An Improved Algorithm for Calculating Cloud Radiation

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Abstract. Clouds radiation characteristic is very important in cloud scene simulation, weather forecasting, pattern recognition, and other fields. In order to detect missiles against cloud backgrounds, to enhance the fidelity of simulation, it is critical to understand a cloud's thermal radiation model. Firstly, the definition of cloud layer infrared emittance is given. Secondly, the discrimination conditions of judging a pixel of focal plane on a satellite in daytime or night time are shown and equations are given. Radiance such as reflected solar radiance, solar scattering, diffuse solar radiance, solar and thermal sky shine, solar and thermal path radiance, cloud blackbody and background radiance are taken into account. Thirdly, the computing methods of background radiance for daytime and night time are given. Through simulations and comparison, this algorithm is proved to be an effective calculating algorithm for cloud radiation.

1. Introduction

A Cloud radiation characteristic is very important in cloud scene simulation, weather forecasting, pattern recognition, and other fields. In most cases, the background to a flying missile in space is cloud scenes. In order to detect missiles against cloud backgrounds, to enhance the fidelity of simulation, it is critical to understand clouds’ radiation characteristics. So we must know a cloud’s thermal radiation model very well. Thermal radiation from a cloud includes both cloud thermal emissions along the line of sight and the effect of other thermal emissions scattered into the line of sight, such as scattered sunlight, reflected sky, earthshine, and sun glints.

2. Cloud Radiation Module

We calculated the IR emissivity of a cloud layer from the mixing ratios and effective sizes of cloud ice and snow. The cloud layer infrared emittance $\varepsilon$ at a particular wavelength is defined as

$$\varepsilon = 1 - \exp\left[-\int_{z_{bot}}^{z_{top}} (1 - \omega(z)) \beta(z) \, dz\right]$$

(1)

where $z_{bot}$ is the cloud base height, $z_{top}$ is the cloud top height, $\omega$ is the single-scattering albedo and $\beta$ is the extinction coefficient $\beta$ and $\omega$ can be obtained in terms of the mean effective size and ice water content:

$$\beta = IWC \sum_{n=0}^{2} a_n / D_e^n,$$

$$\omega = 1 - \sum_{n=0}^{3} b_n D_e^n$$

(2)

where $a_n$ and $b_n$ are wavelength-dependent coefficients, and $D_e$ is the effective particle size of nonspherical particles associated with a given size distribution. The mean single-scattering properties are functions of wavelength and depend on the particle size distribution. The effective particle size
provides a measure of the average size of the cloud particles for a given size distribution. Here we define the effective particle size as following [2]:

\[
D_e = \frac{3}{2} \frac{\int_{L_{min}}^{L_{max}} V(L)n(L)dL}{\int_{L_{min}}^{L_{max}} A(L)n(L)dL}
\]

where, \(V\) and \(A\) are the volume and projected area of an ice particle, respectively. \(L_{min}\) and \(L_{max}\) are the minimum and maximum sizes in the size distribution.

The next step is judging whether a pixel of the focal plane stalled on a satellite is in daytime or night time and giving relevant radiance equations.

In order to calculate the radiance for each pixel, some radiant quantities must be interpolated over the solar and observer zenith angles measured relative to the local vertical as well as the altitude. The BRDF must be interpolated over the two zenith angles and azimuth angle that are measured with respect to the surface normal. If the surface normal is not directed toward the observer (\(\theta_o > 90^{\circ}\)), the pixel is assumed to be in shadow, therefore no radiance is returned. Furthermore, if the solar zenith \(\theta_s\) is greater than 90\(^{\circ}\), the pixel is considered to be in “night time”. Thus omit solar scattering and solar path radiance.

For “daytime”, the equation is [3]

\[
L = [H_s \times \cos(\theta_s)]P_b \times O_p + \left( [H_s \times \cos(\theta_s)]P_b \times O_p \times (P_D / 24) + [\varepsilon \times \tau \times L_b \times O_p] \times (1 + P_D / 24) + [P_D \times (L_{ss} + L_{st})] \times (1 + P_D / 24) + [L_{ps} + L_{pt}] \times O_p + L_b \times (1 - O_p) \right)
\]

where, \(H_s\) is solar irradiance, \(\theta_s\) is solar zenith angle measured relative to the cloud surface normal, \(P_b\) is cloud bidirectional reflectance distribution function, \(O_p\) is cloud opacity, \(\varepsilon\) is solar zenith angle measured relative to the local vertical, \(P_D\) is directional reflectance of the cloud, \(\tau\) is directionless emissivity of the cloud, \(\tau\) is transmission from altitude \(z\) to the observer, \(L_b\) is blackbody radiance determined by the local temperature, \(L_{ss}\) is solar sky shine radiance, \(L_{st}\) is thermal sky shine radiance, \(L_{ps}\) is solar path radiance, \(L_{pt}\) is thermal path radiance, \(L_b\) is blackbody radiance determined by the local temperature. In the right hand side of equation (4), the first part represents reflected solar radiance; the second part represents diffuse solar radiance; the third part represents cloud blackbody; the fourth part represents solar and thermal sky shine; the fifth part represents solar and thermal path radiance; the last part represents background radiance.

While for “night time”, solar scattering and the solar path radiance are excluded. The equation is

\[
L = [\varepsilon \times \tau \times L_b \times O_p] + [P_D \times (L_{ss} + L_{st})] + L_{ps} \times O_p + L_b \times (1 - O_p)
\]

The cloud opacity, \(O_p\) is obtained using the cloud extinction, multiplied by the vertical distance between the cloud top and cloud bottom. It is used to adjust the cloud radiance for small optical depth.

\[
O_p = 1 - e^{-(z - z_{bot})}
\]

where, \(x\) is cloud extinction, \(z\) is altitude, \(z_{bot}\) is the altitude of the cloud bottom. The term is proportional to \(P_D / 24\) approximate the diffuse radiance from the cloud’s environment. The background radiance, \(L_{bkg}\), represents the radiance of the underlying terrain. It can be determined from a statistical description of the reflectance of the ground. Given a pair of mean reflectance and variance values, we can calculate a random emissivity for each pixel, and determine the radiance for “night time” conditions using the equation

\[
L_{bkg} = L_b \times \tau \times \varepsilon_g + L_p
\]

where, \(\varepsilon_g\) is emissivity of the ground. In the right hand side of equation (7), the first part represents ground blackbody radiation; the second part represents thermal path radiance.

For daylight conditions, the equation is
\[ L_{\text{bkg}} = L_b \times \tau \times e_g + H_s \times \cos(\theta_s) \times (1 - e_g) + (L_{ps} + L_{pt}) \]  

In the right hand side of equation (8), the first part represents ground blackbody radiation; the second part represents reflected sunlight; the third part represents solar and thermal path radiance.

The mean extinction efficiency calculated for 20 size distributions are shown in figure 1. Figure 2 shows the mean absorption efficiency and figure 3 shows the mean asymmetry factor. Figure 4 shows the variation of mean extinction efficiency. Figure 5 shows the variation of mean absorption efficiency and figure 6 shows the variation of mean asymmetry as a function of wave number.

Figure 1 The mean extinction efficiency ($\lambda=17\mu m$). Figure 2 The mean absorption efficiency ($\lambda=20\mu m$).

Figure 3 The mean asymmetry factor ($\lambda=24\mu m$). Figure 4 The variation of mean extinction efficiency.

Figure 5. The variation of absorption efficiency. Figure 6. The variation of mean asymmetry factor.

3. Conclusion

Through simulations and comparison, this algorithm is proved to be useful in calculation of cloud thermal radiation, cloud scene simulation, and applications where the infrared radiation from a cloud clutter background is needed.

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