# Calculation of Cirrus Cloud Reflectance Based on MODIS Cloud Parameters

**Authors:** Zhao Fengmei, Dai Congming, Wei Heli, Dai Congming

**Date:** 2017-11-01T00:00:00+00:00

## Abstract

Cirrus cloud reflectance is an important parameter of interest in research on weather, climate, and Earth' s energy balance. Fast algorithms for cirrus reflectance have important applications in remote sensing retrieval of cirrus cloud characteristic parameters. Based on the variation of cirrus reflectance with parameters such as cirrus optical thickness, effective particle size, solar zenith angle, viewing zenith angle, and relative azimuth angle, the discrete ordinates method (DISORT) is employed to compute cirrus reflectance, and a fast lookup table describing the variation of cirrus reflectance with relevant parameters is pre-constructed, thereby establishing a rapid algorithm for cirrus reflectance. Using cirrus optical thickness, solar zenith angle, viewing zenith angle, relative azimuth angle, and other factors detected by the MODIS satellite as input parameters, cirrus reflectance was calculated and compared with actual MODIS measurements, yielding a correlation coefficient of 0.94 and a mean bias of less than 18.5%, which demonstrates that the fast algorithm for cirrus reflectance calculation is reasonable and feasible.

## Full Text

## Preamble

### Calculating the Reflectance of Cirrus Clouds Based on MODIS Cloud Parameters

ZHAO Feng-mei[1],[2], DAI Cong-ming[2]*, WEI He-li[1],[2], ZHU Xi-juan[3], MA Jing[3]
[1]School of Environmental Science and Optoelectronic Technology, University of Science and Technology of China, Hefei 230026, China
[2]Key Laboratory of Atmospheric Optics, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Hefei, Anhui 230031, China
[3]Science and Technology on Optical Radiation Laboratory, Beijing Institute of Environmental Features, Beijing, 100854, China

## Abstract

The reflectance of cirrus clouds is a critical parameter in weather, climate, and earth energy balance studies. Fast algorithms for calculating cirrus reflectance play an important role in remote sensing retrieval of cirrus cloud properties. Based on the variation of cirrus reflectance with parameters such as cirrus optical thickness, effective particle size, solar zenith angle, observation zenith angle, and relative azimuth angle, we used the discrete ordinate method (DISORT) to calculate cirrus reflectance and pre-established a fast lookup table (LUT) for cirrus reflectance as a function of these parameters. Using MODIS satellite measurements of cirrus optical thickness, solar zenith angle, observation zenith angle, and relative azimuth angle as input parameters, we calculated cirrus reflectance. A comparison between the calculated reflectance and MODIS measured values yielded a correlation coefficient of 0.94 and an average bias of less than 18.5%, demonstrating that the fast algorithm is reasonable and feasible.

**Keywords:** Cirrus cloud; Reflectance; Calculation; MODIS

## Introduction

Cirrus clouds, typically located in the upper troposphere and lower stratosphere, regulate Earth' s atmospheric radiation budget through three primary mechanisms: reflecting solar radiation (albedo effect), absorbing thermal radiation from the surface and lower atmosphere, and emitting infrared radiation (absorption effect). Unlike warm water clouds, cirrus clouds consist of non-spherical ice crystals with diverse shapes and sizes. Their shape, size, and optical thickness determine whether the albedo effect or absorption effect dominates the earth' s energy balance, making it difficult to accurately quantify the impact of cirrus clouds on the surface-atmosphere system energy budget. This represents one of the unresolved challenges in atmospheric science.

Accurate calculation of cirrus reflectance is essential for remote sensing and atmospheric background radiation studies. The forward model for precisely calculating cirrus reflectance serves as the foundation for retrieving cirrus microphysical properties using scattering methods. Cirrus reflection of solar radiation and emission of thermal radiation have non-negligible effects on optical detection instruments above the troposphere. Thin cirrus clouds also influence clear-sky atmospheric background radiation, making them important for global climate change research. Consequently, cirrus clouds represent both a scientific hotspot and a challenging research problem.

Observations of cirrus clouds primarily include aircraft sampling and remote sensing detection. Satellite remote sensing provides extensive foundational data for improving and validating cloud physical models and climate prediction models. MODIS (Moderate Resolution Imaging Spectroradiometer) measures cirrus reflectance using the 1.375 m water vapor absorption band and its relationship with the 0.645 m band reflectance.

Numerical simulation methods form the basis for remote sensing retrieval of cirrus clouds. Zhao et al. used the line-by-line integration method to calculate atmospheric molecular absorption combined with the discrete ordinate radiative transfer method (DISORT) to establish a radiative transfer model for cirrus conditions, simulating the scattering properties of cirrus composed of solid hexagonal column ice crystals at 1.064  m. Cao et al. used the Combined Atmospheric Radiative Transfer (CART) software to simulate cirrus atmospheric reflectance in the 0.4-2.5  m band, analyzing its variation with wavelength, optical thickness, effective size, cirrus height, and surface type, and examined relationships among reflectance at 0.55  m, 1.38  m, and 2.75  m.

## 1. Method for Calculating Cirrus Reflectance

### 1.1 Average Single-Scattering Properties of Cirrus Clouds

The single-scattering properties of cirrus clouds depend on ice crystal shape, size, and wavelength. Using the scattering property database for several ice crystal types calculated by Yang et al., we employ a Γ distribution to describe the size distribution of ice crystals in cirrus clouds. Combined with spline fitting methods, we can obtain a database of average single-scattering properties for cirrus clouds composed of single ice crystal types across various effective sizes and wavelengths. This study considers particle shape, type, and size distribution, incorporating weighted proportion coefficients for different ice crystal types to derive the average single-scattering properties of cirrus clouds:

Average single-scattering albedo:

$$\varpi = \sum_i D_i P_i \varpi_i$$

Average extinction coefficient:

$$\sigma_{ext} = \sum_i D_i P_i \sigma_{ext,i}$$

Average scattering phase function:

$$P(\Theta) = \frac{\sum_i D_i P_i \sigma_{ext,i} P_i(\Theta)}{\sigma_{ext}}$$

where $i$ represents the $i$-th ice crystal shape, $D_i$ denotes the scale parameter of ice crystals, $P_i$ represents the percentage of the $i$-th ice crystal type, and $\sigma_{ext,i}$ and $P_i(\Theta)$ are the extinction cross-section and phase function, respectively. Current understanding suggests that tropical cirrus clouds are primarily composed of three ice crystal shapes: aggregates, solid hexagonal columns, and bullet rosettes, with corresponding proportion coefficients of 41.6%, 33.7%, and 24.7%, respectively.

[Figure 1: see original paper] shows the variation of average single-scattering albedo and average scattering efficiency factor with effective particle size at 0.66  m wavelength. Figure 1(a) demonstrates that the average single-scattering albedo is essentially close to 1 (all greater than 0.99). Figure 1(b) reveals that when ice crystal particle size is greater than or equal to 20  m, the average scattering efficiency factor is approximately 2, indicating that cirrus clouds at 0.64  m primarily affect visible light through scattering, with absorption contributing only a negligible fraction of extinction.

[Figure 2: see original paper] presents the average phase function as a function of scattering angle. The results show that combining the three ice crystal types produces very strong forward scattering, creating a sharp forward peak in the phase function. Distinct halo peaks appear near scattering angles of 22° and 46°, with a broad maximum between 140°–160° resulting from external and internal reflections. The peak near 7° is primarily due to scattering characteristics of bullet rosette ice crystals.

### 1.2 Construction of Cirrus Reflectance Lookup Tables (LUTs)

DISORT is a method proposed by Chandrasekhar (1950) for solving radiative transfer in planetary atmospheres, applicable across wavelengths from ultraviolet to microwave. Liou (1973a) demonstrated that DISORT is both useful and effective for calculating radiation fields in aerosol and cloudy atmospheres. This study uses the Stamnes DISORT 2.0$\beta$ version to calculate cirrus reflectance, expanding the scattering phase function into Legendre polynomials and applying the $\delta$-fit method to truncate forward scattering coefficients.

Cirrus bidirectional reflectance is defined as:

$$R(\mu_0, \phi_0, \mu, \phi) = \frac{\pi I(\mu_0, \phi_0, \mu, \phi)}{\mu_0 F_0}$$

where $I$ represents radiance, $F_0$ is the solar irradiance at the top of the atmosphere, and $\mu_0, \phi_0, \mu, \phi$ denote the cosine of solar zenith angle, solar azimuth angle, cosine of observation zenith angle, and observation azimuth angle, respectively. Equation (4) shows that cirrus reflectance depends on cirrus optical properties (optical thickness, single-scattering albedo, and phase function) and geometric angles (solar zenith angle, observation zenith angle, relative azimuth angle).

We calculated cirrus reflectance under various solar positions and viewing geometries using DISORT. The solar zenith angle and observation zenith angle both range from 0° to 75° (determined by observation geometry constraints), each with 16 sample points at 5° intervals. The relative azimuth angle between observation and solar directions ranges from 0° to 180° with 19 sample points at 10° intervals. Cirrus optical thickness ranges from 0.002 to 90, and ice crystal effective size is set to 50  m. This establishes a cirrus reflectance database at 0.66  m for various optical thicknesses and solar/observation geometries.

[Figure 3: see original paper] shows cirrus reflectance variation with optical thickness ($\tau$), effective size ($D_e$), solar zenith angle, and relative azimuth angle at 0.66  m. Figure 3(a) demonstrates that cirrus reflectance increases rapidly with optical thickness. When $\tau \geq 3$, the increasing trend continues but the growth rate decreases (reflectance changes minimally when optical thickness exceeds 20, so this range is not shown). When $\tau < 3$, reflectance and optical thickness exhibit an approximately linear relationship. Figure 3(b) shows reflectance variation with ice crystal effective size. For very small particles (e.g., $< 15$  m), reflectance decreases with increasing particle size (particularly at larger optical thicknesses). For larger particles, reflectance shows negligible variation with effective size; therefore, this study fixes particle size at 50  m. Figure 3(c) reveals that cirrus reflectance increases with solar zenith angle; calculations also show reflectance increases with observation zenith angle (not shown). Figure 3(d) indicates that relative azimuth angle has minimal impact on reflectance when less than 20° or greater than 140°, but must be considered at other angles. Overall, optical thickness has the greatest influence on cirrus reflectance, while geometric angles (observation zenith angle, solar zenith angle, relative azimuth angle) have more complex effects that can be considered piecewise. The influence of effective size can be neglected for larger particles.

Based on the established lookup table, given cirrus optical thickness, solar zenith angle, observation zenith angle, and relative azimuth angle, the corresponding cirrus reflectance can be quickly retrieved.

## 2. Calculation Results and Analysis

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key sensor on NASA’ s EOS Terra and Aqua satellites, covering 36 spectral bands from visible to longwave infrared. This study uses MODIS Level 2 cloud product MOD06 and geolocation product MOD03 from the Terra satellite. MOD06 provides cloud optical thickness, effective size, cloud phase, and measured cirrus reflectance. MOD06 cirrus reflectance is derived using a dual-channel algorithm with the 1.38  m water vapor absorption band and visible bands. Since the 1.38  m band is strongly absorbed by water vapor, solar radiation transmitted through cirrus clouds is almost completely absorbed by lower atmospheric water vapor, making the reflected radiation in this band originate solely from cirrus scattering—hence MODIS uses this band for remote sensing of cirrus reflectance.

[Figure 4: see original paper] shows cirrus optical thickness from MOD06 for ice cloud pixels in the region 85°E-115°E, 5°S-10°N at UTC 02:55 on July 13, 2002. Two regions were selected for study: a red box near (90°E, 7°N) and a yellow box near (98°E, 9°N). [Figure 5: see original paper] presents reflectance values quickly retrieved from the lookup table using MODIS cirrus product parameters, with Figures 5(a) and 5(b) corresponding to the red and yellow boxed regions in Figure 4(a), respectively. Black areas in Figures 4 and 5 represent non-ice cloud pixels. Comparison of Figures 4(b) and 5(a) shows that calculated cirrus reflectance variations correspond well with optical thickness variations.

[Figure 6: see original paper] displays cirrus reflectance values read directly from MOD06, with Figures 6(a) and 6(b) corresponding to the red and yellow boxed regions in Figure 4. Comparison of Figures 5 and 6 demonstrates that reflectance values calculated from the fast lookup table are consistent with MODIS measurements. MOD06 cirrus optical thickness and effective size are retrieved using the Nakajima-King method applied to atmospheric window channels at 1.6  m and 2.1  m. The consistency between our LUT-calculated reflectance and MODIS-measured reflectance, derived from different remote sensing mechanisms, validates the effectiveness of using DISORT with actual cirrus parameters and confirms the correctness of our fast algorithm.

[Figure 7: see original paper] compares calculated and observed cirrus reflectance for different pixels. Analysis reveals a correlation coefficient of 0.94. Except for a few outliers, calculated values are slightly higher than observed values, with a fitted slope of 1.1. Potential error sources include: MODIS quantitative remote sensing errors for very thin cirrus, leading to larger relative errors at small optical thicknesses; resolution mismatches between infrared channels used for cloud phase/retrieval and the 1.38  m channel; differences between assumed ice crystal shape proportions and actual particle compositions; and potential errors in MODIS cirrus reflectance retrieval for mixed ice-water cloud pixels.

To further validate the algorithm’ s applicability across different regions, we analyzed a mid-to-high latitude area (38°N, 128°E) at UTC 02:05 on July 12, 2002. Similar to Figure 7, calculated and observed reflectance values show consistent trends, though the average relative error is slightly larger at 18.5%. Since ice crystal shapes in mid-to-high latitude cirrus are more complex, the LUT developed for low-latitude cirrus may introduce larger errors in these regions.

[Figure 8: see original paper] shows the mean calculated and observed reflectance values for different optical thickness ranges (each value represents a range of $\tau$). The results indicate that mean calculated values are slightly higher than mean observed values across all optical thickness ranges, consistent with Figure 7. The overall average relative error is 16.8%, decreasing with increasing optical thickness. The maximum relative error of 20% occurs when optical thickness is 0–1, while the minimum error of approximately 7.8% occurs when optical thickness exceeds 7. Relative error shows some fluctuation when optical thickness is 1–3 due to individual pixels with large optical thickness but small measured values, possibly caused by instrument limitations and environmental factors leading to cirrus misidentification.

## Conclusion

This study simulated cirrus reflectance composed of three ice crystal types, demonstrating that cirrus reflectance increases with optical thickness and exhibits complex geometric relationships with solar and observation angles. We developed a fast algorithm for cirrus reflectance using a pre-established lookup table with interpolation, which has important applications for rapid remote sensing retrieval of cirrus properties. Using cirrus optical properties from MOD06 as inputs, calculated reflectance values agree well with MODIS 1.38  m observations, with a fitted slope of 1.1 and average relative error of 16.8% in low-latitude regions, and 18.5% in mid-to-high latitude regions. These results validate our DISORT-based fast lookup table algorithm for cirrus reflectance. Future work will extend this algorithm to all wavelengths for retrieval of cirrus optical and microphysical parameters, and for studying atmospheric and cloud radiative properties in cirrus backgrounds.

**Acknowledgments:** We thank NASA Goddard Earth Sciences Distributed Active Archive Center (GES DAAC) for providing MODIS Level 2 cloud product data.

## References

1. Dowling D R, Radke L F. A Summary of the Physical Properties of Cirrus Clouds[J]. Journal of Applied Meteorology, 1990, 29(9): 970-978.
2. K.N. LIOU. Atmospheric Radiation (Second Edition)[M]. Translated by Guo Caili, Zhou Shijian. Beijing: China Meteorological Press, 2004.
3. Goldfarb L, Keckhut P, Chanin M, et al. Cirrus climatological results from lidar measurements at OHP (44°N, 6°E)[J]. Geophysical Research Letters, 2001, 28(9): 1687-1690.
4. Baum B A, Platnick S. Introduction to MODIS cloud products[M]. Springer Berlin Heidelberg, 2006: 74-91.
5. Zhao Yanjie, Wei Heli, Chen Xiuhong, et al. Simulation study on the reflectance of cirrus clouds at the wavelength of 1.064  m[J]. Laser Technology, 2008, 32(5): 523-526.
6. Cao Yanan, Wei Heli, Chen Xiuhong, et al. Simulations of the reflectance of cirrus clouds in shortwave spectral region[J]. Acta Optica Sinica, 2012, 32(8): 19-25.
7. Wei Heli, Chen Xiuhong, Dai Congming. Combined atmospheric radiative transfer (CART) model and its applications[J]. Infrared and Laser Engineering, 2012, 41(12): 3360-3366.
8. Yang P, Liou K N, Wyser K, et al. Parameterization of the scattering and absorption properties of individual ice crystals[J]. Journal of Geophysical Research: Atmospheres, 2000, 105(D4): 4699–4718.
9. Zhao Yanjie, Wei Heli, Chen Xiuhong, et al. Scattering Properties of Cirrus Clouds in the Shortwave Spectral Region[J]. Journal of Atmospheric and Environmental Optics, 2007, 2(3): 169-174.
10. Stamnes K, Tsay S C, Wiscombe W, et al. Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media[J]. Applied Optics, 1988, 27(12): 2502-2509.
11. Hu Y X, Wielicki B, Lin B, et al. $\delta$-Fit: A fast and accurate treatment of particle scattering phase functions with weighted singular-value decomposition least-squares fitting[J]. Journal of Quantitative Spectroscopy &

Radiative Transfer, 2000, 65(4): 681-690.

12. Gao B C, Yang P, Han W, et al. An algorithm using visible and 1.38- m channels to retrieve cirrus cloud reflectances from aircraft and satellite data[J]. IEEE Transactions on Geoscience and Remote Sensing, 2002, 40(8): 1659-1668.
13. Nakajima T, King M D. Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. I - Theory[J]. Journal of the Atmospheric Sciences, 1990, 47(15): 1878-1893.

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv —Machine translation. Verify with original.*