Mitigation Strategy for the Impact of Low Energy Laser Pulses in CALIOP Calibration and Level 2 Retrievals

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Abstract. Since mid-2016, the frequency of low energy laser pulses emitted by the CALIPSO lidar has been slowly increasing due to pressure losses in the canister housing the laser. While originally confined primarily to the South Atlantic Anomaly (SAA) region, these low energy pulses now occur intermittently around the globe. Low energy pulses can cause calibration biases and degrade the science quality of level 2 retrievals. We describe a new low energy mitigation (LEM) algorithm that will be implemented incrementally in future versions of the CALIOP data processing to identify and reject affected profiles during calibration and feature detection. The LEM algorithm effectively eliminates low energy calibration biases, improves level 2 retrievals, and minimizes level 2 data loss.

Keywords: CALIPSO, CALIOP, laser energy

1 Introduction

The space-based lidar CALIOP was launched onboard the CALIPSO satellite in 2006 and since has provided a 16+ year record of vertically resolved aerosol and cloud measurements. The CALIOP transmitter is an Nd:YAG laser that is Q-switched and diode pumped, emitting at 532 and 1064 nm. In mid-2016 the laser began experiencing intermittent low energy pulses due to pressure losses inside the laser canister that allow coronal arcing across the Q-switch. The low energy pulses primarily occur over the

South Atlantic Anomaly (SAA) region (Fig. 1), where energetic particles increase the occurrence of coronal arcing. In recent years low energy pulses have become more prevalent outside the SAA, albeit at lower frequencies. Low energy pulses primarily have 532 nm energies < 10 mJ compared to nominal values of 90–100 mJ.

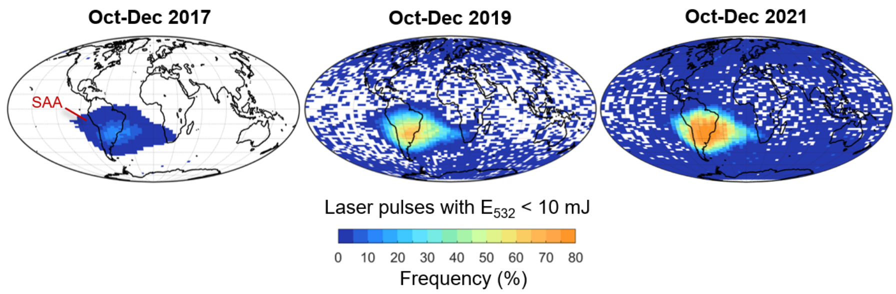

Fig. 1. Spatial distribution of low energy pulses. During Oct-Dec 2021, 37% of laser pulses in the SAA have low energy compared to 1% outside the SAA.

The most noticeable impacts on V4.1 level 1 and V4.2 level 2 data products are shown in Fig. 2 where optically thin aerosol is undetected and false feature detections occur at all altitudes in affected profiles. This example is an extreme case near the SAA, but false detections occur similarly outside the SAA at a lesser frequency. Whereas existing noise filters eliminate the influence of low energy pulses for the 532 nm night calibration, the 532 nm day and 1064 nm channels are both impacted at SAA latitudes. The goal of the CALIPSO project is to remove the low biases in level 1 calibration coefficients and rectify the science quality of level 2 retrievals affected by low energy pulses. This will be accomplished by a new low energy mitigation algorithm (LEM) that strategically rejects data affected by low energy pulses during the level 1 calibration and level 2 feature detection processes.

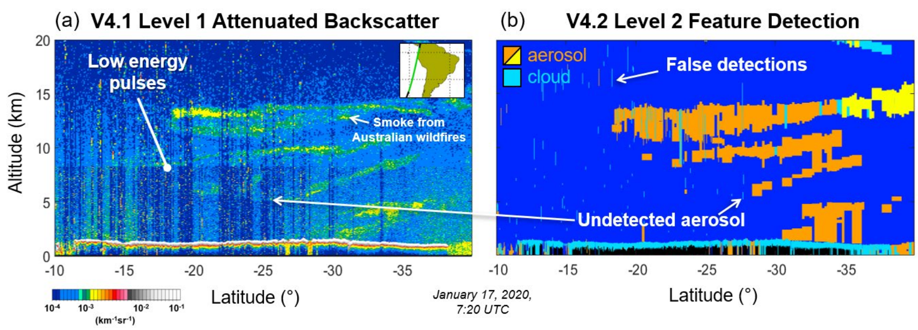

Fig. 2. (a) V4.1 532 nm attenuated backscatter and (b) V4.2 feature detection/classification for a CALIOP granule affected by low energy laser pulses near the SAA.

2 Low Energy Mitigation (LEM) Algorithm

The LEM algorithm balances two competing desires: maintain science quality similar to that of data with nominal laser energy and reject as little data as possible. To do this, LEM accounts for onboard averaging and level 2 averaging. This is important because these averaging processes extend the ill effects of low energy to neighboring profiles, even those with nominal energies. The fundamental resolution measured by the lidar receiver is 15 m vertical x 333 m horizontal. The signal is averaged onboard the satellite prior to downlink to reduce transmitted data volume. The coarsest horizontal interval downlinked is a 5 km data "frame". Within a frame, five altitude regions are defined with different amounts of vertical and horizontal averaging, shown schematically in Fig. 3. We name the smaller averaging intervals within each altitude region as "subregions". Below 8.2 km, data are downlinked at 333 m "single-shot resolution".

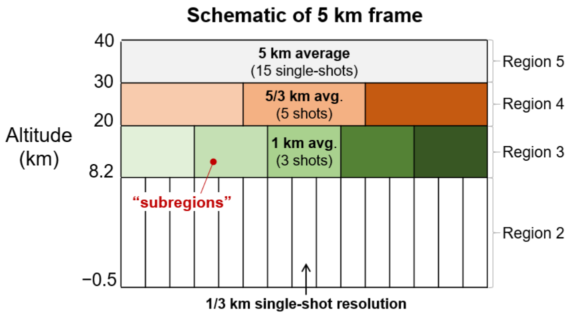

Fig. 3. Schematic of a 5 km frame showing how data is averaged onboard prior to downlink. For clarity, region 1 is not shown (−0.5 to −2 km).

The impact of a low energy pulse in any one of these subregions depends on how many single-shot samples are averaged together: one profile with low energy in region 4 may have a small impact on the 5-shot average, but below 8.2 km where there is no horizontal averaging onboard, that low energy profile is surely unusable. To minimize data rejection while maintaining sufficient single sample SNR, LEM adopts a low energy threshold of $E_{532} < 10$ mJ and imposes the following constraints on individual profiles and subregions:

- Profiles with low energy are rejected in single-shot resolution regions 1 and 2.
- Subregions must contain at least 2 (out of 3) profiles with good laser energy in region 3 and 2 (out of 5) in region 4.
- *Some* un-rejected data must exist in each 1 km segment in regions 2 and 3 after applying the previous constraints to ensure a continuous profile.

It is important that enough valid profiles are included in the 5 km frame for features to be detected reliably in level 2. When too many profiles or subregions have been rejected, then the entire 5 km frame is also rejected. To enforce this requirement, the following additional constraints are implemented.

- At least 6 (out of 15) un-rejected profiles must exist in region 2.
- At least 3 (out of 5) un-rejected subregions must exist in region 3.
- At least 1 (out of 3) un-rejected subregion must exist in region 4.

The previous constraints ensure the data quality of 5 km frames used in 532 nm daytime calibration and for feature detection in level 2 processing. However, the level 2 feature detection algorithm also searches for weakly scattering features at 20 km and then 80 km resolution [1]. These resolutions were selected to approximately double the SNR for each subsequent average. Because the previous constraints will at times reject whole 5 km frames, LEM requires that at least 75% of the 5 km frames expected for a 20 km or 80 km average are not rejected. This allows the coarser resolutions to achieve at least ~86% of the expected SNR doubling or quadrupling. If fewer that 75% of 5 km frames are available, then feature detection is not invoked for the coarse resolution and the contributing data are removed from subsequent coarser averages. Note that all minimum numbers and fractions given above are preliminary and subject to change.

3 LEM Application to Calibration

The current V4.1 calibration procedure for the 532 nm nighttime channel contains outlier rejection filters that successfully eliminate the influence of low energy pulses. However, additional filtering is necessary for the 532 nm daytime and 1064 nm channels. The 532 nm daytime calibration coefficients are calculated by comparing day and night clear-air scattering ratios matched by granule elapsed time at a high altitude where particulate loading is diurnally invariant [2]. The scattering ratios are based on 200 km horizontal averages that are further averaged across ±52 consecutive granules. Thus, low energy pulses within the 200 km segment in any of the 105 granules can affect the average. This effect is especially acute at SAA latitudes where multiple granules within the average pass through the SAA, causing the bias in Fig. 4a and a substantial increase in uncertainty. The LEM algorithm has been implemented for the 532 nm daytime calibration procedure in the V4.5 level 1 data release. It enforces subregion/frame acceptance criteria within each 200 km segment, thereby rejecting data affected by low energy. As a result, biases in the V4.1 532 nm day calibration at SAA latitudes are eliminated (Fig. 4a) and the calibration uncertainty is significantly reduced.

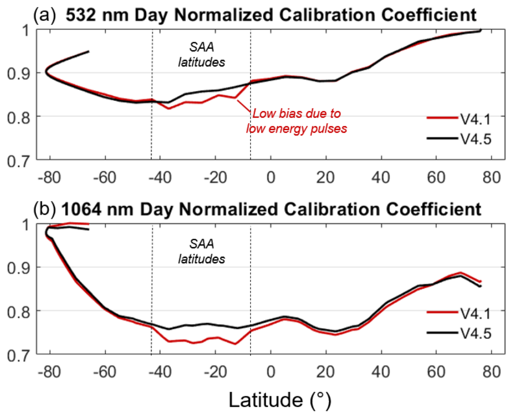

Fig. 4. November 2020 normalized calibration coefficients for V4.1 (red) and the low energy mitigated V4.5 (black) as a function of granule elapsed time converted to latitude.

The LEM strategy for 1064 nm calibration is more aggressive. The 1064 nm calibration procedure scales 532 nm calibration coefficient based on "calibration quality" ice clouds, where the 1064 nm/532 nm ratio of signals is assumed = 1.01 [3]. The scale factors derived from these clouds are based on averages over ±52 consecutive granules, matched by granule elapsed time. Low energy pulses are not trapped by the quality filters in V4.1, which leads to biased scale factors and ultimately biased 1064 nm calibration coefficients particularly at SAA latitudes. In V4.5, an additional quality filter is added: calibration quality clouds cannot contain any low energy pulses within their 5 km average. Adding this LEM filter effectively eliminates the 1064 nm calibration bias at SAA latitudes (Fig. 4b).

4 LEM Application to Level 2 Feature Detection

Following the release of V4.5, the LEM algorithm will be added to level 2 processing to reject segments of level 1 attenuated backscatter affected by low energy pulses prior to feature detection. Various quality control flags will be included in the level 2 products to document LEM operations and special fill values will indicate where data has been rejected. Note that no data rejection will occur to the level 1 data products. Fig. 5 shows the impact of LEM for the scene presented in Fig. 2. False detections are eliminated, rejected data are clearly indicated with fill values, and previously undetected aerosol is now detected. The science quality of remaining data is markedly improved in this extremely complex example.

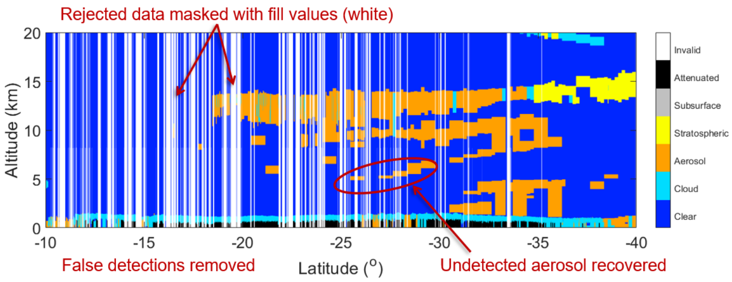

Fig. 5. Feature detection/classification for the same granule as Fig. 2, but with LEM applied.

Based on preliminary assessments, LEM is expected to recover a substantial amount of level 2 data. Outside the SAA in late 2021, only 0.6% of 5-km frames are entirely rejected. The remaining 2.3% of frames containing low energy pulses meet LEM criteria and are recoverable (97.1% of frames are unaffected low energy pulses). Inside the SAA, data recovery is more challenging given the greater number of low energy shots. During the same period, 41% of frames are rejected and 28% are recoverable in the SAA (only 31% are unaffected).

5 Conclusion and Implementation Plan

The LEM algorithm is effective at removing biases in 532 nm day and 1064 nm calibration coefficients and improving the science quality of level 2 retrievals. By applying data rejection to small, targeted segments based on native averaging intervals, LEM minimizes data loss due to low energy pulses. The CALIPSO project will include LEM in the calibration procedures for the 2022 release of the V4.5 level 1 data product. The project plans to incorporate LEM in a subsequent post-V4.5 level 2 data release after 2022 to provide adequate time for validation.

References

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