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Apparent Spatial Blurring and Displacement of a Point Optical Source Due to Cloud Scattering

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Apparent Spatial Blurring and Displacement of a Point Optical Source due to Cloud Scattering

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Abstract

A Monte Carlo algorithm is used to determine the apparent spatial blurring of a terrestrial 1.07 micron optical point source due to cloud scattering as seen from space. The virtual image of a point source over a virtual source plane area 22.4×22.4 square kilometers arising from cloud scattering was determined for stratus clouds (NASA cloud number 5) and altostratus clouds (NASA cloud model 9) as a function of cloud optical thickness and look angle. Blurring of the optical source arises from photon scattering by cloud water droplets. Displacement of the virtual source is due to the apparent illumination of the cloud top region directly above the actual source which when viewed at a nonzero look angle gives a projected displacement of the apparent source relative to the actual source. These features are quantified by an analysis of the Monte Carlo computational results.

Keywords: satellite, array detector, clouds, scattering, Monte Carlo.

Acknowledgments

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Mathematical Symbols

IJK	IJK coordinate frame with origin at the center of the earth and the K -axis passing through the event.
$\hat{I}, \hat{J}, \hat{K}$	unit vectors parallel to the I -, J -, K -axis, respectively.
$N_{droplet}(r)$	cloud droplet size distribution with respect to droplet radius r particulates/(cm ³ micron).
$D_{droplet}$	density of water droplets in a cloud (droplets/cm ³).
W_{cloud}	density of liquid water in cloud (in units of g/cm ³).
r_d	cloud water droplet mode radius (microns).
$\langle r^2 \rangle$	average square of the droplet radius (microns ²).
$\sigma_{extinction}$	total cloud extinction cross section.
$\sigma_{absorption}$	cloud absorption cross section.
$\sigma_{scatter}$	cloud scattering cross section.
$\langle d_{extinction} \rangle$	mean free extinction path
$\tau_{optical}$	cloud optical thickness (unitless).
$\hat{x}_{E, IJK}$	position of the actual optical point source with respect to the IJK coordinate frame.
$\hat{x}_{N, IJK}$	position of the last scattering center (denoted as the N th scattering center) prior to the photon escaping into space with respect to the IJK coordinate frame.
$\hat{n}_{photon, IJK}$	direction of travel of the photon that escapes from the outer atmospheric sphere with respect to the IJK coordinate frame.
$\hat{x}_{sat, IJK}$	position of a satellite with respect to the IJK coordinate frame.

$\hat{x}_{N/E,IJK}$	vector from $\hat{x}_{E,IJK}$ to $\hat{x}_{N,IJK}$ with respect to the IJK coordinate frame.
$\hat{x}_{P/E,IJK}$	position of a virtual source point with respect to the position of the actual optical source in the IJK coordinate frame.
$\hat{i}_{vs}, \hat{j}_{vs}, \hat{k}_{vs}$	unit vectors defining the direction of the principle axes of the virtual source plane.
$\hat{n}_{sat/E,IJK}$	unit vector specifying direction to satellite with respect to actual optical source in the IJK coordinate frame.
Θ_{LA}	look angle or satellite look angle.
$N_{k,m,n}^{photons}$	photon distribution matrix containing the distribution of escaped photons with respect to look angle (k index) and x and y position (m and n indices, respectively) on the virtual source plane for a given NASA cloud number and cloud optical thickness.
$B_{k,m,n}$	relative virtual source brightness per pixel. k,m,n define look angle and pixel position, respectively.
ϑ_k	lower look angle value for k th look angle bin. Look angle bins are 4° wide.
T_k	effective cloud transmission for a given mean look angle (i.e. k index value).
B_k	total relative virtual source brightness for a given look angle (i.e. k index value).
$\Theta_{mean,k}$	mean look angle associated with k th 4° look angle bin.
N_{pixels}	number of rows and columns in the virtual source plane.
$S_{k,m}$	rectangular superpixel of dimension $1 \times N_c$ where k denotes a mean look angle and m denotes a pixel position along the x -direction.
$x_{mean,k}$	mean displacement of the virtual source image along the x -direction for the k th mean look angle.

1 Introduction

The purpose of this study is to determine the appearance of a terrestrial point optical source as seen through a cloud layer from space. It is the apparent source image that is projected onto the focal plane of an array detector. As a result of cloud photon scattering the source as seen from a distant point in space no longer appears as a point source but rather as a spatially distributed or blurred source. Furthermore, this blurred source appears displaced, unless the observation point is directly overhead, and its total brightness is reduced due to photon absorption. These effects have implications regarding the accuracy to which an actual optical source can be located when viewed from space through clouds and are quantified in this study by means of Monte Carlo calculations.

The Monte Carlo code used for this study is the same as the one used previously to determine the transmission of light through clouds and the cloud response time function [1]. A high level description of the model underlying this Monte Carlo calculation is given in Sec. 2. A brief summary of the NASA cloud models is given in Section 3 including the definition of cloud optical thickness. The new algorithms needed to determine the statistical nature of the apparent optical source are developed in Sec. 4. The results of the Monte Carlo calculations for cloud number 5 (9) are presented in Sec. 5 (8), and our conclusions are summarized in Sec. 6.

2 Description of Monte Carlo Cloud Model

A model has evolved for the purpose of estimating the effects of the atmosphere and clouds on the transport of photons from a point-like source to a distant optical sensor. This model is the basis for a Monte Carlo computational computer code. The atmosphere and a cloud layer are represented geometrically by concentric spherical shells about a spherically shaped earth (Figure 1). Spherical geometry is used as opposed to planar geometry in order to avoid excessive atmospheric absorption effects for light propagating in near-horizon directions. The event is a point like source at a specified altitude above the earth's surface. For any given cloud model, one may assign a cloud optical thickness and a cloud base altitude. A photon traveling within the atmosphere is subject to extinction events. At each extinction event the photon is either absorbed or scattered. Our model considers extinction due to water droplets in clouds, aerosol particulates in the atmosphere, and air molecules. In addition, reflection or absorption of light at the earth's surface is taken into account. The distance between extinction events can be determined from the scattering and absorption coefficients, which are altitude dependent. The Monte Carlo code incorporates the scattering and absorption coefficients for two atmospheric aerosol models, a rural mid-latitude winter model with 0% relative humidity and a tropical maritime model with 80% relative humidity, and the scattering and absorption coefficients for 18 NASA cloud models. These data were available at wavelengths 0.4278, 0.75, and 1.07 microns [2]. The Henyey-Greenstein scattering phase function is used to determine statistically the aerosol and cloud water droplet scattering angles. The scattering coefficient for visible light photons by air molecules is easily calculated [3]. The Rayleigh scattering phase function is used to determine statistically the air molecule scattering angles. Although there are a few weak molecular absorption bands within the visible light band, the effects of molecular absorption are presently neglected. For the purposes of this study, the basic information that this Monte Carlo code returns is the fate of the source photon (was it absorbed or did it escape into space), the vector position of the escaped photon on the outer atmospheric shell, and the unit vector indicating the direction of photon travel. These vectors are specified with respect to the *IJK* coordinate frame defined in Figure 1. The basic algorithms and parameter values on which this Monte Carlo code is based have been presented previously [1].

Figure 1 Schematic showing the basic geometrical features of the cloud model. The K axis has its origin at the center of the earth and passes through the optical event (E). The angle Θ defined by KES is the satellite look angle. The event can be anywhere within the atmosphere.

3 Characterization of Clouds

Some of the characteristics of the NASA cloud models are summarized in Table 1. The cloud droplet particle size distribution $N_{droplet}(r)$ is approximated by [4]

$$N_{droplet}(r) = ar^2e^{-br}. \quad (1)$$

which is in units of particles/(cm³ micron). The parameters a (in units of 1/(cm³ microns³) and b (in units of 1/micron) are unique to each cloud type. The values for a and b and all related parameters for various cloud types can be determined from Eqs. (1) - (4) using the data in Table 1. The density of water particles $D_{droplet}$ (droplets/cm³) in a cloud is

$$D_{droplet} = \int_0^{\infty} N_{droplet}(r) dr = \int_0^{\infty} ar^2e^{-br} dr = \frac{2a}{b^3}. \quad (2)$$

The liquid water content W_{cloud} (in units of g/cm³) is given by

$$W_{cloud} = \frac{4\pi}{3} \int_0^{\infty} ar^5e^{-br} dr = \frac{4\pi \cdot 5! \cdot a}{3b^6} = 502.655 \frac{a}{b^6}. \quad (3)$$

The droplet mode radius r_d corresponds to the maximum in the cloud droplet particle size distribution [Eq. (1)] and corresponds to

$$r_d = \frac{2}{b}. \quad (4)$$

The average square of the radius (in units of microns²) of the water droplet $\langle r^2 \rangle$ is

$$\langle r^2 \rangle = \frac{12}{b^2} = 3r_d^2. \quad (5)$$

The mean geometrical cross section for isotropic scattering is the mean cross sectional area of the water droplet; however, a photon passing very near to the edge of an object will suffer diffraction effects. This effect accounts in part for the peak in the forward optical scattering cross section of micron-size water droplets (see Sec. 5.7.1, Figure 4 of ref. [1]). Consequently, the extinction cross section is larger than the geometric cross section. Since the possibility also exists that a photon encountering a water droplet will be absorbed, the extinction cross section $\sigma_{extinction}$ where

$$\sigma_{extinction} = \sigma_{scatter} + \sigma_{absorption} \quad (6)$$

is given by

$$\langle \sigma_{extinction} \rangle = 2 \cdot \pi \langle r^2 \rangle = 6\pi r_d^2 \quad (7)$$

since $2\pi r_{droplet}/\lambda$ is greater than 30 for 5- to 50-micron size water droplets [5, p. 107; 6, p. 33, Fig. 3.5]. The mean free extinction path $\langle d_{extinction} \rangle$ of a photon in a particular cloud corresponds to

$$\langle d_{extinction} \rangle = \frac{1 \times 10^8 b^5}{48\pi a} \quad (\text{cm}) \quad (8)$$

for a in the units of $1/(\text{cm}^3 \text{ microns}^3)$ and b in units of $1/\text{micron}$, respectively [4, p. 5 - 9].

The optical thickness of a cloud $\tau_{optical}$ is by definition [7, p. 2393, Eq. (3); 8, p. 79]

$$\tau_{optical} = \sigma_{scatter} \int_0^{T_{cloud}} N(z) dz = \langle \sigma_{scatter} \rangle D_{droplet} A_{cloud} = \frac{A_{cloud}}{\langle d_{scatter} \rangle}. \quad (9)$$

$N(z)$ is the density of water droplets as a function of height in the cloud, A_{cloud} is the thickness of the cloud, and $\langle d_{scatter} \rangle$ is the mean free path of the photon between scattering events. The cloud optical thicknesses quoted in Table 1 and our computational results are based on $\langle d_{scatter} \rangle$ for photons of wavelength 0.4278 microns, which are tabulated in Table 4 of reference 1. The value of $\langle d_{scatter} \rangle$ for cloud number 5 and 9, for example, is 53.7 and 64.7 meters, respectively.

Table 1: NASA cloud models [4, p. 6].

Cloud Number	Cloud Description	Base Altitude (m)	Thickness (m)	Cloud Optical Thickness	Water Content (g/m ³)	Mode Radius (microns)	Composition
1	Cumulus	500	500	5.6	0.1	5.5	water
2	Cumulus	1000	3000	115.4	0.5	8.0	water
3	Cumulus	4000	500	4.7	0.1	6.5	water
4	Strato-cumulus	300	2000	55.3	0.2	4.5	water
5	Stratus	150	1000	18.6	0.15	5.0	water
6	Cumulo-nimbus	500	500	5.6	0.1	5.5	water
7	Cumulo-nimbus	1000	9000	551.7	1.0	10.0	water
8	Cumulo-nimbus	10000	2000	2.9	0.1	40.0	ice
9	Altostratus	2000	4000	61.8	0.15	6.0	water
10	Altostratus	6000	4000	1.2	0.02	40.0	ice
11	Alto cumulus	2000	5000	97.1	0.15	4.8	water
12	Cirrus Arctic	4000	2000	0.3	0.005	20.0	ice
13	Cirrus Mid-Latitudes	6000	3000	0.2	0.005	40.0	ice
14	Cirrus Tropic	8000	4000	0.3	0.005	40.0	ice
15	Cirrostratus Arctic	4000	3000	0.5	0.005	20.0	ice
16	Cirrostratus Mid-Latitude	6000	4000	0.3	0.005	40.0	ice
17	Cirrostratus Tropic	8000	5000	0.4	0.005	40.0	ice
18	Nimbostratus	1000	3000	37.3	0.1	5.0	water

4 Monte Carlo Apparent Source Photon Statistics

The basic Monte Carlo code used in this study is the same as that used to determine the cloud response time function and effective transmission of light from a point as seen through clouds by a distant satellite [1]. The basic information supplied by this Monte Carlo code is the fate of the photon: either the photon is absorbed or it escapes into space. If the photon escapes into space, then the photon position vector and unit direction vector with respect to the IJK coordinate frame are supplied. The IJK coordinate frame has its origin at the center of the earth with the K -axis passing through the optical event. This model has axial symmetry about the K -axis. From this basic information the attenuation of the photons through a cloudy atmosphere, the apparent displacement of the source and its associated spatial distribution can be determined. The algorithms which transform this basic data into the desired source statistics are now given.

4.1 Lateral Dispersion of the Virtual Source Image

Let the line of observation be a line from the point source to a distant point of observation. Let the virtual source plane be a plane that contains the actual source point and is perpendicular to the line of observation. The spatial distribution of the virtual source image as seen from a distant point can be determined from that subset of photons which escape the atmosphere and have a direction of travel very nearly parallel to the line of observation. The spatial distribution of the virtual source image belonging to this subset of photons corresponds to the intersection of the trajectory of each photon in the subset with the virtual source plane.

The effects of photon scattering are shown schematically in two dimensions in Figure 2. The line Ea in Figure 2 corresponds to the source plane, and the line ab is very nearly parallel to the line of observation by definition.

This definition of the virtual source image is now translated into an algorithm for determining the spatial distribution of the virtual source image as deduced from the Monte Carlo calculations.

Step 1. Let $\hat{x}_{E,IJK}$ be the position of the actual optical point source with respect to the IJK coordinate frame.

Step 2. Let $\hat{x}_{N,IJK}$ be the position of the last scattering center (denoted as the N th scattering center) prior to the photon escaping into space with respect to the IJK coordinate frame.

Step 3. Let $\hat{n}_{\text{photon},IJK}$ be the direction of travel of the photon that escapes from the outer atmospheric sphere with respect to the IJK coordinate frame.

Step 4. Let $\hat{x}_{\text{sat},IJK}$ be the position of a satellite with respect to the IJK coordinate frame.

Step 5. Let $\hat{x}_{N/E,IJK}$ be the vector from $\hat{x}_{E,IJK}$ to $\hat{x}_{N,IJK}$ with respect to the IJK coordinate frame where

$$\hat{x}_{N/E,IJK} = \hat{x}_{N,IJK} - \hat{x}_{E,IJK}. \quad (10)$$

Step 6. Let $\hat{x}_{P/E,IJK}$ be the vector position of the point on the virtual source plane which is the intersection of photon trajectory with the virtual source plane (e.g. point a in Figure 2).

$\hat{x}_{P/E,IJK}$ is given by

$$\hat{x}_{P/E,IJK} = (\hat{k}_{vs} \times \hat{x}_{N/E,IJK}) \times \hat{n}_{\text{photon},IJK}. \quad (11)$$

Figure 2 Two-dimensional schematic showing a scattered photon trajectory. All positions are relative to the IJK coordinate frame whose origin is the center of the earth. The various surface boundaries are actually portions of concentric spherical surfaces (see Figure 1).

where $\hat{k}_{vs}$ is defined in Eq. (12) below.

Step 7. The appearance of the virtual source image is the same by symmetry for a given satellite look angle Θ_{LA} irrespective of the satellite azimuthal angle with respect to the IJK coordinate frame. In addition, the lateral distribution of the virtual source image as seen from a distant satellite has reflection symmetry through the plane containing the satellite and the unit vector $\hat{K}$. Therefore, the spatial distribution of the virtual source image can be characterized with respect to a virtual source (vs) coordinate frame having its x -axis corresponding to the intersection of the virtual source and reflection planes.

The unit orthogonal vectors $\hat{i}_{vs}$, $\hat{j}_{vs}$, $\hat{k}_{vs}$ which specify the principle axes of the vs coordinate frame are defined as follows:

$$\hat{k}_{vs} = \hat{n}_{\text{photon}, IJK} = \hat{n}_{\text{sat}/E, IJK} \quad (12)$$

$$\hat{j}_{vs} = \frac{\hat{K} \times \hat{n}_{\text{photon,IJK}}}{|\hat{K} \times \hat{n}_{\text{photon,IJK}}|} \quad (13)$$

$$\hat{i}_{vs} = \hat{j}_{vs} \times \hat{k}_{vs} \quad (14)$$

where

$$\hat{n}_{\text{sat/E,IJK}} = \frac{\hat{x}_{\text{sat,IJK}} - \hat{x}_{E,IJK}}{|\hat{x}_{\text{sat,IJK}} - \hat{x}_{E,IJK}|} \quad (15)$$

Only those photons are observable at the satellite whose direction of travel $\hat{n}_{\text{photon,IJK}}$ is essentially the same as the direction from the source to the satellite, which is $\hat{n}_{\text{sat/E,IJK}}$.

Step 8. Location of a virtual source point with respect to the actual source point in the virtual source coordinate frame $\hat{x}_{\text{P/E,vs}}$ is given by

$$\hat{x}_{\text{P/E,vs}} = T_{\text{vs/IJK}} \hat{x}_{\text{P/E,IJK}} \quad (16)$$

where the coordinate transformation $T_{\text{vs/IJK}}$, which transforms a vector in the *IJK* coordinate to the *vs* coordinate frame, is specified by Eqs. (12) - (14).

Step 9. The look angle Θ_{LA} corresponding to a particular source plane is given by

$$\Theta_{LA} = \arccos(\hat{K} \cdot \hat{n}_{\text{sat/E,IJK}}) \quad (17)$$

4.2 Photon Distribution Matrix

In order to evolve an apparent lateral source distribution through a particular cloud layer as a function of Θ_{LA} , each photon that is transmitted through the cloud is identified in terms of its direction of travel Θ_{LA} and respective $\hat{i}_{vs} \cdot \hat{x}_{\text{P/E,as}}$ and $\hat{j}_{vs} \cdot \hat{x}_{\text{P/E,vs}}$ components (note that $\hat{k}_{vs} \cdot \hat{x}_{\text{P/E,vs}} = 0$). The matrix element for a particular $N_{k,m,n}^{\text{photons}}$, called the photon distribution matrix, is incremented by 1 each time a photon escapes from the top of the atmosphere and satisfies the condition that $\vartheta_k \leq \Theta_{LA} < \vartheta_{k+1}$, $x_m \leq \hat{i}_{vs} \cdot \hat{x}_{\text{P/E,vs}} < x_{m+1}$, and $y_n \leq |\hat{j}_{vs} \cdot \hat{x}_{\text{P/E,vs}}| < y_{n+1}$ where the bin limits are given by

$$\vartheta_k = k \cdot 4^\circ, \quad k = 0, 1, \dots, 24 \quad (18)$$

$$x_m = (-N_{\text{pixel}}/2 + m) \cdot w_{\text{pixel}}, \quad m = 0, 1, \dots, N_{\text{pixel}} - 1 \quad (19)$$

$$y_n = (-N_{\text{pixel}}/2 + n) \cdot w_{\text{pixel}}, \quad n = 0, 1, \dots, N_{\text{pixel}} - 1. \quad (20)$$

with w_{pixel} set to 21.875 meters and N_{pixel} equal to 1024. The absolute value of $\hat{j}_{vs} \bullet \hat{x}_{P/E,vs}$ is taken since the final distribution has reflection symmetry through the $\hat{i}_{vs}, \hat{k}_{vs}$ plane. From this histogram of data the lateral distribution of the virtual source image can be determined for each Θ_{LA} as function of x_{vs}, y_{vs} . The complete $N_{k,m,n}^{photons}$ matrix can be reconstructed based on symmetry arguments.

The mesh plots in Figure 4, Figure 7, Figure 21, and Figure 22 are the result of integrating 16×16 pixels to give a 64×64 mesh (rather than a 1024×1024 mesh) over the same area ($22.4 \times 22.4 \text{ km}^2$). There was one photon distribution matrix calculated for each cloud optical thickness and cloud number; the photon distribution matrix $N_{k,m,n}^{photons}$ was calculated for cloud numbers 5 and 9, and cloud optical thicknesses 0 (clear air), 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 50, 100.

4.3 Virtual Source Brightness per Pixel

The $N_{k,m,n}^{photons}$ matrix is renormalized so that it corresponds to the relative virtual source brightness per pixel. This means that if the source were observed in vacuum the total relative source brightness would equal one, assuming an earth reflectivity of zero. The relative source brightness per pixel $B_{k,m,n}$ is given by

$$B_{k,m,n} = \frac{N_{k,m,n}^{photons}}{2\pi [\cos\vartheta_k - \cos\vartheta_{k+1}]} \cdot \frac{4\pi}{N_{source}} \quad (21)$$

The parameter N_{source} is the total number of source photons emitted in the Monte Carlo calculation. The Monte Carlo calculations are terminated when either the number of escaped photons reaches one million or the number of source photons emitted reaches 4.29 billion.

4.4 Effective Transmission and Virtual Source Brightness

If the relative virtual source brightness $B_{k,m,n}$ is summed over the m,n indices, then one gets the total relative virtual source brightness for a given look angle (i.e. k index value). The total relative virtual source brightness B_k corresponds by definition to the effective cloud transmission T_k defined previously [1]. Thus,

$$T_k = B_k = \sum_{m=0}^{(N_{pixels}-1)} \sum_{n=0}^{(N_{pixels}-1)} B_{k,m,n} \quad (22)$$

where k implies a mean look angle of

$$\Theta_{mean,k} = (k + 1/2) 4^\circ \quad (23)$$

and N_{pixels} is the second and third dimension of the $B_{k,m,n}$ matrix. It is necessary that the grid enclose the entire apparent source region; otherwise, the effective cloud transmission and total relative virtual source brightness as deduced from Eq. (22) will be deficient.

5 Computational Results and Discussion

5.1 Computational Model

The model on which these computational results are based assumed a point optical source at an altitude of 10 meters, a rural mid-latitude winter atmosphere, an earth surface reflectivity of 0.4, and a source photon wavelength was 1.07 microns. The top of the atmosphere extended to 30,000 meters. These calculations were done for NASA cloud models 5 and 9 with cloud optical thicknesses of 0 (clear air), 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 50, and 100. The base altitude of cloud number 5 was 150 meters, and base altitude of cloud number 9 was 2000 meters (Table 1). The angular resolution in the look angle was 4° . Photons were projected onto a virtual source plane that had a square width of 22.4 km with the real source at the center. The virtual source plane was divided into a grid consisting of 1024×1024 square pixels having a width of 21.875 meters. Plots pertaining to the analysis of the Monte Carlo calculations for cloud number 5 are presented below with discussion. The corresponding plots for cloud number 9 are contained in the Appendix (Sec. 8).

5.2 Virtual Source Image Profiles

The relative virtual source image brightness per pixel $B_{k,m,n}$ [Eq. (21)] is plotted as a function of x and y in the virtual image plane for fixed k (constant look angle). The x and y plot directions used in Figure 4 through Figure 9 are illustrated in Figure 3 below. These xy plot coordinates are such that the satellite is in the xz reflection plane with $x_{sat} = 0$, $y_{sat} = 0$, $z_{sat} = R_{sat}$. The real point source is at $x_{source} = 0$, $y_{source} = 0$, $z_{source} = 0$. $B_{k,m,n}$ mesh plots and corresponding xz and yz cross sectional plots for cloud number 5, cloud optical thickness 20, and look angles 2° and 74° are shown in Figure 4 through Figure 9 and illustrate some of the important features in the data.

Figure 3 Schematic showing the effects of a cloud layer on the apparent position of a point source as seen from a satellite.

Figure 4 Mesh plot of $B_{k,m,n}$ corresponding to NASA cloud model 5, cloud optical thickness 20, and satellite look angle 2° . Square pixel width here is 350 meters (Sec. 4.2).

Figure 5 Cross sectional plot of $B_{k,m,n}$ in Figure 4 of as a function of x for $y = -175$ meters.

Figure 6 Cross sectional plot of $B_{k,m,n}$ in Figure 4 of as a function of y for $x = 175$ meters.

Figure 7 Mesh plot of $B_{k,m,n}$ corresponding to NASA cloud model 5, cloud optical thickness 20, and satellite look angle 74° . Square pixel width here is 350 meters (Sec. 4.2).

Figure 8 Cross sectional plot of $B_{k,m,n}$ in Figure 7 of as a function of x for $y = -175$ meters.

Figure 9 Cross sectional plot of $B_{k,m,n}$ in Figure 7 of as a function of y for $x = 175$ meters.

5.3 Peak Displacement of the Virtual Source Image

It is of interest to know the displacement of the peak in the virtual source image as seen from a satellite. The values for $B_{k,m,n}$ as deduced from the Monte Carlo calculations were associated with a square pixel width of 21.875 meters. By symmetry, the peak value of $B_{k,m,n}$ (e.g. Figure 8) should be in column (n) 512 and 513, which lie on opposite sides of the x -axis since N_{pixels} is even; the actual source is at (0,0). The center of these columns is offset from the x -axis by plus or minus half a pixel width (10.9375 meters). The x displacement of the peak value from the real source point is plotted in Figure 10 and Figure 11 as a function of look angle for several cloud optical thicknesses. The fluctuations or noise in the peak displacement in Figure 10 and Figure 11 is due to statistical variation in the number of photons collected in each bin of $B_{k,m,n}$. The satellite look angles range in these plots from 2° to 74° in steps of 4° . Beyond approximately 74° , depending upon the cloud optical thickness, the peak becomes buried in the fluctuations of the overall distribution. Without giving up the spatial resolution that is desired, the signal-to-noise in the peak value of $B_{k,m,n}$ was improved by determining the peak in the m super row $S_{k,m}$ where

$$S_{k,m} = \sum_{n=513}^{512+N_c} B_{k,m,n} \quad (24)$$

Figure 10 Plot of the displacement in the peak brightness $S_{k,m}$ [Eq. (24)] versus look angle for cloud number 5 and the cloud optical thicknesses noted on the right. Superpixel column width was 8 pixels wide (175 meters) and the superpixel row width along the x -direction was one pixel (21.875 meters). See Sec. 5.3 for explanation of fluctuations in the data trends.

Figure 11 Continuation of Figure 10 for moderate cloud optical thicknesses.

For cloud number 5, the number of consolidated n columns N_c used in Figure 10 and Figure 11 was 8, and for cloud number 9, the number of consolidated n columns N_c used in Figure 27 and Figure 28 was 64.

5.4 Mean Displacement of the Virtual Source Image

The mean displacement along the x -direction $x_{\text{mean},k}$ for the k th look angle of the virtual source image is defined to be

$$x_{\text{mean},k} = \frac{\sum_{m=0}^{(N_{\text{pixels}}-1)} \sum_{n=0}^{(N_{\text{pixels}}-1)} [m - (N_{\text{pixels}}-1)/2] w_{\text{pixel}} B_{k,m,n}}{\sum_{m=0}^{(N_{\text{pixels}}-1)} \sum_{n=0}^{(N_{\text{pixels}}-1)} B_{k,m,n}} \quad (25)$$

where N_{pixels} is 1024 and the width of the square pixel w_{pixel} is 21.875 meters. The results of this analysis are shown in Figure 12. Because of the asymmetry in the virtual source image along the x -direction (e.g. Figure 8), $x_{\text{mean},k}$ tends to be larger than the corresponding values of x_{peak} found in Figure 10 and Figure 11. The radius of the circle centered on the mean position of the virtual source image which encloses 0.5 of the total intensity of the virtual source image is shown in Figure 13.

Figure 12 Mean displacement of the virtual source in the x -direction as a function of look angle for selected cloud optical thicknesses (cot values noted on right side) for cloud number 5. The significance of the dashed lines is discussed in Sec. 5.5.

Figure 13 Radius of circle which encloses half of the virtual source intensity as a function of look angle and selected values of cloud optical thickness (cot) for cloud number 5. The circle is centered on the mean position of the virtual source image.

5.5 Geometric Displacement Model

An attempt was made to determine the apparent source displacement in terms of a simple geometric model in which the light was emitted from a point source located at an effective cloud top altitude h . The essence of this geometric model is shown in Figure 14. In terms of the parameters in Figure 14, the arc length of the apparent source displacement is ds where

$$ds = R\alpha \quad (26)$$

$$\alpha = \text{asin} \left(\frac{u \sin \theta}{R} \right) \quad (27)$$

$$u = (R + h) \cos \theta - \sqrt{R^2 - [(R + h) \sin \theta]^2}. \quad (28)$$

The displacement ds in this model was least squares fitted to the Monte Carlo mean x displacement in Figure 12 for a given cloud optical thickness as a function of effective cloud top altitude h for respective look angles $\Theta_{\text{mean},k}$. The optimized displacement ds is plotted in Figure 12 and represented by the dashed lines for the corresponding cloud optical thicknesses noted in Figure 12.

Figure 14 Geometric model for estimating the displacement of the source from an effective cloud top height and look angle.

Figure 15 Effective cloud top altitude versus actual cloud top altitude for cloud number 5.

Figure 16 Cloud top height versus cloud optical thickness for cloud number 5.

The results of this simple geometric model corroborate the plausibility of the Monte Carlo results and show the general trends in the apparent source displacement as a function of satellite look angle and cloud optical thickness. The effective cloud top altitude as a function of actual cloud top altitude is shown in Figure 15. The height of the cloud as a function of cloud optical thickness for cloud number 5 is shown in Figure 16.

5.6 Virtual Source Brightness

The total relative virtual source brightness also corresponds to the effective cloud transmission (4.4). The total relative virtual source brightness as seen by a satellite array detector whose field of view just encompasses the 22.4×22.4 square km image source plane is shown in Figure 17 through Figure 20. The virtual image is reasonably well contained on the virtual source image plane for cloud optical thicknesses 0, 1, 5, 10, 20, 30, 50 having look angles less than 78° , 78° , 74° , 74° , 70° , 70° , 66° , respectively, for the case of cloud number 5. These limiting angles were determined by examining data for all cases such as exemplified in Figure 7 through Figure 9. The results in Figure 17 through Figure 20 compare closely to the results of our previous cloud transmission study [1], which corroborates our interpretation of $B_{k,m,n}$ and the numerical results obtained in this study.

Figure 17 Linear plot of total relative source brightness as a function of cloud optical thickness for cloud number 5 for selected satellite look angles (sla).

Figure 18 Semilog plot of the data in Figure 17.

Figure 19 Linear plot of the total relative source brightness as a function of satellite look angle for selected cloud optical thicknesses (cot).

Figure 20 Semilog plot of the data in Figure 19.

6 Summary and Conclusions

The Monte Carlo results presented in this report show that a point optical source viewed through clouds from space appears attenuated, displaced and blurred due to photon absorption and cloud scattering. The total relative source brightness is attenuated as shown in Figure 17 through Figure 20 due to photon absorption by the earth and cloud water droplets. The results of the Monte Carlo calculations suggest a model for the apparent displacement of the source as seen from space. In this model the region near the top of the cloud appears from space to be the source of illumination rather than the actual point source. Consequently, for those cases in which the source is viewed from a nonzero look angle, the projection of this source down to the surface of the earth gives rise to an apparent displacement of the source from its actual position as illustrated in Figure 3 and Figure 14. This apparent displacement in the source is quantified by the Monte Carlo calculations in terms of the displacement of the peak brightness per pixel as shown in Figure 10 and Figure 11 as a function of look angle and cloud optical thickness. The apparent displacement of the source increases with cloud optical thickness and, for a given cloud optical thickness, it also increases with cloud top altitude. The apparent displacement in the source was also characterized in terms of the mean position of the apparent relative source brightness along the x -axis as shown in Figure 12. The angular shape of these curves as a function of cloud optical thickness ($\cot$) is represented approximately by the dashed lines in Figure 12 which correspond to the results of a simple geometric model in which the effective height of the apparent source is optimized (Sec. 5.5). The degree of blurring was characterized in terms of a circle containing 50% of the total relative source brightness and centered on the mean position of the virtual source image (Figure 13). The total relative source brightness, which also corresponds to the effective transmission [1], was characterized in terms of the cloud optical thickness and look angle. Analogous results for cloud number 9 are shown in the Appendix (Sec. 8).

7 References

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8 Appendix: Computational Results for NASA Cloud 9

BA: CN 9, COT 20, SLA 2

Figure 21 Mesh plot of $B_{k,m,n}$ corresponding to NASA cloud model 9, cloud optical thickness 20, and satellite look angle 2° . Square pixel width here is 350 meters (Sec. 4.2)

BA: CN 9, COT 20, SLA 74

Figure 22 Mesh plot of $B_{k,m,n}$ corresponding to NASA cloud model 9, cloud optical thickness 20, and satellite look angle 74° . Square pixel width is 350 meters (Sec. 4.2).

Figure 23 Cross sectional plot of $B_{k,m,n}$ in Figure 21 of as a function of x for $y = -175$ meters.

Figure 24 Cross sectional plot of $B_{k,m,n}$ in Figure 21 of as a function of y for $x = 175$ meters.

Figure 25 Cross sectional plot of $B_{k,m,n}$ in Figure 22 of as a function of x for $y = -175$ meters.

Figure 26 Cross sectional plot of $B_{k,m,n}$ in Figure 22 of as a function of y for $x = 175$ meters.

Figure 27 Plot of the displacement in the peak brightness $S_{k,m}$ [Eq. (24)] versus look angle for cloud number 9 and the cloud optical thicknesses noted on the right. Superpixel column width was 64 pixels wide (1.4 km) and the superpixel row width along the x -direction was one pixel. See Sec. 5.3 for explanation of fluctuations in data trends.

Figure 28 Continuation of Figure 27 for moderate cloud optical thicknesses.

Figure 29 Mean displacement of the virtual source in the x -direction as a function of look angle for selected cloud optical thicknesses (denoted on right side) for cloud number 9. The significance of the dashed lines is discussed in Sec. 5.5. The lack of tailup as the look angle approaches 90° for the larger cloud optical thicknesses is due to the loss of photons scattered outside of the virtual source plane and not being counted.

Figure 30 Radius of circle which encloses half of the virtual source intensity as a function of look angle and selected values of cloud optical thickness (cot) for cloud number 9. The circle is centered on the mean position of the virtual source image. The 50% radii for the larger cloud optical thickness is saturated here due to the finite limits of our photon collection area.

Figure 31 Effective cloud top altitude versus actual cloud top altitude for cloud number 9

Figure 32 Cloud top height versus cloud optical thickness for cloud number 9.

Figure 33 Linear plot of total relative source brightness as a function of cloud optical thickness for cloud number 9 for selected satellite look angles (sla)

Figure 34 Semilog plot of the data in Figure 33.

Figure 35 Linear plot of the total relative source brightness as a function of satellite look angle for cloud number 9 and selected cloud optical thicknesses (cot).

Figure 36 Semilog plot of the data in Figure 35.

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