The CALIPSO mission: Spaceborne lidar for observation of aerosols and clouds

David M. Winker[a], Jacques Pelon[b], M Patrick McCormick[c]

[a]NASA Langley Research Center, MS/435, Hampton, VA 23681
[b]Universite Pierre et Marie Curie, 4 Place Jussieu, Paris, France
[c]Hampton University, Hampton, VA

ABSTRACT

Current uncertainties in the effects of aerosols and clouds on the Earth radiation budget limit our understanding of the climate system and the potential for global climate change. The CALIPSO satellite will use an active lidar together with passive instruments to provide vertical profiles of aerosols and clouds and their properties which will help address these uncertainties. CALIPSO will fly in formation with the EOS Aqua and CloudSat satellites and the other satellites of the Aqua constellation. The acquisition of simultaneous and coincident observations will allow numerous synergies to be realized by combining CALIPSO observations with complementary observations from other platforms. In particular, cloud observations from the CALIPSO lidar and the CloudSat radar will be complementary, together encompassing the variety of clouds found in the atmosphere, from thin cirrus to deep convective clouds. CALIPSO is being developed within the framework of a collaboration between NASA and CNES and is scheduled for launch in 2004.

Keywords: lidar, remote sensing, aerosols, clouds, climate

1. INTRODUCTION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO, formerly called PICASSO-CENA) mission is a satellite mission being developed within the framework of a collaboration between NASA and the French space agency, CNES. The CALIPSO mission will provide unique measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system. The Lidar In-space Technology Experiment (LITE) demonstrated the potential of space lidar for observation of clouds and aerosols[1]. The CALIPSO mission builds on this experience with a payload consisting of a two-wavelength polarization-sensitive lidar, and passive imagers operating in the visible and infrared spectral regions. The lidar profiles provide information on the vertical distributions of aerosols and clouds, cloud ice/water phase (via the ratio of signals in two orthogonal polarization channels), and a qualitative classification of aerosol size (via the wavelength dependence of the backscatter). Data from the three instruments will be used together to measure the radiative and physical properties of cirrus clouds. CALIPSO will be flown in a polar orbit as part of the Aqua constellation which, besides CALIPSO, consists of the Aqua, Aura, CloudSat, and PARASOL satellites. The satellites of the constellation will fly in a sun-synchronous polar orbit with a nominal ascending node equatorial crossing time of 13:30 local time. The orbit of CALIPSO will be maintained to provide space-time coincidence with observations from the other satellites of the constellation. CALIPSO is planned for launch in 2004, followed by a three year on-orbit mission.

2. SCIENCE OBJECTIVES

Climate models indicate that aerosols can significantly impact the Earth radiation budget through the scattering and absorption of incoming sunlight, which act as a significant radiative forcing[2]. Changes in the atmospheric aerosol can also impact cloud formation and radiative properties, as well as altering precipitation[3,4]. It now appears likely that anthropogenic aerosols resulting from industrial activities and agricultural burning are affecting weather and climate in some regions of the world[5]. Aerosols can also have health impacts in heavily polluted regions. It is now recognized that aerosol can be transported long distances, spreading the impacts over large regions. Unlike greenhouse gases, tropospheric aerosols are highly variable in space and time due to variable sources and short atmospheric residence times[6]. Thus, their effects are also highly variable. Because of this variability and the current limited capabilities to monitor aerosols using satellite instruments, basic questions remain on the global distribution and composition of aerosols. Model estimates of the radiative forcing from aerosols are highly uncertain, largely because current capabilities to observe aerosol from space are insufficient to constrain key assumptions in these models. The CALIPSO mission will en-

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hance current capabilities by providing: global, vertically-resolved measurements of aerosol distribution; an ability to perform height-resolved discrimination of aerosol into several types; and observations of aerosol at night and over bright and heterogeneous surfaces.

The sensitivity of the climate to forcings from aerosols, greenhouse gases, and other sources is largely controlled by the interactions between clouds and radiation[7]. Advances in modeling capabilities to predict climate change requires improved representations of cloud processes in models and decreased uncertainties in parameterizations of cloud-radiation interactions[8]. The largest uncertainties involve the use of models to (a) predict cloud properties based on atmospheric state, and (b) calculate radiative energy fluxes using these cloud properties. In particular, the largest sources of uncertainty in estimating longwave radiative fluxes at the Earth's surface and within the atmosphere are connected with current difficulties in determining the vertical distribution and overlap of multilayer clouds and their ice-water path. As demonstrated by LITE, satellite lidar has a significant ability to profile multi-layer cloud structures. CALIPSO together with the cloud-profiling radar on CloudSat, will provide comprehensive observations of cloud vertical structure on a global scale.

Because of the short time scales and nonlinear relationships typical of cloud processes, nearly simultaneous observations of atmospheric state, aerosol and cloud optical properties, and radiative fluxes are necessary to test the ability of cloud models to reproduce the physics of cloud-radiation feedbacks. The five satellites of the Aqua constellation will, together, provide an unprecedented, comprehensive suite of coincident measurements of atmospheric state, aerosol and cloud optical properties, and radiative fluxes. This combined dataset will allow fundamental advances in our understanding of the links between aerosols, clouds, and radiation necessary to more accurately assess future climate change.

The primary science data products to be obtained from CALIPSO which will address these objectives are listed in Table 1, along with their associated measurement uncertainties. Flux products will be obtained by combining CALIPSO cloud and aerosol measurements with measurements of broadband radiances from the CERES instrument on the Aqua satellite[9].

Data Product	Measurement Capabilities and Uncertainties
Aerosols	
Height, thickness	for layers with $\tau > 0.005$
Extinction profile	40%
Clouds	
Height	for layers with $\tau > 0.01$
Thickness	for layers with $\tau < 5$
Extinction profile	within a factor of 2 for $\tau < 5$
Ice/water phase	Layer by layer
Ice cloud emissivity	±0.03
Ice particle size	±50% for $\varepsilon > 0.2$
Radiation	
Surface LW fluxes	2.5 W/m^2 (zonal
Atmospheric LW fluxes	15% uncertainty

Table 1. CALIPSO Science Data Products and Uncertainties

3. PAYLOAD

The CALIPSO payload consists of three nadir-viewing instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer (IIR) and the Wide Field Camera (WFC). These instruments are designed to operate autonomously and continuously, although the WFC acquires science data only under daylight conditions. Science data are downlinked using an X-band transmitter system which is part of the payload. The physical layout of the payload is shown in Figure 1, with key instrument characteristics listed in Table 2.

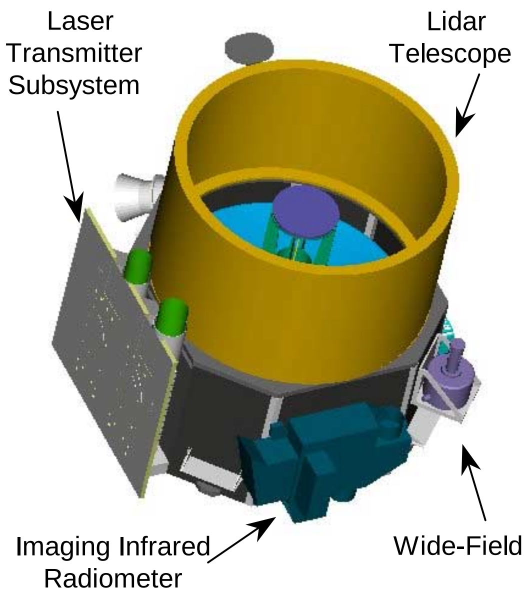

Figure 1. The CALIPSO Payload.

Characteristic	Value
CALIOP	
wavelengths	532 nm, 1064 nm
polarization	532 nm, ǀǀ and ⊥
pulse energy	110 mJ each wavelength
footprint	100 m
vertical resolution	30-60 m
horizontal resolution	333 m
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

Table 2. CALIPSO Instrument Characteristics

The design of the lidar is shown schematically in Figure 2. A diode-pumped Nd:YAG laser produces linearly-polarized pulses of light at 1064 nm and 532 nm. The atmospheric return is 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. Signal processing and control electronics are contained in boxes mounted on the payload housing. The receiver telescope is an all-beryllium 1-meter diameter design similar to the telescopes built for GLAS and ELISE. The telescope (Figure 3) has been completed and is now being integrated into the payload. The telescope primary mirror, secondary mirror, metering structure, and inner baffle are all made of beryllium. A carbon composite light shade will be added to prevent direct solar illumination of the mirrors. A fixed field stop is located at the telescope focus. 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.

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. Each laser produces 110 mJ of energy at each of the two wavelengths at a pulse repetition rate of 20.2 Hz. 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 radiator panel, avoiding the use of pumps and coolant loops. Each laser is housed in its own sealed canister filled with dry air at standard atmospheric pressure.

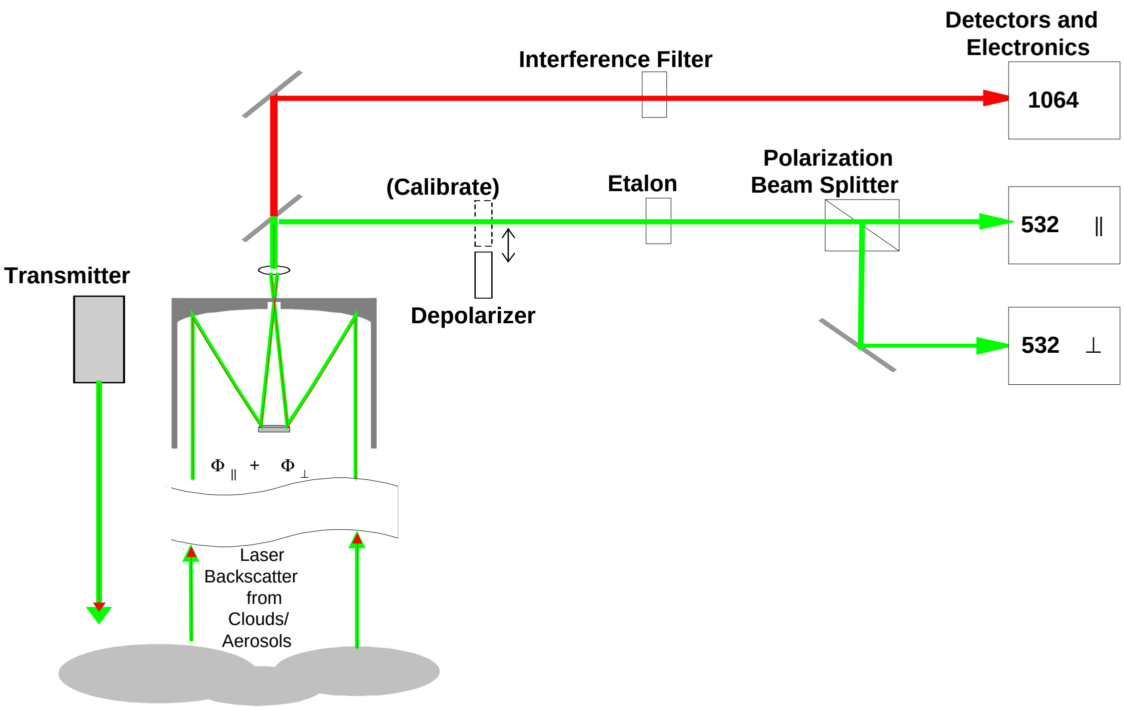

Figure 2. Optical schematic of CALIOP.

A space-qualifiable prototype flight laser (the Risk Reduction Laser, or RRL) - meeting all performance requirements of the flight lasers - was developed and tested to reduce risk in the development of the flight lasers. The RRL was used to conduct an extended life test which began in September 1998. The RRL exceeded 2 billion shots in August 2001, equivalent to a 3-year lifetime, without significant degradation. The test program was used to validate the flight laser design

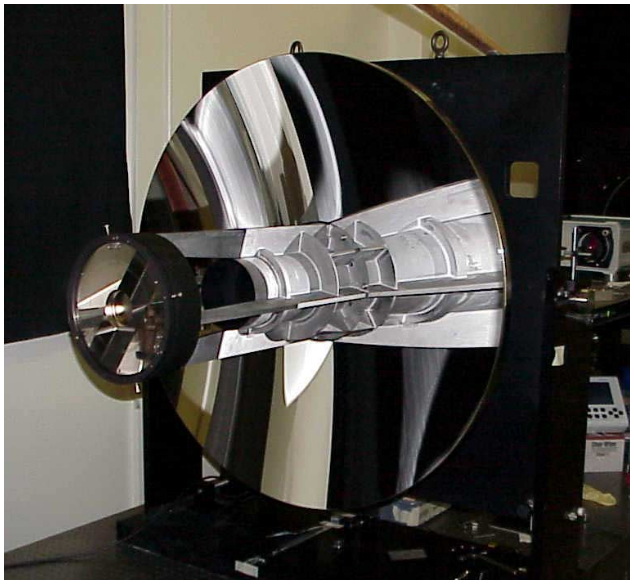

Figure 3. Flight telescope in final alinement testing.

Figure 4. Flight laser in pressurized housing.

and contamination control procedures. Both flight lasers have been fabricated (Figure 4) and they successfully completed space qualification testing in June 2002.

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. The lidar profiles are averaged to a resolution of 60 meters vertical and 1 km horizontal in the upper troposphere and to 180 meters vertical and 5 km horizontal in the stratosphere. The lidar is calibrated by normalizing the return signal in between 30 km and 35 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[10]. Design parameters of the lidar are summarized in Table 3.

Characteristic	Value
Laser:	diode-pumped Nd:YAG
pulse energy	110 mJ: 532 nm 110 mJ: 1064 nm
pulse rate	20.2 Hz
polarization purity	> 99% (532 nm)
cooling	passive
boresight range	+/- 1 degree
beam divergence	100 μrad
Receiver:	
telescope diameter	1 meter
FOV	130 μrad
detector/passband:	
532 nm	PMT/ 35 pm
1064 nm	APD/ 400 pm
Spatial resolution:	
lower troposphere	333 m horiz, 30 m vert
upper troposphere	1 km horiz, 60 m vert
stratosphere	5 km horiz, 180 m vert

Table 3. Key lidar parameters

The CALIPSO payload also contains two passive instruments: the Imaging Infrared Radiometer (IIR), provided by CNES; 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 are chosen to optimize joint lidar/IIR retrievals of cirrus emissivity and particle size. The IIR is built around an Infrared Sensor Module (Figure 5), developed for the IASI instrument. Use of a microbolometer detector array in a non-scanning, staring configuration allows a simple and compact design to perform measurements at a 1 km resolution with a NETD better than 0.3 K (at 210 K) in all spectral bands. 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 a spatial resolution of 125 meters. The WFC provides meteorological context for the lidar measurements and allows highly accurate spatial registration, when required, between CALIPSO and instruments on other satellites of the Aqua constellation. WFC data will be used during daytime for the retrieval of cloud properties.

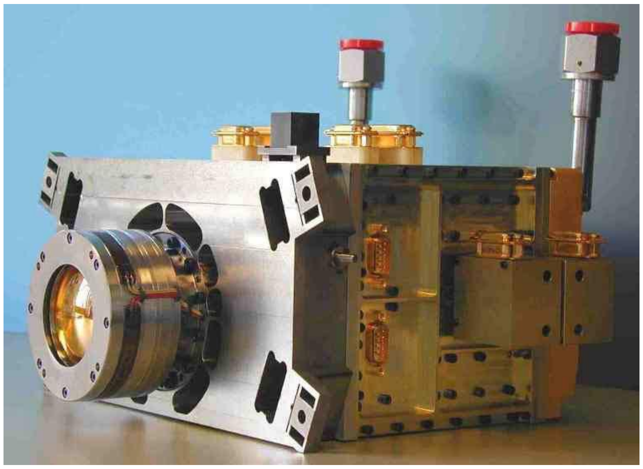

Figure 5. Infrared Sensing Module, flight unit, of the IIR.

4. OBSERVING STRATEGY

CALIPSO will fly in formation with the EOS Aqua satellite as part of the Aqua constellation. The Aqua constellation is a group of 5 satellites which will fly in loose formation to allow investigation of the Earth system by synergistically combining data from multiple platforms. The Aqua satellite was launched in May 2002. The Aura, CALIPSO,

CloudSat, and PARASOL satellites are all scheduled for launch in 2004. CloudSat carries a 95 GHz cloud profiling radar and PARASOL carries a multi-channel wide field of view, polarization sensitive imager similar to POLDER. The CALIPSO orbit will be controlled to provide space-time coincidence with observations from the other satellites of the constellation. The satellites of the constellation will fly in a sun-synchronous 705-km circular orbit with an ascending node equatorial crossing time of 13:30 local time.

The CALIPSO orbit will be 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 the TOA radiative fluxes from the clouds observed by the two platforms will differ by less than 10 W/m^2, which is the expected 1-sigma uncertainty in the instantaneous CERES measurements themselves. Based on experience with the JASON satellite, which uses the same PROTEUS spacecraft bus as CALIPSO, satellite pointing can be controlled to about 300 meters. If more accurate co-registration of CALIPSO and Aqua observations is required, correlation of WFC imagery with the MODIS scene will allow spatial co-registration of the two data sets to better than 100 m during the day. The CloudSat satellite will fly in formation with the CALIPSO satellite, at an average separation of about 12 seconds, and will be controlled to provide coincident radar and lidar observations of clouds.

Table 4 lists the measurements needed to address the CALIPSO science objectives and indicates a number of the synergies available from combining CALIPSO observations with the additional measurements available from the other instruments of the constellation.

5. MEASUREMENTS

Simulated CALIPSO 532 nm raw data derived from LITE observations over southern Africa are shown in Figures 6 and 7. This data segment shows several layers of cloud located above a layer of biomass smoke which is capped by an inversion at about 4 km altitude. The clouds vary from subvisible cirrus, near the tropopause at 17 km, to optically thin cirrus between altitudes of 10 km and 15 km and highly attenuating cloud, probably supercooled water droplets, located below 10 km. Because the LITE instrument did not measure depolarization, clouds above about 10 km were prescribed to be ice in this simulation, with particle depolarization of 30%. Clouds below about 10 km, aerosols, and the Earth's surface are prescribed to be non-depolarizing. Note that even a layer of thin, subvisible cirrus near 17 km altitude stands out clearly in both parallel and perpendicular channels.

Science Objective	Measurement	CALIPSO	Constellation
1. Direct aerosol forcing	Aerosol vertical distribution and extinction profiles	CALIOP	
	Aerosol optical depth	CALIOP	MODIS, PARASOL
	Aerosol type information	CALIOP	MODIS, PARASOL
	Aerosol absorption		Aura - OMI
	Broadband radiances		Aqua-CERES
2. Indirect aerosol forcing	Aerosol and cloud vertical distributions	CALIOP	
	Cloud reflectance and droplet size		Aqua - MODIS
	Broadband radiances		Aqua - CERES
3. Longwave surface and atmospheric fluxes	Cloud height and thickness, multilayering	CALIOP (thin cloud)	CloudSat – CPR (thick cloud)
	Cloud ice-water phase	CALIOP (profiles)	PARASOL, MODIS (cloud-top only)
	Cirrus emissivity and particle size	CALIOP + IIR + WFC	Aqua-MODIS, AIRS
	Other cloud properties		CloudSat, PARASOL, MODIS, AIRS, AMSR/E
	Broadband radiances		Aqua-CERES
4. Cloud radiative feedbacks	All elements of (3) plus:		
	Cloud optical depth	CALIOP	MODIS, PARASOL

Table 4. Science and measurement objectives.

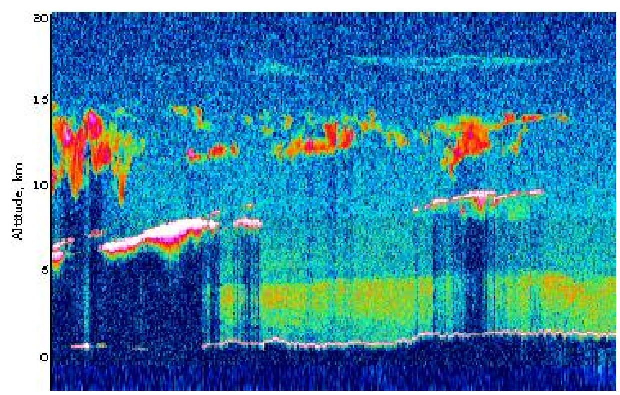

Figure 6. Simulated CALIPSO 532 nm observations (parallel channel).

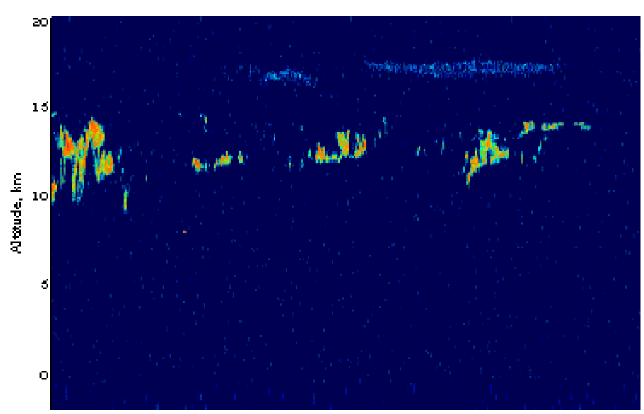

Figure 7. Simulated CALIPSO 532 nm observations (perpendicular channel).

CALIOP is required to accurately measure signal returns from the aerosol-free region between 30 km and 35 km 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. Figure 8 shows the predicted layer detection sensitivity of the lidar in terms of the minimum detectable volume backscattering coefficient, β_{532}, for a given amount of signal averaging. These results were obtained using the current instrument design specifications and a performance model based on standard target detection theory. These results assume vertical averaging of 60 m. The horizontal bars in the figure show representative magnitudes of aerosol and cirrus backscatter. The range of aerosol backscattering shown corresponds to the 5^{th} and 95^{th} percentiles of the lower troposphere values observed by LITE.

Most cloud layers can be detected at the highest resolution of the downlinked data, using single shots below an altitude of 8 km and averaged horizontally over 1 km above 8 km. Further averaging is required to detect most aerosol layers and very weak clouds. Figure 8 indicates all cloud and most aerosol layers can be detected with 20 km averaging, but the production algorithm will perform additional averaging to provide even greater detection sensitivity. In the production algorithm, the averaging is increased in several steps to obtain the optimum balance between spatial resolution and detection sensitivity. The layer detection and extinction retrieval algorithms are based on a novel multipass scheme and operate on multiple spatial resolutions[11, 12].

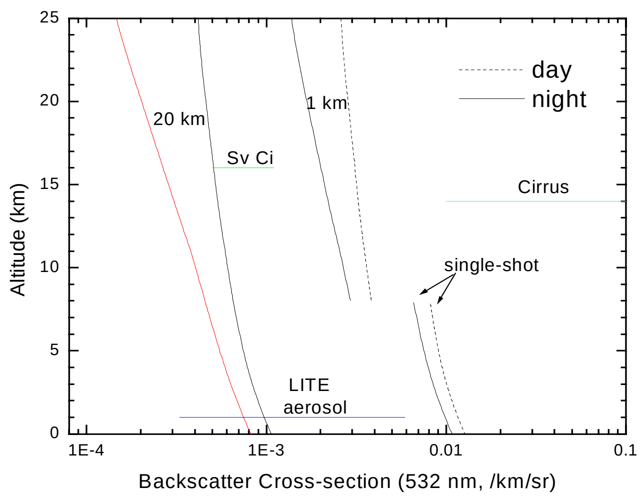

Figure 8. Backscatter detection sensitivity at 532 nm for vertical averaging of 60 m and either a) no horizontal averaging; b) horizontal averaging over 1 km; or c) averaging over 20 km.

5.1 Aerosol Measurements

CALIPSO not only observes the vertical profile of aerosols, but also provides unique, vertically resolved information related to aerosol type: aerosol particles can be classified as large or small based on the spectral dependence of the backscatter signal and the depolarization signal indicates whether the particles are dry or hydrated. CALIPSO provides these capabilities over bright and heterogeneous land surfaces, at night, and under other conditions which are difficult or impossible for passive sensors, such as above clouds or beneath thin cirrus. Figure 9 illustrates the ability of lidar to observe complex distributions of of aerosols and clouds from space. A dust layer lies on top of a marine boundary layer which is heavily loaded with aerosol and embedded broken clouds. To the left, the dust layer has become detached from the boundary layer. Note that aerosols can be observed below an attenuating cirrus layer located at 10-15 km altitude at the right side of the figure.

Combined with MODIS and CERES on the Aqua satellite, CALIPSO will allow observationally-derived estimates of direct aerosol forcing on regional and global scales. Aerosol *indirect* radiative effects can be estimated from a statistical analysis of ensembles of broken, low-level, single-layered cloud systems which are embedded in aerosol plumes of various types. Kaufman and Fraser[13], for example, have used AVHRR observations to deduce statistical relationships between aerosol optical depth, cloud droplet size, and cloud reflectance associated with smoke plumes over the Amazon

Region. This same approach is applicable to MODIS data. CALIPSO will allow improved assessments of aerosol indirect forcing through improved aerosol measurements as well as by unambiguously distinguishing clouds embedded in aerosol layers from those located above or below the layer

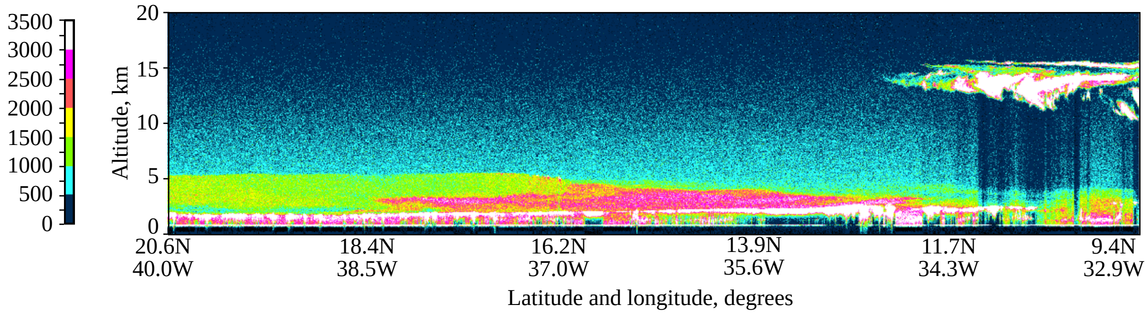

Figure 9. LITE 532 nm night-time raw data showing Saharan dust over the Atlantic Ocean on 17 September 1994. A layer of dust (below 5 km) is located above a cloud-capped marine boundary layer (~1 km). At the right, a layer of cirrus is seen at an altitude of 15 km.

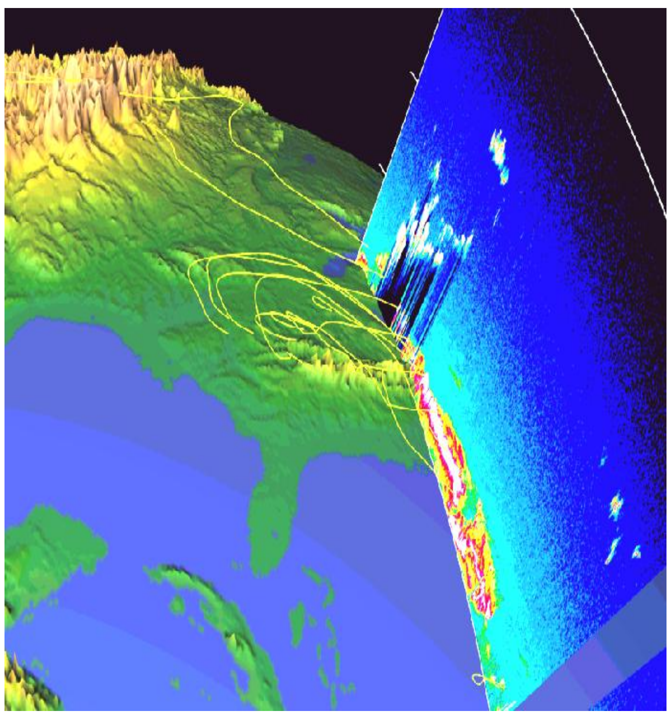

Figure 10. LITE data showing a deep haze layer over the eastern US and western Atlantic Ocean. Back trajectories show transport at the 850 mb level over the previous 5 days.

Ultimately, the most fruitful exploitation of CALIPSO aerosol data will involve model assimilation. Chemical transport models are now capable of generating realistic aerosol distribution from source inventories of the major aerosol species[14,15]. It has been found that model performance can be improved by assimilating observations of aerosol optical depth derived from passive satellites[16]. Assimilation of observations provides useful constraints on the model, mitigating errors due to source, sinks, and transport processes within the model. Models currently perform poorly in predicting the vertical distribution of aerosol, and global lidar observations will provide constraints with which to test and improve model parameterizations. Correct prediction of the aerosol vertical profile is particularly important because aerosol residence time, and thus the radiative impact, increases significantly when the aerosol is lofted above the boundary layer.

Models can also provide insights not available from observations. As illustrated in Figure 10, models can be used to relate observed aerosol to source regions and, combined with source inventories, can be used to gain insights into chemical speciation of the aerosol and the partitioning of aerosol between natural and anthropogenic origin. Model assimilation can also potentially be used as a sophisticated interpolation scheme to take the sparse observations from nadir-pointing lidar, and create a time-dependent, 3-D representation of the global aerosol field.

5.2 Cloud Measurements

A major source of uncertainty in surface flux estimates is a lack of knowledge of the degree of cloud overlap in multi-layered cloud systems[17]. Both surface observations and LITE data[18] indicate that roughly half of all cloud systems are multilayered. Current cloud retrievals from passive satellite sensors detect only an upper cloud layer or retrieve one

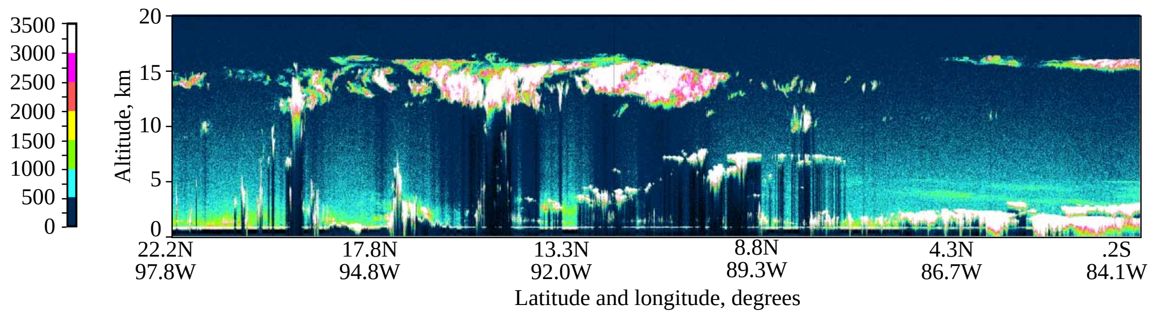

Figure 11. LITE 532 nm night-time raw data showing multiple cloud layers observed over the tropical Pacific Ocean on September 14, 1994.

equivalent cloud layer. In contrast, Figure 11 indicates the capabilities of lidar to observe the vertical structure of multi-layer cloud. Although the lidar beam is blocked by dense boundary layer clouds and deep convective clouds, LITE demonstrated that space lidar has a significant ability to profile multilayer cloud. LITE profiles penetrated to an altitude of 1 km or less in 70% of all cloud cases.

Both the infrared emissivity and particle size of cirrus can be estimated from the large difference in absorptivity of ice between the three IIR channels[19]. 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, allowing improved retrievals of cloud particle size. CERES will provide the matched TOA radiative fluxes necessary to evaluate the radiative forcing as a function of thin cirrus cloud properties. By combining CALIPSO measurements of cloud vertical structure with simultaneous CERES broadband radiation and cloud optical property measurements from CALIPSO and Aqua, estimates of surface LW flux and LW heating rates within the atmosphere will be significantly improved. Additional improvement will be realized from combining coincident observations of deep clouds from CloudSat with CALIPSO and Aqua observations. Measurements of the linear polarization of the lidar return signal will provide the first spaceborne vertical profiles of cloud particle phase, allowing a determination of the vertical distribution of cloud particle liquid and ice phases. CALIPSO measurements will also validate MODIS and AIRS cloud property retrievals for optically thin clouds.

6. SUMMARY

The CALIPSO mission is designed to provide unique and important observations of clouds and aerosols. The comprehensive, combined data set to be acquired by CALIPSO and the other satellites of the Aqua constellation, will allow the fundamental advances in our understanding of the links between aerosols, clouds, and radiation which are needed to accurately assess future climate change. Realizing this potential will require careful coordination with supporting modeling and correlative measurement efforts.

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