CALIPSO Lidar Calibration Algorithms. Part I: Nighttime 532-nm Parallel Channel and 532-nm Perpendicular Channel

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ABSTRACT

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission was launched in April 2006 and has continuously acquired collocated multisensor observations of the spatial and optical properties of clouds and aerosols in the earth’s atmosphere. The primary payload aboard CALIPSO is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which makes range-resolved measurements of elastic backscatter at 532 and 1064 nm and linear depolarization ratios at 532 nm. CALIOP measurements are important in reducing uncertainties that currently limit understanding of the global climate system, and it is essential that these measurements be accurately calibrated. This work describes the procedures used to calibrate the 532-nm measurements acquired during the nighttime portions of the CALIPSO orbits. Accurate nighttime calibration of the 532-nm parallel-channel data is fundamental to the success of the CALIOP measurement scheme, because the nighttime calibration is used to infer calibration across the day side of the orbits and all other channels are calibrated relative to the 532-nm parallel channel. The theoretical basis of the molecular normalization technique as applied to space-based lidar measurements is reviewed, and a comprehensive overview of the calibration algorithm implementation is provided. Also included is a description of a data filtering procedure that detects and removes spurious high-energy events that would otherwise introduce large errors into the calibration. Error estimates are derived and comparisons are made to validation data acquired by the NASA airborne high–spectral resolution lidar. Similar analyses are also presented for the 532-nm perpendicular-channel calibration technique.

1. Introduction

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission is an international Earth observing platform constructed and operated jointly by the United States and France (Winker et al. 2007). Since its launch on 28 April 2006, CALIPSO has been making nearly continuous measurements of clouds and aerosols in the earth’s atmosphere. Uncertainties in the roles played by clouds and aerosols in the earth’s radiation budget limit our understanding of the climate system and the potential for global climate change (Bernstein et al. 2007). The CALIPSO mission was designed specifically to address these uncertainties (Winker et al. 2009). Clouds and aerosols are highly variable in space and time, and thus long-term and continuous satellite observations are essential for understanding their spatial distributions and climatic impacts on regional and global scales.

The CALIPSO payload consists of three coaligned near-nadir viewing instruments: a 2-wavelength polarization-sensitive lidar [the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)], a three-channel imaging infrared radiometer (IIR), and a single-channel high-resolution
Two internal files provide input to the level 1B process. The CALIPSO calibration-coefficient history data file contains daily nighttime 532-nm parallel-channel calibration-coefficient estimates that are subsequently
applied when calibration coefficients cannot be calculated. The CALIPSO polarization gain ratio (PGR) data file stores the PGR, which is used to quantify the differences in the responsivity and gain of the two 532-nm detection channels. The PGR operation calculates the ratio of the nearly equal optical fluxes incident on the parallel- and perpendicular-channel detectors as a spatial pseudodepolarizer is inserted into the 532-nm receiver optical path (Hunt et al. 2009).

2. Basic equations and nomenclature

a. Lidar equation and calibration coefficient

The lidar signals are acquired as profile elements separated by approximately 15 m in range along the path of the laser pulse. An illustration of the CALIPSO nominal spacecraft geometry and the lidar signal altitude registration is provided in Fig. 2. The profile data are averaged vertically and horizontally, as described in Winker et al. (2009), and then downlinked and sent to the NASA Langley Atmospheric Sciences Data Center as CALIPSO level 0 data (King et al. 2004).

The instrument payload controller automatically adjusts the data acquisition start time for each shot so that altitudes of the signal elements, after onboard averaging, correspond to the altitude elements in a predefined fixed-altitude array. This altitude registration and the level 0 geolocation are based on spacecraft position and attitude data from the onboard GPS system, processed through orbital propagation software. The first step in
The term \( T^2 \) represents the two-way signal attenuation from the lidar to the scattering volume and is defined as

\[
\beta(z, k_p) = \beta_a(z, k_p) + \beta_m(z, k_p). \tag{3}
\]
where $\sigma$ is the volume extinction coefficient, given as

$$\sigma(z, k_p) = \sigma_m(z, k_p) + \sigma_a(z, k_p) + \sigma_O(z, k_p),$$

and $\sigma_m$, $\sigma_a$, and $\sigma_O$ are extinction coefficients resulting from molecular scattering, aerosol scattering, and ozone absorption, respectively.

Although the atmospheric parameters $\beta$ and $\sigma$ are considered to be functions of altitude $z$, the two-way signal attenuation is a function of optical pathlength through the atmosphere above the scattering volume and hence can be considered a function of either altitude or range.

The sections that follow analyze the calibration algorithms in terms of the signal as defined by the range-scaled energy- and gain-normalized profiles for the 532-nm parallel and perpendicular channels. However, to make the equations less cumbersome, the notation is simplified using

$$X_b(z) = C_b \beta_b(z) T^2(z)$$

and

$$X_a(z) = C_a \beta_a(z) T^2(z)$$

while maintaining an understanding of the implicit dependencies on the profile index and off-nadir angle.

b. Output data products

The calculated 532-nm parallel and perpendicular calibration coefficients are applied to corresponding profiles of $X(z)$ to produce profiles of attenuated backscatter coefficients having units of km$^{-1}$ sr$^{-1}$, as follows:

$$\beta'(z, k_p) = \frac{1}{C_b(k_p)} X_b(z, k_p) = \frac{\beta(z, k_p)}{T^2(z, k_p)},$$

and

$$\beta'_a(z, k_p) = \frac{1}{K_p(k_p) C_a(k_p)} X_a(z, k_p),$$

where $K_p$ is the PGR, which is derived from the averaged perpendicular- and parallel-channel signals measured during the polarization calibration operation, and $K_p$ is a conversion factor that quantifies the relative magnitudes of the parallel- and perpendicular-channel detector gains, detector quantum efficiencies, amplifier gains, and optical efficiencies downstream of the polarization beam splitter (Hunt et al. 2009; Alvarez et al. 2006).

The data products archived upon the completion of the level 1B processing include profile and calibration products. In the level 1B data product, the attenuated backscatter profiles are reported as 532-nm total attenuated backscatter (parallel plus perpendicular) and 532-nm perpendicular attenuated backscatter, as defined by the following equations:

$$\beta'_b(z, k_p) = [\beta(z, k_p) + \beta_a(z, k_p)] T^2(z, k_p)$$

and

$$\beta'_a(z, k_p) = \beta_a(z, k_p) T^2(z, k_p).$$

The calibration products are composed of the calibration coefficients and calibration uncertainties for the 532-nm parallel channel and the PGR and PGR uncertainties for the 532-nm perpendicular channel (Anselmo et al. 2007).

3. Nighttime 532-nm parallel-channel calibration

The CALIOP calibration procedure begins with the calibration of the 532-nm parallel channel for nighttime conditions. The 532-nm parallel-channel calibration coefficient is determined from the ratio of the range-scaled energy- and gain-normalized signal $X_b$ to estimates of attenuated backscatter computed from a modeled atmospheric density profile in the 30–34-km altitude region, where the backscatter source is primarily molecules (Russell et al. 1979; Hostetler et al. 2006; Reagan et al. 2002). Details on the mathematical basis for the algorithms, calibration procedure, uncertainty analysis, and artifact removal are described in the following subsections.

a. Mathematical basis

The 532-nm parallel-channel calibration-coefficient equation is formed by rearranging Eq. (6) to solve for $C_b$ as

$$C_b = \frac{X_b(z_c) \hat{\beta}_b(z_c) T^2(z_c)}{\hat{\beta}_b(z_c)},$$

where $X_b$ is measured by CALIOP, $\hat{\beta}_b$ and $\hat{T}^2$ are derived from molecular and ozone number densities provided by NASA GMAO (Rienecker 2008; Bloom et al. 2005), and $z_c$ designates the calibration altitude. The $\hat{\cdot}$ notation denotes the parameters that are estimated from external data sources.

The parallel backscatter coefficient $\hat{\beta}_b$ can be broken down into the volume molecular and volume aerosol backscatter components

$$\hat{\beta}_b = \hat{\beta}_{m,b} + \hat{\beta}_{a,b},$$

where $\hat{\beta}_{m,b}$ is the parallel component of the molecular volume backscatter coefficient and $\hat{\beta}_{a,b}$ is the parallel component of the aerosol volume backscatter coefficient.
The parallel component of molecular backscatter is calculated from an estimate of the total molecular backscatter \( \hat{\beta}_m \) and the expected depolarization ratio for molecular backscatter \( \delta_m \). The total molecular backscatter is the product of the molecular number density and the total Rayleigh scattering cross section, and the term \( k_{bw} \) defines the dispersion of the refractive index and the King correction factor of air at 532 nm (She 2001; Hostetler et al. 2006; Reagan et al. 2002).

The ratio of perpendicular to parallel backscatter for the Cabannes line of the backscatter to be detected (She 2001). The ratio of perpendicular to parallel backscatter for the Cabannes line is \( \sim 0.003 \) 66 (Cairo et al. 1999); hence, the parallel component of the molecular backscatter is very nearly identical to the total molecular backscatter for CALIOP:

\[
\hat{\beta}_m(z_C) = \frac{1}{1 + \delta_m} \hat{\beta}_m(z_C) = 0.996 \hat{\beta}_m(z_C),
\]

where \( \delta_m = \frac{\hat{\beta}_{n||}}{\hat{\beta}_{m||}} = 0.003 \) 66

is the depolarization ratio for Cabannes scattering.

The volume molecular backscattering coefficient is estimated using

\[
\hat{\beta}_m(z_C) = \frac{\hat{\sigma}_m(z_C)}{S_m} = \frac{\hat{\sigma}_m(z_C)}{(8\pi/3)k_{bw}},
\]

where \( S_m = (8\pi/3)k_{bw} \) is the Rayleigh extinction–backscatter ratio or the lidar ratio for the molecular scattering and the term \( k_{bw} = 1.0401 \) defines the dispersion of the refractive index and the King correction factor of air at 532 nm (She 2001; Hostetler et al. 2006; Reagan et al. 2002).

The volume molecular scattering coefficient \( \hat{\sigma}_m \) at a given altitude \( z_C \) can be estimated using

\[
\hat{\sigma}_m(z_C) = \frac{N_A P(z_C)}{R_g T(z_C)} Q^s,
\]

where \( P(z_C) \) and \( T(z_C) \) are the atmospheric pressure (in hPa) and temperature (in K), respectively, at altitude \( z_C \); \( N_A = 6.022 \times 10^{23} \text{ mol}^{-1} \) is Avogadro’s number; \( R_g = 8.314 \text{ 472 J K}^{-1} \text{ mol}^{-1} \) is the gas constant; and \( Q^s = 5.167 \times 10^{-27} \text{ cm}^2 \) is the 532-nm total Rayleigh scattering cross section per molecule (Hostetler et al. 2006; Bucholtz 1995).

The presence of aerosol within the 30–40-km calibration altitude range requires the application of an aerosol backscatter correction to the calibration procedure. To account for the aerosol backscattering in the calibration algorithm, the calibration coefficient is recast in terms of the total parallel scattering ratio \( \hat{R}_|| \):

\[
C_|| = \frac{X_||(z_C)}{\hat{\beta}_{m||}(z_C) R_||(z_C) T^2(z_C)},
\]

where \( \hat{R}_||(z_C) = \frac{\hat{\beta}_{m||}(z_C) + \hat{\beta}_{a||}(z_C)}{\hat{\beta}_{m||}(z_C)} \).

A global model of \( \hat{R}_|| \) that provides an estimate of the relative contribution of aerosol backscatter present at altitudes within the calibration range can be derived from other measurements such as the 20-yr Stratospheric Aerosol and Gas Experiment (SAGE) II aerosol record (Thomason and Peter 2006). The current calibration procedure does not include such a model and globally defines \( \hat{R}_|| \) to unity. Plans are in progress to modify the calibration to include the contribution of aerosol backscatter in future versions of the CALIOP data products.

The two-way signal attenuation term \( T^2 \) describes the attenuation of the signal from the lidar transmitter to the scattering volume and back to the receiver. The two-way signal attenuation to the calibration altitude \( z_C \) can be written as

\[
T^2(z_C) = \exp \left\{ -2 \int_{z_m}^{z_C} \left[ \hat{\sigma}_m(z') + \hat{\sigma}_a(z') + \hat{\sigma}_{O_3}(z') \right] dz' \right\},
\]

where \( \sigma_m, \sigma_a, \) and \( \sigma_{O_3} \) are extinction coefficients resulting from molecular scattering, aerosol scattering, and ozone absorption, respectively. Because the current calibration procedure does not include contributions of stratospheric aerosol, \( \sigma_a \) is set to zero.

Figure 3 contains an example that compares the measured signal \( X_|| \) and signals derived from the model \( \hat{R}_|| \) and \( T^2 \), as defined by Eqs. (18) and (20). Both the measured signals and model estimates were averaged over one week for 4–10 February (Fig. 3a) and 4–10 August 2007 (Fig. 3c). The averaging was performed in three steps. First, the profile elements contained within the calibration altitude range (30–34 km) were averaged horizontally over 165 km along the lidar measurement ground track. Second, the mean value of each averaged profile was calculated and stored as a function of the midlatitude value of each ground track segment. Third, the calculated means were averaged over 1°-latitude segments to produce the averages displayed in Fig. 3. In an additional step, the model estimates were scaled by
the mean of the calibration coefficients $C_k$ for the same time period [refer to Eq. (6)]. The latitudinal range of the CALIPSO nighttime measurements shifts with season between maximum bounds of $82^\circ$N and $82^\circ$S, as demonstrated by the differences in latitude coverage of the calibration data 7 February (Fig. 3b) and 7 August 2007 (Fig. 3d). The data in Fig. 3 and later figures are plotted as a function of “extended latitude.” Extended latitude is a plotting technique to maintain visual continuity of the curves by artificially extending the latitude beyond the turnaround point at the northernmost or southernmost excursion of the orbit. This plotting technique is used to display a complete nighttime orbit segment without discontinuities. To calculate extended latitude, the difference between the local maximum latitude and the actual latitude is added to the local maximum latitude. The orbit track locations near the south polar region for August 2007 (Fig. 3d) show how the latitude coverage for each track repeats on either side of the node transition.

The signals in $X_k$ are closely matched to the model estimates, with two exceptions. The first exception occurs near the tropical latitudes, where the measured signals are higher than the model estimates. This is consistent with the SAGE II stratospheric aerosol measurements acquired during 2001–02 over the tropical latitudes, which report estimates of backscatter ratios ranging from 1.03 to 1.10 (Hostetler et al. 2006; Thomason et al. 2007). Because the current CALIOP calibration algorithm does not correct for the presence of aerosol in the stratosphere, a small error of approximately 3% is incurred for calibrations near the tropical region (see section 4a and Fig. 9). The second exception is near the Southern Hemisphere night-to-day terminator, where the signal decreases as the satellite enters sunlight and thermal changes begin to effect the alignment of the lidar transmitter and receiver (Hunt et al. 2009).

b. Calibration procedure

The vertical extent of the standard CALIOP calibration region extends down from 34 to 30 km. This region is high enough in the stratosphere to be relatively (albeit not completely) free of aerosols, and it is low enough to ensure that the mean molecular number density will generate an acceptably large backscatter signal. As explained in Hunt et al. (2009), before being transmitted back to Earth, the backscatter data in this high-altitude region are averaged on board the satellite to a spatial resolution of 300 m vertically and 5 km horizontally. However, the SNR in the calibration region.

![Fig. 3. Averaged values of measured signal (solid line) and model estimates (dotted line) are displayed as functions of extended latitude for (a) 4–10 Feb and (c) 4–10 Aug 2007. The averaged values for both the measured signal and model estimates were calculated over 30–34 km in the vertical and 165 km in the horizontal directions. CALIPSO nighttime measurement locations for (b) 7 Feb and (d) 7 Aug 2007.](image-url)
still remains quite low and significant amounts of additional averaging are required to produce accurate estimates of the calibration coefficients. The calibration procedure therefore performs increased averaging in three steps: 1) horizontal averaging, 2) vertical averaging, and 3) the application of a running average.

The data in the calibration region are first averaged to a horizontal resolution of 55 km. These profiles of averaged data are then converted into composite profiles of intermediate calibration coefficients by application of Eq. (18); that is, a profile of range-resolved calibration coefficients is formed by computing the ratio of the horizontally averaged data are then converted into composite profiles. The smoothing technique is presented in section 3d.

The data in the calibration region are first averaged to a horizontal resolution of 55 km. These profiles of horizontally averaged signal profiles of intermediate calibration coefficients within each of the composite profiles.

The final step further averages the calibration-coefficient estimates by smoothing the sequence of values via a 27-point running average filter, resulting in an effective 1485-km average between independent samples. The smoothed calibration coefficients are used to interpolate/extrapolate calibration coefficients continuously throughout the orbit. These, in turn, are applied to the X|| profiles to produce attenuated backscatter coefficient profiles.

The algorithm used to compute the nighttime 532-nm parallel calibration coefficient can be summarized with the following equations:

\[ C_{||}(y_k) = \frac{1}{j_{30-km} - j_{34-km} + 1} \sum_{j=j_{30-km}}^{j=j_{34-km}} \frac{1}{11k+5} \sum_{j=11k-5}^{j=11k+5} X_{||}(z_j, y_k) \beta_{m||}(z_j, y_k) R_{||}(z_j, y_k) T^2(z_j, y_k) \]

\[ \bar{C}_i(y_k) = \frac{1}{27} \sum_{k=13}^{k=13} C_{||}(y_k) \]

\[ j^2(z_j, y_k) = \exp \left\{ -2 \sum_{i_c=10}^{j} \left[ \sigma_a(z_{i_c}, y_k) + \sigma_a(z_{i_c}, y_k) + \sigma_b(z_{i_c}, y_k) \right] \Delta z \right\} \]

where \( i \) is the index for the \( i \)th signal profile (5-km horizontal resolution) within the \( k \)th 55-km calibration region and \( j \) is the index for the \( j \)th vertical sample in a signal profile (vertical resolution = 300 m), in which \( j_{30-km} \) and \( j_{34-km} \) are the vertical indices corresponding to 30 and 34 km, respectively. Here, \( y \) and \( z \) represent the horizontal and vertical distances along the ground track, respectively, and \( C_{||}(y_k) \) and \( \bar{C}_i(y_k) \) are the unsmoothed and smoothed calibration coefficients computed every 55 km along the track, respectively.

The implementation of the two-way signal attenuation in Eq. (21) only considers the integration of the transmission from the \( j \)th vertical sample to 40 km, as the atmospheric attenuation above 40 km is negligible. Equation (20) is then revised as

\[ \Delta z = 0.3 \text{ km.} \]
c. Error analysis

Uncertainties in the calibration coefficient are the result of both random and systematic errors; that is,

$$\left( \frac{\Delta C_{\parallel}}{C_{\parallel}} \right)^2 = \left( \frac{\Delta C_{\parallel}}{C_{\parallel}} \right)^2_{\text{RAN}} + \left( \frac{\Delta C_{\parallel}}{C_{\parallel}} \right)^2_{\text{SYS}}. \quad (24)$$

Assuming uncertainties that should reasonably apply in the stratosphere for 532 nm in the calibration altitude between 30 and 34 km, the current best estimates of the components of the systematic error are listed in Table 1. Estimates of the contributing error terms will be improved as more knowledge is gained on the accuracy of the products used to compute them. At present, the various components combine to give an overall relative systematic error $\Delta C_{\parallel}/C_{\parallel}$ of $\sim5\%$.

Random error in the calibration coefficients is dominated by shot noise in the lidar measurements. We estimate the random component of the calibration uncertainty by using continuously updated values of the noise scale factor (NSF; Liu et al. 2006; Hostetler et al. 2006). Use of the NSF technique enables accurate estimates of the random noise in a signal without requiring a large number of samples. Values of the NSF are computed as part of the level 1B process and are included in the output data product. Although the NSF for a specific detector can be derived theoretically, in practice it is typically computed by dividing the standard deviation of the background signal by the square root of the mean. Techniques for the derivation and application of the NSF to various measurement scenarios are described in detail in Liu et al. (2006).

The random uncertainty in the averaged $C_{\parallel}(y_k)$ is given by

$$\Delta C_{\parallel}(y_k) = \frac{f_1(N_{\text{range}})}{N_F \times (j_{30\text{-km}} - j_{34\text{-km}} + 1)} \left\{ \left( \sum_{j=j_{30\text{-km}}}^{j_{34\text{-km}}} \sum_{r=11k+5}^{11k+5} j_{30\text{-km}} E_{532} f_{532} f_{532} f_{532} f_{532} \right)^2 \right\}^{1/2}, \quad (26)$$

where $\Delta P_{\text{BG},\parallel}$ is the average over a major frame (5-km horizontal resolution using 15 lidar shots) of the standard deviation of background signal, $G_A$ is the average amplifier gain over the major frame, and $N_F$ is the

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<th>Table 1. Components of systematic error in the calculation of the 532-nm parallel calibration coefficient.</th>
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<td>$\frac{\Delta C_{\parallel}}{C_{\parallel}}$</td>
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number of signal profiles in a calibration region \( (N_F = 11) \). The factor \( f_1(N_{\text{range}}) \) is used to correct for the correlation between neighboring samples, which is due to the limited bandwidth of the detector preamplifier. The value of \( f_1(N_{\text{range}}) \) at any point is a function of the number of range bins that are vertically averaged on board the satellite.

The NSF is a function of the detector gain and the gain of the downstream electronics and does not change significantly on a daily basis. The NSF is computed during daytime by using

\[
\text{NSF} = \frac{\Delta P_{BG,||} / G_A}{\sqrt{V_{BG,1\text{frame,avg}}}},
\]

where \( V_{BG,1\text{frame,avg}} \) is the mean background signal averaged over a major frame. During nighttime operations, the lunar/stellar background is not high enough for accurate NSF measurements, and hence the NSF values for the nighttime are calculated using the average of the previous daytime NSF values.

d. Data filtering high-energy transient effects

Prior to performing the horizontal-averaging step in the calibration process [i.e., step 1 of Eq. (21)], the sampled data are filtered for signal spikes resulting from high-energy proton or cosmic ray events. The high-energy events that cause the signal spikes can occur randomly throughout the orbit, but they mostly occur in the South Atlantic anomaly (SAA), where the inner Van Allen radiation belts make their closest approach to Earth’s surface (Hunt et al. 2009). If left unchecked, the high-energy transients generate significant error in the calculation of the calibration coefficients.

The high-energy removal filter technique uses a combination of an adaptive filter and a noise-to-signal ratio (NSR) test to remove out-of-range signals prior to calibration (Lee et al. 2008). The filter technique is applied to each calibration region as a three-step process to successively filter the signals deemed as valid by the previous step.

In the first step, an adaptive filter is applied to each signal profile \( X_l \) (5-km horizontal and 300-m vertical resolution) within a calibration region (30–34 km in altitude and 55 km in horizontal extent). The high-energy removal filter technique uses a combination of an adaptive filter and a noise-to-signal ratio (NSR) test to remove out-of-range signals prior to calibration (Lee et al. 2008). The filter technique is applied to each calibration region as a three-step process to successively filter the signals deemed as valid by the previous step.

The second step of the filter technique applies an NSR test to the signals in the calibration region that were identified as valid by the adaptive filter. The NSR test is applied to each 4-km vertical by 55-km horizontal...
The NSR is calculated as the ratio of the standard deviation and the mean of all the valid signals \( \text{NSR} = \frac{\sigma_{\text{std}}(X_{\text{valid}})}{\mu(X_{\text{valid}})} \) and the resulting value is compared to an empirically defined NSR threshold value. The NSR threshold level is set to selectively identify only those variations in signal resulting from high-energy events. Calibration regions that fail the NSR test are excluded from the calibration process and are instead assigned a calibration coefficient computed from historical trending of valid calibration coefficients. For accepted calibration regions, all valid signal elements in the individual profiles are averaged into a single calibration-ready profile. The calibration-ready profile is the same as described in step 1 of Eq. (21). If any of the elements in this profile are empty (which can happen if the adaptive filter rejects all samples at a particular altitude), the entire calibration region is rejected and assigned a daily calibration-coefficient estimate. The time-referenced daily calibration-coefficient estimates are then posted to a calibration-coefficient history data file. The daily calibration-coefficient estimates are obtained from the calibration-coefficient history data file by searching for the latest date prior to the date of data acquisition.

Figure 6a contains the NSR values plotted as a function of extended latitude for the same orbit described in Fig. 5. For this example, the NSR threshold is set at 2.2 and is marked as a solid line. Figures 6b,c illustrate how the adaptive filter and the NSR test are applied for single calibration regions. In each figure, the 11 \( X_n \) signal profiles from a calibration region are displayed as functions of altitude. The calibration region in Fig. 6b is located near the center of the SAA, and the calibration region in Fig. 6c is located near the edge of the SAA. In comparing the signal levels for the two regions, the number and intensity of the high-energy events are higher for the region near the center of the SAA (Fig. 6b). The shaded regions mark the valid signals identified by the application of the adaptive filter. The signal elements outside of the shaded regions are not included in the NSR test. In applying the NSR test to the valid signals, the NSR value yields \( \sim 15 \) for Fig. 6b and \( \sim 1.6 \) for Fig. 6c. The NSR value for Fig. 6b exceeds the NSR threshold and the calibration region is assigned a daily calibration-coefficient estimate. The NSR value for Fig. 6c is within the NSR threshold limit and the calibration-ready profile is calculated by horizontally averaging the valid signal elements in the individual profiles.

In the third step, the adaptive filter is applied to the mean of the calibration-ready profile. The minimum and maximum threshold values in \( X_M \) are defined using Eqs. (28) and (29) with parameters specific to each calibration region. Here, the latitude \( l \) is the midpoint latitude of the calibration region, and \( X_{\text{mid}}(l) \), which approximates the mean of the calibration-ready profile, is computed using the molecular number density from the vertical midpoint of the calibration region. The parameters \( \Delta P_{BG,i}^n, \bar{C}_A^\phi, \) and \( C_0^\phi \) [Eq. (29)] are calculated as averages over the calibration region, and \( n_{\text{bins}} = 300 N_F \), where \( N_F \) is the number of signal profiles in a calibration region (\( N_F = 11 \)).
This final filter test determines if the mean of the values in the calibration-ready signal profile is within a specified range of the approximate mean stored in the parameter $X_k(l)$. If the calibration-ready profile passes this filter test, then it is used by the calibration procedure as described in step 1 of Eq. (21). If the calibration-ready profile does not pass the final filter test, then the calibration region is assigned a daily calibration-coefficient estimate.

Figure 6d contains the calibration-ready profile produced by horizontally averaging the valid profile elements displayed in Fig. 6c. The mean of the calibration-ready profile is drawn as a vertical dotted line, and the minimum and maximum threshold values defined by the second application of the adaptive filter are drawn as vertical solid lines. The mean of the calibration-ready profile shown is within the limits of the dual threshold and is therefore used in the calibration procedure.

Figure 5c shows calibration coefficients computed using both filtered and unfiltered signals in the calibration process. The filtered and unfiltered calibration coefficients are plotted as solid and dotted lines, respectively. These results demonstrate that, by applying this filter technique, the CALIOP calibration procedure can correctly calculate the 532-nm calibration coefficients in a wide variety of different noise environments.

4. 532-nm nighttime parallel-channel calibration assessment and validation

Assessments and validations of the nighttime 532-nm parallel-channel calibration are performed continuously throughout the mission. The performance of the calibration procedure is assessed by using the CALIOP attenuated backscatter data to calculate clear-air attenuated scattering ratios and comparing the CALIOP results to the theoretical clear-air scattering ratio of 1. We refer to cloud-free regions of very low aerosol loading as clear air. We limit the altitude range over which the scattering ratios are calculated to between 8 and 12 km. Experience has shown that the altitude region between 8 and 12 km often exhibits very low aerosol loading such that the observed total scattering ratio is very near 1. Validation is performed by comparing CALIOP level 1B attenuated backscatter profiles to those derived from the NASA airborne HSRL. This comparison determines the biases that exist within the CALIOP calibration. The following sections provide a detailed description and results of both the assessment and validation procedures.

a. Clear-air attenuated scattering ratio assessment

CALIOP nighttime 532 nm calibration is internally assessed by compositing attenuated scattering ratio estimates.
from regions identified as clear air and comparing them to values appropriate for a purely molecular atmosphere (i.e., $R^9 = 1$). If the calibration is correct and the aerosol loading is sufficiently low, then the clear-air scattering ratios calculated from the level 1B data should not differ from the estimates for molecular backscatter by more than the relative calibration uncertainty (i.e., ±5%).

In applying this benchmark to the calculated clear-air attenuated ratios, several factors that may bias the calibration assessment must be considered. These factors include the accuracy of the scattering model, the presence of noise in the measured data, and the degree of aerosol contamination found within so-called clear-air regions. This last factor is directly related to the minimum detectable backscatter coefficient for CALIOP, which in turn is a function of instrument design and the layer detection scheme applied to the data (Vaughan et al. 2005; McGill et al. 2007).

The scattering model is the same as the one used for the 532-nm parallel calibration process described in section 3a, in which the molecular and ozone number densities are provided by NASA GMAO. Noise in the data can be reduced by averaging; however, small biases resulting from aerosol loading below the CALIOP detection threshold will remain. Any aerosols that are in the selected clear-air regions will cause the scattering ratios to have larger values than those for completely clear air.

The clear-air regions are determined using the CALIOP lidar level 2 cloud and aerosol layer data product (Vaughan et al. 2004, 2009). Regions are selected if they contain clear air above 8 km and extend continuously for at least 200 km along the orbit track. Figure 7 contains an illustration of the clear-air selection process using lidar level 1B 532-nm total attenuated backscatter coefficients from 1 February 2007, beginning at 0438:06 UTC. The red boxes between 8 and 12 km in altitude and 200 km in length illustrate clear-air regions.

For each 200-km segment, profiles of clear-air attenuated scattering ratios are calculated as the ratio of 532-nm total attenuated backscatter signals to the scattering model derived from molecular and ozone number densities provided by GMAO. Total attenuated scattering ratios are used because the contributions to the clear-air scattering ratios from the perpendicular channel are negligible.

These scattering ratio profiles are defined as

$$R_{CA}^{9}(z_{8-12}, k) = \frac{\beta^{9}(z_{8-12}, k)}{\beta_{m}^{9}(z_{8-12}, k)},$$

where $k$ is the profile index and $z_{8,12}$ designates the altitude range between 8 and 12 km. Both the attenuated backscatter and attenuated scattering model include terms for molecular backscatter and for the extinction resulting from the molecular and ozone constituents within the atmosphere. The measured attenuated backscatter coefficients can also include contributions to both backscatter and extinction from faint aerosols below the CALIOP detection limit. Expanding Eq. (30) yields
If the signal is properly calibrated and the aerosol attenuation between 40 and 12 km is negligible, then the mean of the clear-air attenuated scattering ratio profiles should fall within the calibration range of uncertainty of \( \pm 0.05 \). However, at the single-profile resolution, the noise in the signal dominates the error associated with calibration. To reduce the noise, the calculated means of each clear-air attenuated scattering ratio profile \( R_{CA}^{'}(z_{8-12}, k) \) are averaged over the 200-km segment [Eq. (32)]:

\[
R_{CA200}^{'} = \frac{1}{600} \sum_{k=1}^{600} R_{CA}^{'}(z_{8-12}, k). \tag{32}
\]

Figure 8 illustrates the noise in four consecutive clear-air attenuated scattering ratio profiles at single-profile resolution \( R_{CA}^{'}(z_{8-12}, k) \) from 1 February 2007. The profiles extend from 8.3 to 12 km in altitude and are horizontally spaced by approximately 1 km. Over this altitude region, three single-shot profiles (333-m horizontal resolution) are averaged on board to produce a single composite profile. For reference, a scattering ratio of 1.0 is drawn as a dashed line in each plot. The mean attenuated scattering ratio for each profile is indicated by the solid vertical line and noted in each plot. In all four examples, the mean attenuated scattering ratio values fall outside of the expected \( \pm 0.05 \) because of both the signal noise in the single-profile data and the possibility of low-level aerosol present within the scattering ratio region.

In Fig. 9, the means of each clear-air attenuated scattering ratio profile at single-profile resolution \( R_{CA}^{'}(z_{8-12}, k) \) for a 200-km (600 profiles) segment are plotted as a solid line. The average mean attenuated scattering ratio of the entire segment \( R_{CA200}^{'} = 0.97 \) is plotted as a bold solid line. Although the single-profile mean attenuated scattering ratios are noisy, the average mean attenuated scattering ratio over the 200-km segment falls within the expected range of \( \pm 0.05 \).
Averaged mean clear-air attenuated scattering ratios \( R_{CA200} \) have been accumulated for each month of the mission. The monthly plots of nighttime \( R_{CA200} \) for February, May, July, and September 2007, as well as for January and March 2008, are shown in Fig. 10. The \( R_{CA200} \) values are displayed as a function of time relative to the start of the nighttime orbit segment. The latitudes of the measurement locations are marked as dotted lines and labeled near the top of each plot. The \( R_{CA200} \) values are gray circles and the black markers are the medians of \( R_{CA200} \) over each 10-s interval.

The results obtained from the assessment show that the majority of the medians of \( R_{CA200} \) are within 5% of the expected value of 1. The plots all show a dip in the tropical region, which is due to the presence of unmodeled stratospheric aerosols within the calibration region. Note that, for some months, the ratios near the polar regions are outside the expected range. The cause for this is currently under investigation, but it is currently believed to be an accurate reflection of enhanced aerosol loading within the lower troposphere in the polar regions.

b. Validation with HSRL

A validation study of CALIOP nighttime 532-nm parallel-channel calibration was performed by comparing

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**Fig. 9.** The solid line indicates the mean of each clear-air attenuated scattering ratio profile at single-profile resolution within a 200-km segment (600 profiles). The 200-km averaged mean clear-air scattering ratio (solid bold line) is 0.97 and falls within the expected mean value of 1.

**Fig. 10.** Nighttime clear-air mean attenuated scattering ratios for February, May, July, and September 2007, as well as for January and March 2008, as a function of time from the start of the nighttime orbit segment. The latitude locations are superimposed near the top edge of the plots. The clear-air mean attenuated scattering ratios are gray circles and the black markers are the medians over each 10-s interval.
spatially coincident data acquired with the NASA airborne HSRL to the CALIOP nighttime 532-nm total attenuated backscatter coefficients to determine biases in CALIOP calibration. The airborne HSRL is internally calibrated to a high accuracy (~1%–2%; Hair et al. 2008) and does not rely on normalization of estimated backscatter from assumed clear-air regions for calibration. As such, it provides an ideal dataset for assessment of CALIOP calibration errors. To date, 68 flights of the airborne HSRL were flown along the CALIPSO ground track and timed to the CALIPSO overpass.

The calibration errors were calculated as the relative difference between clear-air HSRL and CALIOP attenuated backscatter profiles as

$$\Delta C(z_{CA}, k_p) = 100.0 \frac{\beta'_{HSRL}(z_{CA}, k_p) - \beta'_{CALIOP}(z_{CA}, k_p)}{\beta'_{HSRL}(z_{CA}, k_p)},$$

(33)

where $z_{CA}$ represents cloud-free regions at least 1.5 km below the HSRL aircraft and 2 km above the ground. Data used for the comparisons were further screened for the presence of clouds above the altitude of the HSRL aircraft that would cause attenuation in the CALIOP profiles not taken into account in the HSRL data and would invalidate the comparisons. This screening process was accomplished using the CALIOP level 2 vertical feature mask data product (Anselmo et al. 2007; Vaughan et al. 2004). On average, the coincident HSRL measurements were selected from a 1-h (~430 km) window centered at the time that the satellite passed over the aircraft.

The NASA HSRL has been making coincident measurements with CALIPSO since the start of the CALIPSO mission. Figure 11 shows the mean calibration error estimate for each day (temporally averaged) as a function of latitude. The data are color coded by month. The variability in the daily estimates is determined as the standard deviation of the temporally averaged error profiles for each day. The results show that the mean nighttime 532-nm parallel channel calibration is within 4.9% of HSRL.

The positive bias (~3%–7%) seen in the error estimates indicates that the HRSLS 532-nm total attenuated backscatter coefficients are systematically larger than those of CALIPSO. The source of this bias is the presence of stratospheric aerosols within the CALIPSO calibration region. Recent estimates put the magnitude of the scattering ratio of the stratospheric aerosols in the range of 1.03 to 1.10, with variations depending on latitude and season (Hostetler et al. 2006; Thomason et al. 2007). Accounting for the presence of stratospheric aerosols in the calibration equation [i.e., as in Eqs. (18) and (19)] would effectively eliminate the bias. As noted earlier (see section 3a), such modifications are planned for future versions of the CALIPSO data products.

5. 532-nm perpendicular-channel calibration

Calibration of the 532-nm perpendicular channel is transferred from the 532-nm parallel channel using data acquired during the polarization calibration operation (Hunt et al. 2009). During the calibration, a spatial pseudodepolarizer is inserted into the 532 nm receiver optical path, thereby randomizing the polarization of the return so that nearly equal optical fluxes are incident on the parallel- and perpendicular-channel detectors. The ratio of the two measured signals is the PGR and is used to quantify the differences in the responsivity and gain of the two detection channels. The 532-nm perpendicular-channel calibration coefficient is then defined as the product of PGR and the 532-nm parallel-channel calibration coefficient.

a. Mathematical basis

The polarization calibration operation is performed during the nighttime conditions and its duration varies between 5 and 20 min. During the polarization calibration operation, the signals are averaged horizontally over the entire polarization calibration segment and vertically from 18 to 25 km. The ratio of the averaged perpendicular- and parallel-channel signals is defined as
\[ \hat{K}_p = \frac{X_{\perp}^{\text{PGR}}}{X_{\parallel}^{\text{PGR}}}, \]  
where \( X_{\perp}^{\text{PGR}} \) and \( X_{\parallel}^{\text{PGR}} \), the averaged perpendicular and parallel signals, respectively, are defined as

\[ \bar{X}_{\perp}^{\text{PGR}} = \frac{1}{N(j_U - j_L + 1)} \sum_{k=1}^{N} \sum_{j_L}^{j_U} X_{\perp}^{\text{PGR}}(z_j, y_k) \]  
and

\[ \bar{X}_{\parallel}^{\text{PGR}} = \frac{1}{N(j_U - j_L + 1)} \sum_{k=1}^{N} \sum_{j_L}^{j_U} X_{\parallel}^{\text{PGR}}(z_j, y_k). \]

Here, \( N \) is the total number of profiles acquired during polarization calibration operation and \( j_L \) and \( j_U \) are the vertical indices corresponding to the lowest and highest polarization calibration altitude bins, respectively. The 532-nm perpendicular calibration coefficient is then defined as

\[ C_1(y_k) = \hat{K}_p \hat{C}_1(y_k), \]

where \( \hat{C}_1(y_k) \) is defined in Eq. (22).

b. Error analysis

Estimates of the uncertainties in the PGR \( \hat{K}_p \) are calculated and stored in the level 1B data product. Uncertainties in \( \hat{K}_p \) are due to both random and systematic errors:

\[ \left( \frac{\Delta \hat{K}_p}{\hat{K}_p} \right)^2 = \left( \frac{\Delta \hat{K}_p}{\hat{K}_p} \right)^2_{\text{RAN}} + \left( \frac{\Delta \hat{K}_p}{\hat{K}_p} \right)^2_{\text{SYS}}. \]

The systematic error is due primarily to nonideal polarization effects in the transmitter and receiver and is further described in Hunt et al. (2009). The random uncertainty in the averaged \( \hat{K}_p \) is estimated using the NSF and given by

\[ (\Delta \hat{K}_p)_{\text{RAN}} = \hat{K}_p \left\{ f_1(N_R) \left[ \sum_{k=1}^{N} \sum_{j_L}^{j_U} \left[ \frac{r_j}{E_{532}^{\text{NSF}}} \right]^2 \left( y_k \right) X_{\parallel}^{\text{PGR}}(z_j, y_k) + \left( \frac{r_j^2 \Delta P_{BG,\parallel}(y_j)}{E_{532}^{\text{NSF}}G_{A,\parallel}} \right)^2 \right] \right\}^{1/2} \]

where \( \hat{K}_p \) is the mean of the individual ratios \( K_p \), which is defined as \( K_p(y_k) = X_{\perp}^{\text{PGR}}(z_{L:U}, y_k) / X_{\parallel}^{\text{PGR}}(z_{L:U}, y_k) \), where the \( X_{\perp}^{\text{PGR}} \) profile elements are averaged over the polarization calibration operation altitude range defined as \( z_{L:U} \).

Because the pseudodepolarizer directs essentially equal optical intensities on both detectors and because the long durations of the PGR calibration operations permit extensive signal averaging, the SNR for both the parallel and perpendicular components of the PGR calculation is quite high. Consequently, the random error in \( \hat{K}_p \) has remained at \( \sim 1\% \) or less throughout the mission. Possible systematic errors in the PGR measurement have not been quantified but are expected to be smaller than the random error. The most likely upper bound for the total relative uncertainty in the PGR measurement is thus on the order of \( \sim 1.5\% \).

6. Discussion

Planned algorithm enhancements (or upgrades or improvements) include the addition of a stratospheric
aerosol model into the calibration process. This model will likely be based on analysis of data from CALIOP and from Global Ozone Monitoring by Occultation of Stars (GOMOS), one of the three instruments dedicated to atmospheric composition sounding on board the European Space Agency (ESA) satellite Envisat, which launched on 1 March 2002 (Kyrölä et al. 2004). Once the stratospheric aerosol model is implemented within the calibration procedure, all of the CALIOP level 1B data will be reprocessed and archived at the NASA Langley Research Center Atmospheric Science Data Center. There are also plans to continuously monitor the performance of the calibration procedure using the clear-air attenuated scattering ratio assessment presented in section 3a and to periodically schedule CALIOP calibration validation flights with the HSRL.

7. Summary

The traditional molecular normalization calibration scheme applied to the CALIOP nighttime 532-nm parallel channel has a long and well-documented history of success in the lidar community. A new capability of removing spurious high-energy events that would otherwise introduce large errors into the calibration was added to the CALIOP calibration process. The HSRL validation data shows that the CALIOP calibration is performing well within the expected error budget (~5%). The 532-nm perpendicular channel is calibrated relative to the 532-parallel channel using data acquired during the PGR operation.

The calculated 532-nm parallel and perpendicular calibration coefficients are applied to corresponding signal data to produce profiles of attenuated backscatter coefficients with units of km$^{-1}$ sr$^{-1}$. The data products archived at the NASA Langley Research Center Atmospheric Sciences Data Center (available online at http://eosweb.larc.nasa.gov/) include both profile and calibration products. The attenuated backscatter profiles are reported as 532-nm total attenuated backscatter (parallel plus perpendicular) and 532-nm perpendicular attenuated backscatter. The calibration products are composed of the calibration coefficients and calibration uncertainties for the 532-nm parallel channel and the PGR and PGR uncertainties for the 532-nm perpendicular channel.

REFERENCES


