Backscatter Color Ratios of Cirrus Clouds Measured by the Cloud Physics Lidar

M. A. Vaughan[1], M. J. McGill[2], Z. Liu[3], Y. Hu[1], and R. E. Kuehn[4], and S. D. Rodier[4]

NASA Langley Research Center, Hampton VA USA 23681-2199
NASA Goddard Space Flight Center, Greenbelt MD USA 20771
National Institute of Aerospace, Hampton VA USA 23666-6147
Science Systems and Applications, Inc., Hampton VA USA 23666

ABSTRACT

The Cloud Physics Lidar (CPL) is a three-wavelength, polarization-sensitive elastic backscatter lidar that flies aboard NASA's high-altitude ER2 research aircraft. This work presents spatial and optical analyses of the combined cirrus cloud measurements acquired by CPL during eight separate field campaigns occurring from 2002 to 2007. Particular attention is given to the retrieval and characterization of the backscatter color ratio, defined as the ratio of the particulate backscatter coefficients measured at 1064 nm and 532 nm. Recent space-based lidar missions rely on assumptions about the backscatter color ratio to calibrate their 1064 nm measurements. Because the signal-to-noise ratio of the CPL data is substantially higher than that of space-based systems, CPL can calibrate its 1064 nm channel using the well-established molecular normalization technique. Analysis of the CPL data sets can therefore provide the independent evaluation of cirrus cloud backscatter color ratios that is required to validate fundamental components of the calibration schemes employed by space-based lidars.

INTRODUCTION

Over the past decade, the Cloud Physics Lidar (CPL [1]) has made extensive measurements of cirrus clouds during numerous long-duration field campaigns. CPL typically flies aboard NASA's high-altitude ER2 research aircraft, and its three-wavelength (355 nm, 532 nm, 1064 nm), polarization-sensitive (at 1064 nm) configuration is especially well suited for assessing the spatial and optical properties of cirrus. In this work we present a comprehensive analysis of cirrus cloud measurements acquired during eight different field campaigns. These experiments took place between 2002 and 2007, spanning latitudes between 52° N and 4° N, and longitudes from Nova Scotia westward to the Hawaiian Islands, and thus should provide a reasonable representation of the scattering characteristics of northern hemisphere.

CPL has long been the lidar of choice for field campaigns that seek to investigate cirrus clouds using a fully coincident combination of remote sensing and in-situ measurement techniques. With the launch of the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission [2] on April 28, 2006, CPL acquired a new and substantial role as one of the primary resources for validating CALIPSO measurements of cirrus clouds. Like CPL, the CALIPSO lidar is a multi-wavelength (532 nm and 1064 nm), polarization-sensitive (at 532 nm) elastic backscatter system. CALIPSO orbits the Earth ~15 times per day, making continuous measurements of attenuated backscatter profiles over a constant altitude range from ~40-km above mean sea level (MSL) to ~2-km below. Because the ER2 typically flies at an altitude of 20 km or above, CPL too can measure the entire vertical extent of the troposphere. Thus, in addition to sharing many basic design similarities, the two lidars also share similar down-looking measurement geometries and enjoy a considerable overlap in their vertical sampling ranges.

While CALIPSO and CPL are similar in many ways, there are also several significant differences between the two instruments. In particular, CPL enjoys a substantial advantage in signal-to-noise ratio (SNR). This difference manifests itself in the methods used to calibrate the two systems. At 532 nm, both lidars can use the traditional technique of normalizing their signals with respect to a molecular scattering model in a high altitude, aerosol-free region of the atmosphere. To obtain reliable calibration coefficients using this approach, the CALIPSO backscatter data must be averaged over many hundreds of kilometers [3]. At 1064 nm, the two lidars must use different calibration targets, as the molecular backscatter cross-section is a factor of ~16 lower at 1064 nm than at 532 nm. Due to its superior SNR, CPL is largely impervious to the diminished scattering efficiency at 1064 nm, and can therefore employ the molecular normalization approach at both wavelengths. CALIPSO cannot: the large reduction in backscatter magnitude, when combined with the relatively high dark noise generated by the avalanche photodiode detector, renders the molecular signal unsuitable for calibrating CALIPSO's 1064 nm data. For this reason, CALIPSO uses cirrus clouds as a calibration target, with the assumption that backscatter, like extinction, is spectrally independent at 532 nm and 1064 nm [4]. The identity of the extinction coefficients in the spectral region of the CALIPSO wavelengths is well established [5]. Previous work also suggests that a median value of the backscatter color ratio of $\chi = \beta_{1064}/\beta_{532} = 1$ would be appropriate, albeit with some caveats about the bimodal shape of the distribution [6]. However, as we show in the sections that follow, based on an analysis of over 400 hours of CPL measurements, a much more reasonable value is $\chi = 0.84 \pm 0.19$.

DATA SELECTION AND ANALYSIS

CPL data is publicly distributed via the CPL web site at http://cpl.gsfc.nasa.gov/. In Table 1 we summarize the dates and locations for all field measurements used in the current study. Both the normalized relative backscatter (NRB) files and the final optical properties (OP) files are used. The NRB files contain range-corrected, energy normalized profiles of altitude-resolved backscatter data, N(z), averaged to a temporal resolution of 1-second. Each 1-second average represents a distance of ~200 meters along the ER2 ground track. By applying the calibration coefficients obtained from a separate CPL-supplied calibration file, the NRB profiles are converted to attenuated backscatter coefficients,

$$\beta'(z) = \left(\beta_m(z) + \beta_p(z)\right) T_m^2(z) T_p^2(z), \qquad (1)$$

where $\beta_k(z)$ is the volume backscatter coefficient for scattering species k, $T_k^2(z)$ is the two-way transmittance for scattering species k, and the subscripts m and p represent, respectively, contributions from molecules and particulates (e.g., cloud particles). Each NRB file also contains a profile of the local molecular number density, obtained from nearby rawinsonde measurements. The number density profiles are used to estimate and remove the molecular two way transmittance component of attenuated backscatter coefficients, yielding profiles of particulate-attenuated total backscatter, B(z), such that

$$B(z) = \frac{\beta'(z)}{T_m^2(z)} = \left(\beta_m(z) + \beta_p(z)\right) T_p^2(z), \qquad (2)$$

Layer heights, optical depths (τ), and extinction-to-backscatter ratios (S, AKA lidar ratios) are retrieved from the OP files. The layer boundaries and the derived profiles of $B_{532}(z)$ and $B_{1064}(z)$ are then used to compute the layer integrated attenuated backscatters, γ'_{532} and γ'_{1064}, where

$$\gamma'_\lambda = \int_{z_{top}}^{z_{base}} \beta_{\lambda,p}(z) T_{\lambda,p}^2(z) dr \qquad (3)$$

Numerically, γ'_λ is computed as follows:

$$g_\lambda = \frac{1}{2}\sum_{j=top}^{base-1}\left(z_j - z_{j+1}\right)\left(B_\lambda\left(z_j\right) + B_\lambda\left(z_{j+1}\right)\right)$$

$$\Delta g_\lambda = \frac{1}{2}\left(z_{top} - z_{base}\right)\left(B_\lambda\left(z_{top}\right) + B_\lambda\left(z_{base}\right)\right) \quad (4)$$

$$\gamma'_\lambda = g_\lambda - \Delta g_\lambda$$

where $g_\lambda \approx \int_{z_{top}}^{z_{base}} \left(\beta_{\lambda,m}(z) + \beta_{\lambda,p}(z)\right) T^2_{\lambda,p}(z)\,dr$

and $\Delta g_\lambda \approx \int_{z_{top}}^{z_{base}} \beta_{\lambda,mp}(z) T^2_{\lambda,p}(z)\,dr$.

Assuming that $\chi = \beta_{1064,p}(z) / \beta_{532,p}(z)$ is constant throughout each cloud, robust estimates of χ can be derived from γ'_{532} and γ'_{1064} using

$$\chi' = \gamma'_{1064} / \gamma'_{532} \,. \quad (6)$$

Table 1: CPL field campaigns used to derive spatial and optical statistics. Data was compiled from all flights during each campaign, excluding only those for which the measurements were compromised due to an instrument malfunction.

Mission	Date	Range
CRYSTAL-FACE	July 2002	14° N – 29° N
TX-2002	November – December, 2002	26° N – 38° N
THORPEX-Pacific	February – March, 2003	16° N – 40° N
GLAS Cal-Val	October 2003	33° N – 47° N
THORPEX-Atlantic	November – December, 2003	32° N – 53° N
CC-VEX	July – August, 2006	23° N – 40° N
CLASIC	June 2007	28° N – 40° N
TC4	July – August, 2007	3° N – 39° N

Only the uppermost layer in each profile is included in the analyses. The data was further restricted to those clouds for which $\gamma'_{532} \geq 0.015\,sr^{-1}$ and for which the 1064 nm layer integrated depolarization, δ_{1064}, was greater than 0.2. Imposing the γ'_{532} threshold value minimizes the effects of noise, while simultaneously ensuring that only strongly scattering clouds are selected. Similarly, requiring $\delta_{1064} \geq 0.2$ restricts the data set to cirrus clouds only.

RESULTS

The γ'_{532} distribution harvested from the CPL measurements is shown in Figure 1. The clouds analyzed are quite clearly cirrus: the mean cloud top for these data is 12.6 km ± 2.3 km, and the mean δ_{1064} value is 0.41 ± 0.09. The γ'_{532} distribution is seen to be highly asymmetric, with a mean of 0.022 sr^{-1} ± 0.007 sr^{-1}, and a median value of just under 0.020 sr^{-1}. For the most part, these clouds totally attenuate the lidar backscatter signal, so that no additional layers are detected below.

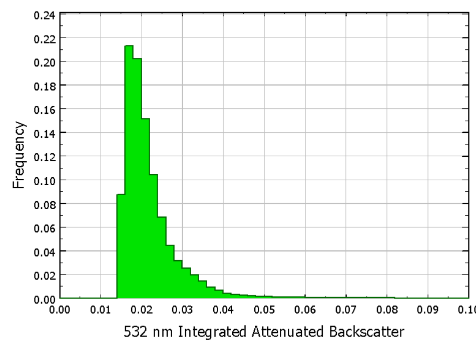

Figure 1: γ'_{532} distribution derived from 155,039 CPL measurements of cirrus cloud.

The relationship between backscatter (γ') and extinction (τ) is non-linear, and is modulated by both the cloud lidar ratio (S) and the layer effective multiple scattering (η). Assuming a mean lidar ratio of 25 sr for the CPL measurements [7], the single scattering optical depth (i.e., η = 1) for the median γ'_{532} value can be computed according to the formula derived by Platt [8]:

$$\tau = -\frac{1}{2\eta}\ln\left(1 - 2\eta S \gamma'\right) \quad (7)$$

The single scattering optical depth for the median value of $\gamma'_{532} = 0.01997\,sr^{-1}$ is 3.25, which is consistent with the maximum optical depth that can be measured by CPL

[1]. Obtaining the larger integrated backscatter values requires contributions to the signal from multiple scattering within the cloud (i.e., $0 < \eta < 1$).

The distribution of backscatter color ratios estimated using equation (6) is shown in Figure 2. The distribution is approximately symmetric about a mean of 0.84, with a standard deviation of 0.19. The difference between these measurements and the expectations of the space-based lidar community (i.e., $\chi = 1$) is thus seen to be quite large. The variability of the distribution is also substantially larger than expected [4].

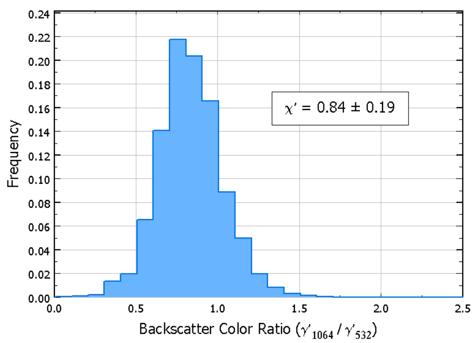

Figure 2: distribution of backscatter color ratios corresponding to the distribution of 532 nm integrated attenuated backscatter shown in Figure 1.

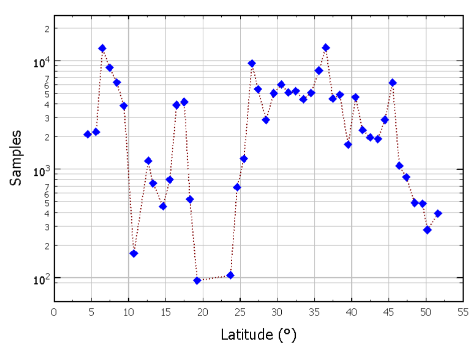

Figure 3: Samples acquired as a function of latitude for the high, dense cirrus measured by CPL

To begin investigating factors that may be contributing to the color ratio distribution, we look first at possible latitudinal changes. Unlike space lidar measurements, CPL data is acquired in limited geographic areas, dictated by the research objectives of the various field missions. Despite this limitation, CPL still provides reasonable coverage for a range of latitudes between ~52° N and ~4° N. The actual number of high, dense cirrus samples acquired for each 1° of latitude is shown in Figure 3.

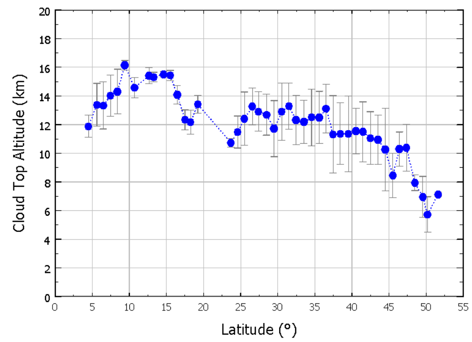

Figure 4: Cloud top as a function of latitude for the CPL data set

For the purposes of this study, dense cirrus is defined by the γ'_{532} threshold. To be identified as high cirrus, a cloud only need be the uppermost ice cloud detected in any profile. The latitudinal distribution of cloud tops used in this study is shown in Figure 4. As expected, the height of the cirrus is seen to rise from north to south, consistent with the change in mean tropopause height over the same latitude band.

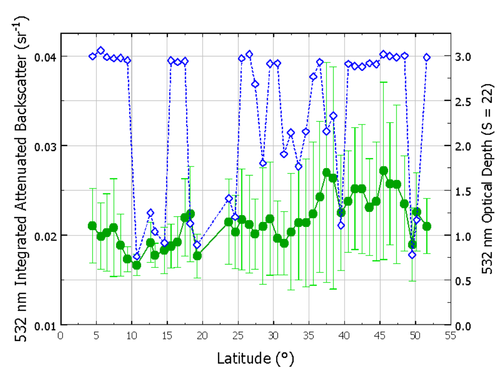

Figure 5: Latitudinal distribution of γ'_{532} (green circles, left Y-axis) and τ_{532} (blue diamonds, right Y-axis).

The latitudinal distributions of integrated backscatter and estimated cloud optical depth are shown in Figure 5. Below ~35° N, γ'_{532} appears to remain relatively constant, hovering around ~0.020 sr^{-1}. There appears to be a step increase in γ'_{532} northward of 35° N. The cause of this phenomenon is currently unknown. However, the measurements acquired south of ~30° N were acquired predominantly over water. Above 30° N, the fraction of measurements acquired over land rises significantly, and this difference in land vs. water data acquisition may contribute to the changes seen.

As seen in Figure 6, the latitudinal distribution of γ'_{532} is not reflected by the backscatter color ratios. Instead, a sharp discontinuity in χ' is observed at ~14° N, where the values increase from just under 0.8 to slightly above 1.0. As the region between 6° N and 10° N is well samples (see Figure 3), this would not appear to be a statistical aberration. At present, however, we are not prepared to suggest possible causal mechanism(s) for the change. A somewhat similar, but less dramatic, change occurs north of 48° degrees, but the sampling in this region is rather sparse.

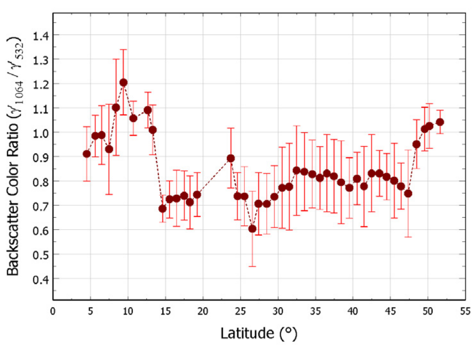

Figure 6: backscatter color ratio as a function of latitude for six years of CPL measurements

CONCLUSIONS

In this study we have analyzed dense cirrus clouds measured by the Cloud Physics Lidar during eight separate field campaigns that took place between July 2002 and August 2007. We find backscatter color ratios that are substantially lower than had been expected based on previous reports. We further find that the distribution of values is broader than had been anticipated by the space-based lidar community. Of particular interest, we also note that there appears to be some latitudinal variation in χ', perhaps suggesting microphysical differences in the composition of high altitude cirrus. These observations should have a significant impact on the 1064 nm calibration schemes implemented by space-based lidars, as the CPL-measured color ratio of $\chi' = 0.84 \pm 0.19$ varies considerably from the value of 1.0 typically assumed by these systems for calibration purposes.

REFERENCES

[1] McGill, M. J., D. L. Hlavka, W. D. Hart, V. S. Scott, J. D. Spinhirne, and B. Schmid, 2002: The Cloud Physics Lidar: Instrument description and initial measurement results, *Appl. Opt.*, **41**, 3725– 3734.

[2] Winker, D., M. Vaughan, and B. Hunt, 2006: The CALIPSO mission and initial results from CALIOP, *Proc. SPIE*, **6409**, doi:10.1117/12.698003.

[3] Hostetler, C. A., Z. Liu, J. A. Reagan, M. A. Vaughan, D. M. Winker, M. T. Osborn, W. H. Hunt, K. A. Powell, and C. R. Trepte, 2006: CALIPSO Algorithm Theoretical Basis Document: Calibration and Level 1 Data Products, PC-SCI-201, Release 1.0 (available at http://www-calipso.larc.nasa.gov/resources/project_documentation.php)

[4] Reagan, J. M., X. Wang, and M. T. Osborn, 2002: Spaceborne lidar calibration from cirrus and molecular backscatter returns, *IEEE Trans. Geosci. Remote Sens.*, **40**, 2285– 2290.

[5] Kent, G. S., D. M. Winker, M. T. Osborn, and K. M. Skeens, 1993: A Model for the Separation of Cloud and Aerosol in SAGE II Occultation Data, *J. Geophys. Res.*, **98** (D11), 20725–20735.

[6] Beyerle, G., M. R. Gross, D. A. Haner, N. T. Kjome, I. S. McDermid, T. J. McGee, J. M. Rosen, H.-J. Schäfer, and O. Schrems 2001: A lidar and backscatter sonde measurement campaign at Table Mountain during February–

March 1997: Observations of cirrus clouds, *J. Atmos. Sci.*, **58**, 1275–1287.

[7] Vaughan, M. R. Kuehn, S. Young, M. McGill, Z. Liu, and Y. Hu, 2008: Validating Cirrus Cloud Optical Properties Retrieved by CALIPSO, Proceedings of the 24th International Laser Radar Conference (ILRC), *in press*.

[8] Platt, C., D. Winker, M. Vaughan, and S. Miller, 1999: Backscatter to extinction ratios in the top layers of tropical mesoscale convective systems and in isolated cirrus from LITE observations, *J. App. Meteorol.*, **38**, 1330–1345.