Laser Remote Sensing from Space and CALIPSO

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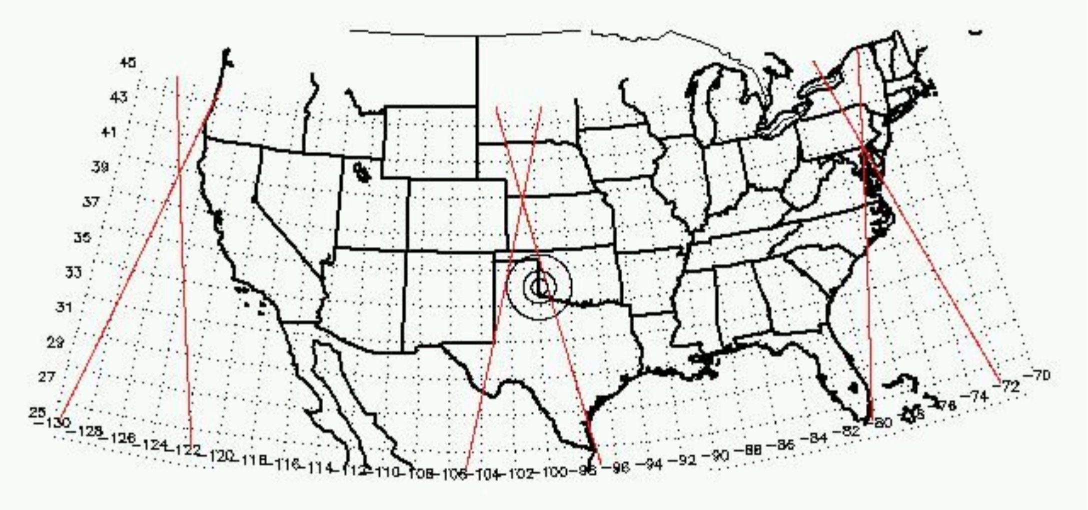
Overview

- Lidar from Space – Why and How
- CALIPSO – Example of a Lidar from Space
  - LITE Predecessor
  - Why CALIPSO?
  - Description of Lidar
  - Examples of hardware
  - Atmospheric Test Results
  - Launch Plans
  - Lidar Science Data

Why Do Lidar from Space?

- Lidars give combination of unique measurement capabilities that other sensors can't provide
  - Range-resolved measurements for full atmospheric profile
  - Day and Night Coverage
  - Highly spectrally selective measurements
- Global Coverage of the Earth
  - Ground track will produce a sparse grid pattern from 82° N to 82° S latitude
  - Pattern will repeat every 16 days
  - One Orbit Every 90 minutes

One-Day Coverage



What is different about 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
- Space Environment
  - Radiation (Galactic, Solar, Van-Allen Belts)
  - Vacuum – Outgassing and Contamination concerns
  - Microgravity – Alignents different than on Earth
  - Atomic Oxygen – Erosion and reaction
  - Micrometeroids and space junk
  - Charging of Surfaces – Corona Discharge
  - Thermal environment – controlled through careful design using radiators and heaters
- Launch Environment
  - Alignments and structure must withstand vibration and shock
  - Limited Weight can be lifted – Typical 100 – 500 kg range for instrument
- Limited power available – Typical 100 – 500 W available from solar arrays for instrument
- Semi-Autonomous Operation over multiple years – Daily data downlink, weekly uplinks

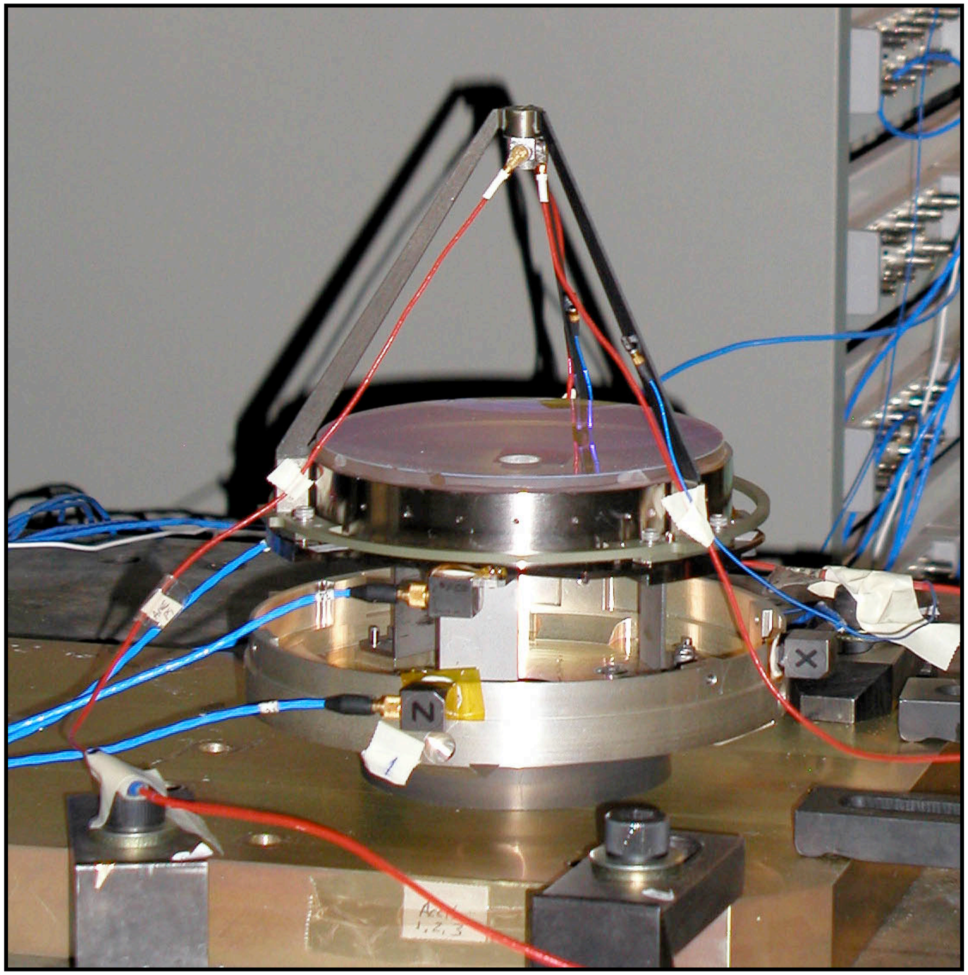
Lidar in Space
Building for Reliability

- High Cost of Space Missions requires that a space lidar be designed and built to achieve maximum reliability affordable within cost and schedule constraints
- Standard Aerospace Engineering practices followed, combined with unique lidar specific techniques
- High Reliability Parts Program
  - Electronic Parts are all “screened” – tested for lifetime – this limits what parts can be used
  - All classes of parts must have passed radiation testing
  - Optical parts must be able to withstand radiation, Ultra-violet, laser fluence (if appropriate), vacuum, atomic Oxygen
- Parts, Sub-assemblies, Assemblies must pass Qualification Test Program
  - Thermal-vacuum
  - Vibration
  - Acoustic
  - Shock
  - Electromagnetic Interference
  - Health/Performance tests in conjunction with each of the above

Space Lidar Reliability Continued

- Strict Contamination Control Program used throughout
- All “processes” used to build the lidar are documented and traceable to NASA or military standards
- All materials have full traceability – base material through final lidar
- All Design, Build, and Test is planned, reviewed, and carried out with complete documentation – Large amounts of paper
- Satellite is designed with automated “Failure Detection Isolation and Recovery (FDIR)” – on-board software protects satellite against faults that could damage system
- Risk Control Plan used – identify risks, estimate probability and consequence, design to mitigate
- Use Redundant systems when risk too high and money available

Why so much testing?



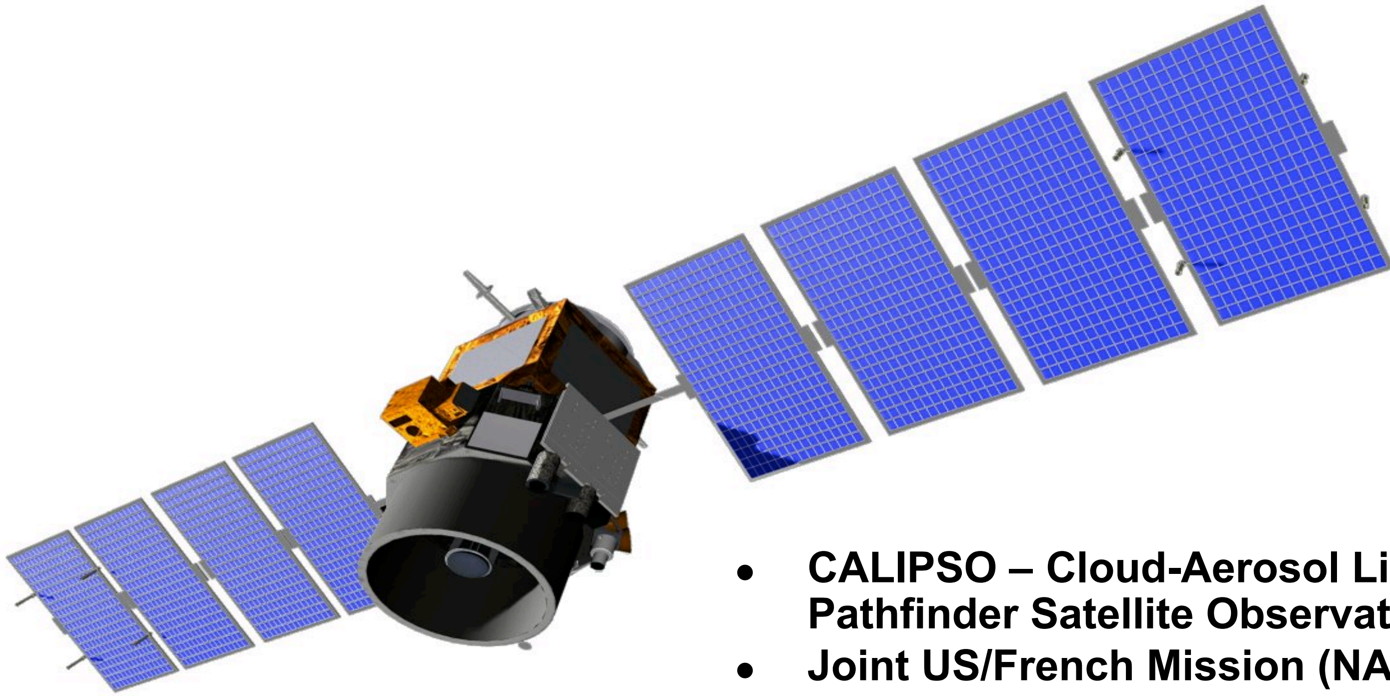
A lidar beam expander optic instrumented for a vibration test with accelerometers

- Sophisticated Models are constructed as part of the design to ensure requirements are met. For Example:
  - Structural
  - Thermal
  - Lidar (radiometric – signal-to-noise)
  - Electrical timing
  - Optical
- Testing helps to:
  - Verify margins
  - Prove out workmanship
  - Eliminate infant mortality in parts
  - Reduce Risk
- "Don't trust a model until it agrees with a test. Don't trust a test until it agrees with a model"

Some Lidars in Space

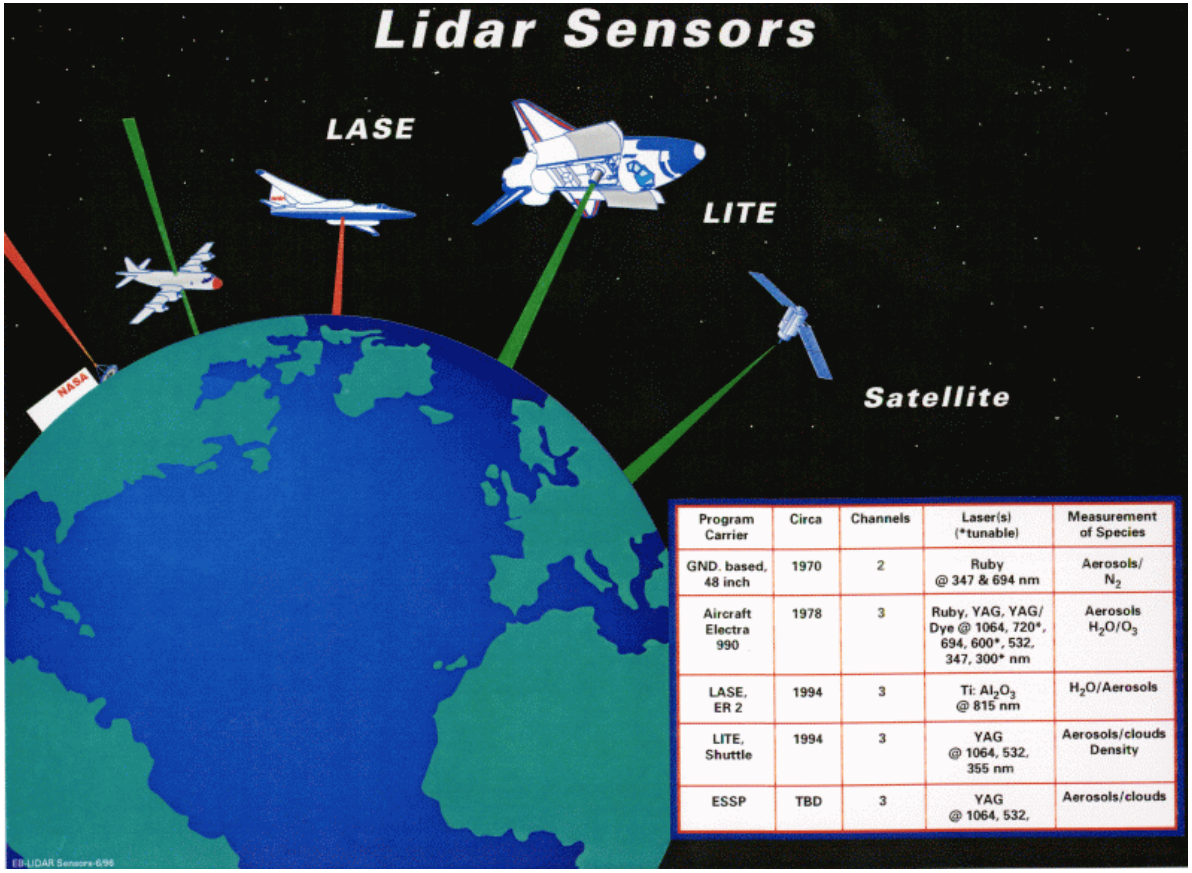
Apollo 15	1971	Ranging
Clementine	1994	Ranging (Mapped the Moon)
LITE	1994	Profiling (Shuttle)
Balkan	1995	Profiling
NEAR	1996	Ranging
SLA-01	1996	Ranging
MOLA II	1996	Ranging (Mapped Mars)
SLA-02	1997	Ranging
Icesat/GLAS	2003	Ranging/Profiling (Icesheets)
MLA	2004	Ranging (Will Map Mercury)
CALIPSO	2006	Profiling of Aerosols and Clouds
LOLA	2008	Ranging (Will Map the Moon)
ADM-Aladin	2009	Wind Measurements

The CALIPSO Program



- CALIPSO – Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
- Joint US/French Mission (NASA/CNES)
- Principal Investigator – Dave Winker NASA LaRC
- Payload designed and built by Ball Aerospace in collaboration with NASA
- Three year mission to study the atmosphere
- Scheduled to launch April 21
- http://www.nasa.gov/mission_pages/calipso/multimedia/index
- http://www-calipso.larc.nasa.gov/

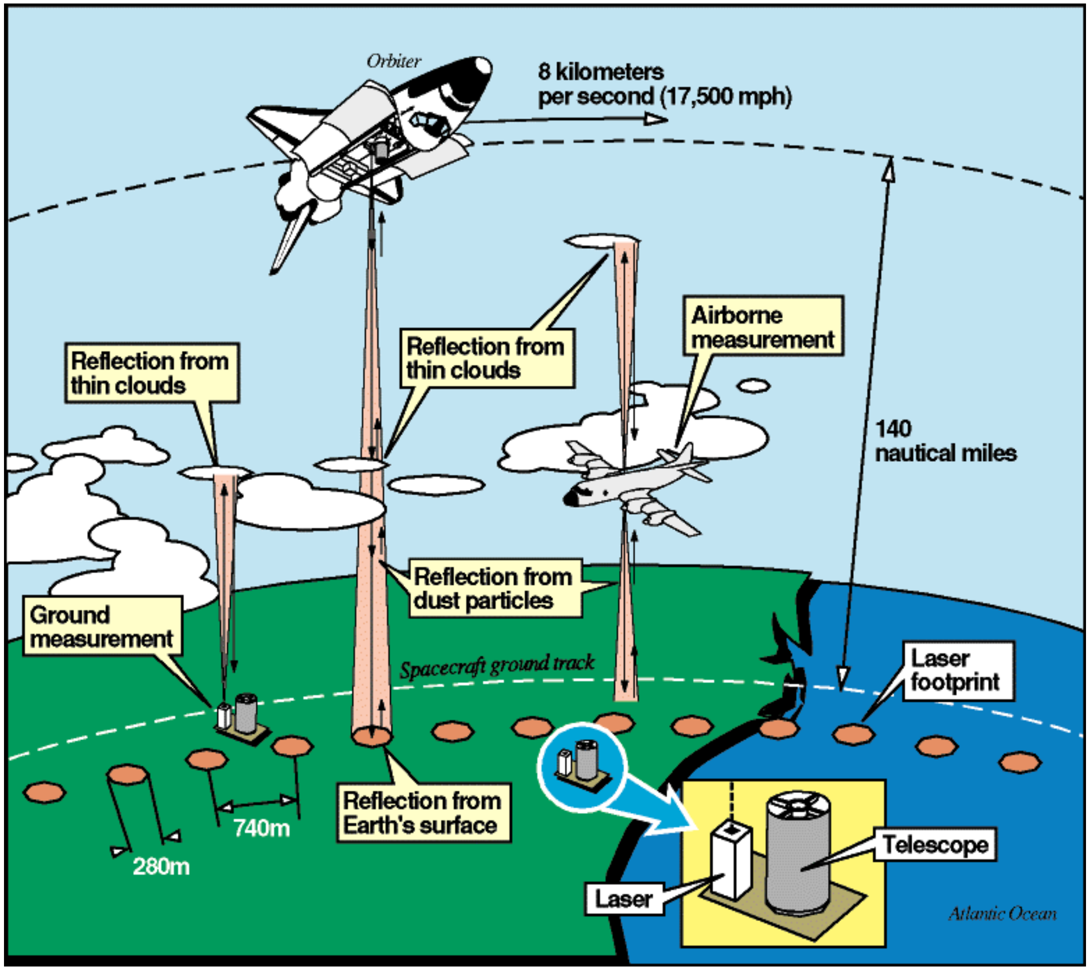
CALIPSO evolved from numerous Ground, Airborne and Shuttle Programs



Program Carrier	Circa	Channels	Laser(s) (*tunable)	Measurement of Species
GND. based, 48 inch	1970	2	Ruby @ 347 & 694 nm	Aerosols/ N_2
Aircraft Electra 990	1978	3	Ruby, YAG, YAG/ Dye @ 1064, 720*, 694, 600*, 532, 347, 300* nm	Aerosols H_2O/O_3
LASE, ER 2	1994	3	Ti: Al_2O_3 @ 815 nm	H_2O/Aerosols
LITE, Shuttle	1994	3	YAG @ 1064, 532, 355 nm	Aerosols/clouds Density
ESSP	TBD	3	YAG @ 1064, 532,	Aerosols/clouds

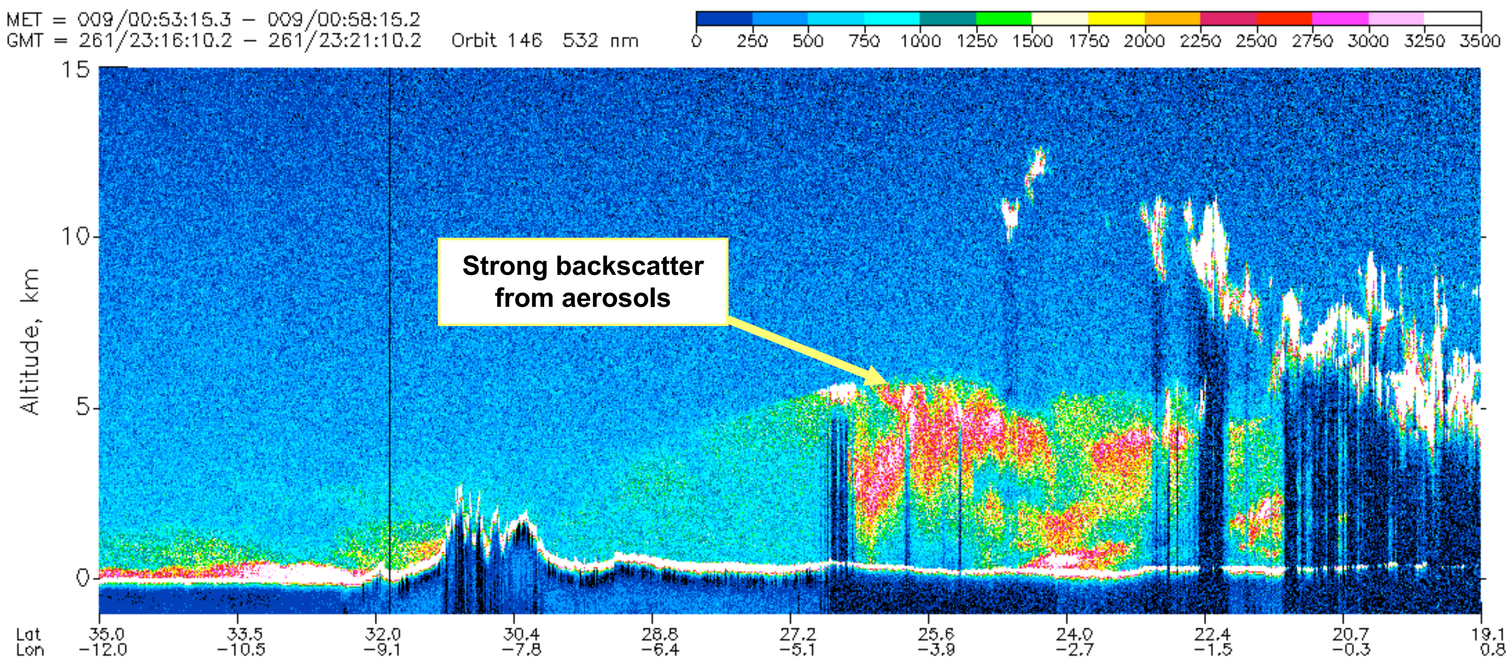
- LITE – NASA LaRC
  - the first lidar designed for atmospheric studies to fly in Earth orbit
  - validate key enabling technologies required for operational spaceborne lidars
  - explore as many applications of spaceborne lidar as possible
  - Technology issues include laser design and operation in space, thermal management, alignment and control, and autonomous system operation.

NASA LITE Mission Overview



- **LITE was operated for 53 hours, resulting in over 40 GBytes of data covering 1.4 million kilometers of ground track.**
- **LITE was flown on the Space Shuttle Discovery as part of the STS-64 mission between September 9 and September 20, 1994.**
- **LITE provided views of multilayer cloud structures**
- **LITE provided observations of the distribution of desert dust, smoke, and other aerosols.**
- **LITE provided the first global observations of planetary boundary layer height.**

Saharan Dust Transport



- **Above is displayed a color-modulated plot of LITE Level 1 532 nm profile data over the Sahara during orbit 146 at approximately 23 GMT on September 18, 1994. The image displays 5 minutes of LITE data.**
- **The color assigned to each pixel represents the intensity of the return signal in digitizer counts. The count values range from zero for no return to a value less than 4000 for the strongest return.**
- **Prominently featured at the start of this orbit transect is the Atlas Mountain range near 31N, 8W. This mountain range approximately separates a more optically thick aerosol air mass to the southeast from a relatively cleaner air mass to the northwest.**

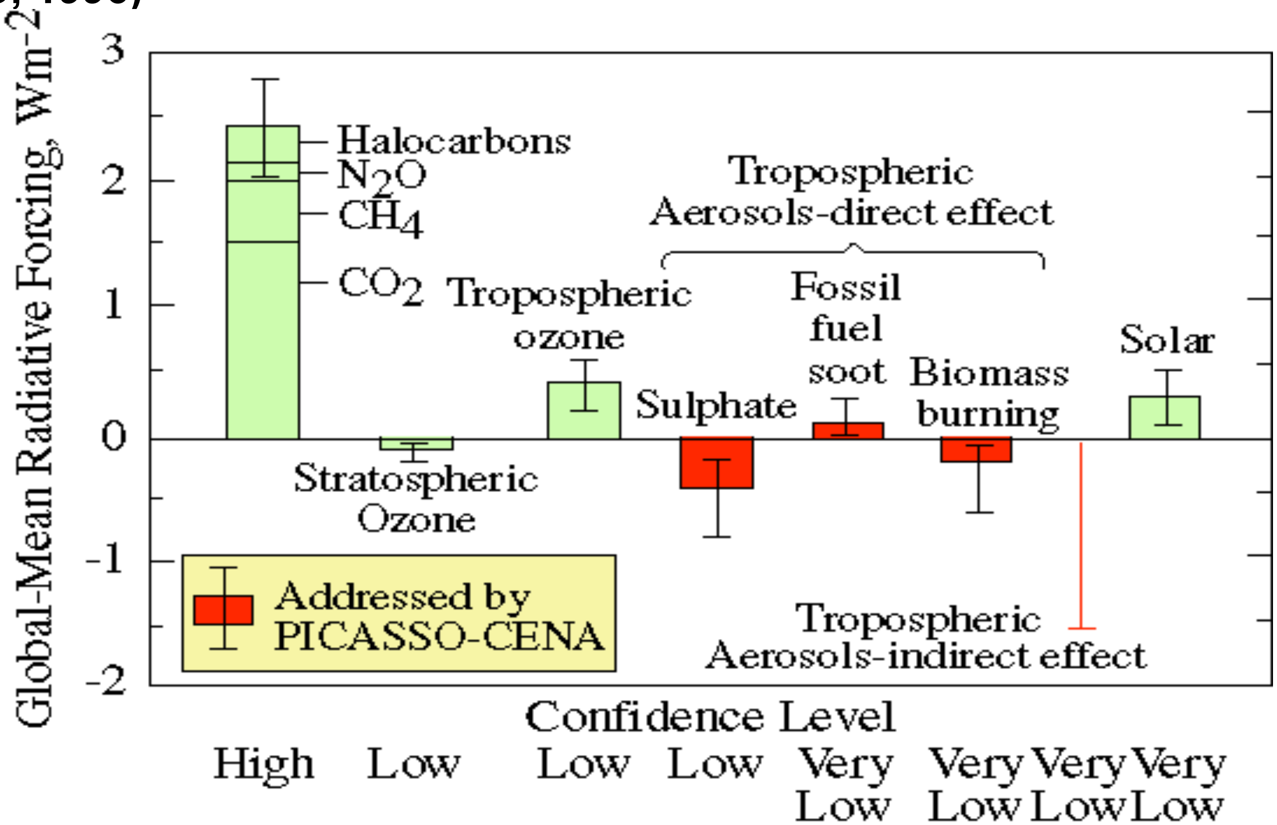
http://www-lite.larc.nasa.gov/n_the_images.html

Multi-layer Cloud Observations from the LITE Lidar

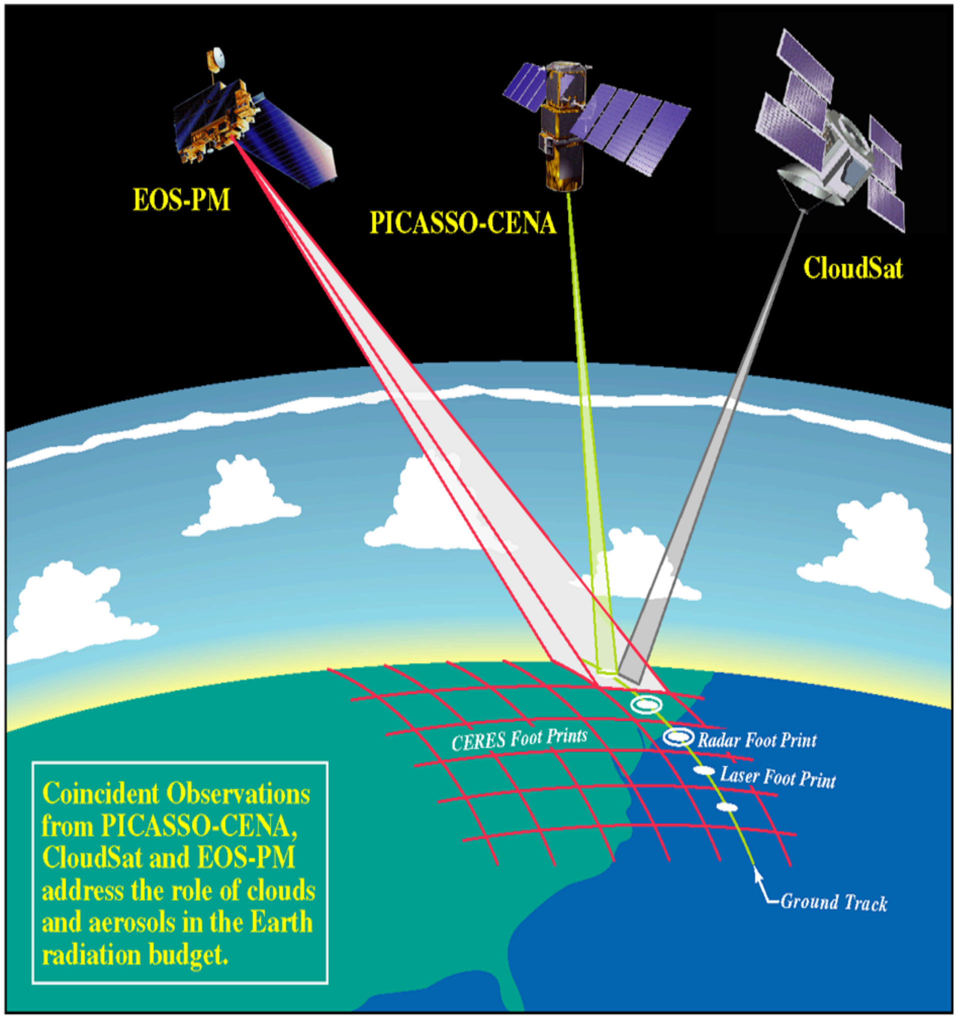
LITE 532 backscatter signal over the tropical Pacific Ocean on September 14, 1994

Need for CALIPSO

- **Recent assessments by the international science community conclude that better global observations of clouds and aerosols are required to reduce uncertainties in predictions of future climate change**
- **Aerosol forcing counters the warming caused by greenhouse gases (source: IPCC, 1996)**

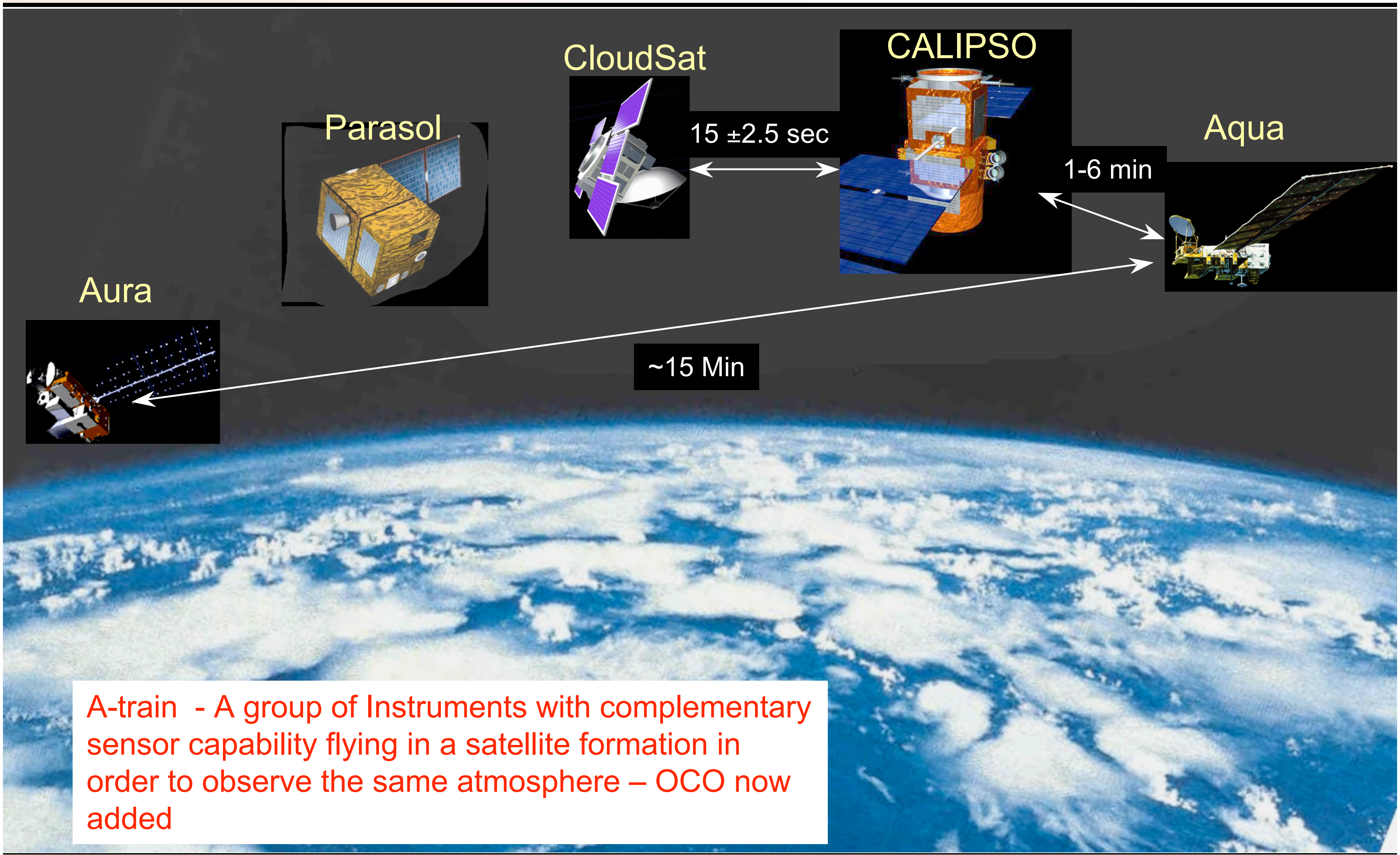


CALIPSO Mission Concept
Three Sensors



- **Three-channel lidar**
  - **532nm/1064 nm**
  - **532 nm has two polarization channels**
  - **Footprint on ground is 70 m, repeats every 330 m**
- **Imaging IR radiometer**
  - **8.65 micron, 10.6 micron, 12.05 micron**
  - **64 km by 64 km view with 1 km ground resolution**
  - **Includes blackbody reference and deep space view**
- **Wide-field camera**
  - **Visible Camera - 645 nm**
  - **61 km cross track view, 125 m resolution**

Aqua (A) Train for Multiple Observations



A-train - A group of Instruments with complementary sensor capability flying in a satellite formation in order to observe the same atmosphere – OCO now added

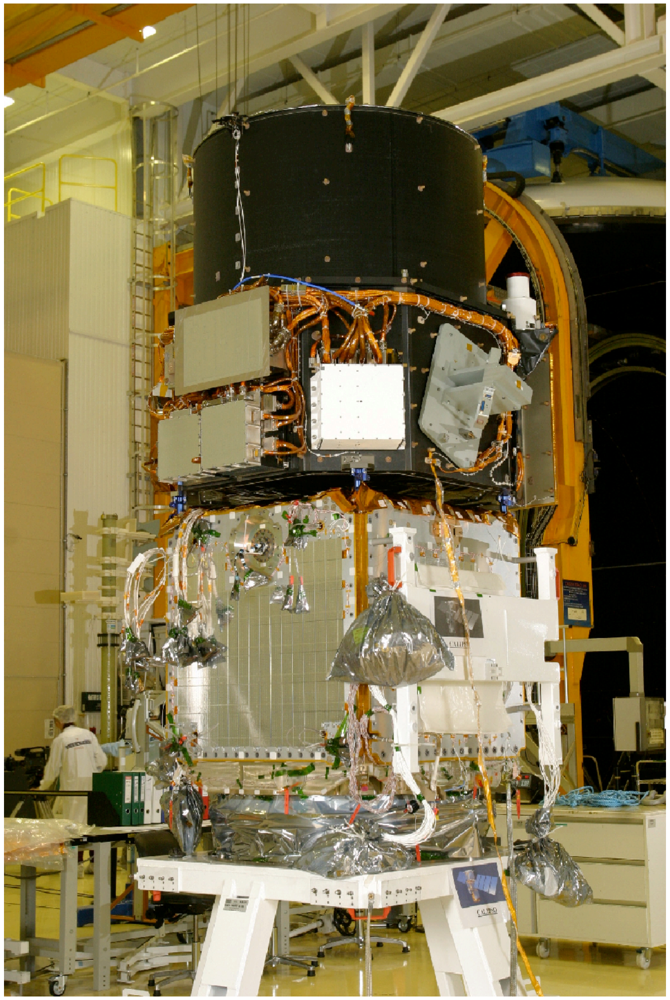
Science from the Combined Satellite Measurements

- Aerosol Properties – optical, microphysical, and chemical
- Cloud Properties – optical, microphysical, radiative for ice, water and mixed phase
- Cloud Aerosol Interactions – aerosol act to seed clouds
- Air Quality and Pollutant Transport – Study long range transport, anthropogenic vs. natural sources, gas/aerosol interactions
- Direct and Indirect Aerosol Radiative Forcing – improve models
- Surface and Atmospheric Radiative effects
- Cloud – Radiation Dynamical Feedback Processes
- Properties of Mixed Phase Clouds
- Polar Stratospheric Clouds – distribution, properties and lifecycle

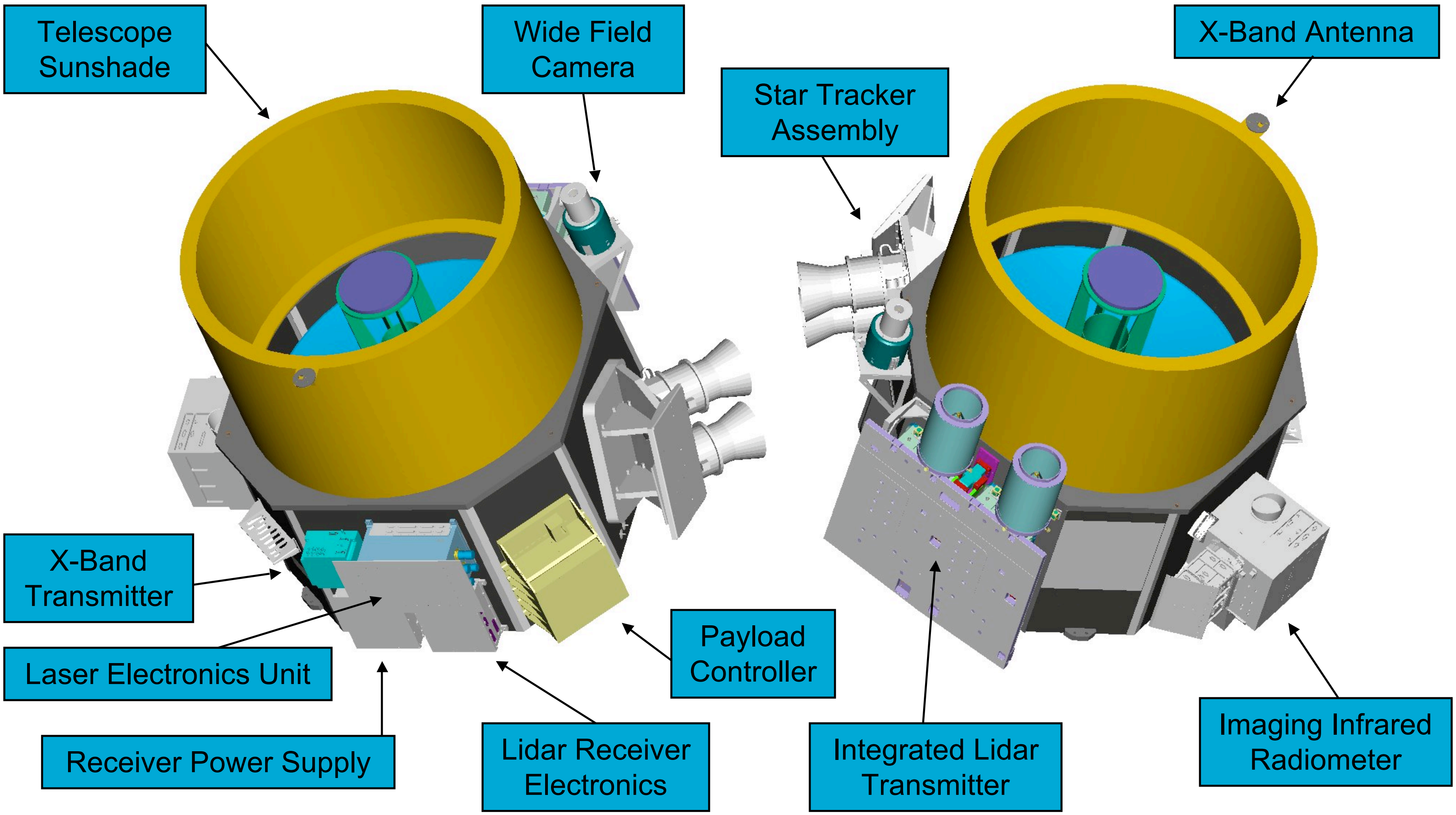
Space-Qualified Hardware for the CALIPSO Lidar

CALIPSO

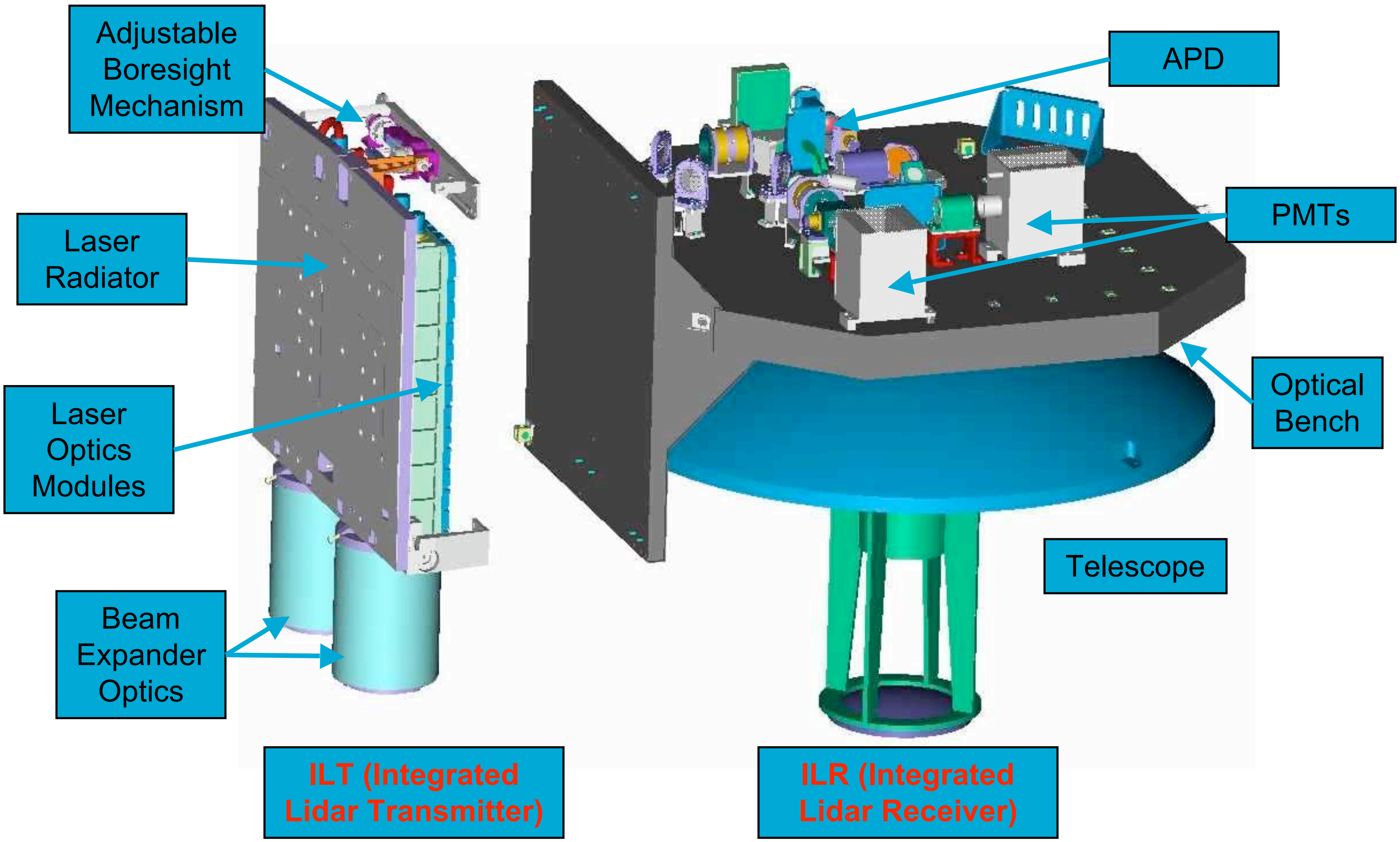
- **BATC built and qualified the Payload – Delivered January 2004**
- **Alcatel Space (France) built the Spacecraft (Proteus)**
  - **Spacecraft provides power, pointing capability, command/control capability, propellent/thrusters for orbit adjustments**
- **Integration with the spacecraft at Alcatel in Cannes, France completed May 2005.**
  - **Included a complete set of environmental tests**
- **Launch date scheduled for April 21 2005 (one week) for a Sun-synchronous, 705 km orbit**
  - **Launch is out of VandenBerg Air Force Base, California**



Different Views of Payload



Lidar Core – Transmitter and Receiver



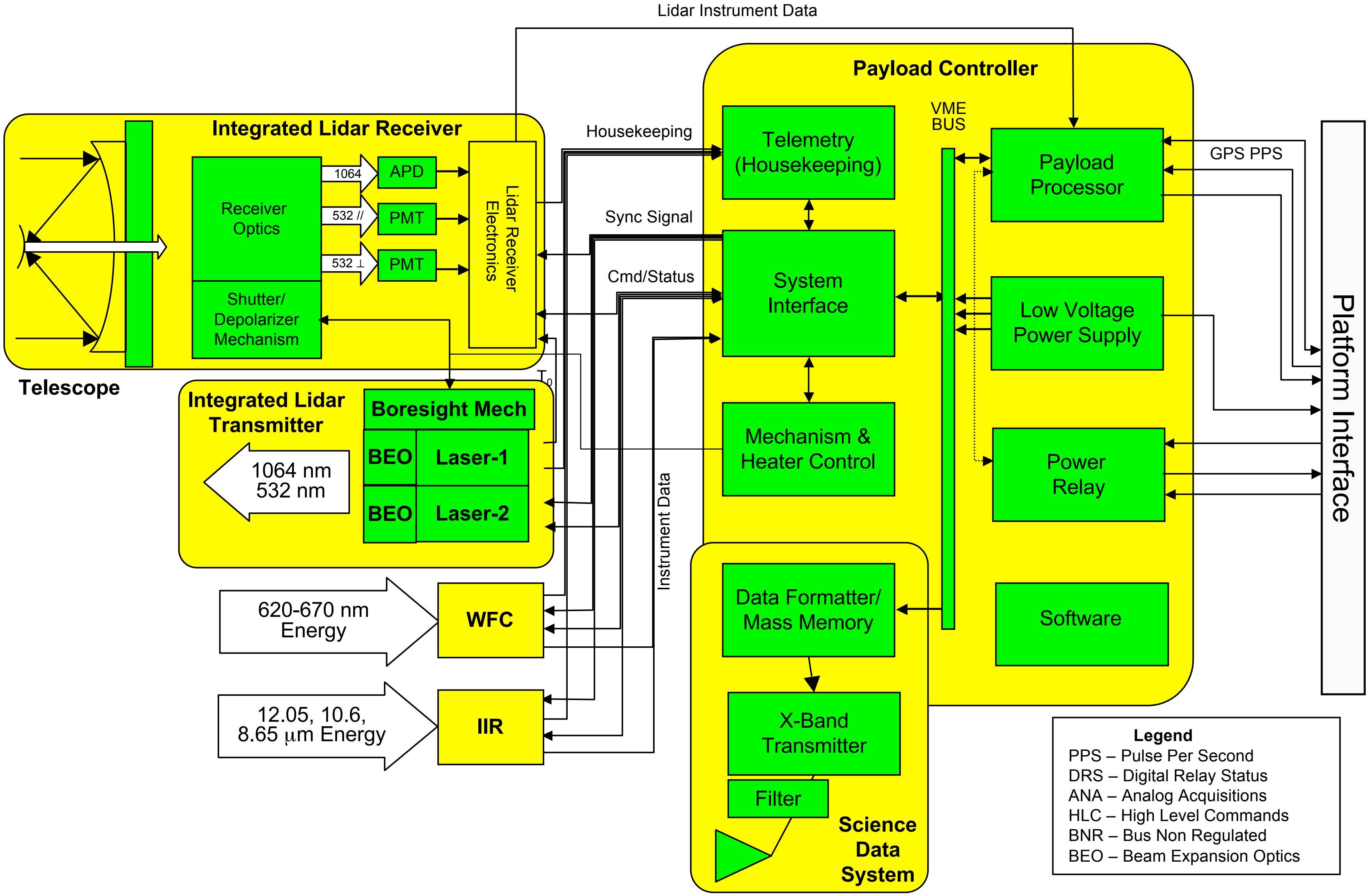
CALIPSO Lidar Highlights

- **Rayleigh-Mie Lidar for Clouds and Aerosol**
- **Polarization Sensitive at 532 nm to distinguish ice from water clouds**
- **Two-Wavelength 532 nm/1064 nm to give particle size**
- **Signal is Normalized to Rayleigh return and output laser energy on each shot – self calibrating**
- **Two (fully redundant) Nd:YAG Lasers emitting equal pulse energies (110 mJ @ 20 Hz) at 1064 nm and 532 nm**
- **Biaxial transmitter and receiver with automated laser pointing alignment mechanism, 1.5 microrad steps over 3º**
- **One-meter diameter receiver collection aperture using silver-coated beryllium telescope, 130 microrad system Field of View to limit background light**
- **Graphite-Epoxy optical bench used for strength and high structural stability, low thermal expansion coefficient**
- **Range-resolution of 30 m, along track resolution of 330 m (20.7 Hz rep rate)**
- **GPS, Startracker data, Geoide model, used to give pointing angle and Altitude**

CALIPSO Lidar Highlights

- Three optical detection channels
  - 532 nm dual channels utilize Photomultiplier Tubes. Detect orthogonal polarizations.
  - 1064 nm channel utilizes Avalanche Photodiode
- Commandable mechanism allows shutter or (calibration) depolarizer to be inserted
- Optical filtering done with interference filters and etalon (532 nm only) matched to lasers
- Linear detection is utilized. Analog-to-Digital Converters are 10 MHz, 14 bits, stacked to give 23 effective bits of dynamic range
- On-board data processing performs preliminary lidar data handling and averaging plus engineering telemetry
- Total Data volume (all instruments) transmitted to ground will be 4.7 Gbytes per day

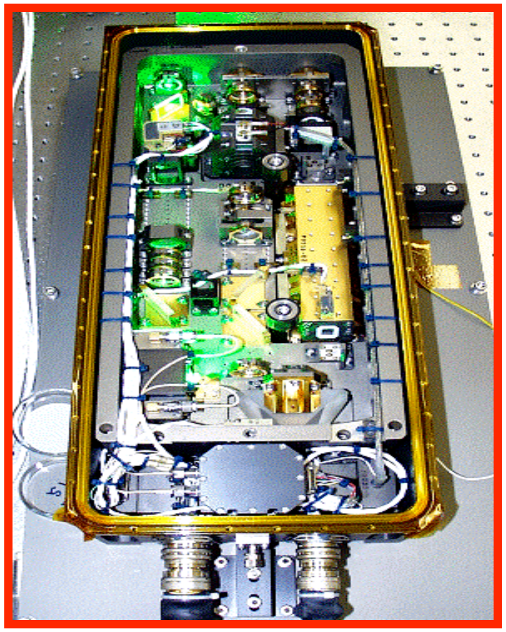
Payload Schematic



Legend
PPS – Pulse Per Second
DRS – Digital Relay Status
ANA – Analog Acquisitions
HLC – High Level Commands
BNR – Bus Non Regulated
BEO – Beam Expansion Optics

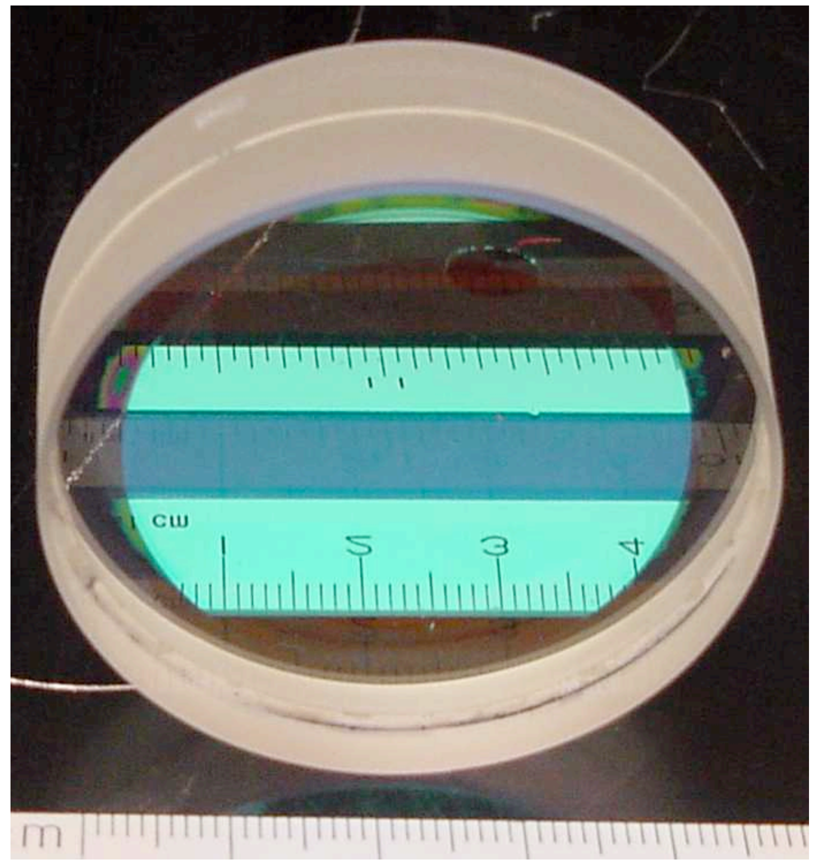
Space Qualified Lasers

- **Built by Fibertek of Herndon VA, with Ball**
- **Engineering Unit built that demonstrated full mission lifetime (2 billion shots).**
- **Laser is Nd:YAG in a zigzag slab with 192 diode bar pumps**
- **Utilizes a KD*P Q-switch (20 ns pulses) and a KTP frequency Doubler**
- **110 mJ/pulse for each color @ 20 Hz**
- **Spectral linewidth (Multi-transverse mode)**
  - < 150 pm @ 1064 nm,
  - < 35 pm @ 532 nm
- **532 nm Output polarized to > 1000:1**
- **Conductive Cooling – Heaters/radiators**
- **Ball designed Beam Expander Optics set laser divergence to approximately 100 microrad**
- **Weight 35 kg, uses 100 W**
- **Redundant Lasers used – each designed for full mission life**



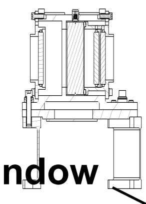
Qualified Fabry-Perot Etalons for Receiver

- “Sandwich” Etalon Design developed by Coronado Instruments
- Clear aperture – 30 mm
- Diameter – 50 mm
- Reflective coating >90%
- Bandwidth – 39 pm
- Effective finesse – 18
- Engineering temperature controlled housing and known wavelength test laser (HPBW <1 pm) used at Coronado to verify performance during manufacture



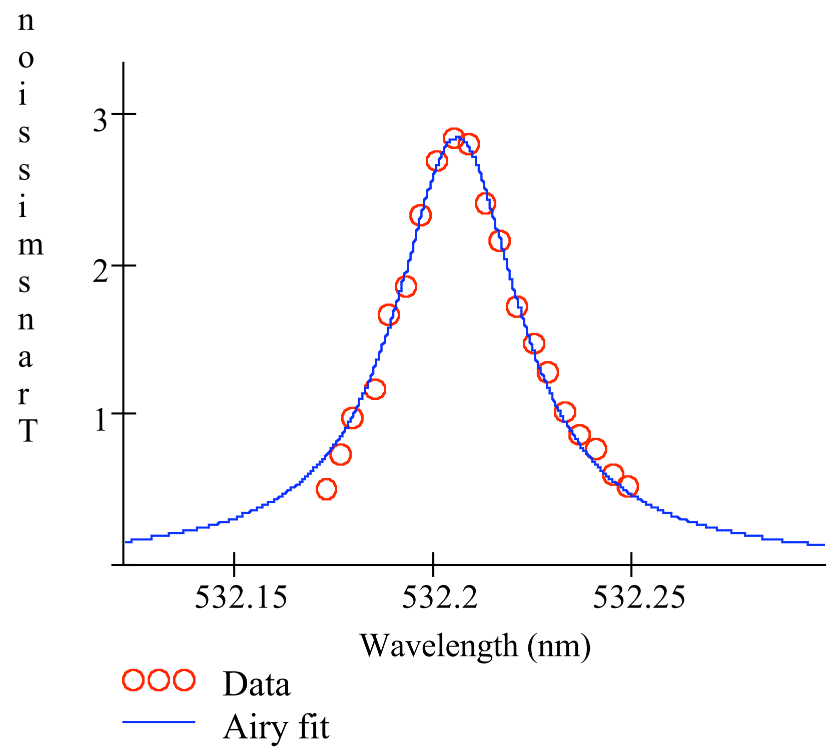
Etalon Oven Housing

- Housing provides temperature adjustment from 32ºC to 48ºC – provides tunability over one linewidth
- Extensive testing of engineering version verified mount survives launch environment
- Design maintains a low stress on etalon to minimize polarization effects
- Flight Subassembly went through a qualification program of environmental testing prior to installation on bench

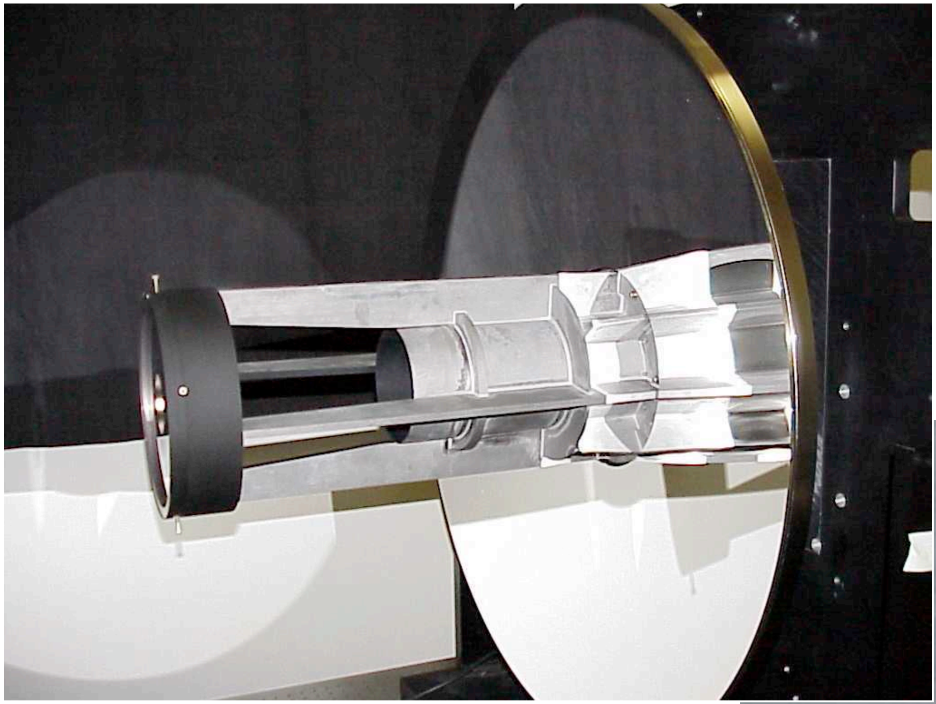


Flight Etalon Performance

- Flight etalon tilted to 15.2 mrad and temperature of 39.5ºC
- Measured transmission wavelength scanning a narrow band laser (<1 pm)
- Matched Airy function
- Peak transmission at 532.206 nm
- Etalon was aligned on bench so center wavelength matched laser wavelength
- Tuning verified and shown to be stable throughout the Payload and Satellite integration (approximately 2 years).



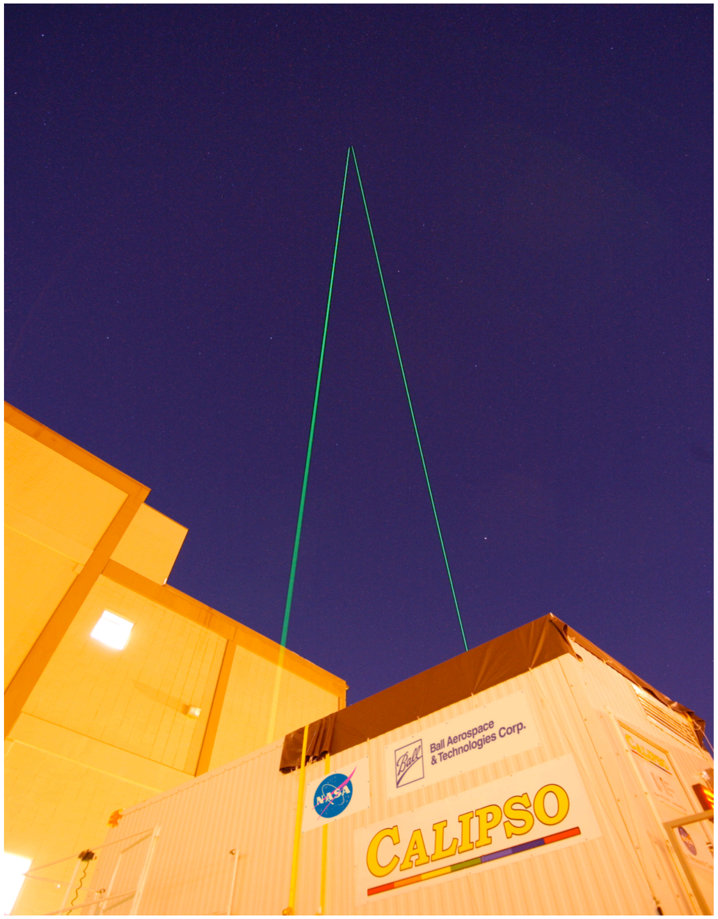
All-Beryllium Cassegrain Receiver Telescope



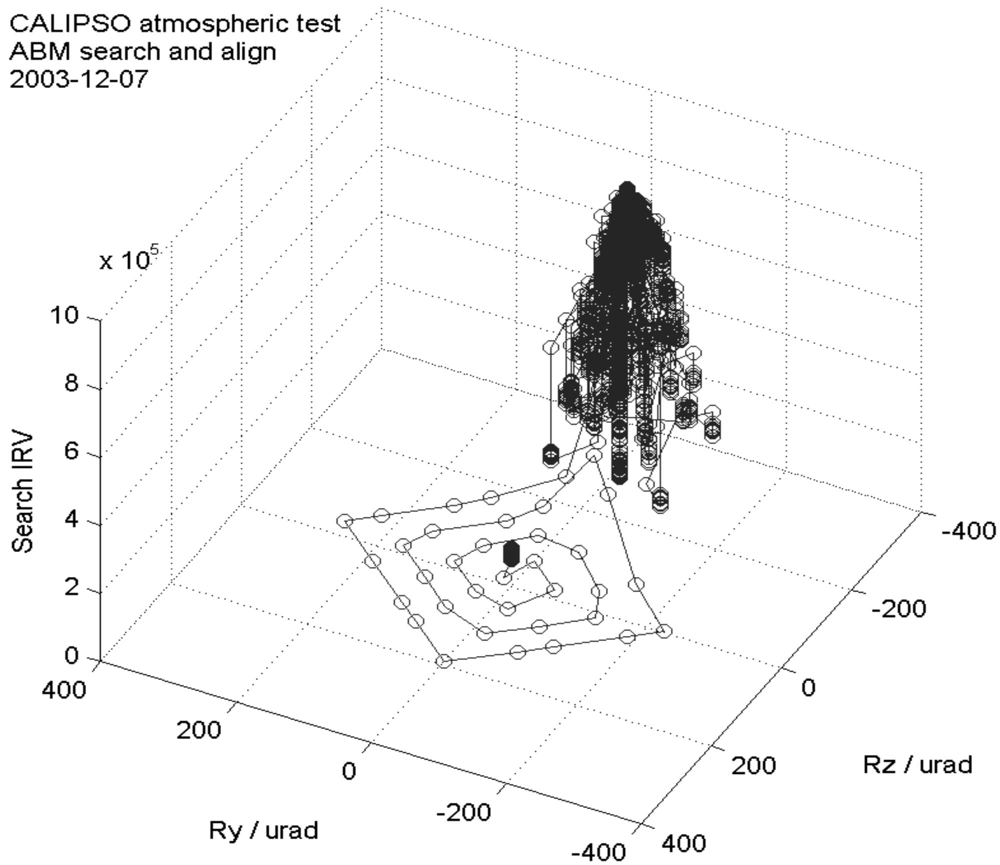
- Light-weighted Design - < 36 kg
- Wavefront < 2 Waves P-V at 632 nm
- 1 meter clear aperture
- Nickel-plated with silver coatings

Examples from Atmospheric Lidar Testing

- **Atmospheric Testing Performed at Ball in December 2003 and May 2005 at VAFB**
- **Tests were used primarily as an end-to-end demonstration of the lidar capability and autonomous boresight capability**
- **Demonstrated that the lidar alignment was stable over 18 months and trip to France and back**
- **NASA provided a second lidar for correlated studies, analysis in process**

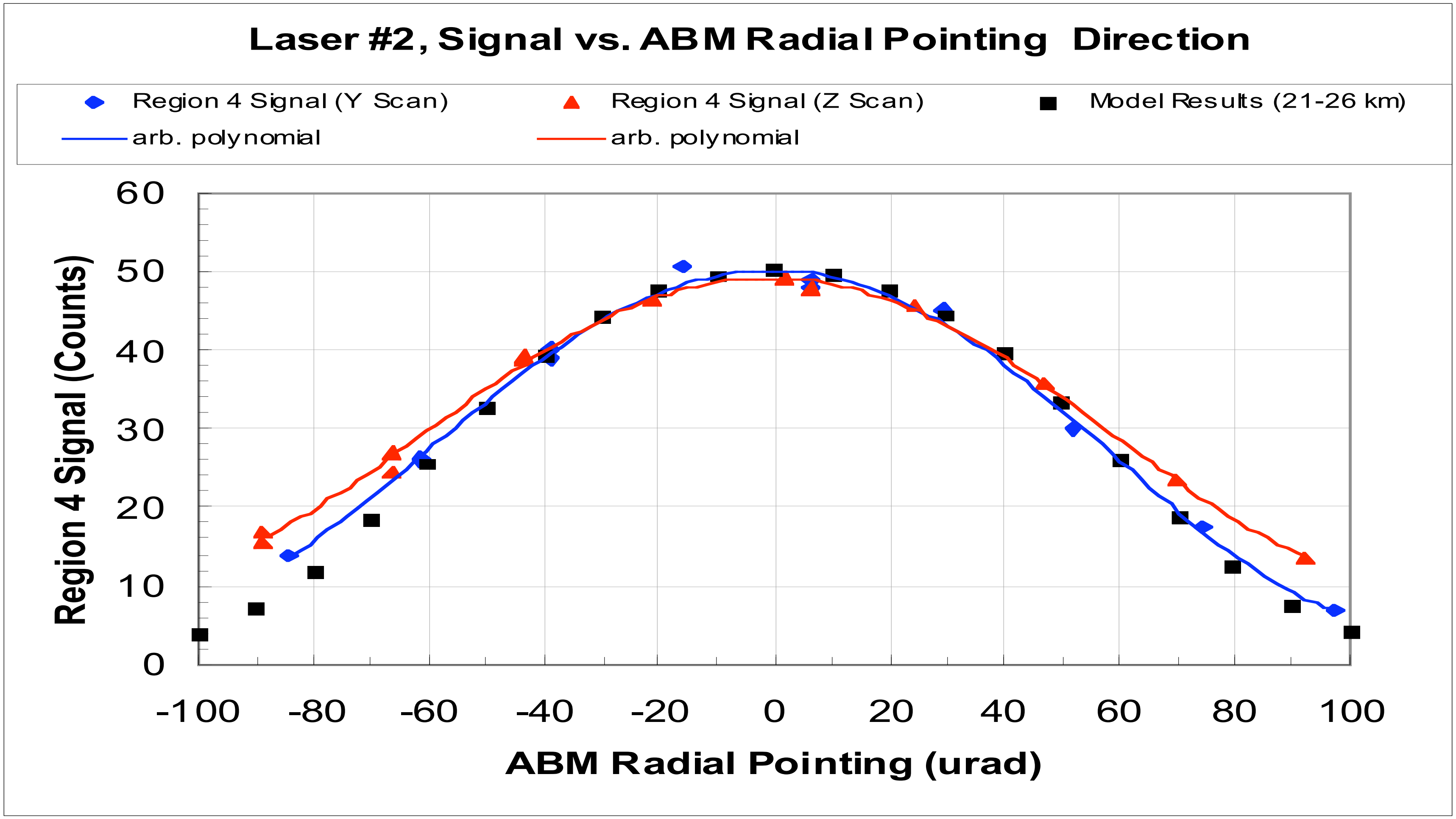


Boresight Search & Align Example



- Lidar Signal from clear sky
- Autonomous Search (diamond pattern) starting from (0,0)
- Autonomous Alignment of the lidar overlap function
- Search/Align required < 20 minutes.
- Manual testing to verify true optimal alignment found
- Goal on-orbit is to do this once

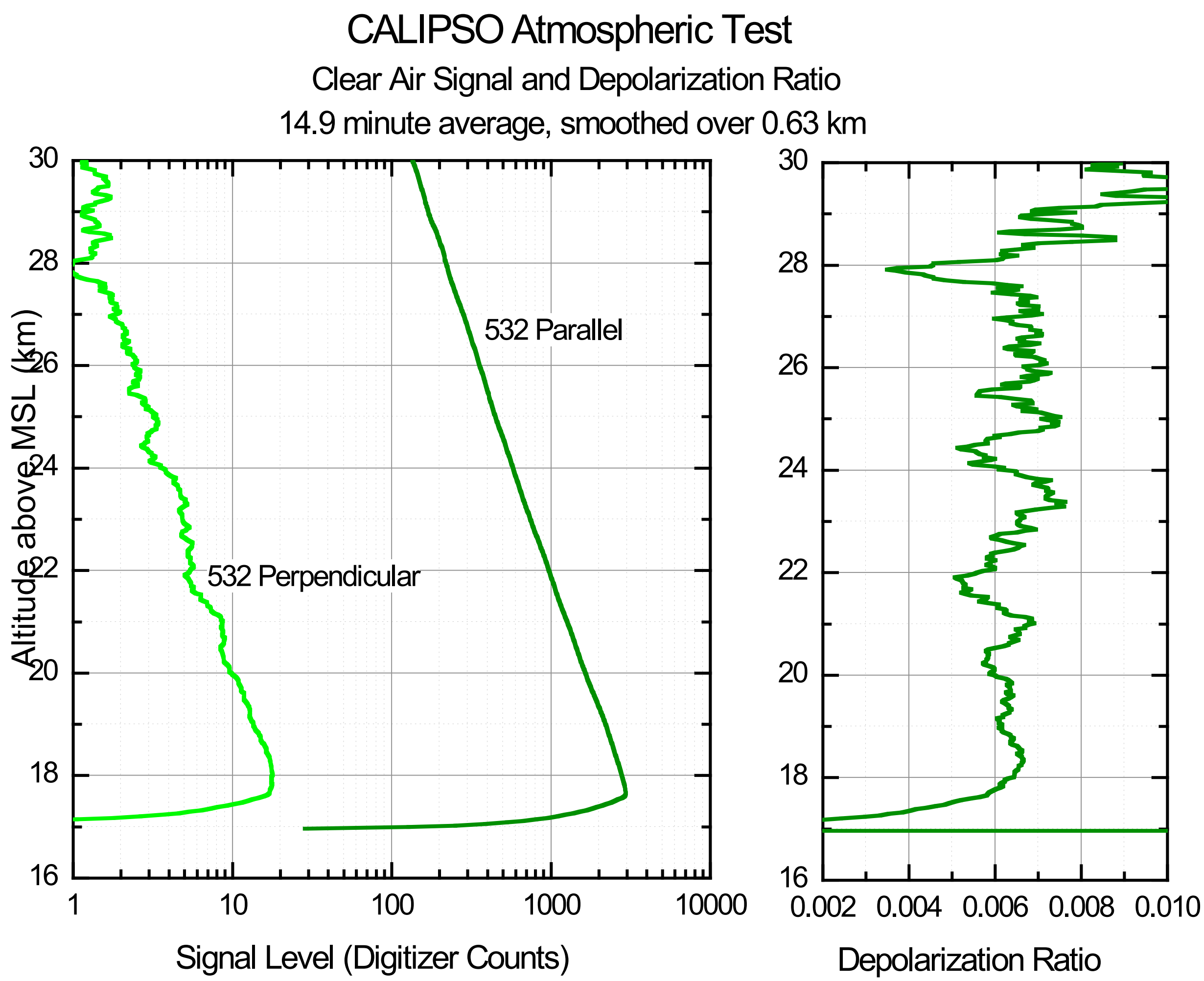
Laser Pointing Scan Over the Receiver FOV – Lidar Overlap Function



Lidar Polarization Measurements

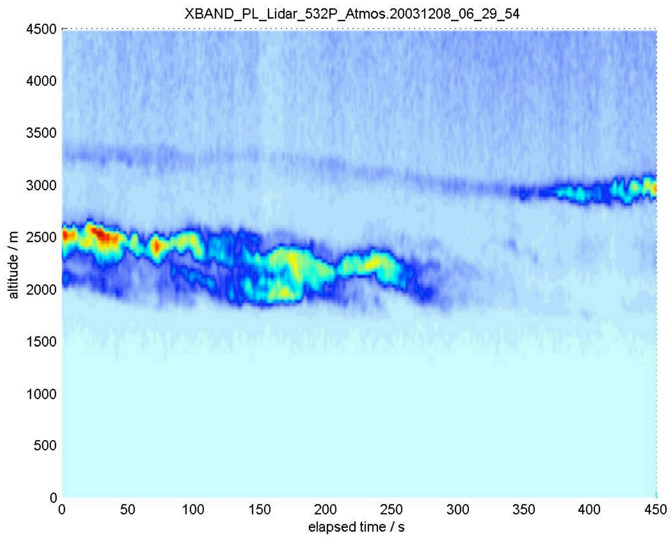
- Goal is to measure the depolarization of the (linearly) polarized laser by clouds to differentiate between water and ice
- Depolarization by Rayleigh scattering (clean air) can be used as an indication of system performance
- Etalon attenuates the rotational Raman components in the scattering – Rayleigh vs Cabannes (see Chiao-Yao She paper on class website)
- Estimated theoretical depolarization is 0.4%, measurement was 0.7%, met the requirements on instrument contribution
- However, only part of full receiver aperture used, there may be more instrumental effects. So final test awaits orbit
- On-orbit, Depolarizer will be used to assist calibration

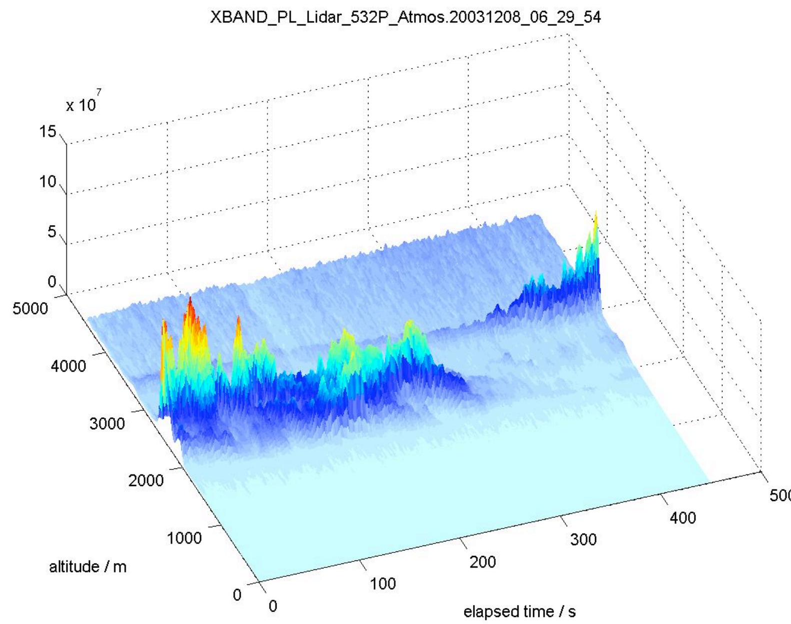
Depolarization Data



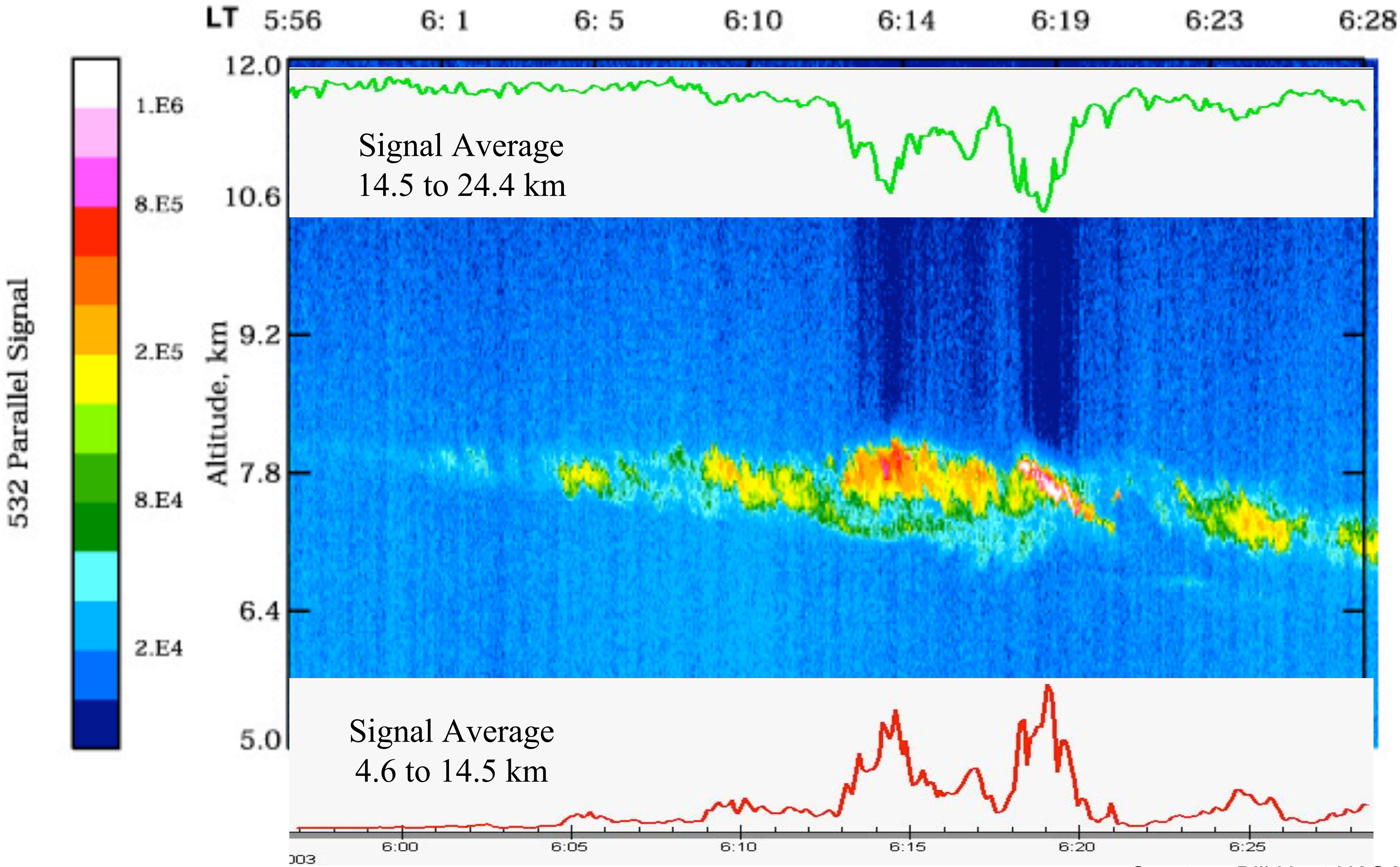
Courtesy Bill Hunt, NASA

Examples of Cloud Backscatter Data
Two-Layer Cloud





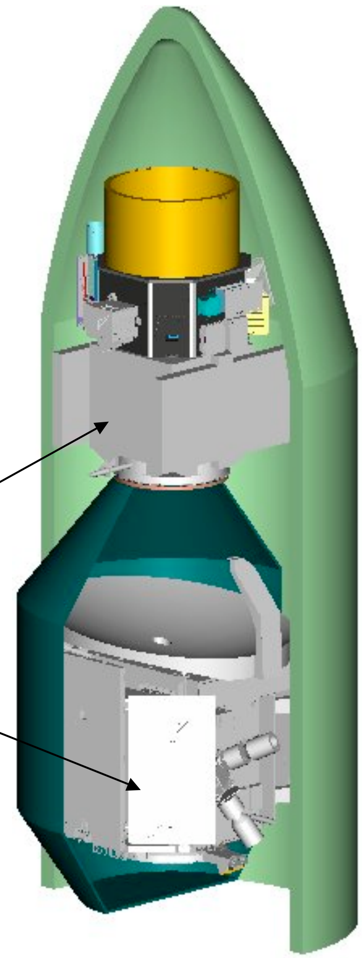
Second Example of a Cloud Data – Thin to Thick



Courtesy Bill Hunt NASA

Launch Segment Scheduled for April 2006

- **To Be Launched with Cloudsat (JPL/Ball)**
- **Delta II 7420-10C with DPAF**
  - **Standard 3-m (10') fairing**
- **Mass to orbit**
  - **Total 1653 kg**
  - **CALIPSO 650 kg**
  - **Cloudsat 1003 kg**



After Launch

- Commissioning of satellite takes 45 days
  - Deploy out of fairing
  - Establish command communication with satellite (S-band link)
  - Deploy solar arrays
  - Establish orbit and attitude and location in A-train formation
  - Outgas all the structure
  - Establish data communication (X-band link)
  - Turn on each instrument sequentially
  - Verify Lasers
  - Align Lidar overlap function
  - Optimize Lidar subsystems – etalon, polarization calibration, voltages
  - Begin collecting Science
  - All data is trended and verified to be acceptable
- Science Assessment Phase takes the next 45 Days
- Mission Operations located in France
- Data storage and analysis at NASA LaRC

Science Data Handling

- On-board data processing algorithms are used to reduce the data volume (final is 4.7 Gbyte/Day)
  - Range to Mean Sea Level calculated for each shot using GPS and Geoid data
  - Background light levels are removed
  - Baseline shape removed
  - Laser output energy for each pulse recorded
  - Lidar data is spatially averaged together (horizontally and vertically) to match typical atmospheric variation

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

Final Data Products

- Data is downlinked to Alaska station daily then routed via United Space Networks to NASA LaRC
- Automated Algorithms have been developed at NASA utilizing the LITE data – Based on range-resolved profiles of attenuated backscatter coefficients for each wavelength:
  - Boundary Location
  - Feature Classification – discriminate clouds from aerosols, determine ice-water phase, subtype of aerosol chosen
  - Optical Properties – calculate extinction and backscatter coefficients using a linear iterative method to solve lidar equation
- The final processed data is then made available to the different research communities for use in their work
- See numerous papers by Dave Winker, Mark Vaughan, and co-workers at CALIPSO website and in SPIE.