Airborne validation of spatial properties measured by the CALIPSO lidar

Matthew J. McGill,[1] Mark A. Vaughan,[2] Charles R. Trepte,[3] William D. Hart,[4] Dennis L. Hlavka,[4] David M. Winker,[3] and Ralph Kuehn[2]

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[1] The Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite provides a new and exciting opportunity to study clouds and aerosols in the Earth's atmosphere using range-resolved laser remote sensing. Following the successful launch of the CALIPSO satellite, validation flights were conducted using the long-established Cloud Physics Lidar (CPL) to verify CALIPSO's calibration and validate various CALIPSO data products. This paper presents results of the initial comparisons made between the spaceborne CALIPSO lidar and the airborne CPL. Results are presented to validate measurement sensitivity and the spatial properties reported in the CALIPSO data products. Cloud layer top determinations from CALIPSO are found to be in good agreement with those from CPL. Determinations of minimum detectable backscatter are in excellent agreement with theoretical values predicted prior to launch.

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1. Introduction

[2] The successful launch of the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite in April 2006 ushered in a new era in satellite-based remote sensing [*Winker et al.*, 2003, 2007]. The primary payload aboard CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a dual wavelength, polarization-sensitive backscatter lidar that measures vertical profiles of the spatial and optical characteristics of clouds and aerosols in the Earth's atmosphere.

[3] The CALIPSO satellite is an important component of NASA's "A-train" constellation, which is a group of five formation-flying remote sensing satellites. The instruments in the A-Train were chosen to provide a comprehensive suite of measurements, both passive and active, to enable improved understanding of the Earth's atmosphere. The A-Train is named for the Aqua satellite [*Parkinson*, 2003] which leads the procession. Closely following Aqua are the CloudSat [*Stephens et al.*, 2002], CALIPSO, PARASOL [*Steinmetz et al.*, 2005], and Aura [*Schoeberl et al.*, 2006] satellites. The A-Train satellites fly in a 705-km Sun-synchronous orbit with a 1330 local time equatorial crossing time. With the simultaneous addition of CALIPSO and CloudSat, A-Train researchers will for the first time have access to a global suite of collocated vertical profile measurements to augment the horizontal plane data acquired by existing passive sensors.

[4] The CALIPSO satellite became operational on 7 June 2006. While CALIPSO data will be a valuable source of research data, it is important that the CALIPSO measurements be validated so that the research community can use CALIPSO data with confidence. Accordingly, after initial data verification, aircraft flights were conducted to verify CALIPSO calibration and to validate the level 1 data products.

2. CALIPSO-CloudSat Validation Experiment (CC-VEX)

[5] During the period 26 July to 14 August 2006, the ER-2 Cloud Physics Lidar (CPL) [*McGill et al.*, 2002, 2003] was used for validation of the CALIPSO satellite lidar. The CPL provides high-resolution profiling of clouds and aerosol layers for use in cloud and radiation studies. The CPL is a state-of-the-art system operating at 1064 nm, 532 nm, and 355 nm, with linear depolarization measured using the 1064 nm channel. Measuring the backscattered signal at multiple wavelengths provides information about cloud and aerosol optical properties and the depolarization measurement can be used to determine the ice-water phase of clouds. The CPL provides data products similar to those of the CALIPSO satellite lidar and as such is an excellent CALIPSO simulator and validation tool.

[6] The high-altitude NASA ER-2 aircraft was used for the validation flights owing to its ability to fly above 20 km altitude and thereby provide "satellite-like" measurements. The flights were meant to simultaneously validate multiple aspects of the NASA A-Train of satellites, including the CloudSat radar. The payload for the CC-VEX mission included the CPL, the Cloud Radar System (CRS) [*Li et*

[1]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[2]Science Systems and Applications, Inc., Hampton, Virginia, USA.
[3]NASA Langley Research Center, Hampton, Virginia, USA.
[4]Science Systems and Applications, Inc., Greenbelt, Maryland, USA.

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Table 1. Fundamental Differences Between CPL and CALIPSO

Parameter	CPL	CALIPSO
Repetition rate	5 kHz	20.25 Hz
Vertical resolution	30 m	60 m (above ~8 km)
Platform speed	~200 m/s	~7500 m/s
Detection	photon counting	analog
Receiver footprint at surface	2 m diameter	88 m diameter
Multiple scattering reduction of cirrus extinction coefficient [*Winker*, 2003]	$\eta \sim 0.98$	$\eta \sim 0.70$

al., 2004], the MODIS Airborne Simulator (MAS) [*King et al.*, 1996], and a visible camera.

[7] The CC-VEX mission was based out of Warner-Robins Air Force Base in Georgia to allow flights over ocean, subtropical cirrus, and convective anvils. A total of 13 flights were conducted, and 4 of the flights were at night to permit determination of minimum detectable signal. During the CC-VEX mission all validation objectives were met.

[8] A primary purpose for using a well characterized instrument such as CPL for validation of satellite lidar is that CPL data, having higher signal-to-noise, can be more easily calibrated than the satellite data. Spaceborne lidar signals are low, particularly at 1064 nm, which makes standard calibration schemes difficult. Thus calibration from the airborne instrument can be checked against, and/or used to improve, the calibration of the spaceborne instrument.

3. Comparative Measurements

[9] CPL data has been used to validate CALIPSO level 1 data products, including calibrated backscatter profiles, and some level 2 data products, including layer detection. Future work will utilize CPL data for validation of other level 2 data products (e.g., layer boundaries, optical depth, depolarization). The focus of this paper is on validation of spatial properties with subsequent work devoted to validation of the optical properties.

[10] For purposes of intercomparison, there are similarities and differences between CPL and CALIPSO that must be considered. Both CPL and CALIPSO are backscatter lidars, which means an "apples to apples" comparison is performed. Both CPL and CALIPSO fly above the tropopause, so both instruments measure the full extent of the troposphere, and both CPL and CALIPSO make dual wavelength and depolarization measurements. Table 1 lists the primary differences between the two instruments. From these differences, two primary caveats must be kept in mind when performing comparisons. First, there is imperfect collocation between the aircraft and satellite, which means the instruments view slightly different scenes (or, alternately, assumptions of horizontal homogeneity must be invoked). During the CC-VEX flights, the aircraft was off the subsatellite track by as little as 36 m and not more than 1716 m at the temporal coincidence. Second, differences in platform speeds and advection of the atmosphere mean that, could it be achieved, an exact coincidence between the aircraft and satellite would be instantaneous, and thus offer little in the way of useful comparison data. Nevertheless, when layers vary little in the horizontal plane, as in this case, direct comparisons can be made.

[11] Figure 1 shows CPL and CALIPSO profiles during the satellite underflight on 11 August 2006 (only the 532 nm profiles are shown; the 1064 nm profiles are similar). This was a nighttime flight over a convective system in

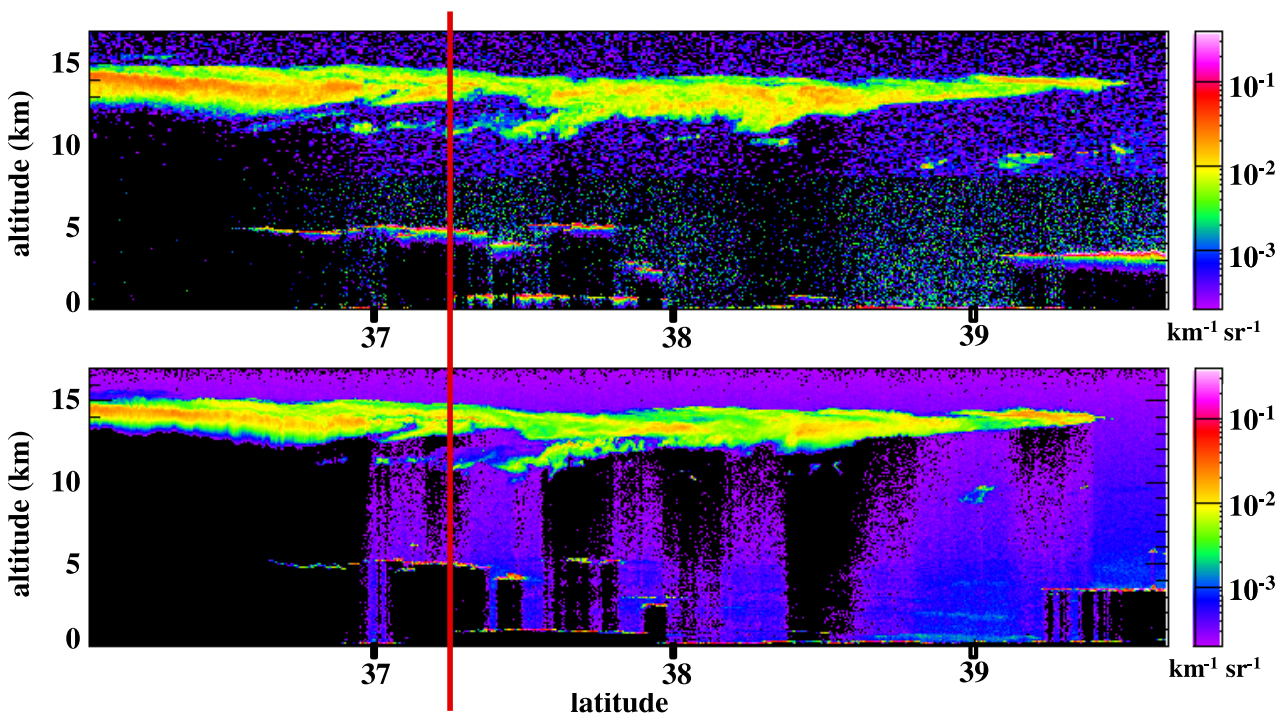

Figure 1. The 532 nm attenuated backscatter profiles from (top) CALIPSO and (bottom) CPL for the underflight of 11 August 2006. The vertical red line indicates the point at which the satellite and aircraft were coincident. This was a nighttime underpass, therefore solar background noise is a minimum in this example.

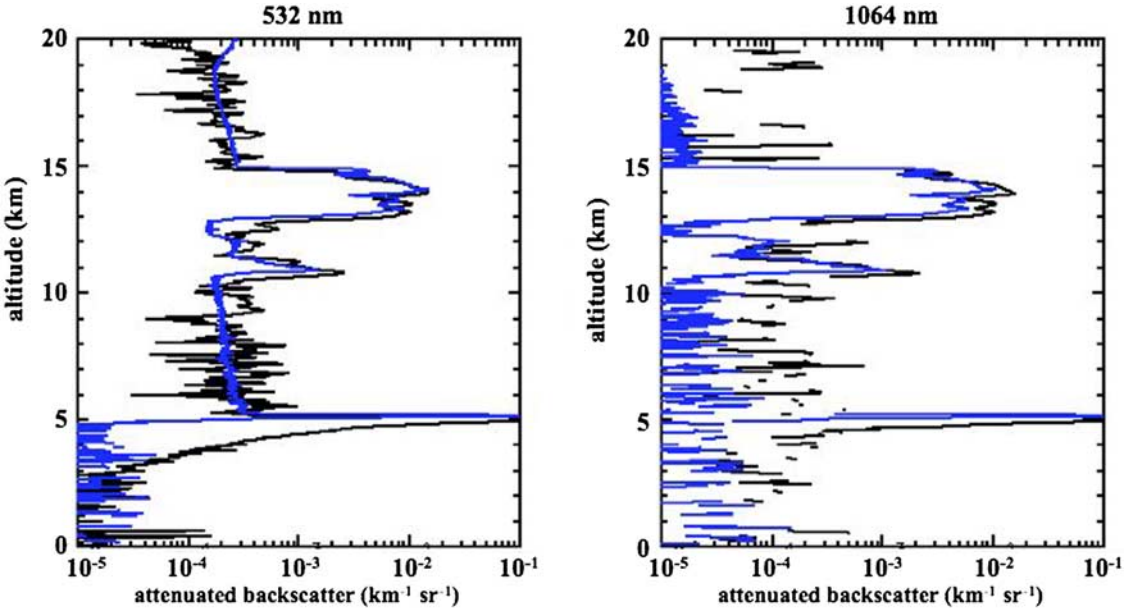

Figure 2. Attenuated backscatter profiles from CALIPSO (black) and CPL (blue) for the underflight of 1 August 2006. These profiles are at the point of nearest coincidence. CALIPSO data are the level 1 data (averaged to 5 km horizontal resolution), and CPL data have been averaged to the same horizontal resolution. Note the transient response in the CALIPSO 532 nm profile when the dense stratus cloud is encountered (~5 km altitude).

western Kentucky. The vertical red line indicates the point of nearest coincidence, and at that instant the ER-2 was 498 m off the satellite track. Although it took 32 min for the aircraft to cover the same distance that the satellite covered in 60 s (the CPL data image corresponds to 32 min of data while the CALIPSO data image corresponds to 60 s of data), the similarity between the two images is striking. Figure 2 shows individual profiles from the coincident point.

[12] Daytime data is, of course, noisier because of contamination by solar background. Figure 3 shows CPL and CALIPSO 532 nm profiles from the 31 July 2006 underflight. This was a daytime flight over a broken cloud scene in the western Caribbean off the Yucatan peninsula. Although the CALIPSO data is noticeably more noisy because of solar background, once again the correspondence between the CPL and CALIPSO data is remarkable. On this flight the ER-2 was 566 m off the satellite track at the time of nearest coincidence. Figure 4 shows the single profiles from the coincident point.

[13] The abrupt change in the CALIPSO data that occurs at 8.3 km altitude, clearly visible in the image of Figure 3, is due to changes in the onboard data averaging scheme. To conserve data downlink bandwidth, CALIPSO employs a vertically varying averaging scheme. The backscatter profiles from ~20.2 km altitude down to ~8.3 km are averaged onboard the satellite to a vertical resolution of 60 m and a horizontal resolution of ~1 km (three consecutive laser pulses). From ~8.3 km to the surface the resolution of the downlinked data is 30 m vertical and ~1/3 km horizontally (i.e., a single laser pulse). Additional description of the onboard data averaging done aboard CALIPSO are given by *Winker et al.* [2004].

[14] Examining the single profile graphs (Figures 2 and 4) illustrates several key features of the data. First, the overall agreement between the CPL and CALIPSO profiles demonstrates that the CALIPSO data is well calibrated and can be used with confidence. Second, one can see that solar background makes weak features such as subvisible cirrus harder to detect. Third, the cloud top boundaries are seen to be nearly identical between the two instruments. While the variability in the cloud bottom boundaries is somewhat larger, for the cirrus layers this difference can be attributed largely to spatial mismatch between the two platforms (~0.5 km between footprint centers) and to additional multiple scattering contributions present in the CALIPSO signal [*Winker*, 2003]. The shape of the CALIOP profile within the stratus cloud may be affected by a nonideal detector transient that is characteristic of the CALIPSO 532 nm photomultiplier tube (PMT) detectors when illuminated by extremely strong backscatter signals. Examination of variability in cloud bottom boundaries is the subject of ongoing statistical analysis to quantify differences and separate out different effects (e.g., detector transient response versus aircraft collocation).

[15] A transient response feature is often seen in PMTs, but is not an inherent feature of PMT performance. In the absence of a strong backscattering signal, an ideal detector will return immediately to its baseline state. However, the transient response of the CALIPSO PMTs is nonideal. Following a strong impulse signal, such as from the Earth's surface or a dense cloud, the signal initially falls off as expected but at some point begins decaying at a slower rate that is approximately exponential with respect to time (distance). In extreme cases, the nonideal transient recovery can make it wrongly appear as if the laser signal is penetrating the surface to a depth of several hundreds of meters. To demonstrate this phenomenon, Figure 5 shows a CALIPSO data image over Antarctica clearly illustrating

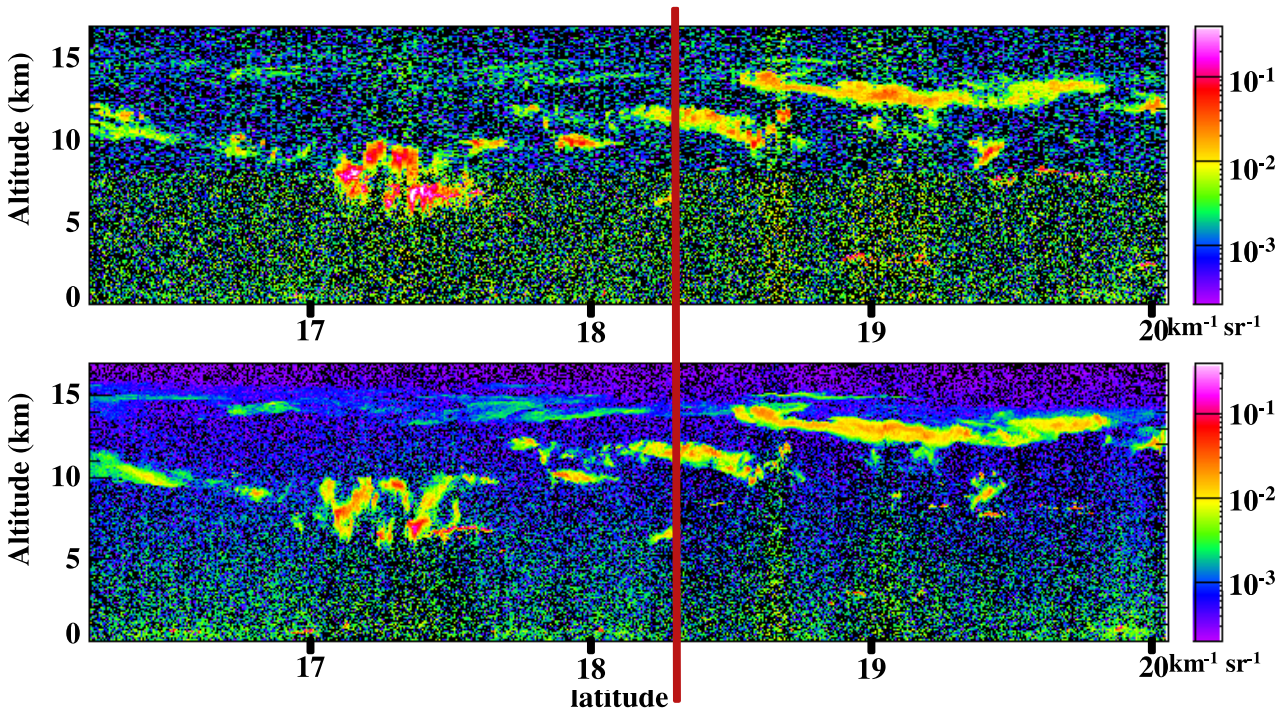

Figure 3. The 532 nm attenuated backscatter profiles from (top) CALIPSO and (bottom) CPL for the underflight of 31 July 2006. The vertical red line indicates the point at which the satellite and aircraft were coincident. This was a daytime underpass; therefore solar background noise is greater than the example shown in Figure 1.

that 532 nm signal appears to continue hundreds of meters beneath the ice surface while the 1064 nm signal does not exhibit this behavior. Thus comparison of 532 nm and 1064 nm profiles can often be used to assess the presence of this anomalous transient recovery.

4. Assessment of Minimum Detectable Backscatter

[16] An important parameter to validate using the airborne lidar is the minimum detectable backscatter, which determines the weakest feature that can be detected. From an engineering standpoint, validating the minimum detectable signal verifies the instrument is operating at optimum performance. From a science standpoint, the minimum detectable backscatter is an important parameter for radiative studies to ensure that all optically thin, yet radiatively important, features are captured by the lidar signal processing algorithms [*Vaughan et al.*, 2004].

[17] Although the minimum detectable backscatter (MDB) varies as a function of altitude, scattering target, wavelength, and vertical and horizontal averaging, it can be defined for a given set of parameters. In the case of CALIPSO, the Algorithm Theoretical Basis Document (ATBD) [*Vaughan et al.*, 2005] predicts a MDB at 532 nm for subvisible cirrus at 15 km altitude at resolution of 60 m vertical by 5 km horizontal to be 7.0×10^{-7} m^{-1} sr^{-1} (nighttime) and $\sim 1.1 \times 10^{-6}$ m^{-1} sr^{-1} (daytime). Using a simple signal thresholding technique the MDB for cirrus, from nighttime CALIPSO data, was determined to be $8.0 \times 10^{-7} \pm 1.0 \times 10^{-7}$ m^{-1} sr^{-1}, in good agreement with the theoretical values. Table 2 summarizes results for both 532 nm and 1064 nm, daytime and nighttime, for the specific case of cirrus at 15 km altitude.

[18] Although we cannot validate the CALIPSO MDB for aerosols, per se, using CPL, we can validate two other important and related aspects of CALIPSO performance: Rayleigh backscatter and layer-finding capabilities. Accurate calculation of the lidar calibration constant is critical. Both CALIPSO and CPL use a similar calibration scheme whereby the attenuated backscatter profile is matched to a Rayleigh profile at high (e.g., aerosol-free) altitude. Calibration in this manner is a standard and well accepted method of calibrating backscatter lidar returns [*Russell et al.*, 1979; *Del Guasta*, 1998] Because CALIPSO and CPL use similar, but completely independent, means of executing the calibration scheme it is insightful to compare results. Figure 6a shows a comparison of retrieved Rayleigh backscatter for both CALIPSO and CPL at 532 nm. Both profiles agree well with expected Rayleigh backscatter calculated from rawinsonde soundings. Some disagreement is expected between the CALIPSO-retrieved Rayleigh profile and that derived from the rawinsonde because CALIPSO generates Rayleigh profiles using global data from the Global Modeling and Assimilation Office (GMAO) rather than the local rawinsonde used for CPL processing. The results in Figure 6 were generated by averaging CALIPSO data to 50 km horizontal by 60 m vertical and then compiling a histogram of Rayleigh backscatter values at each altitude. The profile thus represents the mean of the distribution and the error bars indicate the spread of the distribution. Results for CPL were derived similarly, except data was averaged to 5 km horizontal by 30 m vertical. Comparisons such as this illustrate that both instruments are

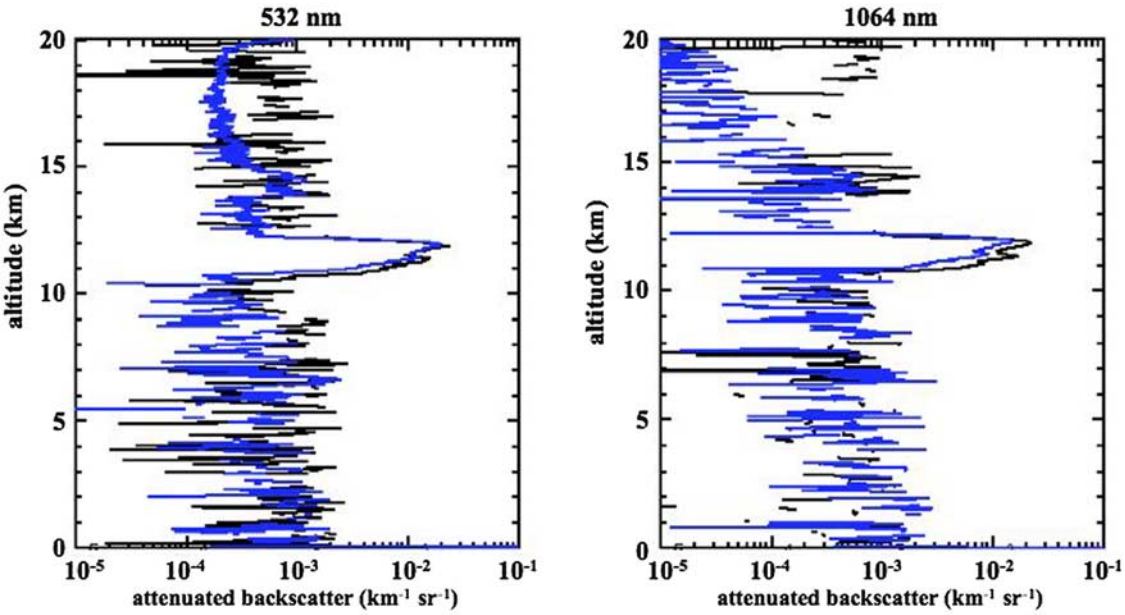

Figure 4. Attenuated backscatter profiles from CALIPSO (black) and CPL (blue) for the underflight of 31 July 2006. These profiles are at the point of nearest coincidence. CALIPSO data are the level 1 data (averaged to 5 km horizontal resolution), and CPL data have been averaged to the same horizontal resolution.

well calibrated. Figure 6b is similar, but for the 1064 nm signals. The 1064 nm error bars are larger, owing to the relative lack of Rayleigh scatterers at the longer wavelength, but the agreement is good.

[19] Comparison of layer-finding capabilities is an important validation of CALIPSO data products and is closely tied to determination of MDB. Figure 7 shows the vertical cloud mask (cloud only, no aerosol) with the location, shown in white, of all clouds identified by the CALIPSO layer detection algorithm for the scene shown in Figure 3. Cloud boundaries detected in the CPL data are overplotted in red (cloud top) and green (cloud bottom). Allowing for the spatial/temporal issues involved with comparing the satellite and aircraft data, and for the different architectures of the two layer detection schemes, the agreement in cloud layer identification between the two instruments is excellent. The CALIPSO layer detection algorithm uses a nested, multigrid averaging scheme that searches for successively fainter layers at increasingly coarse spatial averaging resolutions [*Vaughan et al.*, 2004, 2005]. Conversely, the CPL algorithm processes data at a single spatial resolution [*McGill et al.*, 2003]. As a result of these different approaches to layer detection, and the different spatial sampling of the two instruments, a point-by-point compar-

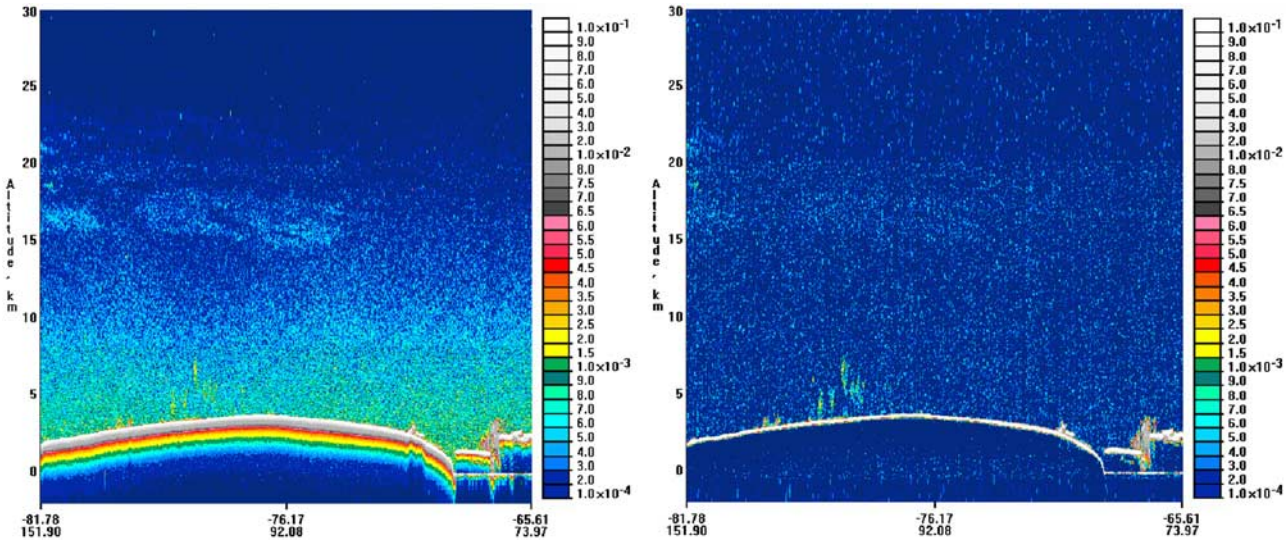

Figure 5. CALIPSO image over Antarctica from 19 June 2006. Note the detector transient response present in the surface return in (left) the 532 nm data compared to (right) the 1064 nm data.

Table 2. Results of Minimum Detectable Backscatter (MDB) Determination for Subvisual Cirrus at 15 km Altitude, 60 m Vertical by 5 km Horizontal Resolution, Compared to Values Expected From Theoretical Calculations

	Predicted MDB Values (From CALIPSO ATBD)	MDB Determined From Data
532 nm nighttime	7.0×10^{-7} m^{-1} sr^{-1}	$8.0 \times 10^{-7} \pm 1.0 \times 10^{-7}$ m^{-1} sr^{-1}
532 nm daytime	1.1×10^{-6} m^{-1} sr^{-1}	$1.7 \times 10^{-6} \pm 0.3 \times 10^{-6}$ m^{-1} sr^{-1}
1064 nm nighttime	1.2×10^{-6} m^{-1} sr^{-1}	$8.6 \times 10^{-7} \pm 1.2 \times 10^{-7}$ m^{-1} sr^{-1}
1064 nm daytime	1.4×10^{-6} m^{-1} sr^{-1}	$1.0 \times 10^{-6} \pm 0.3 \times 10^{-6}$ m^{-1} sr^{-1}

ison of the cloud heights reported by CALIPSO and by CPL is complicated. Despite these differences in spatial sampling and detection resolution, Figure 7 demonstrates that CALIPSO does an excellent job of detecting cloud layers and the corresponding CPL data validates the CALIPSO layer-finding algorithm.

[20] The sensitivity of the CALIPSO measurements and the effectiveness of its detection scheme are further illustrated by the cirrus layer that is faintly visible at ~16.5°N in both the CALIPSO and CPL images shown in Figure 3. On the basis of CPL signals, this cirrus layer is probably subvisible. CALIPSO detected the cloud between 14.973 km and 14.253 km, and measured an integrated attenuated backscatter coefficient of 3.47×10^{-4} sr^{-1}. To detect this layer, CALIPSO's fully automated search routine first averaged the data to a horizontal resolution of 80 km. Because the CPL detection algorithm searches the data at a finer spatial resolution, CPL detection of the same layer is intermittent: over the same latitude range, the CPL algorithm detected cirrus in 21% of the measured profiles. The increase in background noise caused by sunlight reflected from the layer at 10 km likely caused the CPL analysis to miss detection of some of the weaker high cloud layer. Nevertheless, for the clouds detected, CPL results provide further validation of the CALIPSO measurement. The CPL integrated attenuated backscatter coefficient ranged between a minimum of 4.38×10^{-5} sr^{-1} and a maximum of 1.30×10^{-3} sr^{-1}, with a mean value of 4.77×10^{-4} sr^{-1}. The mean top and base altitudes detected by CPL were 15.000 km and 14.291 km, respectively. Therefore, despite being barely visible in the CALIPSO browse image, CALIPSO does a good job at detecting the cloud altitude and in determining the integrated backscatter. We note that cloud detection for both CALIPSO and CPL, as with any lidar, is determined within ± one range bin (e.g., ±60 m for CALIPSO, ±30 m for CPL).

5. Summary and Conclusions

[21] The newly launched CALIPSO satellite is now measuring continuous lidar backscatter profiles of atmospheric clouds and aerosols. To validate performance of the CALIPSO lidar, the Cloud Physics Lidar was flown on the high-altitude NASA ER-2 aircraft. Using measurements made by the long-established CPL instrument as a well-documented basis for comparison, this paper presented an initial validation of the sensitivities and spatial properties reported in the CALIPSO level 1 data products. Comparison of the satellite lidar data with that from the underflying aircraft lidar demonstrates that the CALIPSO lidar is well calibrated and functioning at the anticipated level of performance.

[22] Although only representative examples were presented in this paper, evaluation of numerous data sets shows

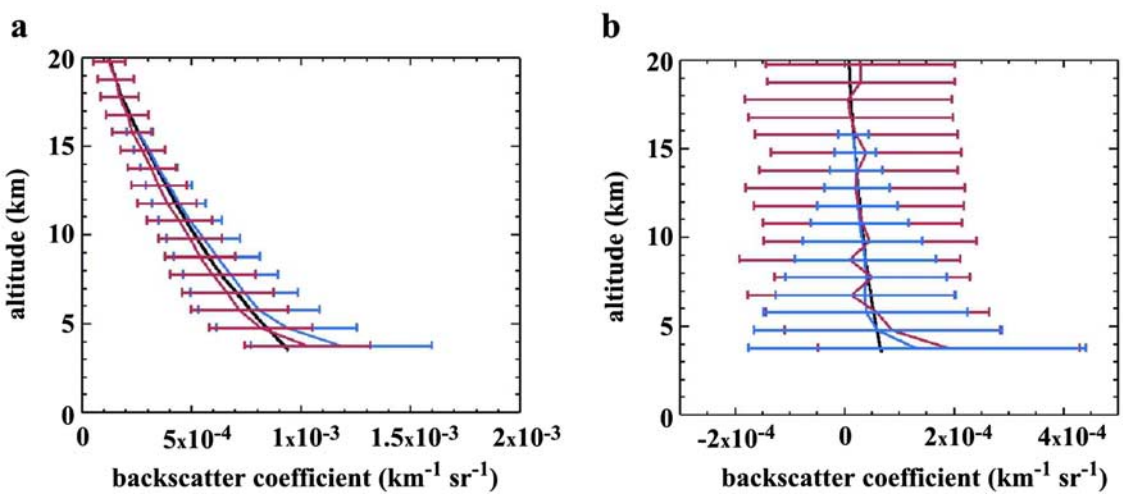

Figure 6. Comparison of Rayleigh profiles from both CALIPSO (red) and CPL (blue). (a) The 532 nm comparison and (b) the 1064 nm comparison. In both cases, the solid black line is a Rayleigh profile computed from rawinsonde soundings (used for CPL calibration at high altitude). Both CPL and CALIPSO profiles agree well with the expected values at altitudes above 5 km (below 5 km contamination by aerosol signal becomes more problematic).

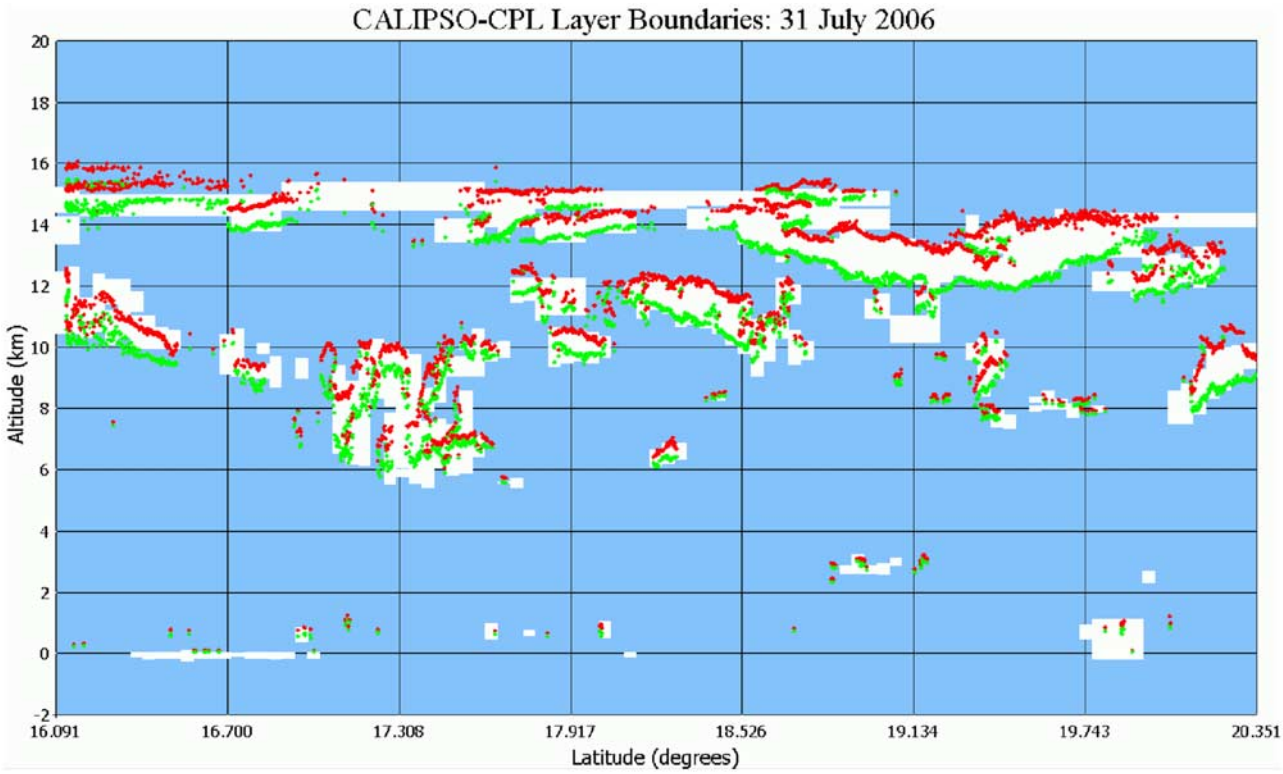

Figure 7. Cloud boundaries identified for the scene shown in Figure 3. CALIPSO cloud boundaries are shown in white. CPL cloud boundaries are overplotted in red (cloud top) and green (cloud bottom).

that the CALIPSO attenuated backscatter profiles agree well with the CPL results, which demonstrates that the CALIPSO data is well calibrated. Examination of minimum detectable backscatter again verifies that the CALIPSO profiles are well calibrated when compared to CPL, and that the minimum detectable backscatter levels are in excellent agreement with those predicted in the CALIPSO ATBD. Cloud layer top determinations from CALIPSO are found to be in good agreement with those determined independently from CPL data. Cloud base determinations are in good agreement for optically thin clouds, while optically dense cloud layers, such as stratus, exhibit an exponential artifact thought to be caused by nonideal detector transient response.

[23] Overall, use of the CPL instrument on the ER-2 platform has worked extremely well for CALIPSO validation efforts. The initial results reported in this paper validate the CALIPSO calibration accuracy and provide confidence to users of the CALIPSO data.

[24] **Acknowledgments.** We gratefully acknowledge the support of NASA-HQ program manager Hal Maring, all the wonderful folks who made the CC-VEX field campaign a success, and the entire CALIPSO team.

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W. D. Hart and D. L. Hlavka, Science Systems and Applications, Inc., Code 613.1, Greenbelt, MD 20771, USA.

R. Kuehn and M. A. Vaughan, Science Systems and Applications, Inc., MS 475, Hampton, VA 23681, USA.

M. J. McGill, NASA Goddard Space Flight Center, Code 613.1, Greenbelt, MD 20771, USA. (matthew.j.mcgill@nasa.gov)

C. R. Trepte and D. M. Winker, NASA Langley Research Center, MS 475, Hampton, VA 23681, USA.