

REVISED CALIBRATION STRATEGY FOR THE CALIOP 532 NM CHANNEL: PART I – NIGHTTIME

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ABSTRACT

The CALIPSO lidar (CALIOP) is a satellite-borne, down-looking system that measures backscattered signals from the atmosphere at 532 nm and 1064 nm and linear depolarization ratios at 532 nm. Accurate calibration of all lidar channels is a critical issue in the retrieval of optical properties. For the nighttime portion of an orbit, the 532 nm parallel channel calibration coefficient is determined by comparing the signals in the 30 km to 34 km altitude range to a scattering model derived from molecular and ozone number densities provided by NASA's Global Modeling and Assimilation Office. Transient effects from high energy protons and/or cosmic rays can generate very strong noise excursions in the CALIOP detectors, which, if allowed to propagate into the calculations, will introduce significant errors in the derived calibration coefficients. To eliminate these errors, an adaptive data filtering is incorporated into the CALIOP calibration procedure. This paper describes the filtering technique implemented in the current version of the CALIOP production software, and illustrates its effectiveness using examples drawn from the CALIPSO dataset.

1. INTRODUCTION

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is the primary instrument onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) payload [1] that was launched on April 28, 2006. CALIOP is a two-wavelength (532 nm and 1064 nm), polarization-sensitive (532 nm) lidar that provides global, vertically resolved measurements of the spatial distributions and optical properties of clouds and aerosols. Accurate calibration of all lidar channels is a critical issue in the retrieval of optical properties. Of primary importance is the calibration of the 532 nm parallel channel, as both the 532 nm perpendicular channel and the 1064 nm channel are calibrated relative to the 532 nm parallel channel [2,3]. For the nighttime portion of an orbit, the 532 nm parallel channel calibration coefficient is determined by normalizing the 532-parallel signals in 30 km to 34 km altitude range to a scattering model derived from molecular and ozone number densities provided

by NASA's Global Modeling and Assimilation Office (GMAO). This region of the atmosphere is assumed to be essentially free of aerosols, and thus the aerosol scattering ratio used in the normalization procedure is fixed at $R_{norm} = \beta_{total} / \beta_{molecular} = 1$. For the daytime portion of the orbit, the same calibration technique cannot be used, because the noise associated with solar background signals degrades the backscatter signal-to-noise ratio (SNR) in the calibration region below usable levels. The daytime calibration coefficients are therefore interpolating using the values derived from the nighttime measurements made immediately preceding and following each daytime segment [4].

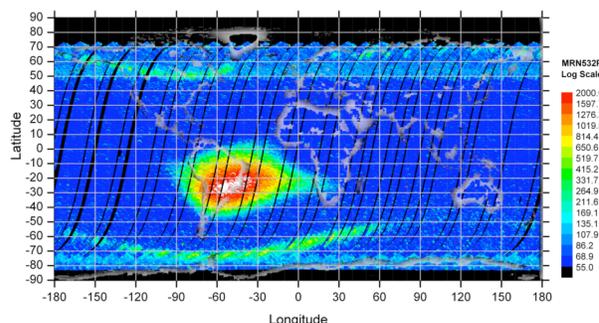


Figure 1: A global time history of photomultiplier dark noise measurements made by CALIOP shows the location of the South Atlantic Anomaly (SAA) region (centered at approximately 25° S and 50° W), along with other regions of enhanced radiation.

The radiation environment along the CALIPSO orbit track presents special problems for CALIOP calibration. Transient effects from high energy protons and/or cosmic rays can introduce extreme noise excursions into the backscatter signal, and these in turn can generate significant error in the calculation of the calibration coefficients. These effects are especially prevalent in the South Atlantic Anomaly (SAA), where the inner Van Allen radiation belts make their closest approach to the Earth's surface (see Figure 1). However, because pre-launch modeling of the expected backscatter signals did not account for these random, rogue spikes, no special data filtering routines were initially included in the CALIOP calibration algorithms. The effects of omitting these routines are illustrated in

Figure 2, which shows the 532 nm attenuated backscatter coefficients for an orbit segment from August 2, 2006. The data values are noticeably lower in a well demarcated band from 71° S to 77° S. As seen in Figure 3, which shows both high-resolution and smoothed values of the 532 nm calibration coefficient, the region of lower attenuated backscatter coefficients corresponds exactly to the uniform extent of elevated calibration coefficients. Figure 3 also shows the correlation between the high-resolution calibrations and the mean value of the raw backscatter data from which they are derived.

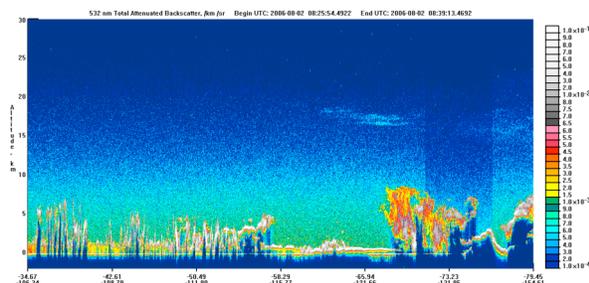


Figure 2: Attenuated backscatter coefficients from August 2, 2006 derived using 532 nm calibration coefficients computed with no filtering for strong noise signals. The region lower values seen between 71° S and 77° S is the result of calibration errors due to radiation-induced noise.

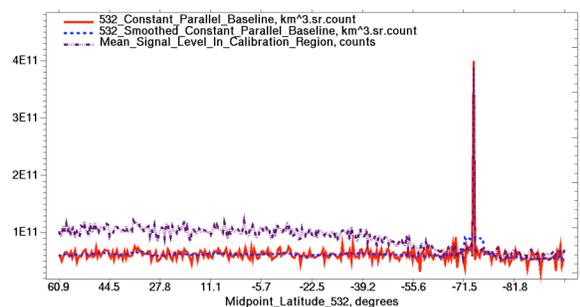


Figure 3: 532 nm calibration coefficients without filtering strong noise signal. The red solid line shows high-resolution calculations computed over consecutive 55-km horizontal distances and the blue dashed line is a 715-km running average of the high-resolution values (left axis). The purple dashed dot dot line shows the mean 532 nm signals in the calibration region (right axis). The smoothed values were used to generate the data shown in Figure 1.

2. DATA FILTERING STRATEGIES

The data used in the calibration process is the range-corrected, gain and energy normalized backscatter signal, $X(r)$, is defined as

$$X(r) = \frac{r^2 P(r)}{EG} \quad (1)$$

where r is the range to the sample volume, $P(r)$ is the background-subtracted raw data, E is the laser energy,

and G is the electronic gain. A representative distribution of $X(r)$ values, derived from all nighttime measurements between July 31 to August 14, 2006, is shown in Figure 4. Several data filtering strategies were initially considered, including a simple notch filter, a running median filter, and noise scale factor filtering. The median filter proved to be inappropriate for application to a highly asymmetric distribution such as the CALIOP calibration signals, and was rejected. The simple notch filter, constructed with a lower bound of $X_{\min} = -1.35 \times 10^6$ and an upper bound of $X_{\max} = 6.05 \times 10^6$, worked well for isolated spikes such as occurred in the 2006/08/02 example (see Figure 5), but failed when applied to the more chaotic noise environment characteristic of the SAA (e.g., as in Figure 6).

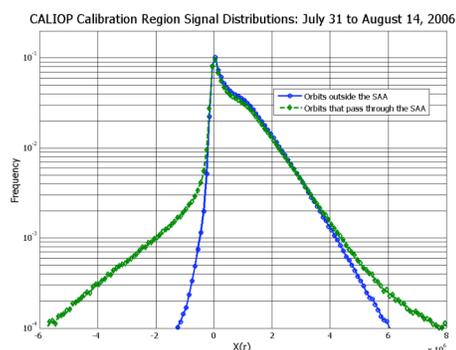


Figure 4: Distributions of $X(r)$ in CALIOP's 30-km to 34-km calibration region using all data acquired between 2006/07/31 and 2006/08/14.

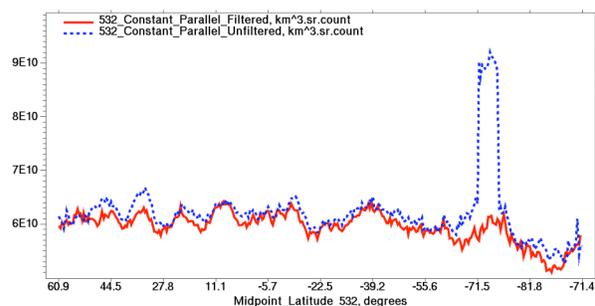


Figure 5: 532 nm calibration coefficients for the 2006/08/02 example computed with (red line) and without (blue line) the application of the notch filter.

The most effective filter, and the one implemented in the CALIPSO production software, is based on the noise scale factor (NSF) that characterizes the parallel channel photomultiplier in the CALIOP receiver. While this value can be derived theoretically, in practice the NSF is computed by dividing the standard deviation of the background signal by the square root of the mean [5]. When the value of the NSF is well known in advance, it can be used to estimate the random noise in a signal without requiring a large number of samples. The CALIOP Level 1 analyses compute continuous updates of the parallel channel

noise scale factor using the procedures described in [5]. Incorporation of these results into the NSF filter is described in the following paragraphs.

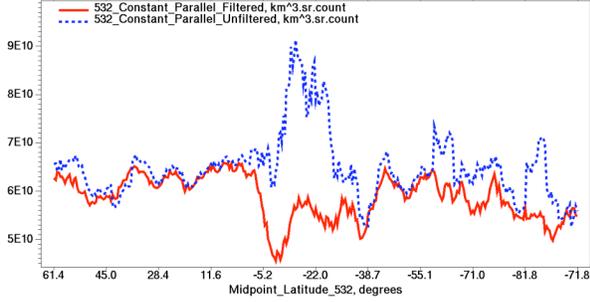


Figure 6: 532 nm calibration coefficients for an orbit segment that passes through the SAA; segment start is 06:07:53 UTC on 2006/08/04; unfiltered calculations are shown in blue, and notch filtered data calculations in red.

Each high-resolution calibration region contains eleven consecutive 5-km frames (i.e., a 55-km horizontal extent). For each frame we construct a “filtered and averaged profile” by applying the NSF to the backscatter data prior to calculating the average of the samples. The filter computes the uncertainty in $X(r)$ due to random noise for the individual data points as a function of latitude, ℓ , as follows:

$$\Delta X(\ell, r, E, G) = \frac{1}{\sqrt{300}} \sqrt{\frac{r^2}{E} NSF^2 \hat{X}(\ell) + \frac{r^4}{E^2} \left(\frac{N_b + 1}{N_b} \right) \left(\frac{\Delta \bar{V}_b}{G} \right)^2} \quad (2)$$

Here NSF is noise scale factor, $\Delta \bar{V}_b$ is the RMS baseline noise, 300 is the number of data points averaged in the calibration region, N_b is number of points used to calculate the RMS baseline noise, and $\hat{X}(\ell)$ is an approximation of $X(r)$ at ℓ computed by a linear scaling of the molecular number density from the vertical midpoint of the calibration region. This uncertainty takes into account both the background noise and random error (shot noise) in the signal. A notch filter for the current profile is then defined with limits

$$X_{\min} = \hat{X}(\ell) - k_{\min} \Delta X_{\text{profile}} \quad \text{and} \quad (3)$$

$$X_{\max} = \hat{X}(\ell) + k_{\max} \Delta X_{\text{profile}} \quad (4)$$

where k_{\min} and k_{\max} are empirically determined scaling constants that adjust range of the signals passed by the filter. These values must be set large enough to include all valid signals, but small enough to exclude all radiation-induced noise spikes. Based on the signal distribution in Figure 4, these constants are set to $k_{\min} = 9$ and $k_{\max} = 15$. This NSF notch filter is

applied to each of the 300 $X(r)$ samples with the 55-km calibration region. We then compute the noise-to-signal ratio (NSR) using all valid signals within the region. Regions will be rejected from further consideration if there are zero valid samples within any altitude range in the composite profile, or if the calculated NSR is greater than a nominal value of 2.2. The calibration coefficients for rejected regions are assigned a default value computed from historical trending of valid calibration coefficients. For accepted frames, the $X(r)$ values are averaged horizontally to produce a single, composite profile, $X_{\text{avg}}(r)$. The NSF filter is applied again to this profile using $\hat{X}(\ell)$ computed at the horizontal midpoint of the region, ℓ_{mid} . The uncertainty in the averaged value of X in the region is:

$$\Delta X_{\text{region}} = \left(\frac{1}{11} \right) \Delta X(\ell_{\text{mid}}, \bar{r}, \bar{E}, \bar{G}) \quad (5)$$

The threshold filter for the current calibration region is set to:

$$X_{\min} = \hat{X}(\ell_{\text{mid}}) - c_{\min} \Delta X_{\text{region}} \quad (6)$$

$$X_{\max} = \hat{X}(\ell_{\text{mid}}) + c_{\max} \Delta X_{\text{region}} \quad (7)$$

where $c_{\min} = c_{\max} = 3$ are empirically determined constants. If the NSF filter rejects all of the $X_{\text{avg}}(r)$, the calibration coefficient is assigned a default value computed from historical trending; otherwise, a high-resolution calibration coefficient is computed using the molecular normalization technique described in [3].

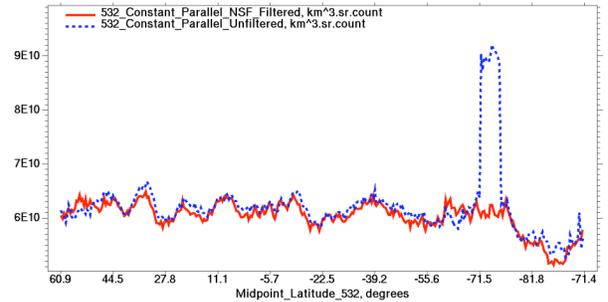


Figure 7: A comparison of 532 nm calibration coefficient values derived with (red solid line) and without (blue dashed line) the NSF filter.

3. APPLICATION OF THE NSF FILTER

Figure 7 compares the calibration coefficients computed using the NSF filter to the unfiltered results previously shown in Figure 5. The very large error at $\sim 74^\circ$ S in the unfiltered results is seen to be successfully removed by application of the NSF filter. Figure 8 shows the results of applying the NSF filter to the same data shown in Figure 1. As expected, the sharp discontinuities in the magnitude of the attenuated

backscatter coefficients at $\sim 71^\circ$ S and $\sim 77^\circ$ S disappear entirely in the revised image.

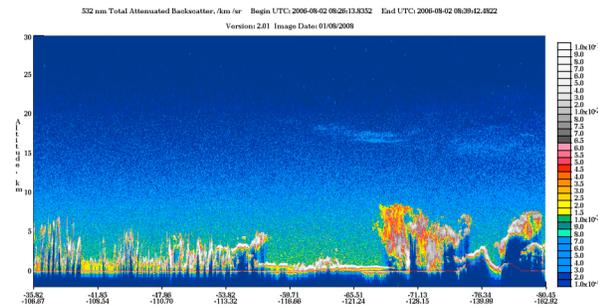


Figure 8: As in Figure 2, but with the NSF filter used in the calibration procedure prior to deriving the 532 nm attenuated backscatter coefficients.

Figure 9 compares the calibration coefficients computed with and without the NSF filter for the same 2006/08/04 data previously shown in Figure 6. Particularly within the SAA, the NSF-derived calibration coefficients show a marked improvement when compared to the fixed width notch filter results shown in Figure 6. Improvement is also seen deeper into the southern hemisphere. Whereas the fixed width filter appears to introduce a low bias to the computations in this region, results obtained using the adaptive NSF filter exhibit greater stability.

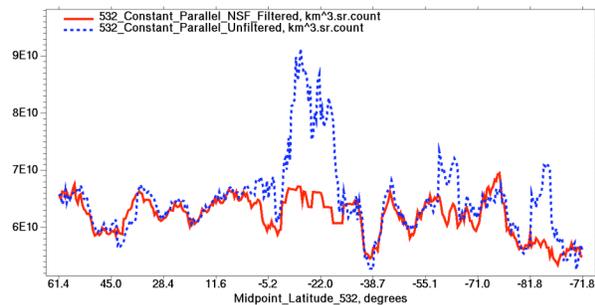


Figure 9: As in Figure 6, but now comparing the NSF filtered results (red) to the original, unfiltered results (blue).

For the data in Figure 9, the NSF filter identified enough valid data to permit direct calculation of the calibration coefficients. Figure 10, on the other hand, compares calibration coefficients computed with and without the NSF filter when CALIPSO passed through the heart of the SAA, where the noise can completely overwhelm the signal. Between 5.2° S and 38.7° S, the NSR is greater than the threshold (2.2), and thus the historical default calibration coefficient values are assigned in this region.

4. SUMMARY

Calibration of all channels of the CALIOP lidar depends critically on the accurate calibration of the 532 nm parallel channel. Because very strong radiation-induced

noise spikes can introduce significant calibration errors, a data filtering scheme is required. Simple filtering methods such as fixed width notch filter are shown to be inadequate. An improved filtering method that uses the noise scale factor is introduced. The width of the NSF notch filter is updated for each calibration region based on the current signals. The results shown here demonstrate that, by applying the NSF filter, the CALIOP calibration procedures can correctly calculate the 532 nm calibration coefficients in a wide variety of different noise environments.

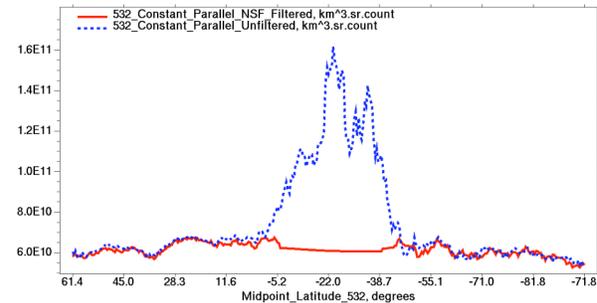


Figure 10: Comparison 532 nm calibration coefficients with (red) and without (blue) the NSF filter when passing through the center of the SAA. The data shown here were acquired on the orbit immediately prior to the data shown in Figure 9.

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