Display of The Earth Taking into Account Atmospheric Scattering

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Abstract

A method to display the earth as viewed from outer space (or a spaceship) is proposed. The intention of the paper is application to space flight simulators (e.g., reentry to the atmosphere) and the simulation of surveys of the earth (comparisons with observations from weather satellites and weather simulations); it is not for geometric modeling of terrains and/or clouds viewed from the ground, but for displaying the earth including the surface of the sea viewed from outer space taking into account particles (air molecules and aerosols) in the atmosphere and water molecules in the sea.

The major points of the algorithm proposed here are the efficient calculation of optical length and sky light, with lookup tables taking advantage of the facts that the earth is spherical, and that sunlight is parallel.

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I.3.3 [**Computer Graphics**]:Picture/Image Generation
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Key Words: Earth, Atmospheric Scattering, Optical Length, Sky light, Color of Water, Photo-realism, Radiative Transfer

1 INTRODUCTION

Research on image synthesis of realistic 3-D models is one of the most popular fields these days. Displays of natural scenes such as mountains, trees, sea, clouds have been attractively rendered, and an image synthesis of the earth has also been developed. Images of the earth are widely used in movies or TV commercials, e.g., the CG library of earth images[6] was recently released for use in this field. These images, however, are focused on how to create attractive images without any requirement of physical based accuracy. However, physically-based images are required for the study of the simulation of surveys of the earth, such as observation from weather satellites in comparison to weather simulation, and flight simulators in space. The color of the earth when viewed from space varies according to the relationship between the view direction and the position of the sun. In the famous words of the astronaut, "the earth was blue". When we observe the earth from relatively close to the atmosphere, the atmosphere surrounding the earth appears as blue, and the atmosphere near the boundary of the shadow due to the sun appears red (i.e., sunset). The color of clouds also varies according to the sun's position. These phenomena are optical effects caused by particles in the atmosphere, and cannot be ignored. The color of the surface of the sea is not uniform, such as navy blue; it has various colors which depend on incident light to the sea and absorption/scattering effects due to water molecules.

This paper proposes an algorithm of physically-based image synthesis of the earth viewed from space. The method proposed here has the following advantages:

(1) Calculation of the spectrum of the earth viewed through the atmosphere; the earth is illuminated by direct sunlight and sky light affected by atmospheric scattering.

(2) Calculation of the spectrum of the atmosphere taking account of absorption/scattering due to particles in the atmosphere.

(3) Calculation of the spectrum on the surface of the sea taking into account radiative transfer of water molecules.

The major parts in 1) and 2) are concerned with the calculation of optical length and sky light. For these calculations, numerical integrations taking into account atmospheric scattering are required, but they are effectively solved by using several (various) lookup tables making good use of the facts that the shape of the earth is a sphere and that sunlight is a parallel light. For 3), we show that an analytical solution is available instead of numerical integrations.

In the following sections, the basic idea of the lighting model for rendering the color of the earth taking into account atmospheric scattering, rendering the color of clouds, and spectrum calculation of the sea is described. Finally, several examples are demonstrated in order to show the effectiveness of the method proposed here.

2 BASIC IDEAS

In order to render the earth, the following elements should be taken into account: a geometric model of the earth, the atmosphere (air molecules, aerosols), sea, clouds, and the spectrum of the sunlight.

This paper discusses rendering an algorithm of the earth, the atmosphere, sea, and clouds viewed from outer space or various positions within the atmosphere; the following optical characteristics should be considered:

(1) The color of the atmosphere: the atmosphere contains air molecules and aerosols, and scattered sunlight from those particles reaches the viewpoint; the intensity of the light reaching the viewpoint is obtained by integrating scattered light from every particle on the ray, and the light scattered from the atmosphere around the earth also reaches this viewpoint.

(2) The color of the earth's surface: the earth is illuminated by both direct sunlight and sky light. Sunlight is absorbed when light passes through the atmosphere, and sky light consists of light scattered by particles in the air. On the way, passing through the atmosphere the light is attenuated, and its spectrum changes.

(3) The color of the sea: sunlight reaching the surface of the sea is divided into reflected light at the surface and light scattered from water molecules. Both of them pass through the atmosphere and reach the viewpoint.

(4) The color of clouds: sunlight is scattered from particles of clouds, the scattered light is attenuated and reaches the viewpoint.

These phenomena should be simulated as precisely as possible in the calculation of the spectrum of the earth and the atmosphere. As we intend to concentrate on close views of the earth, the bumped terrain model of the earth is used instead of a simple sphere; the continents are modeled by 3D fractals, and the sea is expressed by a sphere consisting of some curved surfaces. Geometric models such as a spaceship are also dealt with.

For hidden surface removal, the scanline algorithm for free form surfaces developed by the authors is employed[11]; the surfaces are expressed by Bézier surfaces.

3 MODELING OF THE EARTH

Even though we may use a modeling in which the earth is treated as a sphere and the land is modeled by bump mapping, we consider the earth as having two components, land and sea: the sea consist of eight cubic Bézier patches, and the land consists of a set of curved surfaces.

The land data is made by mapping small patches onto the sphere, which are subdivided by using fractals after giving the altitude data for each mesh point overlapped onto a world map: the random midpoint displacement algorithm is employed as a fractal.

A scanned image of the map is used as the texture of the land. Therefore the color is not the real color of the earth.

4 SPECTRUM OF THE ATMOSPHERE

Previous work taking account scattering/absorption due to particles include; a) the display of Saturn's rings (reflective ice particles)[1], b) for light scattering from particles in the air, shafts of light caused by spot lights[12], and light beams passing through gaps in the clouds or through trees[8], c) scattered light due to nonuniform density particles such as clouds and smoke[12][4], d) sky color taking account atmospheric scattering[5]. In this paper we focus our discussion on the atmosphere. On this topic, Klassen[5] approximated the atmosphere as multiple layers of plane-parallel atmosphere with uniform density; however, this method results in a large error near the horizon. We discuss here a spherical-shell atmosphere with continuous variation of density in order to improve accuracy. Though his method can only render the color of the sky viewed from a point on the earth, the method discussed here can render the color of the atmosphere viewed from space.

The color of the atmosphere is much influenced by the spectrum of the sunlight, scattering/absorption effects due to particles in the air, reflected light from the earth's surface, and the relationship between the sun's position and the viewpoint (and direction). The sunlight entering the atmosphere is scattered/absorbed by air molecules and aerosol, and ozone layers. The characteristics of scattering depend on the size of particles in the atmosphere. Scattering by small particles such as air molecules is called Rayleigh scattering, and scattering by aerosols such as dust is called Mie scattering. Light is attenuated by both scattering and absorption.

Figure 1: Intensity calculation for the ray intersecting only with the atmosphere.

4.1 Assumptions for Spectrum Calculation

For the spectrum calculation, we use the following assumptions:

(1) The multiple scattering of light between air molecules and aerosols in the atmosphere is ignored because of its negligible values and large computational cost, so only single scattering is considered. The interreflection of light between the earth's surface and particles in the air is also neglected because of the same reasons.

(2) For visible wavelengths, absorption in the ozone layer is negligible compared to absorption by air molecules and aerosols.

(3) The density distributions of air molecules and aerosols are taken into account; their densities vary exponentially with altitude[16].

(4) It is assumed that light travels in a straight line even though the actual path is curved due to the variation of index of refraction with altitudes.

4.2 Atmospheric Scattering

Let's consider scattering due to air molecules and aerosols.

First, single scattering due to air molecules is described. The light reflected due to Rayleigh scattering, I, is generally given by the following equation;

$$I(\lambda,\theta) = I_0(\lambda) K \rho F_r(\theta)/\lambda^4$$
$$K = \frac{2\pi^2(n^2-1)^2}{3N_s} \qquad (1)$$

where I_o is the intensity of incident light, K is a constant for the standard atmosphere (molecular density at sea level), θ the scattering angle (see Fig. 1), F_r the scattering phase function indicating the directional characteristic of scattering (given by $3/4(1+cos^2(\theta)))$, λ the wavelength of incident light, n the index of refraction of the air, N_s the molecular number density of the standard atmosphere, and ρ the density ratio. ρ depends on the altitude h ($\rho = 1$ at sea level) and is given by

$$\rho = exp(\frac{-h}{H_0}), \qquad (2)$$

where H_0 is a scale height ($H_o = 7994$m), which corresponds to the thickness of the atmosphere if the density were uniform.

Eq. (1) indicates that the intensity of scattering is inversely proportional to the 4th power of the wavelength. Short wavelength light is very strongly attenuated by traversing the atmosphere, but long wavelength light is scarcely affected. This is why the sky appears blue in the daytime. Conversely, at sunset or sunrise, the distance traversed by the light increases, and the color of sky changes to red because of increased scattering of short wavelengths. The attenuation coefficient β (i.e., the extinction ratio per unit length) is given by

$$\beta = \frac{8\pi^3(n^2-1)^2}{3N_s\lambda^4} = \frac{4\pi K}{\lambda^4} \tag{3}$$

As shown in Fig.1, the light reaching viewpoint P_v can be obtained as the remainder after scattering and absorption due to air molecules along the path between P_b and P_v. The light at P has been attenuated due to travel in the atmosphere (P_cP), and the light scattering from P is also attenuated before reaching P_v.

To calculate the attenuation caused by particles for light of wavelength λ traversing distance s, we use the optical depth, which is obtained by integrating β of Eq. (3) along the path s. Let's denote the integration variable s and the distance S, then the optical depth is given by

$$t(S,\lambda) = \int_0^S \beta(s)\rho(s)ds = \frac{4\pi K}{\lambda^4}\int_0^S \rho(s)ds \tag{4}$$

Next, single scattering due to aerosols is described. Scattering optics and the density distribution for aerosols differ from air molecules; Eq. (4) is different, too. Because the size range of particles of aerosols is very great, Mie scattering is applied for the phase function in Eq. (1) which exhibits a strong forward directivity. The Henyey-Greenstein function is well known as a phase function. Recently, Cornette[18] improved it, which gives a more reasonable physical expression:

$$F(\theta,g) = \frac{3(1-g^2)}{2(2+g^2)}\frac{(1+cos^2\theta)}{(1+g^2-2gcos\theta)^{3/2}}, \tag{5}$$

where g is an asymmetry factor and given by

$$g = \frac{5}{9}u - (\frac{4}{3} - \frac{25}{81}u^2)x^{-1/3} + x^{1/3},$$
$$x = \frac{5}{9}u + \frac{125}{729}u^3 + (\frac{64}{27} - \frac{325}{243}u^2 + \frac{1250}{2187}u^4)^{1/2},$$

where if $g = 0$ then this function is equivalent to Rayleigh scattering. u is determined by the atmospheric condition (e.g., haze) and wavelength; u varies from 0.7 to 0.85(see [18]).

Like the density distribution of air molecules, the density of aerosols decreases exponentially with altitude, but the rate of decrease is different from that of air molecules. The density can be obtained by setting the scale height, H_o, of Eq. (2) to 1.2km[16].

4.3 Intensity Calculation due to Atmospheric Scattering

Let's discuss a ray from viewpoint P_v to the earth, the light reaching the viewpoint has the following three passes: a) the ray passing through only the atmosphere, b) the ray intersecting with the earth, c) the ray passing through only space. For c) intensity calculation is not required. The calculation methods for a) and b) are described in the following.

4.3.1 Spectrum calculation for only the atmosphere

Figure 2: Intensity calculation for the ray intersecting with the earth.

Let's discuss light scattering due to air molecules on the ray passing just through the atmosphere. The discussion for aerosols is omitted because the optics is similar except for $1/\lambda^4$ dependence. As shown in Fig.1, the light reaching P_v can be obtained as the remainder after scattering and absorption due to air molecules along the intersection line between the ray and the atmosphere, P_bP_a. The intensity of the light scattered at point P (at distance s from P_v) in the direction of P_v, I_p, is obtained by Eq.(1). The light scattered at P is attenuated before arriving at P_v. The intensity of the light arriving at P, I_p, can be obtained by setting the integration interval to P_cP in Eq. (4) of optical depth, that is

$$I_p(\lambda) = I_s(\lambda)KF_r(\theta)\rho\frac{1}{\lambda^4}exp(-t(PP_c,\lambda)), \tag{6}$$

where I_s is the solar radiation at the top of the atmosphere, and $t(PP_c,\lambda)$ the optical depth from the top of the atmosphere to point P (l is the integration variable) and given by

$$t(PP_c,\lambda) = \int_P^{P_c}\beta(l)\rho(l)dl.$$

As the light scattering from P is also attenuated before reaching P_v, the intensity of the light reaching P_v, I_{pv}, can be obtained by multiplying the attenuation by the intensity at P, that is

$$I_{pv}(\lambda) = I_p(\lambda)exp(-t(PP_a,\lambda)). \tag{7}$$

As the distance to the sun can be considered almost infinite, the sunlight can be assumed to be a parallel beam. Thus the scattering angle at every point along P_aP_b can be considered constant. That is, I_v reaching P_v can be obtained by integrating scattered light due to air molecules on P_aP_b:

$$\begin{aligned} I_v(\lambda) &= \int_{Pa}^{Pb} I_{pv}(\lambda)ds \\ &= I_s(\lambda)\frac{KF_r(\theta)}{\lambda^4}\int_{P_a}^{P_b}\rho\ exp(-t(PP_c,\lambda) - t(PP_a,\lambda))ds \end{aligned} \tag{8}$$

4.3.2 Spectrum calculation of the earth

Let's consider the ray intersecting with the earth as shown in Fig.2. The intensity scattered due to particles on the path, P_aP_b, can be obtained in the same manner as the description in 4.3.1. When point P coincides with point P_b (i.e., on the earth surface), the light reaching the viewpoint is obtained by adding reflected light from the earth to the light scattered due to molecules on P_aP_b. The intensity of light reaching viewpoint P_v, I'_v, is expressed by

$$I'_v(\lambda) = I_v(\lambda) + I_e(\lambda)exp(-t(P_aP_b,\lambda)), \tag{9}$$

where I_v is the scattered light of Eq. (8). I_e is reflected light at the earth;the direct component of sunlight and ambient light. The ambient light is mainly sky light. By considering

Figure 3: Calculation of sky light and shadow detection due to the earth.

attenuation of sunlight reaching the earth surface, I_e is given by

$$I_e(\lambda) = r(\lambda)(cos\alpha \; I_s(\lambda) \; exp(-t(P_cP_b, \lambda)) + I_{sky}(\lambda, \alpha)), \tag{10}$$

where $r(\lambda)$ is the diffuse reflection of the earth, α the angle between the normal vector of the earth and light vector (sunlight), and I_{sky} sky light. The direct component is small at the region where α is large (i.e., nearby the boundary of shadow) and tends to be reddish because of its long optical length.

Sky light is scattered light due to particles in the atmosphere. The radiance distribution of sky light can be obtained by setting the viewpoint on the earth in Eq.(8). As we are discussing the earth as viewed from space, shadows caused by obstacles on the surface are ignored, even though we take into account shadows due to the earth itself. That is, for shadow calculation, the earth is assumed to be a sphere with a smooth surface. Sky light due to scattered light from clouds is also ignored here. The illuminance at point Q on the earth due to the whole sky is obtained by using the following method: let's consider an element on a hemisphere whose center is Q (see Fig.3), calculate the intensity at each element on the hemisphere, and project each element onto the base of the hemisphere, then the illuminance is obtained by integrating the intensity of each element by weighting its projected area[13].

I_{sky} is calculated as follows: as shown in Fig.3 (a), the base of the hemisphere is divided into a mesh. Let's consider point P_{ij} on the hemisphere, which is mapped onto the hemisphere of the mesh point p_{ij} inversely, and calculate the intensity in the direction of QP_{ij}. The illuminance due to the whole sky is obtained by adding intensities at every mesh point within the base circle of the hemisphere. As shown in Fig. 3(a), the x-axis is set so that the sun exists on the $x - z$ plane; the region in the half circle (e.g., $y > 0$) is enough to get I_{sky} because of symmetry.

The radiance distribution of the sky is determined by angle α between the normal of the surface of the earth and the direction of the sunlight. Even though the direction of the sunlight is different at each point on the earth, the illuminance due to sky light (integrated values) at any point with the same angle α has the same value (e.g., Q and Q' in Fig.3). This means that the illuminance due to sky light at arbitrary angle α can be obtained by linear interpolation of a precalculated lookup table of I_{sky}. Note that I_{sky} is not zero at regions where there is no direct sunlight ($\alpha > 90$ degrees, e.g., P_s in Fig.3), so that I_{sky} for $\alpha = 0$ to $\alpha = 110$ degrees must be prepared in the lookup table.

4.3.3 Detection of shadow caused by the earth

As shown in Fig.3 (b), point P on the ray exists in the shadow region caused by the earth (we refer to it as a *shadow volume*), the scattered light in this region is zero because there is no incident light. Therefore it is sufficient to consider only attenuation in this region.

As the shadow volume is expressed by a cylinder, which is obtained by sweeping the circle (i.e., the contour of the earth viewed from the sun), the shadow segment on the ray can be calculated as the intersection segment between the cylinder and the ray.

4.3.4 Calculation of optical depth

The optical length of air molecules is calculated by numerical integration of Eq. (4) (in the case of aerosols, the density distribution and the extinction coefficient are different). The optical length is calculated by trapezoidal integration of sampled density. The optical length at sampling point P_i on the ray is obtained by adding the optical length of interval $P_{i-1}P_i$ to the optical length at P_{i-1}. Therefore the integration of the optical depth should start from the viewpoint. The optical length between the light source and point P_i on the ray is also required (e.g., PP_c in Fig.1). This calculation is required at every sampling point on the ray; optimization should be considered because of computational expense. We use a lookup table to save on computation time.

The density distribution of particles in the atmosphere varies exponentially with altitude. This means that the errors in the numerical integration become large when it is performed with a constant interval. Intervals which are inversely proportional to the density are desired; that is small intervals for low altitude and long intervals for high altitude. In order to realize this condition, the atmosphere is assumed as multiple spherical-shells. The radius of each sphere is set so that the difference in density between every adjacent sphere is within a given value. As a result, the difference between the radii of the shell is small for low altitude, and is large for high altitude, as shown in Fig.4. As Rayleigh scattering governs the calculation of optical length, the radius of each sphere is determined by the density distribution of air molecules. Let's consider N layers of spheres. The radius is given by(see Fig. 4)

$$r_i = H_0 log(\rho_i) + R, \quad \rho_i = 1. - i/N, \tag{11}$$

where R is the radius of the earth. For $i = N$, r_N is set to the radius of the atmosphere. For aerosols, the scale height is smaller than that for air molecules; aerosols mainly exist at low altitude. Therefore aerosols exist in the dense radii of shells; this fact assures the correctness of the above mentioned algorithm.

Figure 4: Calculation of optical depth.

The sampling points used in the integration are employed as the intersection points between the ray (view sight or light ray) and the multi-imaginary spheres and these intersection are easily obtained. The density at every sampling point is easily found from the lookup table indexed by the index numbers of the sphere, which is easily get from the altitude of the point.

The optical length between the sun and an arbitrary point on the ray can easily be precalculated because the earth is a sphere and sunlight is parallel light. As shown in Fig.4, let's consider a cylinder defined by sweeping the circle which passes through the center of the earth and is perpendicular to the light direction. Every optical length at the intersection (i.e. circle) between the cylinder and each one of the multi-imaginary spheres is equal (e.g., P and P' in figure). The optical lengths at the intersection points between the cylinders with radius C_j and the spheres with radius r_i is calculated(e.g.,P_aP in fig.) and are stored in the lookup table. The optical depth at arbitrary point P on the ray is easily calculated by linear interpolation, after the radius of the cylinder including P and the radius of the sphere are calculated. The lookup table here is 2D array: $[r_i, C_j]$. After getting indeces i and j from point P, the optical depth can be obtained by linear interpolation from $[r_i, C_j]$,$[r_{i+1}, C_j]$, $[r_{i+1}, C_{j+1}]$,$[r_i, C_{j+1}]$.

As described above, the light intensity of one wavelength reaching the viewpoint can be calculated by numerical integration with respect to pass length. Therefore the light intensity in the range of visible wavelengths (r, g, b in this paper) can be calculated.

5 THE COLOR OF CLOUDS

Since the geometric modeling of clouds is not our main subject, we are displaying the earth as viewed from space, clouds are simply modeled by applying 2D fractals. That is, the density distribution of clouds is expressed by mapping the fractal images of the necessary Mandelbrot set (0.39032+ 0.23775i is used in this paper)[15]. To take into account clouds with various altitudes, multiple imaginary spheres are employed to map fractal images on them.

Their color is determined by the following two light paths. One is on the light which passes through the atmosphere of scattered light due to cloud particles, again passing through the atmosphere, and reaches the viewpoint. Another one is on the light which passes through the atmosphere, reflected light at the earth's surface is attenuated by cloud particles, again passing through the atmosphere. Multiple scattering in clouds is ignored here.

Figure 5: Calculation of color of water surface.

The size of particles in clouds is larger than that of air molecules or of aerosols. Light scattered by such large particles is little influenced by wavelength. (However, the spectrum of incident sunlight onto clouds depends fairly strongly on the sun position.) The light reflected from clouds depends on the phase function (the angle between the view vector and light vector); the phase function is expressed by Eq.(5) (see reference[18] on the value u). In the case of clouds not being illuminated by the sunlight because of the shadow due to the earth; the shadow detection is executed by using the shadow volume described before. The shadows on the earth due to clouds are ignored in this paper. In the near future, a more precise model for clouds is slated in order to get images of the earth viewed from relatively close to the earth's surface.

6 COLOR OF THE SEA

Let's consider the light reaching a viewpoint from the surface of the sea, There are three paths (see Fig. 5): (1) reflected light on the water surface, (2) scattered light due to particles within the water leaving the water surface (3) attenuated light passing through the sea after reaching the bottom of water.

Calculation methods of the color of water have been developed by Max[8], Fournier[2], Ts'o[17], and Mastin[7] . However their methods focused on (1) and shapes of waves, and did not refer to (2)(scattered light due to particles in the water). The method proposed here takes into account (1) and (2). Furthermore the attenuation of the light passing through the atmosphere is taken into account. For (3), the light from the bottom of the sea can be neglected because of the depth of the sea.

When the light is incident to the water surface, the light path is divided into reflection and refraction. The relation between the reflection and refraction on the water surface obeys Fresnel's law of reflection. Incident light is refracted at the water surface; the relation between the incident angle and reflection angle obeys Snell's law. The refracted light is scattered/absorbed by water molecules in the sea, and reaches the viewpoint after refracting at the water surface again. For this phenomena, Gordon and McCluney [3, 9] proposed a quasi-single-scattering (QSS) model based on the radiative transfer equation. However, in the model the sun's position is limited to the zenith. We improved upon this. The light intensity transmitted in water, I_{PQ}, is given by

$$I_{PQ}(\theta_{ii}, \theta_{io}, z) = \frac{I_i(\lambda)T_i(\theta_{ii}, \theta_{i0})T_o(\theta_{ji}, \theta_{jo})\beta(\delta, \lambda)}{n^2(\cos\theta_{io} + \cos\theta_{ji})c(\lambda)[1 - \omega_0(\lambda)F(\lambda)]}$$
$$\times(1 - exp(-zc(\lambda)[1 - \omega_0(\lambda)F(\lambda)](\sec\theta_{ji} + \sec\theta_{io})),$$

(12)

where λ is wave length, z the depth of the sea, θ_{ii} the angle between the surface normal at point P and the direction of the viewing direction, θ_{io} the angle between the direction of the zenith and the direction of incident sunlight, θ_{jo} the angle between the reverse direction of the zenith and the sunlight after refraction, $I_i(\lambda)$ the irradiance of sunlight just above the water surface, n the refractive index of water, T_i and T_o the transmittance of the incident light at point S and P, respectively, $c(\lambda)$ the attenuation coefficient of light which expresses the ratio of lost energy of light when the light travels a unit length, β a volume scattering function ω_0 the albedo of water , and F the fraction of the scattering coefficient in a forward direction. Data of β, ω_0, and F used in this paper is obtained from [10]. Eq. (12) shows that the color of water depends on the depth, the incident angles and viewing direction. The surface of the sea is not flat, and is a spherical surface (i.e., the normal vector of each point on the surface is different); the color of the sea varies according to the position because the incident and viewing angles to the surface normal at each position are different.

As described above, both the incident light to the sea and the color (intensity) of the sea are attenuated by the atmosphere. By using the same method as described in 4.3.2, this effect can be calculated by taking into account two optical lengths; from the sun to the surface and from the surface to the viewpoint.

7 EXAMPLES

Fig. 6 shows an example of the color of the atmosphere. The color of the earth is assumed to be black in order to demonstrate the atmospheric color only. The position of the sun is behind and to the left of the observation point. Even though the earth is assumed to be a black body, it looks blue, and the boundary of the earth is white.

Fig. 7 shows the images of the earth with texture-mapped continents viewed from space; the location of the observation is at altitude 36,000 km, which corresponds to the altitude of the Japanese weather satellite called *Himawari*, at 135°E 0° N and the direction of the sun is 70° E 20° N. In Fig. (a), the color of the sea, direct sunlight, and sky light are taken into account, but the attenuation from the earth to the viewpoint is ignored(i.e., it corresponds to the color when the observer stands on the earth). In Fig. (b), atmospheric scattering/absorption is also taken into account (i.e., the color of the atmosphere is added). In Fig. (c), clouds are added.

Figs. 8,9 show examples of the earth viewed from relatively close-by; the viewpoint is at altitude 500km at 0° E 60° N. The direction of the sun in Fig. 8 is 0° E 20N, and the directions of the sun in Fig. 9 are 200° E 20°N and 240° E 15°N. Fig. 8 corresponds to noon(daytime), and Fig. 9 correspond to evening or dawn sky. In Fig. 9(b), one can observe the shadow (the dark part in the red atmosphere) due to the earth. The color of clouds changes to red due to the change of color of direct sunlight. These examples depict beautiful variations in color of the earth and the atmosphere. The space shuttle in the figure consists of 178 Bézier patches.

Let's show the photographs taken by the first Japanese astronaut aboard space shuttle, Dr. M. Mouri(NASDA), in Fig.10 (altitude 300km, September, 1992). Fig.11 displays the results of our simulation. One may observe differences between the photos and the simulation results. One of the reasons on Fig.11(a) may be due to the poor modeling of clouds and lands. In Fig.(b) some horizontal layers(e.g., orange color) are observed, one of them may be aerosols due to explosion of Volcano in Philippine. These facts suggest the necessity for further researching.

For hidden surface removal, the scanline algorithm for curved surfaces [11] is employed, and for anti-aliasing the multi-scanning algorithm[14] is employed. The calculation was done on an IRIS Indigo Elan. The computation times for Fig.7 (c) and Fig. 9 were 3.8 minutes and 12.0 minutes, respectively(image size=500 x 490).

8 CONCLUSION

We have proposed an algorithm for physically-based image synthesis of the earth viewed from space. As shown in the examples, the proposed method gives us photo-realistic images taking into account the color of the earth, clouds, and the sea. The advantages of the proposed method are as follows:

(1) The spectrum of the surface of the earth is calculated by taking into account direct sunlight and sky light as affected by atmospheric scattering.
(2) The spectrum of the atmosphere is calculated by taking into account absorption/scattering due to particles in the atmosphere.
(3) The spectrum on the surface of the sea is calculated by taking into account radiative transfer of water molecules.
(4) The optical depth and illuminance due to sky light are efficiently calculated by using several lookup tables taking advantages of the facts that the earth is spherical and that sunlight is parallel.

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Figure 6: The color of the atmosphere (the earth is assumed to be black).

Figure 7: The earth viewed from space.

Figure 8: The earth viewed from relatively close-by.

Figure 9: The earth viewed from relatively close-by.

Figure 10: Real photographs from space shuttle (courtesy of NASA).

Figure 11: Comparisons with simulation.