The CALIPSO Spaceborne Lidar

Carl Weimer

cweimer@ball.com

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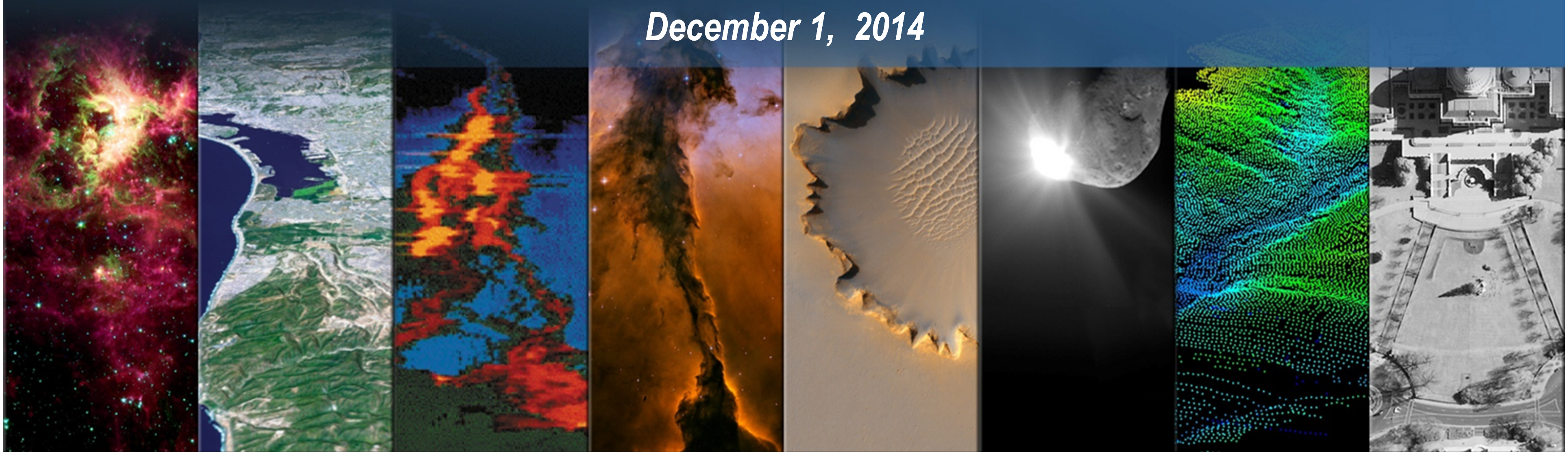


Agility to Innovate, Strength to Deliver

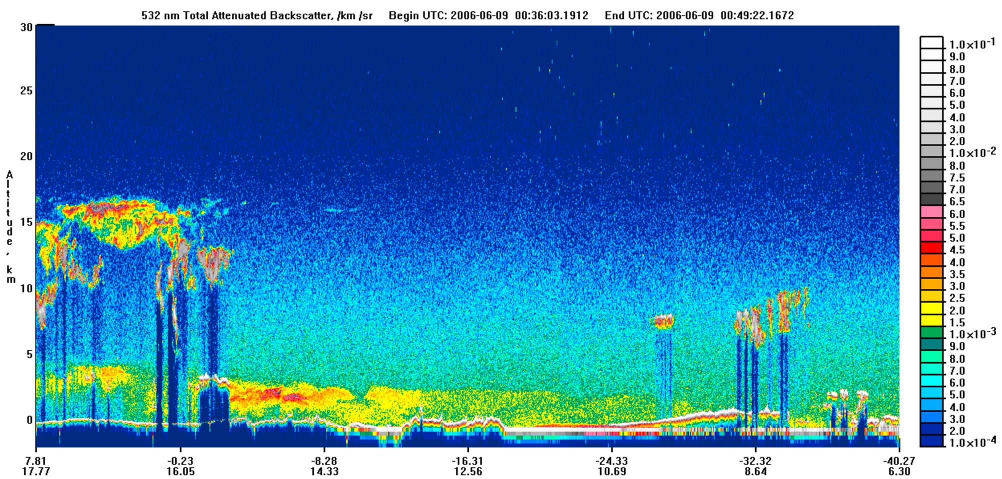
Ball Aerospace
& Technologies Corp.

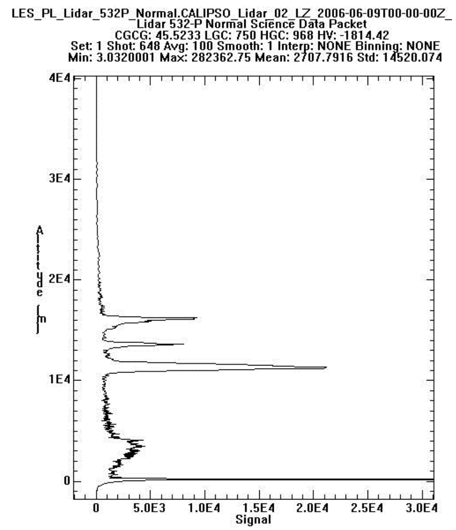
Some Lidars/Altimeters in Space

Apollo 15	1971	Ranging (Moon)
Clementine	1994	Ranging (Moon)
LITE	1994	Profiling – Aerosols and Clouds (Earth)
Balkan	1995	Profiling
NEAR	1996	Ranging – (Asteroid)
SLA-01	1996	Ranging
MOLA II	1996	Ranging (Mapped Mars)
SLA-02	1997	Ranging
ICEsat/GLAS	2003	Ranging/Profiling (Mapped Earth)
MLA	2004	Ranging (Mapped Mercury)
CALIPSO	2006	Profiling of Aerosols/Clouds (Earth)
Phoenix	2008	Profiling Aerosols/Cloud (Mars)
LOLA	2009	Ranging (Mapped Moon)
STORRM	2011	Range Imaging (at ISS)

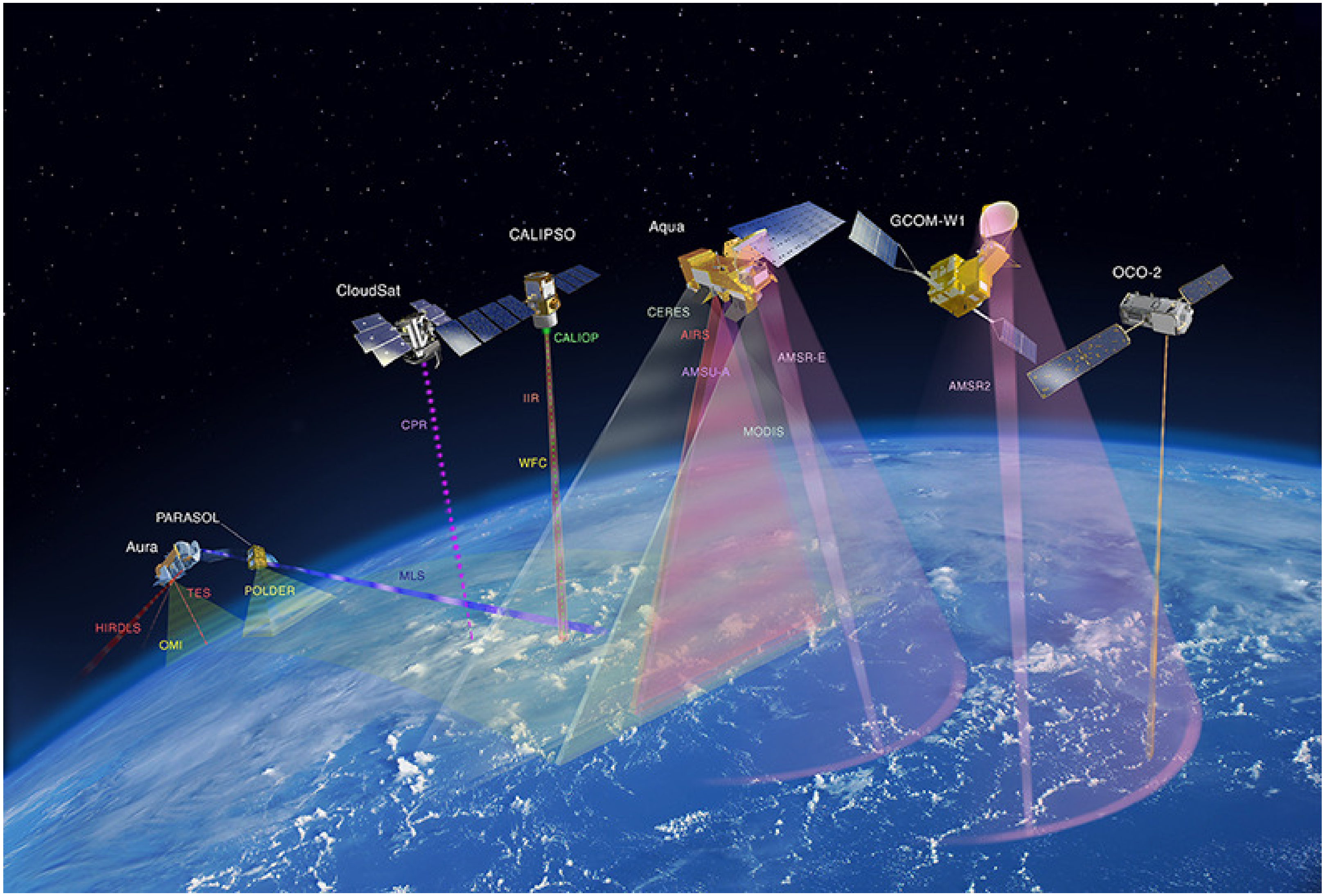
Motivation for Space-Based Lidars

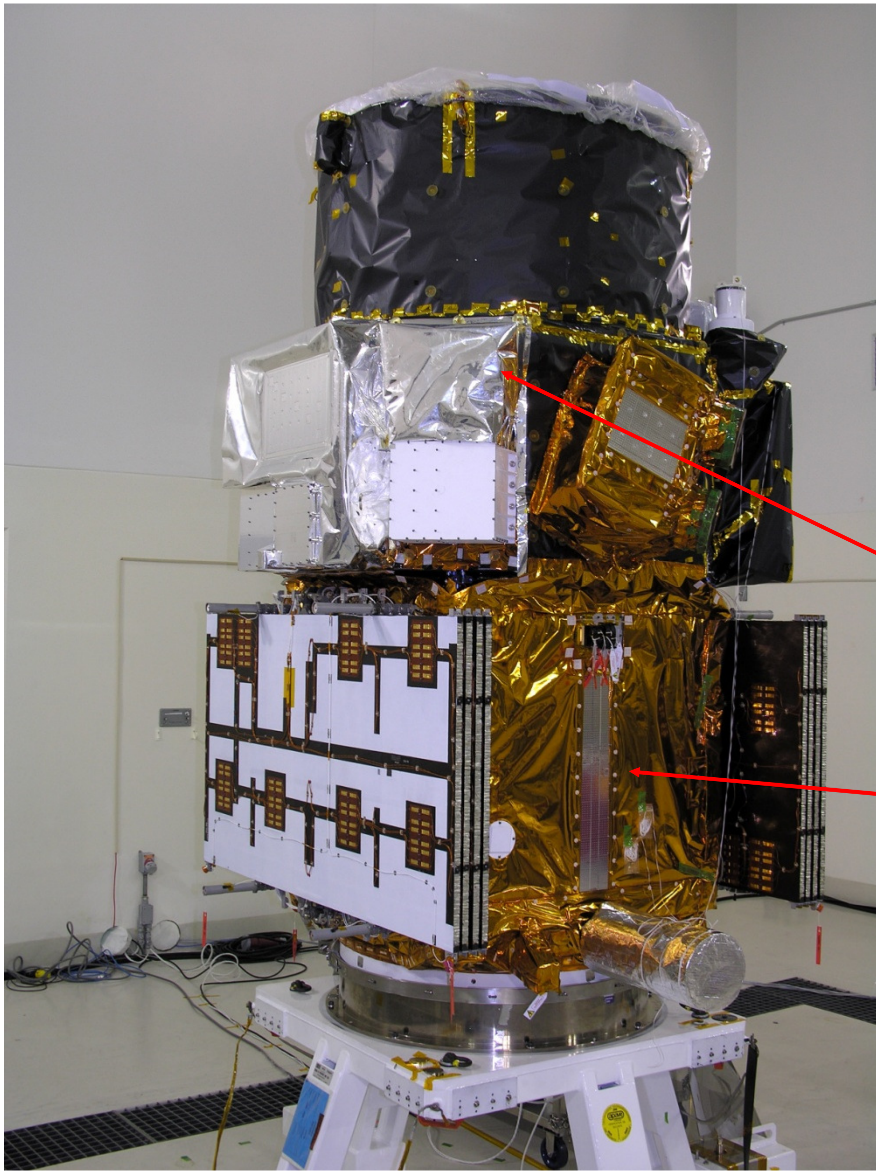
- **Some advantages of Lidar for Earth Remote Sensing from Space**
  - Global Coverage
  - Vertically profile atmosphere, forests, oceans to give volumetric (3-D) information and layering
  - Day and night operation
  - High: Sensitivity, spectral resolution, spatial sampling (3-D)
  - Diversity of wavelengths/colors
  - Access to a variety of linear and nonlinear physical phenomena (e.g. Brillouin scattering, Doppler shifts) for instrument use and for science





CALIPSO and the A-Train: Earth Remote Sensing





CALIPSO includes the CALIOP Lidar – two-wavelength (532/1064nm), polarization sensitive, profiling lidar. It uses elastic scattering from aerosols, clouds, and air

Earth System Science <u>Pathfinder</u> (ESSP) mission

Principal Investigator – David Winker – NASA LaRC

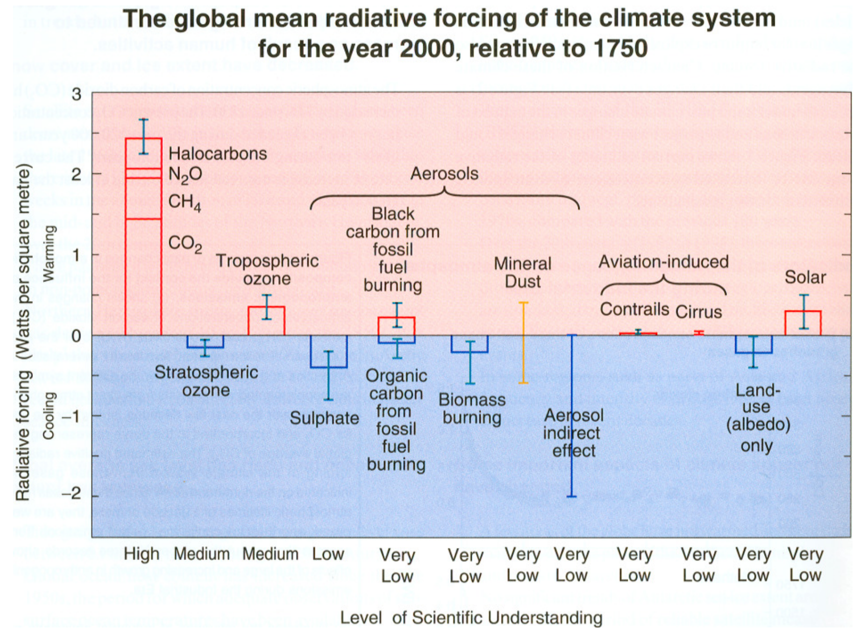
Co-PIs – Patrick McCormick (Hampton University) and Jacque Pelon (IPSL)

Launched April 2006

CALIPSO Science Objectives

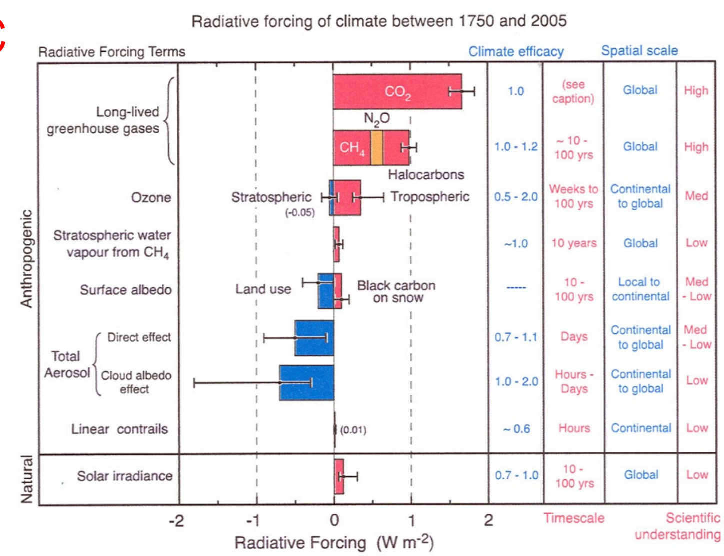
- **Measure the radiative impacts:**
  - — Direct aerosol forcing and uncertainty
  - — Indirect aerosol forcing and uncertainty
  - — Surface and atmospheric fluxes
  - — Cloud-climate feedbacks

© IPCC 2001

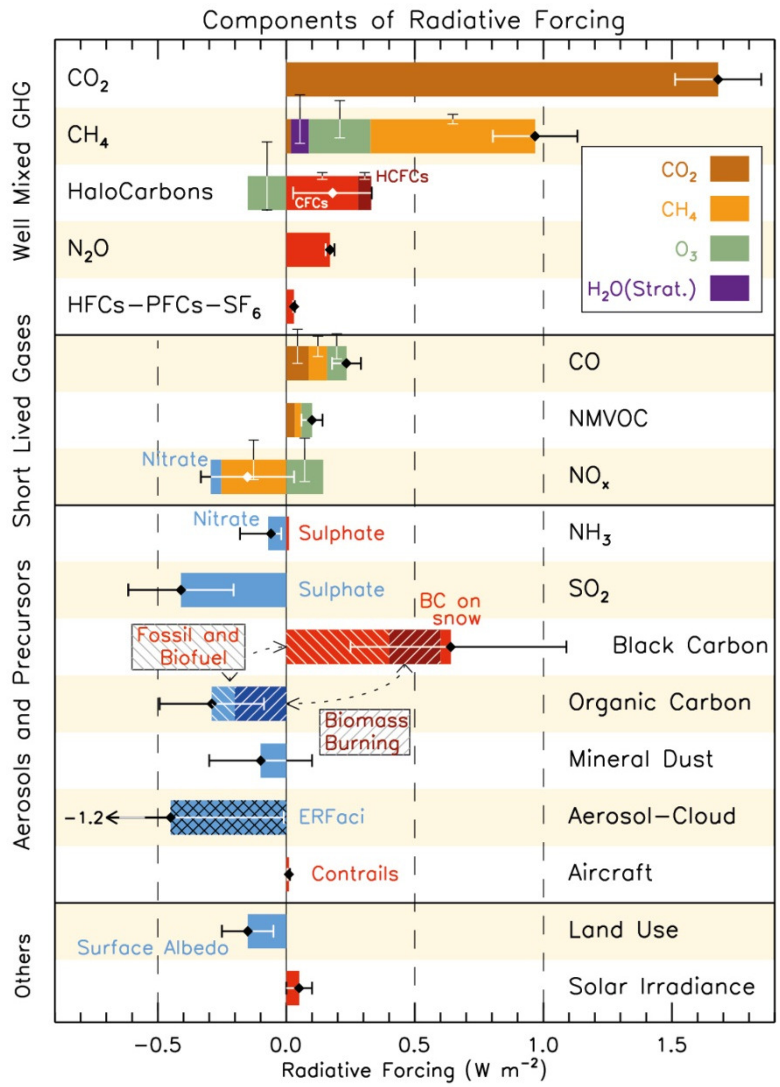


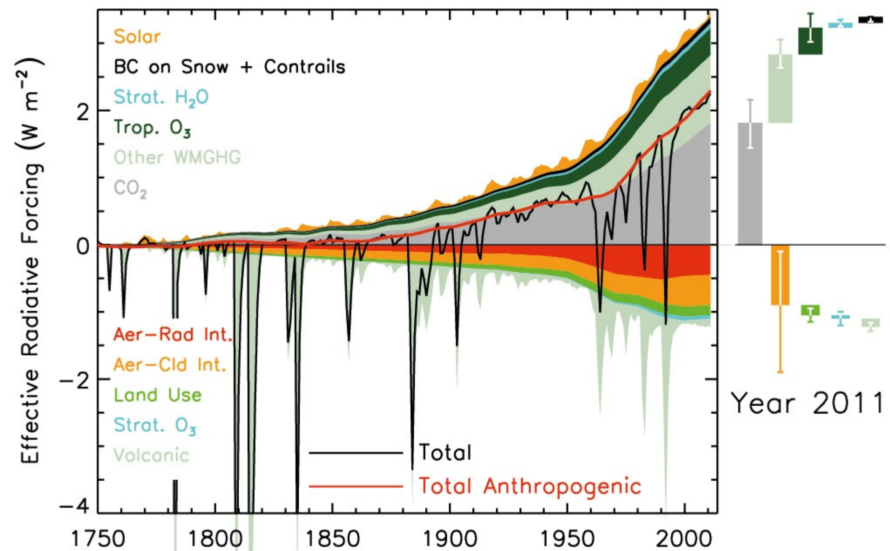
- **IPCC results give a measure of the state of knowledge and its evolution**
  - — The 2001 illustrates the original motivation for CALIPSO
  - — CALIPSO results didn't impact 2007 results, yet
  - — Recent report (2013) now includes results from CALIPSO for both cloud and aerosol impact on climate

© IPCC 2007



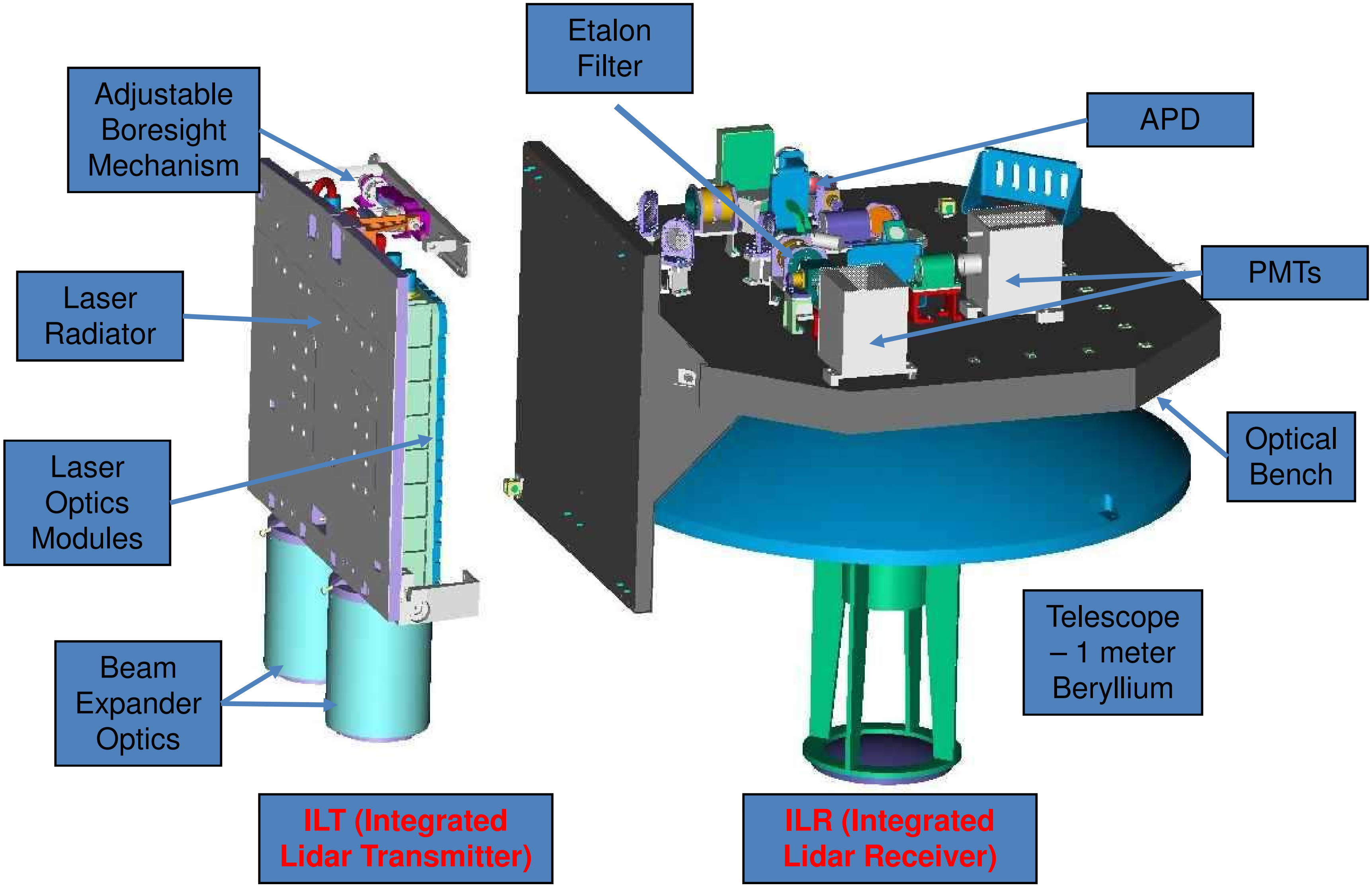
Latest IPCC Report Results





CALIPSO is just one of many satellites used to support the model validations that create these summaries

Lidar Core –Technologies of the Transmitter and Receiver



CALIPSO Lidar – Random Numbers

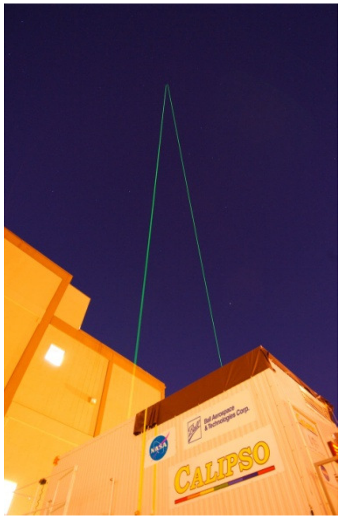
- Lidar Data “Curtain”
  - 70 meter diameter beam footprint on the ground
  - 330 meter steps between shots
  - 30 meter vertical range bins
  - Extends from the ground to 40 km (130,000 ft - clean air)
- Lasers
  - 4 Watt average power, 11 MWatt peak (20 nsec pulse), 20 Hz repetition, Wallplug 100 W
  - Diode-pumped Nd:YAG with external KTP doubling crystal
  - Each laser pulse contains 10^{18} photons
  - Linearly polarized > 1000:1
  - Multi-Transverse EM mode
  - All the light is contained in very narrow wavelength bands
    - 0.035 nm at 532 nm (1 part per 15,000)
    - 0.100 nm at 1064 nm (1 part per 11,000)
- Photomultiplier Detectors used at 532 nm are sensitive to single photons (but not photon counting)
  - Avalanche Photodiode used for 1064 nm – less sensitive but much more rugged (also 550 V vs 2 kV)
- Receiver is dual polarization sensitive at 532 nm
  - < 1% polarization crosstalk
- Telescope – 1 m diameter, f/4.3, all-Beryllium telescope , high-stiffness and low-mass
- Structure – Low CTE (< 1 ppm/°C) Graphite

What is different doing Lidar from Space?

- Long distance from atmosphere – 400- 800 km Low Earth Orbit (LEO) –
  - Low Signal-to-Noise because of $1/R^2$ term in lidar equation
  - Looking down through atmosphere- strongest scatter from furthest distance
  - Ground/Ocean scatter sets far boundary condition
  - Satellite motion, typical LEO velocity 7000 m/s – limits averaging time, can cause doppler shift if laser has a component along-motion
  - Strong Solar background light signal – Solar spectrum reflected from clouds or ice is the most demanding
  - Attitude control critical to pointing where you want
    - Well-developed techniques
  - Severe vibration during launch

- Space Environment
  - Radiation (Galactic, Solar, Van-Allen Belts)
  - Vacuum – Outgassing and Contamination concerns
  - Microgravity – Optical alignments shift after launch
  - Atomic Oxygen – Erosion and reaction with surfaces
  - Micrometeroids and space junk (recent collision was 80 km higher in orbit)
  - Charging of Surfaces – Corona plus Arc Discharge
  - Thermal environment – Controlled through careful design using radiators and heaters

Calibrations – Engineering to Science



An informal and non exhaustive description of calibrations and characterizations

- Detector Responsivity
- Detector Temporal Response
- Filter Performance
- Polarization Crosstalk
- Laser Energy
- Laser Spectral Performance
- Atmospheric Test
- Etc.

→ **Preflight Instrument Calibration and Characterization** — Complete sensor calibration and characterization by LaRC/Ball Aerospace prior to delivery to CNES/Alcatel

↓ **Prelaunch Atmospheric Test** — Verify performance at VAFB just before CALIPSO launch

Launch

- **Onboard Instrument Calibrations**
  - BITS (Temporal Response)
  - Etalon Scan (Wavelength)
  - Depolarizer (Gain Ratio)
  - Boresight Scan (Alignment)
  - Laser Energy
  - Shutter (Dark Noise)
- **Atmospheric Target Calibration**
  - Cirrus Depolarization
  - IIR
  - Rayleigh Calibration (532 nm)
    - Signal
    - Depolarization
  - Cloud Color Ratio for 1064 nm cal
- **Cross-Satellite Calibrations Including:**
  - MODIS Aerosol OD
  - CloudSat Combined Cloud Product
  - AMSR-E Ocean Wind Speed
  - MODIS Ocean Color
- **Ground/Aircraft**
  - Sun Photometer Networks
  - HSRL/CPL Aircraft
  - Ground Lidar Networks

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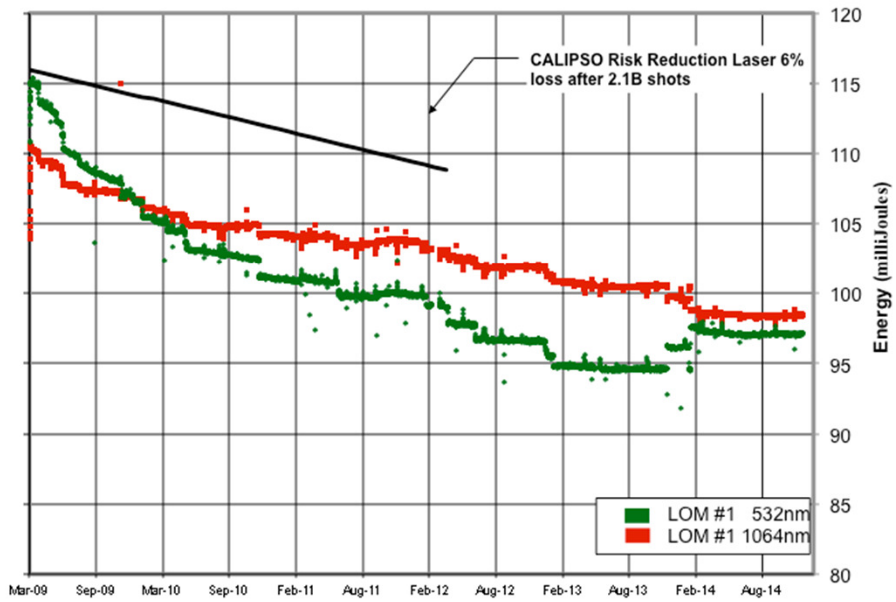
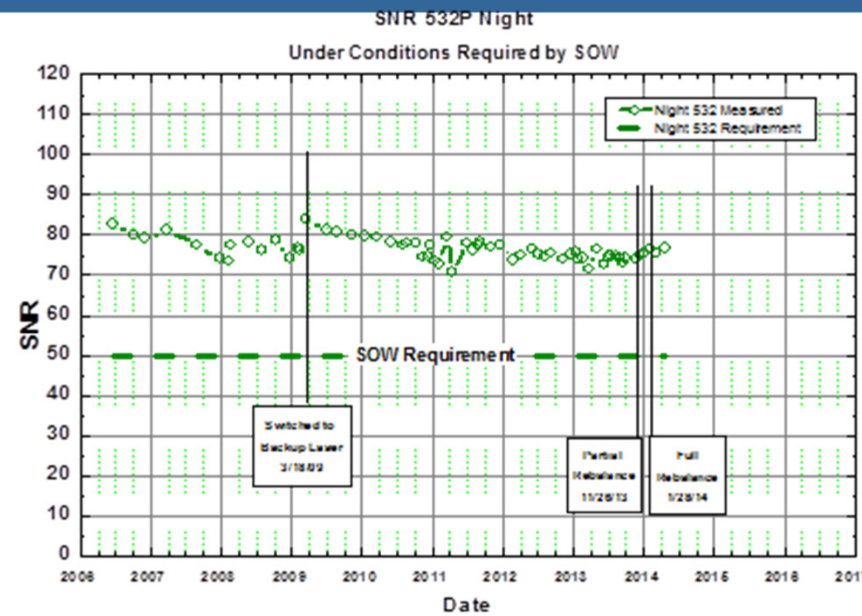
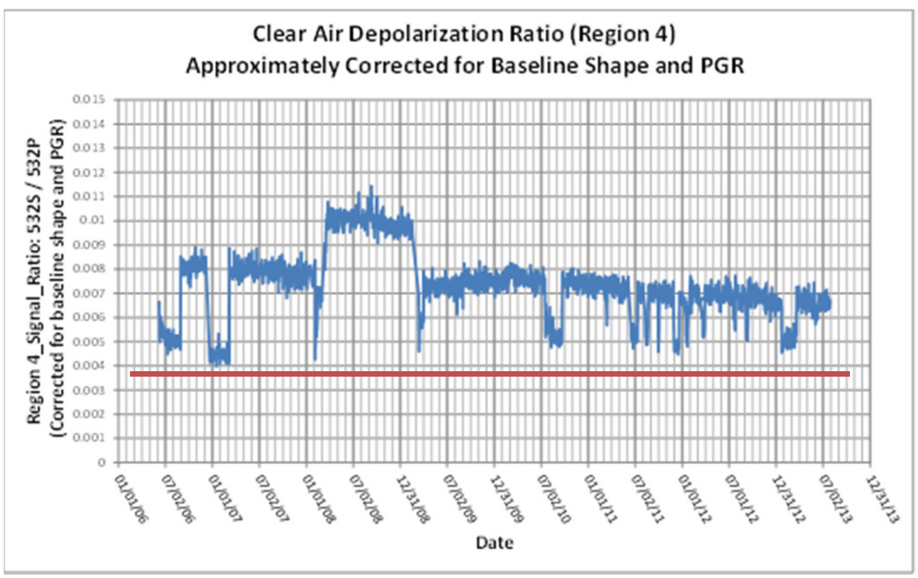
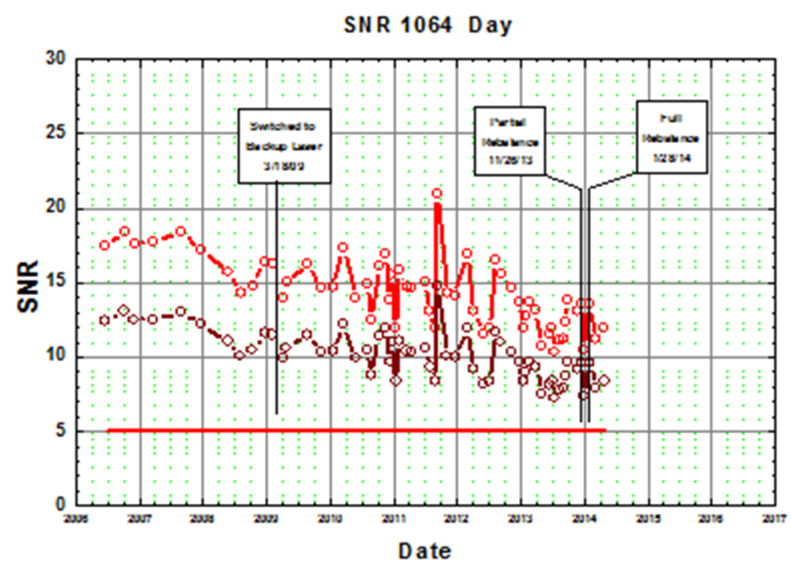
Not Shown: Autonomous Fault Checking and trending on 96 telemetry points

Examples On-board and Atmospheric Calibrations



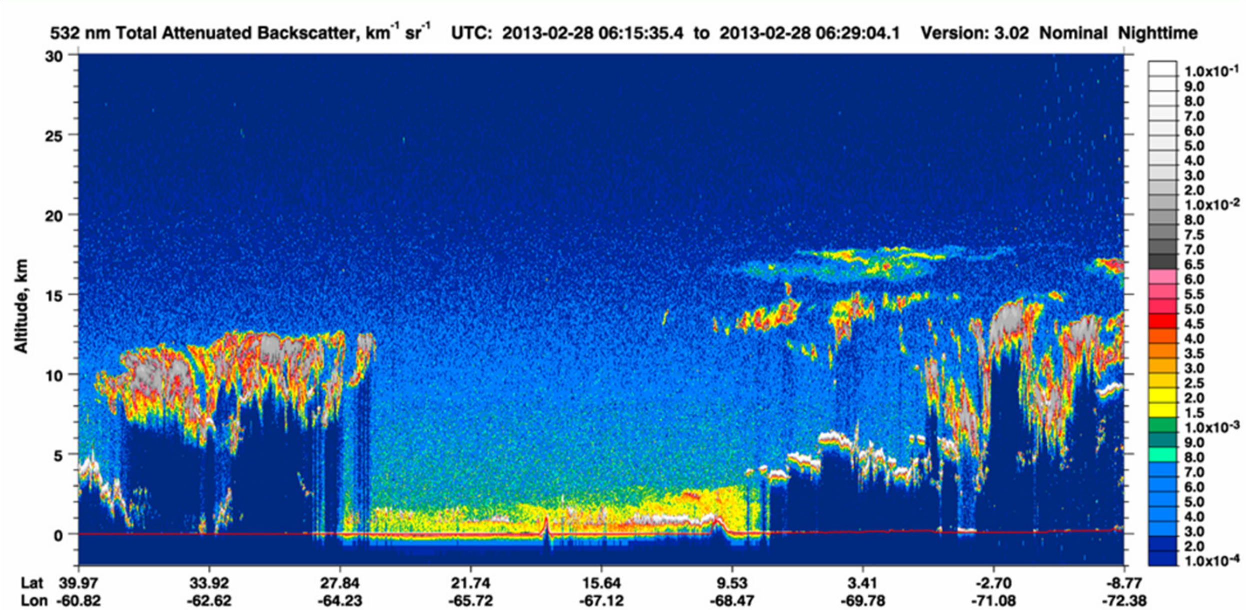


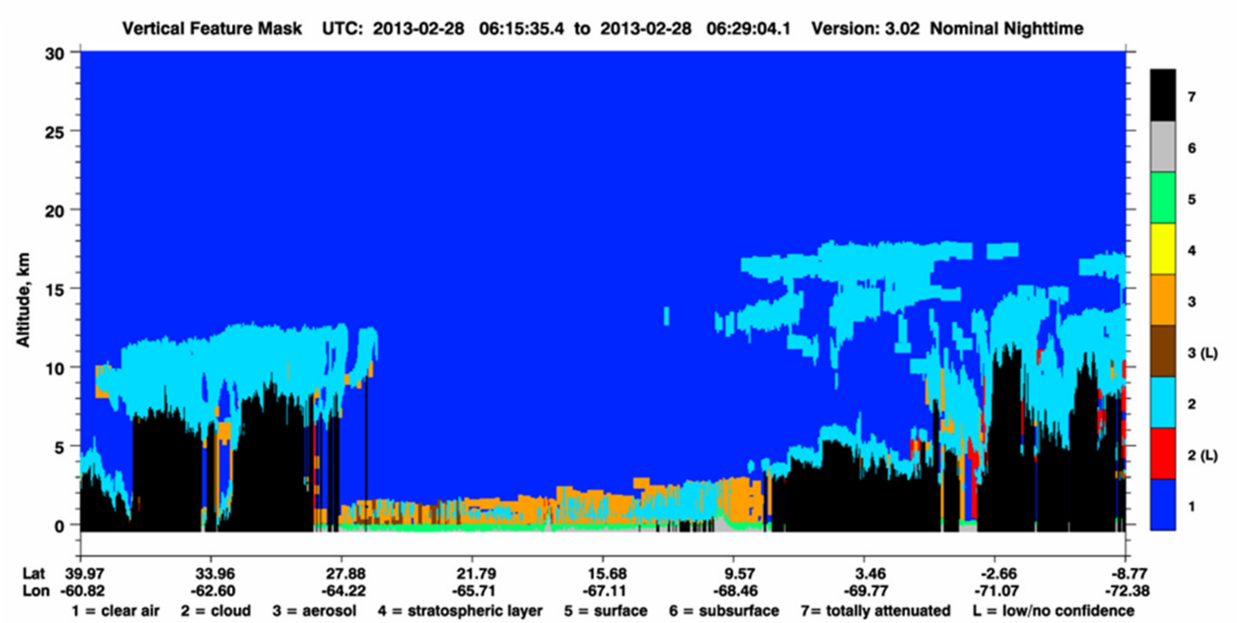




Courtesy of Ron Verhappen and Bill Hunt, NASA LaRC

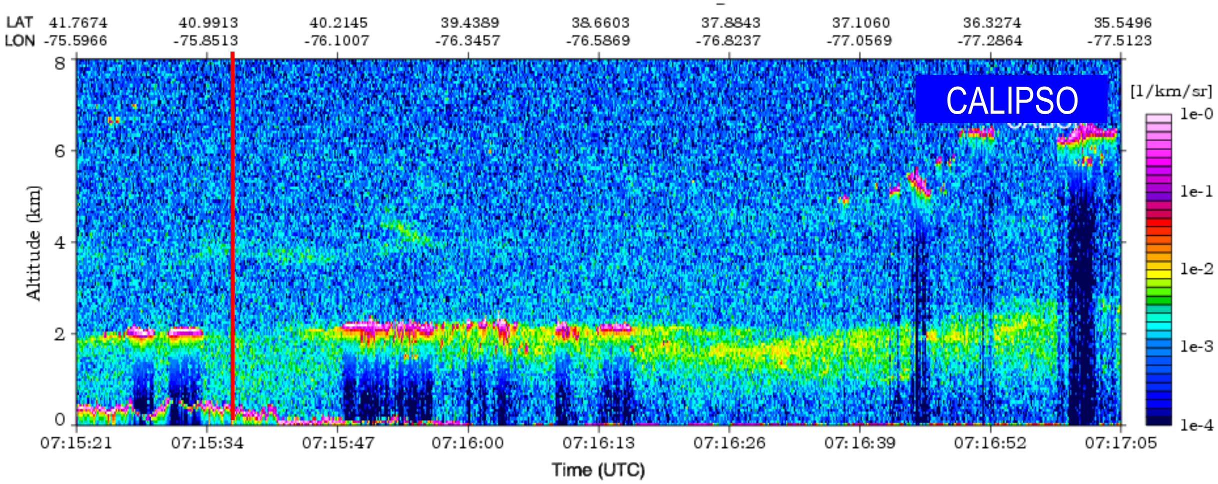
Examples of Science Data: Clouds and Aerosol Typing



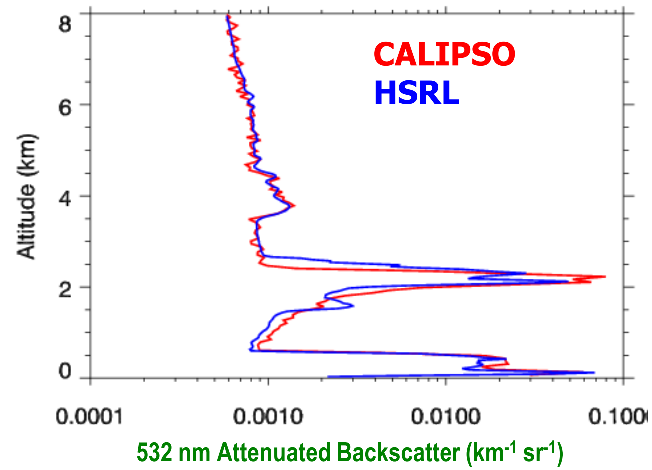


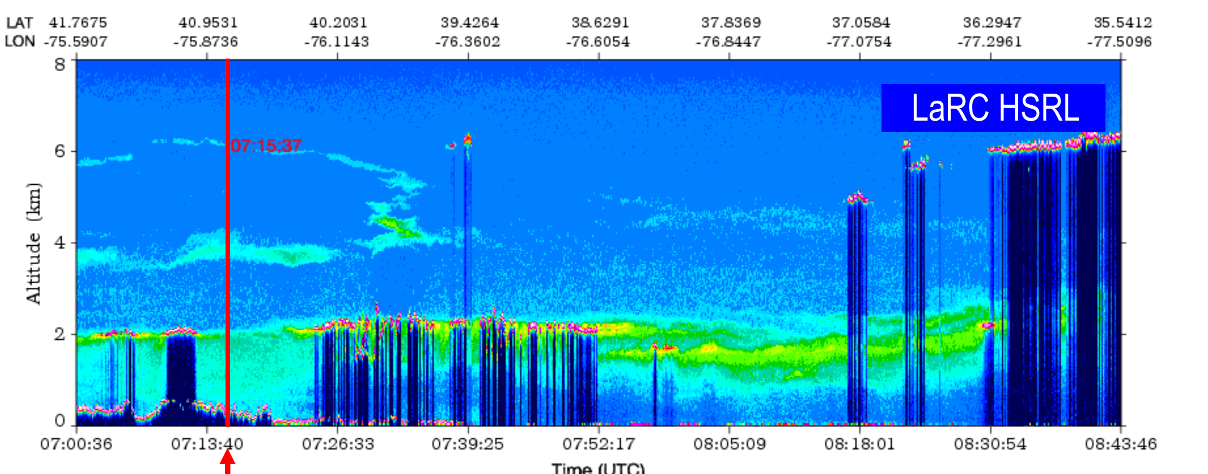
Quicklook data from: http://www-calipso.larc.nasa.gov/products/

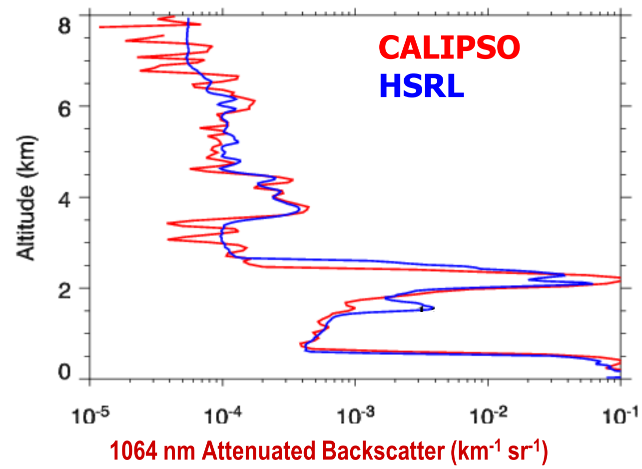
Example: Aircraft Calibration of Aerosols



Coincidence







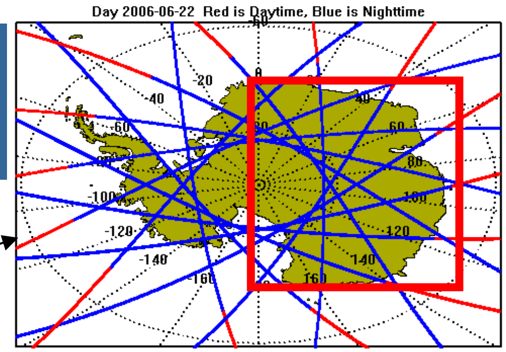
Coincidence

NASA LaRC High Spectral Resolution Lidar is being flown on Aircraft to support validating CALIPSO Data

Graphics courtesy of Dave Winker (LaRC)

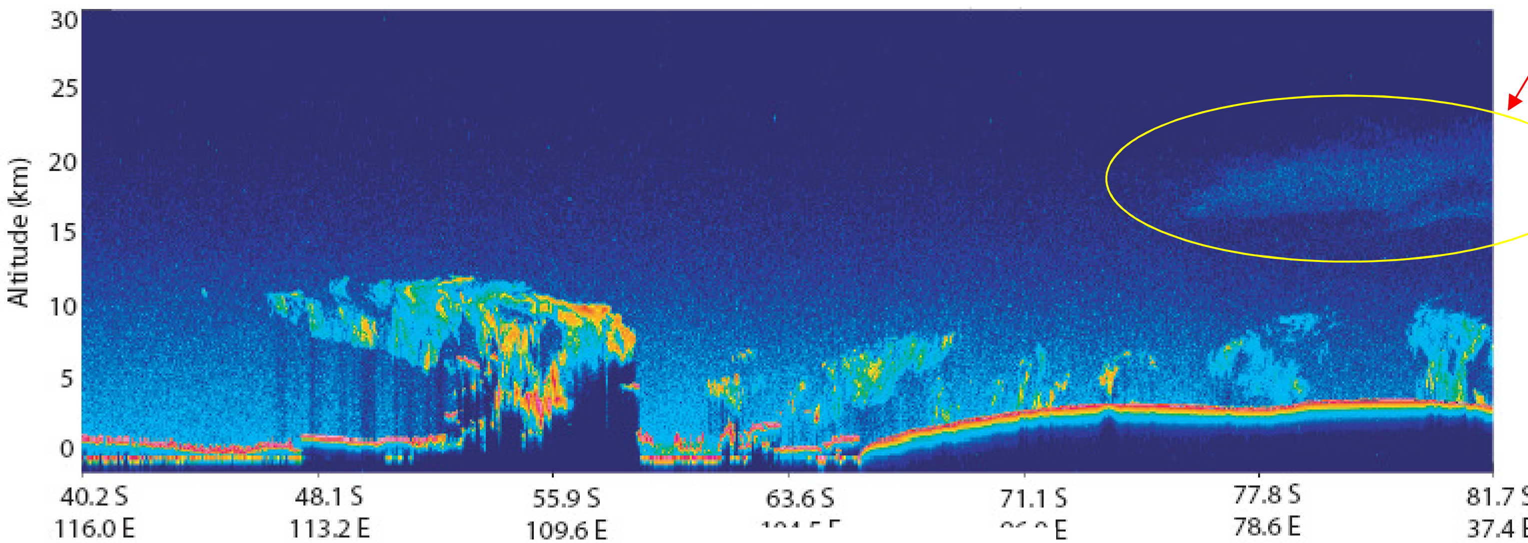
Example: CALIPSO and CloudSat Data

See
http://cloudsat.
atmos.colostate
.edu/data



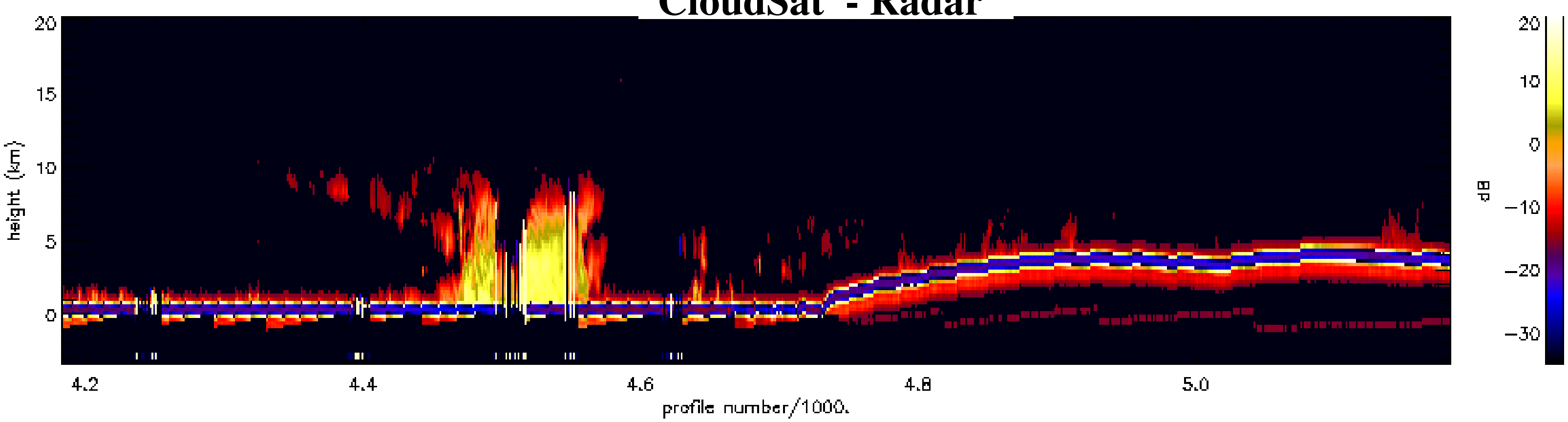
Antarctica

CALIPSO-Lidar



Polar
Stratospheric
Cloud

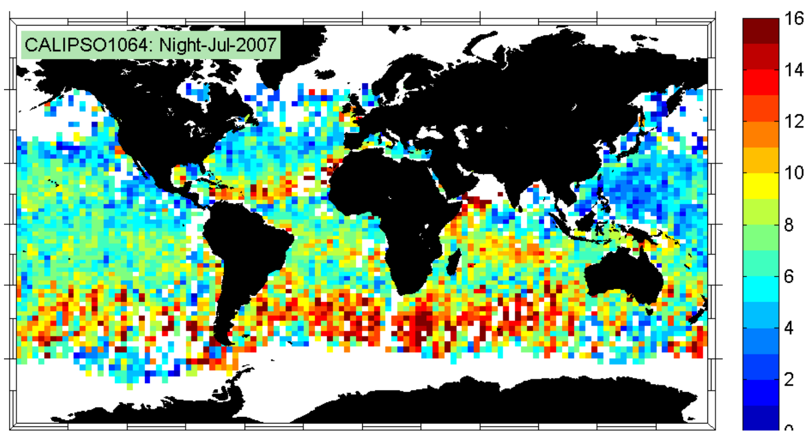
CloudSat - Radar

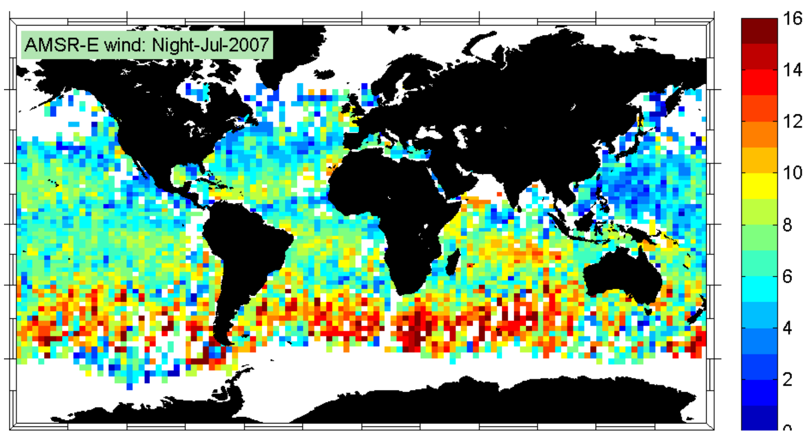


Graphics
courtesy of
Dave
Winker
LaRC

CALIPSO as a Pathfinder – Ocean Windspeed

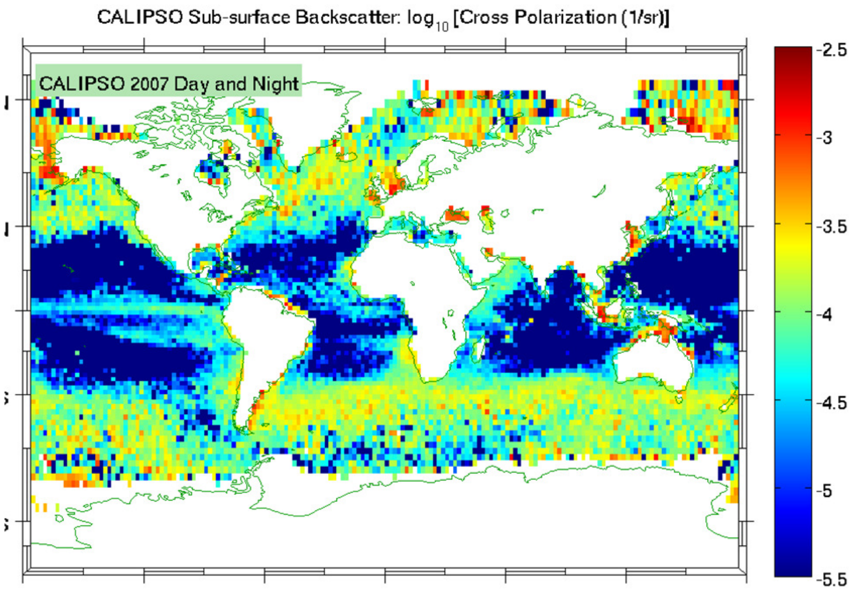
- Wind over the ocean changes the surface roughness
- Change in roughness causes the reflectivity to change per Cox Munk relationship
- This works at all wavelengths – allows cross-comparison between microwave system (AMSR-E on AQUA) and CALIPSO
- Agreement to < 1.4 m/s rms when averaged over large microwave footprint dimensions
- CALIPSO allows accurate measurements over small (70 m) footprint

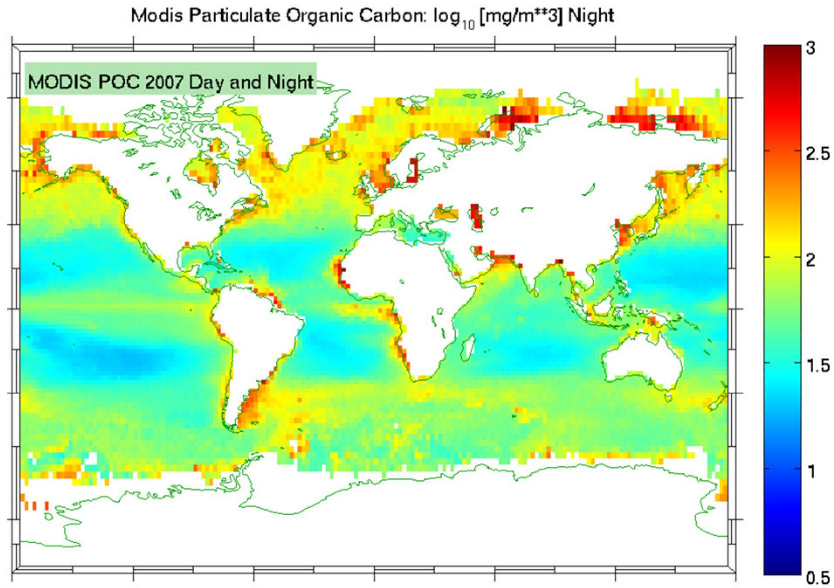


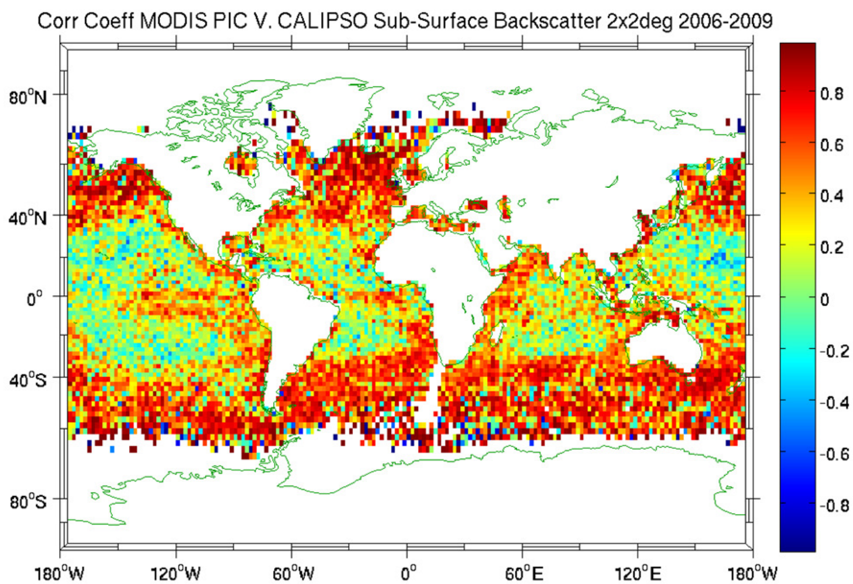


Courtesy of Yong Hu NASA LaRC

CALIPSO as a Pathfinder – Looking into the oceans







Courtesy of Yong Hu
NASA LaRC

See Behrenfeld et al. GRL 2013

Some Metrics for Success

Eight Years into a Three Year Mission

- **Requirements still being met after >8 years**
  - Senior review process renews for 2 year periods
  - Consumables will last to > 2017 – but Single String Payload means risk are growing
  - New ground laser testing to try and extend laser life
- **Total Laser Shots On-Orbit: 5 Billion**
  - 1 GJoule of optical energy delivered (around 200 mJ per laser pulse, split between 1064 nm/532 nm)
  - 100 seconds total laser "on-time" (20 nanosecond pulse length)
- **Data Downlink:**
  - 12.5 TeraBytes of Science Data delivered to NASA LaRC
  - 98.8% Capture Efficiency (one Downlink per day)
  - Added in "Expedited Data" delivery mode that delivers with < 4 hours latency for science mission planning purposes
- **Published Peer-Reviewed Papers to date – 1191**
  - http://www-calipso.larc.nasa.gov/

The Future for Lidar Earth Remote Sensing from Space

- **National Research Council Decadal Survey in 2007 proposed 17 new Earth science missions, most concerned with climate change, 7 of those missions involve laser remote sensing. They include:**
  - 3 laser altimeters for mapping ice (ICESatII), ~~vegetation (DESDynI)~~, high resolution digital elevation maps (LIST)
    - ICESat II is now being built for a 2018 (?) launch
  - 2 lidars for measuring greenhouse gases (CO_2 and ozone/water) – (ASCENDS for CO_2 in pre-Phase A)
  - 1 for advanced (HSRL) aerosol/cloud characterization (ACE) - (in pre-Phase A)
  - 1 for measuring tropospheric winds (3-D Winds)

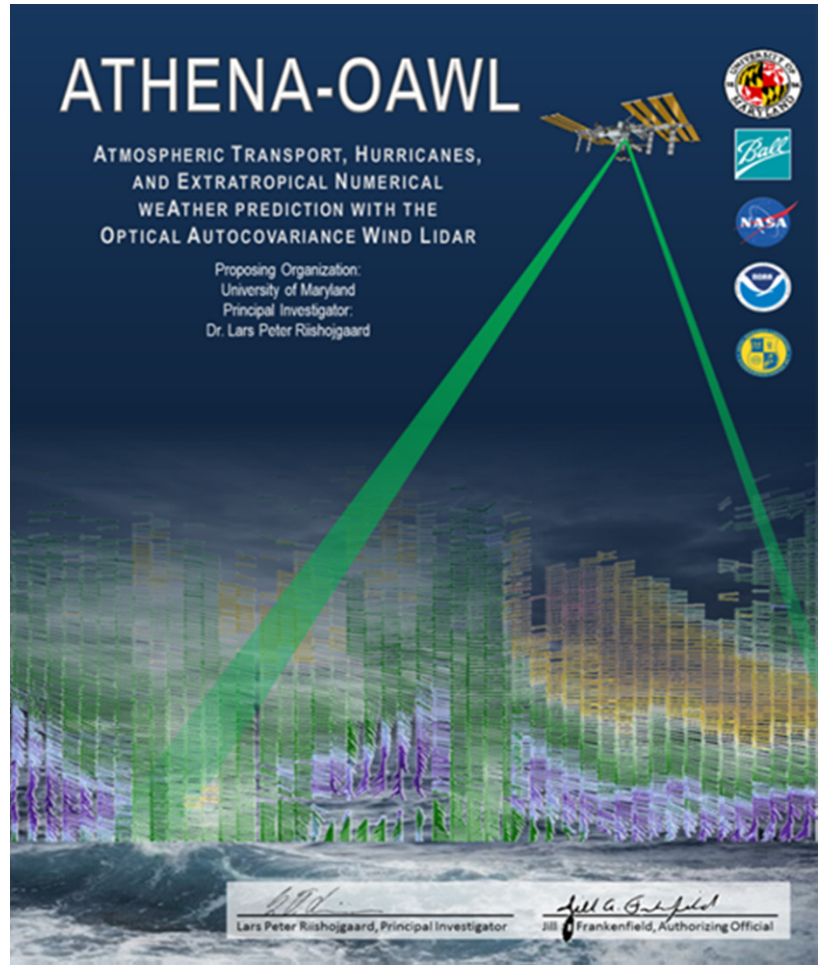
- **Europeans are building three lidar missions**
  - ADM-Aeolus – tropospheric winds – launches 2015
  - Earthcare – advanced aerosol/clouds- launches 2016
  - MERLIN – Methane column measurements

- **ISS lidar missions in development:**
  - iLOVE – Lidar for Observation of Vegetation Environment from ISS (JAXA)
  - CATS - ISS – Cloud-Aerosol Transport system for ISS (launches this month!)
  - JEM-EUSO – Extreme Universe Space Observatory – lidar for ranging to cosmic showers in atmosphere
  - GEDI - Global Ecosystem Dynamics Investigation – forest canopy height mapping

- **NASA Earth Venture Program**
  - Cost Capped ($30M, $94M, $150M) missions that have a focused science objective
  - Competed on regular cycles (48 months, 18 months, 48 months) via Announcements of Opportunities

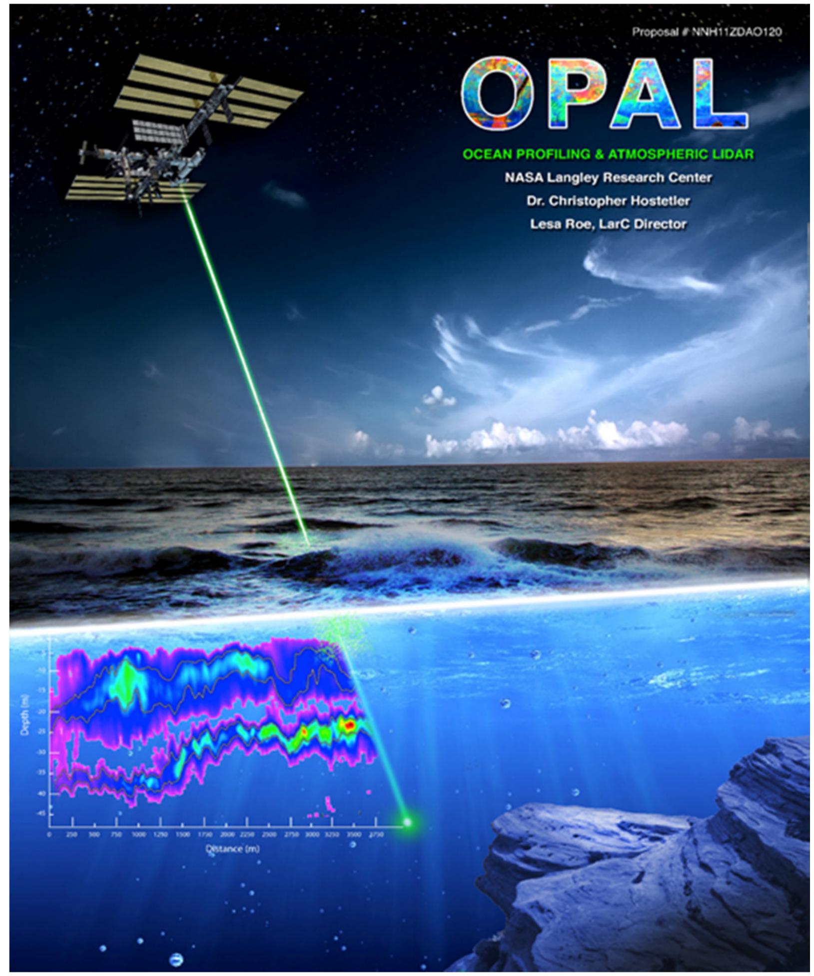
New Mission Concept for Earth Venture – ATHENA-OAWL

- Proposed in 2013 by University of Maryland (PI – Lars Peter Riishojgaard; Deputy PI -Mike Hardesty of CIRES)
- Troposheric Winds from ground to stratosphere via Doppler shifts measured from aerosol backscatter
- Direct ingestion of data into Numerical Weather Models for testing forecast improvements
- 532 nm only for space version to minimize cost/risk
- OSSE's of different configurations completed
- Expanded version – HAWC-OAWL in development for HSRL and Winds at 532 nm and 355 nm (PI-Tucker at Ball)

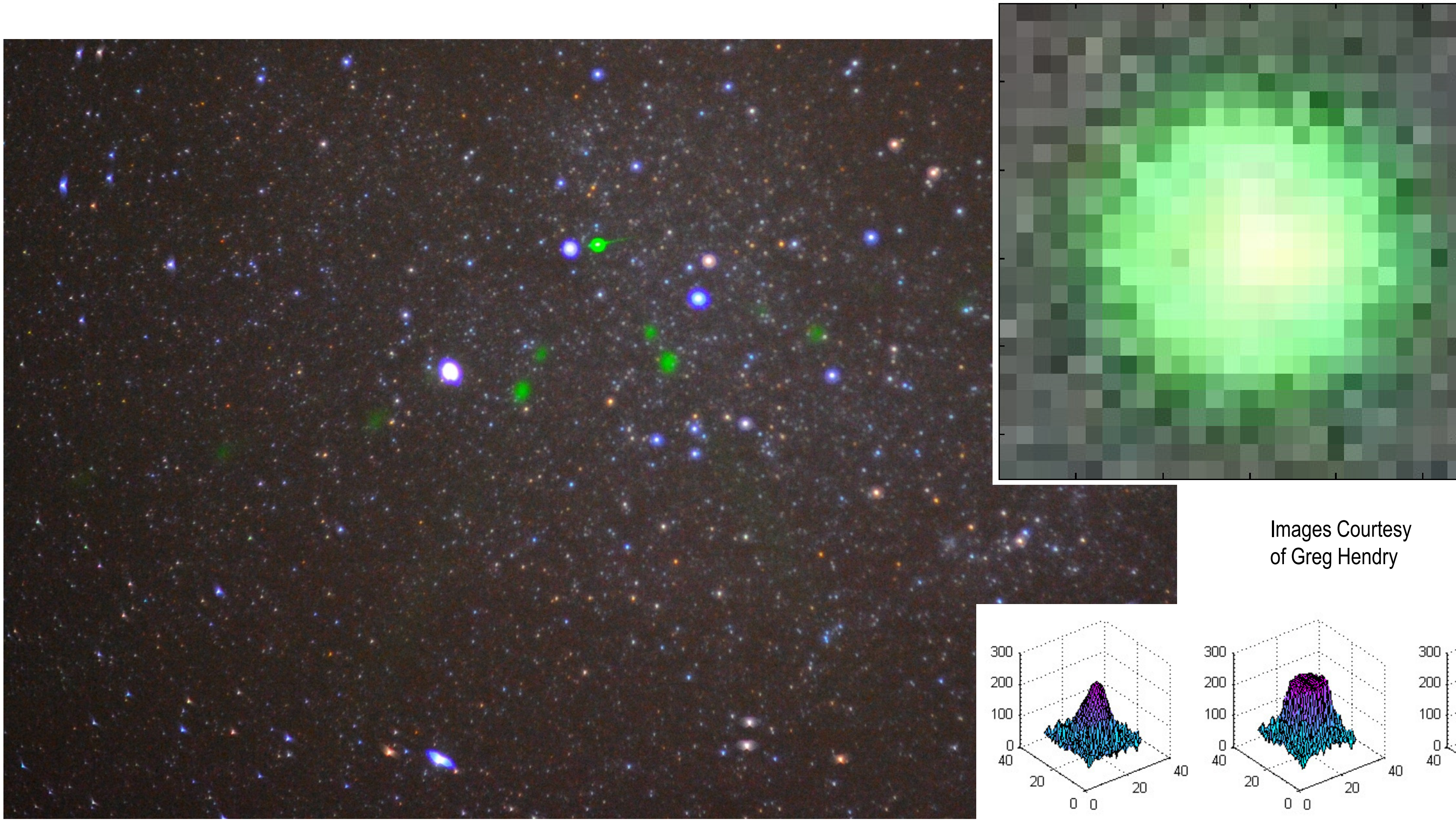


New Mission Concept for Earth Venture – OPAL

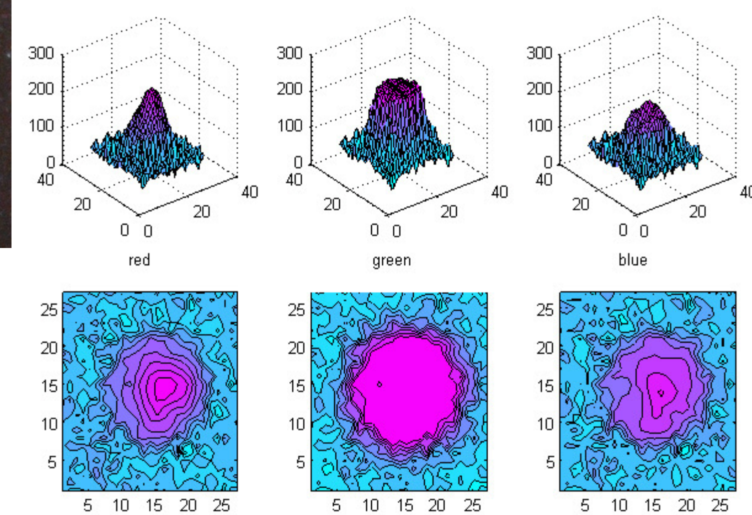
- Proposed in 2011 by NASA LaRC (PI- Chris Hostetler)
- Expands on CALIPSO's capability to look into the oceans to study ocean-atmospheric interactions
- High Spectral Resolution Lidar based on Iodine filter – separates particulate from Rayleigh/Brillouin scattering
- 1064nm/532 nm
- Aircraft – Ship studies are ongoing
  - Earth-Venture Sub-orbital award just made extending this work



Images of CALIPSO Laser



Images Courtesy of Greg Hendry



Check-out UFO database at:
http://www.nuforc.org/webreports/055/S55212.html

Thank You! Questions?