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Initial performance assessment of CALIOP

David M. Winker,[1] William H. Hunt,[2] and Matthew J. McGill[3]

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[1] The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP, pronounced the same as "calliope") is a spaceborne two-wavelength polarization lidar that has been acquiring global data since June 2006. CALIOP provides high resolution vertical profiles of clouds and aerosols, and has been designed with a very large linear dynamic range to encompass the full range of signal returns from aerosols and clouds. CALIOP is the primary instrument carried by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, which was launched on April 28, 2006. CALIPSO was developed within the framework of a collaboration between NASA and the French space agency, CNES. Initial data analysis and validation intercomparisons indicate the quality of data from CALIOP meets or exceeds expectations. This paper presents a description of the CALIPSO mission, the CALIOP instrument, and an initial assessment of on-orbit measurement performance.
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1. Introduction

[2] Aerosols and clouds play important roles in the Earth's radiation budget, in the hydrologic cycle, and have impacts on air quality. The CALIPSO mission was developed to provide global profiling measurements of cloud and aerosol distribution and properties to complement current measurements and improve our understanding of weather and climate [*Winker et al.*, 2003]. CALIOP, the primary instrument carried by CALIPSO, is the first satellite lidar optimized for aerosol and cloud measurements and is also the first polarization lidar in space. CALIOP is based on a Nd:YAG laser operating at 1064 nm and 532 nm. The outgoing laser beam is linearly polarized and two polarization-sensitive 532 nm receiver channels provide measurements of the degree of linear polarization of the return signal. Using the two 532 nm receiver channels and a channel measuring the total 1064 nm return signal, CALIOP measures the detailed vertical distribution of aerosols and clouds along with their microphysical and optical properties. Measurements of signal depolarization allow the discrimination of spherical and non-spherical cloud and aerosol particles [*Sassen*, 1991]. Two-wavelength signals provide qualitative information on particle size and aid in discrimination of cloud and aerosol and the identification of aerosol type.

[3] The lidar technique provides direct measurements of range so it provides the most detailed and accurate information on cloud and aerosol height. With sufficient averaging, CALIOP is also able to detect and characterize weak aerosol layers and thin clouds with optical depths of 0.01 or less [*McGill et al.*, 2007], and so complements the information gained from existing satellites. CALIPSO flies as one of 5 satellites in the so-called "A-train" constellation of satellites, which provides numerous measurement synergies with the CloudSat cloud profiling radar and the various passive instruments of the A-train making cloud and aerosol measurements [*Stephens et al.*, 2002]. Observations from CALIOP will ultimately be used to improve the representation of aerosols and clouds in models used for climate prediction, weather forecasting, and air quality.

2. Mission Description

[4] CALIPSO was launched from Vandenburg AFB on 28 April, 2006 together with the CloudSat satellite. CALIPSO flies in formation with the EOS Aqua and CloudSat satellites as part of the NASA Afternoon Constellation, or A-train [*Stephens et al.*, 2002]. All the satellites of the A-train are in a 705 km sun-synchronous polar orbit with an equator-crossing time of about 1:30 PM, local solar time, and a 16-day repeat cycle. The orbit inclination of 98.2° provides global coverage between 82°N and 82°S. The orbit is controlled to repeat the same ground track every 16 days with cross-track errors of less than ±10 km.

[5] The CALIPSO satellite flies behind the Aqua satellite, providing cloud and aerosol measurements which are coincident and near-simultaneous with observations from the MODIS, AIRS, and CERES instruments on Aqua. To minimize changes in cloud and aerosol properties between observations by the two platforms, the along-track separation is controlled to be less than two minutes. Because aerosol properties are not retrieved from MODIS observations affected by sunglint, the CALIPSO orbit is slightly inclined to that of Aqua so that CALIPSO is located 215 km to the east of Aqua when crossing the equator on the day side of the orbit. With this geometry the CALIPSO footprint remains outside of the sunglint pattern seen by the Aqua-MODIS instrument. CloudSat is controlled to fly 10–15 seconds ahead of CALIPSO and to overlap the CALIOP footprint with the footprint of the CloudSat radar.

[6] CALIPSO flies in a nadir-pointing attitude so that the CALIOP footprints nominally fall on the satellite ground-track. The satellite attitude is controlled to point CALIOP 0.3° from geodetic nadir in the forward along-track direction.

[1]NASA Langley Research Center, Hampton, Virginia, USA.
[2]Science Systems and Applications, Inc., Hampton, Virginia, USA.
[3]NASA Goddard Spaceflight Center, Greenbelt, Maryland, USA.

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Table 1. Spatial Resolution of Downlinked Data

Altitude Range, km	Horizontal Resolution, km	532 nm Vertical Resolution, m	1064 nm Vertical Resolution, m
30.1 to 40.0	5.0	300	—
20.2 to 30.1	1.67	180	180
8.2 to 20.2	1.0	60	60
−0.5 to 8.2	0.33	30	60
−2.0 to −0.5	0.33	300	300

This small off-nadir angle avoids strong specular lidar returns from still water (ponds, rivers).

3. Instrument Description

[7] The CALIOP transmitter includes two fully redundant Nd:YAG lasers. Only one is used at a time. Each laser produces simultaneous, co-aligned, pulses at 1064 nm and 532 nm. The lasers generate 20 nsec pulses at 1064 nm. A frequency doubling crystal converts roughly half this energy to 532 nm producing, nominally, 110 mJ of energy at each of the two wavelengths. Energy monitors measure the output pulse energy at each wavelength before expansion. A beam expander reduces the angular divergence of the transmitted laser beam to produce a beam diameter of 70 meters at the Earth's surface. The laser pulse repetition frequency of 20.16 Hz produces footprints every 333 m along the ground. The instrument operates continuously, providing observations during both day and night portions of the orbit.

[8] Backscatter signals are collected by a 1-meter diameter telescope. A field stop at the focus of the telescope defines the receiver field of view of 130 μrad (full angle) and provides rejection of background sunlight. An etalon with a passband of 35 pm is used in combination with a dielectric interference filter in the 532-nm channel to further reduce the solar background, while an interference filter alone is sufficient for the 1064 nm channel. The outgoing laser pulses are linearly polarized with a purity greater than 99%. A polarization beamsplitter is used to separate components of the 532 nm return signal polarized parallel and perpendicular to the plane of the outgoing beam. A depolarizer located ahead of the beamsplitter can be moved into the beam for relative calibration of the two 532 nm channels. An avalanche photodiode (APD) is used for detection in the 1064 nm channel. Photomultiplier tubes (PMTs) are used for detection at 532 nm as they provide large linear dynamic range and higher sensitivity than the APD. Dual 14-bit digitizers on each channel provide the 22-bit dynamic range required to encompass the full range of molecular, aerosol, and cloud backscattering encountered in the atmosphere.

[9] The analog signals from each detector are digitized at 10 MHz (corresponding to a 15 m range interval). Instrument timing is controlled to begin sampling when the laser pulse reaches an altitude of 115 km. Detector signals between altitudes of 112 km and 97 km and between 80 km and 65 km, where the lidar return signal is insignificant, are averaged to measure the solar background and DC signal level. Only the samples acquired below 40 km from the 532 nm channel (and 30 km for the 1064 nm channel) are downlinked as profile data. To reduce the telemetry bandwidth, samples are averaged onboard the satellite before downlinking according to the scheme shown in

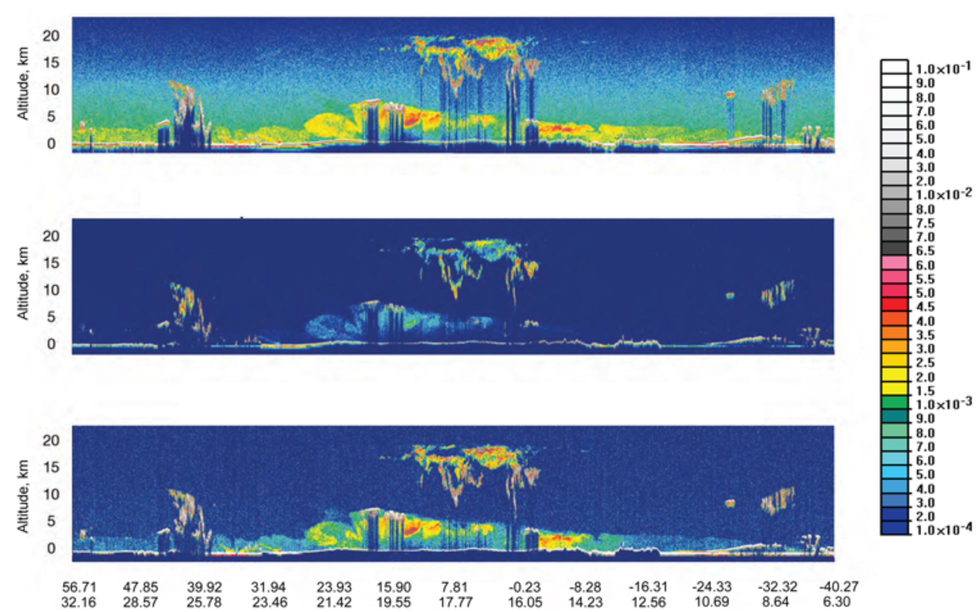

Figure 1. CALIOP observations on June 9, 2006, acquired along an orbit track from northern Europe across Africa into the south Atlantic. The three panels show lidar return signals (attenuated backscatter) from the three CALIOP channels, calibrated in units of $km^{-1}sr^{-1}$. Shown are (top) total 532 nm return, (middle) 532 nm perpendicular return, and (bottom) total 1064 nm return. Strong returns from clouds and from the surface appear in grayscale. Yellows and reds represent weak cloud and strong aerosol scattering, and greens and blues represent molecular scattering and scattering from weak aerosol and cloud layers.

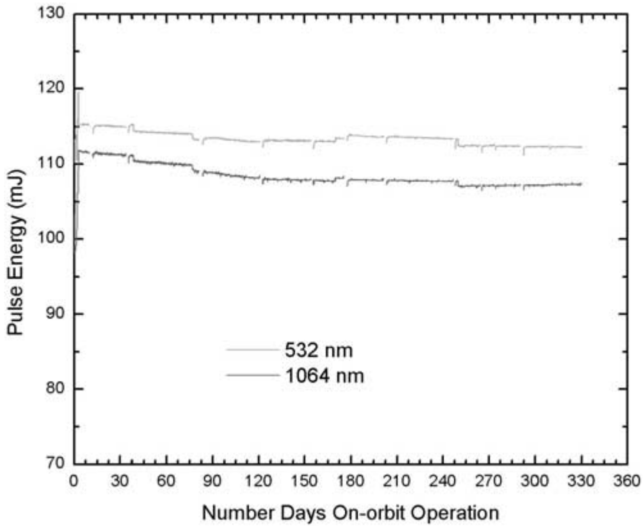

Figure 2. Laser pulse energy history during the 330 days of laser operations between June 6, 2006, and June 6, 2007.

Table 1. Further details on the instrument and data acquisition are given by *Winker et al.* [2004].

4. On-Orbit Measurement Performance

[10] CALIOP "first light" occurred on 7 June 2006. As this is written, CALIOP has completed 12 months of near-continuous operation, and initial assessments indicate excellent on-orbit performance. Level 1 data products from CALIOP are the calibrated, geolocated profiles of total backscatter return at 532 nm and 1064 nm and the perpendicular component of the 532 nm backscatter return. These profiles of "attenuated backscatter" are the calibrated return signals, which are not corrected for attenuation. The 532 nm channel is calibrated using the classical technique of normalizing the signal to high altitude molecular returns [*Winker et al.*, 2004]. The 532 nm perpendicular channel is calibrated relative to the parallel channel using the on-board depolarizer, as described in the previous section. The 1064 nm channel is calibrated relative to the 532 nm channel using backscatter signals from cirrus clouds [*Reagan et al.*, 2002]. Figure 1 shows examples of each of these products acquired early in the mission. Figure 1 shows a nighttime transect from northern Europe southward across Africa into the Atlantic Ocean west of South Africa. Inspection of the three panels illustrates some of the capabilities of CALIOP to observe aerosols and clouds.

[11] High cirrus located over tropical Africa, reaching altitudes of 17 km, is seen in the center of the image. The cirrus backscatter signal strength is similar at both wavelengths, due to the relatively large size of the cirrus particles. The cirrus is strongly depolarizing and produces a significant signal in the perpendicular channel. Significant attenuation produces the vertical dark stripes seen underneath optically thick features. Molecular scattering at 532 nm appears in the parallel channel coded in shades of blue and, near the surface, green. Molecular signals in the other two channels are negligible. Water clouds located near the top of the dust layer around 20°N and a stratiform cloud deck near 25°S produce very strong return signals. All three CALIOP receiver channels were designed with a linear dynamic range large enough so that even these strong cloud returns remain on-scale.

[12] Layers of desert dust are seen beneath and immediately to the north of the cirrus, over the Sahara Desert. Dust particles are relatively large and irregular, and so also produce strong signals in the 1064 nm and perpendicular channels. An extensive layer of smoke, originating from biomass fires in southern Africa, can be seen south of the equator. Unlike the Sahara dust, this aerosol is non-depolarizing and produces negligible signal in the perpendicular channel, and also scatters more weakly at 1064 nm than at 532 nm. It can be seen that the aerosol north of about 25°N is also non-depolarizing and more weakly scattering at 1064 nm. In this case the aerosol is dominated by secondary aerosol originating from anthropogenic activity in Europe. CALIPSO Level 2 algorithms provide identification of aerosol and cloud layers, classify aerosol into several types, and classify clouds by ice/water phase [*Vaughan et al.*, 2004].

[13] Only one of the two lasers has been used to date during on-orbit operations. Figure 2 shows the time history of pulse energy during the first year of on-orbit operations of this laser. Three small, sudden, drops in energy were seen after about 40, 80, and 250 days of on-orbit operation, superimposed on a very slow decreasing trend. The Nd:YAG slab in the laser is pumped by 192 laser diode bars. The magnitude of these three sudden drops is consistent with the sudden dropout of one diode bar, which is expected to cause the total pulse energy to decrease by about 1 mJ. These sudden drops were also seen during on-

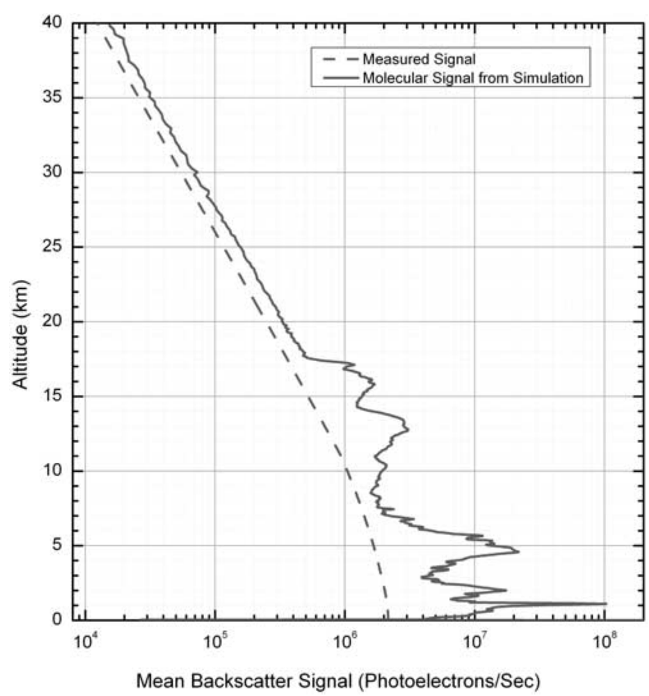

Figure 3. Observed average 532 nm return signal (solid line) and predicted molecular signal (dashed line), in terms of detected signal photoelectrons/sec.

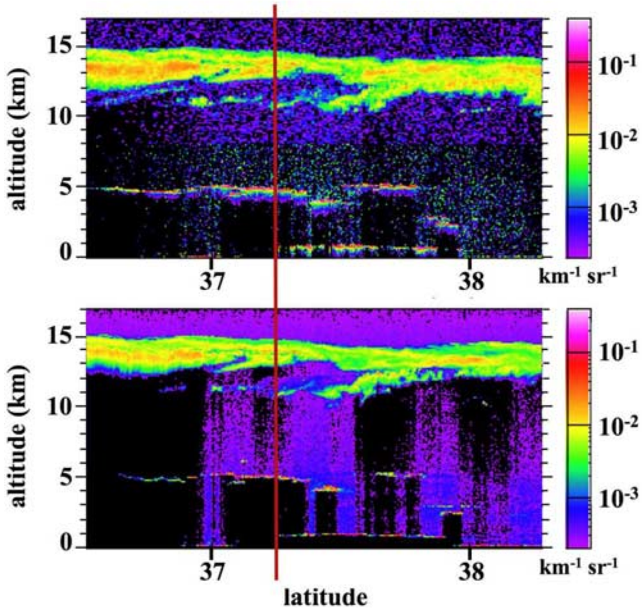

Figure 4. Coincident nighttime data from the 532 nm channels of (top) CALIOP and (bottom) CPL acquired on August 11, 2006. The vertical line indicates the location of exact temporal coincidence.

orbit operation of the GLAS lasers on the ICESat satellite [*Abshire et al.*, 2005], and are expected. The laser output can be seen to be stable following each of these events. A slight, unexplained, increase in pulse energy was seen after about 180 days of operation. The overall long-term trend is in line with expectations based on lifetime testing, which indicate a three-year lifetime for each laser.

[14] Figure 3 shows an observed profile of 532 nm attenuated backscatter from the surface to 40 km. At 30 km the average backscatter signal is about 0.01 photoelectrons per 30 m range bin. The data has been averaged over about 24,000 shots to improve SNR and allow comparison with the signal predicted from a purely molecular atmosphere having a 532 nm backscatter coefficient of 1.5×10^{-3}/km/sr at the surface. Above 18 km the atmosphere is cloud-free and aerosol contributions to the signal are insignificant. In this region, the observed signal strength is about 30% greater than predicted by the instrument performance model, probably due to an overestimate of optical transmission losses by the instrument performance model. Figure 3 also illustrates that the response remains linear well into the region where the average signal is much less than one photoelectron per range bin. SNR measurements made soon after launch gave values that were above the predicted values for all three channels, both day and night, and were at least 50% above requirements. Later measurements showed a drop of less than 10% over the first six months of operation, which is in line with expectations.

[15] A number of aircraft underflights have been conducted for validation of CALIPSO measurements. Figure 4 shows results from a nighttime validation flight conducted on 11 August, 2006 where the Cloud Physics Lidar (CPL) [*McGill et al.*, 2002] was flown on the NASA ER-2 along the CALIPSO ground track. The CPL operates at the same two wavelengths as CALIOP and has polarization capability at 1064 nm. The upper and lower panels show profiles of an extensive cirrus deck acquired by CALIOP and CPL, respectively. Below the cirrus deck, at about 5 km, the tops of stratiform clouds are seen and in the right half of Figure 4 the stratiform clouds become optically thin so that the lidar profiles extend to the surface. On this flight, the cross-track error between the ER-2 and the CALIOP footprint locations was less than 500 m, and the similarity of the cloud features is evident. The time of exact temporal coincidence is indicated by the vertical line. Due to the different velocities of the two platforms, the CALIOP image represents 30 seconds of data acquisition while CPL required nearly 17 minutes to cover the scene. The comparison shows generally good agreement between the two instruments in terms of sensitivity, spatial details, and signal calibration. One artifact that has been noticed in CALIOP 532 nm returns from strongly scattering targets is a delayed recovery from the large transient signal. This behavior is due to the particular PMT detectors used and is not seen in the 1064 nm channel. This artifact can be seen in the comparison of returns from the stratiform cloud near 5 km and from the surface in the two panels of Figure 4.

5. Summary

[16] CALIOP is the first polarization lidar to fly in space and has been acquiring unique observations of aerosols and clouds since June 2006. Initial validation intercomparisons have been performed and preliminary data products are now available through NASA Langley Atmospheric Sciences Data Center (ASDC). Descriptions of data products are given by *Vaughan et al.* [2004] and are also posted on the ASDC web site. Quantitative analyses of CALIOP data are now underway. In addition to new insights which will come from CALIOP data used alone, combining data from CALIOP with coincident observations from other A-train instruments will allow numerous measurement synergies to be realized.

[17] **Acknowledgments.** We would like to acknowledge the support of the NASA and the Centre National d'Etudes Spatiale (CNES) in the development of the CALIPSO mission. We also thank the NASA Langley ASDC for distribution of CALIPSO data, see http://eosweb.larc.nasa.gov.

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W. H. Hunt, Science Systems and Applications, Inc., 1 Enterprise Parkway, Suite 200, Hampton, VA 23681, USA.

M. J. McGill, NASA Goddard Spaceflight Center, Code 613.1, Greenbelt, MD 20771, USA.

D. M. Winker, NASA Langley Research Center, Mail Stop 475, Hampton, VA 23681, USA. (david.m.winker@nasa.gov)