TREATMENT OF MULTIPLE-SCATTERING EFFECTS IN EXTINCTION RETRIEVALS IN COMPLEX ATMOSPHERIC SCENES PROBED BY CALIPSO

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ABSTRACT

The approximation that transmitted photons undergo only one scattering event before returning to the receiver is usually not valid for space-borne lidars where, even with small transmitter divergences and receiver fields-of-view (FOV), the diameter of the beam footprint is often comparable with photon mean free paths. Here we report an approach to parameterizing the effects of multiple scattering on the CALIPSO (Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations) [1] lidar backscatter signals to improve the quantitative analysis of the signals.

Using the results of Monte-Carlo modeling of the CALIPSO measurement geometry and various combinations of atmospheric targets, the effects of multiple scattering on the CALIPSO lidar signal are parameterized in terms of standard multiple scattering functions, $\eta(r)$. Our studies have included single cloud and aerosol layers as well as examples of vertically-adjacent, dissimilar layers.

One novel aspect of the CALIPSO lidar data processing algorithms is the multi-pass, multi-scale detection and analysis of atmospheric features. This approach minimizes biases caused by averaging signals from features of dissimilar strengths, spatial scales and physical and optical properties. Here we describe the incorporation of our multiple-scattering parameterizations into the various steps in the CALIPSO analysis.

1. INTRODUCTION

1.1. Multiple Scattering in CALIPSO Analyses

One major effect of multiple scattering on lidar signals is a reduction in the rate of attenuation of the signal with range and this reduction must be accounted for to retrieve accurate extinction profiles from elastic backscatter lidars such as carried by CALIPSO.

Using Platt's [3] parameterization of the relative contribution of multiple scattering to the total backscattering signal,

$$\eta(r) = 1.0 - 0.5\ln(TS(r)/SS(r))/\tau(r_t, r). \qquad (1)$$

Here TS and SS are, respectively, the total and singly-scattered contributions to the lidar signal and $\tau(r_t,r)$ is the optical thickness between the top of the feature and range r. The total contribution includes multiple- and single-scattering. The value of $\eta(r)$ for many atmospheric features has been found [4] to be not strongly dependent on the magnitude of the local extinction coefficient when probed with a space lidar system like CALIPSO. The parameterization of multiple scattering effects in cirrus and in aerosols produces $\eta(r)$ with markedly different behavior. However, for the CALIPSO measurement geometry, the behavior of $\eta(r)$ does not vary strongly with cirrus particle habit or aerosol type. Therefore, the large variability of multiply-scattered signals can be modeled with just a few $\eta(r)$ functions. The parameterization of Eq. 1 has been found to vary significantly with extinction in water clouds, where pulse stretching effects become significant [2]. Thus this parameterization is applied only to ice clouds and aerosol layers where pulse stretching is minimal due to either the sharply forward peaked phase function (cirrus) or the tenuousness of the layers (aerosol).

For situations where pulse stretching is small, we can use this parameterization to modify the single-scattering lidar equation in the following manner, in order to account for the reduction in the rate of attenuation of the signal with range:

$$\beta'(r) = (\beta_M(r) + \beta_P(r))T_M^2(0,r)T_P^2(0,r), \qquad (2)$$

where

$$T_P^2(0,r) = \exp[-2\,\eta(r)\,\tau_p(0,r)] \qquad (3)$$

is the particulate two-way transmittance, β' is the attenuated backscatter coefficient, β is the volume backscatter coefficient and the M and P refer to molecules and particles respectively. The development, using Monte-Carlo modeling, of the $\eta(r)$ parameterization for the sorts of atmospheric features to be probed by CALIPSO is described below.

2. MONTE-CARLO MODELING

2.1. Method

The Monte-Carlo modeling method used here is a development of that described previously [5] so only the salient features will be covered here. The method is a forward Monte-Carlo method in which simulated photons are transmitted into a model atmosphere and scattered randomly according to the phase functions and extinction of the atmospheric constituents. The aerosol phase functions used here are from a set of six standard models developed for CALIPSO, largely derived from an extensive analysis of AERONET aerosol data [6]. The cirrus phase function is for hexagonal columns [7]. The distance traversed by the photons between collisions is determined by a random function based on the optical path length.

In order to avoid potential sources of bias, few variance reduction methods are used. The main method by which the variance in the simulated signal is reduced is by calculating the return signal from the sum of the probabilities that the photon will return to the receiver after each collision.

The original Monte-Carlo code of [5] has been extended for this work by the addition of molecular scattering, and by the inclusion of multiple layers of particulates. The Monte-Carlo simulation study examined various combinations of atmospheric scatterers. Results were obtained for isolated cloud and aerosol layers, for various aerosol and cloud combinations, and for multi-component aerosol layers.

2.2. Isolated Layers

2.2.1. Clouds

Cirriform ice clouds are of great interest, as they have significant impacts on the Earth's radiation budget. Moreover, it is not just their optical characteristics but also their vertical distributions that are important. The CALIPSO lidar is able to probe the full depth of most ice clouds with good height and horizontal resolution, under any lighting condition. For various isolated cirrus layers where the extinction is constant with height, Monte-Carlo modeling has shown that η varies little with range, and has a value of approximately 0.75 for the CALIPSO measurement geometry.

2.2.2. Aerosols

Unlike cirrus, the η functions for isolated aerosol layers vary with the depth of penetration into the layer. For layers having constant extinction with height, the results have been fitted with analytical functions of the depth of penetration that are plotted with the Monte-Carlo data in Fig. 1.

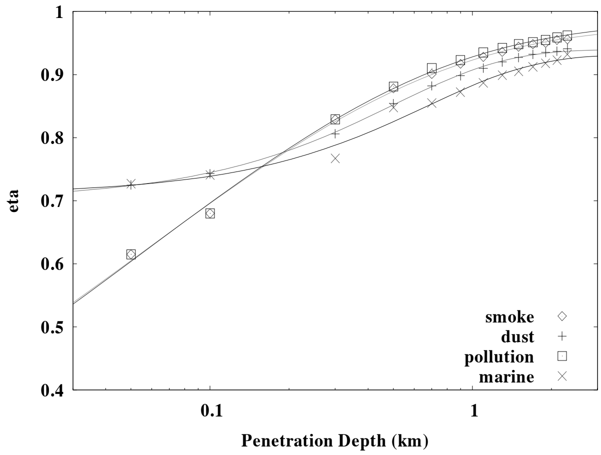

Fig. 1: Multiple scattering parameterizations for isolated aerosol layers.

2.3. Vertically-Adjacent Layers

When dissimilar layers are in vertical contact (e.g., a marine sea breeze layer beneath a polluted continental aerosol layer, or layers of the same type but significantly different extinction) the parameterization of the multiple scattering can be more complicated than in isolated layers, as multiply-scattered photons emitted from the upper feature continue down into the lower feature or features. The Monte-Carlo modeling showed that the nature of this behavior is dependent on the scattering phase functions and the extinctions in the adjacent layers. Some examples are given below.

2.3.1. Smoke below cirrus

The behavior of η in smoke underlying cirrus is shown in Fig. 2. This behavior is defined as a function of penetration depth into the smoke layer in our analysis.

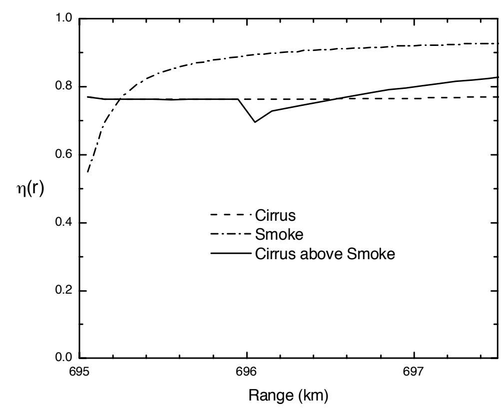

Fig. 2: Behavior of η in 3-km deep cirrus, and smoke layers, and smoke (696-698 km) below 1 km of cirrus.

2.3.2. Adjacent aerosol layers

The modeling results showed that the CALIPSO aerosol models have phase functions that are similar enough that the multiple scattering effects depend very little on aerosol type. Therefore, regardless of the combination of aerosols layers, the combined multiple scattering function could be approximated very closely (to an accuracy of about 10 per cent) by simply extending the η of the top feature down through the other layers. This behavior is apparent from Fig. 3.

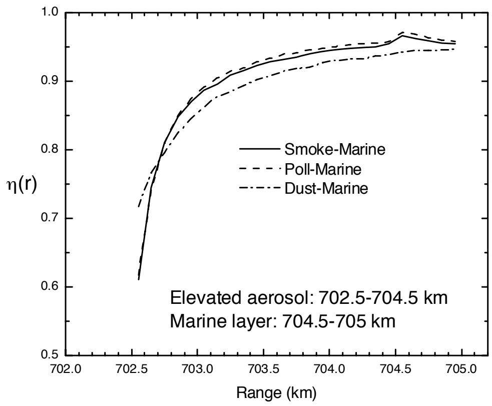

Fig. 3: Multiple scattering in vertically-adjacent aerosol layers. A 2-km deep layer of various aerosol types overlies a 1-km deep marine aerosol layer.

3. CALIPSO ANALYSIS PROCEDURE

The various steps in the CALIPSO analysis procedure have been described elsewhere [8, 9], and thus the details will not be repeated here. In this work we will limit our description to the extension of the existing method to include a more thorough treatment of the effects of multiple scattering

3.1. Feature detection and location

The retrieval of extinction profiles from CALIPSO data is based on the analysis of a continuous sequence of 16 calibrated attenuated backscatter profiles, each the result of averaging individual profiles (recorded every 0.3 km along track) to 5-km horizontal resolution. Each of these 5-km profiles is scanned for the presence of strongly scattering atmospheric features. Subsequently, the 5-km profiles are averaged further to 4 profiles at 20-km horizontal resolution, and then one at 80-km resolution and each of these profiles is scanned in turn, so as to enable the detection of increasingly weaker features. Thus, atmospheric features are detected and located at 3 different horizontal resolutions [9]. This method avoids the "unphysical" retrieval results that would arise from the averaging of signals of dissimilar strengths and atmospheric types.

3.2. Feature classification

Once features have been detected and located in the lidar "scene", they are then classified according to type, based on characteristics of the lidar signals and the geographic location and altitude of the feature. There are 8 classes of cloud and 6 classes of aerosol. Each class of feature has associated optical properties including a backscatter phase function (or lidar ratio) and a range-resolved multiple scattering function, $\eta(r)$.

Each element of the 16 by 550 element array that describes the 80-km along track by 30-km high scene is then assigned a feature number. Because they are detected at different horizontal resolutions, features may occupy several columns. The potential complexity of a typical CALIPSO scene is illustrated in Fig. 4. (For clarity the number of rows is reduced there to 36.)

3.3. Specification of η

The parameterizations of the results of the Monte-Carlo simulations presented above are then used to specify the multiple scattering parameter η according to whether a feature is an isolated layer or vertically adjacent to other layers. Each element of the 16 by 550 element array is thus assigned the appropriate value of the multiple scattering function. Note that because features are detected at different horizontal resolutions they can be adjacent to different types of features in different columns. Consequently, different columns of a multi-column feature can have different η profiles. Feature 16 in Fig. 4, for example, will have three different η profiles in its four columns.

3.4. Extinction Retrieval

The extinction retrieval algorithm processes a scene from the top of the atmosphere down to the surface, across all horizontal resolutions, calculating the extinction of each feature it encounters and correcting the underlying features for this attenuation before analyzing them in turn.

Because features can occupy many columns, a profile must be calculated that, at each altitude, is the average of every column containing the feature. In Fig. 4, for example, the average profile describing feature 16 is the result of averaging three columns in rows 23 and 24 and four in row 25. Without the progressive attenuation correction described above, it would not be possible to calculate a valid average profile for this feature. The analysis of the resulting, average attenuated backscatter profile requires a matching average profile of the multiple scattering function. This is calculated similarly, by averaging the elements of the array described in 3.3 that correspond to the location of the feature under analysis. Note that the small perturbations, in the underlying features, to the η profile of the overlying features in 2.3, allow this simple averaging to be a valid linear approximation to the non-linear dependence of Eq. 2-3 on $\eta(r)$. (E.g. Note the small variation in Fig 2. of $\eta(r)$ between 696 km and 698 km from the value for the overlying cirrus). The average profile of particulate backscatter for the feature is then calculated from these average profiles of β' and η by solving the multiple scattering lidar equation Eq. 2-3 in the forward direction using a Newton's Method iteration scheme. The particulate extinction is then obtained by multiplying the backscatter by the lidar ratio for the feature [1].

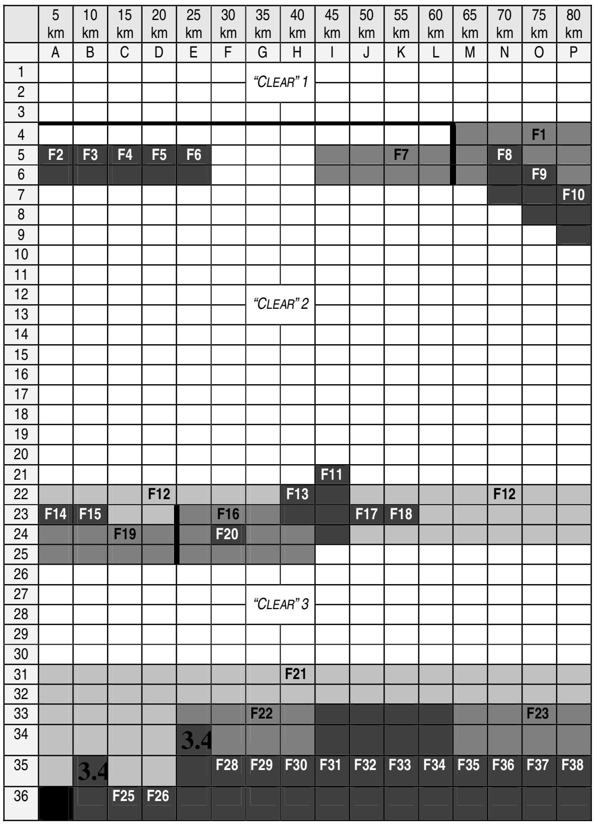

Fig. 4: Simplified depiction of features detected by CALIPSO. The weakest features (12 and 21) were detected only after averaging horizontally to 80-km resolution so are assumed to extend over this distance. Stronger features (1, 16, 19, 22, and 23) were detected at 20-km resolution and occupy 4 columns, while the others were strong enough to be detected in one column.

REFERENCES

1. Winker D. M. and Pelon J., The CALIPSO Mission, *In: IGARSS 2003: Proceedings: IEEE 2003 International Geoscience and Remote Sensing Symposium: Learning from Earth's Shapes & Colors*, Centre de Congrès Pierre Baudis, Toulouse, France. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Vol. 2, 1329 – 1331, 2003.
2. Miller S.D. and Stephens G. L., Multiple scattering effects in the lidar pulse stretching problem, *J. Geophys. Res.*, Vol. 104, D18, 22205-22219, 1999.
3. Platt C. M. R., Remote Sounding of High Clouds. III: Monte Carlo Calculations of Multiple-Scattered Lidar Returns, *J. Atmos. Sci.*, Vol. 38, 156–167, 1981.
4. Winker D. M., Accounting for Multiple Scattering in Retrievals from Space Lidar, In: Proc. SPIE: 12th International Workshop on Lidar Multiple Scattering Experiments, Christian Werner, Ulrich G. Oppel, Tom Rother; Eds, Vol. 5059, 128 – 139, 2003.
5. Winker D. M. and Poole L. R., Monte Carlo calculations of cloud returns for ground-based and space-based lidars, *Appl. Phys.* B, Vol. 60, 341-344, 1995.
6. Omar A., Vaughan M. A., Winker D. M., Hostetler C. A., Jae-Gwang Won, and Reagan J. A., Selection Algorithm for the CALIPSO Lidar Aerosol Extinction-to-Backscatter Ratio, *In: IGARSS 2003: Proceedings: IEEE 2003 International Geoscience and Remote Sensing Symposium: Learning from Earth's Shapes & Colors*, Centre de Congrès Pierre Baudis, Toulouse, France. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Vol. 3, 1526 – 1530, 2003.
7. Takano Y. and Liou K. N., "Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals," *J. Atmos. Sci.* **46**, pp. 3-18, 1989.
8. Young S. A., Vaughan M. A., and Winker D. M., Adaptive Algorithms for the Fully-Automated Retrieval of Cloud and Aerosol Extinction Profiles from CALIPSO Lidar Data. *In: Lidar Remote Sensing in Atmospheric and Earth Sciences: reviewed and revised papers presented at the twenty-first International Laser Radar Conference (ILRC21)*, Québec, Canada, L. R. Bissonnette, G. Roy and G. Vallée, Eds, Québec, Defence R&D Canada, Valcartier,, Vol. 3, 1517 – 1519, 2003.
9. Vaughan M. A., Winker D. M., and Hostetler C. A., SIBYL: A Selective Iterated Boundary Location Algorithm for Finding Cloud and Aerosol Layers in CALIPSO Data, *Ibid.*, 791–794, 2002.