Cloud and Aerosol Height Distribution Retrieval and Analysis Employing Continuous Operation Lidar Data

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Introduction

New technology now permits ground-based lidar to operate full time and profile all significant aerosol and cloud structure of the atmosphere up to the limit of signal attenuation. Such systems are in operation at U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) sites and are known as micropulse lidars (MPL) as referenced by Spinhirne (1993).

The effect of clouds and aerosol on the atmospheric energy balance and adequate representation of clouds in climate models are key ARM problems. Full knowledge of aerosol and cloud distributions is difficult to obtain by passive sensing alone. Aerosol and cloud retrievals in several important areas can be significantly improved with active remote sensing by lidar. Applications of lidar for radiation-related measurements are well known. Lidar has long been the standard for monitoring the stratospheric aerosol layer. The Experimental Cloud Lidar Pilot Study (ECLIPS), for example, attempted to assemble cloud height measurements from a number of research lidar sites as referenced by Platt et al. (1994).

The distribution of cloud base height is a basic parameter for the surface radiation budget. A 3-year dataset has been obtained at the Southern Great Plains (SGP) site, and observations are beginning in other locations. Observational results include cloud base height distributions and aerosol profiles. Correlation of cloud and aerosol structure has been observed. These expanding datasets offer a significant new resource for atmospheric radiation analysis. The nature of the datasets, data processing algorithms, derived parameters, and application results will be presented.

Instrument

The basis of the MPL design is the use of lasers with high pulse repetition frequencies (PRF) and low pulse energies. When highly efficient optics, filters, and detectors are used, it is possible to obtain profiling of all significant cloud and aerosol structure of the atmosphere with eye safe pulse energies in a compact, low power instrument design.

The design is an outgrowth of work to develop spacecraft lidar where high efficiency is also important. The basic design for the instruments, which operate at 523 nm, has been described previously by Spinhirne et al. (1995).

A diode pumped Nd:YLF laser operating at 2.5-kHz pulse repetition rate is used. Improvements in instrument parameters for the more recent instruments allow systems to provide 24-hour profiling of tropospheric aerosol structure in addition to comprehensive cloud profiling. The original instrument had a pulse power of 2 µJ. The 8-µJ energy of the new instruments is still well within the estimated 25-µJ eye safe limit for their 20-cm aperture.

In addition to the transmitter-receiver unit, the system is composed of a small power supply and a PC computer data system. Setup and use by non-technical operators has been demonstrated. The new technology is now readily available for general use, and widespread application of these, or similar, instruments is to be expected.

Data Processing and Results

The current application of the MPL instruments is for atmospheric observation relating to measurement needs for understanding radiation in the atmosphere. For clouds, cloud presence, cloud base height, cloud top height (thin clouds), multiple cloud layers (thin or broken clouds), and profiles for cloud scattering cross section and cloud optical thickness (thin clouds) are being processed operationally, or techniques for processing are under development. For aerosol scattering, the retrieved parameters are to be cloud cleared aerosol scattering profiles, including stratospheric aerosol layers (night only), although validation for background conditions remains to be completed. Planetary boundary layer (PBL) height may be obtained in cases where it is defined by the aerosol structure. Aerosol optical thickness retrievals are also possible from combined analysis with supporting data. An important issue is the techniques by which a very large amount of data are to be routinely processed.

The initial procedure in data processing is to remove instrument factors. Several corrections are needed. The detector system is photon-counting, and a signal correction is required for photon coincidence at high count rates. At low altitude, there must be a correction for lidar receiver factors. This so-called overlap correction is calculated using a horizontal MPL profile which allows for the assumption that the aerosol backscatter is constant for a significant range. The overlap correction ceases to exist beyond some range r_0. In a plot of the natural log of the range-corrected signal verses range, the overlap corrected signal will follow the slope of the signal beyond r_0, while the original signal decays in the near range. The overlap correction has been routinely applied to recent data.

Lidar data from the initial instrument at the ARM SGP CART site first became available in December 1993. Since that time, data in the form of 1-minute averages have been available almost continuously. A new 8-µJ instrument began on-site testing during the last third of 1995 and is now the operational unit at the ARM CART site. With the introduction of the improved instrument, data quality of the lidar products has significantly improved.

In order to make it possible to browse data and see atmospheric structure, bi-weekly atmospheric lidar profile images are available for ARM site data. Images are created using 10-minute averages for the lidar return profiles from 0 km to 15 km. The images can be accessed through the Cloud and Aerosol Lidar web page with a suitable web browser by opening the following URL: http://virl.gsfc.nasa.gov. The image in Figure 1 is an example. In the image, strong signal returns, such as thick clouds, show as black. Aerosol plumes show as dark gray. Days marked on the horizontal axis start at 00 UTC. The region at the top of the PBL aerosol structure, which extends to 4.5 km, appears to be the favored location for cloud development. Thin cirrus also is easily identifiable. Correlation of cloud and aerosol structure has been observed in many of these images.

The initial requirement of the ARM program for the MPL instrument was as a high-altitude cloud ceilometer. The ability to detect and define the height of all clouds was

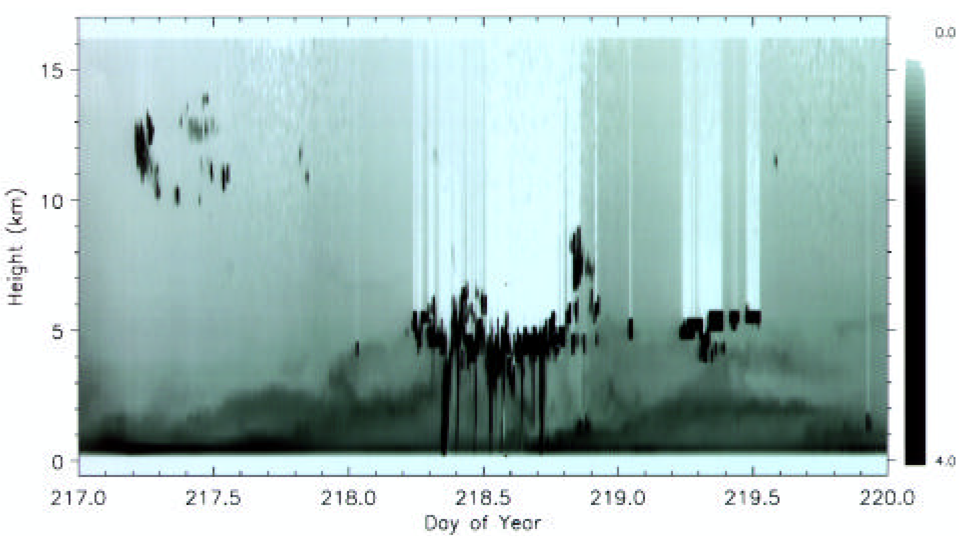

Figure 1. MPL002 data from 04-06 August 1996 acquired at the ARM Oklahoma field site showing clouds and aerosol structure.

not available from commercial ceilometers. A cloud presence and cloud base height retrieval has been applied to all ARM MPL data and results are available from the web site or the ARM data system. The current cloud recognition algorithm is based on a threshold analysis that is adjusted for the expected signal noise. The cloud detection differentiates 1- minute profiles that are clear or cloudy and thus gives a very accurate measure of cloud fraction. The limiting factor is the definition of how low of scattering cross section is considered a cloud.

In order to classify and find the height levels of multiple cloud layers and boundary layer height from the aerosol structure, improved edge-sensing techniques are in development. One method stems from the work of Suk and Hong (1984). The method is based on performing six independent statistical tests on a sliding small window as it scans the whole MPL profile image, moving a half window width at a time. For a cloud or PBL edge to be found, it must cross any two sides of the window. If a majority of tests indicate an edge, then the algorithm reports that an edge is found at that window location.

Another technique is an image edge detection algorithm developed by A. Galbraith of the University of Arizona. This method encompasses mapping horizontal running standard deviations for each vertical profile and correlated sequences of consecutive profiles. Highly correlated sequences of consecutive profiles are grouped into sub-areas to enhance edge detection. The standard deviation map is used as a flag to indicate "cloud" or "no cloud" status for each pixel. Cloud edge locations are finalized with statistical tests.

Figure 2 shows results from the current cloud recognition algorithm. Cloud base distributions are shown taken from 1-minute average profiles over a period of nearly 2.5 years. The distributions show the predominance of clear sky, which is well over 50 percent, with low clouds the most frequently observed clouds. The dataset is for the first detected cloud base. High cirrus as a cloud base is infrequent, partially due to the fact that in any multiple cloud situation, lower clouds will get counted first. The more advanced processing gives the height of multiple cloud layers, when seen from the surface. Figure 3 shows the corresponding fraction of detected clouds from the MPL data. Cloud climatology statistics such as this will be very important for studying cloud cover changes over periods of decades. The MPL cloud height dataset is used by studies involving ARM data such as the CAGEX[a] experiment by Charlock (1996).

(a) CERES/ARM/GEWEX - Clouds and Earth's Radiant Energy System/Atmospheric Radiation Measurement/ Global Energy and Water Experiment.

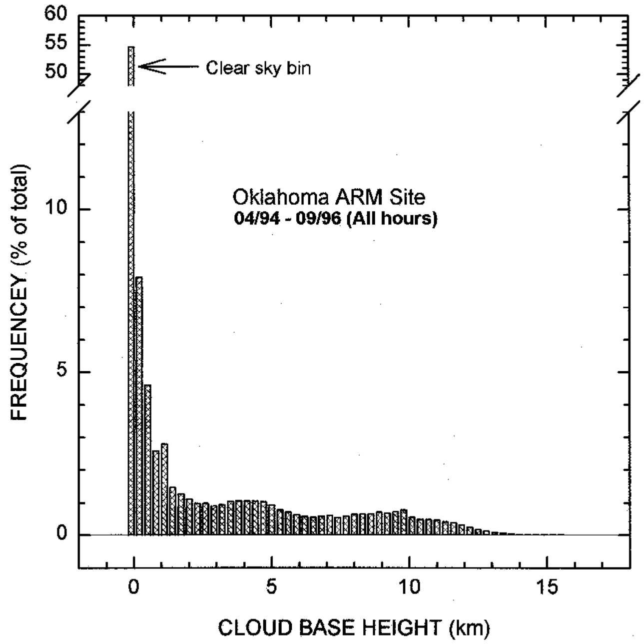

Figure 2. Cloud base distribution from micropulse lidar based on 1-minute average profiles over a period of almost 2.5 years. Clear sky was by far the most frequent sky condition observed.

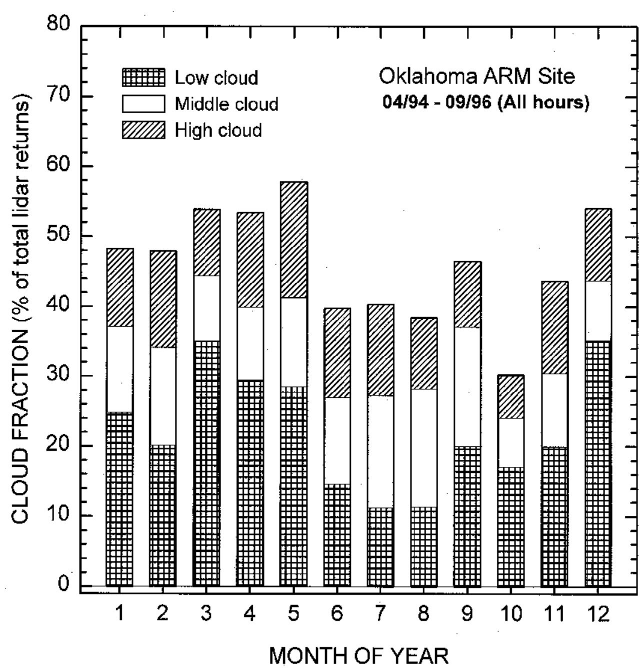

Figure 3. Cloud fraction distribution from micropulse lidar based on the same dataset as in Figure 2. The distributions of low, middle, and high clouds for each month are totaled.

The MPL cloud base height data are applied in Figure 4 to study the performance of a commercial cloud ceilometer instrument for determining the correct cloud height statistics. The ceilometer is designed for cloud detection up to 7.6 km. The comparison shows that there is a significant fraction of thin clouds below that altitude that are not detected. In addition, there is an altitude bias of 300-500 m in height for the ceilometer cloud base heights. The height bias would likely be the result of the long pulse length and less sensitive detection of the ceilometer. Overall, the ceilometer cloud heights are not adequate for the interpretation of surface radiation.

An advanced application of the MPL data is to retrieve the optical thickness and extinction cross section of both thin cirrus (when the optical thickness is approximately less than two) and aerosol. The processing algorithms are under development. A well-known cirrus analysis uses the height profile of the signal to interpret the radiation at the surface (Platt 1979). The 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 extinction cross section, which allows the optical depth and extinction to be determined.

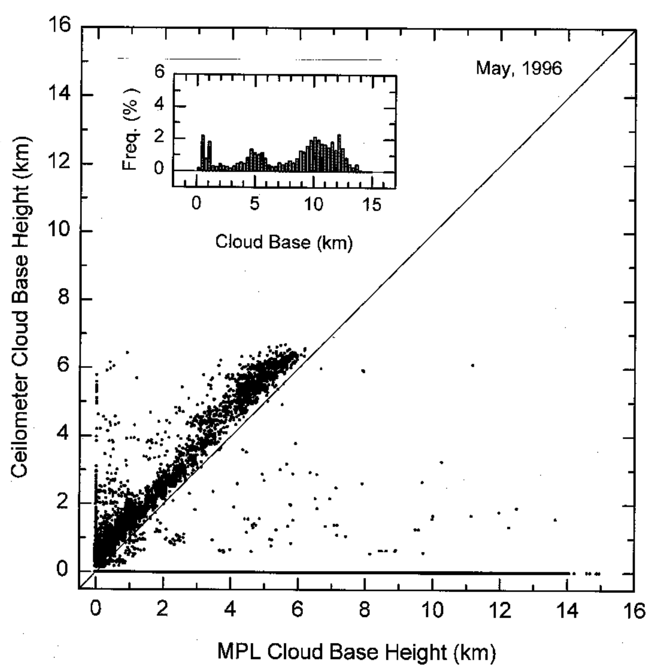

Figure 4. Comparison of MPL cloud detection and the results from a commercial ceilometer. The inset graph indicates the percent frequency of the total clouds that are missed by the ceilometer.

In some cirrus cases, the optical thickness and extinction cross section profile may be estimated from the lidar measurement alone. Because of the small field-of-view (FOV) of the MPL system (100 µrad), a multiple scattering correction is not required as for most lidar systems with much larger FOV. 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.

The aerosol optical thickness and extinction profile may be similarly analyzed from the lidar data. To obtain the data in terms of atmospheric scattering cross section, a calibration of the receiver against clear air scattering must be obtained. The backscatter may be calibrated by assuming molecular scattering for the cleanest conditions of the upper troposphere and stratosphere, a good assumption for the 523-nm MPL wavelength. With the assumption of constant extinction to backscatter ratio, the lidar equation may be solved for extinction and optical thickness.

Another complementary technique is to use collocated sun photometer optical thickness when available. The separately measured solar optical thickness can be used to constrain the lidar extinction cross section retrieval or, conversely, to validate direct lidar retrievals as given above. The application of the analysis procedure for the MPL data is being tested now.

An example of a data profile which shows PBL aerosol and a thin cirrus layer is given in Figure 5. Three profiles are plotted. The increase in total backscatter above the Rayleigh baseline (which shows molecular backscattering only) marks the aerosol contribution in Figure 5. Misrepresentation of the aerosol strength is obvious without the overlap correction applied. The top of the planetary boundary layer is diffuse in this example, fading away at 3.5 km. A subvisible cirrus signal is seen between 10 and 11 km. Profiles such as these are in the process of being analyzed for corrected backscatter and extinction cross section.

In addition to the instrument at the ARM site in Oklahoma, a second generation instrument just began operation at the first of three ARM sites in the tropical western Pacific. There are plans to soon begin operation of instruments at Arctic and Antarctic sites and in the Canary Islands. The data from these instruments should provide a measurement of the vertical structure of cloud and aerosol in the atmosphere that is new and important for radiation and climate analysis.

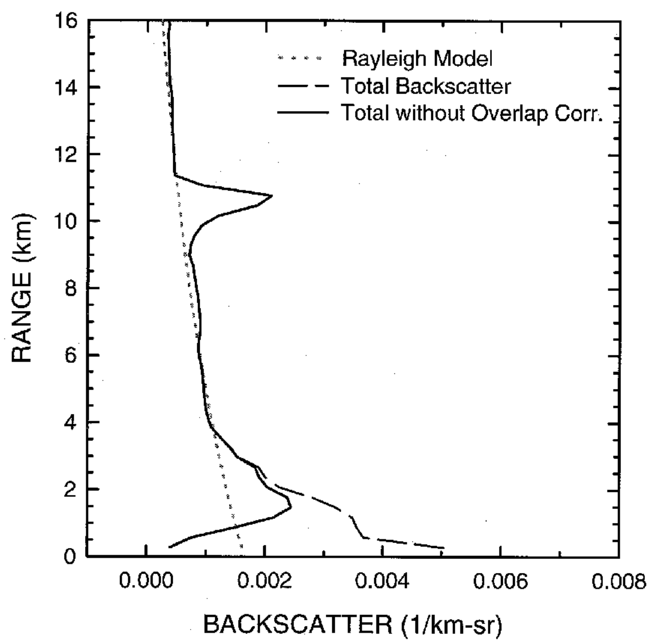

Figure 5. MPL002 backscatter profile (September 2, 1996) from the Oklahoma ARM site which includes subvisual cirrus at 10 km and boundary layer aerosols.

Summary

The basis of the MPL design is the use of a laser with a high pulse rate and low, eye safe, pulse energies. Cloud boundary classification of MPL data is currently being processed by a threshold analysis technique. A dataset spanning almost 2.5 years at the ARM CART site in Oklahoma has been created and is on the Web. An improved classification procedure based on image analysis techniques is being tested and will provide cloud top and thickness results up to the limit of signal attenuation. A quantitative data analysis procedure based on the lidar equation has been implemented for attenuated aerosol backscatter profiles, and analysis to provide vertically resolved measurements of cirrus and aerosol extinction cross sections is in development. The definition of planetary boundary layer height boundaries is possible. The cross section measurements will be applied with ground visible and infrared radiance measurements to study basic cloud and aerosol radiation effects. The MPL dataset will soon be significantly enhanced when instruments are installed in the tropical Pacific and at high latitude regions.

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