Modeling Daytime and Night Illumination

Cagatay Undeger
Department of Modeling and Simulation
Informatics Institute, Middle East Technical University
Ankara / Turkey
(cagatay@undeger.com)

Keywords: Sun and moon, astronomical modeling, illumination modeling, daytime modeling, night modeling, environment modeling, environmental science

Abstract

Modeling illumination of outdoor objects by natural light sources - the Sun, the Moon and the stars - is a very difficult problem due to highly complex physics of light rays and the Earth's atmosphere. Although there are many studies in the literature on modeling of astronomic and atmospheric phenomena, of emission, scattering and absorption of light rays through the atmosphere, and of the illumination of surfaces; it is very difficult to reach these algorithms, equations and their parameter values readily available in a single source. In this paper, we present an approach that collects available methodologies in the literature into one consistent model for direct (non-scattered) illumination during daytime and at night, which is a part of an ongoing project that started in November 2002.

1. INTRODUCTION

In many military simulation projects, realistic visualisation of the environment and modeling of human eye and optical sensors are important requirements to be satisfied. To develop such a realistic simulation, illumination of the surrounding environment (e.g. terrain, sea and atmosphere), the static terrain features (e.g. houses, bridges, railways) and the dynamic entities (e.g. soldiers, tanks, helicopters) should be determined in high fidelity. The illumination of these outdoor details (object surfaces) is mostly due to the Sun, the Moon and the stars. Therefore, the first step in our approach starts with representation of the date and time, and with determination of the astronomical state (location and/or phase) of the Sun and the Moon with respect to the objects to be illuminated. When we acquire the location of the Sun and the Moon, and the illuminated surface fraction of the Moon, we are then able to compute the amount of light emitted/reflected from these light sources and reached to the outer edge of the atmosphere. The effect of atmosphere is the most complex part of the problem to model since the distance travelled by the light through the atmosphere, the scattering and the absorption of the light due to the air molecules significantly affect the amount of illuminance received by the object surfaces. In this paper, we propose an approach to model the direct light that the object surfaces receive after the reduction of illuminance caused by scattering and absorption. And finally, we present the model to determine the amount of light reflected to the observer by these surfaces. This paper will not focus on modeling the light that a surface receives after one or multiple scattering in the atmosphere.

The organization of the paper is as follows: In Section 2, we present the methodology used to define date and time accurately. In Section 3, the computation of the location and phase of the light sources - the Sun, the Moon and stars - are described. The light emitted/reflected from these light sources is examined in details in Section 4. In Section 5, the approach used to model the travel of the light through the atmosphere is presented, and in Section 6, illumination of object surfaces are examined. And finally, Section 7 is the conclusion.

2. DATE AND TIME

The first step in our modeling is the representation of time. For an accurate determination of time, it is common to use the Julian date (JD), which is the interval of time in days and fractions of a day, since 4713 BC January 1, Greenwich noon (Julian proleptic calendar) [1]. JD is frequently used for precise representation of timescales such as Terrestrial Time (TT) (the astronomical standard for the passage of time on the surface of the Earth) or Universal Time (UT) (a timescale based on the rotation of the Earth). Almost 2.5 million Julian days have elapsed since the initial time. JD 2,400,000 was November 16, 1858, and JD 2,500,000 will be on August 31, 2132 at noon UT. JD is computed using Algorithm 1 [2]. In the algorithm, line 1 checks whether the month is January or February or not, and line 5 checks and braches for Gregorian (starts October 4, 1582) (line 6) or Julian calendar (line 8). Line 9 adds a fraction of hours, minutes and seconds to the days, and finally, line 10 returns the Julian Date.

Algorithm 1. Compute Julian Date (JD)

```
If month < 3 then
    Let year be year - 1
    Let month be month + 12
Let a be integer(year/100)
If year>1582 or ( year=1582 and (month>10 or
(month=10 and day≥4))) then
    Let b be integer( 2 - a + a/4 )
Else
    Let b be zero
Let days be day + hour/24 + minute/1440.0 +
second/86400.0
Let JD be integer(365.25·(year+4716)) +
integer(30.6001·(month+1)) + days + b - 1524.5
```

3. LIGHT SOURCES

3.1. Location of Target

For representing the state of the light sources with respect to the object to be seen (target), we should first define the location of the object, which is assumed to be given in geographic coordinates (longitude and latitude) and sea level elevation in meters. In the following two sections, the formulas for computing the coordinates of the Sun and the Moon relative to the target location will be presented.

3.2. Location of Sun with Respect to Target

To compute the astronomical location of the Sun, we first determine the location with respect to the Earth in geocentric ecliptic coordinates (vertical axis of ecliptic coordinates is the normal to the ecliptic, the plane of the orbit of the Earth about the Sun) (see Figure 1) given in radians λ , β and distance τ in astronomical units, au (1 au = 149,597,870,961 ± 6 m = 23,455 earth radii) using Equation 1 [3]:

$$
\begin{aligned}
T &= (JD - 2451545)/36525 \\
M &= 6.24 + 628.302 \cdot T \\
\lambda &= 4.895048 + 628.331951 \cdot T \\
&\quad +(0.033417 - 0.000084 \cdot T) \cdot Sin(M) \\
&\quad +0.000351 \cdot Sin(2M) \\
\beta &= 0 \\
\tau &= 1.000140 - (0.016708 - 0.000042 \cdot T) \cdot Cos(M) \\
&\quad -0.000141 \cdot Cos(2M)
\end{aligned}
\qquad \textbf{(1)}
$$

Next, we convert (λ, β, τ) to rectangular ecliptic coordinates (see Figure 1) in (x, y, z) using Equation 2 [3]:

$$
\begin{aligned}
x &= \tau \cdot Cos(\lambda) \cdot Cos(\beta) \\
y &= \tau \cdot Sin(\lambda) \cdot Cos(\beta) \\
z &= \tau \cdot Sin(\beta)
\end{aligned}
\qquad \textbf{(2)}
$$

And we convert (x, y, z) to rectangular equatorial coordinates (vertical axis of equatorial coordinates is the North Pole, thus the axis of rotation of the Earth) (see Figure 1) in (x', y', z') using Equation 3 [3]:

$$
\begin{aligned}
E &= 0.409093 - 0.000227 \cdot T \\
x' &= x \\
y' &= y \cdot Cos(E) - z \cdot Sin(E) \\
z' &= y \cdot Sin(E) - z \cdot Cos(E)
\end{aligned}
\qquad \textbf{(3)}
$$

Then we convert and (x', y', z') to geocentric equatorial coordinates (see Figure 1) in (α, δ, υ) using Formula 4, where function $f(v1_{(x,\ y,\ z)}, v2_{(x,\ y,\ z)})$ returns the counter-clockwise (with respect to x/y plane) angle from first vector to second vector:

$$
\begin{aligned}
\alpha &= f((1,0,0),(x',y',0)) \\
\delta &= \begin{cases} f((x,y,0),(x',y',z')) & z' \geq 0 \\ -f((x,y,0),(x',y',z')) & otherwise \end{cases} \\
\upsilon &= \sqrt{x^2 + y^2 + z^2}
\end{aligned}
\qquad \textbf{(4)}
$$

Finally, we convert (α, δ, υ) to local zenith coordinates (see Figure 1) given in azimuth (*heading*) and altitude (*pitch*) in degrees using Algorithm 2 [2], where function *msd(x)* returns mean sidereal time in radians given in Algorithm 3:

Algorithm 2. Convert geocentric equatorial coordinates to local zenith coordinates

```
Let lon and lat be longitude and latitude of
the target in radians respectively
Let ra and de be α and δ in radians
respectively
Let sidereal be msd(JD)·2π/24
Let h be sidereal + lon − ra
Let a be Sin(lat)·Sin(de) + Cos(lat)·Cos(de)·Cos(h)
Let Altitude be ArcSin(a) in degrees
Let zs be Sin(ArcCos(a))
If zs < e^-5 then
    Let Azimuth be π in degrees
    Exit
Let ac be
(Sin(lat)·Cos(de)·Cos(h) − Cos(lat)·Sin(de))/sz
Let as be Cos(de)·Sin(h)/sz
If |as| < e^-5 then
    Let Azimuth be π in degrees
    Exit
Let at be ArcTan(as/ac)
If at < 0 then
    Let at be 2π + at
Let Azimuth be at + π in [0,360) degrees
```

Algorithm 3. Compute Mean Sidereal Time

1. **Let** si **be** $280.46061837 + (360.98564736629)\cdot(JD - 2451545)) + (0.000387933 \cdot T^2) - (T^3 / 38710000)$
   { si is in degrees }
2. **Map** si **to** [0,360) degrees
3. **Return** mean sidereal time **as** $si \cdot 24/360$

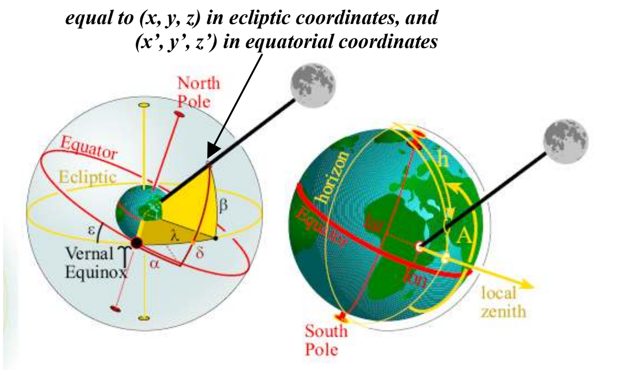

Figure 1. The geocentric ecliptic (*λ, β*) and equatorial (*α, δ*) coordinates; and the rectangular ecliptic (*x, y, z*) and equatorial (*x', y', z'*) coordinates (left); the local zenith coordinates (right) [3].

3.3. Location/Phase of Moon with Respect to Target

For acquiring the location and the phase of the Moon, we first determine the moon location in geocentric ecliptic coordinates in (*δ, β, τ*) using Equation 5, where au (1 astronomical unit) is 149597870 km, and $radii_{earth}$ is 23455 per au.

$$
\begin{aligned}
LU &= 3.8104 + 9399.7091 \cdot T \\
MU &= 2.3554 + 8328.6911 \cdot T \\
MM &= 6.23 + 628.3019 \cdot T \\
DD &= 5.1985 + 7771.3772 \cdot T \\
FF &= 1.6280 + 8433.4663 \cdot T
\end{aligned}
$$

$$
\begin{aligned}
\lambda = LU \quad & +0.1098 \cdot Sin(MU) + 0.0222 \cdot Sin(2DD - MU) \\
& +0.0115 \cdot Sin(2DD) + 0.0037 \cdot Sin(2MU) \\
& -0.0032 \cdot Sin(MM) - 0.002 \cdot Sin(2FF) \\
& +0.001 \cdot Sin(2DD - 2MM) \\
& +0.001 \cdot Sin(2DD - MM - MU) \\
& +0.0009 \cdot Sin(2DD + MU) + 0.0008 \cdot Sin(2DD - MM) \\
& +0.0007 \cdot Sin(MU - MM) - 0.0006 \cdot Sin(DD) \\
& -0.0005 \cdot Sin(MM + MU)
\end{aligned}
$$

$$
\begin{aligned}
\beta = 0.0895 \cdot Sin(FF) & + 0.0049 \cdot Sin(MU + FF) \\
& +0.0048 \cdot Sin(MU - FF) + 0.003 \cdot Sin(2DD - FF) \\
& +0.001 \cdot Sin(2DD + FF - MU) \\
& +0.0008 \cdot Sin(2DD - FF - MU) \\
& +0.0006 \cdot Sin(2DD + FF) \\
\tau = au/(0.016593 & + 0.000904 \cdot Cos(MU) \\
& +0.000166 \cdot Cos(2DD - MU) + 0.000137 \cdot Cos(2DD) \\
& +0.000049 \cdot Cos(2MU) + 0.000015 \cdot Cos(2DD + MU) \\
& +0.000009 \cdot Cos(2DD - MM)) / radii_{earth}
\end{aligned}
\tag{5}
$$

For the conversion of geocentric ecliptic coordinates to local zenith coordinates, the procedures employed for the Sun are similarly applied to the Moon to get its local zenith coordinates.

For the Moon phase, we compute the selenocentric elongation of the Earth from the Sun in radians, *Ø*, which is the ratio of the illuminated surface area of the disk to the total area (the ratio of the illuminated length of the diameter), using Equation 6 [2]:

$$
\begin{aligned}
LE &= ArcCos(Cos(\beta_{moon}) \cdot Cos(\lambda_{sun} - \lambda_{moon})) \\
R &= au \cdot \tau_{sun} \\
\phi &= ArcTan(R \cdot Sin(LE) / (au \cdot \tau_{moon} - R \cdot Cos(LE))
\end{aligned}
\tag{6}
$$

Then, the bright (illuminated) surface fraction of the Moon, p, between 0 (no moon) and 1 (full moon) is computed employing the Moon phase in Equation 7 [2]:

$$
\rho = (1 + Cos(\phi)) / 2 \tag{7}
$$

And finally to determine the side of the bright face of the Moon, in other words to determine whether the bright face is to the right or to the left side of the Moon, Equation 8 is developed. This information is used for visualisation of the Moon.

$$
\begin{aligned}
A_{sun} &= \text{azimuth of the Sun in [0,360) degrees} \\
A_{moon} &= \text{azimuth of the Moon in [0,360) degrees}
\end{aligned}
$$

$$
\begin{cases}
right & (A_{sun} < A_{moon} \;\&\; (A_{moon} - A_{sun}) > 180) \; or \\
 & (A_{sun} > A_{moon} \;\&\; (A_{sun} - A_{moon}) < 180) \\
left\ or\ middle & otherwise
\end{cases}
\tag{8}
$$

3.4. Stars

The position / distribution of stars and other planets are ignored in our model, and total illumination from all stars is used for star light approximation in later sections. For further information about the stars see [3][4] and about the other planets see [2][5].

4. ILLUMINATION OF LIGHT SOURCES

Up to now, we determined the location of the Sun and the location & phase of the Moon. Now we require to compute the light (illuminance) emitted or reflected from these sources and reaching just outside the earth atmosphere. Illuminance is defined as the total luminous flux incident on a surface per unit area [6], and usually measured in lux, which is equal to candela per square meter (cd/m^2).

4.1. Sun

The standard extraterrestrial solar illuminance just outside the atmosphere of the earth when the earth is at a mean distance from the sun on a plane normal to the sun, also called the solar illumination constant (E_{SC}) is taken as 127,500 lux [7]. The extraterrestrial solar illuminance for a given day (E_{ST}) can be estimated employing E_{SC} in Equation 9 [8], where ε is the eccentricity of the earth's orbit that is equal to 0.01672.

$$E_{ST} = E_{SC} \cdot \frac{(1+\varepsilon \cdot Cos(2\pi \cdot (JD-2)/365.2))^2}{1-\varepsilon^2} \qquad \textbf{(9)}$$

This formula can further be simplified and made more efficient by the approximation given in Equation 10 [9].

$$E_{ST} = E_{SC} \cdot (1+0.034 \cdot Cos(2\pi \cdot (JD-2)/365.2)) \qquad \textbf{(10)}$$

4.2. Moon

In order to compute the Moon illuminance, the light reflected from the surface of the Moon should be computed first. The illuminance reflected from the surface of the Moon is caused by two light sources; the direct illuminance from the sun and the indirect illuminance from the Sun reflected by the Earth (earthshine). The direct illuminance, (E_{sm}) is approximately 1300 Watt/m^2 and the indirect illuminance reflected from the earth (E_{em}) is approximately given in Equation 11, where 0.19 Watt/m^2 is the full earthshine, and P_E is the earth phase [3] [10]. Earth phase is (π – $\varnothing$), where $\varnothing$ is the Moon phase computed by Equation 6. For the extreme angles of Moon phase and the Earth phase, *0* and π, the algorithm becomes infeasible. Therefore, $\varnothing$ should be check and corrected for these extreme cases before use (e.g. Let $\varnothing$ be *Maximum Of* (0.0001, *Minimum Of* (π – 0.0001, $\varnothing$)).

$$E_{em} = 0.095 \cdot \left(1 - Sin\left(\frac{P_E}{2}\right) \cdot Tan\left(\frac{P_E}{2}\right) \cdot Ln\left(\frac{1}{Tan\left(\frac{P_E}{4}\right)} \right) \right) \qquad \textbf{(11)}$$

Having E_{sm} and E_{em}, now the extraterrestrial moon illuminance for a given day (E_{MT}) can be computed using Equation 12 [3][10], where 683 stands for converting Watt/m^2 to lux at a monochromatic light wavelength of 555 nm, which is the wavelength human eye is most sensitive to [11][12], R_M is the radius of the Moon (=1737.4 km), τ_{moon} is the distance of the Moon to the Earth computed by Equation 5, and O_{ef} is the opposition effect [13][20] computed using our Equation 13, which is a linear approximation for the data in [13]. The opposition effect is the sudden increase in brightness when the Moon is at opposition (i.e. opposite the Sun) and moon phase is approaching to 0°. In that condition, the Moon is substantially brighter than one would expect due to the increase in the illuminated area (growing from a thin crescent to a full disk), and part to an increase in the intrinsic surface brightness of the part that is in sunlight. The additional brightness in going from 7° to 1° is about 1.27 times according to [13] and 1.3 times according to [20].

$$E_{MT} = 683 \cdot 2/3 \cdot O_{ef} \cdot C \cdot \frac{R_M{}^2}{\tau_{moon}{}^2} \cdot \left(E_{em} + E_{sm} \cdot \left(1 - Sin\left(\frac{\phi}{2}\right) \cdot Tan\left(\frac{\phi}{2}\right) \cdot Ln\left(\frac{1}{Tan\left(\frac{\phi}{4}\right)} \right) \right) \right) \qquad \textbf{(12)}$$

$$\phi_d = \phi \text{ in degrees}$$

$$O_{ef} = \begin{cases} 1.27 - 0.045 \cdot (|\phi_d| - 1) & \phi_d \le 7 \\ 1 & otherwise \end{cases} \qquad \textbf{(13)}$$

4.3. Stars

The total illuminance from all stars reaching the Earth's surface in a clear sky is taken approximately 0.00022 lux [14]. Therefore, the illuminance of all stars just outside the atmosphere (E_{STT}) can be estimated using Equation 14 derived from the inverse function of atmospheric extinction described in later sections. The constant 0.810584 ($e^{-0.21}$) is the atmospheric extinction for a clear sky with moon at 90 degrees altitude.

$$E_{STT} = 0.00022/0.810584 = 0.0002714 \qquad \textbf{(14)}$$

5. LIGHTING THROUGH ATMOSPHERE

In order to illuminate an object on Earth, the light reaching the outer edge of the Earth's atmosphere should go through the atmosphere a long way about 8.4 km in the minimum (see Figure 2). During that period, the light is both absorbed and scattered. By absorption, the power of direct light falling on to the objects are weakened; and by scattering, the power of indirect light falling on to the objects are strengthened. This indirect lighting makes the objects illuminated even in the shadow, thus it has a very important role in object illumination, but the focus of this paper is primarily the direct lighting. For further information on indirect lighting, see [8][19].

The light illuminance from the Sun and the Moon passing through the atmosphere is absorbed during the way, and finally reach to a point on the Earth's surface after some atmospheric extinction. The illuminance reaching on a plane normal to the light ray (E_{DN}) is computed by multiplying the extraterrestrial illuminance just outside the atmosphere for a given day with the light extinction through the atmosphere. E_{DN} is computed using Equation 15 [9], where E is the incoming illuminance (E_{ST}, E_{MT} or E_{STT}), C is the extinction coefficient of the Earth's atmosphere, and m is the optical air mass, the relative distance travelled to the Earth's surface through the atmosphere. The optical air mass is smaller if smaller distance is passed through the atmosphere, and greater vice versa (see Figure 2).

$$E_{DN} = E \cdot e^{-C \cdot m} \qquad \textbf{(15)}$$

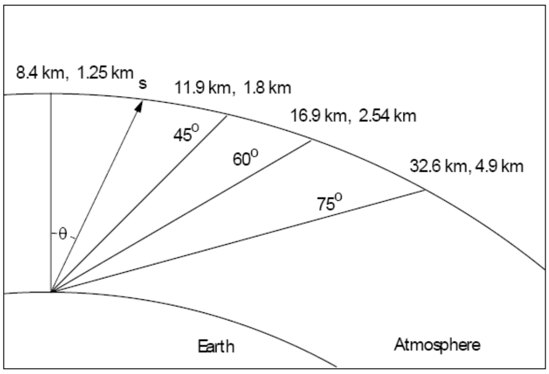

Figure 2. Optical length for different paths in the atmosphere [15]

For a simple model, C is approximately given in Table 1, and m is approximately computed as the inverse of the sine function of the light source (the Sun or the Moon) altitude angle α_s in radian as given in Equation 16. Note that m is 1 when the altitude of the light source is $\pi/2$ (just above the sky).

Table 1. The extinction coefficient of the Earth's atmosphere (simple model)

Sky condition	C
Clear	0.21
Partly cloudy	0.80

$$m = 1/Sin(\alpha_s) \qquad \textbf{(16)}$$

For a more complicated but realistic model, the extinction coefficient of the Earth's atmosphere at wavelength of 555 nm can be computed using Equation 17, and optical air mass can be acquired using Equation 18 [15][16], where turbidity is a measure of fraction of scattering due to haze/fog; in other words, the ratio of the optical thickness of the haze/fog atmosphere to the optical thickness of the pure atmosphere.

$$\begin{aligned} C_{aerosol} &= (0.04608 \cdot turbidity - 0.04586) \cdot 0.555^{-1.3} \\ C_{rayleigh} &= 0.008735 \cdot 0.555^{-4.08} \\ C_{ozone} &= 0.02975 \\ C &= C_{aerosol} + C_{rayleigh} + C_{ozone} \end{aligned} \qquad \textbf{(17)}$$

$$m = \begin{cases} \dfrac{1}{Cos\left(\dfrac{\pi}{2} - \alpha_s\right) + 0.15 \cdot (3.885 + \alpha_s)^{-1.253}} & \alpha_s > -1 \\ 500 & otherwise \end{cases} \qquad \textbf{(18)}$$

This model is determined using the formulas in [15][16][17], and the effect of aerosol, rayleigh and ozone particles' extinctions are taken into account, integrated with a dynamic computation of turbidity considering the meteorological range due to haze or fog.

Turbidity can be estimated using the meteorological range (maximum visible horizontal distance), which is the distance in daytime at which the apparent contrast between a black target and its background at horizon becomes equal to the threshold contrast (0.02) of an observer. We developed Equation 19 by fitting a function to the curve given in [16] (see Figure 3) and by clipping turbidity to fit in range [1.75, 267.81] to prevent extreme values.

$$\begin{aligned} to &= 0.26 \cdot \log_{10}(vr + 0.5) / \log_{10} 4 \\ tt &= \begin{cases} 2^{-2.3 \cdot Ln(to)} & to > 0.03 \\ 2^{-2.3 \cdot Ln(0.03)} & otherwise \end{cases} \\ turbidity &= \begin{cases} tt & tt > 1.75 \\ 1.75 & otherwise \end{cases} \end{aligned} \qquad \textbf{(19)}$$

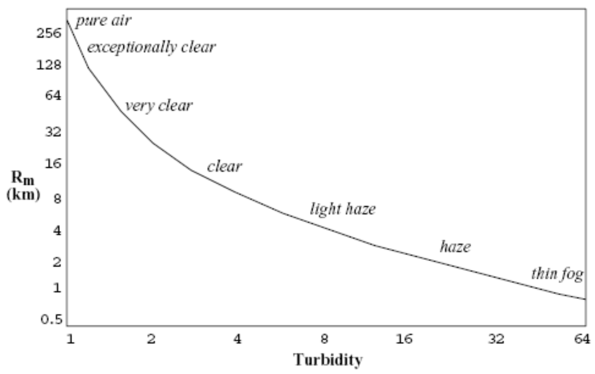

Figure 3. Meteorological range vs. turbidity [16]

6. SURFACE LIGHTING

Using the formulas given in the previous sections, the illuminance reaching on a plane normal to the light ray (E_{DN}) is computed for each light source (the Sun or the Moon). The next step is the computation of the illumination on the surface of an object (E_{DV}) by Equation 20 [9], which is proportional to the cosinus of the angle between the light ray and the surface normal (θ_s).

$$E_{DV} = E_{DN} \cdot Cos(\theta_s) \quad \textbf{(20)}$$

The final step in this paper is the determination of the amount of light reflected to the observer direction (R_{light}). The reflection characteristics of a surface is usually represented as the composition of four approximating basis functions (see Figure 4) namely specular ray (e.g. for mirrors), normal lobe (e.g. for non-glossy surfaces), forescatter lobe (e.g. for glossy surfaces) and backscatter lobe (e.g. for particulate surfaces such as sand or dry soil; and sometimes termed the opposition effect) reflections.

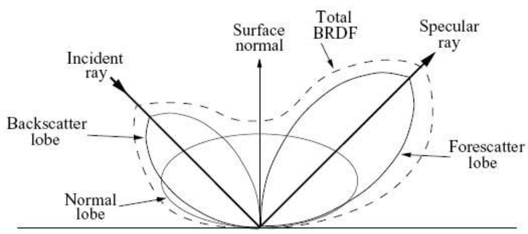

Figure 4. Basis functions of the surface reflection [8]

In our model, we only consider normal lob (diffuse) reflection since it is simple to determine and much of the real-world surfaces in the nature have a high proportion of normal lobe reflection. Incident light reflected about the surface normal, independent of the incident direction, is contained within the normal lobe, and the earliest simplest normal lobe reflection model is that proposed by Lambert [8][18] as given in Equation 21, where K_{norm} is the material normal lobe contribution due to material type and absorption (tone). One may take K_{norm} close to 1 assuming that the surface is dull white. To get the total reflected light, we simply sum up the amount of reflected light received from the Sun, the Moon and the stars.

$$R_{light} = E_{DV} \cdot K_{norm} \cdot \frac{1}{\pi} \quad \textbf{(21)}$$

7. CONCLUSION

In this paper, we have done a comprehensive survey and brought a number of methodologies from the literature all together to develop an approach for modeling the travel of the light all the way from the light sources, the Sun, the Moon and the stars, to the objects to be illuminated in order to correctly model illumination of outdoor surfaces such as terrain, buildings, bridges, soldiers, tanks, aircrafts, etc. We built a consistent model with appropriate algorithms, equations and parameter values that will lead one to implement an object illumination model without the need to refer to any other material.

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Cagatay Undeger received his B.Sc. degree from Kocaeli University in 1998 and went to the Department of Computer Engineering, Middle East Technical University, where he obtained his M.S. degree and Ph.D. degree in 2001 and 2007 respectively. Meanwhile studying towards his M.S degree, he worked as a research assistant at the same department and involved in the first project of Middle East Technical University Turkish Armed Forces Modeling & Simulation Center. After getting his M.S. degree, he worked for Turkish General Staff Scientific Decision Support Center as a modeling and simulation expert from 2001 to 2008; and later on he worked in Meteksan Savunma Sanayii A.Ş., Bilkent Holding as Science and Technology Projects Manager from January to September 2008, and meanwhile he worked at the Department of Computer Engineering, Bilkent University as a part-time instructor. He is currently working at the Department of Modeling and Simulation, Informatics Institute, Middle East Technical University.