Monte Carlo radiative transfer simulation for the near-ocean-surface high-resolution downwelling irradiance statistics

Citation

As Published
http://dx.doi.org/10.1117/1.OE.53.5.051408

Publisher
Society of Photo-Optical Instrumentation Engineers (SPIE)

Version
Final published version

Accessed
Mon Dec 10 19:04:26 EST 2018

Citable Link
http://hdl.handle.net/1721.1/88497

Terms of Use
Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.

Detailed Terms

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.
Monte Carlo radiative transfer simulation for the near-ocean-surface high-resolution downwelling irradiance statistics

Zao Xu
Dick K. P. Yue
Monte Carlo radiative transfer simulation for the near-ocean-surface high-resolution downwelling irradiance statistics

Zao Xu* and Dick K. P. Yue
Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, Massachusetts 02139

Abstract. We present a numerical study of the near-surface underwater solar light statistics using the state-of-the-art Monte Carlo radiative transfer (RT) simulations in the coupled atmosphere-ocean system. Advanced variance-reduction techniques and full program parallelization are utilized so that the model is able to simulate the light field fluctuations with high spatial \(O(10^{-3})\) mm and temporal \(O(10^{-3})\) s resolutions. In particular, we utilize the high-order correction technique for the beam-surface intersection points in the model to account for the shadowing effect of steep ocean surfaces, and therefore, the model is able to well predict the refraction and reflection of light for large solar zenith incidences. The Monte Carlo RT model is carefully validated by data-to-model comparisons using the Radiance in a Dynamic Ocean (RaDyO) experimental data. Based on the model, we are particularly interested in the probability density function (PDF) and coefficient of variation (CV) of the highly fluctuating downwelling irradiance. The effects of physical factors, such as the water turbidity of the ocean, solar incidence, and the detector size, are investigated. The results show that increased turbidity and detector size reduce the variability of the downwelling irradiance; the shadowing effect for large solar zenith incidence strongly enhances the variability of the irradiance at shallow depths. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.53.5.051408]

Keywords: ocean optics; radiative transfer; irradiance statistics; rough surface scattering.

Paper 131433SS received Sep. 17, 2013; revised manuscript received Dec. 20, 2013; accepted for publication Jan. 7, 2014; published online Feb. 5, 2014.

1 Introduction

The near-ocean-surface underwater irradiance fluctuations are mainly induced by the refraction of solar incident light at the random ocean surface and further diffused by the multiple scattering of ocean particles. Understanding the physics behind the temporal and spatial statistical characteristics of underwater irradiance, including probability distribution and power spectrum density, have drawn potential interests in many areas, such as near-surface radiometric sensing, phytoplankton photosynthetic physiology, and underwater imaging. The difficulty of understanding the statistical characteristics results from the complexity of both dynamic ocean surface waves and light radiation transfer in the turbid ocean. Since the 1970s, extensive experimental studies have been conducted mainly focusing on the effects of ambient conditions, such as inherent optical properties (IOPs), depths, and sky radiance diffuseness, on the statistics of the underwater downwelling irradiance. Recently, under the Radiance in a Dynamic Ocean (RaDyO) project, researchers presented a preliminary experimental effort on the various forms of probability distributions of the downwelling irradiance. On the other hand, theoretical investigations of the probability distribution of the downwelling irradiance have been made through analytical derivations. However, theoretical study does not consider certain key factors affecting probability distribution of the irradiance such as the shadowing effect at the steep surface for a large solar zenith incidence. Numerical simulations of radiative transfer equation (RTE) have been the most important approaches to understand the underwater light fields. Among them, the Monte Carlo method has been known as the most popular approach to simulate light RT in the ocean for decades, but most of the previous work does not focus on the light field fluctuations induced by the deterministic surface wave fields. Only recently, numerical investigations about the near-surface light field fluctuations have been made utilizing Monte Carlo RT simulations. However, those studies have not provided a systematic investigation of the probability distribution of the light fields as the function of various factors, e.g., the shadowing effect and the detector size.

In this paper, we present the work of developing the state-of-the-art Monte Carlo RT models (two-dimensional (2-D) and three-dimensional (3-D)) to simulate the high-resolution fluctuations of the near-surface downwelling irradiance. The spatial resolution of the detector can reach to \(O(10^{-1})\) mm and temporal resolution up to \(O(10^{-1})\) s. In particular, the shadowing effect of the surface is also considered in the numerical model for the case of large solar zenith angle incidence. The paper is presented in the following manner: Sec. 2 describes briefly the key steps of the Monte Carlo RT model including light-surface interactions; Sec. 3 presents a careful validation of the numerical model using comparisons with the field data; Sec. 4 demonstrates the results of key factors influencing the statistical characteristics of irradiance using the numerical simulations, including turbidity of the ocean, detector size, and shadowing effect of the surface.

*Address all correspondence to: Zao Xu, E-mail: xuzao@mit.edu
2 Method

2.1 Monte Carlo RT Simulation

The propagation of solar radiation at the upper-ocean column is well described by the RTE in the water/air column and ray-tracing at the air-sea interface (where the wavelength of light is much shorter than the characteristic length of surface waves). One of the most efficient ways to simulate these two processes is the Monte Carlo method. Since the RTE is an integro-differential equation, it can be solved by first solving every order of Neumann series of an integral equation and then summing up solutions of all orders which are solved with Monte Carlo integration. More importantly, each order of the Neumann series can be physically interpreted as the scattering and absorption events of a photon, and the summation of solutions of all orders can be performed by tracing the path of photons during scattering and absorption events.

Therefore, the basic steps of Monte Carlo RT simulations can be simply concluded in the following manner. First, launch a photon with unit energy from the source in the incidence direction and determine the traveling path length \( \ell \) using the formula \( \ell = -\frac{\ln(r_1)}{c} \), where \( r_1 \) is the random number between 0 and 1 and \( c \) is the beam attenuation coefficient. After traveling a distance \( \ell \), we generate another random number \( r_2 \): if \( r_2 \) is greater than the single scattering albedo \( \omega_0 \), which in general indicates the turbidity of ocean, we assume that the photon is deceased and then start launching a new photon; otherwise, we assume the photon is changing the direction due to the scattering event. The new direction is determined by the scattering phase function. After each scattering event, we repeat the process of photon traveling until the photon is deceased. If the photon hits the air-sea interface, it splits into two parts: reflection and refraction, whose energies can be obtained by multiplying the Fresnel reflection and refraction coefficients, respectively. The advantage of Monte Carlo method to simulate the RT process is that it has a very clear physical interpretation and it is relatively simple to program.

In order to obtain high-resolution spatial/temporal distributions of the underwater radiation fields, several approaches are utilized to increase the efficiency of the Monte Carlo RT simulations including the variance-reduction techniques and the parallelization of the program.

In order to achieve high-resolution spatial/temporal distributions of the underwater radiation fields, several approaches are utilized to increase the efficiency of the Monte Carlo RT simulations including the variance-reduction techniques and the parallelization of the program.

The variance-reduction techniques we use in the study are the photon path length sampling and the detector directional importance sampling.\(^{20}\) For photon path length sampling, it is assumed that the bottom of the deep ocean is a highly absorbing boundary. Therefore, it is computationally wasteful if a lot of photons collide with the bottom. Using the biased density function, we can determine the photon path \( \ell \) as
\[
\ell = \ell_b - \frac{\ln\left(e^{\epsilon_f(s)} + r_1(1 - e^{\epsilon_f(s)})\right)}{c},
\]
where \( \ell_b \) is the distance from the scattering event to the bottom along the direction of travel.

For the detector directional importance sampling, it is mainly used for the simulation of temporal light field fluctuations where only a small number of detectors are placed. Assume the original scattering phase function is \( p(\mu_s) \), where \( \mu_s = \cos(\theta_s) \) and \( \theta_s \) is the angle between photon directions before and after scattering. For each scattering event after the photon passing through the air-sea interface, the modified phase function can be written as
\[
p'(\mu_s) = (1 - \epsilon)p(\mu_s) + \epsilon p(\mu'_s),
\]
where \( \epsilon \in [0, 1] \) is a free parameter to be optimized, \( \mu'_s \) is the cosine of the angle between the direction to the detector and the photon direction after scattering. The modification of the phase function results in a weight factor for the photon
\[
w_i = p(\mu_s)/p'(\mu_s).\]

With the help of biased sampling of the phase function, a large amount of the scattered photon tends to travel toward the detector so that we are able to achieve the faster convergence during the Monte Carlo RT simulation.

Another way to improve the convergence is to use parallel computing. The parallelization of the Monte Carlo program is straightforward. We utilize message passing interface to realize the parallelization of the program. Each individual photon is launched and traced at the different processors and the results from every processor are collected at the end of the program. Using the parallelized program, we are able to launch up to \( O(10^{11}) \) photons and achieve convergence for extremely high spatial resolutions (detector size \( R \sim 10^{-11} \) mm) for the large spatial simulation domain \( \left[ O(10^2) \right] \).

Among many quantities that we simulate to obtain to describe the solar underwater light fields, the downwelling irradiance \( I_d \) is the most commonly used and is collected by a plane detector. It is defined by
\[
I_d(x) = \int_0^{2\pi} \int_0^{\pi/2} L(x; \theta; \phi) \cos \theta \sin \theta \, d\theta \, d\phi,
\]
where the radianc \( L(x; \theta; \phi) \) is the function of both position \( x \) and direction \( (\theta, \phi) \); here, \( \theta \) and \( \phi \) are the polar angle and azimuthal angle, respectively.

However, for both field measurements and Monte Carlo simulations, due to finite size of the detector and the spatial fluctuation of \( I_d \) induced by wavy surface, the downwelling irradiance is the spatially averaged quantity which strongly depends on the size of the detector \( R \). Therefore, we define the spatially averaged downwelling irradiance \( E_d(x) \) for the later studies. For the 2-D case, the horizontal coordinate is \( x \) and \( E_d(x) \) is defined as
\[
E_d(x) = \frac{1}{R} \int_{x-R/2}^{x+R/2} I_d(x') \, dx'.
\]

2.2 Ocean Surface Reconstruction

Ocean surface slope determines the photon refraction and reflection features when it passes through the air-sea interfaces. However, for realistic free ocean surface with steep surface waves, the slope information alone is not accurate enough to predict the focusing of light by the surface. Therefore, we choose to utilize the deterministic surface wave elevations in the numerical model. Under the linear wave assumption, the wave elevations are reconstructed through linear superposition of many wave modes based
on the empirical wave spectrum, e.g., the ECKV (Elfouhaily, Chapron, Vandemark, and Katsaros) spectrum. Assume the wavenumber spectrum of the 3-D waves are \( S(k_x, k_y) \), where \( (k_x, k_y) \) are the 2-D wavenumbers. To numerically reconstruct the ocean surfaces, we need to discretize the 2-D wavenumber space so that \( k_{xn} = n\Delta k_x \) and \( k_{ym} = m\Delta k_y \), \((-\infty < n < \infty, -\infty < m < \infty)\). Then the amplitude of the wave component with a wavenumber of \( (k_{xn}, k_{ym}) \) can be obtained as

\[
A(k_{xn}, k_{ym}) = \sqrt{2S(k_{xn}, k_{ym})\Delta k_x \Delta k_y}.
\]

(6)

The reconstructed surface elevation based on the linear wave approximation is expressed as

\[
\eta(x, y) = \sum_{n=\infty}^{\infty} \sum_{m=\infty}^{\infty} A(k_{xn}, k_{ym}) \cos(k_x x + k_y y + \psi),
\]

(7)

where \( \psi \) is the phase of ocean surface waves and is assumed to be uniformly distributed between 0 and \( 2\pi \). Under such linear reconstruction, the surface wave slopes have a Gaussian distribution based on the central limit theory. A more realistic wave can be obtained using the high-order spectrum method to consider the nonlinear effect of free surface ocean waves.

Figure 1 shows an example of spatial patterns of \( E_d \) under rough ocean surfaces for a normal solar incidence (where the solar zenith angle is small). In this figure, the beam attenuation coefficient is chosen to be as small as 0.02 m\(^{-1}\) so that strong focusing effect by the surface waves can be clearly demonstrated. Figure 1(a) presents a typical vertical pattern of \( E_d \) at the upper ocean where a large amount of high-frequency capillary waves exists, which are obtained from the 2-D Monte Carlo RT simulation. Figure 1(b) illustrates a detailed view of the pattern near the surface. It is shown that due to the focusing of radiation by the extremely small waves, the patterns of \( E_d \) are quite chaotic and must be quantified using statistical approaches. Figure 1(c) presents a horizontal view of \( E_d \) obtained by the 3-D Monte Carlo RT simulation under a wavy surface with relatively small amount of capillary waves. The patterns of \( E_d \) due to the focusing of light by relatively large irregular waves can be clearly observed.

### 2.3 High-Order Correction to Photon-Surface Intersection

For very large solar zenith angles (solar light coming from horizon), the shadowing of the steep surface waves must be considered. To take into account the shadowing effect of ocean surface on the refracted light, we utilize the faceted surface to represent the real ocean surfaces. We assume the minimum length of the ocean surface waves is down to \( O(1) \) mm; the size of the facet has been determined based on the smooth surface. The smooth surface is obtained by applying a low-pass filter for the ocean spectrum. Under the faceted surface treatment, both shadowing and multiple refraction effects of the steep rough surface can be considered when photons pass through.

However, approximating the smooth surface as the discrete facets results in errors of locating the exact positions of intersection of the photon beams and the ocean surfaces. It also affects the computational efficiency at the same time, especially for a large solar zenith incidence. As Fig. 2 shows, for a 2-D ocean surface, a photon beam which is defined by the equation \( z = n_0 + z_0 \) hits the \( n \)’th facet of ocean surface \( \eta(x) \) with the intersection point located at \( x = x_n \). However, the position of the true intersection point of the photon beam and the ocean surface is \( x_i \). The error is \( \Delta x = x_i - x_n \). One solution is to make the facet as small as possible, but this will greatly increase the computational effort and damage the efficiency of program. To achieve both efficiency and accuracy for Monte Carlo RT simulations at the air-sea interface, we apply the technique of high-order correction to intersection points to find the \( \Delta x \) so that for even sparsely discretized ocean surface we are able to achieve relatively high accuracy for the beam-surface intersection points. To obtain \( \Delta x \), we expand the ocean surface elevation \( \eta(x) \) into a Taylor series at \( x_i \) for the \( n \)’th facet intersection.
\[ \eta(x_t) = \eta(x_i) + \Delta x \eta'(x_i) + \frac{\Delta x^2}{2} \eta''(x_i) + \frac{\Delta x^3}{6} \eta'''(x_i) + O(\Delta x^4), \]
where \( \eta'(x), \eta''(x), \) and \( \eta'''(x) \) are the first, second and third derivatives of \( \eta(x) \), respectively. Recall that equation of the photon beam is
\[ \eta(x_t) = a x + \eta(x_i). \]

If we keep up to the second-order term of \( \Delta x \) and ignore the higher orders, we can solve \( \Delta x \) as
\[ \Delta x = \frac{2 \alpha^2 - \eta'(x_i)}{\eta''(x_i)}. \]

Readers can keep higher orders to achieve higher accuracy. Since we already know the information of the surface, it is easy to find all orders of derivative of \( \eta(x) \). Therefore, by choosing sparsely discretized ocean surfaces and applying the high-order corrections to beam-surface intersection points, we are able to enhance both efficiency and accuracy of simulations at the same time.

Figure 3 shows an example of the vertical patterns of \( E_d \) (in logarithm) for the case of large zenith incidence (\( \theta_{\text{sun}} = 85 \) deg) both when the shadowing effect is ignored [Fig. 3(a)] and the shadowing effect is considered [Fig. 3(b)]. It is clear that the shadow effects have great influence on the pattern and statistics of the irradiance fields, especially at the near-surface depths.

### 3 Model Validation

In order to quantitatively investigate the near-surface statistics of \( E_d \), it is necessary to carefully validate the model using model-to-data comparisons. For the specific problem of fluctuating \( E_d \), we compare the simulated probability density function (PDF) of the normalized downwelling irradiance \( \langle E_d \rangle / \langle E_j \rangle \) and coefficient of variation (CV) of \( E_d \) obtained from the RaDyO Santa Barbara channel experiments.\(^{15,22} \)

Here, \( \langle \cdot \rangle \) means statistical average. The CV of \( E_d \) is defined as
\[ \text{CV} = \left( \frac{\langle E_d^2 \rangle}{\langle E_d \rangle^2} - 1 \right)^{1/2}. \]

The ocean surface waves used for comparisons are based on the omnidirectional wave number slope spectra obtained from the RaDyO field measurements in the same day of \( E_d \) measurements.\(^{29} \)

Figure 4(a) shows the slope spectra used in the comparison, where the circle represents the experimental data. Based on the experimental data, we fit the spectra and reconstruct the ocean surface wave elevations. To erase the effects of the periodical conditions imposed on the Monte Carlo model, we choose the 2-D ocean wave with the horizontal domain as wide as 50 m, and the interested water depth up to 10 m. The detector size \( R \) used for the comparison is consistent with the experiment (\( R = 2 \) m). Three light wavelengths are chosen to represent three different IOPs. They are \( \lambda = 443, 532, \) and 670 nm. The beam absorption coefficients \( a \) for the three wavelengths are 0.126, 0.089, and 0.4787 m\(^{-1} \), respectively; the beam scattering coefficients \( b \) for the three wavelengths are 0.67, 0.610, and 0.4478 m\(^{-1} \), respectively. The scattering phase function is chosen as the Petzold phase function. The solar incidence angle is chosen to be \( \theta_{\text{sun}} = 30 \) deg according to the condition of measurements. Considering the clear sky condition, we assume the diffuseness of the sky radiance is 0 and the
sky is black for simplicity. For each simulation setup, 10 realizations of surface wave fields are utilized to generate the downwelling irradiance fields. Therefore, all interested statistical quantities, e.g., PDF of \( E_d/(E_d) \) and CV, are ensemble averaged. For each Monte Carlo RT simulation, \( 3.2 \times 10^{10} \) photons are launched to achieve full convergence for all depths.

Figure 4(b) shows the CV of \( E_d \) as a function of depth \( z \) for both experimental data and simulation results at three different light wavelengths. It can be seen that the numerical simulations are able to make very precise predictions of CV for all depths (up to 10 m) and for all three wavelengths compared to experiments. Figure 4(c) shows the probability simulations are able to make very precise predictions of different light wavelengths. It can be seen that the numerical depths.

As a demonstration of the Monte Carlo RT model for the study of the statistical properties, we systematically investigate two important factors that potentially affect the statistics of near-surface downwelling irradiance \( E_d \): detector size \( R \) and turbidity or the single scattering albedo \( \omega_0 \). In this study, \( \omega_0 \) ranges from 0 to 0.9 and \( R \) is chosen to be 10, 1, 0.1, and 0.01 mm. As described, we use ECKV spectra as the free ocean surface spectra. The minimum and maximum wavenumbers are chosen as 0.628 and 6283 rad m\(^{-1} \), respectively. In the simulation, we assume that the solar zenith angle is zero (normal incidence on the ocean) and the sky radiance is approximated as the black sky in order to maximize the focusing effects of the surfaces; the horizontal domain is 50 m and the vertical domain is 10 m which corresponds to five optical depths (\( c = 0.5 \) m\(^{-1} \)). The phase function used is Heney–Greenstein phase function with asymmetry factor \( g = 0.924 \). The probability distribution of the normalized downwelling irradiance \( E_d/(E_d) \) is calculated based on its spatial distribution for different depths under various detector sizes. Similar to previous case, for each condition, all results are ensemble averaged using 10 surface wave realizations.

Figures 5(a) and 5(b) demonstrate the PDFs of \( E_d/(E_d) \) for \( R \) and \( \omega_0 \), respectively. We can see that the shape of PDF is strongly dependent on both \( R \) and \( \omega_0 \). For the case of small detector size and clean water, the probability distribution is highly asymmetric and has a long tail for high values of \( E_d/(E_d) \), e.g., when the single scattering albedo \( \omega_0 = 0.1 \), the highest value of \( E_d/(E_d) \) can reach to 10, with the corresponding probability density down to \( 10^{-10} \). With increasing turbidity and decreasing detector size, the probability of \( E_d/(E_d) \) for large values (tail of PDF) diminishes. For extremely large \( R \) and \( \omega_0 \), the PDF of \( E_d/(E_d) \) becomes more symmetric and close to Gaussian with a unit mean value.

The effects of the \( R \) and \( \omega_0 \) on the PDF of the \( E_d/(E_d) \) can also be better shown by looking at the CV of \( E_d \) (Fig. 6). Figures 6(a) and 6(b) demonstrate CVs as functions of \( \omega_0 \) and \( R \), respectively. Three different depths are chosen in order to understand the depth dependence on these two effects. It can be seen that CV of \( E_d \) generally decreases with increasing turbidity \( \omega_0 \) and detector size \( R \). The decreasing rates of CV of \( E_d \) for increasing \( \omega_0 \) are strongly dependent on depths. At the shallower depth, CV of \( E_d \) almost linearly drops with \( \omega_0 \); while at deeper locations,
CV quickly drops and reaches the asymptotic value as $\omega_0$ is increased. For increasing $R$, the dropping rate of CV is relatively larger at the shallower depth and smaller at the deeper depth.

### 4.2 Shadowing Effect

To understand the shadowing effect on the underwater downwelling irradiance fluctuations, we compare the PDF and CV of $E_d$ with and without considering the shadowing effect in the Monte Carlo simulations (Fig. 7). In this study, similar to above cases, the ECKV ocean spectra are applied and the detector size is $R = 2$ mm. The solar zenith angle is $\theta_{\text{sun}} = 85$ deg to represent the solar light from the horizon and demonstrate the difference of the two cases. Figures 7(a) and 7(b) show the comparisons for the PDFs between considering shadowing effect and not considering shadowing effect at $z = 1$ m and $z = 4$ m, respectively. We can see that at the shallower depth, due to the shadowing effect, the PDF with consideration of shadowing effect is strongly modified by the block of incident light by surface waves. The PDF neglecting shadowing effect is quite like those under normal incidence or small solar incidence, while PDF with shadowing effect taken into account becomes irregular. For larger depths, however, it can be observed that the PDFs for both cases do not deviate from each other very much.

Both of them become Gaussian-like with unit mean value. This is due to the fact that at greater depths, the multiple scattering of ocean particles becomes a dominant effect on the $E_d$ and it smooths out its fluctuations. Figure 7(c) presents a more straightforward picture of the effect of surface shadowing on variability of $E_d$ and its dependence on depth $z$. For the depth $z < ~3$ m, the CV of $E_d$ with the shadow effect is dramatically larger than that without considering shadow effect due to the low-intensity areas right behind the steep surface waves. For depths $z < ~3$ m, the two cases become almost the same when light is fully diffused.

Recent study shows that under small solar zenith incidences for clear oceans and at very shallow depth, the probability distribution of $E_d/(E_d)$ is close to gamma distribution, while for turbid oceans or at great depths, the probability distribution is more like lognormal. However, Fig. 7 indicates that, under large solar zenith incidences, the gamma distribution fails to describe the PDF of $E_d/(E_d)$ at the shallow depth, but lognormal is likely to work for greater depths.

It is also noted that detector and ocean’s turbidity play a similar role in influencing the variability of $E_d$ as spatial filters. It is observed that current theoretical models of PDF usually work better for greater $R$ and $\omega_0$. For extremely small $R$ and $\omega_0$, the PDF usually becomes very complicated and should be treated numerically.

### 5 Conclusion

In conclusion, we develop a state-of-the-art Monte Carlo RT simulation capability to study solar underwater light variability, with particular interest in PDF and CV of the downwelling irradiance $E_d$ caused by the focusing effects of the rough ocean surface waves. In addition to various advanced variance-reduction techniques and full program parallelizations, the numerical model is able to handle reflection/refraction of light for the complicated surface and solar incidence conditions, such as the shadowing of steep surface waves for large solar zenith angles. We particularly apply the high-order correction of the beam-surface intersection points to obtain relatively high accuracy for the interaction of light and air-sea interfaces and increase the computational efficiency at the same time.

To study the statistics of high fluctuated downwelling irradiance near the surface, the model is capable of detecting light field with high spatial [$O(10^{-3} \text{ mm})$] and temporal [$O(10^{-3} \text{ s})$] resolutions. We carefully validate the models using data-to-model comparisons. The comparisons between simulated results and field data obtained during the RaDyO experiments for multiple light wavelength and at various depths indicate very good agreements.

Based on the model, we take a systematic investigation of PDF and CV under the influence of two important physical factors, water turbidity of the ocean and the detector size. Effects of shadowing of the surface waves on the PDF and CV are also studied. We show that increased turbidity and detector size reduce the variability of the downwelling irradiance; the shadow effects for large solar zenith strongly enhance the variability of irradiance at shallow depths. It seems that for large solar incidence the shadowing effects play a more important role than other factors on the statistics of the near-surface light field statistics. Therefore, the systematic understanding of this effect indicates possibility of directly obtaining the topology of the air-sea interface.
On the whole, this numerical capability of Monte Carlo RT simulation provides a great potential for future studies of both forward and inverse problems about surface effects on underwater light fields fluctuations.

Acknowledgments
This study was supported by the Office of Naval Research through the RaDyO project.

References

Biographies of the authors are not available.