Cloud Optical Depth Retrievals From Solar Background "Signals" of Micropulse Lidars

J. Christine Chiu, Alexander Marshak, Warren J. Wiscombe, Sandra C. Valencia, and E. Judd Welton

***Abstract*—Pulsed lidars are commonly used to retrieve vertical distributions of cloud and aerosol layers. It is widely believed that lidar cloud retrievals (other than cloud base altitude) are limited to optically thin clouds. Here, we demonstrate that lidars can retrieve optical depths of thick clouds using solar background light as a signal, rather than (as now) merely a noise to be subtracted. Validations against other instruments show that retrieved cloud optical depths agree within 10%–15% for overcast stratus and broken clouds. In fact, for broken cloud situations, one can retrieve not only the aerosol properties in clear-sky periods using lidar signals, but also the optical depth of thick clouds in cloudy periods using solar background signals. This indicates that, in general, it may be possible to retrieve both aerosol and cloud properties using a single lidar. Thus, lidar observations have great untapped potential to study interactions between clouds and aerosols.**

***Index Terms*—Cloud, cloud–aerosol interactions, lidar, remote sensing, zenith radiance.**

I. Introduction

MICROPULSE lidar (MPLs) systems, developed in 1992 [1], are now widely used to retrieve heights of cloud layers and vertical distributions of aerosols layers [2], [3]. The MPL time-dependent returned signal is proportional to the amount of light backscattered by atmospheric molecules, aerosols, and clouds. However, measured photon counts must be converted to attenuated backscatter profiles, and during the process a number of noise sources need to be accounted for [4] and [5].

One source of noise is solar background light, which is measured by the MPL detector in addition to backscattered laser light. The MPL has a narrow field of view and filter bandwidth to reduce solar noise, but the contribution remains significant near solar noon or when a bright cloud is overhead. Fortunately, this noise can be estimated. Due to a time interval of 400 μs between consecutive pulses, data can be retrieved up to a range of 60 km. However, there is no discernible backscatter beyond 30 km. Therefore, we can estimate solar background light using sample bins between 45 and 55 km.

One man's noise is another man's signal. When lidars point straight up, the solar background noise is the solar zenith radiance, which can be used to retrieve cloud optical properties [6], [7]. We are unaware of any retrieval algorithm that uses the solar background light observed by lidars as a signal. This letter aims to address this issue by providing a proof-of-concept for using solar background "signal" from MPL to retrieve cloud optical depth. We will also evaluate results against those retrieved from other methods, and discuss the potential of our method to shed light on aerosol-cloud interactions.

II. Approach

Solar background signal is estimated from lidar bins beyond 30 km in units of photon counts. For retrieval purposes, photon counts must be converted to actual radiance. This conversion is instrument-dependent. [8] described a laboratory calibration procedure capable of converting raw detector counts to calibrated radiance. The authors demonstrated that the calibrated MPL solar background radiance agreed with zenith radiance measurements from principal plane observations using a colocated AERONET sunphotometer [9]. Thus, it is possible to calibrate MPL systems using the colocated AERONET sunphotometers instead of the more time-consuming laboratory calibration. The sunphotometer calibration method would also account for MPL calibration drifts during the period of MPL deployment (due to filter degradation and window cleanliness). In this letter, we followed their method and derived MPL calibration coefficients using AERONET data when available.

MPLs of the atmospheric radiation measurement (ARM) program and of the NASA MPL Network (MPLNET [10]) both operate at a 523-nm wavelength. The general relationship between zenith radiance and cloud optical depth at this wavelength is depicted in Fig. 1, based on 1-D plane-parallel radiative transfer. Clearly, this relationship is not a one-to-one function. There are two cloud optical depths that give the same zenith radiance: one corresponds to thinner clouds and the other to thicker clouds. Thus, it is impossible to unambiguously retrieve cloud optical depth from solar background signal of a one-channel MPL. To remove this ambiguity, a criterion is needed to distinguish thick clouds from thin clouds or no clouds. A simple criterion adapted here assumes that if a lidar beam is completely attenuated, the detected clouds correspond to the larger optical depth.

Retrievals from MPL solar background signal are intercompared with those from three other instruments. The first instrument is the ARM multifilter rotating shadowband radiometer

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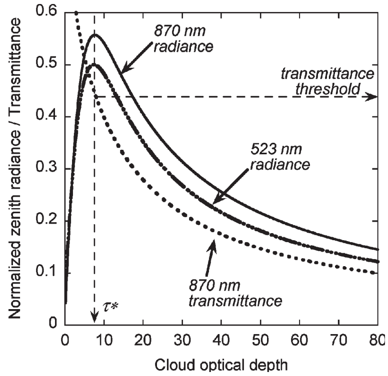

Fig. 1. Downward 523- and 870-nm radiance and transmittance versus cloud optical depth calculated by the 1-D radiative transfer model DISORT [11] with a surface albedo of 0.05 and 0.35, respectively. Solar zenith angle is 60°. τ^* is the optical depth that corresponds to the maximum radiance and the transmittance threshold at 870 nm.

(MFRSR), which provides 20-s averages of both direct and diffuse solar flux in narrowbands centered at 415, 500, 615, 673, 870, and 940 nm. We used direct and diffuse transmittance at 415 nm, together with 1-D radiative transfer theory, to retrieve cloud optical depth, similar to the method of [12].

The second instrument is the ARM one-channel narrow field-of-view (1NFOV) radiometer, which provides 1-s zenith radiance at 870 nm. Retrieval method from 1NFOV observations is same as that from MPL using the relationship shown in Fig. 1, but with different surface albedo and wavelength. Similar to MPL, additional information is needed to yield a final retrieval from those two possible optical depths. We used a transmittance threshold to discern cloud scenes [13], [14]. When MFRSR-calculated transmittance is greater (smaller) than the threshold, the detected clouds have a smaller (larger) optical depth. The threshold is given as the transmittance at the cloud optical depth τ^* that corresponds to the maximum radiance of the curve shown in Fig. 1. Note that the threshold is not a constant but depends on solar zenith angle.

The third instrument provides multichannel zenith radiance observations; it is either the ARM two-channel narrow field-of-view (2NFOV) radiometer or AERONET CIMEL sunphotometers. 2NFOV measures zenith radiance at 673 and 870 nm with 1-s temporal resolution. CIMELs take ten measurements of zenith radiance with 9-s temporal resolution only when clouds block the sun (i.e., cloud mode). In this letter, only CIMEL measurements at 675 and 870 nm were used. Note that the method from dual-channel radiances unambiguously retrieves cloud optical depths over vegetated surfaces. It is based on the fact that in these two spectral regions, clouds have nearly identical optical properties while vegetated surfaces reflect quite differently. Details and error analyses in retrievals using zenith radiances can be found in [6], [7], and [14].

III. Retrieval Results

Retrievals from solar background signal of MPL, presented in this section, are compared with those from: 1) one-channel radiances and fluxes at the ARM Oklahoma site; 2) two-channel radiances in the ARM Marine Stratus Radiation Aerosol and Drizzle (MASRAD) field campaign at Point Reyes, California; and 3) sunphotometer measurements at the NASA Goddard Space Flight Center (GSFC) site.

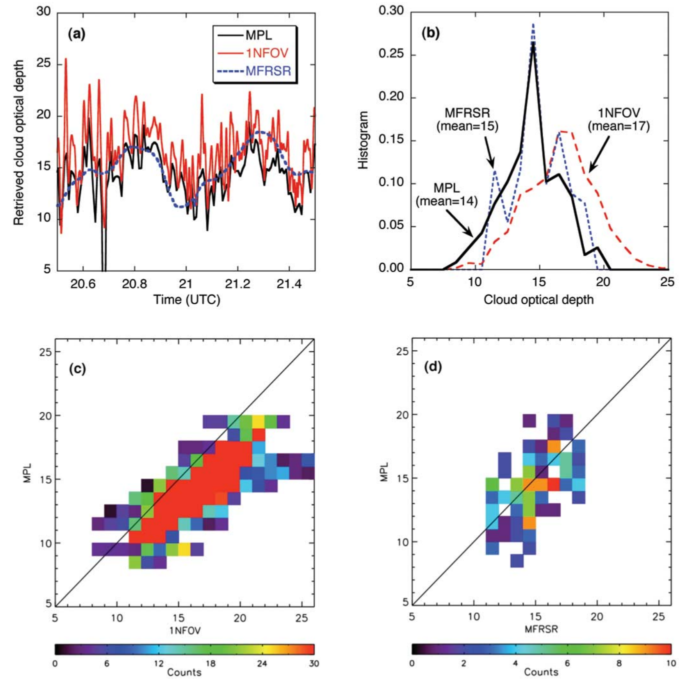

Fig. 2. Retrieved cloud optical depths for one of CLOWD cases at the ARM Oklahoma site on March 14, 2000. (a) Time series, (b) histograms, (c) a scatter plot of retrievals from MPL versus those from 1NFOV, and (d) same as (c), but for retrievals from MPL versus those from MFRSR. Note that MPL, 1NFOV, and MFRSR provide measurements every 30, 1, and 20 s, respectively.

Case 1: ARM Oklahoma Site

Due to high frequency of and high climate sensitivity to thin clouds, ARM created a working group, Clouds with Low Optical (Water) Depth (CLOWD), to focus on microphysical properties of clouds with low liquid water paths [14]. In their study, comparisons and evaluations of different remote sensing methods were performed. Among those retrieval methods, MPL was excluded because lidar measurements were supposed to work only for optical depths less than ~3. Beyond optical depth of 3, lidar returns are limited due to strong cloud attenuation. However, as will be demonstrated next, using solar background signal we are able to overcome this limitation and retrieve larger cloud optical depths from MPL.

One of the CLOWD cases, a single-layer overcast warm cloud at the ARM Oklahoma site on March 14, 2000, is selected for illustration. Calibrations of MPL solar background signals were conducted against 6-month observations of AERONET CIMEL. Retrievals from MPL are compared with those from one-channel zenith radiances and fluxes, which were measured by 1NFOV and MFRSR.

Fig. 2(a)–(d) present the time series, histograms, and scatter plots of cloud optical depths retrieved from MPL, 1NFOV, and MFRSR. Retrievals from these three methods show similar temporal variations. The average cloud optical depth of MPL is 14, which is close to that retrieved from MFRSR. However, retrievals from MPL are generally 10%–15% smaller than those from 1NFOV. This bias can be seen in Fig. 2(c) as well, which reveals a good linearity below the diagonal line between retrievals of MPL and 1NFOV. Due to a smaller sample size, the linearity between MPL and MFRSR retrievals is not clear in Fig. 2(d).

Case 2: ARM Point Reyes Field Campaign

The MASRAD experiment was conducted at Point Reyes, California, during May–September 2005. One of the scientific goals of this experiment was to understand the relationship between cloud microphysics/structures, drizzle, and radiation in marine stratus clouds [15]. Due to the locations of instruments, we compared our retrievals from MPL with those from zenith radiances measured by 2NFOV.

Note that sample volumes from 2NFOV and MPL are quite different. These two instruments have different fields of view (FOV) and sampling resolutions. 2NFOV has an FOV of 0.021 rad (1.2°) and a temporal resolution of 1 s. MPL has an FOV of only 100 μrad, but averages samples over 30 s in order to collect a sufficient amount of photons. Because of the relatively larger FOV of 2NFOV, clouds might partly cover the FOV, which leads to the clear-sky contamination problem [7]. On the contrary, the cloud situation for MPL is either clear-sky or overcast at the natural timescale of cloud evolution due to the extremely narrow FOV. However, because of the 30-s averages, measurements of MPL are a mixture of clear and cloudy signal returns. To make a meaningful intercomparison between retrievals of MPL and 2NFOV, only overcast cases are compared here to reduce the uncertainty resulting from two different sample volumes.

Overcast cases were objectively selected as follows: when MFRSR retrievals were found continuously greater than 5 for at least 1 h, we defined the time period as overcast. An example of an overcast sky image is shown in Fig. 3(a). Unlike the Case 1, we were unable to calibrate solar background signal of the MPL against CIMEL observations in this field experiment, because no CIMEL was deployed. Therefore, we first empirically derived the calibration coefficient by comparing retrievals from uncalibrated solar background signal with those from 2NFOV for only one overcast case. This coefficient was then applied to all other 110 overcast cases.

A scatter plot of cloud optical depths retrieved from MPL versus those from 2NFOV is shown in Fig. 3(b). Surprisingly, even though we only used one case to derive the calibration coefficient, for all overcast cases the majority of retrieval pairs are close to the diagonal line, and optical depths agree within 10%–15%. The difference in the average cloud optical depths of the two methods is only 1.

A. Case 3: MPLNET

Case 3 is based on measurements of the MPLNET at NASA/GSFC. In contrast to previous cases, this was a broken cloud case. Because of the ambiguity of retrievals from only one channel, we manually separated thin from thick clouds. When the returned signal was not completely attenuated, it was assumed that clouds were thin. Calibrations of MPL solar background signals were conducted against one-year principal plane observations of AERONET CIMEL.

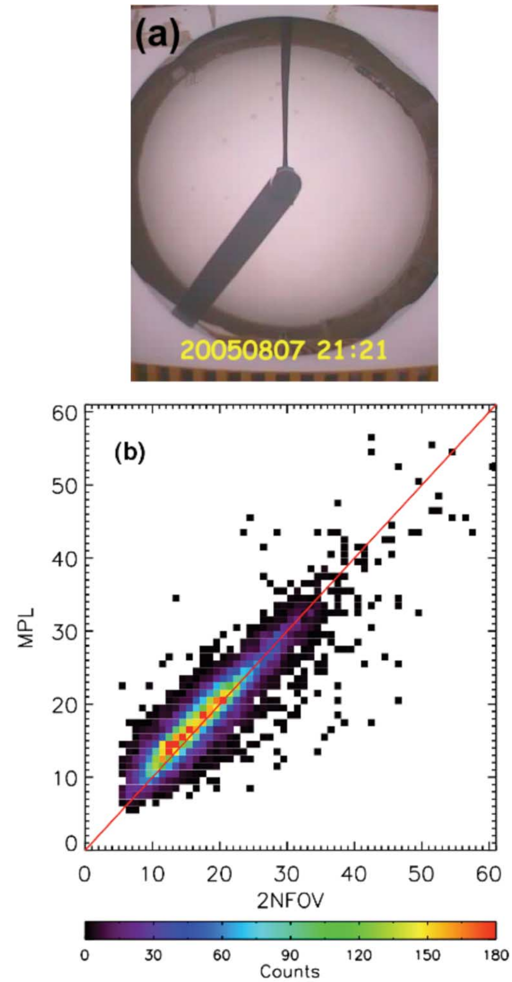

Fig. 3. (a) Example of an overcast sky image taken at the Point Reyes National Seashore, CA, during the ARM field campaign and (b) a scatter plot of retrieved cloud optical depths from MPL versus those from 2NFOV for all overcast cases.

We validated our retrievals against an AERONET CIMEL operated in "cloud mode" [6]. Fig. 4(a)–(c) shows the time series of vertical backscatter profile of MPL, and corresponding retrievals from MPL and CIMEL. The mean cloud optical depths from MPL and CIMEL are 41 and 44, respectively, and their correlation is around 0.86. Except for a few outliers, errors of retrievals from MPL are again around 10%–15% compared to those retrieved from CIMEL.

The retrieval method using solar background signal is not problem-free, however. Recall that a given zenith radiance corresponds to two possible cloud depths (as shown in Fig. 1). We have plotted together the two possible optical depths for Case 3 in Fig. 5—the solid line corresponds to smaller optical depths and the dashed line corresponds to larger optical depths. For certain radiance, these two optical depths are substantially different and it is easy to remove any ambiguity using a "returned" or "no-returned" signal as described above. For instance, when lidar pulses are completely attenuated (no-returned), the larger cloud optical depth is the obvious choice (e.g., 16.8–17.1 UTC). Similarly, when lidar pulses are not

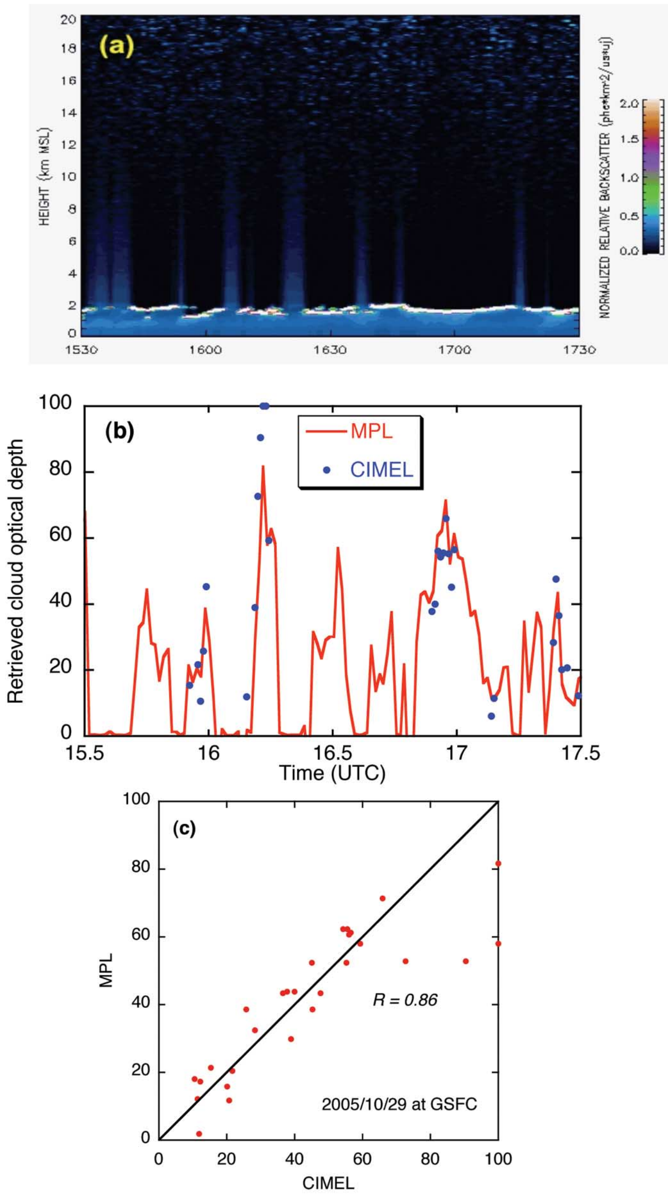

Fig. 4. (a) Time series of MPL backscatter vertical profile at GSFC on October 29, 2005. More details can be found in http://mplnet.gsfc.nasa.gov, and http://climate.gsfc.nasa.gov/viewImage.php?id=161. (b) The time series and (c) a scatter plot of corresponding cloud optical depths retrieved from MPL and CIMEL are also shown here.

completely attenuated (returned), the smaller optical depth is the clear solution (e.g., 17.25 UTC). The problem arises when both of these optical depths result in completely attenuated lidar pulses. In these cases, the margin of difference is too small for us to confidently determine which optical depth is the correct solution (demonstrated by the circles in Fig. 5). In summary, thin clouds (optical depths less than 3) can be detected directly from the attenuated lidar signal. Thick clouds (optical depths greater than 15) can be retrieved from solar background light using the method demonstrated above. Cloud optical depths ranging approximately from 3 to 15 are still difficult to be resolved. Retrieval of these intermediate optical depths will require further information, such as another lidar wavelength or additional instrumentation.

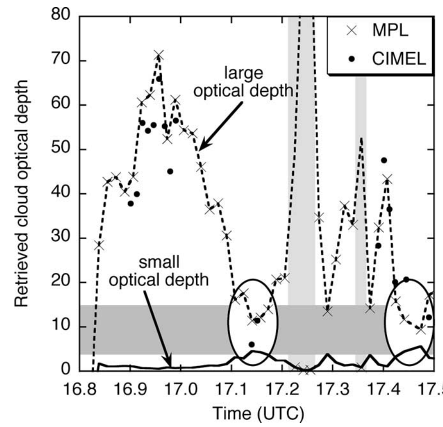

Fig. 5. Enlargement of Fig. 4(b) around 17 UTC, coplotted with two possible optical depth solutions that correspond to the same zenith radiance. The two lighter gray areas are time periods when lidar pulses are not completely attenuated (returned), indicating thin or no clouds. The darker gray area represents a range of optical depths from 3 to 15. When those two possible solutions fall into this range (as indicated by the circles), cloud optical depth cannot be unambiguously retrieved because both solutions lead to completely attenuated lidar pulses.

IV. Conclusion and Discussions

We proved that the solar background light, which is a noise to lidar applications and must be removed from lidar returns, can be used as a signal to retrieve cloud optical depth. This idea was tested for various cases, locations, and instruments. Compared to cloud optical depths retrieved from other methods, it is found that our retrievals generally agree within 10%–15%. This promising result extends the retrieval ability of MPLs to thicker clouds, and is no longer limited to detecting thin clouds only.

Due to the ability to retrieve vertical profiles of aerosol properties, lidar observations are also an essential element in the study of aerosol indirect effects [16]. However, to better understand the effect of aerosols on clouds, it is crucial to have simultaneous measurements of cloud and aerosol optical properties at the same location. Currently, neither single ground-based instruments nor satellite sensors can provide such datasets. Here, we showed that with broken cloud situations, one can retrieve not only aerosol properties during clear-sky periods via lidar signals, but also the optical depth of thick clouds during cloudy periods via solar background lights. In other words, aerosol and cloud optical properties can be retrieved using the same instrument. This indicates that lidar observations have great potential to serve as a unique dataset allowing us to better understand how changes of aerosol in the environment impact cloud properties.

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