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# Iterative method for determining boundaries and lidar ratio of permeable layer of a space lidar

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ABSTRACT

Space lidar is a unique tool for detecting the 3D properties of cloud and aerosol layers. Layer boundaries and lidar ratio are significant preconditions for retrieving the layer optical properties of a space lidar. The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) team adopts the threshold method to accurately detect a layer top. However, the layer base detection continues to rely on the slope method, which causes considerable uncertainty. Furthermore, a fixed lidar ratio is mainly used for retrieving optical properties of layers of the same layer type, which also contains large uncertainty. To reduce the above uncertainties, we propose an iterative method to determine layer base and lidar ratio of a permeable layer of a space lidar on the basis of lidar ratio and transmission relationship. The simulated and measured experimental results demonstrate that the proposed iterative method simultaneously retrieves layer boundaries and lidar ratio accurately. The proposed iterative method has the potential to become a significant part of data retrieval of a space lidar in the future.



## 1. Introduction

Cloud and aerosol are the main factors that affect the atmospheric environment and global change [1,2]. Passive sensors can obtain column-integrated information of cloud and aerosol in a large region but cannot easily determine those about vertical variations of cloud and aerosol [3]. Nevertheless, as a unique active tool, lidar can detect the vertical properties of cloud and aerosol with high temporal–spatial resolution [4–6]. Therefore, space lidars, such as CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) in 2006, were successfully launched after the Lidar InSpace Technology Experiment (LITE) experiment in 1994 to achieve the global 3D detection of cloud and aerosol [7–9]. However, it was complained that CALIPSO aerosol optical depth (AOD) is lower than sun-photometer AOD due to inaccurate layer boundary information and inappropriate lidar ratios used in the retrieval [10,11]. Therefore, accurate algorithms for layer boundary detection and lidar ratio determination should be developed for the scientific goals of space lidar.

Layer boundaries are input parameters used for classification and retrieval of space lidar [12]. The two key issues of layer detection are related to locating the layer top and the layer base. The methods used for layer detection mainly include the slope method [13], threshold method [14,15], wavelet modulus maxima method [16], and simple multiscale methods [17]. However, these methods remain insufficient for layer detection by relying on space lidar signal. The slope method is extremely sensitive to noise. The threshold method effectively detects the layer top. However, the base detection of CALIPSO continues to rely on the slope method. The simple multi-scale method avoids using the slope of the signal, but it does not consider layer attenuation when locating the layer base. The wavelet modulus maxima method considers the “fastest changing” data points as boundaries, but these data points are not usually the “first changing” ones because the variation of layer boundaries in a space lidar signal is usually unremarkable.

The threshold method is the current most used algorithm for a space lidar (such as CALIPSO), which is initially used by setting a threshold array to check the layers from a lidar profile [18]. Varying thresholds with altitude are obtained from either rawinsonde soundings or a molecular density model and then applied in analyzing the atmospheric scattering attenuation ratio [14]. Clothiaux et al. [19] proposed a threshold method based on an archetypal

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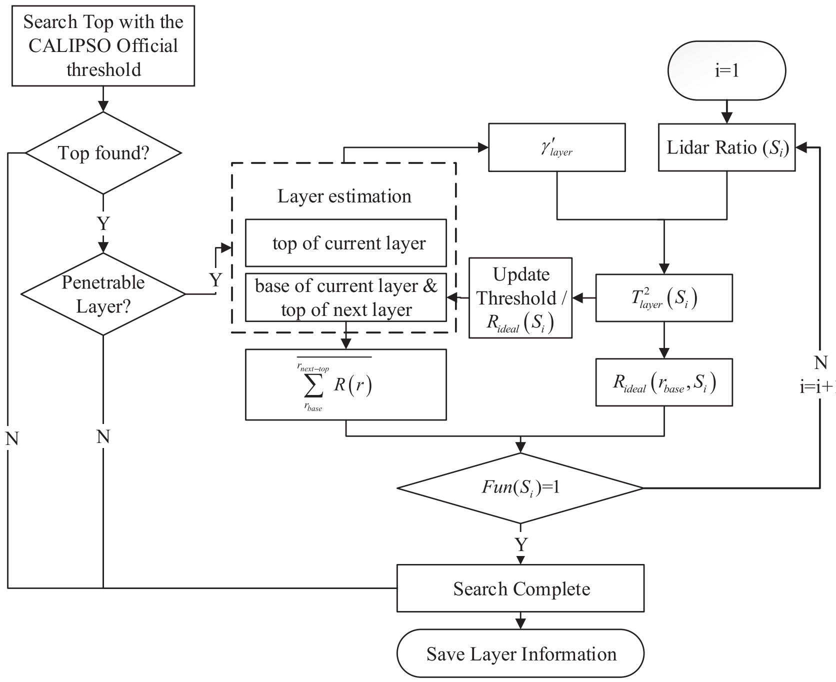


**Fig. 1.** Flow diagram of iterative layer detection method for CALIPSO penetrable layer.

clear-sky model, in which the threshold value is continuously updated during detection. Vaughan et al. [15] improved the threshold method based on attenuation scattering ratio and successfully applied it to CALIPSO. The basic concept of the threshold method is that a height will be marked as a layer top when the lidar signal exceeds the threshold at the height. Furthermore, a height is regarded as the initial base layer height when the signal is lower than the given threshold, and it is subsequently optimized by the slope method [12]. The determination of a layer base can contain large errors because it depends on the slope, but the slope oscillates wildly to nearly zero for a space lidar signal [10]. Therefore, high-precision detection of the layer base remains a challenge.

Furthermore, lidar ratio (the ratio of particle extinction and backscattering coefficient) is highly dependent on the microphysical and chemical structures of particles. In CALIPSO algorithm, a lidar ratio is mainly selected based on its layer type [20], which can contain two error sources. The first error is that the lidar ratio is usually different even for two layers with the same type. Second, errors are still found in the layer classification process. Worse, an inappropriate lidar ratio may lead to as large as 50% aerosol retrieval deviation for a pure elastic backscatter, based on a study of 19 aerosol lidars from EARLINET (European Aerosol Research Lidar Network) [21]. Thus, a real-time automatic method for retrieving the lidar ratio will be valuable for lidar data retrieval.

We propose an iterative method for determining the boundaries and lidar ratio to solve the above problems. The proposed iterative method optimizes layer base height and lidar ratio, in which the transmission calculated from the ratio of the signals at layer base and top [22] is equal to that calculated from the layer integrated–attenuated backscatter and a reasonable lidar ratio [12]. For the proposed iterative method, the varied lidar ratios $S_i$ ($i = 1, \ldots, n$, $n$ is iteration number) with a given step size (such as 1 sr) are generated iteratively. For each $S_i$, the ideal attenuation scattering ratio of the clean region between the current layer base and next layer top can be estimated. Finally, we use a discriminant function to determine the optimal lidar ratio and layer boundaries based on the ratio of the ideal and measured attenuation scattering ratio.

## 2. Theory and method

There are many different representations of a lidar profile to which we could apply for layer detection, but the attenuated scattering ratios (at 532 nm) are usually applied because which offers certain structural advantages for robust layer determination [12]. The attenuated scattering ratio is defined as follows [23]:

$$R(r) = \frac{\beta_{total}(r)}{\beta_{air}(r)} = \left[1 + \frac{\beta_p(r)}{\beta_m(r)}\right] T_p^2(r). \tag{1}$$

where $r$ is the altitude; $\beta_{total}$ and $\beta_{air}$ are total and air attenuated backscatter coefficients, respectively; $\beta_p$ and $\beta_m$ refer to the backscatter coefficients of atmospheric particles and molecules, respectively; and $T_p^2(r)$ represent the two-way transmittance of atmospheric particles. $\beta_{total}$ and $\beta_{air}$ can be derived from the lidar backscatter (CALIOP level 1 data) and atmospheric density profiles, respectively.

The threshold method used by the CALIPSO official algorithm can detect layer top accurately based on $R(r)$. However, the determination of a layer base can contain large errors because it depends on the slope of $R(r)$, but the slope oscillates wildly at nearly zero for a space lidar signal. Furthermore, a fixed lidar ratio is used for retrieving optical properties of layers of the same layer type, which also contains large uncertainty. To reduce the above uncertainties, we propose an iterative method to determine layer base and lidar ratio of a permeable layer, the flow diagram of which is shown in Fig. 1 and introduced in detail subsequently.

(1) Searching initial layer boundaries by using the CALIPSO official algorithm

We detect the heights of layer boundaries by the CALIPSO official algorithm as reported in [12] and regard as the initial values for our proposed iterative method. For clean air, $R(r)$ is approximately constant, but $R(r)$ dramatically changes when an optical thick layer (e.g., cloud or aerosol layer) exists. By definition, the attenuated scattering ratio $R(r)$ at the highest cloud top will be greater than one. Identical to the CALIPSO algorithm, we detect the layer based on a dynamically computed threshold array depending on the magnitude of $R(r)$. A height will be marked as the layer top