Proceedings of CAD / Graphics'91
September 23–26, Hangzhou
Eds: John Staudhammer and Qunsheng Peng
International Academic Publishers

REALISTIC VISUAL SIMULATION OF WATER SURFACES TAKING INTO ACCOUNT RADIATIVE TRANSFER

Kazufumi Kaneda, Gong Yuan, Yoshiyuki Tomoda,
Masashi Baba, Eihachiro Nakamae
Faculty of Engineering Hiroshima University
4-1, Kagamiyama 1 chome Higashi-hiroshima, 724 Japan

Tomoyuki Nishita
Faculty of Engineering Fukuyama University
Higashimura-cho Fukuyama, 729-02 Japan

Abstract

Realistic image synthesis, including water surfaces, is very important for the visual environmental assessment of shore regions. Many techniques for rendering water surfaces have been developed, but none of them concern themselves with the color of water surfaces under various conditions such as depth and transparency of water, weather conditions, etc. A technique for rendering the color of water surfaces realistically is vital for such visual assessment. This paper proposes a method for rendering realistic water surfaces, especially color, taking into account radiative transfer of light in the water. By using the proposed method, realistic images including water surfaces under various water and weather conditions can be rendered.

Key Words: Realistic Image Synthesis, Water surfaces, Radiative Transfer, Color of Water, Water Waves

1 Introduction

Computer generated images are quite useful for assessing the visual impact of large scale construction, because they are superior to hand drawings and to 3D scale models, which have traditionally been used for visual assessment; computer generated images have the advantage that a much more objective evaluation can be expected [1] and many alternative plans can be easily generated. However, when applying computer graphics to visual assessment, one of the main problems is how to render water such as lakes and the sea. In the case of the development of a shore region, such as the construction of large scale facilities on a reclaimed island, or leisure facilities on the shore of a lake, realistic image synthesis including the surface of water is quite an important element in visual environmental assessment.

Many techniques have been developed to attempt to render the surface of water, especially waves.

In 1981, Max [2] proposed a method for representing ocean waves; he composed two kinds of waves, the cosine waves and Stokes waves, to represent waves of both small and large amplitudes. In order to render the reflection of the sky and islands, a ray-tracing procedural model was employed.

In 1986, Peachey [3] displayed ocean waves approaching a sloping beach. By using particle systems [4], this method can also simulate spray resulting from breaking and from the collision of waves with obstacles. Fournier et al. [5] produced realistic images such as billows and waves with spray and foam by introducing multiple-valued functions to the height of the wave in the modeling, and employed reflection mapping to render the reflection on the wave surfaces. Kirk [6] proposed a method for rendering rippling water surfaces with reflections and refractions distorted by a bump mapping technique.

In 1987, Mastin et al. [7] generated ocean scenes by using the Fourier-transformed white-noise images as texture patterns of the ocean waves. Ts'o et al. [8] modeled wave surfaces by using Beta-spline interpolation, and rendered them through a texture mapping technique; reflected and refracted color assigned to two texture maps are composited taking into account Fresnel's law of reflection [9].

In 1990, Watt [10] displayed the interaction of light with water, such as shadowing and light scattering, by using two pass beam tracing.

The methods described above principally attempt to render the realistic shape of waves. However, none of them concern themselves with the color of water surfaces under various conditions such as depth and transparency of water, weather conditions, etc. A method for rendering the color of water surfaces realistically is vital for the visual environmental assessment of shore regions.

This paper proposes a method for rendering the realistic color of water taking into account scattering and absorption of light due to water molecules and particles in the water. By using the proposed method, photorealistic images of the water surface with reflections can be generated.

In the following sections, the radiative transfer of light in the water, a lighting model when the sun is at the zenith and a geometric model of a water surface are described. Finally, several examples including the water surface are demonstrated.

2 Radiative Transfer of Light in the Water

Light travels in the water repeating the processes of scattering and absorption due to water molecules and suspensions, particles which make water turbid. Scattering and absorption due to water molecules predominate in relatively clear water, while those due to suspensions increase in the turbid water. The degree of light attenuation is represented by the attenuation coefficient, $c(\lambda)$, as the following equation.

$$c(\lambda) = a_m(\lambda) + a_p(\lambda) + b_m(\lambda) + b_p(\lambda); \qquad (1)$$

where $a_m(\lambda)$ is a molecular absorption coefficient, $a_p(\lambda)$ is a suspension absorption coefficient, $b_m(\lambda)$ is a molecular scattering coefficient, and $b_p(\lambda)$ is a suspension scattering coefficient. Among these elements of attenuation, molecular absorption has a relatively large weight, and molecular scattering is relatively small except for light with short wave length.

2.1 Radiative Transfer Equation

A ray of light incident into the water is transmitted by the effects of Reyleigh scattering and Mie scattering due to water molecules and suspensions. Single-scattered light keeps its course, while multi-scattered light can be assumed as diffusion with isotropic intensity.

Let's take the optical system shown in Fig. 1. The radiative transfer equation [11] is expressed by

$$\frac{dN(z,\theta,\phi)}{dr} = -c_\lambda(z)N(z,\theta,\phi) + N_*(z,\theta,\phi). \qquad (2)$$

That is, the first term of Eq. (2) represents the component of attenuation due to absorption, and the second one represents that of scattering. Here, dr is differencial length of optical path ($dr = dz/\cos\theta$), $N(z,\theta,\phi)$ is the radiance distribution at a depth z traveling in a direction (θ,ϕ), $c_\lambda(z)$ is a volume attenuation function, and N_* is given by the following equation.

$$N_*(z,\theta,\phi)$$
$$= \int_0^{2\pi}\int_0^{\pi} \beta_\lambda(z,\theta,\phi:\theta',\phi')N(z,\theta',\phi')\sin\theta' d\theta' d\phi', \quad (3)$$

where β_λ is a phase function for scattering from a direction (θ',ϕ') to (θ,ϕ). In the case of that the distribution of water molecules and suspensions is uniform and a refractive index is constant everywhere in the water, β_λ and the volume attenuation function, $c_\lambda(z)$, are by the following two equations [12].

$$\beta_\lambda(\gamma) = \frac{\beta_{\lambda 0}}{(1 - e_{f\lambda}\cos\gamma)^4(1 + e_{b\lambda}\cos\gamma)^4}, \qquad (4)$$

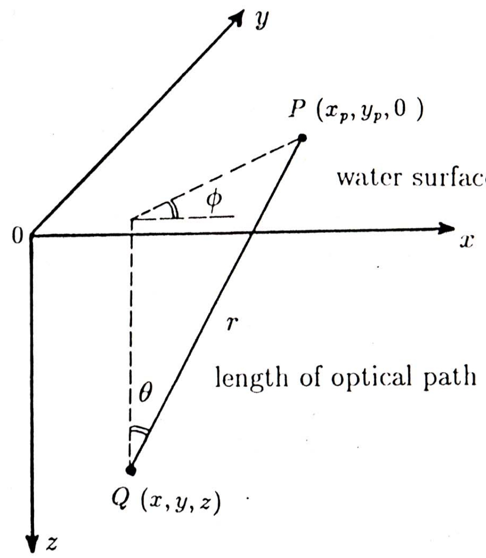

Figure 1: Optical system of radiative transfer.

where the three parameters $\beta_{\lambda 0}$, $e_{f\lambda}$, and $e_{b\lambda}$ have major effects on the magnitude, forward lobe, and backward lobe, respectively, and γ is the angle between the directions (θ', ϕ') and (θ, ϕ).

$$c_\lambda(z) = c_\lambda = a_\lambda + b_\lambda. \tag{5}$$

Here, c_λ, a_λ, and b_λ are attenuation coefficient, absorption coefficient, and scattering coefficient, respectively. The scattering coefficient is given by the following equation.

$$b_\lambda = 2\pi \int_0^\pi \beta_\lambda(\gamma) \sin\gamma d\gamma. \tag{6}$$

2.2 Quasi-Single-Scattering Equation

Gordon and McCluney [13, 14] proposed a quasi-single-scattering (QSS) model based on the radiative transfer equation described above. In the QSS model, the attenuation coefficient, c_λ, is replaced by $c_\lambda(1 - \omega_0 F)$, where ω_0 is the ratio of the scattering coefficient b_λ to c_λ, and F is the fraction of b_λ scattered in a forward direction and is given by the following equation.

$$F = \frac{2\pi}{b_\lambda} \int_0^{\pi/2} \beta_\lambda(\gamma) \sin\gamma d\gamma. \tag{7}$$

If a layer of water with depth z_d is illuminated by collimated irradiance I_i from the zenith, the radiance $N_{z_d}(\theta_i)$ due to the layer leaving the water surface making an angle θ_i with the surface normal is given by the following equation (see Fig. 2).

$$N_{z_d}(\theta_j, \theta_i) = \frac{4I_i}{n(n+1)^2} \frac{T(\theta_j, \theta_i)}{1 + \cos\theta_j} \beta_\lambda(\pi - \theta_j) \frac{\omega_0}{1 - \omega_0 F} \times \left\{1 - \exp\left[-z_d c_\lambda (1 - \omega_0 F)\left(1 + \frac{1}{\cos\theta_j}\right)\right]\right\}, \tag{8}$$

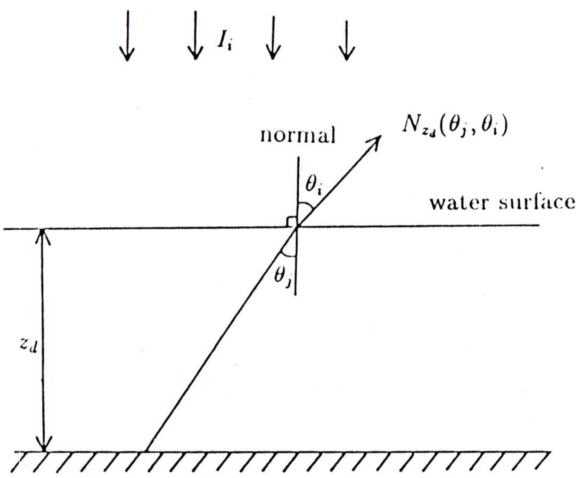

Figure 2: Radiance leaving the water surface based on QSS model.

where n is refractive index of water, and $T(\theta_j, \theta_i)$ is Fresnel transmittance from an angle of θ_j to θ_i and is given by the following equation.

$$T(\theta_j, \theta_i) = \frac{1}{2} \frac{n \cos\theta_i}{\cos\theta_j} \left\{ \left(\frac{2\cos\theta_i \sin\theta_j}{\sin(\theta_i + \theta_j)} \right)^2 + \left(\frac{2\cos\theta_i \sin\theta_j}{\sin(\theta_i + \theta_j)\cos(\theta_i - \theta_j)} \right)^2 \right\}, \tag{9}$$

where the θ_j is the refraction angle obeying Snell's law ($\sin\theta_i / \sin\theta_j = n$).

3 Lighting Model of Water Surfaces

When looking at the point P on the water surface as shown in Fig. 3, the ray of light arriving at the viewpoint consists of two components: reflected light on the water surface and scattered light due to particles within the water leaving the water surface. That is, the intensity of light, I, arriving at the viewpoint is expressed by

$$I = I_r + I_w, \tag{10}$$

where I_r and I_w are the respective intensities of reflected and scattered light.

3.1 Reflected Light

Light reflection on the water surface obeys Fresnel's reflection law; light is reflected in the direction of the reflection angle, which is equal to the incident angle. In this case, reflectance of the water surface is expressed by the following equation.

$$\Gamma(\theta_i, \theta_j) = \frac{1}{2}\left(\frac{\tan^2(\theta_i - \theta_j)}{\tan^2(\theta_i + \theta_j)} + \frac{\sin^2(\theta_i - \theta_j)}{\sin^2(\theta_i + \theta_j)} \right), \tag{11}$$

where θ_i and θ_j are the incident angle and refraction angle, respectively, and obey Snell's law.

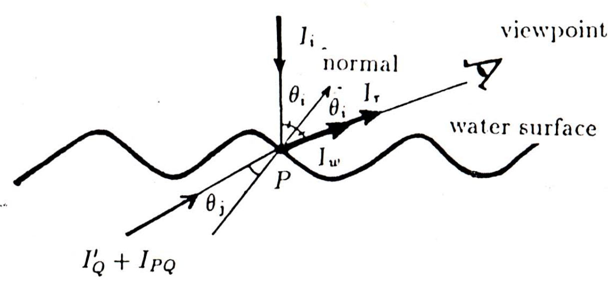

Figure 3: Lighting model for water surface.

Taking into account both direct sunlight and sky light [15] as incident light (ie. $I_i = I_0 + I_s$), reflected light is calculated by using the following equation.

$$I_r = \Gamma(\theta_i, \theta_j)(\delta(\theta_i)I_0 + I_s(\theta_i)), \qquad (12)$$

where $\delta(\theta_i)$ is the function which gives the value 1 when the direction of mirror reflection for the viewpoint is coincident with the direction of direct sunlight, and gives 0 when it is not. I_0 means the intensity of direct sunlight, and $I_s(\theta_i)$ is the intensity of sky light toward the direction of the mirror reflection of the viewpoint and is calculated by refering Eq. (1) in Reference [15].

3.2 Light Leaving the Water Surface

The ray of light leaving the water surface consists of two components (see Fig. 4): reflected light from point Q on the bottom of the water attenuating as it is traveling from Q to P, and scattered light due to particles within the water of depth z_d. That is, the intensity of light, I_w, leaving the water surface and arriving at the viewpoint is expressed by

$$I_w = I'_Q + I_{PQ}, \qquad (13)$$

where I'_Q and I_{PQ} are the respective intensities of the reflected and the scattered light.

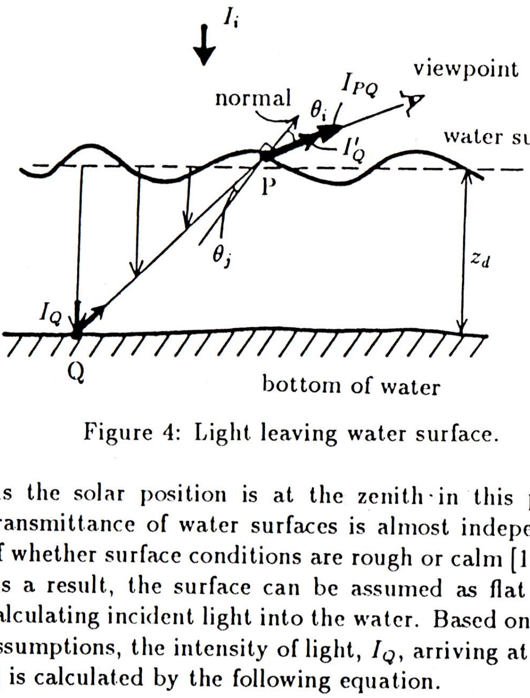

Figure 4: Light leaving water surface.

As the solar position is at the zenith in this paper, transmittance of water surfaces is almost independent of whether surface conditions are rough or calm [16, 17]. As a result, the surface can be assumed as flat when calculating incident light into the water. Based on these assumptions, the intensity of light, I_Q, arriving at point Q is calculated by the following equation.

$$I_Q = T(0,0)I_i \exp(-c_\lambda z_d), \qquad (14)$$

where $T(0,0)$ is Fresnel transmittance when incident light is perpendicular to the surface and is given by using Eq. (9), and I_i is the intensity of sunlight (direct sunlight and sky light). If the bottom of the water is assumed as a perfectly diffuse surface and the diffuse reflectance is R_d, then the intensity of light, I'_Q, arriving at the viewpoint is expressed by

$$I'_Q = R_d I_Q \exp(-c_\lambda r), \qquad (15)$$

where r is the distance between points P and Q.

Taking into account radiative transfer of light in the water, the intensity of scattered light, I_{PQ}, due to particles within the water arriving at the viewpoint is calculated by using Eq. (8).

4 Modeling Water Surfaces

There are many kinds of waves such as a billow, a surge, a ripple, etc. These waves can be modeled by composing various kinds of waves with different amplitudes and wave lengths.

In the proposed method, the modeling of waves is based on a bump mapping technique. Several waves with different amplitudes and wave lengths are generated separately, and they are composited into water surface height data. Height data for each wave are stored in the same format as that of images; height values are assigned to the pixels.

For waves with a relatively large amplitude and wave length, pixel values are calculated by interpolating from the height data given at each grid point. β_2 splines are employed for interpolation, and the height data at the grid points are given by using the Stokes wave equation [18].

$$z(x,t) = \sum_{n=1}^{\infty} a_n \cos nk(x - ct), \qquad (16)$$

where $z(x,t)$ is the height of the waves at time t, a_n is a family of parameters of wave shapes, and k and c are the wave number of cycles per unit distance and wave speed, respectively.

Eq. (16) is modified for a two-dimesional surface by specifying direction variables p and q. A wavey surface can then be discribed by

$$z(x,y,t) = \sum_{n=1}^{\infty} a_n \cos n(px + qy - \omega t), \qquad (17)$$

where $p^2 + q^2 = k^2$, $\omega = kc$, ω is angular frequency.

Controlling the parameters a_n and k, waves with relatively small amplitudes and wave lengths are also calculated by using Eq. (17). In this case, the respective heights of each wave are directly stored in pixels, and the surface normal is generated by the height data of the water surface.

5 Examples

Fig. 5 (a)* shows an example of a fine day. The depth of the the water is 8 meters. The scattering and attenuation coefficients are shown in Table 1.

Fig. 5 (b)* and (c)* show the difference in water color due to the depth of the water in a cloudy day; the depthes of the water in (b) and (c) are 1 and 8 meters, respectively, and the color of the bottom of the water is the same (dark brown) in both figures. These figures demonstrate that the deeper the water is, the more dark bluish the color of the water becomes. Comparing Figs. 5 (a) and (c), the color of the water changes to a light blue because of the reflection of the sky.

Fig. 5 (d)* shows an example of muddy water with a depth of 8 meters. The color of the water becomes slightly greenish; scattering and attenuation coefficients are shown in Table 1.

6 Conclusions

This paper proposes a method for rendering realistic images of water surfaces, especially the color of the water. The calculation of the intensities of reflected light on the water surface and of scattered light leaving the water surface is based on Fresnel's reflection law and on radiative transfer of light in the water. By taking into account both direct sunlight and sky light, more realistic images for the visual environmental assessment of shore regions can be rendered. By using the proposed method, realistic images including water surfaces can be generated under various water conditions such as the depth and the transparency of water under various weather conditions.

References

[1] Nakamae, E., Kaneda, K., Harada, K., Miwa, T., Nishita, T., and Saiki, R. Reliability of Computer Graphics Images for Visual Assessment. *The Visual Computer*, Vol. 7, No. 2 (1991) (to appear).

[2] Max, N. L. Vectorized Procedural Models for Natural Terrain: Waves and Islands in the Sunset. *Computer Graphics*, Vol. 15, No. 3, pp. 317-324 (1981).

[3] Peachey, D. R. Modeling Waves and Surf. *Computer Graphics*, Vol. 20, No. 4, pp. 65-74 (1986).

[4] Reeves, W. Particle Systems — A Technique for Modelling a Class of Fuzzy Objects. *Computer Graphics*, Vol. 17, No. 3, pp. 359-376 (1983).

[5] Fournier, A. A Simple Model of Ocean Waves. *Computer Graphics*, Vol. 20, No. 4, pp. 75-84 (1986).

[6] Kirk, D. B. The Simulation of Natural Features Using Cone Tracing. Proceedings of Computer Graphics Tokyo '86 (Tokyo, 1986) In *Advanced Computer Graphics*, Springer-Verlag, Tokyo, pp. 129-144 (1986).

[7] Mastin, G. A., Watterberg, P. A., and Mareda, J. F. Fourier Synthesis of Ocean Scenes. *IEEE Computer Graphics & Apprications*, Vol. 7, No. 3, pp. 16-23 (1987).

[8] Ts'o, P. Y. and Barsky, B. A. Modeling and Rendering Waves: Wave-Tracing Using Beta-Splines and Reflective and Refractive Texture Mapping. *ACM Transactions on Graphics*, Vol. 6, No. 3, pp. 191-214 (1987).

[9] Hardy, A. C. and Perrin, F. H. Principles of Optics. McGraw-Hill, New York (1932).

[10] Watt, M. Light-Water Interaction using Backward Beam Tracing. *Computer Graphics*, Vol. 24, No. 4, pp. 377-385 (1990).

[11] Preisendorfer, R. W. Radiative Transfer on Discreate Space. Pregamon, New York (1965).

[12] Beardsley, Jr., G. F. and Zaneveld, J. R.V. Theoretical Dependence of the Near-Asymptotic Apparent Optical Properties on the Inherent Optical Properties of Sea Water. *Journal of the Optical Society of America*, Vol. 59, No. 4, pp. 373-377 (1969).

[13] Gordon, H. R. Simple Calculation of the Diffuse Reflectance of the Ocean. *Applied Optics*, Vol. 12, No. 12, pp. 2803-2804 (1973).

Table 1: Scattering coefficient and attenuation coefficient of the three primary colors.

figure	scattering coefficient			attenuation coefficient		
	b_R	b_G	b_B	c_R	c_G	c_B
Fig. 5 (a)	0.03399	0.03500	0.03719	0.41135	0.10853	0.07463
Fig. 5 (d)	0.06798	0.17500	0.07438	0.44535	0.24853	0.11821

*Fig.5 (a)-(d) Refer to Color Plate 43-46 (a) : Example of a fine day (depth 8 meters). (b) : Example of different depths of the water in a cloudy day (depth 1 meter). (c) : Example of different depths of the water in a cloudy day (depth 8 meters). (d) : Example of muddy water (depth 8 meters).

[14] McCluney, W.R. Ocean Color Spectrum Calculations. *Applied Optics*, Vol. 13, No. 10, pp. 2422-2429 (1974).

[15] Nishita, T. and Nakamae, E. Continuous Tone Representation of Three-Dimensional Objects Illuminated by Sky Light. *Computer Graphics*, Vol. 20, No. 4, pp. 125-132 (1986).

[16] Burt, W. V. Albedo over Wind-Roughened Water. *Journal of Meteor.*, Vol. 11, pp. 283-290 (1954).

[17] Cox, C. and Munk, W. Slopes of the Sea Surface Deduced from Photographs of Sun Glitter. *Bull. Scripps Inst. Oceanog Univ. Calif.*, Vol. 6, pp. 401-488 (1956).

[18] Stokes, G. G. Mathematical and Physical Papers. Vol. 1, p. 341, Cambridge University Press (1880).