THE RETRIEVAL OF EXTINCTION PROFILES IN OPTICALLY-INHOMOGENEOUS CLOUD AND AEROSOL LAYERS DETECTED BY THE CALIPSO LIDAR.

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ABSTRACT

The retrieval of profiles of extinction from elastic backscatter lidar data requires the knowledge of the relationship between the two unknowns in the lidar equation, commonly called the particulate extinction-to-backscatter ratio, or lidar ratio, S. Two common approaches to obtaining a value of the lidar ratio are the use of representative, tabulated data, and the use of independent measurements of the optical thickness of the cloud or aerosol feature being studied. In the second approach, the optical thickness of an elevated, isolated layer can often be determined by comparing the magnitude of the backscatter from clear air above and below the layer. If the lidar ratio is assumed to be constant throughout the layer, a constrained retrieval of the extinction profile is possible.

This paper also considers those cases where a layer is physically or optically inhomogeneous and contains more than one type of scatter with the result that the lidar ratio is not constant through the layer. In such cases there are more unknowns than measurements (constraints) and a unique, constrained solution is not possible. For the analysis of such data measured by the CALIPSO lidar, we propose a method that guarantees an extinction profile solution that, when integrated through the layer, gives a calculated optical thickness, τ, that is consistent with the measured signal reduction across the layer.

1. INTRODUCTION

The Cloud Aerosol Lidar Pathfinder Satellite Observations (CALIPSO [1]) mission is due to be launched in March 2005. By combining observations from the on-board instruments (a two-wavelength lidar (CALIOP), an Infrared Imaging Radiometer (IIR) and a Wide-Field Camera (WFC)) with those from other satellites in the A-Train [2], CALIPSO aims to provide key measurements of cloud and aerosol distribution and properties needed for improving predictions of climate change.

The measurement of the distribution of cloud and aerosols from a satellite orbiting the Earth at an altitude of 705 km with a ground speed of 7.5 km s^{-1} is made difficult by the often tenuous nature of the aerosol layers and by the small spatial extent of many of the cloud and aerosol features, and is exacerbated by the relatively low power and pulse rate of the laser transmitter. Tenuous and extensive aerosol layers require the averaging of many individual signal profiles in order to provide signal-to-noise ratios (SNRs) that are high enough for useful analysis. However, stronger cloud features are often of a much smaller spatial extent that precludes the averaging of many profiles. Fortunately the stronger signals from these features require less averaging. It can be seen, then, that any given atmospheric scene viewed by the CALIPSO lidar may contain a variety of features with differing spatial extents and backscattered signal intensities. These different signal regions will require different amounts of averaging and, often, different analysis methods. The algorithms being developed for the analysis of the CALIPSO lidar data incorporate many novel features to enable the analysis of the wide variety and mix of signal types to be performed autonomously. This analysis procedure is described below. The extra complexities associated with the analysis of complex atmospheric features – here defined as those that contain other, vertically-adjacent or embedded features, are detailed in this work.

2. CALIPSO LIDAR LEVEL 2 DATA ANAYLSIS

The purpose of the CALIPSO Level 2 lidar data analysis system is to take the calibrated, level 1 lidar data, locate and classify all atmospheric features, and produce profiles of particulate extinction and other layer-integrated outputs. It incorporates three main, linked components. These are a multi-pass feature finder or Selective Iterated Boundary Locator (SIBYL), a Scene Classifier Algorithm (SCA), and a Hybrid Extinction Retrieval Algorithm (HERA). As the SIBYL [3] and SCA [4] have been described in detail elsewhere, most attention in this paper will be focused on recent developments of the extinction retrieval algorithm [5].

2.1 The Selective Iterated Boundary Locator

The purpose of the SIBYL is to detect and locate any cloud or aerosol features in a block of data. It does this in several passes through the data, averaging increasing numbers of individual profiles to improve the SNR, then attempting to identify regions of the average profile where the signal departs from that expected from a clear atmosphere. In this way, features are detected at 1-km, 5-km, 20-km and 80-km horizontal resolution, corresponding to the averaging of 3, 15, 60 and 240 individual profiles respectively. The feature boundaries thus determined are then passed on to the HERA and SCA.

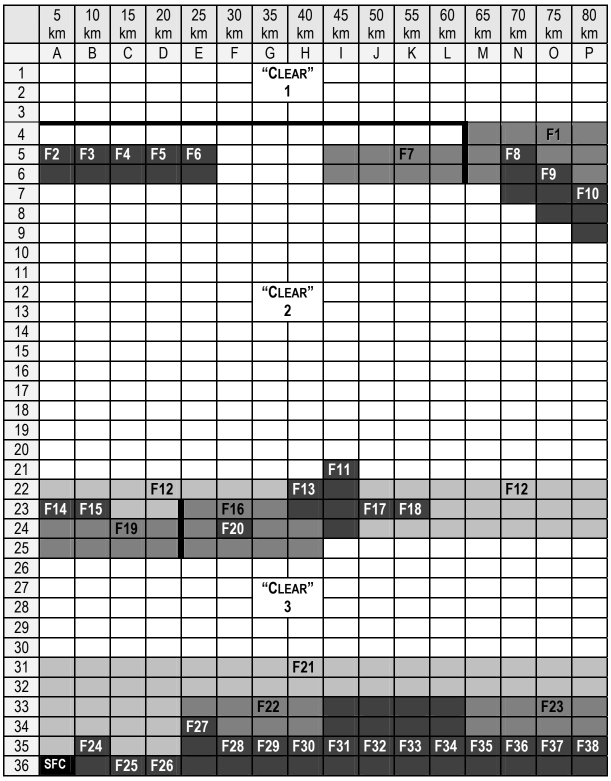

Fig. 1. A representative complex atmospheric scene as viewed by CALIPSO after feature boundary location by the SIBYL. Detected features are plotted in nominal height bins for each of the sixteen mean profiles. These have been averaged to 5-km along-track resolution.

A simplified representation of the features detected by the SIBYL in an 80-km block of LITE data, modified to simulate CALIPSO data, is depicted in Fig. 1. The weak features 12 and 21 were only detected after averaging all 16 profiles, so are assumed to occupy the whole 80-km horizontal extent of the data block. The stronger features 1, 16, 19, 22 and 23 were detected at 20-km resolution while the rest of the features were detected at 5-km resolution.

2.2 The Scene Classifier Algorithm

Once the boundaries have been located, each feature is classified as being either cloud or aerosol. The features are further classified as belonging to various aerosol or cloud types, based on a combination of meteorological and geographical ancillary data, and layer-integrated parameters obtained from the lidar data. The latter include the integrated attenuated backscatter, γ', the depolarization ratio, and the attenuated, 532-nm to 1064-nm backscatter colour ratio.

Once a feature has been classified, appropriate values of the lidar ratio and multiple scattering correction function, $\eta(z)$, are selected for use by the extinction retrieval algorithm. For isolated, elevated, simple features containing only one form of scatterer, the lidar ratio is obtained by the transmittance method, where the feature transmittance, deduced from the comparison of the clear–air signal above and below the feature, is combined with the value of γ' as described by Young [6]. For other features, or where the calculated value of S has an uncertainty exceeding 30%, the value of S is obtained from appropriate tabulated values. The values of $\eta(z)$ are obtained from modelling results [7].

The CALIPSO feature classification process works from the top of the atmosphere down to the surface. As parameters for any particular feature might initially be affected by the attenuation of overlying features, the SCA receives updated attenuation information from the HERA, thereby permitting improved estimates of the appropriate values of S and $\eta(z)$.

2.3 The Hybrid Extinction Retrieval Algorithm

The HERA is responsible for the calculation of the extinction and backscatter profiles and of the corrected, integrated layer products like the optical thickness. The algorithm is described as being hybrid as it combines several different algorithms into an automatic retrieval process. It adapts the retrieval pathway to meet changes in the various properties of the atmospheric feature. These include its classification, complexity, whether it is elevated or in contact with the surface, and the SNR of its backscatter signal and those of the neighbouring clear-air regions. As they decide much of the extinction retrieval pathway, we here define simple and complex features.

Simple features are features, detected by the SIBYL at a single horizontal resolution, that are identified by the SCA as containing only one type of scatterer. As described below, some vertically-isolated simple features can be "solved", i.e. their extinction profile retrieved, using a constrained retrieval.

Complex features are identified as being physically or optically inhomogeneous and contain different types of scatterers. Effectively they are composed of several simple features that are vertically adjacent with other features, or contain embedded features. There are 3 complex features in Fig 1. The first is composed of the vertically-adjacent features 1, 8, 9 and 10. The second, middle, complex feature occupies altitude bins 22 - 24 and extends across the whole 80-km block as does the third complex (boundary-layer) feature. Note that F11 is not included in the middle complex feature as it is not vertically adjacent to another feature, nor does it contain an embedded feature. Features 17, 18 and 20 are examples of embedded features.

3. EXTINCTION RETRIEVAL

The input to the HERA consists of a block of data containing sixteen profiles of attenuated backscatter averaged by the SIBYL to 5-km horizontal resolution, along with information on the location of features detected at any resolution, and other feature properties including values of $\eta(z)$ and S selected by the SCA.

The extinction retrieval works from the greatest altitude at which data are recorded down to the surface (i.e. from smallest to greatest range from the lidar). The latest version of the HERA processes features in order of decreasing altitude, regardless of the horizontal resolution at which they were detected. The clear, or background, regions between the features are also processed, but only at 532 nm, the SNR at 1064 nm in these regions being too low for reliable analysis. Note that these supposedly clear regions may contain aerosol layers that are below the detection threshold of the SIBYL. Aerosol layers with a high S may not be detected, but may still have a significant optical thickness that needs to be included in the column optical thickness.

The extinction retrieval process for 532-nm data is described with reference to Fig. 1. (Note that the altitude bins in the figure are illustrative only. There are actually 550 altitude bins, varying in thickness, covering altitudes between 30 km and –1.85km.) The first step is to average all the clear regions to produce a single profile from the top altitude down to the top of the highest detected feature, F1 in this example. A profile of particulate extinction is then retrieved from this profile and the square of the particulate transmittance calculated over its vertical extent. Then, in order to correct for any attenuation by overlying aerosols, the input profiles in all sixteen columns are divided by this transmittance factor in all the range bins from bin 4 down to the surface.

The complex feature containing F1 and F8 – F10 is analysed next, using the method described in Section 3.2. Underlying regions of columns M – P are now corrected for the attenuation caused by these features in the same way as all columns were previously corrected for the overlying background aerosol attenuation. Note that each column is corrected by a different amount depending on how much each of the features contributes to the attenuation.

The clear region between the last retrieved clear altitude and the top of the next highest feature (cells 4A – 4L in this case) is solved and the underlying columns rescaled as before. Next, each of the simple features 2 – 6 and is solved and underlying regions (level 7 down to the surface) in columns A – E and I – L rescaled.

The next step is to create a clear profile from level 5 down to the top of F11. As each range step has differing numbers of columns contributing the average profile, and as each of these has suffered different degrees of attenuation by overlying features that results in different SNRs in different columns, a weighted mean profile is calculated. Once this is solved, and all 16 columns rescaled from level 21 down, the simple feature 11 is solved. Then follows the retrieval of all the features in the middle complex feature, the clear region below it and finally the boundary layer aerosol.

3.1 Simple Features

Wherever possible, simple, elevated, vertically-isolated features (e.g. F2 and F11) are solved using a retrieval that is constrained by the feature transmittance determined from the ratio of the clear-air signal above and below the feature. If the SNR is too low, or if the feature is totally attenuating or in contact with the surface, then a constrained solution is not possible and a forward, unconstrained retrieval is used.

3.2 Complex Features

Complex features, by definition, contain more unknowns (lidar ratios) than constraints (optical thickness measurements), so a unique, constrained solution is not possible. Therefore, we seek a solution (a set of S values) that gives a τ, averaged over the horizontal extent of the feature, that is consistent with that determined by the transmittance method across the same horizontal region.

Consider the complex feature at the top right of Fig. 1. First the average profile representing F1 is calculated from columns M – P. This profile is solved over its whole vertical extent using the lidar ratio supplied by the SCA. Each column is temporarily rescaled by the transmittance of that proportion of F1 that overlies it, so F8 – F10 are all rescaled differently. F8 – F10 are then solved individually, using lidar ratios supplied by the SCA. The average particulate τ is calculated from columns M – P and compared with the value determined from the ratio of the clear air signals above and below the complex feature (e.g., from rows 1 – 3 above and 10 – 21 below). If the values do not agree, then the lidar ratio of the feature with the largest γ' is adjusted and the whole complex feature solved again. The lidar ratio of any feature is adjusted by a maximum of 30%. If further adjustment is needed, then the lidar ratios of the other features are adjusted in order of decreasing γ' until consistency is reached between the measured and calculated values of τ. An example of the retrieval using a simulation of three vertically-adjacent features is plotted in Figure 2. A cloud with a mean extinction of 10 km^{-1} is embedded in an aerosol layer with a mean extinction of 0.5 km^{-1}. The retrieved backscatter goes to zero outside the feature boundaries.

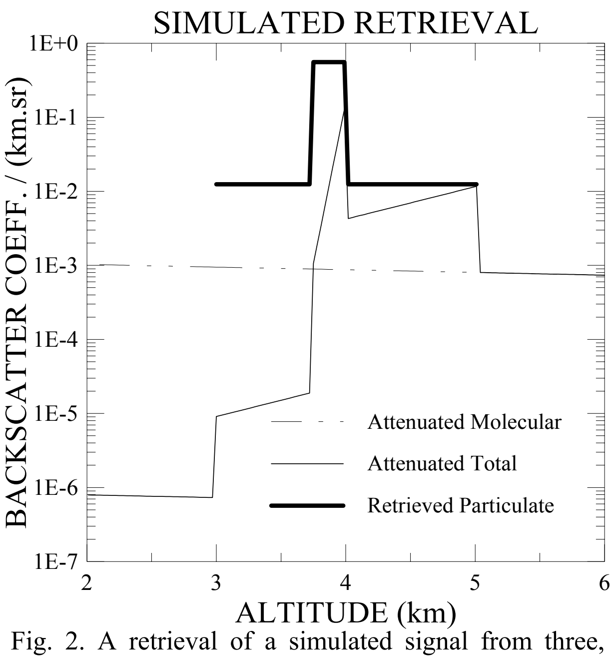

Fig. 2. A retrieval of a simulated signal from three, vertically-adjacent, dissimilar features.

Embedded features like F20 pose an extra degree of difficulty. F20 cannot be solved until the feature in which it is embedded, F16, is solved. However, F20 cannot be solved properly until the attenuation of that part that lies beneath F20 is corrected for the attenuation of F20. An iterative solution is employed whereby the attenuation by F20 is initially set to zero allowing the solution of F16 and hence F20. The attenuation by F20 is improved iteratively until the retrieval of F16 and F20 converges.

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