CALIPSO Lessons Learned:

Retrieval aspects, CAL/VAL, and Scientific Applications

Aeolus Workshop, Frascati, 10-13 Feb 2015
First light: 7 June 2006

Three co-aligned instruments:
- **CALIOP**: polarization lidar
  - 30-60-m range resolution
  - 532 nm, 1064 nm, depol
- **IIR**: Imaging IR radiometer
  - 8.6, 10.5, 12.0 um
  - 1 km footprint, 60 km swath
- **WFC**: Wide-Field Camera
CALIOP Block Diagram

Features:
Analog detection
- 532 nm: PMT’s
- 1064 nm: APD
22-bit dynamic range
Active boresight adjust

Lidar calibration:
- $532_{\parallel}$ – normalization of molecular return
- $532_{\perp}$ – relative to $532_{\parallel}$ using on-board cal H/W
- 1064 – relative to $532_{\uparrow}$ using cirrus backscatter
Total Output Energy: Backup Laser

Primary Laser Shots On-Orbit: 1.61 Billion
Backup Laser Shots On-Orbit: 3.50 Billion

Pump diode bar drops:
year 1: 8
year 2: 4
year 3: 2
year 4: 4
year 5: 0
year 6: 0
CALIOP Retrieval Algorithms and Products

Level 1
1) Geo-locate profiles (3D)
2) Calibration
   532|| calibration
   532⊥-532|| gain ratio
   1064 relative calibration

Level 1 Lidar Product

Multi-Scale Layer Finder

Layer Finder -> Avg

Scene Classification
1) Discriminate cloud and aerosol
2) Identify aerosol type

Vertical Feature Mask (full resolution)

Extinction Retrieval
1) apply extinction algorithm to averaged profiles
2) further averaging as req’d
3) derive attenuation-corrected properties

Cloud and Aerosol Layer Products (1/3, 1, 5 km)

Aerosol Profile Product (120 m x 40 km)

Cloud Profile Product (60 m x 5 km)
Level 2 Processing

• Layers detected via contrast with clear-air scattering
  • Re-normalized below each layer

• Cloud-Aerosol Discrimination
  • Considers: 532 backscatter, 532/1064 ratio, depolarization
  • Probability distribution (PDFs) for cloud, aerosol based on training dataset
  • PDFs are altitude- and latitude-dependent

• Cloud ice-water phase, Aerosol typing
  • Necessary to choose lidar ratios
  • But is also important information

• Extinction retrieval
  • and for ice clouds: ice-water content
CALIPSOO Planned Products

• **Level 1**
  • DP1.1 - profiles of attenuated lidar backscatter (532, 532\(_\perp\), 1064)
  • DP 1.2 – IR radiances (8.65, 10.6, 12.05 \(\mu\)m)
  • DP 1.3 – Visible radiances (650 nm) (WFC)

• **Level 2**
  • DP 2.1A – Cloud/Aerosol layer product
    layer base and top heights, layer-integrated properties
  • DP 2.1B – Aerosol profile product
    backscatter, extinction, depolarization profiles, aerosol type
  • DP 2.1C – Cloud profile product
    backscatter, extinction, depolarization, IWC profiles, cloud ice/water phase
  • DP 2.1D – Vertical mask
    cloud/aerosol locations
  • DP 2.2 – IIR + CALIOP: cloud \(T_B(\lambda)\), emissivity, \(r_e\)
Layer Products

Cloud-Aerosol Mask

Cloud Phase

Level 1 profiles: 532 nm

Polluted Continental

Dust

Marine

Polluted Dust

Smoke
Un-Planned Products

Supported and available:
• Level 1.5: near-realtime cloud-cleared Level 1 product
  • for aerosol assimilation
• Polar Stratospheric Cloud product
• Level 3 Cloud product
  • 2 versions developed for GEWEX CA and COSP/GOCCP
• Level 3 Aerosol product (beta-version, update in work)
• Stratospheric aerosol product (later this year)

Unofficial products:
• Ocean surface wind speed
• Subsurface ocean measurement
• Sea ice cover
CALIOP First Light

532 nm Total Attenuated Backscatter, km/km

Begin UTC: 2006-06-07 11:11:06.82
End UTC: 2006-06-07 11:14:51.1902
Lessons Learned from On-orbit Checkout

- Discovered ranging error
  - Speed of light ≠ 3.0E+8 m/s
  - Required a change to payload software (~ 1 week)
- Intra-orbit drifts in 1064 channel calibration
  - Finally fixed last year
- Discovered excess PMT noise in South Atlantic Anomaly
  - Not seen during LITE (LITE orbit was lower)
  - Required modification of 532 nm calibration algorithm

![532 nm dark noise](image)
A few thoughts

• Learned how to operate the payload in thermal/vac and, during two atmospheric test campaigns. LEOP went very smoothly.

• Laser operation on-orbit much more stable than in lab or thermal/vac

• Comprehensive set of payload health and status measurements is necessary to understand on-orbit performance and diagnose anomalies, especially for the laser

• We have several ‘knobs’ to adjust the laser on-orbit
  • The only adjustment we’ve needed is the SHG conversion efficiency

• Spent considerable effort to minimize non-random noise - perhaps more than necessary to meet mission requirements
  • Has allowed measurements not originally anticipated
  • eg: calibration at 35-39 km altitude and monitoring stratospheric aerosol trends, based on averaging data over 16-days
HSRL on NASA B-200

A key resource for CALIOP validation:
- Aerosol backscatter and depolarization at 532 nm and 1064 nm
- Aerosol extinction via HSRL technique at 532 nm
- Dec 2005: first test flight NASA King Air (B-200)
- 2006-2014: > 110 CALIPSO underflights
532 nm Calibration Assessment

- Below: CALIOP and HSRL 532 nm attenuated backscatter data on 4/17/2009.
- CALIOP-HSRL bias calculated from backscatter signals in the free troposphere.
Validation from Langley HSRL

L1 validation and Calibration

(Rogers et al., 2011)

(Burton et al., 2013)
Thoughts on Validation

• Initially: “look-right” checks
  • At first, problems are obvious

• Have relied heavily on HSRL for aerosol validation, but have used many other resources:
  • Targeted aircraft campaigns
  • International field campaigns
  • Ground-based networks (Aeronet)
  • Satellite intercomparisons

• Yet, existing validation resources are insufficient
  • Have also benefited from comparison of standard retrievals with alternate retrieval algorithms (Liu et al., ACP, 2015)
Applications: > 1250 publications so far (~ 5/week)

Publications by Country (All Years)

- USA, 583
- France, 115
- China, 97
- India, 59
- Germany, 58
- Sweden, 27
- UK, 31
- Canada, 31
- Japan, 50
- South Korea, 16
- Australia, 17
- Italy, 19
- Other Countries, 112

Other Countries
- Norway
- Taiwan
- Netherlands
- Switzerland
- Finland
- Greece
- Israel
- Spain
- Russia
- Belgium
- Denmark
- Iran
- New Zealand
- Puerto Rico
- Brazil
- Cuba
- Pakistan
- Serbia
- Argentina
- Austria
- Cyprus
- Czech
- Republic
- Iraq
- Kyrgyzstan
- Malaysia
- Philippines
- Poland
- Portugal
- Senegal
- Thailand
- Turkey
Major Science Achievements

CALIPSO achievements and CALIPSO-enabled advances:

• The first global 3D climatology of aerosol
  • Leading to the first estimate of all-sky aerosol radiative effects

• Demonstration of the first accurate satellite cirrus retrievals
  • Dramatically improved retrievals of cloud ice-water content

• Advances in the evaluation of GCM clouds (alone and with CloudSat)
  • Quantification of systematic errors in passive cloud retrievals

• Closure of the global surface radiation budget from merged A-train observations (Kato et al. 2012)

• A new understanding of the tropical tropopause transition layer

• Quantification of 2006-2012 stratospheric aerosol forcing trend

• New constraints on ozone hole heterogeneous chemistry
Aerocom Phase I Intercomparison

CALIOP profiles used to characterize aerosol vertical distribution predicted by 11 global models (Koffi et al., 2012)
**Aerosol Direct Radiative Effect**

**Clear-Sky Aerosol SW DRF**

CALIOP allows first estimate of aerosol radiative forcing in cloudy skies

- Based on LaRC C3M product, with merged CALIOP and MODIS aerosol-cloud observations (Kato et al. 2010)

**All-Sky Aerosol SW DRF**

Global radiative forcing from aerosols smaller than estimated from clear-sky observations alone:

- **2008 annual mean DRE**
  - all-sky: -2.34 W/m²
  - clear-sky: -3.30 W/m²
Aerosol type: CALIOP vs. GMAO model

CALIOP and MERRAero VFM on July 7, 2009

a. CALIOP VFM
b. MERRAero Level 2 VFM
c. MERRAero Level 3 VFM

(Nowottnick and da Silva)
Aerosol Assimilation Experiments at NRL

(Zhang, et al., 2014)
CALIOP stratospheric data has been used to constrain stratospheric radiative forcing over the last decade: contributes to understanding the surface temperature “hiatus” (Santer et al., GRL, 2015)

“The radiative forcing of volcanic aerosols is well understood ... There have been no major volcanic eruptions since Mount Pinatubo in 1991, but several smaller eruptions have caused an average radiative forcing for 2008–2011 of −0.11 W m⁻² compared to 1750.” (Solomon et al., Science, 2011)

**Figure 8.13** (Top) Evolution of extinction ratio profile in the tropics from SAGE II (1985–2005) and CALIPSO (2006–2012)
Interannual cirrus radiative feedback

Zhou and Dessler, GRL, 2014:

![Figure 3](image)

Figure 3. Zonal mean cirrus feedback. (a) Response of cirrus clouds fraction to interannual surface warming (shading), calculated by regressing monthly mean anomalies of cloud fraction against monthly mean anomalies of global mean surface temperature (from ERA-Interim). Contours are the 6 year mean cirrus cloud fraction (in %/100 hPa), the gray solid line denotes the ERA-Interim climatological tropopause pressure, and black dashed line is the climatological value plus the response to 1 K surface warming. (c) Cirrus feedback as a function of latitude and CTP. The correlation coefficient is 0.95 between Figures 3a and 3c. Crosses denote pixels where the linear regression slope is statistically distinguishable from zero.
Multi-Model Evaluation

- Nam, Bony, Dufresne, and Chepfer (2012): comparison of predictions from 8 CMIP5 models with CALIPSO-GOCCP

- Several models fail to reproduce the basic characteristics of low cloud:
  - Underestimate vertical development
  - Overestimate fraction of cloud below 1 km

(Nam et al. 2012)
Identification of Cloud Ice/Water Phase

Cloud ice/water phase:
- Polarization techniques (CALIOP, POLDER) superior to spectral techniques (MODIS, AIRS)

AIRS vs. CALIOP:

MODIS vs. POLDER for CALIOP water clouds
“A particular challenge for models is the simulation of the correct phase of the cloud condensate ...”

Frequency of ice vs. temperature: LMDZ, LMDZ+COSP, CALIPSO-GOCCP

Fraction of ice cloud with respect to the total:
- as simulated by the LMDZ global model (black solid line)
- as observed by CALIPSO-GOCCP (solid + circle lines)
- as simulated by “LMDZ + lidar simulator” (dashed lines)

(Cesana and Chepfer, 2013)
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