# Monte Carlo Radiative Transfer Simulations on the Influence of Surface Waves on Underwater Light Fields

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## ABSTRACT

A Monte Carlo model has been developed for calculating the penetration of light into the ocean. For monochromatic light (490 nm) the spatial exact allocation of the scattered parts of underwater light is described in terms of the variation of particle content and the angle of light incidence. Based on this model, it is possible to generate complex spatiotemporal fluctuating light fields according to every possible shape of the water surface. By means of single gravity waves the focusing effect and its importance of radiance supply for water depths up to 100 m is discussed.

## INTRODUCTION

The variability of underwater light depends in particular on the focusing effect of surface waves. The shape of the irregular wave field determines the intensity enhancements and the light variability distribution along the water column. All superposed single waves (capillary as well as swell waves) cause specific spatiotemporal fluctuations of the light regime (see. e.g. HIERONYMI & MACKE, 2010).
The aims of this contribution are to simulate the propagation of light in natural waters by means of a new 2D Monte Carlo method, and based on this model, to show potential light fluctuations due to single waves and irregular wave fields. Ultimately, the relevance of wind and sea state conditions on the subsurface radiation regime shall be investigated.

## MONTE CARLO MODEL

The radiative transfer simulations have been carried out at a wavelength of 490 nm. The implemented inherent optical properties of oceanic (case 1) waters at this waveband are taken from MOREL (2009) and MOREL et al. (2002). This article refers to homogeneous water with chlorophyll content of 0.1 mg m$^{-3}$, a water type that is widespread in the open ocean. The 2D (the azimuth direction is neglected) propagation of a narrow light beam inside the water body is simulated. The model grid covers 100 m depth by 150 m width, with a mesh size of 0.1 m in both dimensions. Photons can leave the boundaries, but never enter again. Internal reflection at the water surface is provided.
By selection of a random number R between 0 and 1, and – in contrast to other MC procedures – from the scattering coefficient b (and not the extinction or attenuation coefficient c) the path length l between scattering processes is obtained

$$l = -\frac{1}{b}\log(R).$$

In order to balance for the resulting excess in photon path length we introduce a continuous weight reduction of the light ray along the covered path, which is characterized by the medium's overall absorption properties. There are no additional losses at the scattering points, only a random change of light propagation. The energy attenuation along the path follows Beer's law

$$I = I_0 \; exp(-a \; l_z),$$

with the initial photon energy $I_0$ of 100 % at point [0,0], the total absorption coefficient of the water, a, and the total covered distance with respect to the z-level, $l_z$.
Since the photon's path is followed with respect to global coordinates, it can be stated whether its intensity contributes to down- or upward directed irradiances. The horizontal summation of all diffuse and direct fractions lead to the mean downward/upward irradiance $E_d$ and $E_u$ respectively, at this particular depth for a perfectly flat surface.
Figure 1 exemplarily shows the spatial propagation of a single light beam in water in the model domain with incidence angles of 0° and 48° (note the color scale is logarithmic). The patterns describe the accumulated downwelling irradiance within 10 cm wide "detectors" and with respect to water depth and horizontal expansion. The allocation patterns of diffuse and direct downward directed irradiance are the basis for light field superposition.

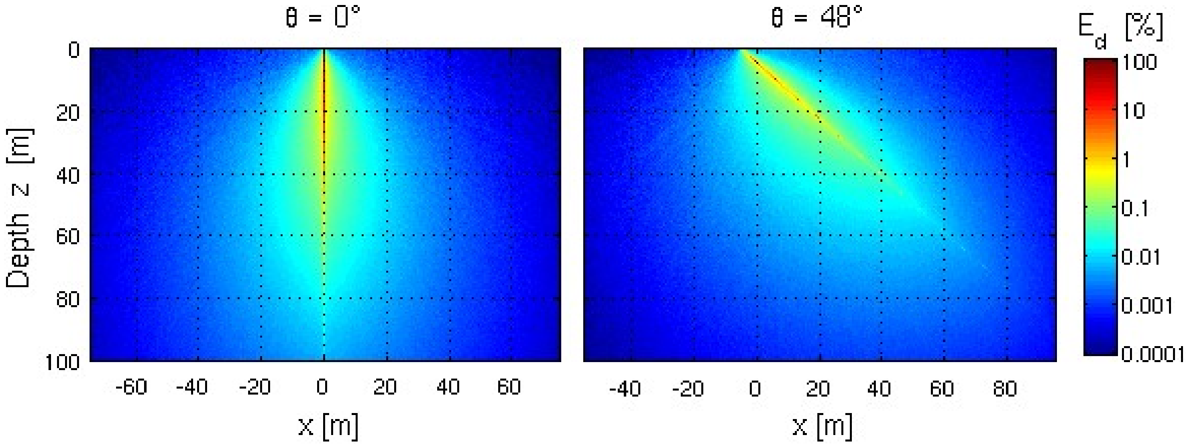


**Fig. 1: Downward irradiance distribution of single light beams in sea water at 0° and 48° light incidence angle (note the logarithmic color scale)**

## OCEAN WAVES

In a first step regular waves are considered. The nonlinear elevation of oceanic gravity waves (of almost all sizes) can be described by means of the Stokes theory of fourth order, according to KINSMAN (1965) this is:

$$\zeta = \zeta_a \cos\theta + \frac{1}{2} k \zeta_a^2 \left(1 + \frac{17}{12}(k\zeta_a)^2\right) cos2\theta + \frac{3}{8} k^2 \zeta_a^3 \; cos3\theta + \frac{1}{3} k^3 \zeta_a^4 \; cos4\theta \,,$$

where $\zeta_a$ is the amplitude, k the wave number, and θ the phase. The term kζ stands for the wave steepness. The nonlinear characteristics of the wave shape (especially of steeper waves) are very important in terms of the resulting light field – the wave crest is steeper and the trough of the wave is flattened.

## SUPERPOSITION OF LIGHT REGIMES

MC calculations have been carried out for a model domain of 100 m by 100 m, with 0.1 m mesh size, and with 200000 photons (which gives a reasonable irradiance distribution picture). The air-to-water transmission is varied with 0.4° steps to the maximum transmission angle of around 48°. According to Snell's law, we can calculate the transmission angle at a 10 cm wave segment with the sun zenith angle and the slope of the wave segment. If we than apply Fresnel's equations, we gain the rate of radiation that is transmitted into the water; this rate than is multiplied with the corresponding irradiance field.
For every wave segment, the downward irradiance field is adopted with respect to the global coordinate system, so that the radiation that enters the water body at that position affects the horizontally neighboring ± 50 m. Beyond these 50 m, the radiative contribution of the single light beam is neglected. Although internal reflection at the flat water surface is considered within every single irradiance pattern, the superposition of light fields does not regard the wave-like deflected surface. This is a potential bias in the combined light field, which is estimated to be small (discussed later).

## RESULTS

The modeled light fields consider the complete diffuse radiation below a single wave up to almost 100 m water depth. Figure 2 shows the simulated downwelling irradiance distribution below three oceanic waves at nadir sun position. The initial $E_d$ value at the surface is 100 %; all subplots relate to the same color scale, which is logarithmic to better distinguish the spatial gradient of the quickly decreasing downward irradiance.
Wave I is 2 m long (wave period round 1.13 s) with a steepness of H/L = 0.06, and still can be included in the ultra gravity wave region. At the focal point more than 5.6 times the surface intensity is accumulated. This occurs directly below the crest at 2.7 m water column. Overlaps of neighboring light fields of second and higher orders can be identified. Waves of this size don't have significant impact on the light regime below the top 40 m layer. The second wave is a very typical wind sea wave of 2 m height and 5 s wave period (39 m wave length). Here, at 40 m depth punctual $E_d$ values of more that 70 % of $E_d$ (z = 0) can be registered. Without wave this value of 70 % would be at 10 m depth. The last wave corresponds to a fully developed wind sea range with 7 m wave height and 8 s period (100 m wave length). Longer waves must be higher to produce considerably intensity peaks. Swell waves begin with ca. 10 s period (156 m length). They cause small discontinuities in the light field at already 2 m wave height; with growing wave height these discontinuities emerge more and more. It should be kept in mind that the wave-corresponding light regimes propagate with the wave's period. Thus, from the dispersion relation of water waves we gain additional temporal information on the light field.
The mean values can be slightly reduced compared to a flat surface due to an increased surface reflection rate at inclined wave segments. Thus, the wave slope distribution determines the total amount of $E_d$ that is transmitted into the water column. Above ca. 40 m numerical noise can occur due to grid discretization and the relative raw incidence angle step size of 0.4°. This may affects the estimation of minima and maxima values per optical depth. But nevertheless, perfect single waves with smooth surface don't exist in reality; small waves as capillary waves superpose the wave structure and cause noise (fluctuations) in the upper layer anyway. However, larger waves provoke intensity maxima at grater depths, e.g. capillary and small gravity waves peak above 2 m water depth, but fully developed gravity waves achieve focal depths below 10 m. This of cause depends on the electromagnetic wavelength, water properties, and also on the wave's steepness.

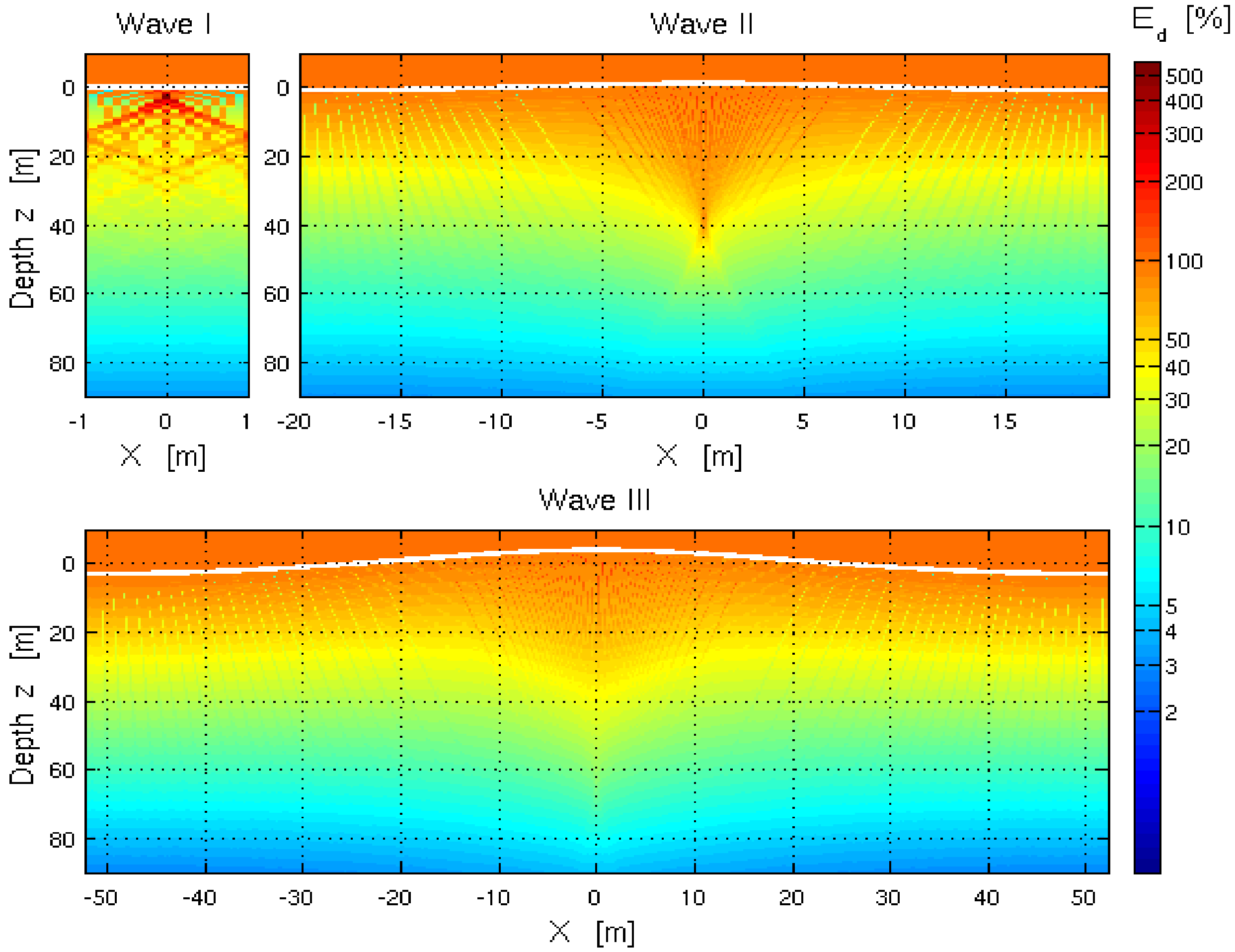


**Fig. 2: Downward irradiance patterns below three waves with respect to 100 % at the surface (note the logarithmic color scale and the not equally scales x-axes)**

Figure 3 presents the corresponding light field statistics of the three waves: the coefficient of variation, CV, and the relative intensity enhancement per optical depth (defined as the water column directly above the 10 cm wide "detector").
CV describes the strength of light fluctuation. Comparative data from offshore measurements can be found in e.g. CERNEZ & ANTOINE (2009); they compute CV with the standard deviation relative to the median $\sigma_M$ and median $\mu$ of $E_d$ at a depth:

$$CV = 100\frac{\sigma_M}{\mu}.$$

Every single wave develops its characteristic CV shape. Normally, the CV maximum marks the depth around the focal plane. Shorter waves potentially develop more intense maxima at lower depths than longer waves. The CV maximum of wave I is at the depth of the second focal plane, here we have a higher standard deviation compared to the first focal plane. But nevertheless, it can be seen that fully developed gravity waves bring more variability into the whole lit water column, and especially below the upper layer of 20 m depth (in case of wave II & III, the first 20 m are subject to noise; the data here are misleading).
DERA & STRAMSKI (1986) defined irradiance pulses that exceed the mean irradiance $E_m$ by a factor of more than 1.5 as underwater light flashes (relating to 1 m depth and short occurrence i.e. high frequency). All three presented waves build up such irradiance peaks along a wide range of depth (up to 65 m). Intensity peaks easily exceed 6 times of the average intensity level, in case of wave II maximal values can reach $3E_m$ at 40 m.

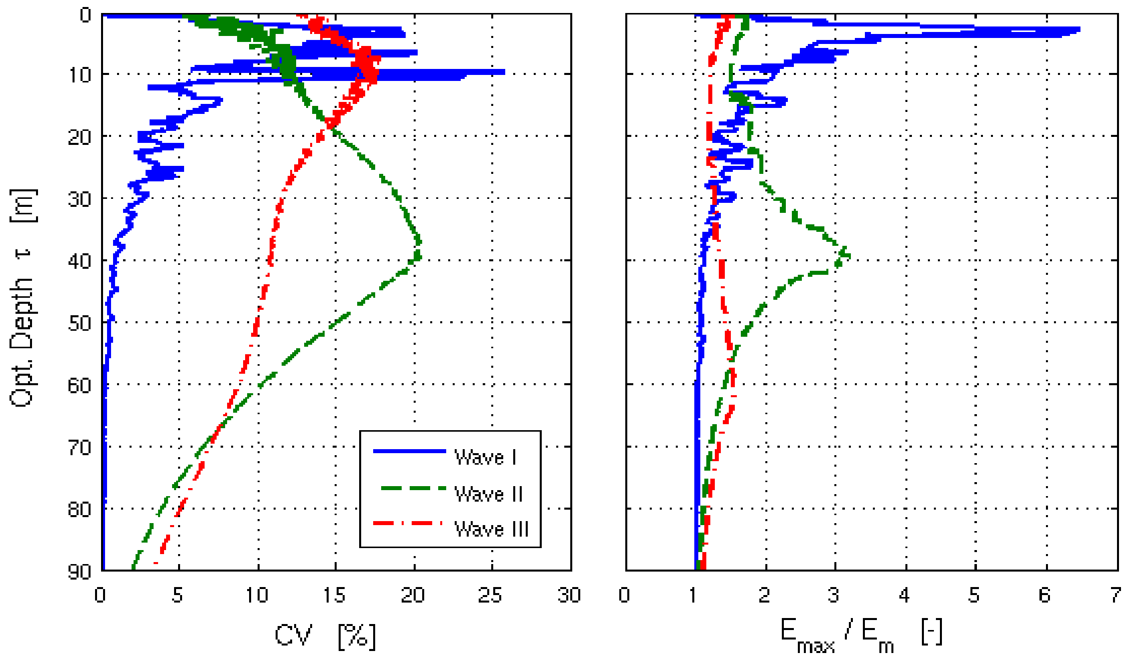


**Fig. 3: Coefficients of variation of $E_D$ and relative intensity enhancements per optical depth for the three waves**

A realistic ocean surface arises from three-dimensional superposition of all kind of waves; from small size capillary (< 1.7 cm) to swells (e.g. up to 20 s period corresponds to round 625 m wave length) and even longer waves. Their effect on the underwater light field is a combination of individual optical geometries, an interaction of various focal points with different propagation velocities. Thereby irradiance patterns smear over; punctual radiance values amplify and diminish. However, underwater light fluctuations at a sea state are dominated by its predominant waves. Details on this issue follow.

## CONCLUSIONS

The diffuse propagation of single light beams into sea water is simulated by means of a Monte Carlo model. The emphasis is on the spatial downwelling irradiance pattern. Example results are shown for sea water with relatively low particle content, monochromatic (bluish) light at 490 nm wavelength, and for two different initial angles of light incidence.
Based on the single-beam-model, we introduce a method of superposing individual light fields according to any water surface deflection and sun position. Three typical ocean waves are implemented to study the focusing effect and corresponding light field fluctuations. The shape of the regular nonlinear gravity waves is realized using Stokes theory of fourth order. Pictures of diffuse downward irradiance below these waves and related statistics are shown. From observations we know that short waves of the small-gravity and capillary wave region are responsible for very intense and high-frequent radiance fluctuations – but only in the top 5 m of the water column (HIERONYMI & MACKE, 2010). Below 5 m depth, fully developed gravity waves (of more than 1 s wave period) dominate the irradiance fluctuations in intensity and periodicity. Based on our simulations and observations, we think that larger wind sea waves are of major importance for the radiative supply of the water column below about 20 m depth. The focusing effect of those waves makes it possible that light can penetrate deeper and with concentrated intensity into the water body. Of course, this enhancement is spatially limited and of short time period. However, even swell waves (> 150 m length) develop considerable discontinuities in the light field, if they are high enough (their occurrence at high sea is than certainly less probable).

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