VALIDATION OF CALIPSO LIDAR (CALIOP) CALIBRATION

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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. To retrieve optical properties of clouds and aerosols, the two polarization channels at 532 nm and 1064 nm channel must all be calibrated. This paper describes methods for validating the CALIOP calibrations.

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) [1] mission builds on the experience of LITE, which flew a three-wavelength lidar on the Space Shuttle in 1994 [2]. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is the key instrument onboard the CALIPSO payload. CALIOP is a two-wavelength (532 nm and 1064 nm), polarization-sensitive (532 nm) lidar that will provide 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. The CALIOP calibration requirements include the measurement of the gain ratio between the two polarization channels at 532 nm [3], and the determination of the lidar calibration coefficients at 532 nm and at 1064 nm. The gain ratio of the two polarization channels is determined onboard by inserting a pseudo-polarizer into the receiver's 532 nm optical path. The 532 nm parallel channel is calibrated by comparing the measured signal to the predicted backscatter from some high altitude region (>30 km) in the atmosphere where an accurate and independent estimate of the backscatter coefficient is available [4]. Calibration of the 1064 nm channel is transferred from the 532 nm signal by comparing the 532 nm and 1064 nm backscatter signals from properly selected cirrus clouds [4]. A series of validation activities using ground-based and airborne lidars and passive instruments are planned for the CALIOP measurement. In this presentation we discuss techniques for validating space lidar calibrations.

2. CALIBRATION and VALIDATION

2.1 532 nm Polarization Gain Ratio

Two of the fundamental parameters derived from the CALIPSO measurements are the total backscatter coefficients at 532 nm, and the corresponding depolarization ratios. Calculation of these quantities from the separate parallel and perpendicular channel measurements requires accurate knowledge of the gain ratio between the two 532 nm channels, which in turn is derived during CALIOP's Polarization Gain Ratio (PGR) operation. This procedure inserts a spatial pseudo-depolarizer into the 532 nm optical path in the receiver, upstream of the polarization beam splitter (Fig.1). Insertion of this device produces a randomly polarized backscatter signal, so that equal optical power is directed into the detectors for the two channels. The polarization gain ratio can therefore be easily determined from the ratio of the 532 nm backscatter signals acquired during the PGR operation. To improve the signal-to-noise ratio (SNR), the acquired data is averaged horizontally over the entire PGR acquisition segment (~ 2100 km), and vertically from 18 to 25 km. With this amount of averaging, the relative random error due to noise can be reduced to below 1%. The altitude range selected ensures that strong cloud signals will be excluded, and thus will avoid errors due to differences in the transient response of the two channels. This vertical average range is programmable, and can be adjusted if required.

Recently, a new validation method for the calibration of space and airborne lidar depolarization measurements has been demonstrated using airborne lidar measurements [5]. This method determines the PGR using solar radiation signals scattered from dense ice clouds. Sunlight scattered by ice clouds can be assumed to be unpolarized for two reasons. One is that the multiple scattering of sunlight within an irregularly shaped ice particle will largely reduce the preferential polarization orientation of scattered sunlight. This polarization effect is significant for spherical particles. The second reason is the multiple scattering among an ensemble of ice particles, which will further depolarize the sunlight. The latter is thought to play a more important role in dense clouds.

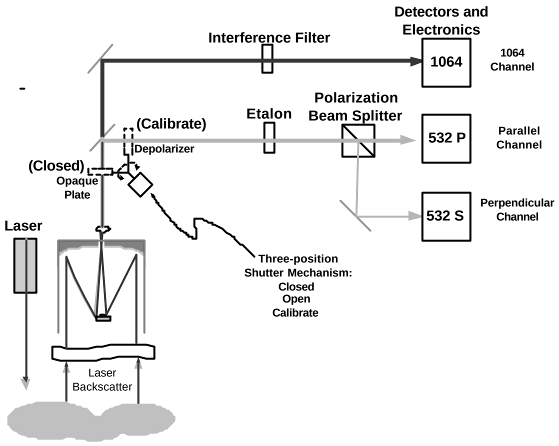

Fig. 1 Diagram of the CALIOP system.

Fig.2 presents an example of ice cloud measurements made by the Cloud Physics Lidar (CPL) [6]. CPL is a three wavelength, polarization-sensitive airborne lidar that provides down-looking measurements of the atmosphere from an altitude of ~20 km. The upper panel shows a time history of 532 nm attenuated backscatter profiles. For much of the flight, a totally attenuating cirrus cloud is observed between 10 and 14 km. The aircraft made four passes over this cirrus layer. The depolarization measurements, shown in the second panel of Fig. 2, indicate that the cloud consists mostly, or perhaps entirely, of ice crystals. The third panel of Fig. 2 shows the ratio of perpendicular to parallel components of the solar background signal at 1064 nm. These data shown in the third and bottom panels are derived by averaging the subsurface measurements (100 samples) for each profile, for which there is no laser backscattering signal. The ratio of these signals remains essentially constant throughout the entire extent of the cirrus layer, except at the edges. The mean value of this ratio of background signals is consistent with the PGR value (solid line in the third panel) determined for this flight via the CPL's half-wave plate calibration technique [6], which is similar in some respects to CALIOP's onboard PGR procedure. Deviations are seen at the edges of the cirrus cloud where the cloud layer is transmissive and the polarization is affected by the lower water clouds and/or ocean surface. This is phenomena is expected, since the scattering of solar radiation from both water clouds and the ocean surface results in significant polarization, and the measured ratios depend on the solar elevation angle as predicted by theory [6].

By applying the technique described in [6], we can use CALIOP measurements of scattered solar background signal from ice clouds to validate the on-board depolarization calibration. Two different approaches are viable. Approach 1 is a linear-fit method. Fig. 3(a) presents scatterplots of perpendicular versus parallel components for all solar background signals derived from the data shown in Fig.2. Fig. 3(b) is similar, but shows data from cirrus only. The background signal is identified as being scattered from an ice cloud by evaluating the depolarization ratio of any feature found in the corresponding lidar profile. If the layer-integrated depolarization ratio of the feature is larger than some predetermined threshold (e.g., 20%), then the feature is classified as an ice cloud and the background signal is consequently identified as being scattered from ice cloud. When a linear fit is applied to the accumulated parallel and perpendicular channel data points, the slope of the fitted line yields the PGR for the two channels. A large spread of data points is seen in Fig. 3(a), while a substantially better correlation is seen when fitting the ice-cloud-only data points shown in Fig. 3(b). The PGR value determined by the ice-cloud-only fitting (1.41) is very close to the value determined by the half wave-plate method (1.44).

An alternative validation approach is to select a high, dense cirrus anvil similar to the one shown in Fig. 2. The ratio of perpendicular to parallel components of the solar background signal is plotted in the third panel. The PGR can then be derived from the mean value of the flattest part of the curve. The flatness of the curve can be used as a metric to select an appropriate ice cloud for analysis.

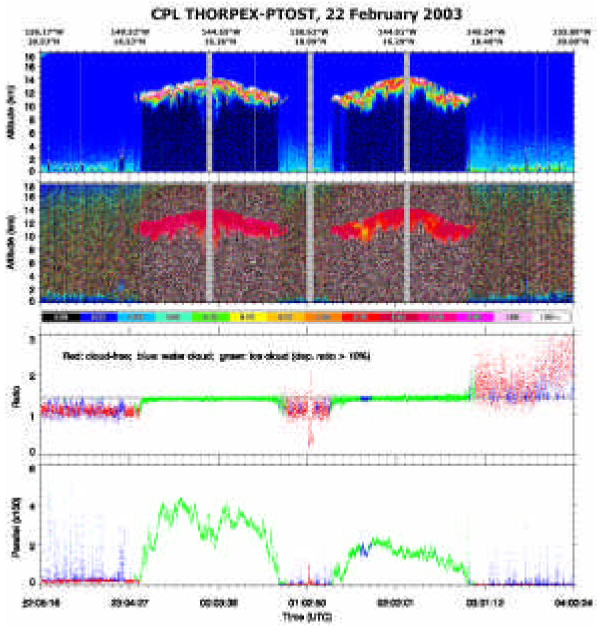

Fig.2 Attenuated backscatter at 532 nm (upper panel), depolarization ratio at 1064 nm along with color bar (second panel from top), perpendicular-to-parallel component ratio (third panel from top), and parallel component (lower panel) of background signal (mostly scattered solar radiation), observed on 22 February 2003 by CPL over the Pacific Ocean.

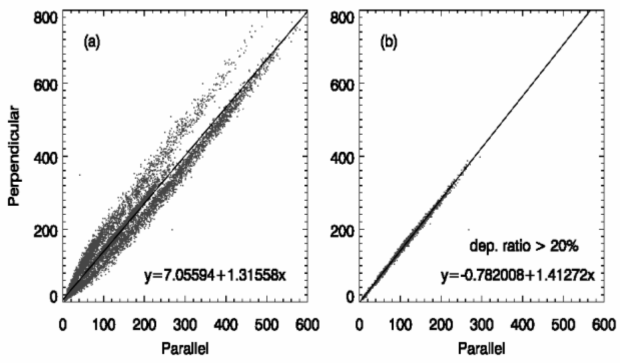

Fig.3 Scatterplots of background signals of perpendicular versus parallel components for (a) all cases and (b) for the ice-cloud only cases with linearly fitted line, for the flight of 19 February 2003.

Results suggest that the ice-cloud calibration techniques can be used as a diagnostic method to check the stability of the CALIPSO gain ratio calibration. The onboard pseudo-polarizer method will be applied only periodically and it requires the insertion of additional on-board optics, whereas the ice-cloud techniques can be applied anytime during daytime observations. It was originally anticipated that the PGR operation would be conducted once per week. However, as the ice-cloud technique can be applied routinely, the frequency of the PGR operation may be significantly reduced.

2.2 532 nm and 1064 nm Signal

The 532 nm parallel channel is calibrated by comparing the magnitude of the measured signal to the predicted backscatter from a region in the atmosphere for which an accurate independent estimate of the backscatter coefficient is available [4]. The altitude range extending from 30-km to 34-km will be initially used to calculate the CALIOP 532 nm parallel channel calibration coefficient. Two factors were considered in selecting this range: choosing a lower region leads to increased uncertainties due to additional aerosol backscatter; choosing a higher region leads to increased uncertainties in the resulting calibration coefficient due to the decreasing molecular backscatter, resulting in lower SNR. The selection of the calibration altitude range was optimized by balancing these two factors. After determining the PGR, the calibration of the 532 nm perpendicular channel is easily transferred from the 532 nm parallel channel.

Because the molecular backscatter in high altitudes is too weak, the normalization technique used to calibrate the 532 nm channel cannot be used for the 1064 nm channel. Instead, the calibration at 532 nm will be transferred to the 1064 nm channel via comparison of the returns from properly selected cirrus clouds, where the spectral dependence of backscatter at the two wavelengths is expected to be fairly stable [4]. Cirrus clouds are good targets for this purpose because they occur with sufficient frequency and provide strong and nearly spectrally flat backscatter and extinction. Another consideration favorable to the use of cirrus clouds for calibration transfer is that, because cirrus clouds occur at high altitudes, corrections for the spectral transmission differences between satellite and the cloud top are relatively small and fairly predictable for the two wavelengths. In fact, given the very low aerosol loadings currently typical of the stratosphere and upper troposphere, spectral transmission differences due to non-molecular constituents can likely be neglected entirely for the CALIOP wavelengths. Tests using the LITE data showed that the calibration coefficient is relatively stable with cloud intensity [4].

O'Conner et al. [7] have proposed a calibration technique using optically thick water clouds. This technique is derived from the relation [7], [8]

$$C = 2\eta S_c \sum_{j=j_{top}}^{j_{base}} X(r_j)\,, \tag{1}$$

where C is the lidar calibration coefficient, η is the multiple scattering factor, S_c is the lidar ratio of water clouds, r is the range from the lidar, and X is the background-subtracted, range-corrected lidar signal. j_{top} indicates the top of cloud and j_{base} denote the apparent cloud base (i.e., that point at which the lidar signal is attenuated to the noise level). S_c is quite certain (~ 19 sr) at visible and near infrared region for different type water clouds. Theoretical computations indicate that the variation of S_c is ~2% at 532 nm and ~4% at 1064 nm for 92 different distributions of the water cloud, and even smaller for water clouds over ocean [9]. η usually ranges from 1 to 0.5 and, for water clouds, usually varies along the laser path. The multiple scattering factor can introduce an uncertainty of ~10% for ground-based lidar [7] and even larger for space-borne lidars into this calibration scheme, and thus to achieve an accurate calibration, η must also be determined accurately. Recently a simple relation between multiple scattering and depolarization ratio has been found via a Monte-Carlo simulation [9]:

$$A_S = 0.999 - 3.906\ \delta_{acc} + 6.263\ \delta_{acc}^{2} - 3.554\ \delta_{acc}^{3}\,. \tag{2}$$

Here

$$A_S(r) = \int_{r_0}^{r} X_S(r')\,dr' \Big/ \int_{r_0}^{r} X_T(r')\,dr' \tag{3}$$

is the accumulated single scattering fraction,

$$\delta_{acc}(r) = \int_{r_0}^{r} X_{T,\perp}(r')\,dr' \Big/ \int_{r_0}^{r} X_{T,||}(r')\,dr' \tag{4}$$

is the accumulated depolarization ratio, subscripts S, T, $\perp$ and $||$ denote single and total scattering, perpendicular and parallel components. Hundreds of measurement scenarios have been modeled in deriving Eq. (2). These scenarios include a diverse set of cloud physical and optical properties, combined with a number of different lidar field-of-views (FOVs). The relation is particularly suitable for space lidars where laser footprint is large; the departure of all the simulated space lidar cases from the fitted curve (i.e., Eq. (2)) is smaller than 2%. If the depolarization ratio measurement is available, the multiple scattering contained in the measured lidar signal in water clouds can then be corrected easily using Eq. (2).

We note that, to derive Eq. (1) by solving the lidar equation, both η and S_c (or their product) have been assumed invariant along the path. This is quite true for S_c in the water clouds as described earlier. However, this is not quite true for η. The technique can be modified easily by correcting the measured signal for multiple scattering. The modified formula is given by

$$C = 2S_c \sum_{j=j_{top}}^{j_{base}} X_S(r_j) = 2S_c A_s(j_{base}) \sum_{j=j_{top}}^{j_{base}} X(r_j) \qquad (5)$$

The best calibration will be obtained from water clouds over ocean surfaces, because the lidar ratios for these clouds have a smaller uncertainty [8]. For properly selected water clouds, a calibration accuracy using this technique could be on an order of several percent (~3% at 532 nm and ~5% at 1064 nm).

We note that C determined using Eq. (5) is the lidar calibration coefficient at the cloud top. Most water clouds occur in the lower atmosphere, from the planetary boundary layer to several kilometers. The calibration coefficient determined by the CALIOP data processing algorithm is calculated in the upper atmosphere (~ 30 km). For accurate comparisons, the lidar calibration coefficient determined using Eq. (5) must be converted to C(30 km), using $C(30\text{ km})=CT^2$, where T^2 is the atmospheric transmittance between 30 km and the cloud top. This conversion can also introduce errors, depending on the accuracy of T^2. The transmittance due to molecular scattering can be estimated well (<1% at 532 nm and negligibly small at 1064 nm). However, the estimate accuracy of the transmittance due to aerosol depends on how well we know the aerosol lidar ratio. To reduce this error, clear air conditions should be chosen, with little aerosol loading above the target cloud.

3. SUMMARY

Calibration is a critical issue in the retrieval of cloud and aerosol properties from CALIOP measurements. This paper outlined briefly the calibration procedures of CALIOP measurements, and presented several validation techniques. The required CALIOP calibrations include polarization gain ratio determination and two-wavelength lidar signal normalization. It has been demonstrated that a technique using solar background signal scattered from ice clouds can be used to validate the PGR measurement using the pseudo-polarizer during the PGR operation. The ice-cloud technique can also be used as a routine procedure to monitor the stability of the PGR.

Because the lidar ratio of water clouds is quite certain (~19 sr), optically thick water clouds can be used to determine the lidar calibration coefficient at both 532 nm and 1064 nm. The 532 nm and 1064 nm channel calibrations accomplished by the CALIOP routine data processing can thus be validated using this water cloud technique. The use of a recently derived relation between multiple scattering and depolarization makes possible an accurate correction for multiple scattering, thereby potentially reducing the calibration error due to the multiple scattering to under 2%. The variation in lidar ratio and error in determining transmittance between the CALIOP baseline calibration range (~30 km) and the top of water clouds can also contribute several percent to the overall uncertainty.

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