Rendering Natural Waters:

Merging Computer Graphics with Physics and Biology

E. Cerezo, F.J. Serón

Advanced Computer Graphics Group (GIGA)
Computer Science Department
Technical School of Engineering
University of Zaragoza
C/ Maria de Luna 3, E-50015 Zaragoza, Spain
`ecerezo@posta.unizar.es`
`seron@posta.unizar.es`
`http://giga.cps.unizar.es/`

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Keywords. Participating Media, Discrete Ordinates, Global Illumination, Bio-optical models

Contact Author: Eva Cerezo

Postal Address:

Departamento de Informática e Ingeniería de Sistemas

Centro Politécnico Superior, edificio A

C/ Maria de Luna 3

E-50015 Zaragoza

Spain

E-mail: ecerezo@posta.unizar.es

Phone-number: +34 976 762356

Fax-number: +34 976 761914

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1 Introduction

Research on the rendering of natural scenes, such as clouds, water, trees, terrain, fire, has become increasingly wide spread. In particular, the creation and rendering of realistic water scenes is one of the challenging tasks in Computer Graphics. Most of the work that has been done is concerned with the effects of the reflection and refraction of light on the water surface: shafts of light, caustics…[1], [2], [3]. Great effort has been taken in studying atmospheric conditions to know how much sunlight and skylight reaches the water surface and the problem of wave generation [4], [5], [6]. However, realistic rendering of water scenes requires the transport of light within the water body to be properly handled.

Due its complexity, when considering light transport in water strong simplifications are usually made (single scattering, isotropy, homogeneous media…). Nishita et al. [7] study the colour of sea surface as viewed from outer space; they include in their model the scattering due to water molecules, but they make an analytic quasi-single scattering approximation. Premoze et al. [8] also consider the problem of light transport, but they have centre their work in the simulation of the appearance of the water surface. Therefore, when carrying the light transport they also make important simplifications: they solve a mono-dimensional equation (the radiance in the medium will depend only on the depth). They do not try to simulate the radiance due to scattering; they estimate it using some empirical equations that relate the radiance just below the air-water surface with the light coming from the sun. Tadamura et al. [9] study the colour of water in applications of lightning design. They are the only ones that consider the presence of light sources within the water (usually, only illumination due to the sun and the sky is considered). But when performing the light transport they only consider single scattering and no illumination of objects inside the water due to scattering. Jensen et al. [10] generalise the bidirectional Monte Carlo ray-tracing method to scenes containing participating media and apply it to render scenes with water. They calculate volume photon maps and use them in the rendering stage to estimate the radiance due to scattering within the media. It is a very general method able to consider non-homogeneous media and anisotropic scattering with complex geometries. With certain media the savings in memory is substantial, compared with some finite element methods, but when applying it to render water the memory increases, specially if the highly-peaked marine scattering behaviour has to be reproduced. So, it can be concluded that the transport of light in water has generally been made aplying strong restrictions to the medium with the only exception of systems using non-deterministic methods such as Monte Carlo.

Our work focuses on the simulation of the transport of light in water in the more general case: non-homogeneous medium, anisotropic scattering and multiscattering. We have applied the method of Languénou et al. [11] that is based on the discretisation of the participating medium in finite volumes (voxels) and on the use the discrete ordinates method to handle directions. Finite volume element techniques are not as flexible as Monte Carlo ones, but they are undoubtedly faster and more effective for simple scenes. We have generalised the method to the case of objects and light sources inside the medium. The presence of light sources considerably increases the complexity of the light transport problem: the illumination does not only depend on the depth, so pure 3D calculus has to be performed. The illumination of the objects due to direct but also scattered light has to be taken into account.

The use of realistic medium parametrizations and a proper handle of the spectral dependence of the medium characterising parameters is also essential. It should be pointed out that the behaviour of marine waters is drastically different of that of pure water. This is caused by the presence of several components in these waters (dissolved salts, dissolved organic compounds, plankton…). The spectral absorption and scattering coefficients as well as the scattering phase functions are strongly affected by these components: the illumination and colour of the water is consequently determined by their presence. The resolution of the transport problem within the water is a prerequisite for the solution of many problems such as the synthesis of realistic underwater images, the underwater visibility, the capture of satellite images, the biologic productivity studies, or the thermodynamics of stratified media in submarine environments.

The structure of this paper is as follows: in Section 2 the radiative transfer equation which describes the behaviour of light in a participating medium is presented, whereas in Section 3 our simulation system is outlined. Section 4 analyses the oceanic medium as participating medium and presents the bio-optical models used to parametrized it. Section 5 discuss the problems that arise due to the special scattering characteristics of the oceanic medium and presents a study of simple images obtained for different waters. In Section 6 conclusions and future work are discussed.

2 Working with Participating Media: the Radiative Transfer Equation

As radiation travels through a participating medium it undergoes three kinds of phenomena: absorption, which causes a diminishment of the intensity, emission, which increases intensity and scattering which causes a redirection of energy. There are two types of difficulties when studying the radiation in this kind of media. First of all, emission, absorption and scattering do not only take place in the medium boundaries, but within any point of the medium. A complete solution of the exchange of energy requires knowledge of the physical properties and the intensity of radiation within every point of the medium. A second difficulty comes from the spectral effects due to the dependence of the characterising parameters with the wavelength, making it necessary a detailed spectral analysis.

The equation that governs the transfer of energy in this kind of media is the radiative transfer equation –RTE-:

$$\frac{dL_\lambda(S,\theta,\varphi)}{dS} = -a_\lambda(S)L_\lambda(S,\theta,\varphi) + a_\lambda(S)L_{\lambda emis}(S,\theta,\varphi) - \sigma_\lambda(S)L_\lambda(S,\theta,\varphi) + \frac{\sigma_\lambda(S)}{4\pi}\int_{w_i=4\pi} L_{\lambda_i}(S,\theta_i,\varphi_i)\Phi_\lambda(S,(\theta_i,\varphi_i)\rightarrow(\theta,\varphi))dw_i \tag{1}$$

$L_\lambda(S,\theta,\varphi)$ is the radiance, ie, the power per unit of projected area perpendicular to the ray per unit of radiation length and solid angle in the direction (θ,φ). The equation gives its local variation when traversing a distance dS. The meaning of the different terms at the right of the equation is as follows:

- The first term refers to absorption: $a_\lambda(S)$ is the so-called absorption coefficient (the fraction of energy lost per unit length, dimension m^{-1})
- The second term corresponds to self-emission: $L_{\lambda emis}(S, \theta, \varphi)$ is the radiant energy emitted, due to spontaneous or stimulated emission
- The third term represents the reduction of the radiance along the propagation direction because of scattering (out-scattering): $\sigma_\lambda(S)$ is the scattering coefficient (dimensions m^{-1})
- The last term accounts for the in-scattering, ie, the increase of radiance along the propagation direction due to the scattering of radiance coming from other directions. $\Phi_\lambda(S, (\theta_i,\varphi_i)\rightarrow(\theta,\varphi))$ is the phase function which describes the angular distribution of the scattered energy.

Another important parameter for characterising the medium is the extinction or attenuation coefficient, which is the sum of the absorption and scattering coefficients:

$$K_\lambda = a_\lambda + \sigma_\lambda \tag{2}$$

The inverse of the attenuation coefficient is called attenuation length (dimension m). In Table 1 these and other important parameters characterising a participating medium are summarised. Their spectral dependence should be noted.

a_λ	Absorption coefficient
σ_λ	Scattering coefficient
$K_\lambda = a_\lambda + \sigma_\lambda$	Extinction coefficient
$\Phi_\lambda((\theta_i,\varphi_i) \rightarrow (\theta,\varphi))$	Scattering Phase Function
$l_\lambda = 1/K_\lambda$	Attenuation length

Table 1. Coefficients characterising a Participating Medium

In this work we do not consider self-emission ($L_{\lambda emis}=0$), so equation (1) simplifies:

$$\frac{dL_\lambda(S)}{dS} = -K_\lambda L_\lambda(S) + \frac{\sigma_\lambda}{4\pi} \int_{w_i=4\pi} L_\lambda(S,\theta,\varphi)\Phi_\lambda(S,(\theta_i,\varphi_i) \rightarrow (\theta,\varphi))dw_i \tag{3}$$

Boundary conditions have to be added to the equation, basically void conditions (no incoming radiances) or surface reflection conditions:

$$L_\lambda(\theta_r,\varphi_r) = E_\lambda(\theta_r,\varphi_r) + \int_0^{2\pi}\int_0^{\pi/2} f_{brdf}((\theta_i,\varphi_i) \rightarrow (\theta_r,\varphi_r))L_\lambda(\theta_i,\varphi_i)\cos\theta_i \sin\theta_i d\theta_i \tag{4}$$

where E_λ is the energy emitted in the (θ_r,φ_r) direction and f_{brdf} is the bidirectional reflectance function.

3 Solving the RTE: our Simulation System

3.1 The General Framework: the Discrete Ordinates Method

In order to solve the radiative transfer equation, different methods have been proposed. Restricting them to those capable of dealing with the more general and realistic case of multi-scattering (a ray may undergo several scattering events), there are the following families of methods: zonal methods, Montecarlo methods and flux methods, that include the P-N or spherical harmonics methods and the multiflux or discrete ordinates methods. In Table 2 the different methods and relevant works are outlined. A good review of these methods can be found in [12].

Zonal	[13], [14], [15]
Monte Carlo	[16], [17]
Spherical harmonics	[18], [19]
Discrete Ordinates	[11], [20], [21]

Table 2. Different methods to deal with Participating Media

We have chosen the discrete ordinates method to solve the radiative transfer equation because it is general, it poses no restrictions to the medium characteristics and is computationally feasible. It is based on the angular discretization of the solid angle about a location over a finite number of directions.

Angular discretization. The integral over solid angles in equation 3 is replaced by sums over a discrete set of directions. Therefore, the variation of the radiance along direction V_m will be given by (λ subscripts have been omitted for clarity):

$$\mu_m \frac{\partial L_m}{\partial x} + \xi_m \frac{\partial L_m}{\partial y} + \eta_m \frac{\partial L_m}{\partial z} = -KL_m + \frac{\sigma}{4\pi}\sum_{t=1}^{n_d} w_t \Phi_{tm} L_t \qquad \textbf{(5)}$$

where n_d is the number of discrete directions, (μ_m, ξ_m, η_m) are the director cosines of direction V_m, and w_t is the weight associated to direction V_t, $m, t \in [1, n_d]$ provided that $\sum_{t=1}^{n_d} w_t = 4\pi$. Angular discretization can be uniform or not.

Spatial discretization. Furthermore, to transform the differential equation into an algebraic one, a spatial discretization is performed: the medium is subdivided into voxels of constant physical properties. In fact, what is computed in the algorithm is not the radiance of the voxel for each direction but the Source Term [22], which in our case reduces to:

$$G_m = \frac{\sigma}{4\pi}\sum_{t=1}^{n_d} w_t \Phi_{tm} L_t \qquad \textbf{(6)}$$

This term represents the gain of radiance in direction m owing to in-scattering. The radiances of the voxel faces and the source term for each of the discrete directions are constant inside the voxel so the RTE (equation 3) can be analytically integrated along a path of length s inside the voxel, obtaining:

$$L_m(s) = L_m(0)e^{-Ks} + \frac{G_m}{K}(1 - e^{-Ks}) \qquad \textbf{(7)}$$

which is the basis of the transfer of energy inside the voxel.

3.2 Resolution Method

Our algorithm is based in the work of Languénou et al.[11] and has been presented elsewhere [23]. Our main contribution to the method has been its generalization so that the system is able to:

? include objects and sources inside the participating medium

? use realistic medium parametrizations

? consider inelastic processes

? validate the results to assure that they are not only qualitatively but quantitatively (physically) correct; in particular the energy absorbed in each of the voxels is also calculated.

The work presented in this paper focuses in the second point. Nevertheless, for cimpleteness, we outline here the general structure of the resolution algorithm.

The resolution method is iterative. First of all, an initialisation step corresponding to the first order of scattering is performed. Then, in the iterative process, each of the iterations corresponds to one scattering. The results of this process are the source terms in each direction in each voxel of the medium and the radiances in the medium's boundaries. Some of these boundaries are "physical" (for example the seabed or the air-water surface in a marine scene) and other just "geometrical" or "non-physical" (they simply delimit the simulation volume). The iterative process follows the one in [11], but a proper handling of the surfaces and objects within the medium has been incorporated. Therefore, those aspects will be emphasized.

The First Step: "Loading" the Medium and the Objects. First of all, the source terms in each voxel are initialised taking into account the contribution of each illuminating source. Direct illumination on the physical boundary surfaces of the medium (seabed, air-water surface…) and on the objects within the water is also computed. These radiances are incorporated as boundary conditions when dealing with the next orders of scattering. For the moment, all surfaces are considered as having Lambertian properties.

The Iteration Process: Computing the Multi-Scattered Light Field. Afterwards, for every single direction a complete traversal of the matrix of voxels is carried out:

- A direction V_m $m \in [1, n_d]$ is selected
- The traversal is done beginning in one of the 8 extreme voxels. It is important for the traversal to follow the "energy flux sense": for a direction with direction cosine >0 the sweep should be done increasing voxel indexes and for one with direction cosine <0, inversely
- In each voxel (for the direction being considered):

1. The direction classifies the six voxel faces into three incoming and three outgoing faces. The radiance of an incoming face will be: zero if the face belongs to a "non-physical" boundary (void boundary condition) or a reflected radiance if it belongs to a "physical" surface or the outgoing radiance of the adjacent voxel

2. The previous source term contribution and the incoming radiances are used to calculate an average radiance L_m in the voxel (assumed constant within the voxel)

3. This average radiance L_m is used to calculate the outgoing radiances. This calculus is done using the equation of energy transfer inside the voxel (equation 7)

4. L_m is also used to calculate the increments of the source terms for the discrete directions due to scattering (calculation of the next order of scattering):

$$\Delta G_t + = \frac{\sigma}{4\pi} w_m \Phi_{mt} L_m, \forall t \in [1, n_d] \tag{8}$$

- Each time a "physical" surface (either belonging to a boundary or to an object) is encountered the radiance of the surface is stored

- Once all the voxels have been treated, next direction is considered

- After having followed all directions, the next order of scattering is considered, initiating again the traversal of the medium for each discrete direction anew.

With this iterative process, the energy initially loaded when initialising the voxels' source terms is propagated throughout the medium. When the contributions to the radiances of the boundaries and to the voxels' source terms are negligible, convergence is met and the resolution process is stopped.

3.3 Storage of Results and Rendering Stage

As already pointed out, all the magnitudes we work with are spectral ones: the source spectrum is divided into intervals, so that one calculation is carried out for each of the discrete wavelength values. To avoid storing the source terms for each direction, an expansion in spherical harmonics is performed in each voxel.

To obtain the images a simple ray-tracer adapted to voxelised participating media (based in [24]) has been used. Every time a ray travels inside a voxel a distance s, equation 7 is used. The expansion coefficients stored in each voxel are used to interpolate the source terms in new directions when rays are cast in the rendering stage. In this stage we obtain the spectrum corresponding to each pixel of the image, no the RGB value. So, two additional problems have to be solved: the pixel´s spectrum has to be converted in to an RGB triplet and all colour information (such as the objects' textures) has to be transformed into spectra. To solve the first problem we have used the CIE colour matching functions [25] and for the second one we have used a method similar to [26].

4 The Ocean as Participating Medium

4.1 Light in the Sea

Oceanic medium can be viewed just as a participating medium: light is scattered and absorbed as it travels through the water. The global effect is the attenuation of the intensity of light which has important consequences: it is a limiting factor for the development of life in water and it it strongly limits visibility making it necessary the use of artificial light beyond certain depths: seeing ranges vary from scarcely one meter in contaminated waters to 30 or 60 meters in very clear ones. So, the design of underwater imaging systems is interesting not only in oceanography but in many different areas such as the marine archaeology, the construction of petrol platforms or the maintenance of submarine cables. The design of these kind of systems can not be based in a trial-and-error scheme because fabrication and placement of underwater systems is extremely expensive. Computer models can play here an important role, allowing an underwater imaging system designer to experiment with different imaging strategies as a function of water quality. The specific case we are trying to solve is related to the problem of tracking submarine cables. Our participating media resolution module would be used to validate and fine tune the digital image treatment system to track power cables (such as the ones that comprise the system of electric energy transport between islands). In these systems, cables are located by means of a sequence of images captured by a camera mounted on an AUV (Autonomous Underwater Vehicle). These images are analysed by appropriated digital imaging systems. Due to the difficulties and the expense of obtaining these kind of images, our application could serve as a device to obtain simulated underwater images to study the performance of different digital imaging systems. A simulation system capable not only to generate images but also radiometric magnitudes, as is our case, will be even more useful.

4.2 Characterising Parameters: Bio-optical Models

The interesting issue about natural waters and, in particular, about the oceanic medium, is that electromagnetic radiation interacts not only with the water but with materials dissolved or suspended in it. This makes ocean phenomenologically rich [27]. Seawater consists in pure sea water, dissolved organic compounds (generally referred to as yellow matter or CDOM -coloured dissolved matter-) and particulate matter both organic (viruses, colloids, bacteria, phytoplankton) and inorganic (created primarily by weathering of terrestrial rocks and soils) [28]. Each of these components contributes in some fashion to the values of the optical properties of a given water body. Bio-optical models try to predict optical properties of water from the concentration of biogenic components. Chlorophyll is a pigment present in all planktonic plants and its concentration in mgm^{-3} is commonly used as the relevant optical measurement of phytoplankton abundance.

Waters can be divided into two categories:

- Case 1 waters, in which the concentration of phytoplankton is high compared to nonbiogenic particles, so that optical properties can be correlated to chlorophyll concentration;

- Case 2 waters, where that correlation does not exist or can not be established.

Roughly 98% of the world's open ocean and costal waters fall into the case 1 category. Estuarine or near-shore waters belong to case 2 category.

Absorption. Water is nearly "opaque" outside the near-ultraviolet to near-infrared wavelengths, henceforth, attention can be restricted to this narrow band. These wavelengths overlap with the wavelengths of the sun's maximum energy output and with a corresponding window in atmospheric absorption. It is this astounding overlap of energy source and open window that has enabled aquatic life to develop. Dissolved salts make seawater a much better conductor of electricity than is pure water, what causes a much higher absorption at very long wavelengths. Yellow matter, detritus and phytoplankton contribution to absorption is relevant. Specially important is the contribution of phytoplankton cells due to their pigments which are strong absorbers of visible light. Absorption by chlorophyll (the most important one) is characterized by strong absorption bands in the blue and in the red with very little absorption in green.

So, depending on the concentrations of dissolved substances, phytoplankton, and detritus, the total spectral absorption coefficient of a given water sample can range from almost identical to that of pure water to one which shows orders-of-magnitude greater absorption than pure water. Morel [29] has proposed a bio-optical model for the spectral absorption coefficient of case 1 waters. All contributions to the absorption coefficient are parameterized in terms of the chlorophyll concentration C (mg m^{-3}):

$$a(\lambda)=\left[a_w(\lambda)+0.06a_c^*(\lambda)\,C^{0.65}\right]\left[1+0.2\exp(-0.014(?-440))\right] \qquad \mathbf{(9)}$$

$a_w(\lambda)$ is the absorption coefficient of pure water (m^{-1}) and $a_c^*(\lambda)$ is non-dimensional chlorophyll-specific absorption coefficient. λ is the wavelength expressed in nm. Chlorophyll concentrations for various waters range from 0.01 mg m^{-3} in the clearest open ocean waters, to 10 mg m^{-3} in productive coastal upwelling regions, to 100 mg m^{-3} in estuaries or lakes.

Scattering. A commonly employed bio-optical model for the total scattering coefficient is that of Gordon and Morel [GoM83]:

$$b(\lambda)=\left(\frac{550}{\lambda}\right)0.30C^{0.62} \qquad \mathbf{(10)}$$

where λ is in nm and C is the chlorophyll concentration in mg m^{-3}.

The phase function can be modelled with two terms:

$$\tilde{\beta}(\Psi) = \frac{b_w(\lambda)}{b(z,\lambda)}\tilde{\beta}_w(\Psi) + \frac{b_p(\lambda)}{b(z,\lambda)}\tilde{\beta}_p(\Psi) \qquad \textbf{(11)}$$

the first one corresponding to the contribution of water molecules and the second one corresponding to particles contribution. The phase function that characterizes scattering in pure sea water is:

$$\tilde{\beta}_w(\Psi) \equiv 0.06225(1 + 0.835\cos^2\Psi) \qquad \textbf{(12)}$$

which is very similar to Rayleigh scattering (almost isotropic) except for the 0.835 factor, attributable to the anisotropy of the water molecules. Nevertheless, as soon as there is a slight amount of particulate matter in the water –always the case for even the clearest water- the phase function becomes highly peaked in the forward direction, and the scattering coefficient increases by at least a factor of ten. The particles cause at least a four-order-of-magnitude increase in scattering between 1° and 90°. Table 3 compares several optical properties for pure sea water and for three different water samples. These data show how greatly different even clear ocean water is from pure sea water. The last column gives the angle Ψ such than one half of the total scattering occurs at angles between 0 y Ψ. This angle is rarely greater than 10° in natural waters.

Water	a (m^{-1})	b (m^{-1})	Ψ(1/2b)(°)
pure sea water	0.0405	0.0025	90.00
clear ocean	0.114	0.037	6.25
coastal ocean	0.179	0.219	2.53
turbid harbour	0.366	1.824	4.68

Table 3. Selected optical properties for different water samples

Figure 1 shows the so-called particle phase function. Highly peaked forward phase functions are characteristic of diffraction-dominated scattering in a polydisperse system (a system containing particles of many different sizes). With regard to the continuous rise even for very small angles, it may be attributed to turbulence.

The scattering coefficient for the water molecules is given by:

$$b_w(\lambda) \equiv 16.06\left(\frac{\lambda_0}{\lambda}\right)^{4.32} \beta_w(90^\circ;\lambda_0) \qquad \textbf{(13)}$$

And the scattering coefficient due to particles can simply be obtained from:

$$b_p(z,\lambda) \equiv b(z,\lambda) - b_w(z,\lambda) \qquad (14)$$

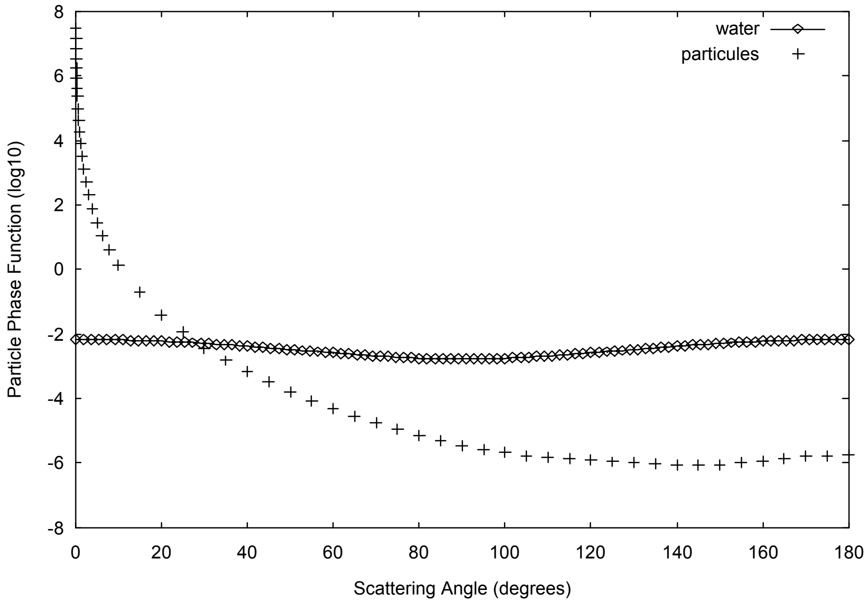

Figure 1. Particle Phase Function.

5. Studying Different Waters

5.1 Adapting our System

The use of highly-peaked forward scattering phase functions give rise to two kind of problems:

1. If the source terms are not a smooth function of direction, the expansion in spherical harmonics does not work

2. If the strong scattering directionality (which means that the angular deviations in the light rays are small) has to be appropriately treated it is necessary to work either to add many more discrete directions to the uniform discretization, or to work with non-uniform discretizations. It should be noted that the privileged scattering direction is different from one voxel to another and is determinated by the position of the voxel relative the light source (see Figure 2).

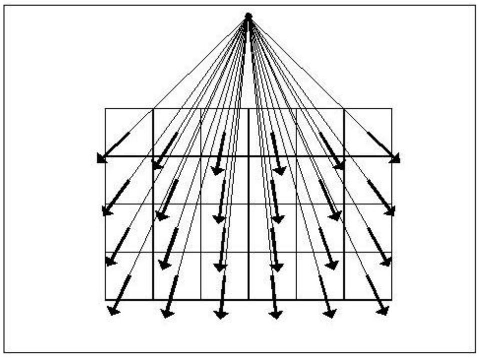

Figure 2. Characteristic directions

To cope with these difficulties and trying to maintain memory requirements as low as possible, we have made two major changes in our simulation strategy:

1. Instead of calculating the spherical harmonics expansion in each voxel, we maintain the source term information in each direction. Instead of interpolating, the concept of "importance" is used to calculate the contribution of each of the source terms in the direction of the ray in the rendering step: the source terms in each direction will contribute according to their magnitude and to their distance (in terms of the cosine of the angle) to the ray direction;

2. In each voxel, a new "characteristic" direction is added to the quadrature (painted bold in Figure 2): the direction is determined by the centre of the voxel and the position of the source (we work, for the moment, with punctual sources). As the rest of the phase function is "smooth", in the uniform discretrization less directions are necessary. The characteristic direction allows to calculate more precisely the first scattering contribution (the most important one) without increasing too much the needs of memory. In the iterative multiscattering process the energy corresponding to the characteristic directions is also distributed throughout the medium.

5.2 Results

An incandescent light source has been placed at a distance of 1 meter from the seabed above the object. A grid of 25x25x25 voxels and a uniform quadrature of 74 directions (plus the characteristic direction) has been used. In order to account for the wavelength dependence of the final colour image the visible spectrum is divided up into 16 values that range from 400 to 700 nm in 20 nm increments. Four different simulations, each of them corresponding to waters with different chlorophyll concentrations, have been carried out and are presented in Figures 3, 4 , 5 and 6.

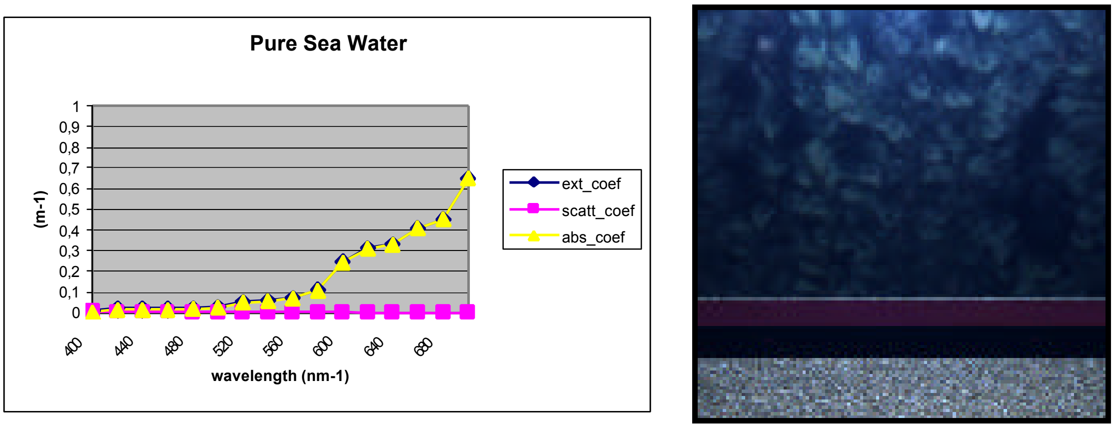

Figure 3. Pure sea water: strong absorption at red wavelengths, very little scattering.

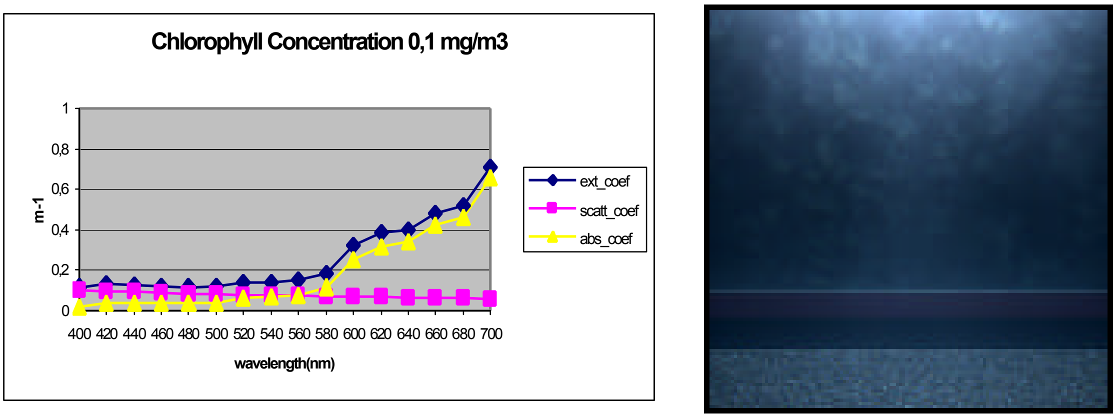

Figure 4. Sea water with very low phytoplankton abundance: scattering increases and colour begins to “move” to green

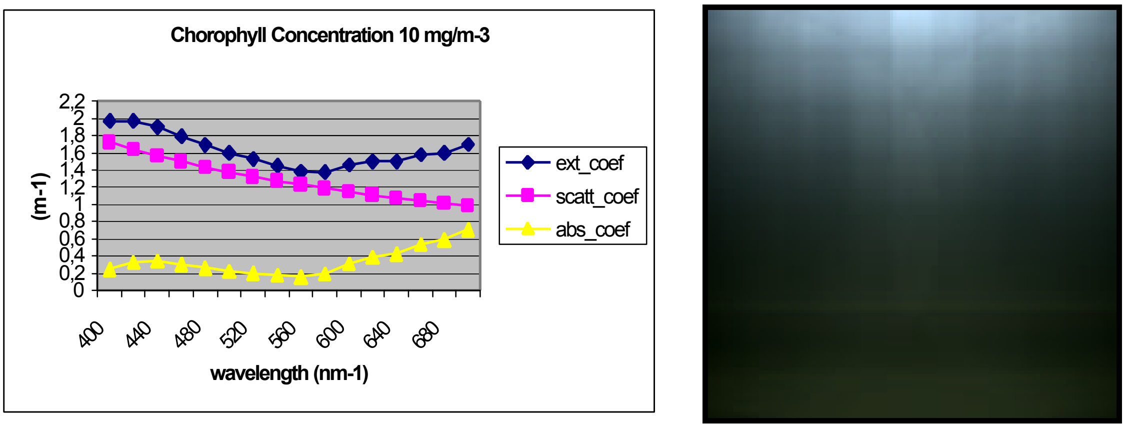

Figure 5. Sea water with important phytoplankton abundance: greater absorption at blue wavelengths, increase of scattering, strong decrease of visibility.

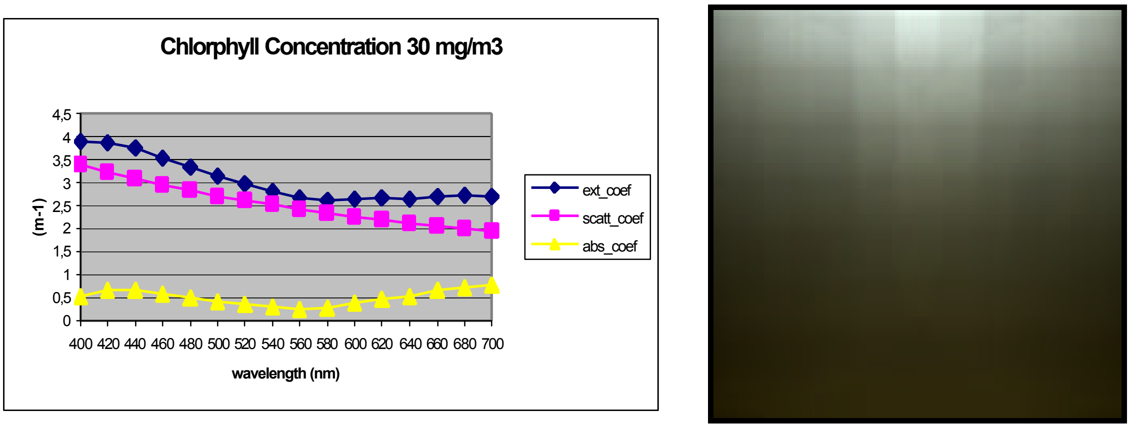

Figure 6. Sea water with very high phytoplankton abundance: strong absorption at blue wavelengths and heavy scattering.

6 Conclusions and Future Work

A couple of simple images calculated in different waters are presented. Results indicate the relevant role played by the spectral behaviour of the absorption and scattering coefficients and by the correct treatment of the phase function in the process of image generation.

This study is part of a wider research line developed by the GIGA (Advanced Computer Graphics Group of the University of Zaragoza) to simulate the behaviour of light in participating media (not only in the visible part of the spectrum). In the case chosen, the visible range, the method developed is used to generate underwater images. The following improvements could be done in this specific area:

- Study of factors such as the nature of the sea bead (algae, sand…) and the spectral radiance on the water surface, due to the sun and the sky contribution
- Consideration of possible inelastic phenomena
- Study of non-homogeneous media.

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