu

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. This direct 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

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 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 radiative transport is governed by Snell's law and Fresnel transmission at the water surface, and absorption and multiple scattering in the water underneath. The complex dynamic processes of the ocean SBL, the nonlinear CGW interactions, the development and transport of FST, and the generation and transport of bubbles are modeled using physics-based computations. The modeling of these hydrodynamic processes is coupled with the computation of radiative transport.

***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 are accounted for up to an arbitrary order in the wave steepness. With high computational efficiency, this approach enables phase-resolved simulations of large-scale nonlinear CGW.

***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.

***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.

***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.

***Radiative Transfer in CGW and FST***: Monte Carlo simulation of radiance transfer (RT) 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. Bubble scattering effects are also considered based on bubble distribution and transport and Mie theory.

## WORK COMPLETED

- ***Development of nonlinear CGW simulation capability***: Developed a direct simulation capability for nonlinear CGW evolution by extending the high-order spectral method for gravity waves to general broadband nonlinear wavefield interactions involving swell, seas, and capillary waves. The focus was on the inclusion of capillary waves, long-short wave interactions, wave breaking dissipation, dissipation due to free surface turbulence and energy input by wind.

- ***Development and validation of unpolarized/polarized Monte Carlo RT simulation***: Developed a three-dimensional coupled atmosphere-ocean Monte Carlo radiative transfer simulation capability for both polarized and unpolarized lights. The RT simulation is time independent, but accounts for the effect of complex unsteady three-dimensional ocean surface including CGW and FST roughness. In RT, 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. In order for practical applications, various techniques including the use of biased sampling algorithms and parallelization of the code (with MPI) were employed to speed up the program. The Mont Carlo RT simulations were validated by comparisons to available experimental data and other model predictions.

- ***Investigation of radiance/irradiance and polarization in CGW/FST environment and under linear and nonlinear waves.*** Investigated the patterns of underwater radiance and polarization induced by the CGW/FST dynamic ocean surfaces and their relations to solar conditions and ocean IOPs. Both linear and nonlinear surface waves were compared in the RT simulations in order to understand the effects of nonlinearity of ocean surface on the underwater light fields. For irregular linear and nonlinear ocean surface waves, the spatial variation of downwelling irradiance was studied.

- ***Development of analytical GP model of probability density function (PDF) of underwater downwelling irradiance.*** In order to understand variability of the fluctuating underwater downwelling irradiance due to dynamic ocean surface focusing effects, we focused on the probability density function (PDF) of the downwelling irradiance and developed an analytical Gauss-Poisson (GP) model to quantify the PDF at the arbitrary depths. The model predictions were compared to experimental data and showed a good agreement with data.

- ***Development of 3D Monte Carlo code of radiative transfer for variable refractive index and primary application to ocean turbulence.*** Studied the unpolarized light radiative transfer properties within an ocean turbulent flow by applying the inhomogeneous radiative transfer equation with variable refractive index. A hybrid 3D numerical program combining Monte Carlo method and ray-tracing technique was developed to simulate the RT process in the inhomogeneous ocean turbulent flow.

## RESULTS

***Validations of the MC RT simulation capability:*** We developed a 3D Monte Carlo (MC) RT simulation capability for unpolarized and polarized light for the atmosphere-ocean system. The model has been systematically validated by direct comparisons with existing theories and numerical model predictions and with the RaDyo field measurements. Figure 1a shows the comparison of unpolarized radiance distribution between MC RT simulation and the prediction by the invariant imbedding method; and figure 1b shows the comparison of degree of polarization between MC RT simulation and RaDyO Hawaii experimental data at the depth z=-8 m. Both model-to-model comparison and model-to-data comparison show good agreements between MC predictions with other models and experimental measurements.

***Effects of ocean surface waves on underwater radiance and polarization pattern:*** Using the MC simulation capability, effects of the ocean surface roughness on the underwater light polarized light fields were intensively examined. Figure 2a shows the dependence of the ratio of maximum mean value of degree of polarization to the sky degree of polarization $<P>_{max}/P_{sky}$ on the mean square slope (MSS) of the ocean surface waves. Four different depths are considered and they are z = -0.3m, -2.2m, -4.9m, and -7.5m. The solar incidence is $\theta_{sun}$=65° and $\varphi_{sun}$=0°; the light wavelength λ=532 nm; IOPs were obtained from the Santa Barbara Channel (SBC) experiment which are total beam attenuation coefficient c=0.610 $m^{-1}$ and total single scattering albedo ω=0.873; Petzold phase function was used. It can be seen that increasing surface roughness leads to smaller degree of polarization and the relation between the maximum underwater degree of polarization and MSS are approximate linear. The dependence of maximum degree of polarization becomes weaker at deeper locations, indicating that the effect of ocean surface waves on polarization diminishes with detector depth.

Consideration of nonlinearity of surface waves is of critical importance in the study of underwater irradiance as it affects the profile of ocean-atmosphere interface. Figure 2b compares the effect of linear and nonlinear waves with same MSS and different MSS respectively on polarization in variance of the mean value of degree polarization <P> at the local maximum inside the Snell's window, at the position of θ=40° and φ=110°. It is seen that the ratio $<P>_{max}/P_{sky}$ for the linear and nonlinear waves with the same MSS(≈0.04) are equal to each other at arbitrary depth. $<P>_{max}/P_{sky}$ induced by the linear waves with MSS=0.03 is a little larger than that of nonlinear waves. The variance of P/<P> at the local maximum point with nonlinear waves is larger than the variances of linear waves with the same and smaller MSS. Therefore, it can be expected that in the case of rougher sea surfaces where nonlinearity becomes more dominant, the variance of the in-water polarization is larger than the previous calculation based on a linear wave assumption.

***Variability of underwater irradiance induced by ocean surface wave:*** To understand the variability and fluctuation of the in-water light fields, we developed a statistical GP model that analytically quantifies the PDF of the downwelling irradiance under random ocean waves. The model assumes that ocean surface as independent and identically distributed flat facets. The theoretical model captures the characteristics of the PDF from skewed to near-Gaussian shape as the depth increases from shallow to deep water. It obtains a closed-form asymptotic for the probability that diminishes at a rate between exponential and Gaussian with increasing extreme values. Figure 3a shows the comparison the PDF of normalized the downwelling irradiance $E_d/<E_d>$ at the depth z=-2.85m with experimental data and predictions by MC simulation. It shows that a very good agreement with the three methodologies has been reached. Figure 3b demonstrates one application of GP model in understanding the how wind-driven ocean surface wave spectrum influences the PDF of underwater irradiance. It can been seen that increasing wind speed results in the monotonic decrease of the normalized irradiance standard deviation $\sigma_\chi$ and as increasing depth $\sigma_\chi$ rapidly approaches the deep water limit as the downwelling irradiance is dominated by volume scattering effect.

***Effects of ocean turbulence flow on underwater radiance/irradiance distributions:*** We considered the radiative transfer process within the inhomogeneous ocean turbulent flow. To solve the non-homogeneous radiative transfer equation with the variable refractive index, we developed the hybrid Monte Carlo method and ray-tracying technique to account for the light beam bending. Figure 4a shows the downwelling irradiance pattern at the depth of z=-80m as the ocean surface is flat. The irradiance pattern reflects the structure of the ocean turbulence. Figure 4b shows the downwelling irradiance pattern at the depth of z=-80m caused by the progressive ocean surface waves and the turbulent flow beneath the surface. It can be seen that basic pattern of the downwelling irradiance is determined by focusing of light at the ocean surface and the pattern is blurred by the turbulent flow.

## IMPACT/APPLICATIONS

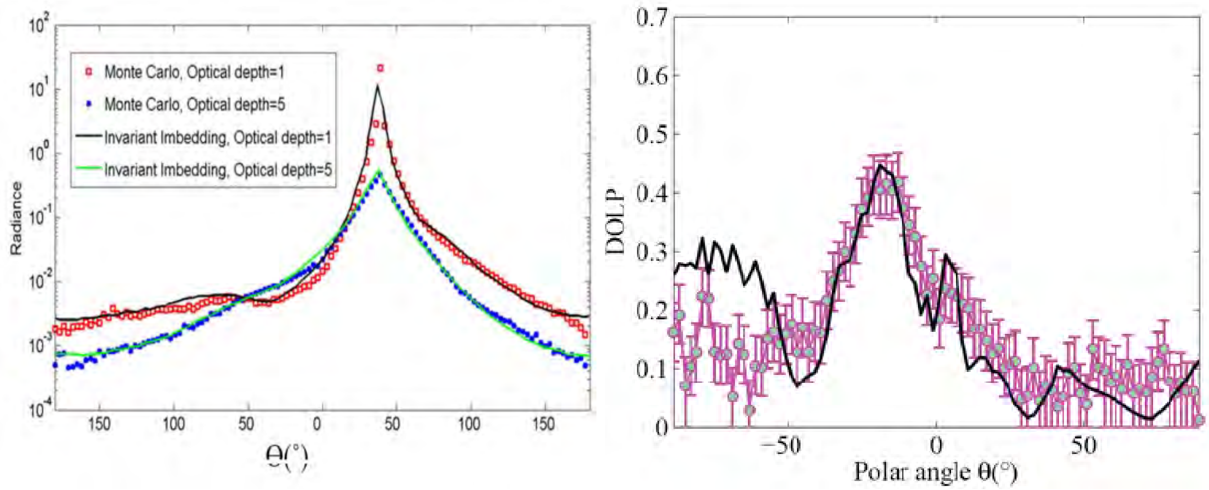
The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of the presence of structures/objects on or above ocean surface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

## PUBLICATIONS


1. Zao Xu, Xin Guo, Lian Shen, and Dick K. P. Yue, 2011, Radiative transfer in ocean turbulence and its effect on underwater light field, *J. Geophys. Res*. (submitted).
2. Zao Xu, Dick K. P. Yue, Lian Shen, and Kenneth Voss, 2011, Patterns and statistics of in-water polarization under conditions of linear and nonlinear ocean surface waves, *J. Geophys Res.* (in press).
3. Meng Shen, Zao Xu, and Dick K. P. Yue, 2011, A model for the probability density function of downwelling irradiance under ocean waves, *Opt. Express*, Vol. 19(18), 17528-17538
4. Zao Xu, Xin Guo, Di Yang, Lian Shen, Yuming Liu, Dick K.P. Yue, Simulation of underwater radiative transfer with varying refractive index and IOP's in the presence of ocean turbulence, Ocean Science meeting, 22-26 February 2010, Portland.
5. Meng Shen, Zao Xu, Yuming Liu, Lian Shen, Dick K.P. Yue, Underwater light polarization distribution and short-term fluctuation induced by nonlinear ocean surface waves, Ocean Science meeting, 22-26 February 2010, Portland.
6. Zao Xu, Dick K.P. Yue, Influence of nonlinearity of ocean surface waves to the spatial and temporal fluctuations of underwater light fields, Ocean Science meeting, 2-7 March 2008**,** Orlando

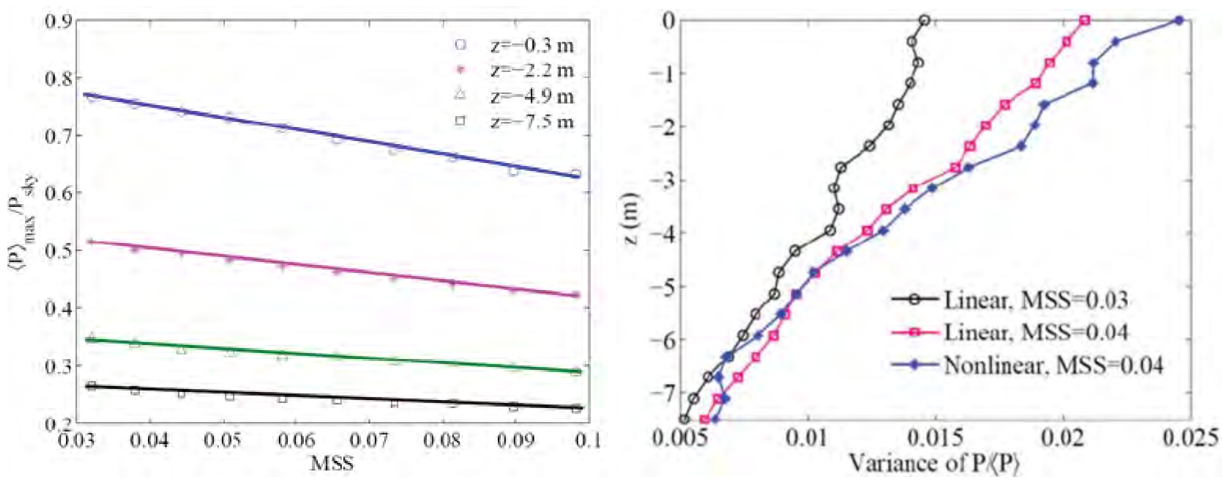

## STUDENTS GRADUATED

2 PhDs (one male, one female), 1 Engineer (male), and 2 BSs (one male, one female)



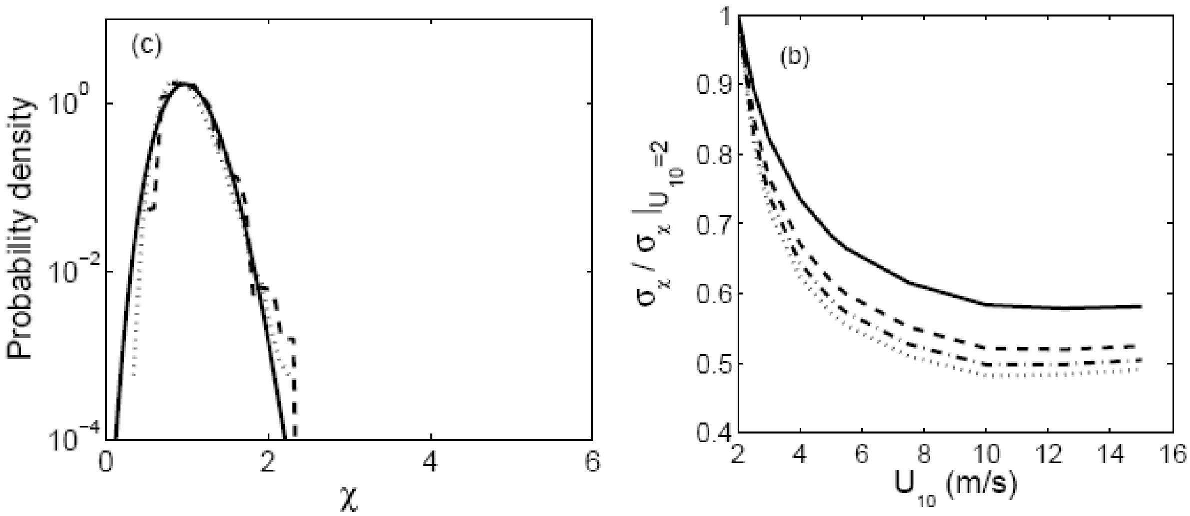

(a) (b)

***Figure 1: (a) Comparison of unpolarized radiance distribution between present MC RT simulation and the prediction by the invariant imbedding method; and (b) comparison of polarization degree between MC RT simulation (black solid line) and RaDyO Hawaii experimental data (red circle).***



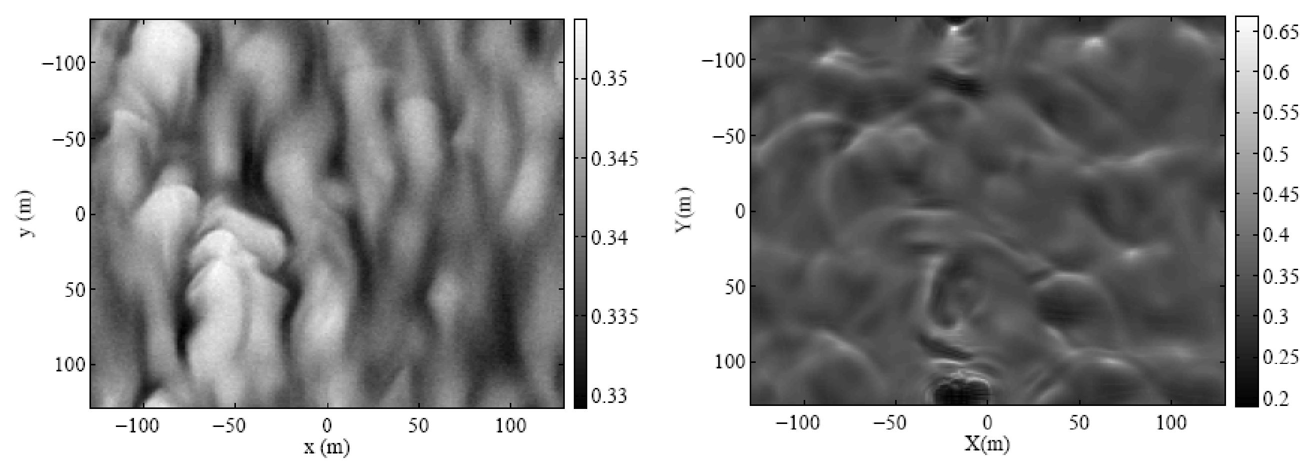

(a) (b)

***Figure 2. (a) Dependence of ratio of maximum mean value of degree polarization to sky degree of polarization $<P>_{max}/P_{sky}$ within the Snell's window on the MSS of the ocean surface at different depths, and (b)effects of the nonlinearity of ocean waves: the variance of the normalized degree of polarization at different depths under linear and nonlinear waves with same MSS and different MSS.***




(a) (b)

***Figure 3 .(a) Comparison of the GP theoretical model (—) for the PDF of the normalized downwelling irradiance $\chi$=E/<E> with Monte Carlo (MC) simulation (•••) and experimental data (– – – ) at depth of 2.85m, and (b) wind speed effect on standard deviation of normalized downelling irradiance $\sigma_\chi$ for different depths: $Dcw_0$= 0.524(—); 1.04 ((– – –); 1.74((–• –•) and $DCw_0 \rightarrow \infty$(•••).***




(a) (b)

***Figure 4. (a) Instantaneous downwelling irradiance $E_d$ at z=-50 m within a turbulent flow under the flat ocean surface, and (b) instantaneous downwelling irradiance $E_d$ at z=-50 m within a turbulent flow under ocean surface waves of peak frequency steepness $k_p a_p$=0.1 propagating in the same direction as the shear flow.***