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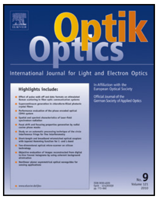

Full length article

Computational modeling of the effect of wind-driven ocean waves on the underwater light field distributions

Ali Gholami*, Hossein Saghafifar

Institute of Optics and Laser, Malek Ashtar University of Technology, Shahin Shahr, Iran

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ABSTRACT

We have developed a numerical model, which is a combination of ray-tracing and optical propagation, to study underwater downwelling irradiance fluctuations, which occur due to the focusing of light by wind-driven surface waves, at different depths and under various conditions. In particular, to have more realistic results, we utilized the Gerstner model to simulate sea surface waves and to take account of water effects such as scattering and absorption, the point spread function (PSF) of water is used. The effects of physical factors such as wind speed, water depth, and light wavelength on the underwater irradiance spatial distribution, probability density function (PDF) and coefficient of variation (CV) of the irradiance are investigated. Irradiance fluctuations occur at high frequencies immediately below the surface, which means they are related to surface waves with short wavelengths. As we look deeper, the effect of surface waves with longer wavelengths becomes apparent. The simulation also shows the dependence of the average of the downwelling irradiance on the surface profile, depth and incident wavelength. The variance of the irradiance reaches a maximum at a certain depth and then rapidly decreases.

1. Introduction

The effects of the air-water interface on the spatiotemporal structure of underwater light field and understanding physics of underwater irradiance fluctuations are of interest in many areas, such as optical remote sensing and ocean surface reflections [1,2], underwater visibility [3], underwater imaging [4–6] and phytoplankton photosynthetic physiology [7,8]. The characteristics of these light fluctuations can contain useful information about surface waves such as their slopes, curvatures and low-scale roughness. The complexity of dynamic sea surface waves and optical radiation transfer in the turbid water makes this area of study quite complicated. The underwater light field varies as a result of several mechanisms, from changes of the solar zenith angle during the day to fluctuations related to the motion of clouds. But the main factor affecting light field variations, which acts over short time periods, is sea surface waves, which give rise to randomly refracting natural light fields – such as those originating from the Sun or the Moon- or light fields from artificial sources – like lasers, search lights, etc. Light beams refract through the irregularly shaped sea surface. Surface waves consist of a combination of several individual waves that act as lenses to focus light at various water depths. As a result of this lensing effect, intense fluctuations of downwelling irradiance can be observed below the surface, as is commonly observed as spatial patterns on the bottom of a swimming pool on a sunny day. The wavelengths of sea surface waves range from less than 1 cm – capillary

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* Corresponding author.
E-mail address: mr.gholami.ali@gmail.com (A. Gholami).

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waves- to hundreds of meters- wind-driven gravity waves- which are merged together to make the sea surface geometry. Smaller waves focus light near the surface and larger ones – with larger wavelengths- focus light at greater depths. Since sea surface waves are generated by the wind, the speed of the wind can affect the underwater light field fluctuations. In fact, at higher wind speeds, the focusing effect decreases because the wave field becomes too complex to effectively focus light [9,10]. Another important factor which is effective in underwater irradiance distributions is the Inherent Optical Properties (IOPs) of water, which affect beams below the surface and in the water column. Although absorption causes a decrease in the absolute intensity of wave- induced irradiance fluctuations, the relative intensity remains the same. Scattering by particles and water gives rises to a diffusing light field and a reduced light focusing effect. At greater depths, the effect of scattering increases and surface- waves induced fluctuations become smooth due to multiple scattering, with the result that the effect of large surface waves becomes dominant. The most dynamic part of the light field is thus in the upper 15 m of the water column [11]. In general, underwater irradiance fluctuations depend mainly on wind speed, the slope of the sea surface, the incident light field, IOPs, and the depth of observation. There have been many experimental studies of the statistical properties of these intense fluctuations in the underwater irradiance, $E_{d,u}$. In one study, the energy spectrum of the down-welling irradiance fluctuation was measured on a clear sunny day [12]. Further experimental investigations used specific irradiance instruments to make in-situ measurements in the top few meters of the sea [9,11,13–21], or in the laboratory to simulate wave-induced irradiance fluctuations [22]. Fluctuation in the underwater light field caused by surface waves has also been the subject of theoretical research. The first simplified model of this phenomenon was presented by Schenck [23], who explained the mechanism of the mentioned fluctuations as a focusing effect of the Sun's rays by wave crests. His simplified model was further used by a number of investigators [17,24]. A first-order single-ray model that neglects diffuse skylight has also been introduced by Snyder and Dera [12]. Several direct simulations have been accomplished recently using Monte Carlo radiative transfer models [19,25–29]. In addition to all of above experimental and simulation work, analytical studies on the effect of the air-sea interface on the light field [30] and on the statistical structure of the probability distribution function (PDF) of downwelling irradiance [31,32] have also been carried out.

In this work, we have used a ray-tracing method [33] in order to perform a 3D simulation of underwater irradiance fluctuations at various depths and different wavelengths of the incident light field. The small-angle scattering theory [34] was used to describe multiple scattering and attenuation in the water. In fact, it is a combined method that despite the simplicity and speed of calculation, has led to precise results. Variations in the probability density function (PDF) of the normalized downwelling irradiance versus depth are investigated and In order to validate this model, we have done a comparison between the simulated PDF and experimental data obtained from [19] at three different depth. We have also investigated the coefficient of variation (CV) of the irradiance for different conditions.

2. Fundamentals of light propagation through water

First, a coordinate system is chosen for modeling of the propagation of light rays through the water. Each point at sea level is represented by *(x,y,z)* The *z* axis is normal to the mean water level, with its positive direction upward. The elevation of any point on the sea surface *(x,y)* is represented as $z = \xi(x, y, t)$. The sea surface can be divided into small square area elements of side (L). It is assumed that the water medium remains unchanged during the light propagation. When a solar beam is incident on the i^{th} area element, a fraction of its energy is refracted. The direction of refraction is given by Snell's Law, which is dependent on the angle between solar beam and the normal to the i^{th} area and the refractive index of water. We have used an empirical formula for the refractive index of water as a function of wavelength, assuming a temperature of 25 °C and no salinity which was derived by Quan and Fry in 1995 [35,36] as:

$$n(\lambda) = 1.31279 + \frac{15.762}{\lambda} - \frac{4382}{\lambda} + \frac{1.1455 \times 10^6}{\lambda^3}$$

Where λ is the wavelength in *nanometers*.

As the light beam propagates through the water, it is scattered and absorbed by water and those particles which are suspended in it. This phenomenon leads to a reduction in the intensity and to the dispersion of the beam with depth. We realize these effects by means of the point spread function (PSF) of water computed from the small-angle scattering theory. At last the beam's horizontal coordinates in the specified depth plane are computed. The irradiance at each point at the depth $z = -D$, is a result of a combination of beams which were received from all possible area elements of the surface. Our interest is to find the distribution and PDF of underwater downwelling irradiance at the depth $z = -D$ .The schematic procedure is illustrated in Fig. 1.

2.1. Modeling of sea surface waves

Ocean waves are generated by the wind. The faster the wind, and the longer the wind blows, and the larger is the area over which the wind blows, the greater will be the waves. There are several methods to modeling ocean waves such as methods based on computational fluid mechanics, ocean wave spectrum and geometric modeling [37]. Among all of these methods, those are based on the ocean wave spectrum are the most widely accepted methods mainly because their parameters are obtained by long-term ocean observations and in addition to that, they need relatively small computational load. Two of the most commonly used methods based on wave spectrum are Gerstner parametric model [38] and Fourier transform method