Popular Summary for

"Airborne Validation of Spatial Properties Measured by the CALIPSO Lidar,"
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The primary payload onboard the Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) satellite is a dual-wavelength backscatter lidar designed to provide vertical profiling of clouds and aerosols. Launched in April 2006, the first data from this new satellite was obtained in June 2006. As with any new satellite measurement capability, an immediate post-launch requirement is to verify that the data being acquired is correct lest scientific conclusions begin to be drawn based on flawed data.

A standard approach to verifying satellite data is to take a similar, or validation, instrument and fly it onboard a research aircraft. Using an aircraft allows the validation instrument to get directly under the satellite so that both the satellite instrument and the aircraft instrument are sensing the same region of the atmosphere. Although there are almost always some differences in the sampling capabilities of the two instruments, it is nevertheless possible to directly compare the measurements.

To validate the measurements from the CALIPSO lidar, a similar instrument, the Cloud Physics Lidar, was flown onboard the NASA high-altitude ER-2 aircraft during July-August 2006. This paper presents results to demonstrate that the CALIPSO lidar is properly calibrated and the CALIPSO Level 1 data products are correct. The importance of the results is to demonstrate to the research community that CALIPSO Level 1 data can be confidently used for scientific research.

Airborne Validation of Spatial Properties Measured by the CALIPSO Lidar

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Introduction

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*, 2003a; Winker *et al*, 2006] 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.

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 [Deschamps *et al*, 1994], and Aura [Schoeberl *et al*, 2006] satellites. The A-Train satellites fly in a 705-km sun-synchronous orbit with a 1:30 pm 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.

The CALIPSO satellite became operational on June 7, 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.

The CALIPSO-CloudSat Validation Experiment (CC-VEX)

During the period July 26 to August 14, 2006, the ER-2 Cloud Physics Lidar (CPL) [McGill *et al*, 2002; McGill *et al*, 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. In addition, the 1064 nm signal is used for a depolarization measurement. 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.

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

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.

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.

Comparative Measurements

CPL data is initially used to validate CALIPSO Level 1 data products, including calibrated backscatter profiles. CPL data is also used for validation of Level 2 data products (e.g., layer boundaries, optical depth, depolarization). However, the focus of this paper will be on validation of spatial properties with subsequent work devoted to validation of the optical properties.

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 sub-satellite 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 means the true coincidence between the aircraft and satellite is instantaneous. Nevertheless, in a statistical sense meaningful comparisons are attainable.

Figure 1 shows CPL and CALIPSO profiles during the satellite underflight on August 11, 2006 (only the 532 nm profiles are shown; the 1064 nm profiles are similar). This was a nighttime flight over a convective system in 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 minutes for the aircraft to cover the same distance that the satellite covered in 60 seconds (the CPL data image corresponds to 32 minutes of data while the CALIPSO data image corresponds to 60 seconds of data), the symmetry between the two images is striking. Figure 2 shows individual profiles from the coincident point.

Daytime data is, of course, noisier due to contamination by solar background. Figure 3 shows CPL and CALIPSO profiles from the July 31, 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 due to 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.

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 easily discern the impact of solar background on the ability to detect weak features such as subvisual cirrus. 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. The disparity in the stratus cloud bottom boundaries is due to increased multiple scattering with perhaps some additional influence from a non-ideal detector transient response that is characteristic of the CALIPSO 532 nm photomultiplier tube (PMT) detectors when illuminated by extremely bright signals.

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 response of the CALIPSO PMTs is non-ideal, and manifests itself as an exponential decay of the backscatter intensity with respect to time (distance). In extreme cases, the non-ideal 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 that lidar signal appears to continue hundreds of meters beneath the ice surface.

Assessment of Minimum Detectable Backscatter

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]

Although the minimum detectable backscatter 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] defines the minimum detectable backscatter at 532 nm for subvisual cirrus at 15 km altitude at the nominal CALIPSO resolution of 60 m vertical by 5 km horizontal as 7.0×10^{-7} $m^{-1}sr^{-1}$ (nighttime) and $\sim1.1\times10^{-6}$ $m^{-1}sr^{-1}$ (daytime). For this specific case, the minimum detectable backscatter 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. The interested researcher can generate similar determinations for any set of parameters.

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. Comparisons such as this illustrate that both instruments are 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.

Comparison of layer-finding capabilities is an important validation of CALIPSO Level 1 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, multi-grid averaging scheme that searches for successively fainter layers at increasingly coarse spatial averaging resolutions.[Vaughan *et al*, 2004; Vaughan *et al*, 2006] 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 capabilities of the two instruments, the layers reported by CALIPSO can appear a bit coarse when compared to CPL. 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.

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. 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.

Summary and Conclusions

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 truth, 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.

Although only representative examples were presented in this paper, evaluation of numerous data sets shows 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 near-perfect agreement with those determined independently from CPL data. Cloud bottom determinations are in good agreement for optically thin clouds, with optically thick cloud layers having errors due to detector transient response (in the case of stratus cloud) or multiple scattering (all optically thicker clouds).

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.

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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
platform speed	~200 m/s	~7500 m/s
detection	photon counting	analog
receiver footprint at surface	2 m dia.	88 m dia.
multiple scattering effects (Winker, 2005b)	$\eta \sim 0.98$	$\eta \sim 0.70$

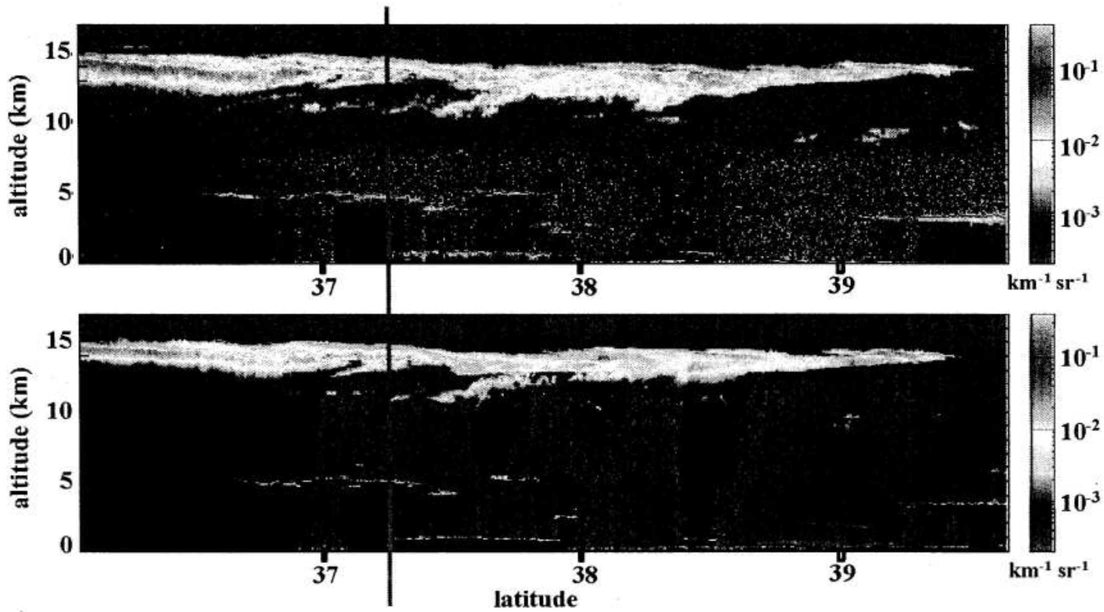

Figure 1: Attenuated backscatter profiles from CALIPSO (top) and CPL (bottom) for the underflight of August 11, 2006. The vertical red line indicates the point at which the satellite and aircraft were coincident. This was a nighttime underpass, therefore solar background noise is a minimum in this example.

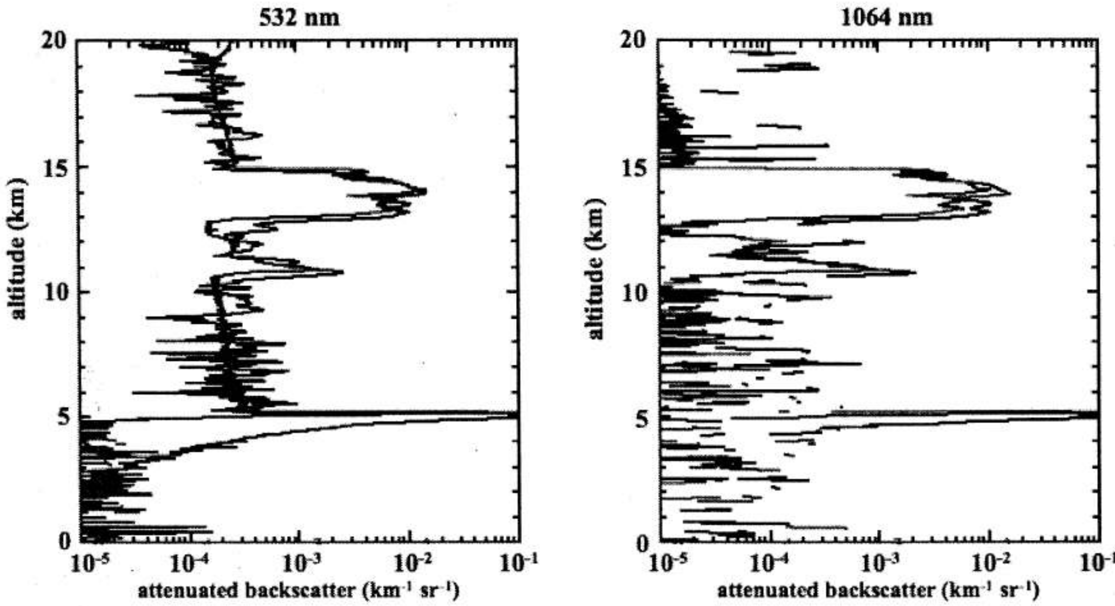

Figure 2: Attenuated backscatter profiles from CALIPSO (black) and CPL (blue) for the underflight of August 11, 2006. These profiles are at the point of nearest coincidence. CALIPSO data is the Level 1 data (averaged to 5 km horizontal resolution), and CPL data has been averaged to the same horizontal resolution. Note the exponential transient response in the CALIPSO 532 nm profile when the dense stratus cloud is encountered (~5 km altitude).

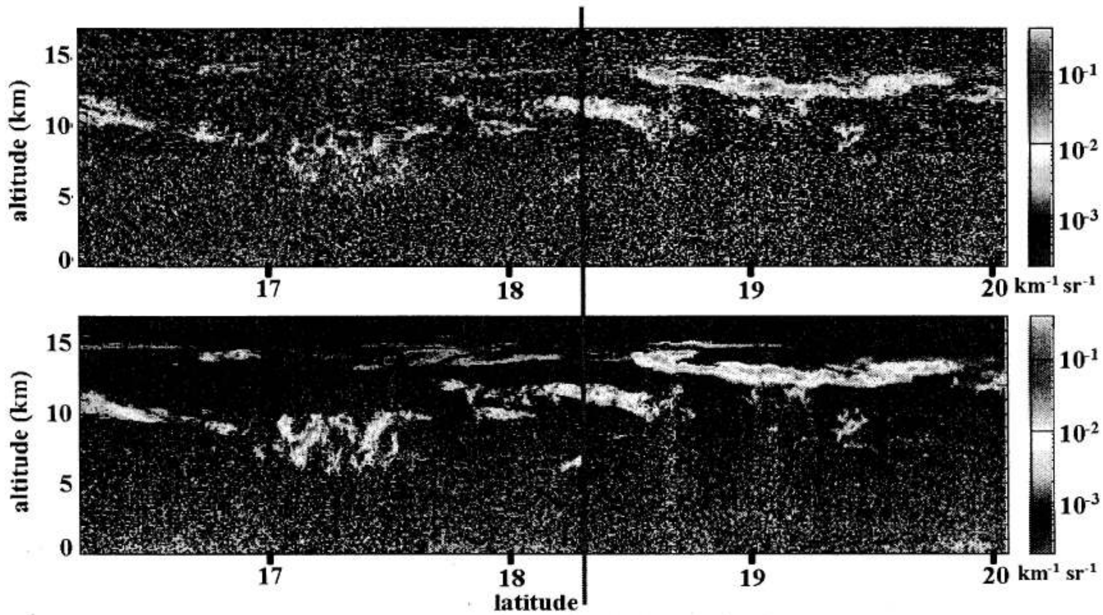

Figure 3: Attenuated backscatter profiles from CALIPSO (top) and CPL (bottom) for the underflight of July 31, 2006. The vertical red line indicates the point at which the satellite and aircraft were coincident. This was a daytime underpass, therefore solar background noise is greater than the example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

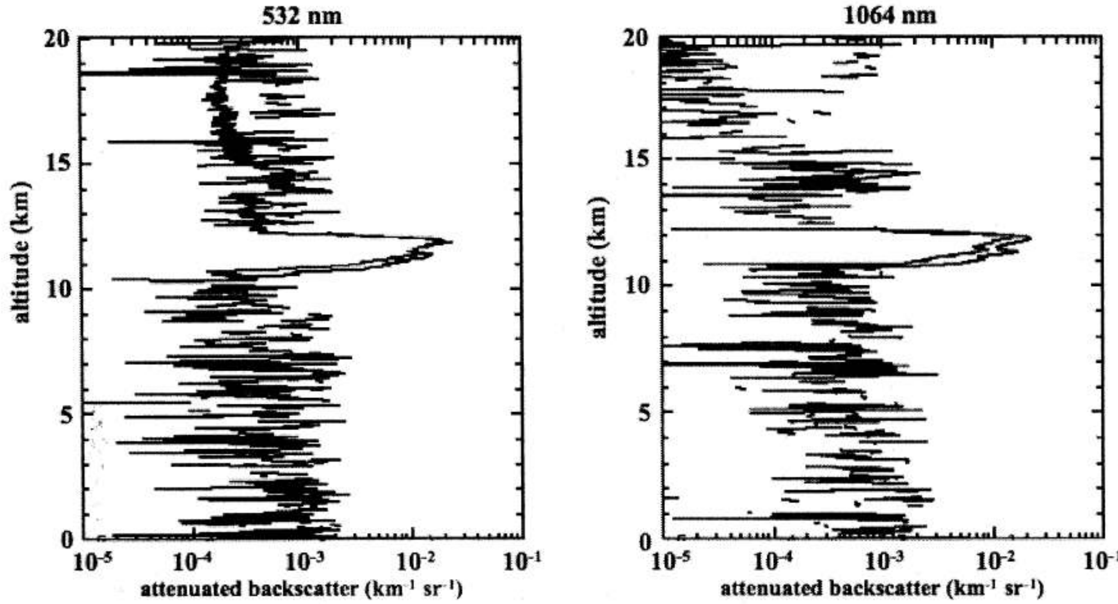

Figure 4: Attenuated backscatter profiles from CALIPSO (black) and CPL (blue) for the underflight of July 31, 2006. These profiles are at the point of nearest coincidence. CALIPSO data is the Level 1 data (averaged to 5 km horizontal resolution), and CPL data has been averaged to the same horizontal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

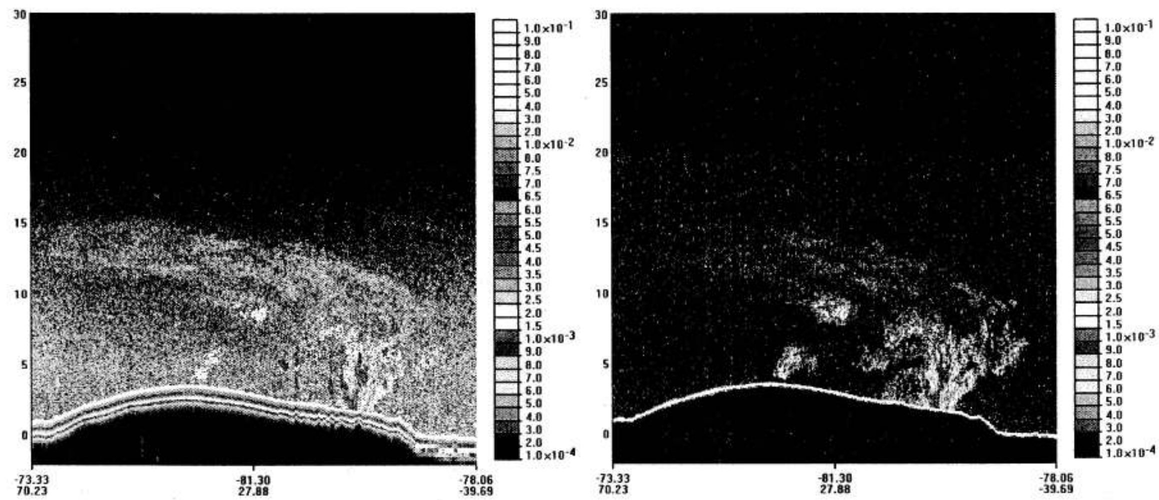

Figure 5: CALIPSO image over Antarctica from August 28, 2006. Note the detector transient response present in the surface return in the 532 nm data (left image) compared to the 1064 nm data (right image).

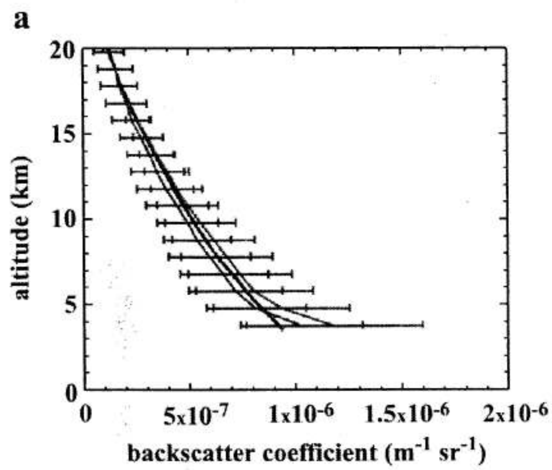

Figure 6: Comparison of Rayleigh profiles from both CALIPSO (red) and CPL (blue). (a) is the 532 nm comparison, (b) is the 1064 nm comparison. In both cases, the solid black line is a Rayleigh profile computed from rawinsonde soundings (used for CPL calibration at high altitude). Both CPL and CALIPSO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

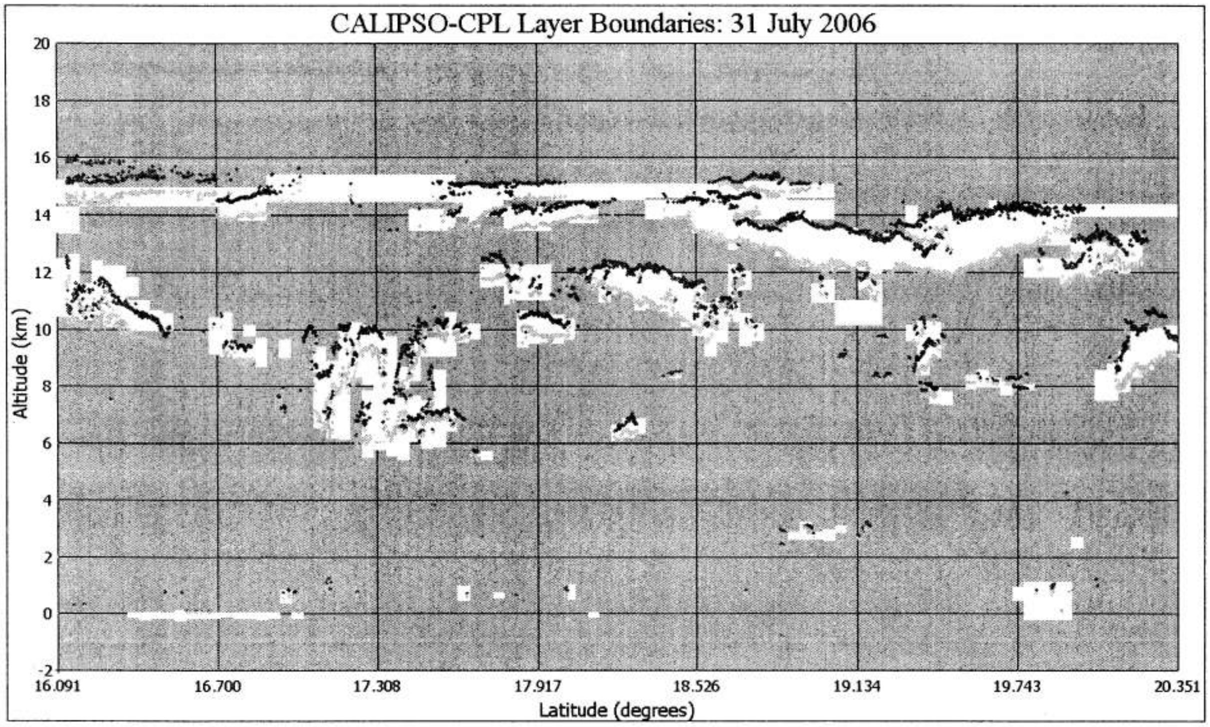

Figure 7: Cloud boundaries identified for the scene shown in Figure 3. CALIPSO cloud boundaries are shown in white. CPL cloud boundaries are overplotted in red (cloud top) and green (cloud bottom).