6.3 PROSPECTS FOR ADVANCING GLOBAL AEROSOL AND CLOUD MEASUREMENTS WITH CALIPSO

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1. INTRODUCTION

The CALIPSO satellite carries the first polarization lidar in orbit, along with infrared and visible passive imagers, and flies as part of the Afternoon Constellation (A-train). The acquisition of observations which are simultaneous and coincident with observations from other instruments of the A-train will allow numerous synergies to be realized from combining CALIPSO observations with observations from other platforms. In particular, cloud observations from the CALIPSO lidar and the CloudSat radar will complement each other, together encompassing the variety of clouds found in the atmosphere, from thin cirrus to deep convective clouds. This paper will present an overview of the CALIPSO mission, including initial results.

Fig. 1. The CALIPSO satellite.

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The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite has been developed as a collaboration between NASA and the French Space Agency CNES [Winker, et al., 2003]. CALIPSO is part of the Afternoon constellation, including also the Aqua, CloudSat, Aura, and PARASOL satellites. CALIPSO and the rest of the formation 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 includes three instruments: (1) the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP, pronounced the same as "calliope") 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) the Wide Field Camera (WFC), a moderate spatial resolution imager with one visible channel. WFC images provide meteorological context and are also incorporated into IIR retrievals of cloud properties. The CALIPSO payload was built by the Ball Aerospace and Technology Corporation (BATC) in Boulder, Colorado, except for the IIR which was provided by CNES. CALIPSO utilizes a PROTEUS spacecraft bus, developed by CNES and Alcatel.

2. INSTRUMENTS

The physical layout of the payload is shown in Figure 2, with key instrument characteristics listed in Table 1. A diode-pumped Nd:YAG laser produces linearly-polarized pulses of light at 1064 nm and 532 nm. The atmospheric returns are collected by a 1-meter telescope which feeds a three-channel receiver measuring the backscattered intensity at 1064 nm and the two orthogonal polarization components at 532 nm (parallel and perpendicular to the polarization plane of the transmitted beam).

The receiver sub-system consists of the telescope, relay optics, detectors, preamps, and line drivers mounted on a stable optical bench. A mechanism located in the collimated portion of the beam contains a shutter and a depolarizer used in calibrating the 532 nm perpendicular channel. A narrowband etalon is used in the 532 nm channel to reduce the solar background illumination. A dielectric interference filter provides sufficient solar rejection for the 1064 nm channel. Dual digitizers on each channel provide the effective 22-bit dynamic range needed to measure both cloud and molecular backscatter signals. An active beamsteering system is used to ensure alignment between the transmitter and the receiver.

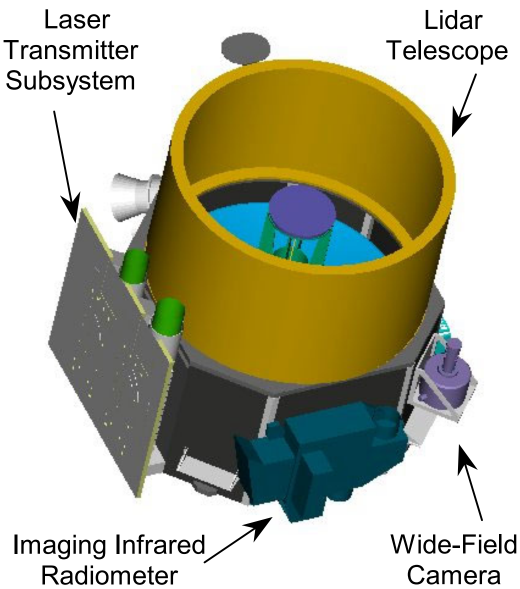

Fig. 2. The CALIPSO payload.

Table 1. CALIPSO Payload Characteristics

CALIOP	
Laser:	
pulse energy	532 nm: 110 mJ 1064 nm: 110 mJ
polarization purity	99.9% (532 nm)
pulse rate	20.16 Hz
Receiver:	
telescope diameter	1 meter
channels, passband	532 nm ||, 37 pm 532 nm ⊥, 37 pm 1064 nm total, 450 pm
footprint	90 m
sampling resolution:	30-60 m vertical 333 m horizontal
WFC	
wavelength	645 nm
spectral bandwidth	50 nm
IFOV/swath	125 m/ 61 km
IIR	
wavelengths	8.65 µm,10.6 µm,12.0µm
spectral resolution	0.6 µm – 1.0 µm
IFOV/swath	1 km/64 km

The laser transmitter subsystem consists of two redundant lasers, each with a beam expander, and the beamsteering system. The Nd:YAG lasers are Q-switched and frequency-doubled to produce simultaneous pulses at 1064 nm and 532 nm. Only one laser is operated at a time. Beam expanders reduce the angular divergence of the laser beam to produce a beam diameter of about 90 meters at the Earth's surface. The lasers are passively cooled using a dedicated thermal radiator panel. Each laser is housed in its own sealed canister filled with dry air at slightly more than standard atmospheric pressure.

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 both vertically and horizontally to reduce the data rate (Table 2). The lidar is calibrated by normalizing the return signal between 30 km and 34 km. A depolarizer can be inserted into the 532 nm beampath to calibrate the perpendicular channel relative to the parallel channel. The 1064 nm channel is calibrated relative to the 532 nm total backscatter signal using cirrus clouds as targets. Additional detail on CALIOP can be found in Winker, et al. [2004].

Table 2. Spatial resolution of downlinked data.

Altitude Range (km)	Horizontal Resolution (km)	Vertical Resolution (m)	
		532 nm	1064 nm
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

The CALIPSO payload also contains two passive instruments: the Imaging Infrared Radiometer (IIR) and the Wide Field Camera (WFC), which are both nadir-viewing and co-aligned with the lidar. The IIR provides calibrated radiances at 8.65 µm, 10.6 µm, and 12.05 µm over a 64 km swath. These wavelengths were chosen to optimize joint lidar/IIR retrievals of cirrus emissivity and particle size. The IIR is built around an Infrared Sensor Module, developed for the IASI instrument. Use of a microbolometer detector array in a non-scanning, staring configuration allows a simple and compact design. A rotating filter wheel provides wavelength selection. The IIR instrument is provided by CNES with algorithm development performed by the Institute Pierre Simon Laplace (Paris). The WFC is a modified Ball star tracker camera, with a single channel covering the 620 nm to 670 nm spectral region providing images of a 61 km swath with spatial resolution of 125 meters.

3. RETRIEVALS AND DATA PRODUCTS

Aerosol and cloud layers are detected using an adaptive threshold technique [Winker and Vaughan, 1994]. Aerosols are then discriminated from clouds using the magnitude and spectral behavior of the lidar return signals [Liu et al., 2004] and extinction profiles are retrieved using a linear iterative technique [Elterman, 1966]. These algorithms are implemented in a unique analysis scheme that employs a nested, multi-scale averaging approach designed to optimize tradeoffs between spatial resolution and signal-to-noise ratio (SNR) [Vaughan, et al., 2004].

Because the magnitude of the lidar return signal varies by several orders of magnitude, depending on the contents of the atmospheric column, the SNR of a single backscatter profile can vary enormously. Strong clouds can be detected in single-shot profiles, but the detection and analysis of weak aerosol layers requires significant horizontal and vertical averaging. If the lidar return signals are analyzed at a uniform high spatial resolution, many weak features will be missed and retrievals may be very noisy. If the data is averaged to a uniform low spatial resolution, strong cloud returns may be averaged together with weaker aerosol signals. Because of the nonlinear processes involved, retrievals on the averaged signals will be biased and will give biased estimates of radiative effects.

Three types of CALIOP Level 2 data products are produced: a vertical feature mask (VFM), which provides a vertical mapping of the locations of aerosol and cloud layers along with layer type information ; layer products, which provide layer-integrated properties of aerosol and cloud layers; and separate aerosol and cloud profile products providing profiles of particulate backscatter and extinction. Further details on CALIOP retrieval algorithms and data products are given in Vaughan, et al. [2004].

The IIR retrieval algorithms are focused on retrieving the emissivity and effective particle size of ice clouds. Lidar cloud heights will be used in IIR retrievals to provide an independent estimate of cloud temperature, to identify single- and multi-layer cloud, and to provide improved identification of cloud-free scenes. Under daylight conditions, WFC data is also used in the algorithm. Two types of Level 2 IIR data products are produced. A Track Product contains retrievals only for IIR pixels coincident with lidar footprints. A Swath Product contains data retrieved from across the 64 km swath of the IIR.

Level 1 and Level 2 data products are summarized in Table 3. Level 1 products are all geolocated, time-referenced and radiometrically calibrated. Further information is available in the CALIPSO Data Products Catalog, available from the CALIPSO web site. Processing and archival of data

Table 3. CALIPSO Data Products.

Level 1	CALIOP	Profiles of 532 nm/1064 nm total attenuated backscatter and 532 nm perpendicular attenuated backscatter
	IIR	Calibrated radiances
	WFC	Calibrated radiances, reflectances
Level 2	CALIOP	Cloud/Aerosol Layer Product: Cloud layer heights, thickness, optical depth, ice/water phase at 1/3, 1, and 5 km Aerosol layer heights, thickness, optical depth and type at 5 km
		Aerosol Profile Product: aerosol extinction and attenuation-corrected backscatter at 40 km
		Cloud Profile Product: cloud extinction and attenuation-corrected backscatter at 5 km
		Vertical Mask - cloud/aerosol ID and type
	IIR	Track product - cloud emissivity and effective particle size along satellite ground track
		Swath Product - cloud emissivity and effective particle size across IIR swath

from all the CALIPSO instruments will be performed at the NASA Langley Research Center Atmospheric Sciences Data Center (ASDC). In accordance with NASA data policy, CALIPSO data will be freely available after validation.

4. OBSERVING STRATEGY

CALIPSO flies in formation with the EOS Aqua satellite as part of the Aqua constellation (or A-train). The Aqua satellite was launched in May 2002 and the Aura and PARASOL satellites were launched in 2004. The launch of CALIPSO and CloudSat will complete the constellation of 5 satellites. The CALIPSO orbit is controlled to provide space-time coincidence with observations from the other satellites of the constellation. The satellites of the constellation fly in a sun-synchronous 705-km circular orbit with a 98^o orbit inclination. The Aqua orbit is controlled to maintain an ascending node equatorial crossing time of 13:30 local time. The CALIPSO orbit is maintained relative to Aqua so that a point on the ground will be observed by the two platforms with an average time separation of 1.5 minutes. This timing constraint ensures that clouds observed by the two platforms will not have time to evolve significantly between the two observations. Based on experience with the JASON satellite, which uses the same PROTEUS spacecraft bus as CALIPSO, satellite pointing can be controlled to within 300 meters. Correlation of WFC and MODIS imagery will allow spatial co-registration of the two data sets to better than 100 m, if necessary, during the day. The CloudSat satellite will fly in formation with the CALIPSO satellite, at an average separation of about 12 seconds. The CloudSat orbit is controlled to keep the footprint of CALIOP within the footprint of the CloudSat radar (approximately 1.4 km wide) to provide coincident radar and lidar observations of clouds.

5. VALIDATION

Validation of CALIPSO data products via intercomparisons with independent measurements is essential to the production of a high quality dataset. A variety of validation activities are planned, including aircraft underflights and measurements from ground-based instruments. Data from ground-based networks such as Aeronet, MPLNet, AD-Net and EARLINET are considered critical to the validation of CALIPSO data. Validation flights with airborne lidars on board the NASA ER-2 and King Air aircraft soon after the commencement of payload operations will provide early validation of Level 1 data products. The CALIPSO team will also participate in field campaigns focused on cloud and aerosol measurements, which provide comparison datasets which are more comprehensive than otherwise available.

6. SCHEDULE

The integrated CALIPSO satellite was shipped to the launch site, Vandenburg AFB, in May 2005. End-to-end atmospheric tests were conducted in December 2003 in Boulder, CO, at the completion of payload integration, and in June 2005 at Vandenburg. Launch was scheduled for October 2005, however, a labor strike and concerns over the flight readiness of the Delta-2 resulted in delays. CALIPSO was finally launched by a Delta-2 launch vehicle in a dual-payload configuration with the CloudSat satellite on April 28, 2006. Data products should become available by the end of 2006.

REFERENCES

Elterman, L., 1966: "Aerosol measurements in the troposphere and stratosphere", *Appl. Opt.* **5**, 1769-1776.

Liu, Z., M. A. Vaughan, D. M. Winker, C. A. Hostetler, L. R. Poole, D. L. Hlavka, W. D. Hart and M. J. McGill, 2004: "Use of Probability Distribution Functions for Discriminating Between Cloud and Aerosol in Lidar Backscatter Data", *J. Geophys. Res.* doi:10.1029/2004JD004732

Winker, D. M., W. H. Hunt, and C. A. Hostetler, 2004: "Status and Performance of the CALIOP lidar," *Proc. SPIE*, **5575**, 8-15.

Winker, D. M., J. Pelon, and M. P. McCormick, 2003: "The CALIPSO mission: Spaceborne lidar for observation of aerosols and clouds," *Proc. SPIE*, **4893**, 1-11.

Winker, D. M., and M. A. Vaughan, 1994: "Vertical distribution of clouds over Hampton, Virginia observed by lidar under the ECLIPS and FIRE ETO programs", *Atmos. Res.* **34**, 117-133.

Vaughan, M. A., S. A. Young, D. M. Winker, K. A. Powell, A. H. Omar, Z. Liu, Y. Hu, and C. A. Hostetler, 2004: "Fully automated analysis of space-based lidar data: An overview of the CALIPSO retrieval algorithms and data products," *Proc. SPIE* **5575**, 16-30.