THE CALIOP 532-NM CHANNEL DAYTIME CALIBRATION: VERSION 3 ALGORITHM

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ABSTRACT

The CALIPSO lidar (CALIOP) makes backscatter measurements at 532 nm and 1064 nm and linear depolarization ratios at 532 nm. Accurate calibration of backscatter measurements is essential for layer detection and the subsequent retrieval of optical properties. A revised 532-nm daytime calibration algorithm has been developed for the version 3 CALIPSO lidar level 1 data release. This revised algorithm produces calibration coefficients by scaling the daytime clear-air scattering ratios to the match the values measured at the same latitude during the nighttime orbit segments. This paper describes the version 3 daytime calibration algorithm and its implementation within the CALIPSO Automated Processing System (CAPS). The results obtained from the revised algorithm are discussed and comparisons are made to validation data acquired by NASA's Airborne High Spectral Resolution Lidar (HSRL).

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, launched in April 2006, now makes continuous global measurements of the vertical structure of the atmosphere [1]. The CALIPSO lidar level 1 (L1) data product is routinely produced at NASA's Langley Research Center, and contains a set of calibrated and geolocated, vertically resolved profiles of 532 nm total and perpendicular attenuated backscatter and 1064 nm total attenuated backscatter. During nighttime operations, the 532-nm parallel channel is calibrated using the traditional high-altitude molecular normalization technique [2]. The nighttime calibration coefficients computed for the 532-nm parallel channel function as the main system calibration: all other channels are calibrated relative to this measurement. For daytime, the CALIOP measurements are strongly affected by the ambient solar background, which causes a substantial deterioration of the signal-to-noise ratio (SNR) for molecular backscatter measurements, thus precluding the use of the high-altitude molecular normalization technique. However, if the magnitudes of the nighttime and daytime signals are uniformly proportional with respect to latitude for a given target (e.g., cloud-free regions between 8 km and 12 km in altitude), then the nighttime calibration coefficient can be readily adapted for daytime conditions via a constant, empirically derived scale factor. However, a comprehensive review of the daytime 532-nm signals revealed that, irrespective of the target chosen, the daytime signals do not remain constant, but instead vary considerably over the course of the orbit, due to thermally-induced misalignment of the transmitter and receiver. This alignment shift causes the signal levels to vary non-linearly over the daytime portion of the orbits, and thus precludes the use of a constant scale factor to transfer calibration from nighttime to daytime measurements. In the version 2 CALIPSO L1 data product, a set of empirically determined scale factors was applied using a 5-point linear approximation [3]. The version 3 L1 release applies a 34-point latitudinally-dependent linear approximation to the previous nighttime mean calibration coefficient. This new approach allows for better characterization of the small scale changes in signal level that take place over the daytime orbit segment. The scale factors are continually updated using 532-nm attenuated scattering ratios calculated in cloud free regions between 8 km and 12 km on consecutive nighttime and daytime orbit segments. The target daytime attenuated scattering ratios are determined by the value of the nighttime attenuated scattering ratios at the same latitude, under the assumption that the diurnal changes in aerosol loading in the upper troposphere/lower stratosphere are negligible.

2. CLEAR-AIR ATTENUATED SCATTERING RATIOS

The clear-air regions for both nighttime and daytime are determined using the CALIPSO lidar level 2 Cloud and Aerosol Layer data product [4] [5]. Regions are selected if they are found to be clear of clouds and aerosols above 8 km and extend continuously for at least 200 km along the orbit track. Figure 1 contains an illustration of the clear-air selection process using CALIPSO L1 532-nm nighttime, total attenuated backscatter coefficients from 1 February 2007, beginning at 04:38:06 UTC. The red boxes between 8 km and 12 km in altitude and 200 km in length illustrate clear-air regions.

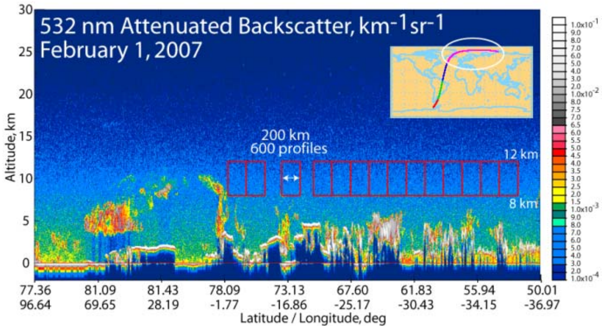

Figure 1. CALIOP 532-nm total attenuated backscatter, $km^{-1}sr^{-1}$ data (1 February 2007) for the orbit section circled in the map insert. (Note: The red boxes between 8 km and 12 km in altitude and 200 km in length illustrate clear-air regions.)

For each 200 km segment, profiles of clear-air attenuated scattering ratios are calculated as the ratio of 532-nm attenuated backscatter signals to a molecular scattering model derived from molecular and ozone number densities provided by NASA's Global Modeling and Assimilation Office (GMAO).

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'=1). Noise in the data can be reduced by averaging; however, small biases due to 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. If the signal is properly calibrated, and the aerosol attenuation between 40-km and 12-km is negligible, the mean of the clear-air attenuated scattering ratio profiles should fall within the calibration range of uncertainty of 1 ± 0.05.

Over the course of the CALIPSO mission, the 532-nm nighttime, clear-air attenuated scattering ratios have maintained relatively constant values as a function of latitude. This is illustrated in Figure 2 using 7-day averages of 200-km averaged, 8-12 km, clear-air attenuated scattering ratios from June to November 2006. The data in Figure 2 and later figures are plotted as a function of "extended latitude". "Extended latitude" is a plotting technique used to maintain visual continuity of the curves by artificially extending the latitude beyond the inflection point at the northernmost or southernmost excursion of the orbit. This plotting technique is used to display a complete orbit segment without overplotting points in the Polar Regions. To calculate extended latitude, the difference between the local maximum latitude and the actual latitude is added to the local maximum latitude.

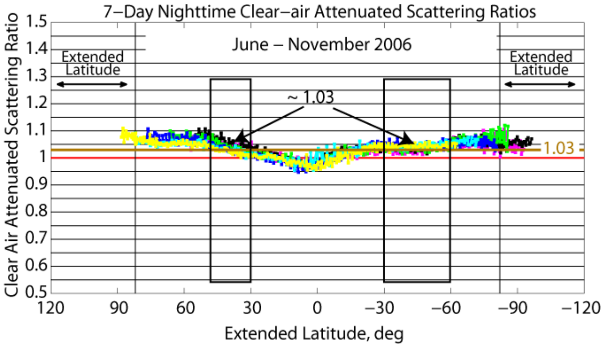

Figure 2. Seven-day averages of 532-nm nighttime 8-12 km, clear-air attenuated scattering ratios from June to November 2006.

The nighttime attenuated scattering ratios consistently show values of approximately 1.03 over mid-latitudes (30S-60S and 30N-45N). In the tropics, the values are lower than 1.03 due to the presence of stratospheric aerosols that contaminate the nighttime calibration region (30-34 km). Near the Polar Regions, the values higher than 1.03 are due to the presence of aerosol within the 8-12 km altitude range.

3. VERSION 3 DAYTIME CALIBRATION ALGORITHM

For version 3, the approach to calibrating the daytime signals is to estimate the 532-nm daytime calibration coefficients by applying a set of latitudinally-dependent scale factors to the previous nighttime mean calibration coefficient. Application of this technique produces 532-nm daytime, 8-12 km, clear-air attenuated scattering ratios that are close to identical to the nighttime clear air attenuated scattering ratios at the same latitude.

The process begins by calculating both the 532-nm nighttime and daytime 8-12 km, clear-air attenuated scattering ratios as described above. For daytime, the attenuated scattering ratios, R'_D, are calculated as

$$R'_D = \frac{X_D}{\left(R'_S C_{mean}\right)\hat{\beta}'_m} = \frac{\beta'}{\hat{\beta}'_m}, \qquad (1)$$

where the daytime attenuated backscatter coefficients, β', are computed as the ratio of the range-scaled, energy- and gain-normalized signal, X_D, and the previous nighttime mean calibration coefficient, C_{mean}. The attenuated scattering ratios, R'_D, are then derived from β' by dividing by molecular model, $\hat{\beta}'_m$, obtained from the GMAO data. For the initial sequence of calculations, the scale factor, R'_S, is set to a constant value of 1.0.

The results obtained from this initial calculation are shown in Figure 3 using 7-day averages of 200-km averaged, 8-12 km, clear-air attenuated scattering ratios for November 21-27, 2006. The nighttime signals (in black) and daytime signals (in green) are not related by a constant linear scaling factor due to thermally-induced changes in the instrument alignment.

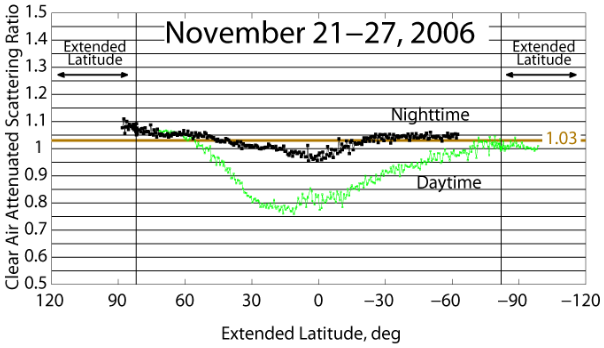

Figure 3: comparison of attenuated scattering ratios measured in clear air regions between 8 km and 12 km for nighttime (black) and daytime with arbitrary calibration (green).

The daytime clear-air attenuated scattering ratios, R'_D, can be used to scale, or correct, C_{mean} such that the resulting attenuated scattering ratios are equal to 1.0:

$$1.0 = \frac{X_D}{\left(R'_D C_{mean}\right)\hat{\beta}'_m}. \tag{2}$$

However, the goal is to produce daytime clear-air attenuated scattering ratios that are nearly the same as the nighttime clear-air attenuated scattering ratios at the same latitude. Multiplying both sides of Eq. 2 by the "Target-nighttime" attenuated scattering ratios, R'_{T-N}, produces scale factors that, when applied to C_{mean}, will give daytime clear-air attenuated scattering ratios consistent with the nighttime values. This is given as:

$$R'_{T-N} = \frac{X_D}{\left(R'_S C_{mean}\right)\hat{\beta}'_m}. \tag{3}$$

where the scale factors, R'_S, are defined as

$$R'_S = \frac{R'_D}{R'_{T-N}}. \tag{4}$$

The minimum allowable R'_{T-N} value is 1.03, which corresponds to the 532-nm nighttime clear-air attenuated scattering ratio values consistent with the mid-latitudes (see Figure 2). To accomplish this, the following rules are applied:

$$\text{If } R'_{T-N} > 1.03,\ R'_S = \frac{R'_D}{R'_{T-N}}. \tag{5}$$

$$\text{If } R'_{T-N} \le 1.03,\ R'_S = \frac{R'_D}{1.03}. \tag{6}$$

When there are no nighttime matches to the daytime locations (at the ends of orbit segments) then the last R'_{T-N} value is extrapolated to the end of the orbit segment.

4. IMPLEMENTATION

The version 3 CALIPSO 532-nm daytime calibration algorithm has been incorporated into the nominal Level 1 CALIPSO Automated Processing System (CAPS). As a daily process, the 200 km averaged, 8-12 km, clear-air attenuated scattering ratios are calculated for each nighttime and daytime orbit segment and stored along with their 200-km mid-point latitude and time relative to the start of the orbit. The attenuated scattering ratios for the previous seven days are accumulated according to time relative to the start of each orbit and then partitioned into 100 second intervals. The median scattering ratio and latitude values for each interval are then used to calculate the latitudinally-dependent daytime calibration scale factors according to the rules specified by equations (5) and (6). The 34-point latitudinally-dependent scale factors are then applied to the previous nighttime mean calibration coefficient to produce the daytime calibration coefficients. A single set of 34-point scale factors are calculated per day, and correspond to the two endpoint locations and 32 points within the orbit segment.

5. RESULTS

Results of the version 3 CALIPSO 532-nm daytime calibration technique are shown in Figure 4 using 7-day averages of the 200-km averaged, 8-12 km, clear-air attenuated scattering ratios for November 21-27, 2006. The attenuated scattering ratios for the nighttime are in black. For daytime, there are three curves. The attenuated scattering ratios calculated with scale factor equal to 1.0 are green, the version 2 results are blue, and the version 3 results are red. The version 3 attenuated scattering ratios are in good agreement with the latitudinally coincident nighttime attenuated scattering ratios over mid-latitudes and at the poles. At the tropics the attenuated scattering ratios are 1.03, as expected. Where the nighttime and daytime location are not coincident (below 60°S), the daytime scattering ratios remain at the same level as that of the nighttime endpoint. Significant improvements from version 2 to version 3 are noted in the Southern hemisphere, and near 30°N and 60°N. In the Southern hemisphere, the version 3 daytime attenuated scattering ratios are 10% lower than in version 2. This is due to better characterization of the small scale changes in signal level that take place over the daytime orbit segment.

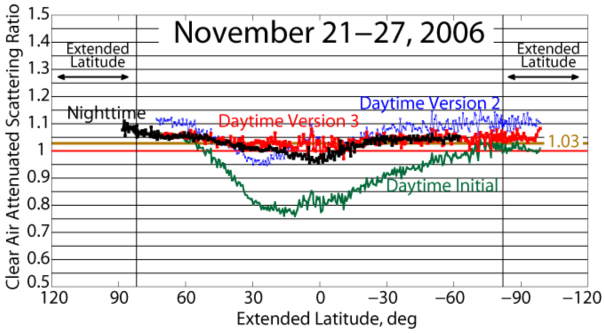

Figure 4: comparison of attenuated scattering ratios measured in clear air regions between 8 km and 12 km for nighttime (black); daytime with arbitrary calibration (green); daytime using the version 2 calibration scheme (blue); and daytime using the new version 3 calibration scheme (red).

A validation study of CALIOP daytime 532-nm parallel channel calibration was performed by comparing spatially coincident data acquired with NASA's Airborne HSRL [6] to the CALIOP daytime 532-nm total attenuated backscatter coefficients in order to determine biases in CALIOP calibration.

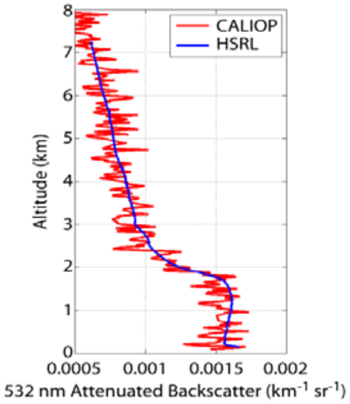

Figure 5: comparison of HSRL (blue) and CALIOP (red) 532 nm attenuated backscatter coefficients acquired during a day-time overpass on 2006-09-20. Data are cloud-cleared, then averaged over ~900 km horizontally. Due to disparities in temporal matching, data in the aerosol-laden PBL (below ~2.2 km) show slight differences in magnitude. Data in the clear air above the PBL show excellent agreement, demonstrating the high quality of the CALIOP daytime calibration scheme.

The Airborne HSRL is internally calibrated to a high accuracy (~1-2%), and does not rely on normalization to estimated backscatter from assumed clear-air regions for calibration. As such, it provides an ideal data set for assessment of CALIOP calibration errors. Figure 5 shows an example from a single flight. To date, the CALIPSO project has conducted 46 daytime HSRL validation flights. The calibration errors for each flight are calculated as the relative difference between clear air HSRL and CALIOP attenuated backscatter profiles. The composite results show that the mean daytime 532-nm parallel channel calibration is within 3.5% of HSRL.

6. SUMMARY

A revised 532-nm daytime calibration algorithm has been developed for the version 3 CALIPSO L1 data release. This revised algorithm produces calibration coefficients that align the daytime clear-air scattering ratios to the latitudinally coincident nighttime measurements. Significant improvements are seen between 30° N and 60°N, and throughout the southern hemisphere.

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