An Operational Spaceborne Lidar Calibration Algorithm for 1064 nm

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ABSTRACT

CALIPSO, a satellite mission within NASA's ESSP Program, includes a two-wavelength polarization-sensitive lidar. Calibration of the lidar is essential for the qualitative retrieval of cloud and aerosol measurements. Using backscatter returns from strong cirrus clouds at 532 nm and 1064 nm, an operational algorithm has been developed to transfer calibration from 532 nm to 1064 nm. The algorithm has been successfully applied to CALIPSO-simulated LITE data. This paper presents these results, along with a description of the algorithm and expected uncertainties.

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission, being developed as a partnership between NASA and the French space agency CNES, is planned for launch in early 2004. The payload consists of a two-wavelength, polarization sensitive lidar along with an imaging IR radiometer and a wide field camera. The CALIPSO satellite will fly as part of the Aqua satellite constellation to provide a suite of combined observations necessary to improve: 1) our understanding of the role of aerosols and clouds in the processes that govern climate responses and feedbacks; 2) the representation of aerosols and clouds in models, leading to more accurate predictions of climate change. Accurate calibration of the CALIPSO lidar is essential to the quantitative retrieval of these aerosol and cloud properties.

Following the procedures employed for LITE[1], in situ calibration of the 532 nm lidar channel will be accomplished via normalization to a high altitude, nearly molecular scattering region. The molecular backscatter is too weak to permit such calibration for the longer 1064 nm channel. For lidars operating at both wavelengths, a viable approach is to transfer the calibration at the shorter wavelength to the longer wavelength via comparisons of spectral backscatter from known/quantifiable scatterers. Cirrus clouds are good targets for this purpose because they occur at high altitudes with sufficient frequency and provide strong, nearly spectrally flat backscatter[2, 3].

2. PHYSICAL MODEL AND MATHEMATICAL DESCRIPTION

Let the normalized lidar signal, X(z), represent the lidar signal after corrections for instrument artifacts, background subtraction, gain and energy normalization, and range correction. Then the normalized cloud signal, X_c, defined as the total normalized signal minus the non-cloud background normalized signal, is given approximately by

$$X_c(z) = C\, T^2_{ct}\, \beta_c(z) T^2_c(z), \text{ where}$$

z is geometric altitude; C is the lidar calibration factor; T^2_{ct} is the round-trip transmittance to cloud top at altitude z_{ct}; β_c is the cloud backscatter for $z < z_{ct}$; and T^2_c is the cloud round-trip transmittance from z_{ct} to $z < z_{ct}$.

Assuming β_c T^2_c is the same for 532 nm and 1064 nm, the ratio of X_c for the two wavelengths at any z within the cloud, or the ratio of the integrals of X_c through the cloud for the two wavelengths, will be approximately

$$\frac{X_{c,1064}}{X_{c,532}} \approx \frac{C_{1064}}{C_{532}} \times \frac{T^2_{ct,1064}}{T^2_{ct,532}}$$

and

$$\frac{C_{1064}}{C_{532}} \approx \frac{X_{c,1064}}{X_{c,532}} \times \frac{T^2_{ct,532}}{T^2_{ct,1064}}.$$

Due to the low signal to noise of noncloud return, it is difficult to remove the noncloud signal from the total signal. Therefore our approach will be to select strong signal returns where the contamination by noncloud returns is minimal. The above equation then becomes

$$\frac{C_{1064}}{C_{532}} \approx \frac{X_{1064}}{X_{532}} \times \frac{T^2_{ct,532}}{T^2_{ct,1064}} \qquad (1)$$

The last term is approximately 0.9 at 12 km, and can be computed from models of aerosol extinction and ozone concentration and the atmospheric density profile.

In the CALIPSO calibration timeline, the 532 nm signal is calibrated prior to performing the 1064 nm calibration. As a result the calibrated attenuated 532 nm backscatter is used instead of the normalized 532 nm signal, and equation (1) becomes

$$C_{1064} \approx \frac{X_{1064}}{\beta_{532} T^2_{532}} \times \frac{T^2_{ct,532}}{T^2_{ct,1064}} \qquad (2)$$

A threshold signal for determining strong cloud returns is determined by computing the 532 nm attenuated backscatter that is equivalent to a scattering ratio = R_t. Currently $R_t = 50$.

If $R_t = \dfrac{\beta_a(z) + \beta_m(z)}{\beta_m(z)}$, then $\beta_{a,532}(z) + \beta_{m,532}(z) = R_t \times \beta_{m,532}(z)$ and the threshold signal becomes

$S = R_t \times \beta_{m,532}(z) \times T^2{}_{532}(z)$.

This threshold is applied only to the 532 nm attenuated backscatter for determining cloud segments of sufficient signal intensity.

Prior to beginning the search for clouds, the 532 nm attenuated backscatter and 1064 nm normalized signal profiles are averaged horizontally over an integer number of major frames to increase SNR. Currently the number of major frames used for nighttime calibration is 1, which is equivalent to 5 km. The search for cloud returns is restricted to the altitude region from 8 to 17 km. This helps eliminate noncirrus cloud returns and facilitates the modeling of transmission terms in the above equations. Also, only the highest altitude cloud with a thickness (as determined by the threshold signal) of at least 180 meters (3 sample points) is used.

Operationally, the algorithm proceeds as follows:

1) Average the calibrated attenuated 532 nm backscatter and the normalized 1064 nm signal horizontally over specified number of major frames. Compute the corresponding molecular backscatter and extinction arrays.
2) Compute signal thresholds for 532 nm equivalent to a scattering ratio of R_t.
3) Search for strong cloud returns between 8 and 17 km using thresholds calculated in Step 2.
4) Determine the highest altitude cloud segment with at least 3 consecutive signals above threshold. (The bottom of the cloud segment occurs the first time a signal does not exceed threshold.)
5) Calculate C_{1064} using equation 2 at each altitude in the cloud segment. Calculate the mean of these constants.
6) Steps 1 – 5 are repeated for the nighttime and daytime portion of each orbit. The mean, standard deviation, and number of samples of C_{1064} for each ½ orbit are calculated and reported in a calibration output file.
7) Perform outlier rejection using median and standard deviation. Recalculate mean and number of samples and add to output file.
8) Calibrate 1064 nm data using mean calibration constants stored in output file.

3. SIMULATION RESULTS

Three orbits of LITE data (orbits 23, 24, and 27), obtained with low gain settings, had a sufficient number of unsaturated calibration quality clouds to test the 1064 nm calibration algorithm. The data for these orbits were run through the CALIPSO simulator to obtain data with the correct averaging resolution and expected noise characteristics. Figure 1 is the result of running the 1064 nm calibration algorithm on CALIPSO simulated data from LITE orbit 23. Figure 1a is a plot of the 1064 nm calibration constant versus peak 532 nm scattering ratio for each calibration cloud profile. It shows that the calibration constant is relatively stable with cloud intensity, although there is more variability with weaker clouds. Likewise, figure 1b shows that the calibration constant is relatively independent of cloud altitude. Figure 1c shows the latitudes where the calibration clouds were obtained.

The results from all three orbits are summarized in Table 1. The mean calibration constant for each orbit is within about 4% of the simulator calibration value. The standard deviations of the calibration constants are on the order of 5%. These results are consistent with the expected uncertainties discussed in the next section. Outlier rejection (rejection of all calibration points outside one standard deviation of the median) is planned to further improve results.

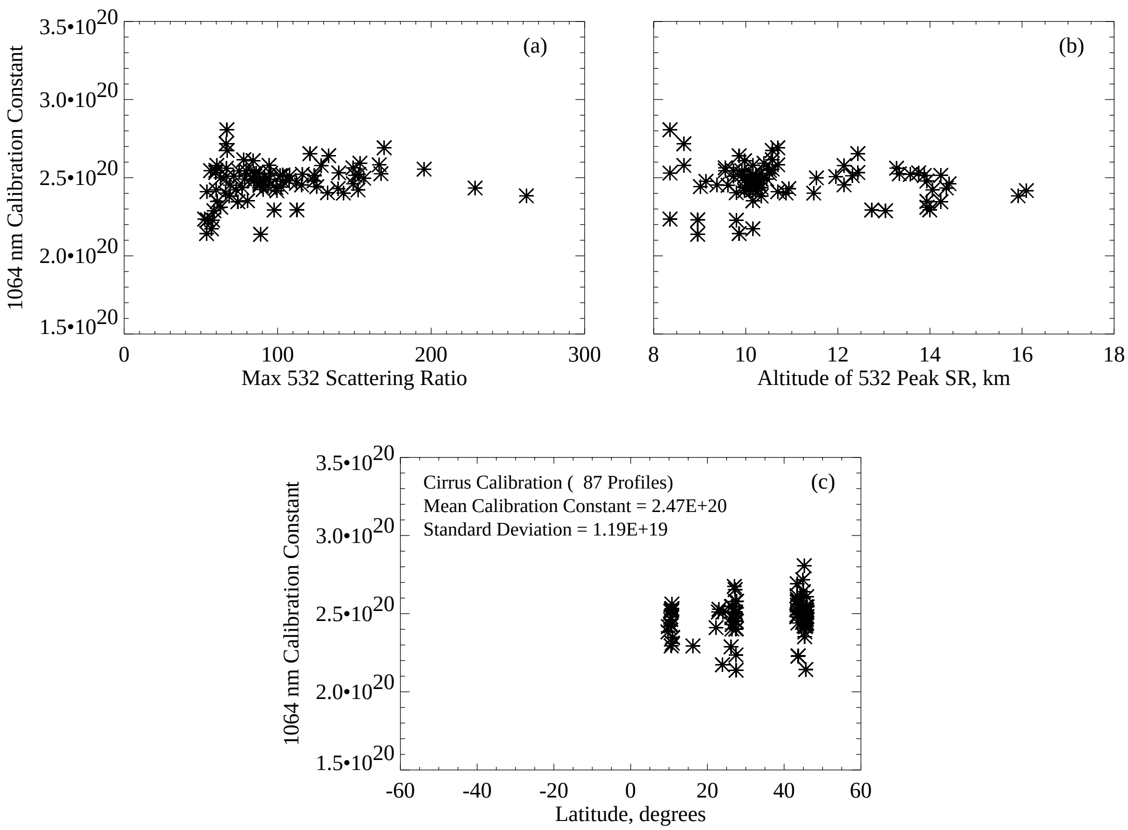

Figure 1. C_{1064} versus: a) maximum 532 nm cloud scattering ratio; b) altitude of peak 532 nm cloud scattering ratio; and c) latitude of calibration cloud profiles for CALIPSO simulation of LITE orbit 23.

Table 1. C_{1064} using CALIPSO Simulated Data

LITE Orbit #	No Outlier Rejection	Outlier Rejection
Orbit 23	2.47E20 ± 1.19E19 (87 profiles)	2.49E20 (66 profiles)
Orbit 24	2.36E20 ± 1.24E19 (38 profiles)	2.39E20 (34 profiles)
Orbit 27	2.48E20 ± 9.97E18 (160 profiles)	2.50E20 (115 profiles)

Truth ~2.49E20

4. ERROR ANALYSIS

The 1064 nm calibration constant can be expressed as:

$$C_{1064} = \frac{X_{1064}}{\beta_{532} T_{532}^2} \times \frac{T_{ct,532}^2}{T_{ct,1064}^2} \times \chi' ,$$

where

$$\chi' = \frac{\beta_{532}}{\beta_{1064}} \times \frac{T_{z<ct,532}^2}{T_{z<ct,1064}^2}.$$

If the relative uncertainty of $\beta_{532} T_{532}^2$ is approximated by the root sum square of the uncertainties of C_{532} and X_{532}, the relative uncertainty of C_{1064} can be expressed as:

$$\left[\frac{\delta C_{1064}}{C_{1064}}\right]^2 = \left[\frac{\delta X_{1064}}{X_{1064}}\right]^2 + \left[\frac{\delta X_{532}}{X_{532}}\right]^2 + \left[\frac{\delta T_{ct,532}^2}{T_{ct,532}^2}\right]^2 + \left[\frac{\delta T_{ct,1064}^2}{T_{ct,1064}^2}\right]^2 + \left[\frac{\delta C_{532}}{C_{532}}\right]^2 + \left[\frac{\delta \chi'}{\chi'}\right]^2$$

The last term represents the uncertainty in the attenuated backscatter color ratio that was approximated as 1. For an average scattering ratio of 50 at 11 km (nighttime) with vertical resolution of 180 meters and horizontal resolution of 5 km, uncertainties are estimated as shown in Table 2.

Table 2. C_{1064} Calibration Uncertainty

$\frac{\delta C_{1064}}{C_{1064}}$	$\frac{\delta X_{1064}}{X_{1064}}$	$\frac{\delta X_{532}}{X_{532}}$	$\frac{\delta T_{ct,532}^2}{T_{ct,532}^2}$	$\frac{\delta T_{ct,1064}^2}{T_{ct,1064}^2}$	$\frac{\delta C_{532}}{C_{532}}$	$\frac{\delta \chi'}{\chi'}$
.095	.05	.05	.02	.002	.044	.04

5. CONCLUSION

An easily-implemented calibration algorithm for spaceborne applications at 1064 nm has been described. Results using realistic CALIPSO simulated data are excellent, with expected calibration uncertainties less than 10%.

REFERENCES

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