25 Years of CALIPSO (1998 – 2023)

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Abstract. Selected for development in 1998 and launched together with CloudSat in 2006, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission terminated science operations in the summer of 2023 after completing 17 years of on-orbit observations. As one of NASA's Earth System Science Pathfinder missions, CALIPSO was truly a pathfinder. CALIPSO observations have provided a new perspective on clouds and aerosol and have not only met but far exceeded the original objectives of the mission. Many unanticipated findings and data applications have been discovered along the way. Flying with many other remote sensing instruments, as part of the A-train constellation, stimulated the discovery of numerous retrieval synergies between lidar and other sensors. This paper describes how the CALIPSO mission came to be, discusses some of the early choices made by the CALIPSO team that shaped the mission, and some of the challenges facing the team in developing the first-ever global climatologies of aerosol and cloud based on lidar observations.

Keywords: space lidar, active remote sensing, clouds, aerosols

1 Introduction

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission began with the selection of the Step-2 proposal to the NASA Earth System Science Pathfinder (ESSP) program in December 1998. The 3rd International Workshop on Space-Based Lidar Remote Sensing Techniques and Emerging Technologies was held in June 2023, just after CALIPSO completed 17 years of observations and a few weeks before the planned termination of CALIPSO payload operations. Therefore the Workshop seemed like a good time to take a retrospective look at how CALIPSO came to be and highlight a few of the challenges that were addressed and a few of the many achievements. More than a decade of global cloud and aerosol profiling, collocated with many other remote sensing observations from the A-train constellation, has revolutionized the way aerosol and cloud studies are done, and provided new ways of evaluating models. CALIPSO broke new ground in many areas, forcing the CALIPSO team to creatively address many challenges.

2 CALIPSO Grew from LITE

The Earth Observing System (EOS), consisting of the Terra, Aqua, and Aura satellites was conceived in the 1980’s, developed in the 1990’s, and launched between 1999 and 2004. The initial vision included an advanced lidar for ozone and water vapor profiling, which was later descoped along with a number of other sensors due to cost.

Meanwhile, the Lidar In-Space Technology Experiment (LITE) was developed as a three-wavelength (1064/532/355 nm) backscatter lidar by NASA Langley Research Center (Langley), beginning in the late 1980’s. LITE flew on the NASA Space Shuttle STS-64 mission in September 1994 [1]. LITE only acquired 53 hours of observations, during the 2-week mission of STS-64 but provided our first global-scale view of cloud and aerosol from a lidar perspective. LITE gave us our first view of atmospheric structure on a global scale and observed many parts of the globe never seen by lidar before. Dense clouds block lidar signals but LITE showed that the global coverage of dense clouds blocking the beam was much less than expected. LITE also observed the vertical distribution of aerosol on a global scale, observing aerosol in many regions never observed by lidar before.

LITE was developed as a technology demonstration but also served as a proof of concept that a satellite lidar could provide unique and essential observations of aerosol and clouds. In addition, the successes of LITE motivated NASA to begin exploring the possibilities of a free-flying lidar satellite. The NASA Earth System Science Pathfinder (ESSP) program was initiated in the mid-1990’s to fly relatively small science missions to fill gaps in the global observing system. Immediately following the LITE mission, design studies of a free-flying lidar to study the global distribution and properties of clouds and aerosols were begun at Langley, targeting the new ESSP program.

Around that time, a joint Langley-JPL workshop was held to discuss possibilities for a satellite mission involving a cloud profiling W-band (94 GHz) radar and an elastic backscatter lidar, due to the realization that the combined capabilities of lidar and W-band radar were necessary to address the need for vertical profiling of cloud occurrence and water/ice mass distributions. Similar discussions were happening at about the same time in Europe [2], which ultimately resulted in the ESA EarthCARE mission [3]. Initial discussions with JPL envisioned an ESSP mission carrying a backscatter lidar, W-band radar, and several passive sensors. In the end the radar and lidar were proposed to ESSP as separate missions due to the cost cap on individual ESSP missions.

A lidar proposal was submitted in 1996 but was unsuccessful, primarily due to cost issues. Looking forward to the next ESSP opportunity, the Langley team contacted members of the French science community and negotiated a partnership where Langley would develop a payload consisting of a two-wavelength, depolarization lidar (Cloud-Aerosol Lidar with Orthogonal Polarization, CALIOP, rhymes with eye-oh-pea), a Wide Field Camera (WFC) with a single visible channel, based on a BATC star tracker, fulfilling the function of the film camera flown on LITE, a payload controller, and an X-band transmitter to downlink science data [4]. The Centre National d’Etudes Spatiale (CNES) was to provide a PROTEUS spacecraft and an infrared imaging radiometer (IIR), reducing the mission cost to NASA to within the ESSP cost cap. The IIR was a compact instrument, built by SODERN (Paris), based on a new technology 2D bolometer array and matching much of the capability of the MODIS infrared channels in a much smaller package. Ball Aerospace Technologies Corporation (BATC) was prime contractor for the payload and fabricated CALIOP, except for the detectors and detector electronics which were designed and built at Langley. This second CALIPSO proposal was selected in December 1998, with the CloudSat proposal selected in 1999 after additional analysis was performed.

3 Early Decisions

Analysis of the LITE laser after STS-64 returned to Earth showed significant contamination-induced laser damage due to the 355 nm laser light. To reduce laser technical risk, it was decided that the CALIOP laser would only operate at 1064 nm and 532 nm, but there was a desire to do something new, beyond LITE. At the time there were few polarization lidars but Ken Sassen had recently published a paper in the Bulletin of the American Meteorological Society pointing out the utility of lidar depolarization measurements [5]. A decision was made that the CALIOP laser would transmit a highly linearly polarized beam and the lidar receiver would have co-polar and cross-polar 532 nm channels.

Following on the experience from LITE, we realized there were a number of design challenges in moving from a two-week experiment on the Space Shuttle to an extended mission on a free flyer. LITE was based on a water-cooled, flashlamp pumped laser. The CALIOP laser would have to be passively cooled and laser lifetime was a major concern since the flight lasers were required to have a design lifetime of 3 billion shots. Diode-pumped lasers were new at the time and laser pump diodes were not as reliable as they are now. Laser damage from contamination was also a concern and the laser would need a ruggedized design to survive G-forces during launch. Because of laser risk concerns raised over the first proposal, a prototype of the flight laser was fabricated, and life testing was begun in time to include results in the proposal to ESSP in order to demonstrate the reliability of the design. The Risk Reduction Laser (RRL) [6] was jointly conceived by Langley and BATC and developed by Fibertek Inc. in collaboration with experts from Langley and BATC. Fabrication of the RRL began about a year before the proposal to ESSP was due. The RRL was based on prior lasers designed for field deployment, but output power was derated by a factor of two from the design values to promote long lifetime. Peak optical power of the laser pump diodes was derated significantly from their design values and power density in the Nd:YAG slab was a small fraction of the damage threshold. Prior experience at Fibertek indicated that operation in an atmosphere containing oxygen reduced contamination risk relative to operation in a vacuum so the flight lasers were designed to operate inside a canister pressured to just over 1 bar with dry air. A comprehensive contamination control plan was developed before fabrication began. The RRL was fabricated and was 50 million shots into an extended life test when the second proposal was submitted in 1998. The RRL was eventually operated for 1.2 billion shots (about 2 years) with only a 4% decrease in pulse energy, verifying the reliability of the design and the success of the contamination control procedures developed to avoid contamination damage.

There is always a desire to fly active sensors in a low orbit, to maximize signal-to-noise ratio (SNR), and fortunately LITE flew on STS-64 at 260 km altitude. There was initial discussion of flying CALIPSO as low as possible. With a primary science objective of better characterizing the impacts of aerosols and clouds on Earth's radiation budget, the CALIPSO science team identified numerous advantages of flying in formation with the EOS-PM satellite (later renamed EOS Aqua) which was to carry MODIS and CERES. The EOS science strategy was for MODIS to observe aerosols and clouds and for CERES to use MODIS cloud observations in its task of measuring broadband radiative fluxes at the top of the atmosphere. Formation flying of CALIPSO with CloudSat was always a key desire, which would not only allow the profiling of virtually all clouds but also enable joint retrievals of cloud properties. The driving synergy with CERES was the ability to use collocated CALIOP and CloudSat profiles of cloud vertical structure in the CERES flux retrieval algorithms. Flying in formation with Aqua, CALIOP could also provide validation of MODIS cloud masking and cloud retrievals [eg: 7] and MODIS would provide context for the CALIOP curtains of cloud and aerosol observations. In the end, the science team felt the synergies of flying with Aqua at 705 km outweighed the increase in SNR that could have been achieved in a lower orbit and we convinced CloudSat to also fly at 705 km. As the A-train developed – adding Aura, POLDER, and OCO-2 – many more synergies were realized.

Formation flying of CALIPSO and CloudSat was a further challenge. At the time, flying in close formation had not been attempted for Earth remote sensing satellites and some cast doubt on its feasibility. But JPL successfully developed procedures to control the CloudSat spacecraft to fly to CALIPSO with an along-track separation of 12 – 15 seconds, while minimizing the cross-track differences between the CPR and CALIOP footprints. The impact of the collocated radar-lidar cloud data on our understanding of global clouds was called out in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

4 Challenges and Innovations

Calibration of the lidar attenuated backscatter returns was to be performed using the atmospheric normalization technique, based on molecular backscatter found above the stratospheric Junge aerosol layer. This technique references lidar returns from the mid-stratosphere to molecular density profiles derived from global re-analysis products, essentially using the molecular atmosphere as a calibration target, and had been used for decades on ground-based lidars [8]. Therefore, the lidar was required to accurately measure weak signals from high altitude molecular backscatter returns, but there was also a requirement to measure the backscatter signals from strongly scattering liquid clouds. This required the analog detection system to have a highly linear dynamic range of six orders of magnitude [9]. This technical challenge was met by Langley engineers.

Calibration was initially performed using lidar returns from 30 km to 35 km, but careful analysis showed that aerosol concentrations in the tropical stratosphere, while low, were enough to cause significant calibration errors which propagated into CALIOP retrievals. Therefore, starting with Version 4 data products, the calibration region was raised to 35 km to 40 km. Raising the altitude required a major change to the Level 1 calibration software as substantially greater averaging was required to maintain the same calibration precision and CALIOP adopted cross-track averaging for the first time [10]. Subsequent analysis has shown the Version 4 calibration has excellent long-term stability. The red curve in Fig. 1 shows a time series of CALIOP 532 nm attenuated backscatter integrated from 25 km to 40 km, where the lidar backscatter is dominated by molecular scattering, and averaged over 50°S – 50°N. The blue dashed curve is the normalized molecular number density from the MERRA-2 re-analysis product, interpolated to the CALIPSO ground track, over the same altitude range. The black curve shows the time history of 532-nm laser pulse energy over the mission. Changes in pulse energy over the mission were dominated by the loss of pump diodes, and a switch between primary and backup lasers in March 2009. The apparent dip in laser energy after 2020 is likely due to a degradation of the laser energy sensor. It is apparent the calibration scheme is able to accurately account for these variations in pulse energy, producing a stable long-term record, as demonstrated by the high correlation of stratospheric attenuated backscatter and molecular density. The discrepancy between the two in early 2022 is due to the eruption of the Hunga-Tonga volcano, which injected aerosol into the 35 km – 40 km altitude region.

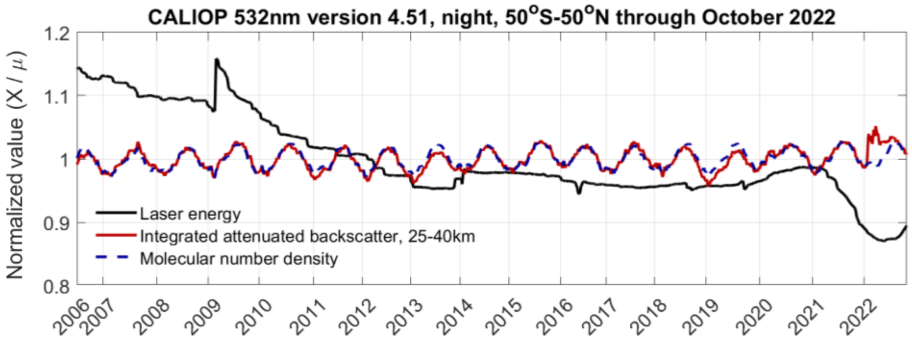

Fig. 1. Normalized trends of laser total pulse energy (black), 532 nm attenuated backscatter profiles integrated between 25 km and 40 km altitude (red), and molecular number density integrated over the same altitude range (blue) [11].

Langley had developed retrieval algorithms over several decades for a ground-based 48” lidar, used for studies of stratospheric aerosol, and for lidars flown on airborne campaigns. Processing the data from these instruments was a relatively manual operation. Observations performed for aerosol studies were often acquired only in cloud-free conditions. CALIOP required the development of new algorithms: algorithms to detect the boundaries of cloud and aerosol layers, to automatically discriminate between aerosols and clouds, and to use the lidar signals to classify aerosol by type in order to estimate the aerosol lidar ratio needed for extinction retrievals [12].

These algorithms were developed before launch but required much development and refinement after launch, not becoming substantially mature till Version 3 products were released in 2010.

Ground-based and airborne lidars often use profile-averaging to increase sensitivity. For CALIPSO, hundreds of kilometers above the atmosphere, this was a necessity for aerosol retrievals. Traveling at a speed of roughly 7 km/sec and firing 20 pulses per second, the along-track spacing of CALIOP footprints was greater than the footprint diameter. For strongly scattering layers (water clouds), each pulse was therefore potentially measuring unique information. On the other hand, weakly scattering layers could not be detected without averaging multiple profiles, sometimes many profiles, together.

To preserve as much information as possible, and avoid averaging clouds and aerosols together, our solution was to develop a nested multi-resolution spatial averaging scheme [13]. The design of this scheme was partly driven by limits on computer processing power around the turn of the millennium. Lidar attenuated backscatter profiles were initially averaged to 5 km. If a cloud or aerosol feature was detected in this 5-km average, the 15 individual shots within the 5-km average were searched for any features which could be identified as single-shot resolution, with a cloud-clearing procedure applied at low altitudes where water clouds would likely be found. The profiles averaged to 5-km were then further averaged to 20 km and to 80 km to detect more tenuous layers. This multi-layer detection scheme significantly complicated the design of the data processing software but was essential to avoid cloud contamination of aerosol retrievals.

CALIOP was the first space lidar with depolarization capability. We had proposed to use depolarization to discriminate between water and ice clouds. This turned out to be a powerful means of vertically resolving cloud thermodynamic phase. Fig. 2 shows that when layer-integrated cloud attenuated backscatter and layer-averaged cloud depolarization are plotted against each other, ice and water clouds naturally fall into two distinct clusters. Thus, the

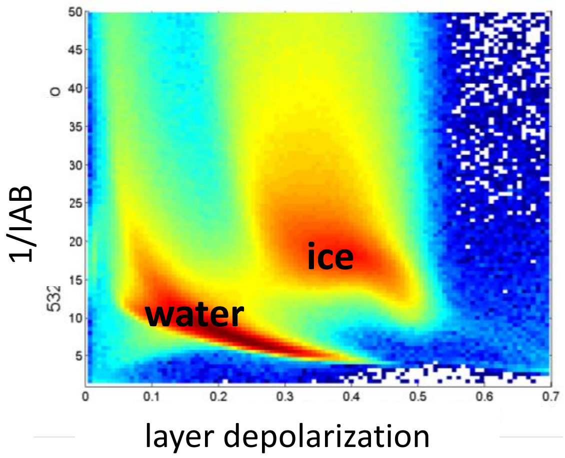

Fig. 2. Inverse of layer-integrated cloud IAB vs. layer-averaged cloud depolarization

discrimination of cloud thermodynamic phase comes directly from Level 1 profile data, not retrievals, and so is nearly assumption-free. The depolarization of the transmitted beam is not perturbed by passing through depolarizing layers, allowing the unambiguous identification of water clouds located under cirrus, which led to a finding that supercooled water clouds (found at temperatures roughly between 0°C and -38°C) were much more prevalent than had been thought [14].

Prior to launch, we did not have a good characterization of aerosol polarization characteristics around the globe, and it was not clear if CALIOP would have sufficient SNR to discriminate dust from spherical aerosols such as sulfate or marine aerosol. Once on orbit, we found that the SNR of the depolarization profiles exceeded our expectations. We were eventually able to use depolarization for aerosol type discrimination even in the stratosphere, where CALIOP was able to discriminate volcanic ash from sulfate [15]. The depolarization capability not only aided the selection of aerosol lidar ratios, but also allowed us to create the first global climatology of aerosol type, which turned out to be an important contribution (see Fig. 3) and to develop new retrieval algorithms which used depolarization profiles to correct the multiple scattering from water cloud returns [16].

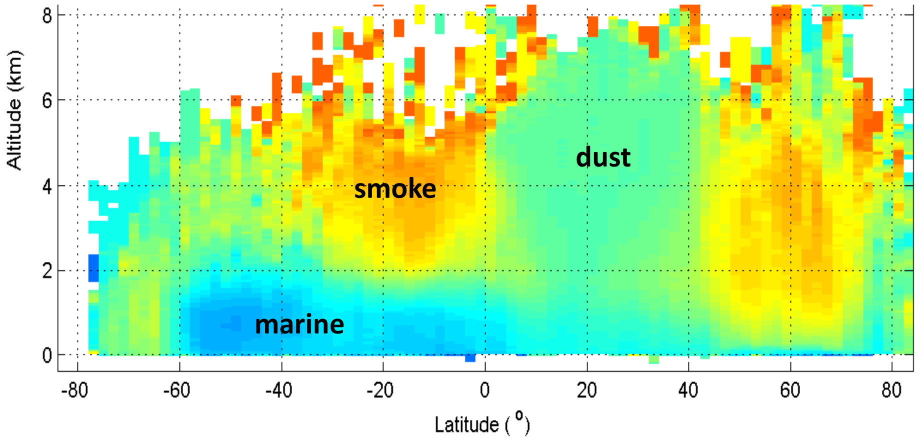

Fig. 3. Zonal mean distribution of aerosol types, June through August 2008. Color coding indicates mean aerosol lidar ratio from 20 (blue) to 45 (green) to 70 (orange).

5 Unique Data Products

Level 3 products (monthly mean retrievals mapped to a uniform global grid) are often the most used satellite data products. The unique characteristics of lidar data, relative to traditional passive sensors, required creative thinking about the design of Level 3 data products. The CALIOP Level 3 Cloud Occurrence Product is built from the Level 2 Cloud Layer Product (L2-CPro). Unlike passive sensors, CALIOP detects clouds at different horizontal scales, depending on how strongly they scatter, and reports these layers in L2-CPro at the scale at which they were detected. Due to the construction of the multi-resolution spatial averaging scheme, the layers reported at the different averaging scales are not simply the result of averaging the Level 1 data set to different horizontal scales and then detecting clouds. Clouds detected at 5 km, 20 km, and 80 km are independent, in the sense that features are detected at the highest of the three horizontal resolutions at which they can be detected but are not detected (again) at lower resolutions [13].

One must make a choice in how to merge these layers together into a Level 3 product. The Level 3 Cloud Occurrence Product uses ice cloud layers detected in single shots and detected after horizontal averaging to 5, 20 or 80 km, to detect weakly scattering thin cirrus (Table 1). Only single-shot data are used for water clouds because water clouds tend to be horizontally inhomogeneous and are often broken at the 1 km or 5 km scale, making water cloud data averaged to 5 km difficult to interpret. L2-CPro also reports the thermodynamic phase of each cloud layer as Ice, Water, or Unknown (when the phase algorithm was unable to choose between water and ice). If the cloud-aerosol discrimination algorithm is confident in the classification of a layer as 'cloud', it is included in the Level 3 Cloud Occurrence Product even if the phase algorithm is unable to determine if the layer is an ice cloud or a water cloud.

Table 1. Cloud layers from the Level 2 Layer Product used in constructing the Level 3 Cloud Occurrence Product. Y(es) and N(o) indicate whether the layers are merged into the Level 3 Cloud Occurrence Product. Detection of 1/3 km layers is only possible below 8.2 km as profiles above 8.2 km are averaged to 1 km horizontally on-board the satellite.

Layer Product:	1/3 km			5/20/80 km		
Cloud Phase:	Ice	Water	Unknown	Ice	Water	Unknown
8.2 – 20 km	---	---	---	Y	Y	Y
4 – 8.2 km	Y	Y	Y	Y	N	Y
0 – 4 km	Y	Y	Y	Y	N	Y

The global cloud amount measured by a satellite sensor depends on the sensitivity of the sensor to cloud [17]. Because CALIOP has higher sensitivity for cloud detection than passive sensors such as MODIS, CALIOP often reports higher cloud cover, especially for high cirrus. This is useful information but sometimes one wants to account for this factor when intercomparing datasets, to look for other discrepancies. In the Level 3 Cloud Occurrence Product, to facilitate 'fair' comparisons with various passive sensors, cloud amount can be computed using all cloud layers detected by CALIOP, or after applying one or more optical depth thresholds to make CALIOP sensitivity similar to that of another sensor (Table 2). Ice clouds are partitioned into a number of different optical depth bins, based on CALIOP extinction retrievals. However, for water clouds, only layers detected on single shots are included in the product and the Level 2 algorithms do not retrieve extinction at single-shot resolution. Therefore, the Cloud Occurrence Product only distinguishes between Opaque and Semi-transparent clouds, depending on whether or not the Earth surface or another cloud layer can be detected beneath a given cloud.

The CALIPSO team participated in a major intercomparison of global cloud climatologies conducted by the GEWEX project [17]. In addition to higher

Table 2. Cloud layer optical depth (τ) thresholds used for partitioning cloud amount in the Level 3 Cloud Occurrence Product.

Cloud Type	Optical Depth Bins
Ice	$0 < \tau < 0.01$
	$0.01 < \tau < 0.03$
	$0.03 < \tau < 0.1$
	$0.1 < \tau < 0.3$
	$0.3 < \tau < 1.0$
	$\tau > 1.0$
	Opaque
Water	Semi-transparent
	Opaque

detection sensitivity, CALIOP can detect multiple cloud layers in a column whereas passive sensors only retrieve an “effective” highest layer. To aid in intercomparisons of CALIOP cloud statistics with passive datasets, we have filtered CALIOP cloud statistics in several different ways and reported the statistics in different versions of the CALIPSO GEWEX product [18]:

- CALIPSO_column reports cloud amounts using all cloud layers detected within the atmospheric column
- CALIPSO_top uses only the uppermost cloud layer in each column
- CALIPSO_passive uses only the highest cloud layer in each column that has cloud optical depth > 0.3
- CALIPSO_opaque uses only the cloud layers which are opaque to CALIOP

The optical depth at which clouds become opaque to CALIOP depends on the reflectance of the underlying surface and lighting conditions, but opaque clouds tend to have optical depth greater than 3. Providing a CALIPSO GEWEX product based on the full CALIOP cloud dataset, as well as several filtered versions, provides flexibility in how this unique dataset can be used for comparisons with more traditional passive datasets. The ‘CALIPSO_opaque’ dataset provides an indication of how often CALIOP is not observing the full column. The ‘CALIPSO_passive’ dataset attempts to mimic the capability of typical Vis-IR imaging sensors and indicates the nature of the impact, relative to the full results of ‘CALIPSO_column’, that results from this limitation.

6 Summary

CALIPSO observations have now ended, but two years of funding remains to reprocess the entire mission dataset and perform final data archive and documentation activities. CALIPSO (and CloudSat) have demonstrated the practicality of active sensors for global profiling of clouds and aerosols: that active sensors can be as reliable and long-lived as passive remote sensing systems. CALIPSO (together with CloudSat) has enabled major advances in understanding, but the interaction of clouds, aerosols, and radiation are still at the heart of uncertainties in the future progression of climate change. We look forward to the launch of the ESA-JAXA EarthCARE mission in 2024, which will carry advanced lidar and radar instruments to begin the next phase of active remote sensing of the atmosphere.

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