Cirrus and Aerosol Lidar Profilometer - Analysis and Results

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Introduction

A cloud and aerosol lidar data set from over a year of near continuous operation of a micro pulse lidar (MPL) instrument at the Cloud and Radiation Testbed (CART) site has been established. MPL instruments are to be included in the Ames Research Center (ARC) instrument compliments for the SW Pacific and Arctic ARM sites. Operational processing algorithms are in development for the data sets. The derived products are to be cloud presence and classification, base height, cirrus thickness, cirrus optical thickness, cirrus extinction profile, aerosol optical thickness and profile, and planetary boundary layer (PBL) height. A cloud presence and base height algorithm is in use, and a data set from the CART site is available. The scientific basis for the algorithm development of the higher level data products and plans for implementation are discussed.

MPL Instrument

The unique features of micro pulse lidar are the ability to profile all significant cloud and aerosol structure of the atmosphere with a compact, fully eye safe instrument that is capable of full-time, long-term unattended operation. The initial instrument was developed at Goddard Space Flight Center as a spinoff of research on efficient lidar for space borne applications. An MPL instrument was first used in the SW Pacific PROBE study in early 1993 and in October 1993 an instrument began full-time measurements at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) field site.

MPL is a conventional time-gated, incoherent detection lidar approach. Beyond that there are three basic differences between the micro pulse lidar and most previous lidar systems. First the laser pulse repetition frequency (PRF) is much higher, kilohertz rather than Hertz, and the pulse energies are much lower, micro-Joules rather than milli-Joules or greater. The low-pulse energy is the factor that permits the systems to be eye safe. The second difference is that the laser is diode-pumped rather than flashlamp-pumped. The solid state lasers are much more efficient and smaller. The third difference is that signal detection is by photon counting. Photon counting is generally a more accurate and problem-free means of signal acquisition for low level signals than analog detection. The details and advantages of the MPL design are discussed by Spinhirne (1993), and Spinhirne et al. (1995) give the specifications of the MPL system in use at the SGP site. Upgraded instruments are to be installed at the SW Pacific and Arctic ARC sites. A high-performance instrument with much higher pulse energies and polarization measurements is in development.

MPL Data

The lidar data are stored as 1-minute average profiles. The signal return in photo electron counts per second n(r) at range r may be given by

$$n(r) \quad CE(r)J[\beta_m(r) \quad \beta_p(r) \quad \beta_c(r)]T^2(r)/r^2 \quad n_b \qquad (1)$$

where β is the backscatter cross section due to molecular, particulate, and cloud scattering as indicated by the subscript and T is atmospheric transmittance. C is a dimensional system calibration constant, J is the laser pulse energy, and E is a near range overlap factor that becomes unity at several kilometers range. n_b is a background signal from daytime solar photons entering the receiver. Signals are acquired for 400 µs or 60-km range. The last 100 µs of the signal is negligibly different from n_b and thus gives a value for the background. A basic signal display form is the range corrected signal, or relative attenuated backscatter cross section, and is given by

$$p(r) \quad [n(r) \quad n_b]r^2 \qquad (2)$$

Image displays of p(r) in a time versus range format are valuable for initial data assessment and may be used for initial image algorithm processing of data. An example of one week of data from the SGP site in this format is given in Figure 1. Such images in graphical interface format (GIF) format are to be a standard data product from the MPL instruments.

Lidar Data Processing Strategy

A two-step processing strategy data processing algorithm is being implemented. In the first step, the goal is to classify the observational case and determine the location of the signal discontinuities, such as cloud base height, that are present. The analysis needs to be done before data has been calibrated and processed. The method that is used is threshold detection analysis but image-based analysis of the data displayed in time-height cross section form is in development. The second step is lidar equation signal analysis of the lidar data. A classification of the data by factors such as cloud presence and cloud type is needed before this step may be completed. The goal of the lidar equation signal analysis is to derive quantitative measurement parameters of cloud and aerosol optical thickness and cross section profiles.

Image Analysis and Classification

The most basic classification approach is threshold crossing analysis to detect the presence of cloud boundaries. A limitation of the approach is that for low signal-to-noise conditions, the threshold must be kept above noise fluctuations, which degrades sensitivity. In addition, the noise is a rapidly changing variable of background and range. However, when only a single profile is tested, improvements due to horizontal correlations are not realized. The sensitivity of thresholding may be maximized by adjusting the threshold as a function of the noise given by square root of n(r). The current cloud base data set is determined by this technique. Cloud height statistics for a ten-month period are shown in Figure 2.

Image analysis takes advantage of spatial correlations. By using image processing approaches to determine the spatial boundaries of clouds and haze layers, advantage can be taken of horizontal correlations of the data as well as the sharp vertical gradients that indicate a cloud return. Edge detection algorithms extract this information and may be used to find cloud base and top. Defining cloud/background regions may be automated using computer vision techniques such as image segmentation, which partitions an image into a set of non-over-lapping regions whose union is the entire image. Local statistics such as mean and variance help determine the partitions. Other techniques to be explored in the future include line extraction and noise cleaning methods.

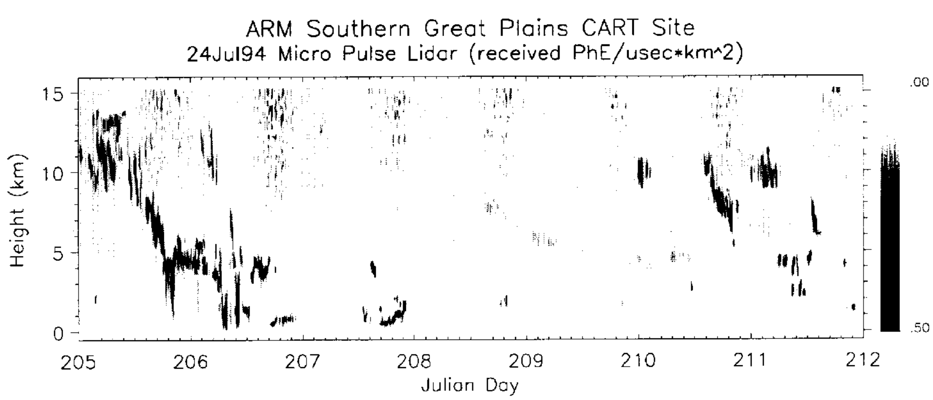

Figure 1. Image of MPL data from the Oklahoma CART site. The data is displayed in range corrected format but with no near range overlap correction of the near ground signal. Similar browse images for all MPL data are to be made available in GIF format.

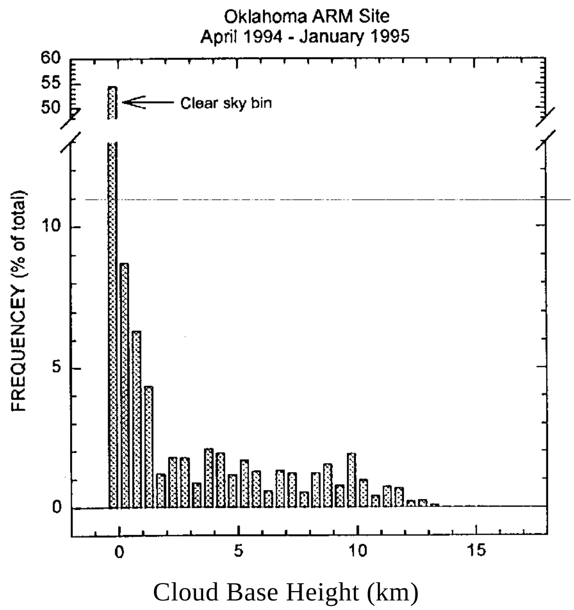

Figure 2. Cloud base height statistics from the MPL system for ten months of operation at the Oklahoma CART site.

Lidar Signal Equation Analysis of Data

The research objective of quantitative analysis of lidar data is to derive independent height resolved radiation variable data sets as appropriate for classified atmospheric conditions. A main goal is to obtain the cirrus optical thickness and extinction profile. Due to small field view of the MPL system (100µrad), a multiple scattering correction is not required. For optical thickness less than approximately one, the attenuation of the molecular and aerosol return signal from beyond the cloud top directly gives the cloud optical thickness of thin clouds. Signal averaging is generally required. When the optical thickness is approximately greater than one and less than two, an alternate approach is to correlate the integrated cloud return signal with the thermal or visible background radiance. The correlation provides a boundary condition to relate the measured backscatter cross section to the extinction cross section which allows the optical depth and extinction to be determined. Cloud optical depth of greater than approximately two cannot be measured directly be lidar.

The aerosol optical thickness and extinction profile may be similarly analyzed. The basic measurement parameter of lidar is the product of backscatter cross section times atmospheric attenuation. The backscatter may be calibrated by assuming molecular scattering for the cleanest conditions of the upper troposphere and stratosphere. With the assumption of constant extinction to backscatter ratio, the lidar equation may be solved for extinction and optical thickness.

A generic description of the procedure is given here. The lidar equation may be given in term of the range and calibration normalized signal as

$$P(r) \quad (n(r) \quad n_b)r^2/CJE(r) \quad \beta(r)T^2(r) \tag{3}$$

The well-known equation for the solution is

$$T^2(r_1,r_2) \quad 1 \quad (\frac{2}{k'})I_{1,2} \tag{4}$$

where

$$I \quad \int_{r_1}^{r_2}\beta(r')T^2(r')dr' \quad \text{and} \quad k' \quad \beta(r)/\sigma(r) \tag{5}$$

if σ is the extinction cross section. The integral I is obtained directly from the lidar signal if the relative calibration constant C is known. C is obtained by normalization in the upper troposphere to the known molecular scattering cross section once the transmission is found. If $I_{1,2}$ is the integral of the signal for the clear air region in the upper troposphere and I_o is the integral with no clouds or aerosol present below r_1 then

$$T^2(r_1) \quad I_{1,2}/I_o \tag{6}$$

it follows that

$$I_{0,1} \quad \left(\frac{k'}{2}\right) \quad \left(\frac{k'}{2I_o}\right)I_{1,2} \tag{7}$$

If a range of optical thickness is encountered in time, as is typical for PBL aerosol or cirrus layers, then (7) represents a system of linear equations by which k' may be determined from least squared analysis. The overall solution of the lidar data for the system calibration constant, the extinction to backscatter ratio, and the desired cirrus or aerosol optical depth when there is a long time history of measurements would be an iterative procedure. A more complete description of the theory involves the separation of terms for the molecular and cirrus or aerosol scattering components (Spinhirne et al. 1990, 1994). The utility of the analysis procedure for the MPL data is to be tested.

Summary

Cloud boundary classification of MPL data is currently being processed by a threshold analysis technique. A data set for over a year's operation at the ARM CART site has been created. An improved classification procedure based on image analysis techniques will provide cloud top and thickness results up to the limit of signal attenuation and also the presence and extent of aerosol layers including PBL height boundaries. A quantitative data analysis procedure based on lidar equation analysis is in development to provide vertically resolved measurements of cirrus and aerosol extinction cross sections. The cross section measurements will be applied with ground visible and infrared radiance measurements to study basic cloud and aerosol radiation effects. An upgraded MPL instrument with greater sensitivity, dual wavelengths, and polarization is in development and should provide for greater accuracy of measurement results.

References

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