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14. ABSTRACT 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 includes 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 transfer (RT). The model is applied to investigate and characterize the ocean surface using underwater radiance measurements. This research builds the foundation for advancing above water imaging as well as sensing of surface and near-surface wave and flow features using passive underwater optical measurements.					
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Quantifying the Dynamic Ocean Surface Using Underwater Radiometric Measurements

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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 transfer (RT).

OBJECTIVES

To develop physics-based modeling and computational prediction and inverse capability for the time-dependent underwater radiative transfer incorporating the dynamical processes on the ocean surface and the upper ocean surface boundary layer (SBL):

- Parameterization of key effects of the dynamical ocean surface on the underwater light patterns and statistics
- Development of new theoretical models and algorithms to substantially speed up forward problem by two or more orders of magnitude
- Establishment of a framework for inverse sensing and reconstruction of ocean surface conditions based on underwater light field measurements
- Inverse modeling of key flow processes at the sea surface based on underwater light measurement; quantification of the feasibility requirements and limits on applicability of the inverse problem

APPROACH

We developed and applied a highly efficient parallelized Monte Carlo radiative transfer numerical tool to simulate the highly fluctuated underwater (unpolarized and polarized) light fields with very high spatial resolution (up to $O(10^{-3})$ mm). The Monte Carlo RT simulation accounts for effects of the irregular surface waves on light refractions and reflections for various solar incidence conditions, particularly the shadowing effect for large zenith solar incidence case. With the numerical tool, the statistical characteristics of the light fields as functions of rough surface boundaries and other ambient environmental conditions were quantified. It could also be used to investigate beam spread function (BSF) of ocean radiative transfer for understanding the effects of the below-surface ocean turbulence on light fields. To obtain more realistic dynamic ocean surface conditions, we extended and applied the direct phase-resolved wave simulation based on the efficient high-order spectral (HOS) method and LES capabilities for nonlinear evolution of capillary and gravity waves as well as their interactions with wind and ocean turbulence (Xu *et al* 2011; Xu *et al* 2012). We obtained the analytical solution of beam spread function of two-dimensional radiative transfer for homogeneous ocean column using spectral method. Instead of applying unit directional beam, we applied generalized source function and found that source beam with small width is able to achieve good approximation to the unit directional beam source and at the same time greatly increase the convergence rate. By applying perturbation theory, we converted the three-dimensional radiative transfer to two-dimensional case under the assumption of forward scattering and small angle scattering.

WORK COMPLETED

- **Development of efficient high-resolution Monte Carlo radiative transfer model and direct quantitative comparisons between RaDyO field measurements and model prediction.** We developed a highly efficient Monte Carlo RT model to investigate the statistics of the underwater light fields. The model is capable of predicting high spatial resolution ($O(10^{-3})$ mm) fluctuating (downwelling) irradiance. We performed quantitative comparisons and validations, incorporating all key RaDyO waves, IOPs and underwater irradiance measurements with combined wavefield (reconstruction and prediction) and RT modeling. Applying the Monte Carlo RT, we investigated the effects of the ocean turbidity and the size of detector on statistics of the downwelling irradiance. Using the numerical tool, we studied the 2D/3D beam spread function for ocean radiative transfer and made the cross-calibrations with newly-developed analytical approaches.
- **Development of analytical model for probability distribution of the underwater light fields for statistical inversion of the upper ocean surface conditions.** We developed a mixture model for the PDF of the underwater irradiance which is able to accurately quantify the probability distributions of the underwater irradiance for irregular surface wavefields with arbitrary steepness, arbitrary ocean IOPs and broad ranges of detector size. More importantly, the model contains only two physics-based parameters, variance and mixing weight which can be obtained with direct and empirical derivations, respectively, using the factors such as ocean surface slope spectra and IOPs of oceans.
- **Development of analytical model of beam spread function for ocean radiative transfer.** We developed a methodology of calculating the beam spread function (BSF) for the ocean radiative transfer by solving the 2D radiative transfer equation with point uni-directional

source. We applied spectral methods in both spatial and angular domain. We validated the analytical model by comparisons with 2D Monte Carlo RT simulations. We tested the convergence properties of the model and found that uni-directional source which is a delta function presents relatively slow convergence. In order to increase the convergence rate, we applied a generalized source function, such as Gaussian function, in the model. It is noted that when increasing the beam width (standard deviation) of the Gaussian function to a certain point, the result is able to approximate that of delta function, but with much greater convergence rate.

RESULTS

The 2D/3D Monte Carlo (MC) RT simulation capability, developed for predicting highly fluctuated underwater light fields with high spatial resolution, was systematically validated by direct comparisons with existing theories and numerical model predictions and with field data including RaDyo measurements. An analytical model for beam spread function (BSF) of ocean radiative transfer was developed and validated. It provided efficient forward models for radiative transfer related inversion algorithms.

- (1) ***Develop and validate the efficient high-resolution 2D/3D RT model:*** We developed a highly efficient parallelized Monte Carlo radiative transfer numerical tool to simulate the highly fluctuated underwater light fields under various irregular ocean surface waves with very high spatial resolution (figure 1a). The light-surface interaction is carefully treated so that shadowing effects and multiple reflections are properly considered in the RT simulations. We made extensive cross-calibrations of our simulation predictions with the field data obtained in RaDyO Santa Barbara Channel (SBC). We applied the measured slope spectrum to the RT simulations and obtained the coefficient of variations (CV) of downwelling irradiance E_d and probability distribution of the E_d . We also studied the 2D/3D beam spread function (BSF) for ocean radiative transfer, which is defined as the scattered fields under uni-directional point source. With numerically obtained BSF, we made further cross-calibrations with newly-developed analytical approaches.
- (2) ***Investigate the effects of ocean turbidity and detector size on statistics of underwater downwelling irradiance:*** With the numerical tool, we systematically investigated two important factors that affect the statistics of near-surface downwelling irradiance E_d : detector size R and single scattering albedo ω_0 . Figure 2A demonstrate the PDFs of $E_d/\langle E_d \rangle$ for different R and ω_0 , respectively. We could see that by decreasing both R and ω_0 the PDFs become more asymmetric and have longer tails at high values. Similarly, as figure 2B shows, by decreasing both R and ω_0 the coefficient of variation (CV) of E_d increases.
- (3) ***Develop analytical solution of beam spread function for ocean radiative transfer:*** Due to the axisymmetric property of the beam spread function, we could simplified the 3D radiative transfer equation into 2D case. Using the spectral method and so-called rotated frame technique, we obtained the analytical solution of the 2D irradiance (scalar or downwelling). Figure 3(a) shows the comparison of the scalar irradiance for scattered fields under a point uni-directional source. The single scattering albedo in this case is 0.5. In order to obtain well converged results, we applied 320 spectral components ($N=320$). It can be seen that the results agree well with those from Monte Carlo simulations. To increase the convergence rate, we utilized the generalized beam source (such as a Gaussian function) instead of a delta function.

We found that for relatively small beam width (such 0.01 rad), the obtained scattered fields can approximate that acquired from delta function (N=160) very well, but with much faster convergence (N=80), as figure 3(b) shows.

IMPACT/APPLICATIONS

The capability of accurate prediction of underwater irradiance probability distribution and variability at the near-ocean-surface may enable the development of novel statistical approaches for accurate reconstructions of complex ocean boundary layer processes.

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PUBLICATIONS

1. Xu, Z. and Yue, D. K. P. (2014), Monte Carlo radiative transfer simulation for the near ocean surface high-resolution downwelling irradiance statistics, *Opt. Eng.* 53(5), 051408 (Feb 05, 2014). doi:10.1117/1.OE.53.5.051408. [Published, refereed]
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3. Xu, Z. and Yue, D. K. P. (2015b), Theoretical predictions of the upper ocean irradiance statistics, *J. Geophys. Res.* (under review)

STUDENTS GRADUATED

1 PhD student and 1 Engineer student

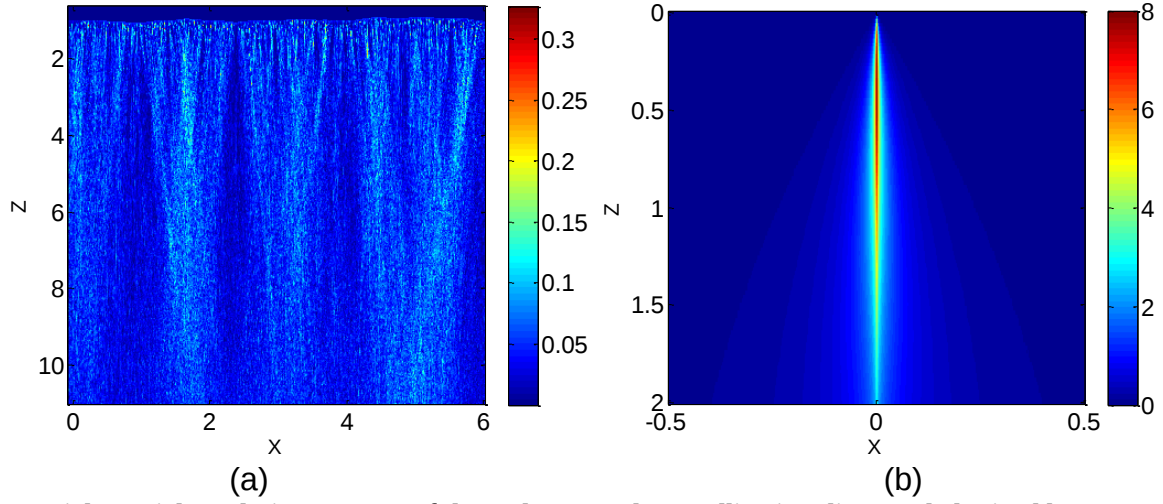


Figure 1. High-spatial-resolution patterns of the underwater downwelling irradiance E_d obtained by Monte Carlo RT simulation: (a) vertical patterns of E_d for rough ocean surfaces and (b) E_d for a uni-directional beam source.

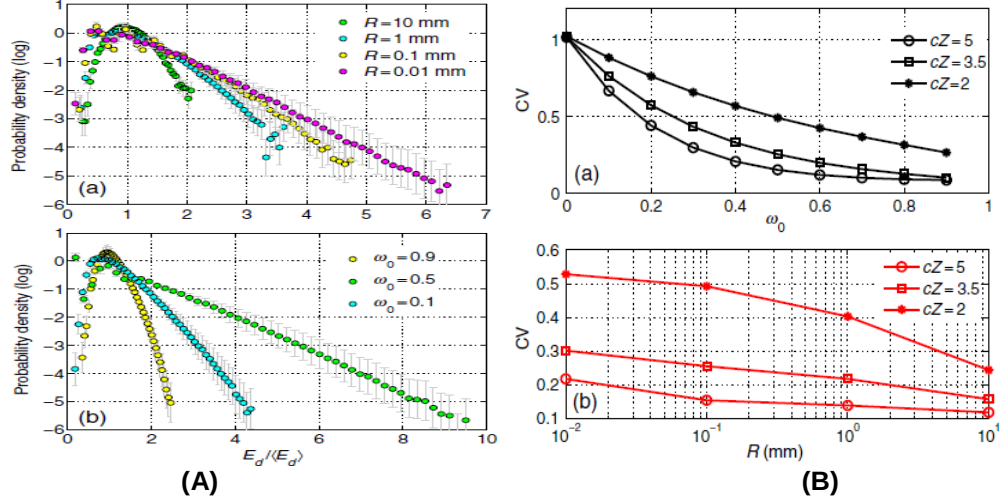


Figure 2. (A) Probability density function of E_d in the case of (a) different detector size and (b) difference single scattering albedo; (B) the coefficient of variation of E_d in the case of (a) difference single scattering albedo and (b) different detector size.

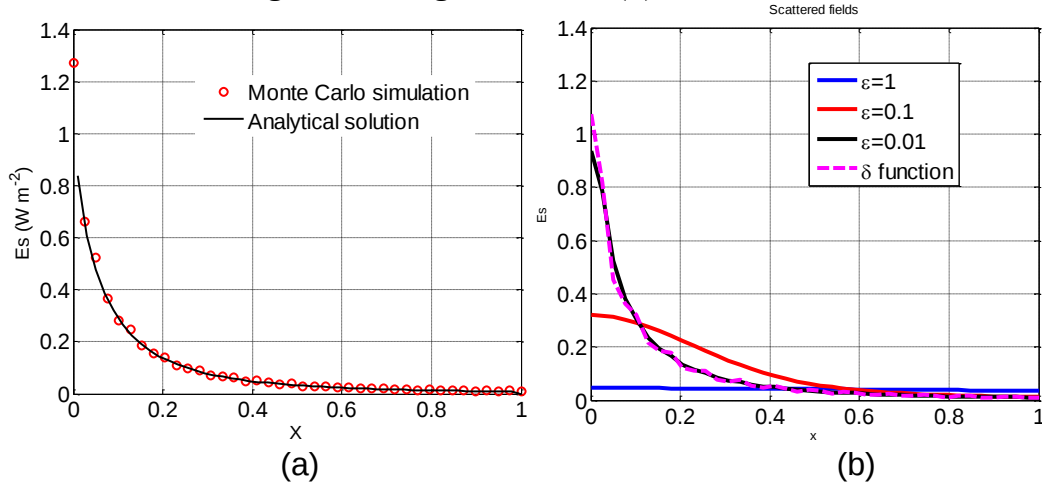


Figure 3. (a) Comparison of beam spread function of scattered field (E_s) obtained between Monte Carlo simulation (o) and analytical solution (—); and (b) comparison of E_s under generalized sources (with different beam widths ϵ) and uni-directional source (δ function).