CALIPSO Lidar Description and Performance Assessment

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ABSTRACT

This paper provides background material for a collection of Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) algorithm papers that are to be published in the Journal of Atmospheric and Oceanic Technology. It provides a brief description of the design and performance of CALIOP, a three-channel elastic backscatter lidar on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. After more than 2 yr of on-orbit operation, CALIOP performance continues to be excellent in the key areas of laser energy, signal-to-noise ratio, polarization sensitivity, and overall long-term stability, and the instrument continues to produce high-quality data products. There are, however, some areas where performance has been less than ideal. These include short-term changes in the calibration coefficients at both wavelengths as the satellite passes between dark and sunlight, some radiation-induced effects on both the detectors and the laser when passing through the South Atlantic Anomaly, and slow transient recovery on the 532-nm channels. Although these issues require some special treatment in data analysis, they do not seriously detract from the overall quality of the level 2 data products.

1. Introduction

This paper describes the design and performance of the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), a three-channel elastic backscatter lidar that is the prime payload instrument on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. It provides background material for a collection of CALIOP algorithm papers that are to be published in the Journal of Atmospheric and Oceanic Technology (Winker et al. 2009).

CALIPSO was launched on 28 April 2006 for a scheduled 3-yr mission probing the vertical structure and properties of clouds and aerosols, with the objective of obtaining a better understanding of how clouds and aerosols form, evolve, and affect weather and climate (Winker et al. 2007). The satellite orbits in close formation with Aqua, CloudSat, Parasol, and Aura as part of the Afternoon Constellation (A-Train) of earth-observing satellites (Stephens et al. 2002), in a sun-synchronous orbit at 705-km altitude with an ascending node equator crossing time of 1330 local solar time (LST). The orbit inclination of 98° provides coverage between 82°N and 82°S, with orbit tracks that repeat every 16 days. CALIPSO is the product of collaboration between the National Aeronautics and Space Administration (NASA) and the

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French space agency Centre National d’Etudes Spatiales (CNES). Ball Aerospace and Technologies Corporation (BATC) was the prime NASA contractor for the payload, and the PROTEUS spacecraft was built by Alcatel under contract to CNES. The payload combines an active lidar instrument (CALIOP) with passive infrared and visible imagers (Winker et al. 2003). CALIOP is the third lidar launched by NASA to study the earth’s atmosphere from space, having been preceded by the Lidar In-Space Technology Experiment (LITE), launched in September 1994 on STS-64 (Winker et al. 1996), and the Geoscience Laser Altimeter System (GLAS), launched in December 2002 on the Ice, Cloud and Land Elevation Satellite (ICESAT) (Spinhirne et al. 2005). CALIOP has already provided far more high-quality global atmospheric data than the two earlier missions, and it continues to add to that dataset.

2. CALIOP description

a. Transmitter subsystem

The lidar consists of a transmitter subsystem that sends a laser pulse down through the atmosphere, a receiver subsystem that collects and measures the light that is backscattered from the laser pulse, a payload computer that controls the subsystems and does some onboard processing of the signals from the receiver, and the data downlink systems (Fig. 1).

The transmitter subsystem includes two lasers, each with a beam expander, and a beam steering mechanism. The Q-switched diode-pumped Nd:YAG lasers, built by Fibertek under contract to BATC, operate one at a time, and each is designed to operate for the full mission lifetime. Only the primary laser has been fired since launch, with the second laser available as a backup.

The lasers are frequency-doubled to produce simultaneous pulses at 1064 and 532 nm. A beam expander on each laser reduces the angular divergence of the output beam, allowing a small receiver field of view (FOV) to be used for better solar background rejection. Each laser is housed in its own sealed canister filled with dry air at standard atmospheric pressure. Energy monitors located within each canister measure the output pulse energy of each shot at each wavelength, and the energy values are downlinked with both the science data and the Health and Status (H&S) data. The two lasers are mounted on a common beam steering system that can adjust their pointing direction for optimizing the boresight alignment between the transmitter and receiver (Seckar 2005). Key laser specifications are given in Table 1.

b. Receiver subsystem

The receiver subsystem consists of a 1-m-diameter all-beryllium telescope, relay optics, detectors, and electronics mounted on a carbon composite optical bench.
A field stop at the telescope focus limits the lidar FOV to an angle close to the laser divergence. The telescope entrance pupil is imaged onto the detectors, thereby eliminating hot spots as a function of viewing angle. A dichroic beam splitter separates the two wavelengths, and a polarization beam splitter separates the 532-nm beam into components parallel to and perpendicular to the laser polarization. Solar background rejection is provided by a narrowband etalon in combination with a dielectric interference filter in the 532-nm channels and an interference filter alone in the 1064-nm channel. A pseudodepolarizer can be moved into the 532-nm beam on command for measurement of the relative sensitivities of the two polarization channels.

After separation, each beam component goes to its own detector. For the 532-nm channel detectors, photomultiplier tubes (PMTs) were chosen because their low dark noise more than compensates for their relatively modest quantum efficiencies. For the 1064-nm channel, an avalanche photodiode (APD) was chosen because its much higher quantum efficiency at that wavelength more than compensates for its higher dark noise.

The outputs of the three detectors go through trans-impedance amplifiers (TIAs), which convert the detector output currents to voltages. To achieve the more than six orders of magnitude dynamic range required by CALIOP, each TIA output is split and sent in parallel to two amplifiers with different gains, each of which is followed by a 14-bit digitizer (designated the high-gain digitizer and the low-gain digitizer for simplicity). The two digitizer outputs are later merged during onboard processing, resulting in an effective dynamic range of more than 21 bits.

The receiver also includes a built-in test system (BITS) that can be activated on command to test the performance of the detectors and electronics by illuminating the detectors with known optical profiles from LEDs. Key receiver specifications are given in Table 2.

c. Lidar pointing direction

The choice of the lidar pointing direction involves balancing several factors. Pointing exactly toward nadir is to be avoided because smooth water surfaces such as small ponds would reflect the lidar beam directly back into the receiver and drive the detector system into heavy saturation, an undesirable situation. A pointing direction very close to nadir facilitates the identification of cirrus clouds with horizontally oriented ice crystals (HOICs) (Platt 1978). In this case the backscatter is dominated by specular reflections from the ice crystals, making identification of HOICs easy but making the measurement of cloud optical properties such as depolarization and optical depth difficult, if not impossible. If the lidar pointing direction is several degrees off nadir, then the specular reflections are avoided and cloud optical properties can be measured. A small off-nadir angle of 0.3° was chosen at the beginning of the mission, allowing statistics on HOIC clouds to be obtained. After acquiring more than a year of cloud statistics at 0.3°, in November 2007 the pointing direction was increased to 3.0° off nadir, where it has remained since that date. The larger angle avoids most specular reflections from HOICs, thus allowing the physical and optical properties of the clouds to be determined more accurately (Hu 2007). The pointing angle offset from nadir was along track in the forward direction in both cases.

d. Data types and downlink paths

Before discussing onboard data processing, it is helpful to understand the two primary data categories and their downlink paths and downlink frequencies. Health and Status data include a large number of engineering parameters along with many parameters derived from the science profile data. H&S data are downlinked several times a day via S band and sent to the CALIPSO Mission Operations and Control Center (MOCC) in Hampton, Virginia, where their relatively small latency (less than

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**Table 1. CALIOP transmitter specifications.**

<table>
<thead>
<tr>
<th>Wavelengths</th>
<th>532 and 1064 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse energy at each wavelength (nominal)</td>
<td>110 mJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>20.16 Hz</td>
</tr>
<tr>
<td>Ground spot spacing</td>
<td>335 m</td>
</tr>
<tr>
<td>Polarization purity at 532 nm</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Beam divergence at each wavelength (nominal)</td>
<td>110 μrad</td>
</tr>
<tr>
<td>Line width at 532 nm</td>
<td>28 pm</td>
</tr>
</tbody>
</table>

**Table 2. CALIOP receiver specifications.**

<table>
<thead>
<tr>
<th>Telescope diameter</th>
<th>1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>130 μrad</td>
</tr>
<tr>
<td>Optical filter bandwidth (532 nm)</td>
<td>35 pm</td>
</tr>
<tr>
<td>Optical filter bandwidth (1064 nm)</td>
<td>400 pm</td>
</tr>
<tr>
<td>Detector effective quantum efficiency (532 nm)</td>
<td>0.11</td>
</tr>
<tr>
<td>Detector effective quantum efficiency (1064 nm)</td>
<td>0.40</td>
</tr>
<tr>
<td>Detector dark count rate (532 nm)</td>
<td>$2.3 \times 10^3$</td>
</tr>
<tr>
<td>Detector dark count rate—beginning of mission (1064 nm)</td>
<td>$2.0 \times 10^7$</td>
</tr>
<tr>
<td>Digitizer sample rate</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Vertical sample spacing</td>
<td>15 m</td>
</tr>
<tr>
<td>Electronic bandwidth</td>
<td>2.0 MHz</td>
</tr>
<tr>
<td>Vertical resolution as determined by bandwidth</td>
<td>30 m</td>
</tr>
<tr>
<td>Digitizer resolution</td>
<td>14 bits</td>
</tr>
<tr>
<td>Maximum dynamic range (merged)</td>
<td>$2.5 \times 10^6$ (&gt;21 bits)</td>
</tr>
</tbody>
</table>
12 h) allows timely evaluation of the payload health and status and the instrument performance. Science data consist of backscatter profiles and ancillary data for all channels for every shot, along with a second copy of the H&S data. They are downlinked daily via an X-band transmitter on the payload and sent to the Atmospheric Sciences Data Center (ASDC) at NASA Langley Research Center in Hampton, Virginia, where they are used for level 1 and level 2 science processing. Because of the large quantity and longer latency (up to 36 h) of the science data, it is useful to extract any science data information needed for instrument performance evaluation and insert it into the H&S data, as will be discussed below.

e. Onboard processing

Onboard computations of position, altitude, and sun elevation allow automatic reconfiguration and timing control. When combined with onboard processing of science data, a large reduction in the downlink data rate is achieved, allowing a full day’s science data to be downlinked in a single X-band contact. Onboard processing also includes extraction of selected science information for insertion into the H&S data, aiding in the timely monitoring of the health and performance of the instrument. The following paragraphs provide more details about onboard processing features.

1) RECONFIGURATION FOR NIGHT OR DAY

The optimum receiver gains and offsets are different for night and day because of the vastly different background noise levels. CALIOP changes these parameters autonomously based upon the value of the sun–earth–satellite (SES) angle, which is computed once per second using data from the platform global positioning system (GPS) receiver. Whenever the SES angle is between 95° and 165° (equivalent to a solar elevation angle of less than −2.5°), the lidar is automatically configured for night; otherwise, it is configured for day.

2) TIMING CONTROL AND GEOLOCATION CALCULATIONS

Before each shot, the footprint location and range to mean sea level (MSL) for the next shot are computed from an on-orbit geoid model, utilizing position and altitude data from the platform GPS receiver and attitude data from the platform star tracker. From these values, the range to target altitude and the time to target altitude are computed (Fig. 2) and the data acquisition timing is set accordingly. Autonomous timing adjustment not only avoids the collection of unneeded data, but it also facilitates the altitude-dependent signal averaging discussed later.

3) DATA ACQUISITION REGIONS

The data acquisition timing sequence begins at the target altitude and proceeds through the four regions shown in boxes in Fig. 2. The operations associated with each region are described below.

(i) Electronic background measurement region (112 to 97 km)

To avoid the large variations in the digitizer level as the solar background varies during the daytime, each channel’s mean background signal is electronically subtracted. The background signals are averaged over the 97–112-km-altitude region, where the backscatter signal is negligible, and the measured background values are subtracted electronically from the detector output signals and also reported in the H&S data. After the mean background signals are removed, they are replaced with fixed dc offsets to ensure that the signal levels at the digitizers are always positive, even in the presence of negative-going noise variations.

(ii) Offset measurement region (80 to 65 km)

After the signals are digitized, the dc offsets that were added before digitization must be subtracted from the digital data before further processing, leaving only the backscatter signals. Because the a priori knowledge of the offsets is insufficient for this purpose, they must be measured. This is done by averaging the digitized signals between 65 and 80 km, where the backscatter is negligible. The measured offsets for all six digitizers are subtracted from their respective digitized signals, and the values are reported in the H&S data, where they are used for diagnostic purposes.

The standard deviation (RMS noise) is computed for all channels for every shot over this same region. Because there is negligible backscatter at this altitude, this measurement gives the sum of the detector dark noise and the noise due to solar background light. The averaged values are downlinked in the H&S data, where they are used for diagnostic purposes, and the single-shot values are downlinked in the science data, where they are used for setting thresholds in the automated layer detection algorithm during level 1 processing.

After the mean offset and the RMS noise values are computed, the individual samples from this region are discarded.

(iii) Backscatter measurement region (40 to −2 km)

Before downlink, the backscatter data from the low- and high-gain digitizers for each channel are combined into a single merged profile. In simplified form, each
sample from the high-gain digitizer is examined to see if it is saturated (full scale). All saturated samples, along with their nearest neighbors, are replaced with rescaled values from the low-gain digitizer. The neighbors are included to allow for phase differences between the two digitizers and for transient effects after the saturated sample. The rescaling factors are computed for each 15-shot frame, and those factors are reported in the H&S data. Any remaining offset after merging is also subtracted during this process.

The profile data rate is further reduced by altitude-dependent averaging, both vertically and horizontally. The least amount of averaging is done at low altitudes, where the natural spatial variability is the greatest, and the greatest amount is done at high altitudes where the atmosphere is more homogeneous. Table 3 shows the amount of horizontal and vertical averaging done on board in each of five backscatter altitude ranges. Table 4 gives the spatial resolutions of the downlinked science data after onboard averaging.

The onboard averaging, along with the merging of data from the high- and low-gain digitizers, reduces the backscatter data rate by a factor of 17.2 relative to the raw data. In addition to the averaging that is done on the science profile data, much more heavily averaged values are extracted from the science data and inserted into the H&S data to aid in performance evaluations in the MOCC. For the H&S data, the profile data from each of the five altitude ranges in Table 3 are averaged vertically over the entire region and horizontally over 120 shots.

### Table 3. Onboard averaging of CALIOP data. No 1064-nm channel data are downlinked from the highest altitude region.

<table>
<thead>
<tr>
<th>Altitude region (km)</th>
<th>Shots averaged</th>
<th>Digitizer samples averaged 532-nm channel</th>
<th>Digitizer samples averaged 1064-nm channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1 to 40.0</td>
<td>15</td>
<td>20</td>
<td>N/A</td>
</tr>
<tr>
<td>20.2 to 30.1</td>
<td>5</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>8.2 to 20.2</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0.5 to 8.2</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>−2 to −0.5</td>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
(iv) Lower offset measurement region
(−11 to −18.5 km)

Mean values from the lower offset region are measured and reported in the H&S data but are not otherwise used.

4) EXTRACTION OF OTHER INFORMATION FOR THE HEALTH AND STATUS DATA

Several other quantities, such as overflow and underflow counts, are computed from the raw low- and high-gain digitizer data and inserted into the H&S data, thus preserving information that would otherwise be lost after onboard processing.

3. CALIOP performance

a. Performance trends

Overall, the performance of CALIOP has met or exceeded nearly all requirements and expectations and has shown little degradation over nearly 2 yr of operation, as will be illustrated in the following sections. The amount of adjustment that has been required to maintain the performance has been minimal, consisting mostly of boresight alignments.

1) LASER PERFORMANCE

(i) Laser energy

Based on energy measurements on every shot at both wavelengths by internal energy monitors, the primary laser has maintained its performance extremely well, continuing to produce more than 94% of its initial energy at both wavelengths (Fig. 3) after almost 2 yr of near-continuous operation (more than 1.1 billion shots on orbit). Although the laser energy can be adjusted by ground command, no adjustments of any kind have been needed to maintain this high level of performance. The backup laser has not yet been fired on orbit.

The CALIOP laser has performed much better than the lasers on some previous spaceborne lidar missions. Winker et al. (1996) describes some problems experienced by the LITE laser, and Afzal (2006) and Afzal et al. (2007) describe the GLAS laser experience. Several factors have contributed to the superior performance of the CALIOP laser (Hovis 2006). Among them are very stringent contamination control, operation at derated energy levels, and careful attention to lessons learned from previous lasers, including a risk-reduction laser similar to the flight design that was operated for more than two billion shots prior to the CALIPSO launch.

(ii) Laser canister pressure

CALIOP has been experiencing a slow loss of pressure in the primary laser canister and will have to switch to the backup laser in early 2009. Between June 2006 and May 2008, the absolute pressure in the primary laser canister dropped from 16 psi to just over 6 psi. The backup laser pressure has remained above 17 psi over the same period (Fig. 4). The loss of pressure has no effect on the laser performance, but it will present a danger of a corona discharge within the canister, and possibly associated damage to the electronics, if the

<table>
<thead>
<tr>
<th>Altitude region (km)</th>
<th>Horizontal resolution (km)</th>
<th>Vertical resolution (m) 532-nm channel</th>
<th>Vertical resolution (m) 1064-nm channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1 to 40.0</td>
<td>5.025</td>
<td>300</td>
<td>N/A</td>
</tr>
<tr>
<td>20.2 to 30.1</td>
<td>1.675</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>8.2 to 20.2</td>
<td>1.005</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>−0.5 to 8.2</td>
<td>0.335</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>−2 to −0.5</td>
<td>0.335</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

FIG. 3. Time history of the energy of the primary laser at both wavelengths, as measured by the internal energy monitors. The loss of energy since the beginning of the mission has been less than 6%, and most of that occurred in several downward steps that are believed to be due to failures of individual diode bars. The diode bar failure rate and the overall energy degradation rate are similar to what was observed during testing of a risk reduction laser prior to the mission.
pressure is allowed to drop too low. A switch to the backup laser is planned for late February 2009, when the primary laser pressure is expected to be about a factor of 2 above the corona threshold of 1.9 psi.

(iii) Low-energy laser shots

Although the peak-to-peak energy variation between shots over a short time is typically less than 1.5%, there are very occasional shots with much lower energy. As of 1 June 2008, about 0.006% of the total shots (100 per day out of 1.74 million) had energies less than 45% of the mean, and that percentage continues to rise. The very low-energy shots occur most frequently in the South Atlantic Anomaly (SAA), a high-radiation region. This implies a probable radiation connection, but changes in the frequency of occurrence of the low-energy shots do not appear to be correlated with any changes in the radiation activity within the SAA. The source of this behavior is the subject of an ongoing study, but neither the mechanism nor the trend is understood at this time. The low-energy shots currently do not occur frequently enough to noticeably impact the science data quality.

2) SIGNAL-TO-NOISE RATIO

The accuracy with which a lidar can measure backscatter signals depends on its signal-to-noise ratio (SNR). The SNR of CALIOP is much lower than that from typical ground-based, airborne, or shuttle-based lidars because of the large distance between the lidar and its targets and the modest power aperture product that is dictated by weight and electrical power limitations. Although the SNR can be improved by more vertical and horizontal averaging, the amount of averaging that is acceptable is limited by the spatial scale of the target. Early in the CALIOP design phase, day and night SNR requirements were established that took into account the required accuracy and the allowable amount of averaging for a number of targets and lighting conditions. Simulations done at various stages of the instrument development, as well as SNR measurements using on-orbit data, have verified that the instrument exceeds all SNR requirements.

(i) SNR: 532-nm parallel channel at night

The SNR value that has received the closest scrutiny is that for the 532-nm parallel channel molecular backscatter from 30 km. This measurement is crucial because it is the basis for the calibration of all channels, day and night. It also is the easiest SNR to verify because the signal is free of solar background and aerosol or cloud contamination issues. The requirement is that this SNR be at least 50 for the specified molecular backscatter coefficient when averaged over 5 km vertically and 1500 km horizontally, averaging distances similar to those used for the nighttime calibration of the 532-nm parallel channel. To avoid undue influence from changes in the backscatter coefficient with latitude, the SNR was determined by measuring the mean and standard deviation of the backscatter sample closest to 30 km over a number of 1500-shot segments and then averaging those values to give the SNR at the downlink resolution. The measured SNR was then extrapolated to the specified backscatter coefficient value and averaging distances for comparison with the requirement, assuming that the SNR scales as the square root of both the signal level and the number of shots.

The initial on-orbit measurement in June 2006 gave SNR = 82.6, more than 60% above the requirement (Fig. 5). The latest measured value is only 4% below the initial value.

(ii) SNR: 532-nm perpendicular channel at night

The SNR requirement for the 532-nm perpendicular channel is the same as for the 532-nm parallel channel when measuring the same signal level. Calculations using data from several polarization calibrations, where the two channels are exposed to the same optical signal levels, give nearly the same SNR for both channels, thus verifying that the perpendicular channel meets its requirement.
(iii) SNR: 1064-nm channel at night

Although there is no nighttime SNR requirement for the 1064-nm channel, it is interesting to examine how that SNR is affected by the increasing APD dark noise. Sun et al. (1997) have shown that APDs in a space environment experience an increase in bulk dark current that is proportional to the cumulative radiation exposure, resulting in a gradual increase in dark noise. Measurements of the CALIOP 1064-nm channel dark noise confirm an increase that is consistent with a linear increase in the bulk dark current (Fig. 6).

The effect of the increased dark noise on the 1064-nm channel nighttime SNR is shown in Fig. 7. The target in this case is a moderate boundary layer aerosol with backscatter coefficient $b(z) = 5 \times 10^{-3}$ km$^{-1}$ sr$^{-1}$, averaged over 1 km vertically and 25 km horizontally. The most recent nighttime SNR for the specified target is about 65% of the initial value.

(iv) SNR: Daytime

Even though extensive efforts have been made to keep the solar background light as low as is reasonable during daylight, the daylight SNR is nevertheless significantly lower than the SNR at night. The noise varies with the scene being viewed and is highest over bright clouds or snow and ice. A daytime SNR requirement was established for each channel, based on specified targets, albedo, and averaging distances. For both 532 channels, the initial measured daytime SNR was more than 30% above the requirement and has only decreased approximately 7% since the start of the mission. The daytime SNR of the 1064-nm channel has decreased approximately 10% but remains about a factor of 3 above its requirement.

3) Calibration Coefficient, 532-nm Parallel Channel at Night

The calibration coefficient is a good indicator of the overall detection sensitivity of the lidar because it defines the relationship between the backscatter coefficient of the target and the signal measured by the lidar. (Powell et al. 2009) In simplified notation, that relationship is given by Eq. (1):

$$C = \frac{r^2 S(z)}{E G A T^2(z) \beta(z)},$$  \hspace{1cm} (1)

where $C$ is the calibration coefficient, $r$ is the range from the lidar to the target, $z$ is the altitude of the target above MSL, $S(z)$ is the measured signal from the target,
**E** is the measured laser energy, \( G_A \) is the known amplifier gain, \( \beta(z) \) is the molecular backscatter coefficient, and \( T^2(z) \) is the two-way atmospheric transmission from the lidar to the target. System characteristics that affect the value of \( C \) include the receiver optical transmission, the detector gain and quantum efficiency, the transmitter–receiver wavelength matching, and the transmitter–receiver boresight alignment. It is not affected by changes in the laser energy because the ratio \( S(z)/E \) should remain constant, independent of \( E \).

Calibration of the 532-nm parallel channel at night is done over an altitude range of 30 to 34 km above MSL, where all the quantities on the right-hand side of Eq. (1) can be determined. Because the atmosphere at this altitude is almost purely molecular, the parameters \( T^2(z) \) and \( \beta(z) \) can be derived from air molecule and ozone number concentrations provided by NASA’s Global Modeling and Assimilation Office (GMAO). With a reasonable amount of averaging, the SNR is large enough to get a good measurement of \( S(z) \), and all the other terms on the right are known.

During level 1 processing, multiple calculations of the 532-nm parallel calibration coefficient are done along the night side of each orbit, with each averaged over 1485 km. The values are relatively constant over the dark portion of a given orbit, but they do vary somewhat over longer time periods, indicating changes in the lidar detection efficiency over time. Figure 8 shows that the calibration coefficient had dropped to about 87% of its initial value in late 2007, but it recovered to more than 95% of its initial value after a boresight alignment and retuning of the etalon.

**4) POLARIZATION GAIN RATIO**

The 532-nm perpendicular channel does not have sufficient SNR to calibrate using a high-altitude molecular signal. Instead, this channel’s calibration coefficient is derived from that of the parallel channel by multiplying the 532-nm parallel channel coefficient by the polarization gain ratio (PGR) (Powell et al. 2009). The PGR is the ratio of the 532-nm perpendicular channel signal to the 532-nm parallel channel signal when both detectors are illuminated equally, as is the case during polarization calibration operations. The PGR is used in conjunction with the 532-nm parallel calibration coefficient to calibrate the 532-nm perpendicular channel.

**5) OTHER CALIBRATION COEFFICIENTS**

Only the 532-nm parallel channel at night has sufficient SNR to be calibrated using high-altitude molecular backscatter. The calibration coefficients for the 532-nm
channels in the daytime and the 1064-nm channel day and night have to be derived from those of the 532-nm parallel channel at night (K. A. Powell et al. 2008, unpublished manuscript). Because those calibrations involve several complicating factors, some of which will be discussed later under Performance Issues, it is not useful to plot performance trends for them at this time.

6) CLEAR-AIR DEPOLARIZATION RATIO MEASUREMENTS

The ratio of the calibrated 532-nm perpendicular channel signal to the calibrated 532-nm parallel channel signal is the volume linear depolarization ratio (or depolarization ratio, for short). CALIOP is designed to measure the depolarization ratio of clouds and aerosols, but is not expected to be sensitive enough to make accurate measurements of the depolarization ratio of clear air, estimated to be approximately 0.0037 at the bandwidth of the CALIOP optical filter (Cairo et al. 1999). Nevertheless, it is informative to look at the values obtained from clear-air measurements because the difference between the measured value and the actual value puts an upper limit on the amount of crosstalk between the two polarization channels. Early in the mission the clear-air depolarization ratio was measured to be 0.006. Later it made an abrupt jump to 0.009, and it has made several jumps between approximately those two values since then. The design objective was to have less than 1% crosstalk between the two 532-nm channels (i.e., when there is no depolarization by the target, the measured depolarization ratio should be less than 0.01). Even with the higher of the measured values, this design objective has been met.

Figure 10 shows the clear-air depolarization trend up to late May 2008. This plot was generated from the ratio of region averages from H&S data, with approximate corrections for baseline shape and PGR. All the abrupt changes in value before 2008 took place upon resuming operation after the instrument had been in Safe mode for at least a few hours. The changes in early 2008 are associated with an etalon scan and subsequent etalon retuning. The reason for the abrupt jumps is not known, but there is reason to believe that they might be associated with unrelieved stress on the etalon after thermal changes. This explanation seems to be supported by the changes related to the etalon scan and retuning.

7) BORESIGHT POINTING DIRECTION

A boresight alignment operation is carried out relatively infrequently to optimize the boresight alignment between the transmitter and the receiver. This operation consists of moving the laser pointing direction to four points offset from the current position by fixed amounts in different directions and making high altitude backscatter signal measurements at each position. Based upon the relative signals at the four points, a new optimum pointing direction is computed and implemented. Boresight alignments are only done at night, since the SNR is too low to do them in the daylight, and normal measurements are disrupted during these operations. Figure 11, which gives the pointing directions after each of the align operations that have been carried out to date, shows that the nighttime alignment has exhibited a very slow long-term drift. The most recent optimum pointing direction is about 40 µrad away from the initial direction. There is some evidence that the gradual drift is the result of distortion of the canister of the primary laser as its pressure drifted downward (Fig. 4).

While the alignment is quite stable at night over a short term, it appears that there are significant shifts during the daylight portion of each orbit, as will be discussed later in section 3b.

8) ETALON TUNING

The passband of the 532-nm channel etalon was chosen to be about the same as the line width of the laser (Fig. 12) to reduce the solar background as much as possible without excessive attenuation of the laser energy. With the filter passband so close to the laser line width, the two center wavelengths must be well matched to optimize the laser throughput. The center wavelength of the etalon is controlled by adjusting its temperature (Zaun 2004). Early in the mission, an etalon temperature scan was carried out in which the etalon temperature was sequentially set to a number of different values and the backscatter signal was measured at each setting. The temperature giving the largest backscatter signal was determined, and the etalon temperature was set to that value.
Because both the etalon and the laser are temperature controlled, they can be kept fairly closely matched for long periods of time without the need for active feedback or frequent adjustments. Because of the time involved, scans are only carried out when there are indications that they are needed. The original set point was maintained until February 2008, at which time another scan was done. This scan showed that the center wavelengths had become mismatched by about 7 pm, causing a signal loss of about 6% (Fig. 13). After this scan the etalon temperature was reset to the new optimum value, restoring the lost signal.

b) Some performance issues

Although the overall performance has been excellent, allowing for the production of high-quality science products, there are some performance characteristics that require special care in data processing to obtain the most accurate results.

1) THERMAL EFFECTS ON CALIBRATION COEFFICIENTS

As was discussed earlier, all other calibration coefficients are derived from the 532-nm parallel channel nighttime calibration coefficients. The process of transferring those coefficients to the 532-nm channel in the daytime and to the 1064-nm channel both night and day has proven to be more difficult than anticipated. Careful offline analysis of the data, including looking at tropospheric molecular signals after cloud clearing and much averaging (K. A. Powell et al. 2008, unpublished manuscript), allows the calibration coefficients to be evaluated much more accurately than can be done during production level 1 processing, when the processing flow is more restricted and the quantity of data that can be used is limited. Such an analysis has shown a surprising amount of variability in the coefficients when the satellite is in sunlight.

(i) Sunlight effect on 532-nm channel calibration

The 532-nm parallel channel calibration coefficients measured during a night orbit segment with the satellite in darkness show little variability, but as soon as the satellite goes into sunlight, the coefficients begin to change noticeably. This effect can be seen in the directly measured calibration coefficients near the end of each orbit.

FIG. 11. Time history of the pointing directions along two perpendicular axes after nighttime boresight alignments. The gradual drift in the $+y$ direction is believed to be due to changes in the laser pointing direction caused by distortion of the laser canister as its pressure decreased.

FIG. 12. An illustration of the close match between the laser line width and the etalon passband. The laser output and the etalon transmission are plotted as a function of the wavelength offset from the peak.

FIG. 13. Results of the etalon temperature scan performed in February 2008 showing the backscatter signal as a function of the etalon temperature set point. The new optimum temperature setting corresponds to a center wavelength shift of about 6.9 pm from the previous setting. Shifting to the new setting resulted in a 6% signal increase.
night orbit. Although direct calibration measurements are not possible during the day portion of the orbit, offline analysis shows that the variation becomes even more pronounced as the lidar progresses further into the sunlight. The initial data release (version 1) did not take this variability into account when computing the daytime calibration coefficients. Figure 14 is an example of the scattering ratios over the day portion of an orbit, computed using the version 1 calibration coefficients (K. A. Powell et al. 2008, unpublished manuscript). The value should be close to unity at all times, but instead it shows a systematic dip to about 0.70 approximately 2200 s after going into daylight. This general behavior is consistent from month to month, but the size of the dip varies with season, with midsummer showing the smallest dip. This behavior points to a thermally induced misalignment as being the cause of the variation. BATC has done some end-to-end modeling that tends to support this theory (Lieber et al. 2007).

Offline analysis of the first 18 months of data has made it possible to derive more accurate daytime calibration coefficients for the past data and to predict more accurate values for future data. These improved values were incorporated into the version 2 processing software, and all of the data have now been reprocessed with that software version. Even further refinement is expected in future data releases.

(ii) Sunlight effects on 1064-nm channel calibration

Transfer of the 532-nm channel calibration coefficients to the 1064-nm channel has proven to be even more complicated. The calibration approach that is currently being used is to obtain the 1064-nm channel calibration coefficients by multiplying the 532-nm channel calibration coefficients by the relative sensitivities of the 1064- and 532-nm channels, which we will call the channel ratio. The channel ratio is obtained by measuring the ratio of the backscatter signals at the two wavelengths from strong high-altitude cirrus clouds, after correction for extinction above the clouds. By restricting the measurements to strongly scattering clouds, the contribution of the molecular backscatter is negligible, so the measured backscatter is almost entirely due to particulate backscatter. Because of the large particles, the ratio of the backscatter at the two wavelengths was initially assumed to be unity and constant throughout an orbit. However, further study of the data has shown that the channel ratio is not constant over an orbit. Not only does it show differences between day (satellite in sunlight) and night (satellite in shadow), with characteristics somewhat similar to those discussed for the 532-nm channel calibration coefficients, but it also shows a latitudinal dependence both night and day. Figure 15 illustrates both of these effects. When the satellite is in the earth’s shadow (blue crosses), the 1064/532 channel ratio rises in a nearly linear manner as the satellite goes from north to south. This behavior is typical of the nighttime behavior at all times of year, although the slope is a weak function of the time of year. Once the satellite hits sunlight (red circles), there is some sign of a momentary increase in the ratio, and then it drops as the satellite reaches its southernmost point and starts back north. It reaches its lowest value at around 20° north, where it is almost 30% lower than for the same latitude in the dark, before it starts to rise again as the satellite approaches darkness. The amount of difference between night and day is a function of the time of year. The difference is largest in midwinter and is quite small in midsummer. The difference between the ratio in sunlight and shadow seems to indicate a thermally induced misalignment similar to what has been previously discussed for the 532-nm channel in the daytime. In this case, not only must there be misalignment, but the misalignment must affect the two wavelengths differently, causing a change in the channel ratio. The latitudinal dependence of the channel ratio at night is harder to explain. Several possibilities, including a small change in the nighttime alignment, are being considered, but no conclusions have been reached.
Although some changes were made in the 1064-nm channel calibration in the version 2 software, inclusion of the effects described above will have to wait until a still later release.

2) RADIATION-INDUCED NOISE

The CALIOP 532-nm channel detectors occasionally produce radiation-induced current spikes that are as much as two orders of magnitude larger than the pulses produced by single photoelectrons. Such pulses are fairly rare outside the SAA but are much more frequent when passing through the SAA. Individual spikes can adversely affect signal averages in low-signal regions, and multiple pulses can increase the dark noise level, with a corresponding decrease in the SNR. For example, the 532-nm channel RMS dark noise in the middle of the SAA is more than 30 times higher than that outside the SAA, leading to a decrease in the nighttime high-altitude SNR by more than a factor of 5. The effect on the SNR from clouds and aerosols at lower altitudes is much less because the backscatter signal is so much larger. Figure 16 shows the geographic distribution of PMT dark noise, clearly showing regions where there is increased noise due to radiation.

Some special processing steps are taken to minimize the effects of the radiation-induced noise spikes on the 532-nm parallel channel calibration (Powell et al. 2009). Isolated noise spikes are simply removed from the data whenever they can be identified. More extreme measures are needed in the vicinity of the SAA, where calibration measurements are bypassed and historical calibration coefficient values are used if the noise level becomes too high.

3) SLOW TRANSIENT RECOVERY

Measurements of weak signals immediately after a strong signal can give misleading results on the 532-nm channels because the PMTs exhibit a decaying noise tail after being exposed to a large signal. The 1064-nm channel APD does not exhibit this effect. This is illustrated in Fig. 17, which shows the backscatter from the surface of Antarctica for both wavelengths. The browse images for both channels show a strong (probably saturated) return from the ice surface, but the 532-nm channel image on the left shows a rainbow effect from the decaying false signal from below the surface, whereas the 1064-nm channel image on the right does not show this effect. The noise tail is present on the 532-nm channels after any signal, but it is most easily seen and characterized after a surface return, where the backscatter signal goes quickly from a small value to a very large value and then quickly back to zero. More quantitatively, Fig. 18 shows the relative intensity of the noise tail from the 532-nm parallel channel detector as a function of time after a surface return. Although the data shown are for a nearly saturated signal, this plot is a good representation of the relative response after an impulse-like signal of any amplitude, so long as the peak signal is not saturated. It even applies to a moderately saturated signal if the noise tail is taken as relative to the true peak.
rather than the measured peak. The impact of the slow transient recovery on science products is still being investigated, as are potential correction algorithms.

4. Summary

CALIOP is a three-channel elastic backscatter lidar, making measurements at 1064 nm and two polarizations at 532 nm. It utilizes onboard processing to increase its autonomy, decrease its downlink data rate, increase its dynamic range, and extract science data for inclusion in the Health and Status data. Its on-orbit performance has continued to exceed nearly all requirements after more than 2 yr of operation, producing high-quality science data products. The energy of the primary laser has decreased less than 10%, although a slow pressure leak...
will necessitate a switch to the backup laser in early 2009. The signal-to-noise ratios for all channels remain comfortably above their requirements for most cases and have been decreasing at a very modest rate. The exception is in the South Atlantic Anomaly, where the high radiation level generates excessive noise from the 532-nm channel detectors, causing the SNR to drop below requirements and necessitating special processing treatment to deal with the noise pulses. Depolarization measurement capabilities have exceeded expectations, with very low cross talk between channels. Bore sight stability, as well as the resulting calibration constant stability, has been quite good at night but less so in the daytime, so accurate determination of daytime calibration coefficients continues to be a work in progress, especially for the 1064-nm channel. Slow transient recovery of the 532-nm channel causes some error in measurements immediately after a strong backscatter signal. Its impact on science data products has not yet been fully evaluated, but it is thought to be relatively small.

REFERENCES


