CHAOS, CONSTERNATION AND CALIPSO CALIBRATION: NEW STRATEGIES FOR CALIBRATING THE CALIOP 1064 NM CHANNEL

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ABSTRACT

The very low signal-to-noise ratios of the 1064 nm CALIOP molecular backscatter signal make it effectively impossible to employ the "clear air" normalization technique typically used to calibrate elastic backscatter lidars. The CALIPSO mission has thus chosen to cross-calibrate their 1064 nm measurements with respect to the 532 nm data using the two-wavelength backscatter from cirrus clouds. In this paper we discuss several known issues in the version 3 CALIOP 1064 nm calibration procedure, and describe the strategies that will be employed in the version 4 data release to surmount these problems.

1. INTRODUCTION

Calibrating an Nd:YAG elastic backscatter lidar requires high signal-to-noise (SNR) measurements of some target whose scattering properties are well known and can be accurately characterized at the time of the measurement. Because the optical properties of air molecules are well understood, both from theory and confirming measurements, "clear air" regions of the Earth's atmosphere are a very common calibration target. However, using the molecular normalization technique to calibrate measurements made at 1064 nm is complicated by several factors. Most important for CALIPSO, the molecular scattering cross section is smaller by a factor of ~16 at 1064 nm than at 532 nm. In addition to reducing the SNR of the measurement, this smaller molecular scattering cross-section typically results in larger aerosol scattering ratios – and hence more calibration error – than would be seen in the same parcel of air measured at 355 nm or 532 nm. While some ground-based and airborne lidars can effectively use the molecular normalization technique at 1064 nm, the current generation of space-based systems is still far from achieving the SNR required in high altitude (e.g., > 35 km) measurements of presumably pristine air.

To circumvent the low signal magnitudes from the Rayleigh atmosphere at 1064 nm, all space-based lidars to date have chosen to use cirrus clouds as an alternate calibration target. Given a range invariant value for the cirrus cloud backscatter color ratio, defined as

$$\chi_{cirrus} = \beta_{c,1064}(r) \Big/ \beta_{c,532}(r) \qquad (1)$$

where $\beta_{c,1064}(r)$ and $\beta_{c,532}(r)$ are, respectively, the range dependent backscatter coefficients for cirrus clouds at wavelengths of 1064 nm and 532 nm, a calibration scale factor, f, that relates the calibration coefficients at the two wavelengths can be computed using [1]

$$f = C_{1064} \Big/ C_{532} = \chi_{cirrus}^{-1} \left(\mathcal{g}_{1064} \Big/ \mathcal{g}_{532} \right). \qquad (2)$$

C_{1064} and C_{532} are the calibration coefficients for, respectively, the 1064 nm and 532 nm lidar wavelengths. Similarly, $\mathcal{g}_{532}$ and $\mathcal{g}_{1064}$ are the wavelength-dependent integrals, from cloud top to cloud base, of the range-corrected, background-subtracted measurements that have been normalized for their respective laser output energies, the known electronic gains of the receiver, and the range-dependent attenuation due to the molecules and ozone. In principle, $\mathcal{g}_{532}$ and $\mathcal{g}_{1064}$ can be computed directly from the uncalibrated data at the two wavelengths. In practice, however, the CALIOP 532 nm data is always calibrated prior to initiating the 1064 nm calibration procedure, so, for any individual calculation of f, C_{532} is a known value. Recent analyses support the long-held assumption that, in the mean, the backscatter coefficients from moderate to dense cirrus are spectrally independent at 532 nm and 1064 nm, so that χ_{cirrus} also has an empirically established value of 1.01 ± 0.25 [1]. To ensure the use of a uniform calibration target, only the strongly scattering regions of high-altitude clouds are selected for use in the CALIOP 1064 nm calibration process. These 'calibration quality clouds' must be located wholly within the altitude range between 8.2 and 17 km, and must contain three or more consecutive 60 meter range bins for which the 532 nm attenuated scattering ratios exceed 50 [2]. Only this strongest scattering segment of the cloud is used in equation (2). The same selection criteria for calibration quality clouds have been maintained for all CALIPSO data releases up to and including version 3 (V3).

2. A BRIEF HISTORY OF THE CALIOP 1064 NM CALIBRATION PROCEDURE

In the initial release of the CALIPSO data products, C_{1064} was assumed to remain constant throughout the daytime and nighttime portions of each orbit. Consequently, estimates of C_{1064} were obtained directly from equation (2), and a mean calibration coefficient was computed using all calibration quality clouds identified during each daytime or nighttime granule. This mean value was then uniformly applied to all 1064 nm profiles within the granule. Subsequent analyses of the version 1 data products revealed the flaw in this approach. Changes in the thermal gradients within the CALIPSO lidar are now known to cause pronounced intra-orbit changes in the 532 nm calibration coefficients, most especially when the satellite is passing through the daylit side of the orbit [3]. Since C_{1064} is computed with reference to C_{532}, the assumption that C_{1064} remained constant throughout each granule was clearly invalidated. For versions 2 and 3 of the CALIPSO data products, equation (2) was used to compute estimates granule-mean of the calibration scale factor, $\bar{f}$. The required compensation for thermally induced changes in C_{1064} within a granule was thought to be achieved using $C_{1064}(t) = \bar{f}\, C_{532}(t)$, where t represents granule-elapsed time.

It is now known, however, that the calibration scale factor also changes within the course of a granule, indicating that the calibration coefficients at the two wavelengths do not respond uniformly to changes in the thermal environment onboard the satellite. Although the reasons for this behavior are not yet fully understood, the variability in the calibration scale factor has been empirically established, and, as demonstrated in Figure 1, is observed to fluctuate as a function of both season and granule elapsed time.

3. PLANNED REVISIONS TO THE VERSION 4 CALIOP 1064 NM CALIBRATION SCHEME

The curves shown in Figure 1 illustrate the primary change that must be made in the CALIOP version 4 (V4) 1064 nm calibration scheme: f is clearly not constant within a granule, but must instead be computed as a function of granule elapsed time, so that $C_{1064}(t) = f(t) C_{532}(t)$. However, the reliable implementation of a time-dependent calculation is faced with several difficulties. In particular, relying on clouds as an instantaneous calibration target is inherently risky, simply because the occurrence frequency of clouds at any location or within any time frame is not uniformly guaranteed. For V3, this risk is quantified in Figure 2, where the grid cells represent the number of calibration quality clouds detected during daytime granules as a function of granule elapsed time (y-axis) for each calendar month from June 2006 through December 2010 (x-axis). The white grid cells seen along the top edge of the figure represent regions where no suitable clouds were detected for the entire month.

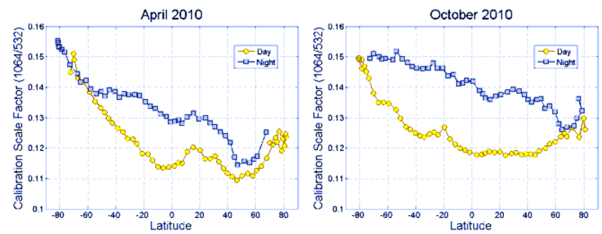


Figure 1: Mean calibration scale factors computed as a function of granule elapsed time and plotted versus latitude for daytime and nighttime measurements acquired during April 2010 (left panel) and October 2010 (right panel).

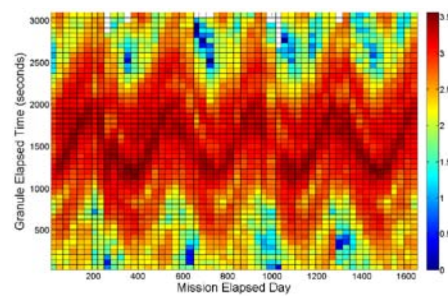


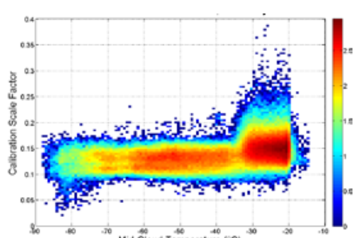
Figure 2: Monthly count of daytime scale factor calculations as a function mission elapsed time (x-axis: June 2006 through December 2010) and granule elapsed time (y-axis). Colors are displayed on a $\log_{10}$ scale, so that dark reds indicate many thousands of samples, whereas dark blues indicate one or two samples. Regions where no calibration quality clouds were detected are shown in white.

Taken together, the large number of data-sparse areas in Figure 2 and the time varying behaviors seen in Figure 1 motivate two more significant changes that will be implemented in the CALIPSO V4 1064 nm calibration procedure. First, estimates of $f(t)$ will be constructed using a multi-granule averaging scheme, as opposed to the single granule per calculation currently used. Doing this will increase the likelihood of accumulating a sufficient number of calibration quality clouds to fully characterize the intra-orbit variability in f. However, since f is also known to vary as a function of mission elapsed time, the number of granules used in this multi-granule averaging scheme must be held to a minimum. Thus the second change will be to employ a refined and more inclusive method for identifying calibration quality clouds, thereby further increasing the likelihood that a sufficient number of samples will be collected in a timely fashion. The new selection criteria include a dynamically assigned altitude search range based on the local temperature profile and tropopause height (to exclude polar stratospheric clouds and ensure the use of tropospheric ice clouds only); threshold values for layer integrated volume depolarization ratio and mid-layer temperature (to ensure that clouds are composed of large, randomly oriented ice crystals); and limits on the magnitude of the 532 nm integrated attenuated backscatter (to ensure robust scattering while simultaneously eliminating water clouds and clouds containing large fractions of horizontally oriented ice crystals). Since clearly we must define what sorts of clouds are acceptable before we can estimate how likely we are to find them, initial work in establishing the configuration parameters required for the V4 calibration scheme has focused on the new calibration cloud selection criteria.

4. REDEFINING 'CALIBRATION QUALITY'

4.1 Altitude and Temperature Ranges

Initial testing to establish parameter limits for identifying calibration quality clouds has focused on cloud temperature thresholds and refinements to the permissible altitude regime. The first step was to replace the global altitude search limits of 8.2 to 17 km with variable search limits adjusted according to local tropopause heights, while still maintaining the requirement for scattering ratios exceeding 50. Doing this greatly increased the number of calibration quality clouds detected in the polar regions. At the same time, however, it also greatly increased the variability of the scale factors computed in these regions. This increased variability is caused by the wider range of mid-cloud temperatures in the lower altitude data set. As is seen in Figure 3, scale factors appear to be naturally partitioned into two clusters that fall on either side of a dividing line at –35° C, with the colder clouds having a lower mean scale factor and showing less variability.



Scale Factor Statistics

	T≤-35°	T>-35°
min	0.017	0.057
max	0.237	0.398
median	0.127	0.147
mean	0.126	0.148
std dev	0.016	0.022
count	109317	125279

Figure 3: Calibration scale factors as a function of mid-cloud temperature for February and March, 2009. Warmer clouds are seen to have larger mean scale factors than colder clouds.

Figure 4 compares V3 scale factors to those computed in the initial parameter tests for V4. The upper panel shows the number of samples acquired for both daytime and nighttime granules. The lower panel shows the corresponding mean calibration scale factors. As seen in the upper panel, changing the altitude search range resulted in a huge increase in the number of samples acquired in the polar regions. At the same time, however, the magnitude of f also rose appreciably in these same regions. Restricting the calibration clouds to only those with mid-cloud temperatures less than –35° C eliminates almost all of the sampling gains achieved with the new altitude limits. Nevertheless, the revised strategy still yields an overall sampling gain in the poles. Use of the colder clouds also results in a slightly lower mean f for all latitudes both day and night.

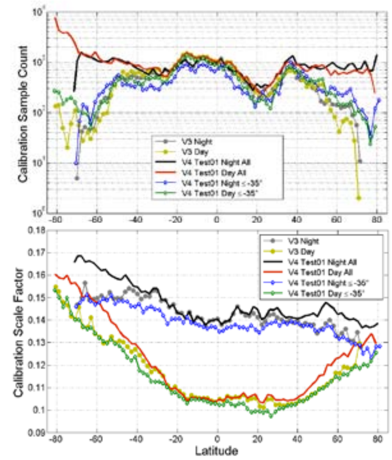


Figure 4: Sample counts (upper panel) and mean scale factors (lower panel) for all daytime and nighttime granules acquired during February 2009. V3 results are shown in yellow (day) and dark gray (night). The initial version 4 test results (new altitude regime only) are shown in red (day) and black (night). The V4 test results with a -35° C temperature requirement added are shown in green (day) and blue (night).

4.2 Integrated Attenuated Backscatter and Depolarization Ratios

The success of the CALIPSO calibration scheme is predicated on this assumption: only cirrus clouds consisting of particles that are large with respect to the CALIOP wavelengths will be used in the calibration scheme [4]. It turns out, however, that in V3 this assumption was occasionally violated. Figure 5 plots layer-integrated volume depolarization (δ_v) as a function of 532 nm integrated attenuated backscatter (γ_{532}) for all single layer nighttime calibration quality clouds in October 2010. Despite the restriction to layers detected at altitudes above 8.2 km, the cluster in the lower right corner of this plot shows the clear signature of water clouds [5], thus further motivating the search for more accurate calibration cloud selection criteria.

While the $\gamma'_{532} - \delta_v$ relationship will provide a greatly improved ability to identify ice clouds [5], the CALIOP data products do not provide estimates of cirrus particle size. We therefore examine cirrus particle size estimates retrieved from the CALIPSO imaging infrared radiometer (IIR) data [6], and correlate these with CALIOP measurements to determine how best to identify large cirrus particles using lidar data alone. As seen in the left panel of Figure 6, the CALIOP integrated backscatter color ratio for V3 calibration quality clouds remains relatively constant above IIR effective diameters above ~35 μm, with a mean value of 0.96 ± 0.05. (Color ratios in this figure are computed for the entire cloud, and not just the strongly scattering segment used in the calibration procedure.) Similarly, the vast majority of these large particles lie in the range of 0.023 sr $^{-1}$ < γ_{532} < 0.038 sr $^{-1}$ (i.e., the horizontal lines shown in the right panel of Figure 6). It therefore seems reasonable to expect that we can isolate the population of large-particle cirrus by imposing similar limits for the V4 calibration scheme.

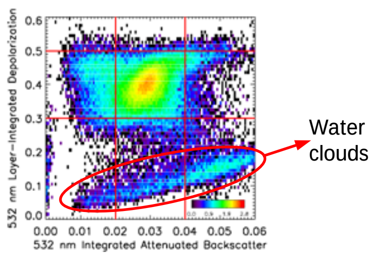


Figure 5: δ_v as a function of γ'_{532} for all V3 calibration quality clouds detected at night during October 2010. The solid red lines suggest possible limits on δ_v and γ'_{532} for V4.

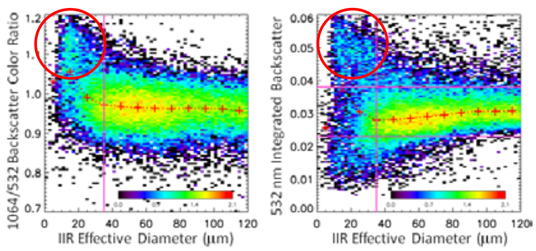


Figure 6: Backscatter color ratio (left) and γ'_{532} (right) as functions of IIR-derived effective particle size for all single layer nighttime clouds used by the V3 1064 nm calibration routine during October 2010. The red crosses represent median values of the distributions. The circled clusters of points in the upper left corners correspond to the water cloud cluster seen in the lower right corner of Figure 5.

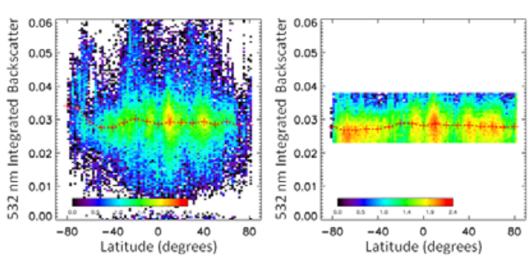


Figure 7: Cloud sample count ($\log_{10}$ color scale) as a function of latitude for all V3 calibration clouds (left) and for all top layer clouds with T < –35° C, δ_v > 0.3, and 0.023 sr $^{-1}$ < γ'_{532} < 0.038 sr $^{-1}$ (right) for October 2010 nighttime data. The red crosses represent median values.

Figure 7 compares the number of nighttime calibration quality samples obtained during October 2010 for V3 (left panel) to the number of samples that would have been obtained instead by selecting only those nighttime clouds that are the highest layer in the column and for which T < –35° C, δ_v > 0.3, and 0.023 sr $^{-1}$ < γ_{532} < 0.038 sr $^{-1}$. The revised selection parameters are seen to provide a much more uniform sampling as a function of latitude, while at the same time delivering a greater number of total samples and a much more homogeneous data set.

5. NEXT STEPS

Once the cloud selection parameters have been firmly established, work will begin to determine the optimum number of granules to average to ensure sufficient sampling while simultaneously minimizing the total number of granules required. Since the dominant error in C_{1064} is the large spread in the empirical estimates of χ_{cirrus}, reducing this uncertainty to acceptable levels will likely require at least 100 samples for each calculation of $f(t)$. Future plans also include pursuing methods for verification and validation of the 1064 nm ice cloud calibration coefficients using water cloud and ocean surface calibration techniques [7, 8].

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