CALIOP: THE CALIPSO LIDAR

David Winker[1], Chris Hostetler[1], William Hunt[2]

[1]*NASA Langley Research Center, MS/435, Hampton, Virginia 23681, USA, E-mail: david.m.winker@nasa.gov*
[2]Wyle Laboratories, Hampton, Virginia, USA

ABSTRACT

The Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP, pronounced the same as the word "calliope") is the primary instrument on the CALIPSO satellite, which is scheduled to launch in early 2005. CALIOP will provide profiles of total backscatter at two wavelengths, from which aerosol and cloud backscatter and extinction will be retrieved. The instrument also measures the linear depolarization of the backscattered return, allowing discrimination of cloud phase and the identification of the presence of non-spherical aerosols. This paper provides information on basic characteristics and performance of CALIOP.

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite is being developed by NASA Langley Research Center in collaboration with the French Space Agency CNES for launch in 2005 [1]. CALIPSO will be flown as part of the Aqua constellation, including also the Aqua, CloudSat, Aura, and PARASOL satellites. CALIPSO and the rest of the formation will fly at an altitude of 705 km and an inclination of 98^o. The primary objective of CALIPSO's 3-year mission is to provide the observations necessary to improve our understanding of the effects of clouds and aerosols on the climate system. The CALIPSO payload consists of (1) the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) to provide vertical profiles of aerosol and cloud backscatter and depolarization; (2) an Imaging Infrared Radiometer (IIR) with three channels in the infrared window region optimized for retrievals of cirrus particle size; and (3) a moderate spatial resolution camera operating in the visible to provide meteorological context and a means to accurately register CALIPSO observations to those from MODIS. CALIOP has been built by the Ball Aerospace and Technology Corporation in Boulder, Colorado. The following sections describe the CALIOP instrument, its on-orbit calibration scheme, and performance.

2. INSTRUMENT DESCRIPTION

CALIOP consists of a laser transmitter subsystem, a receiver subsystem, and the payload controller (PLC) subsystem, which performs control and data handling functions. Although the PLC also manages the IIR and the camera, its resources are primarily devoted to CALIOP. The laser transmitter subsystem consists of two redundant lasers, each with a beam expander, and a beam steering system that ensures alignment between the transmitter and receiver. The Q-switched Nd:YAG lasers use a crossed-porro resonator design to minimize alinement sensitivity and polarization outcoupling to provide a highly polarized output beam. Frequency-doubling produces simultaneous pulses at 1064 nm and 532 nm. Each laser produces 110 mJ of energy at each of the two wavelengths at a pulse repetition rate of 20.16 Hz, although only one laser is operated at a time. Beam expanders reduce the angular divergence of the laser beam to produce a beam diameter of 70 meters at the Earth's surface. The lasers are passively cooled using a dedicated thermal radiator panel, avoiding the use of pumps and coolant loops. Each laser is housed in its own sealed canister filled with dry air at slightly more than standard atmospheric pressure. Transmitter specifications are listed in Table I.

A space-qualifiable prototype flight laser (the Risk Reduction Laser, or RRL) was developed and tested to reduce risk in the development of the flight lasers. This test program was primarily intended to validate the flight laser design and contamination control procedures. The RRL was used to conduct an extended life test which began in late 1998. Operating at a pulse rate of 27 Hz, the RRL fired over 2 billion shots during the life test, equivalent to the number of shots required for the 3-year CALIPSO mission, without significant degradation. Since completion of the RRL lifetest, both flight lasers have successfully completed space qualification testing.

Shown schematically in Fig. 1, the receiver sub-system consists of the telescope, relay optics, detectors, preamps, and line drivers mounted on a stable optical bench. The receiver telescope is an all-beryllium 1-meter diameter design similar to the telescopes built for GLAS and ELISE. The telescope primary mirror, secondary mirror, metering structure, and inner baffle are all made of beryllium. A carbon composite light shade prevents direct solar illumination of the mirrors. A fixed field stop controlling the lidar field of view is located at the telescope focus. A narrowband etalon is used in combination with a dielectric interference filter in the 532-nm channel to reduce the solar background illumination,

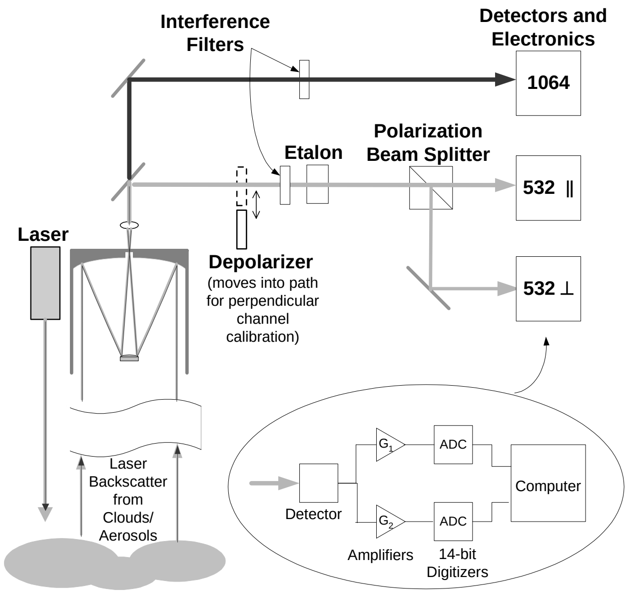

Fig. 1. Functional block diagram of CALIOP.

TABLE I. CALIOP TRANSMITTER PARAMETERS

Laser	Diode-pumped Nd:YAG
Pulse Energy	110 mJ: 532 nm 110 mJ: 1064 nm
Rep Rate	20.16 Hz
Pulse Length	20 nsec
Linewidth	30 pm
Polarization Purity	99.9% (532 nm)
Beam Divergence	100 µrad (after beam expander)
Boresight Range	±1 degree, 1.6 µrad steps
Laser Environment	18 psia, dry nitrogen

while an interference filter alone provides sufficient solar rejection for the 1064 nm channel. Table II lists specifications of the receiver subsystem.

Alignment stability of the transmitter and receiver optical axes is assured by a T-shaped optical bench (see Fig. 2) fabricated of carbon graphite composite which provides a mechanically and thermally stable structure. The laser transmitter assembly is attached to the top of the "T" by a drive mechanism and gimbal assembly allowing precise and accurate pointing adjustments. As-built resource requirements for CALIOP and for the entire payload are listed in Table III.

CALIOP is required to accurately measure signal returns from the aerosol-free region between 30 km and 35 km

TABLE II. CALIOP RECEIVER PARAMETERS

Telescope diameter	1 meter
Field of View	130 µrad
Digitization Rate	10 MHz
Linear Dynamic Range	4E+6 : 1
532 nm Channel:	
Detector	PMT
Etalon Passband	37 pm
Etalon Peak Transmission	85%
Blocking Filter	770 pm
1064 nm Channel:	
Detector	APD
Optical Passband	450 pm
Peak Transmission	84%

as well as the strongest cloud returns. Therefore the lidar has been designed so the linear dynamic range encompasses the full range of molecular, aerosol, and cloud backscattering encountered in the atmosphere, which spans many orders of magnitude. Dual 14-bit digitizers on each channel provide the effective 22-bit dynamic range which is required.

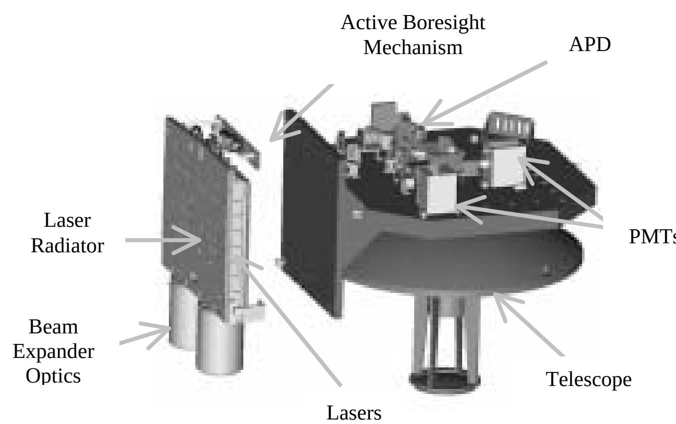

Fig. 2. Expanded 3-D rendering of the CALIOP instrument.

TABLE III. RESOURCE REQUIREMENTS

	CALIOP	Payload
Mass (kg)	156	283
Power (W)	124	228
Dimensions (cm)	100 W x 149 L x 131 H	150 W x 180 L x 131 H
Data rate (kbps)	332	397

The fundamental sampling resolution of the lidar is 30 meters vertical and 333 meters horizontal, determined by the receiver electrical bandwidth and the laser pulse repetition rate. Backscatter data will be acquired from the surface to 40 km with 30 m vertical resolution. Low altitude data will be downlinked at full resolution. To reduce the required telemetry bandwidth, data from higher altitudes will be averaged on-board the satellite to reduce the data rate. The averaging scheme is detailed in Table IV.

TABLE IV. 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

3. CALIBRATION

The lidar is calibrated in three steps. First, the 532nm parallel channel signal is calibrated to the expected molecular volume backscatter coefficient in the 30-34 km region. The molecular backscatter coefficient can be accurately estimated using temperature and pressure profiles from a gridded meteorological analysis product. The 30-34 km region was chosen as the aerosol backscatter in that region is insignificant with respect to molecular backscatter. The parallel-polarized component of the molecular backscatter is calculated from the estimate for the total molecular backscatter by taking into account the bandwidth of the receiver optical filters. Independent estimates of the 532-nm parallel calibration constant are computed at approximately 700-km intervals over the dark side of an orbit and then interpolated to the day side.

Second, the calibration of the 532-nm parallel channel is transferred to the perpendicular channel via insertion of a pseudo-depolarizer in the optical path in the receiver. The pseudo-depolarizer ensures that, regardless of the polarization state of the backscatter incident on the receiver, an equal amount of light is sent to the parallel and perpendicular channels of the receiver downstream of the depolarizer. The pseudo-depolarizer will be inserted periodically, to track any relative change in sensitivity of the parallel and perpendicular channel detectors.

Third, the calibration of the 532-nm channels is transferred to the 1064-nm channel via comparison of high-altitude cirrus cloud signals [2]. Cirrus cloud particles are large compared to the transmitted wavelengths. Because of this, the backscatter coefficients will be nearly equal at 532 nm and 1064 nm. By choosing clouds for which the ratio of particulate to molecular scattering is 50 and above, the calibration can be transferred with high accuracy. This calibration can be performed on both the dark and daylight side of the orbit, wherever cirrus of sufficient backscatter strength exist.

4. ATMOSPHERIC TEST RESULTS

Fabrication of CALIOP was completed in mid-2003, followed by an extensive series of environmental tests required for space qualification. The final step in the testing process was an end-to-end atmospheric test, performed at the Ball Aerospace facilities in Boulder, Colorado during December 2003. The CALIPSO payload, pointing upward, was placed inside an environmentally controlled container with a window in the ceiling. The container was placed outside so that atmospheric profiles could be acquired. A number of tests were conducted over a 4 day period demonstrating the end-to-end performance of the system.

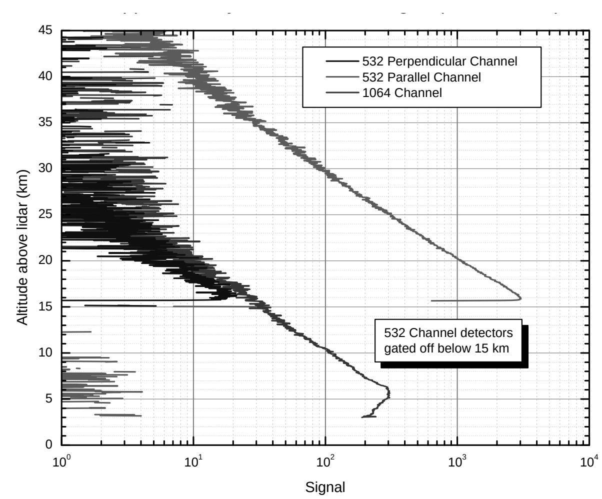

Fig. 3. Clear-air atmospheric test profiles.

CALIOP was designed to operate 700 km outside the atmosphere, so an aperture mask was placed in front of the receiver telescope to reduce the signal from an altitude of 30 km to be equivalent to the signal expected from orbit. Example profiles are shown in Fig. 3, 4, and 5. For atmospheric testing, the transmitter assembly was pointed slightly toward the receiver so that full overlap of the receiver field of view and the transmitted beam occurred at an altitude of about 6 km. The profiles shown in Fig. 3 were acquired in clear air, with the PMT detectors gated on at an altitude of about 15 km, to minimize signal-induced noise effects from the strong low altitude returns. Fig. 4 shows parallel and perpendicular 532 nm profiles which include a thin cirrus cloud. Fig. 5 shows the volume depolarization ratio (defined as $\delta_V = \beta_{perp}/\beta_{par}$) through the portion of this profile containing the cirrus layer. Depolarization in clear air above and below the cloud layer is less than 1%. For an optical bandwidth of 40 pm, the theoretically expected value for a molecular atmosphere is 0.39%, indicating instrumental sources of depolarization bias are small.

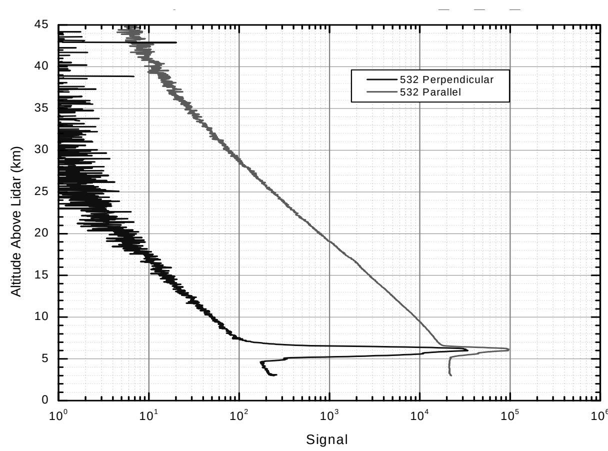

Fig. 4. 532 nm profiles (parallel, right, and perpendicular, left) acquired during atmospheric testing.

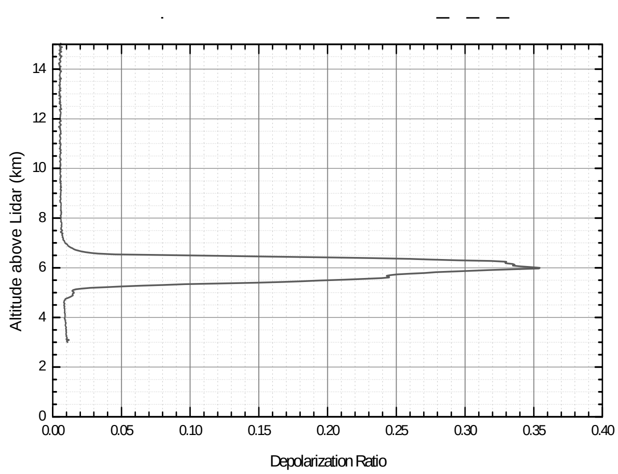

Fig. 5. Volume depolarization ratio profile through a thin cirrus layer acquired during atmospheric testing,.

An important element of the atmospheric test was the operation of the boresight alignment system. The testing successfully demonstrated the transmitter could be accurately aligned with the receiver, and that the alignment was repeatable. Fig. 6 shows the result of a test where the beam profile was measured by scanning the transmitter across the receiver field of view in two orthogonal directions. The measured profiles show good agreement with model estimates, which assumed a 100 μrad Gaussian beam divergence.

5. STATUS

The CALIPSO payload was shipped to France in February 2004 to begin the process of satellite integration and testing. After a series of satellite-level space qualification tests, the completed satellite will be shipped to Vandenburg AFB around the end of 2004. CALIPSO is planned for launch in spring 2005 from VAFB on a Delta II launch vehicle, together with the CloudSat satellite, in a dual-payload configuration.

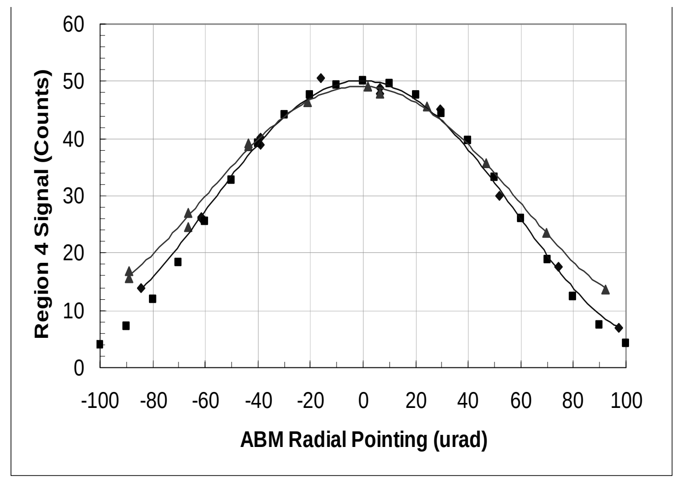

Fig. 6. Beam profiles from boresight x- and y-scans (lines) compared with modeled estimate (symbols) assuming Guassian beam of 100 μrad FWHM.

REFERENCES

1. Winker, D. M., et al., "The CALIPSO mission: Spaceborne lidar for observation of aerosols and clouds," *Proc. SPIE*, vol. 4893, pp. 1-11, 2003.
2. Reagan, J. A., et al., "Spaceborne lidar calibration from cirrus and molecular backscatter returns," *Trans. Geosci.. & Rem. Sens.*, vol. 40, pp. 2285-2290, 2002.