Adaptive methods for retrieving extinction profiles from space applied to CALIPSO lidar data.

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ABSTRACT

The particular difficulties encountered in the automatic analysis of lidar data from space are discussed. Adaptive methods, which select different analysis parameters autonomously according to the nature of the atmospheric target and quality of the lidar signal, are proposed. The application of the resulting Hybrid Extinction Retrieval Algorithm (HERA) to the analysis of lidar data from NASA's planned CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) Mission is illustrated with suitably modified LITE (Lidar In-space Technology Experiment) lidar data.

1. INTRODUCTION - DESCRIPTION OF THE PROBLEM

The analysis of data obtained from satellite-borne lidar entails a number of difficulties not faced in the analysis of ground-based lidar data. These are the result of the combination of the large range of the target from the lidar, typically 500-700 km, the high speed at which the lidar sweeps across the target space (typically 7 km per second), the variation in the nature of the target along the satellite ground track, and limitations on the data acquisition and transfer rate. The large distance means that the signal-to-noise ratio (SNR) of the data will be much lower than for a comparable ground-based system. The relatively low (10-40 Hz) firing rate combined with the high satellite ground speed and variations in the target along this track mean that traditional methods of improving the SNR by averaging a sufficiently large number of profiles must be modified. Finally, the relatively large footprints of satellite lidars mean that extinction retrieval algorithms must be designed to account explicitly for multiple scattering effects.

Because of the non-linear way in which backscatter and extinction are related in a lidar signal profile, averaging of profiles that are significantly different in structure can produce a resulting profile in which the relationship between backscatter and (apparent) extinction is quite different from that in a single profile. Analysis of such a profile can produce results that are unrepresentative of the actual situation in the atmosphere. For this reason, considerable effort is made to average only that number of profiles that will produce a SNR that is sufficient for successful analysis. Because both the along-track target homogeneity and the strength of the signals vary depending on the type of target, different averaging times are required for different targets. The strong signals from water clouds require relatively few profiles to be averaged in order to produce a signal with a SNR high enough for successful analysis. However, a weak aerosol layer in the free troposphere requires very many profiles to be averaged. For the CALIPSO[1] (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) data set, initial horizontal-averaging intervals of 5 km, 20 km and 80 km have been established for different atmospheric targets. Details of this averaging technique and of the way in which specific targets are detected are described in an accompanying paper[2].

In addition to the different horizontal resolutions, strong and weak targets will have different optical properties. The lidar ratio and multiple scattering correction function required for the analysis of the signal from a strong, shallow water cloud will be quite different from the corresponding properties of a deep and tenuous ice cloud or a boundary-layer aerosol. Finally, the different signals from these targets are amenable to different analysis methods. While it is common in the analysis of ground-based lidar data to use a far-point calibration and backward retrieval algorithm to ensure stability of the solution, this will not always be possible for all targets detected by the CALIPSO lidar. The different target signals will, therefore, require different analysis parameters. The standard methods used in the analysis of ground-based lidar data cannot be applied directly and a modified, adaptive analysis scheme will be needed for the automatic analysis of the large volume of CALIPSO lidar data.

The process of analysing CALIPSO lidar data will be divided between separate modules. These modules are responsible for feature boundary location, scene classification, and extinction profile calculation. Details of the Hybrid Extinction Retrieval Algorithm (HERA), and its relationship to the other modules, are covered in this paper.

2. RELATIONSHIP OF THE CALIPSO DATA ANALYSIS MODULES

CALIPSO lidar data will be analysed in 80-km blocks. The Selective Iterated BoundarY Locator (SIBYL) first averages CALIPSO lidar profiles to 5-km, 20-km or 80-km horizontal resolution (corresponding to averages of 15, 60, and 240 individual profiles respectively). It then detects features corresponding to cloud or aerosol layers at these resolutions. Finally, the feature optical thickness is estimated where possible using the transmittance method[3]. Next, the Scene Classifier Algorithm (SCA) determines initial values of lidar ratios and multiple scattering factors for the features. This information is passed to the HERA as a block of data consisting of one 80-km averaged set and as many as four 20-km sets and sixteen 5-km sets, depending on the targets in the scene, each set containing both feature and profile data. A Meteorological Data Manager supplies profiles of molecular backscatter, transmittance and ozone transmittance.

The main function of the HERA routines is to extract particulate (cloud or aerosol) backscatter and extinction profiles, and their uncertainties, at both 532 nm and 1064 nm, from the blocks of data supplied by the SIBYL and SCA modules. First the 80-km profile, as processed by the SIBYL, is analysed in the regions where the SIBYL has identified no features in order to produce a profile of the background aerosol. This may require analysis of several, separate sections of profile both above and below partially transmitting clouds. Then the various features found during the 80-km scan are analysed using the appropriate parameters. Next, the four 20-km average profiles are analysed to produce extinction and backscatter data in the height regions in which the SIBYL detected features. The process is then repeated for the detected features in the sixteen 5-km averages. Note that the background aerosol is not retrieved at 20-km or 5-km resolution, or in any of the 1064-nm data, as the SNR is too low. Finally the retrieved profiles are recombined to produce a composite picture of the extinction over the 80-km block[2].

3. THE HYBRID EXTINCTION RETRIEVAL ALGORITHM

The term "hybrid" is used to characterise the extinction analysis routines described here because they combine different elements of other routines into a single routine suitable for automated processing that adapts the analysis parameters according the nature of the target and of the signal being analysed. Software has been written to allow the performance of these routines to be tested using either simulated signals or LITE lidar data modified in resolution and SNR to resemble CALIPSO lidar data. The current test software has three levels. A top level reads the data from the preceding modules and passes one profile at a time to a shell subroutine where all the analysis parameters are set, and data are passed to the third level, which is the actual extinction routine. The extinction routine in the current software implementation is a linear, iterative-convergent technique[4,5], as this was more easily modified to include the desired multiple scattering parameterisation than were the usual analytical solutions to the lidar equation.

The 80-km average, attenuated backscatter profile is inspected by the HERA prior to analysis in order to identify no-signal regions where features have been identified by the SIBYL at finer horizontal resolutions and removed[2]. The remaining "clear" or feature-free regions are thus subdivided and analysed separately to produce a profile of background extinction. The cumulative transmittance is tracked as the solution proceeds from the top altitude to the last valid range. The extinction background analysis can be refined by testing the overall particulate optical thickness against that supplied in a reference profile, and the calibration factor for that region adjusted iteratively in order to bring agreement. Note that because the aerosol optical thickness in the "clear" regions is very low, the retrieval is insensitive to adjustments in the lidar ratio, and adjustment of the calibration factor is preferred. This adjustment may be required if the calibration error is too large or if the model ozone transmittance profile over the analysis interval is significantly different from the actual profile. The lidar ratios used in the stratosphere and free troposphere are supplied by the SCA.

The analysis of profiles in those height regions where there are cloud or aerosol layer features is initiated using the lidar ratio supplied by the SCA. For features with a measurable transmittance, this lidar ratio is adjusted to bring agreement between the feature optical thickness calculated in the extinction routine and the value measured by the SIBYL. The situations where this iterative improvement is not performed are where the SIBYL is unable to measure the feature optical thickness, either because it is too low to measure reliably, or because it is too high and the lidar signal is totally attenuated. Included in the first situation are profiles measured at 1064 nm, as the transmittance method[3] for determining the optical thickness of optically thin clouds requires a detectable signal from the clear atmosphere on both sides of the feature, and these are not measurable at 1064 nm. The optical thickness cannot be determined directly for aerosol layers in contact with the surface, and iteration is not performed for these situations either.

The lidar ratio may also require adjustment in the extinction routine. For those high opacity features where the forward solution direction is required, the retrieval may become divergent if the lidar ratio is too large. For the same features, too small a lidar ratio will lead to insufficient correction for extinction losses and the retrieved particulate profile may become negative. An iterative search algorithm selects the optimum lidar ratio between these extremes.

4. ADAPTIVE ANALYSIS PARAMETER SELECTION

The selection of the analysis parameters (minimum (r_{min}), maximum (r_{max}) and calibration (r_C) ranges, calibration factor[3] (C_N) , and lidar ratio (S_P)) for the various types of features is summarised below.

a) *Elevated features in which the transmittance can be measured.*
The analysis interval is set between the points in the clear air on either side of the feature. The calibration range is set to r_{max} to force a backward solution, and the calibration factor is the total transmittance down to that height, and includes that of overlying clear and feature regions and that of the current feature as measured by the SIBYL.

b) *Elevated features in which the optical thickness is too low to be measured reliably.*
Analysis of these features proceeds in exactly the same fashion as in *a)* with the exception that no iteration is possible as the feature optical thickness cannot be measured.

c) *Elevated features measured at 1064 nm.*
Analysis of 1064-nm features proceeds in almost the same fashion as for *b)*. However, the analysis interval is set between the top and base of the feature as detected by the SIBYL, as there is no measurable signal in the clear regions outside most features detected at 1064 nm. Also, analysis is only allowable in the forward direction. A backward solution would require a good calibration, usually performed in the clear air below the cloud. However, there is no measurable signal in these regions, and the required cloud transmittance cannot be measured.

d) *Elevated features in which the transmittance is zero (totally attenuating features).*
For the totally attenuating features, analysis is performed in the forward direction using the relatively good calibration at cloud top and the lidar ratio estimated by the SCA from the integrated attenuated backscatter. A backward solution is not performed as, although the product of the lidar ratio and the average multiple scattering factor for the feature can be estimated, the transmittance at some far point cannot be estimated with any certainty, and poor calibration would result. No iteration is performed either, although the extinction algorithm may adjust the lidar ratio if an error condition is detected, see above. In addition, if the retrieved optical thickness calculated during the analysis of a profile exceeds some predefined value, then the solution is terminated at that point and data at lower altitudes are not analysed. At such high values of optical thickness, the relative uncertainty of the attenuated signal is high and the modelled value of the multiple scattering correction factor is likely also to be unreliable.

e) *The Planetary Boundary-Layer aerosol and similar features.*
Because it is not possible for the SCA to determine the optical thickness of features in contact with the surface, it is not possible for the solution to be improved iteratively as is done in some of the cases above. Also, because no estimate of the aerosol backscatter or extinction is available at the lower boundary of such features, forward solutions are preferred. The calibration range is chosen to be at the point in the clear air above the feature for 532-nm signals or at the first point in the feature for 1064 nm.

5. RESULTS

The successful application of the SIBYL / HERA routines is illustrated in Fig. 2, where the attenuated backscatter depicted in the modified LITE scene in Fig. 1 is plotted as values of extinction. The stronger features can be seen plotted on a finer (5-km) horizontal scale, while the weaker cloud and aerosol features are only detected, analysed and plotted on the broadest (80-km) horizontal scale.

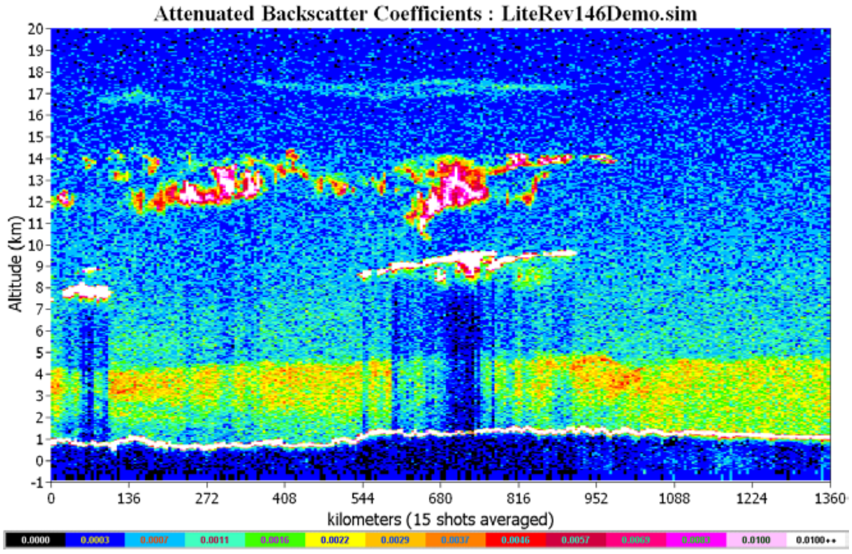

Figure 1: LITE total attenuated backscatter plotted against altitude and distance, modified to CALIPSO resolution

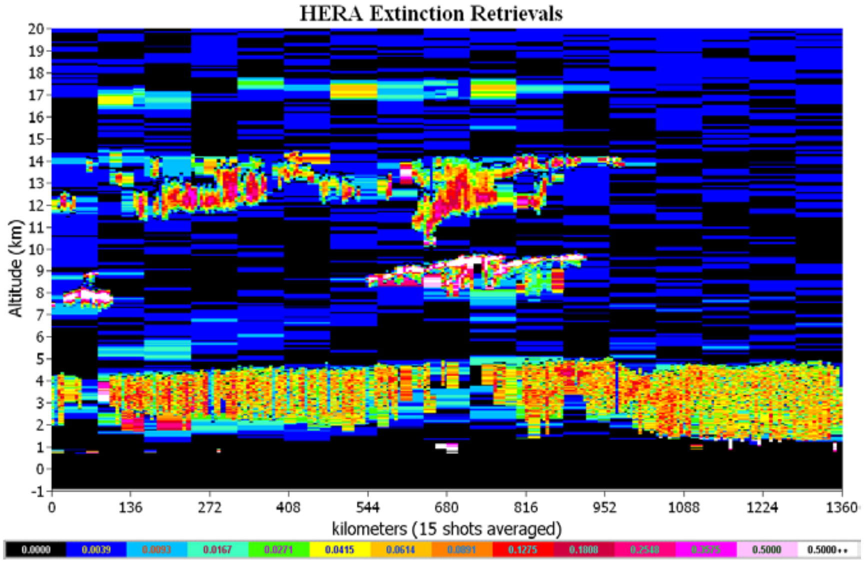

Figure 2: Results of SIBYL / HERA analysis of data in Figure 1, showing processing over different horizontal scales.

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