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Space-based Water Vapor Lidar

Part of Combined Active and Passive Environmental Sounder (CAPES)

Global Investigations of Water Vapor, Temperature, and Relative Humidity, Aerosols, and Clouds

Builds on over two decades of technique/technology development and atmospheric science research with ground-based and airborne lidar systems

Edward V. Browell, Syed Ismail, and Richard A. Ferrare
NASA Langley Research Center

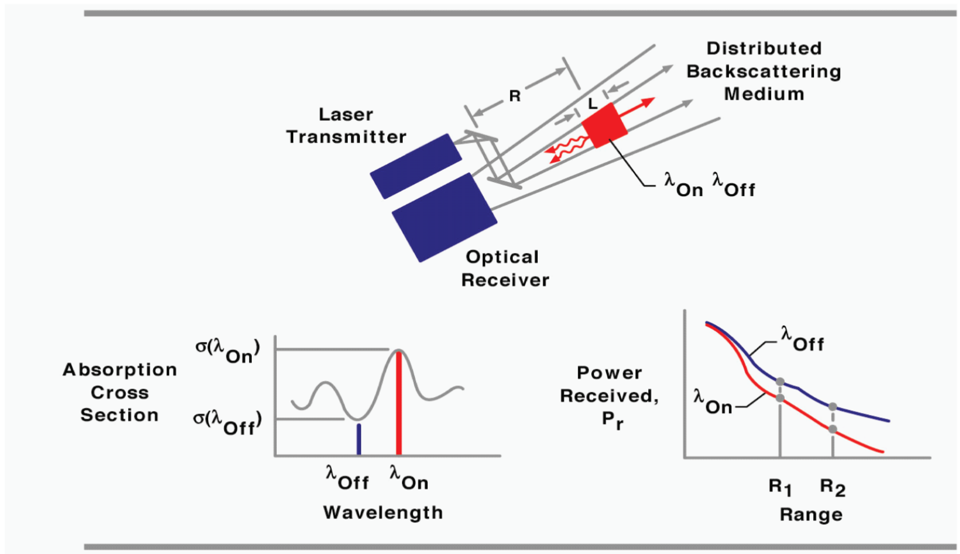
ESTO Lidar Forum - 1/10/06

Scientific Rationale

- Water vapor is principle component of greenhouse effect and plays key role in atmospheric climate and radiation. Better measurements are needed in the mid to upper troposphere.
- Water vapor plays critical role in understanding weather and severe storm phenomena via evaporation, cloud formation, precipitation, and release of latent heat. High resolution water vapor measurements shown to improve forecasting of severe storm behavior.
- Global hydrologic cycle requires improved understanding of water vapor distributions.
- Vertical and horizontal transport of water vapor can be used to study atmospheric dynamical processes like strat-trop exchange.

Active water vapor measurements identified in NASA Weather and Atmospheric Composition "Roadmaps" to address important future science priorities. (May 2005)

Water Vapor Differential Absorption Lidar (DIAL) Concept



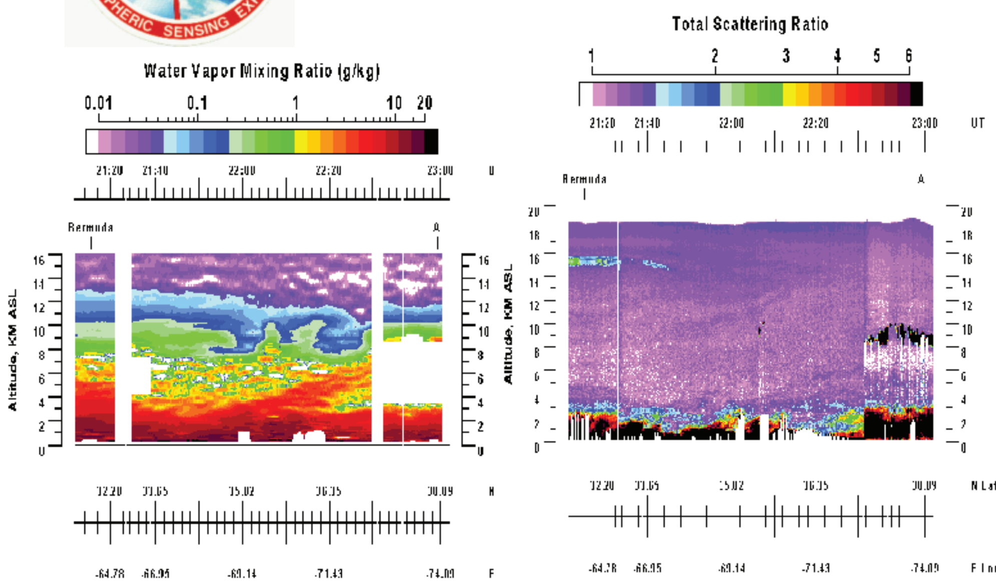
$$N_A = \frac{1}{2(R_2-R_1)\,[\sigma_A(\lambda_{On})-\sigma_A(\lambda_{Off})]} \ln \left[\frac{P_{r_{On}}(R_1) \times P_{r_{Off}}(R_2)}{P_{r_{Off}}(R_1) \times P_{r_{On}}(R_2)}\right]$$

813 or 940 nm H_2O Lines with $\Delta\lambda$<0.1 nm

H_2O DIAL Major Developments

?	First DIAL H_2O Measurements with Continuously Tunable Laser (Gnd-based)	1977
?	First Airborne DIAL H_2O Measurements (Nd:YAG-Pumped Dye Laser)	1981
?	First Airborne H_2O Study Over Atlantic	1982
?	First Airborne DIAL Measurements with Solid-State Laser (Alexandrite)	1989
?	First Exten. Airborne DIAL H_2O Studies	1992
?	First Airborne DIAL H_2O Measurements with Complete Solid-State Laser System	1994
?	First Autonomous DIAL System (LASE) Demonstrated on ER-2 Aircraft	1995
?	First LASE on P-3 for Trop. Studies (SGP)	1997
?	First LASE on DC-8 for Hurricane Studies (CAMEX-3)	1998

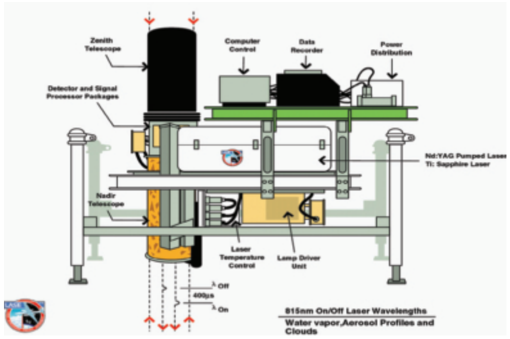
LASE Measurements From Bermuda to Wallops Island, VA (A), 26 July 1996



LASE Field Experiments

Field Experiment	Dates	Aircraft	Base of Operation	Alt. Range (km)
LASE Validation Experiment	Sept. 1995	ER-2	Wallops Island, VA	0-15
TARFOX (Trop. Aerosol Radiative Forcing Observation Exp.)	July 1996	ER-2	Wallops Island, VA	0-15
SGP97 (Southern Great Plains Exp.)	July 1997	P-3	Oklahoma City, OK	0-7
CAMEX-3 (Convection and Moisture Experiment-3)	Aug.-Sept. 1998	DC-8	Cocoa Beach, FL	0-15
PEM Tropics-B (GTE Pacific Exploratory Mission in Tropics-B)	Mar.-Apr. 1999	DC-8	Hawaii, Fiji, Tahiti	0-15
SOLVE (SAGE III Ozone Loss and Validation Experiment)	Dec. 1999- Mar. 2000	DC-8	Kiruna, Sweden	0-12
AFWEX (ARM/FIRE Water V. Exp.)	Nov.-Dec. 2000	DC-8	Oklahoma City, OK	0-12
CAMEX-4 (Convect. & Moisture Exper.-4)	Aug.-Oct. 2001	DC-8	Jacksonville NAS, FL	0-15
IHOP (International H2O Project)	May-June. 2002	DC-8	Oklahoma City, OK	0-12

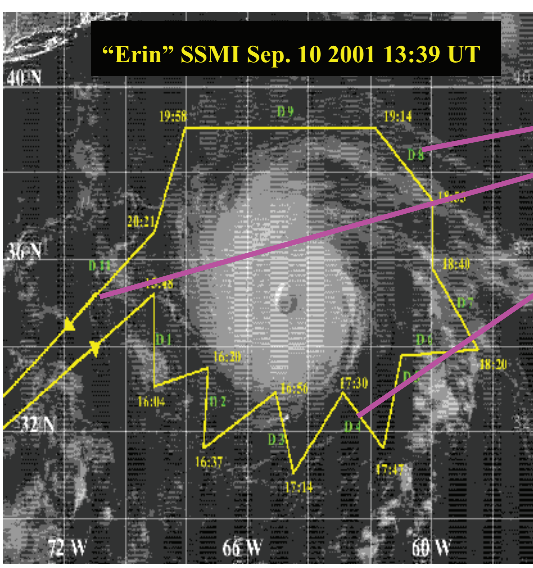
Lidar Atmospheric Sensing Experiment (LASE) on DC-8

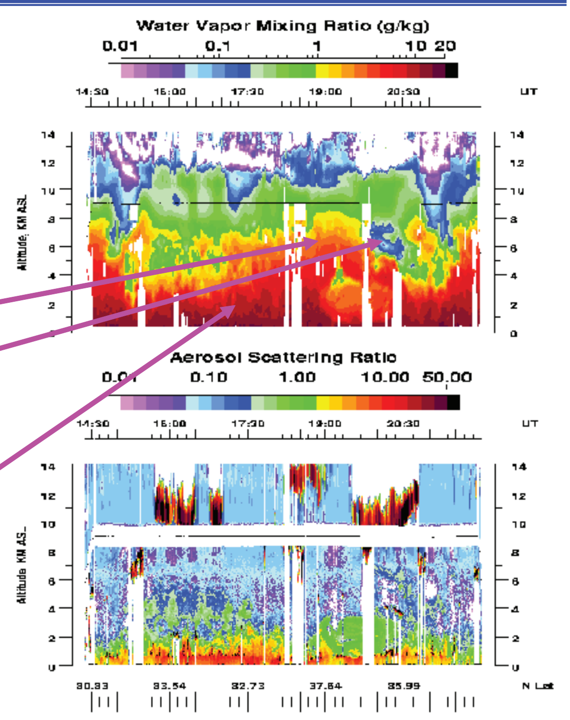


- Laser
  - 5 Hz doubled-pulsed Ti:sapphire
  - 100 mj (on and off lines)
- Wavelengths
  - 815 nm (on-off λ= Δλ= 40-70 pm)
  - Three separate line pairs
- NASA ER-2, P-3, <u>DC-8</u> aircraft
- Simultaneous nadir, zenith operations
- Real-time data analysis and display

CAMEX-4 Hurricane Erin "Optimal Data Assimilation" Flight

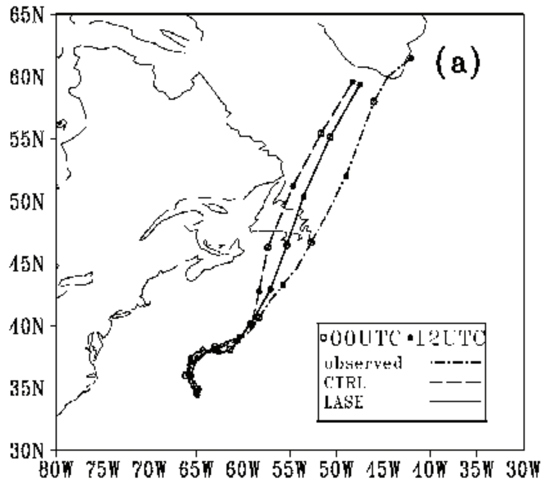
- High water vapor northeast of storm
- Mid-upper level dry region associated with cold trough southwest of storm
- Elevated aerosol layer south of storm



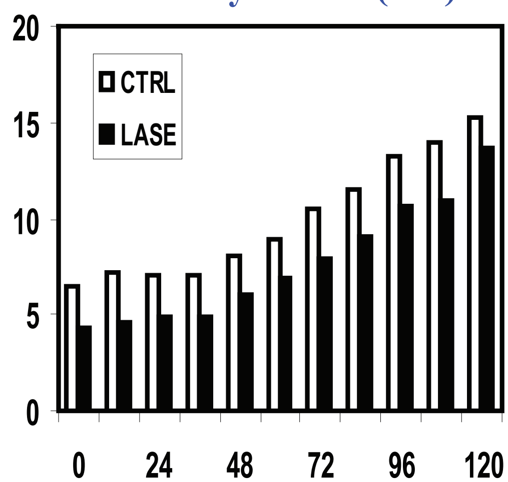


Hurricane Erin 12UTC 10 Sep 2001

120hr Forecast Track



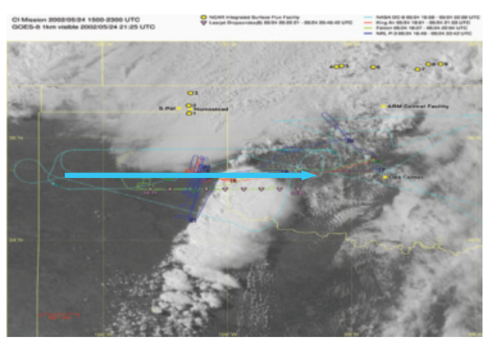
Intensity Errors (m/s)

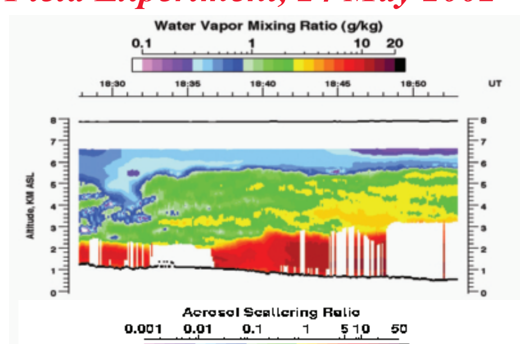


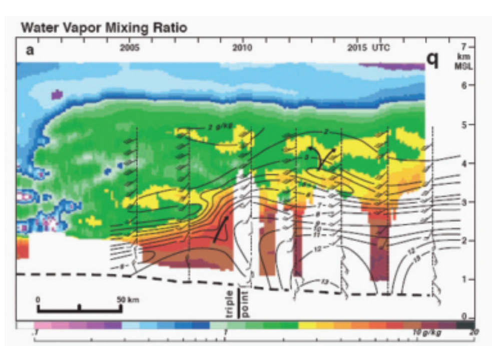
- LASE H_2O data improved track and intensity forecasts.

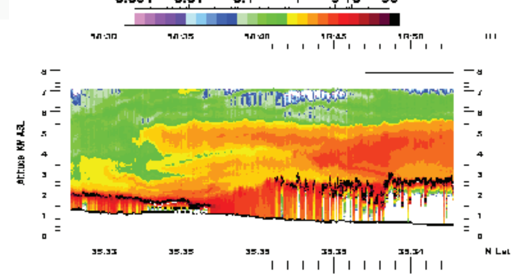
Kamineni et al., 2004; 2005

Convective Initiation (CI), IHOP Field Experiment, 24 May 2002









- High resolution LASE H_2O data improved CI forecasting

Wakimoto et al., 2004; Wulfmeyer et al., 2005

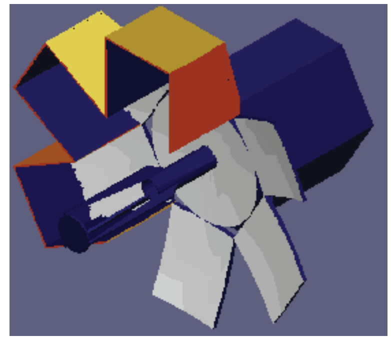
Space-based DIAL H_2O, Aerosol, and Cloud Measurements

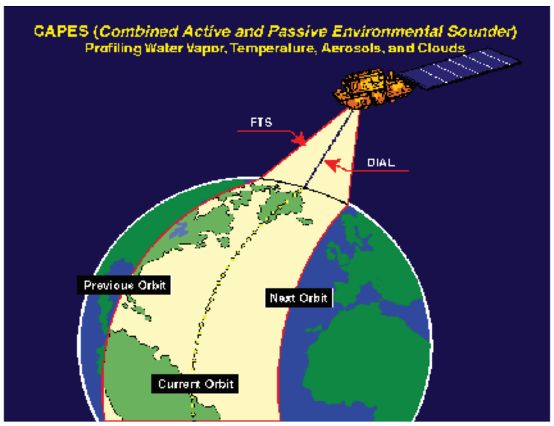
Measurement resolutions (Δz x Δx) and accuracy goals:

- Water Vapor – Lower Trop. 0.5 km x 50 km (10%)
  Mid.-Upper Trop. 1 km x 100 km (10%)
- Aerosol and Clouds: 60 m x 1 km (10%)

Technology Goals:

- Laser transmitter – 0.94 µm, >5W/wavelength
- Deployable Telescope: 3.0 m diameter

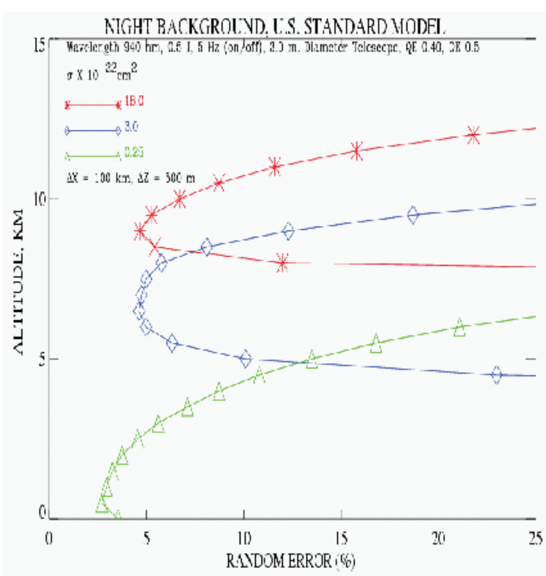


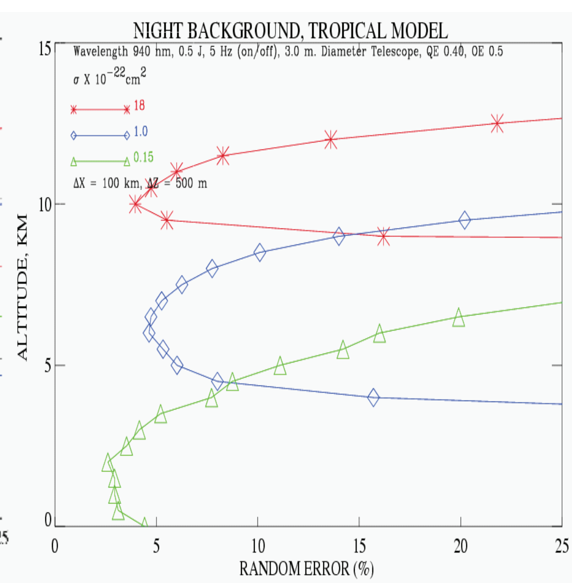


Combined Active (DIAL) and Passive (FTS) Environmental Sounder (CAPES)

- Simultaneous H_2O, T, aerosols, and cloud measurements
- Combines high vertical resolution (DIAL) with high spatial resolution measurements (FTS)
- Improves accuracy of FTS T and H_2O inversion
- Permits relative humidity field retrievals

Space-based H_2O DIAL Simulations from 450 km



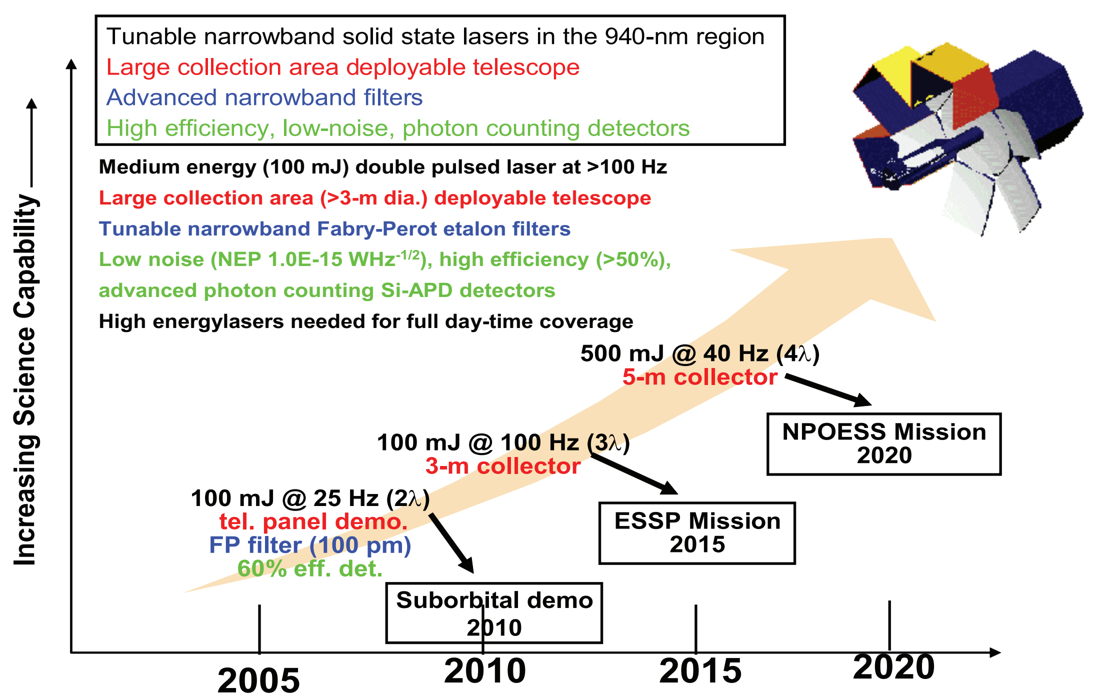


Space-based Water Vapor Lidar

Major Technological Challenges:

- Transmitter
  - Three laser wavelengths: two on-lines (line center & side line) and off-line ~70 pm from line center
  - High-power: >5 W/wavelength with pulse energies of >100 mJ/pulse and >50 Hz/wavelength
  - Lifetime: >3 year
- Receiver
  - Large-effective aperture telescope with area >4 m^2
  - High-performance filters: T >80% with narrow bandwidth for each wavelength

Water Vapor Differential Absorption Lidar

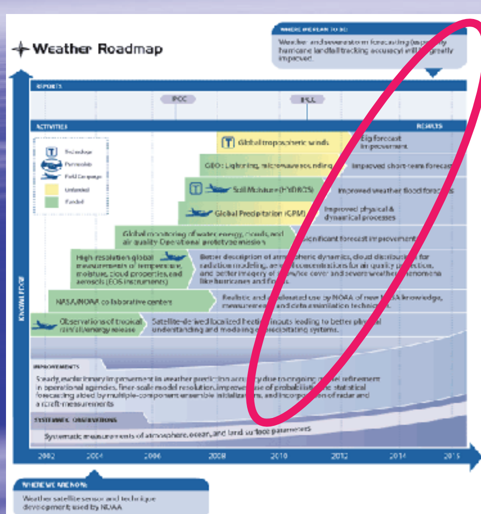


Intensive Mesoscale Field Experiments to Improve Severe Weather Forecast Prediction

Belay Demoz, NASA GSFC
David Whiteman, NASA GSFC

NASA/ESTO Lidar Community Forum
January 10, 2006

NASA and Weather



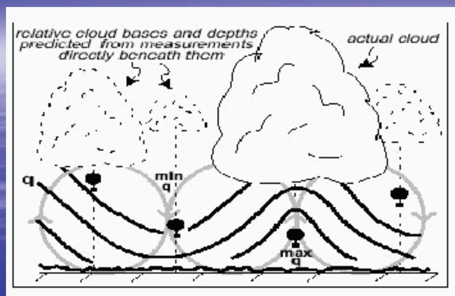
- The goal:
  - To improve weather and severe storm forecasting.

Severe storm forecasting includes

- **Convective initiation**
  - *e.g. Summer thunderstorm initiation*
- **Convergence lines**
  - *e.g. cold fronts*
- **Quantitative Precipitation Forecast (QPF)**
  - *e.g. Flood prediction etc*

Requirements: FREQUENT and HIGH-RESOLUTION observations of WATER VAPOR and WIND profiles in the lower troposphere (Satellite measurements must be augmented by ground-based/airborne)

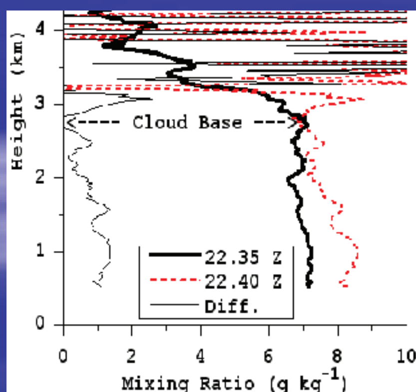
Convection Initiation: Lidar role



(Weckwerth et al. 1996)

Findings:
- Clouds form on top of updrafts
- Updrafts are moister than downdrafts
  - *about 1 g/kg in moisture difference**

Note: An error of 1g/kg in model initialization can mean the difference between generating a thunderstorm or not.



Why ground-based/airborne Lidar?

- Balloon sonde path is not vertical
  - updraft/downdraft merging of the profile
  - Profiles are too far apart (>1hr at best)

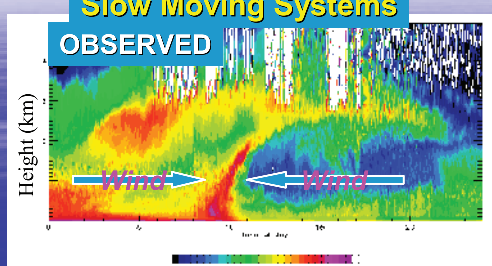
- Passive sensors "lack" sensitivity in the BL
- Satellite measurements have too coarse vertical/horizontal resolution

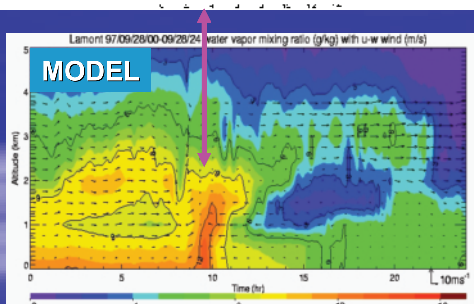
Lidars have shown it is possible to capture the moisture within and outside the updraft plumes.

*Demoz et. al. (2006)

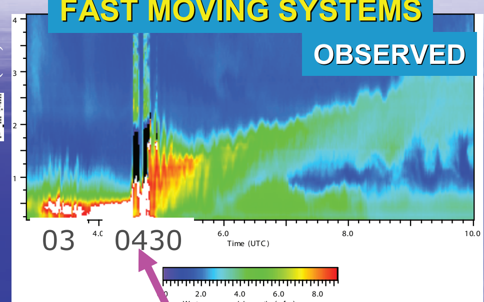
Convergence lines
Model-Observation comparisons of water vapor

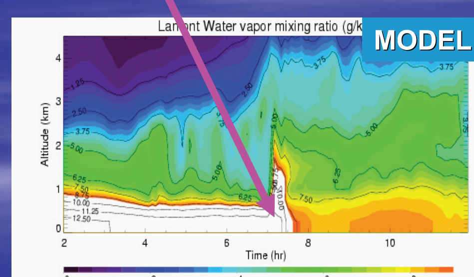
Slow Moving Systems





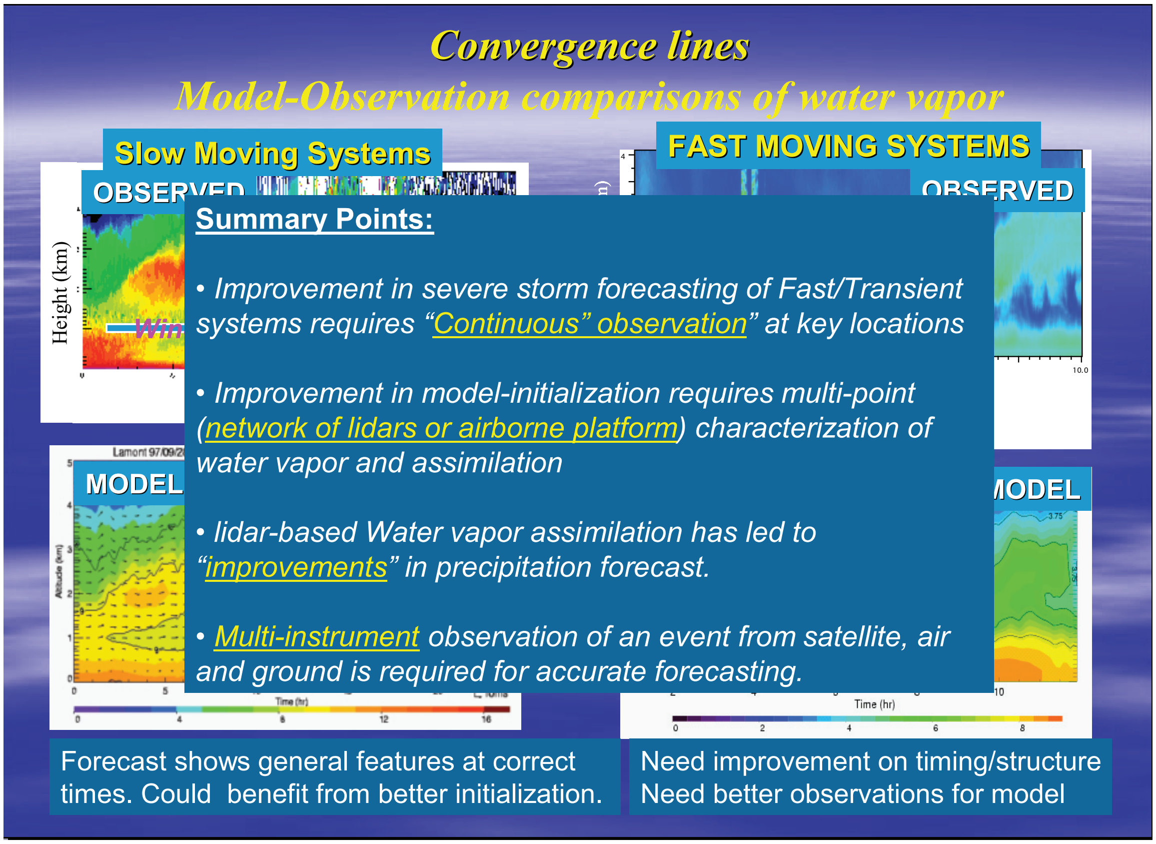
FAST MOVING SYSTEMS

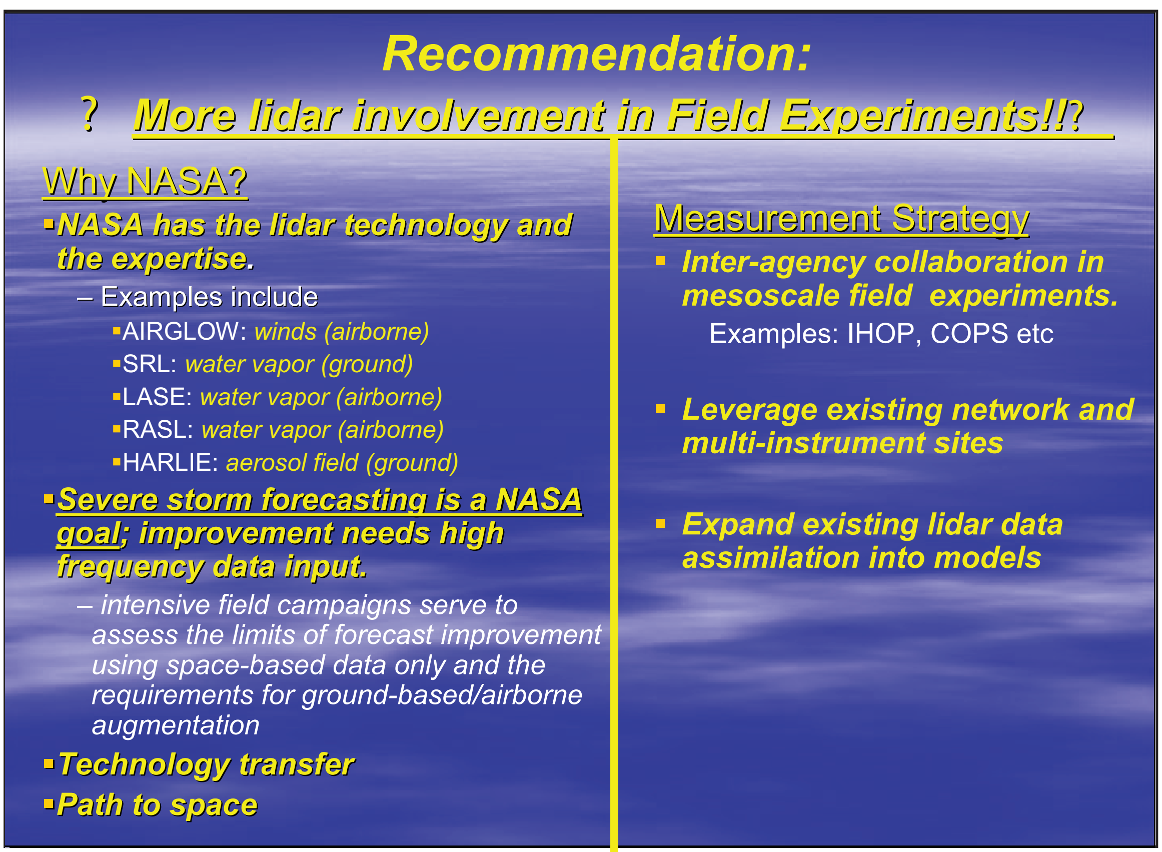




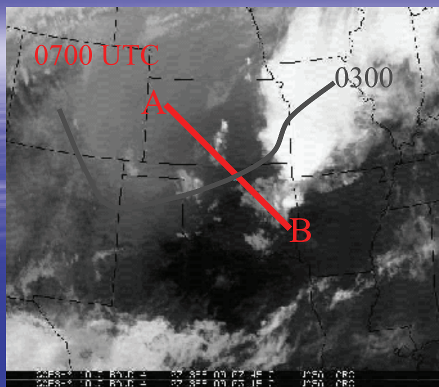
Forecast shows general features at correct times. Could benefit from better initialization.

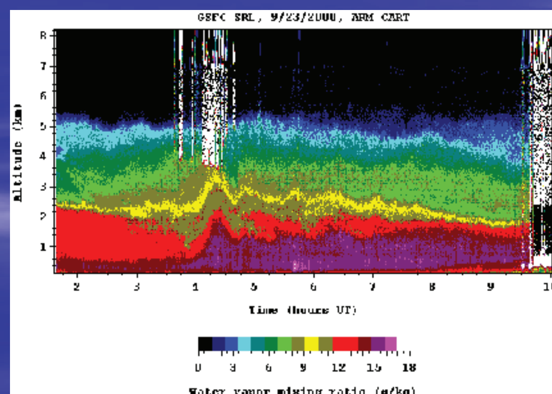
Need improvement on timing/structure
Need better observations for model


Convergence lines
Model-Observation comparisons of water vapor
Slow Moving Systems
FAST MOVING SYSTEMS
OBSERVED
OBSERVED
Height (km)
Summary Points:
• Improvement in severe storm forecasting of Fast/Transient systems requires "Continuous" observation at key locations
• Improvement in model-initialization requires multi-point (network of lidars or airborne platform) characterization of water vapor and assimilation
• lidar-based Water vapor assimilation has led to "improvements" in precipitation forecast.
• Multi-instrument observation of an event from satellite, air and ground is required for accurate forecasting.
MODEL
MODEL
Time (hr)
Time (hr)
Forecast shows general features at correct times. Could benefit from better initialization.
Need improvement on timing/structure
Need better observations for model


Recommendation:
? More lidar involvement in Field Experiments!!?
Why NASA?
▪NASA has the lidar technology and the expertise.
– Examples include
▪AIRGLOW: winds (airborne)
▪SRL: water vapor (ground)
▪LASE: water vapor (airborne)
▪RASL: water vapor (airborne)
▪HARLIE: aerosol field (ground)
▪Severe storm forecasting is a NASA goal; improvement needs high frequency data input.
– intensive field campaigns serve to assess the limits of forecast improvement using space-based data only and the requirements for ground-based/airborne augmentation
▪Technology transfer
▪Path to space
Measurement Strategy
▪ Inter-agency collaboration in mesoscale field experiments.
Examples: IHOP, COPS etc
▪ Leverage existing network and multi-instrument sites
▪ Expand existing lidar data assimilation into models

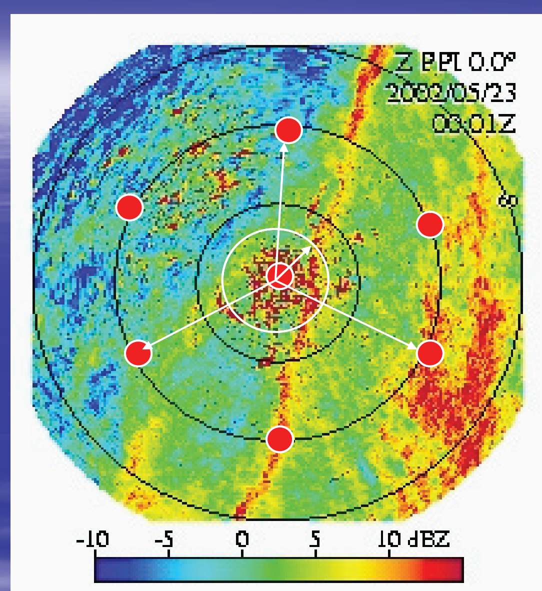
Forecast Bust: 23 September 2000 synoptic view





A proposal in the works: Data Assimilation Study

- 3/4DVAR to study the impact of different water vapor lidar systems
- Use a high-res. model to study trade-off systems
  - Scanning DIAL
    - Unprecedented precision, technology heading to space
  - Networked Raman
    - Much lower resolution, ground and airborne only
    - Automated, eye-safe, lower cost



22 May IHOP2002 dryline: illustrating the scales of interest. Scanning water vapor lidar (30km diameter) is placed at the center surrounded by profiling continuous Raman lidars.

Tropospheric Wind Profiler: Multi-spectral DWL

G. D. Emmitt
Simpson Weather Associates
ESTO workshop

Overview

- Need for direct wind observations from space
- Data utility issues with major technology implications
  - Accuracy
  - Vertical coverage
  - Scanning vs. non-scanning
  - Adaptive Targeting

Need for winds

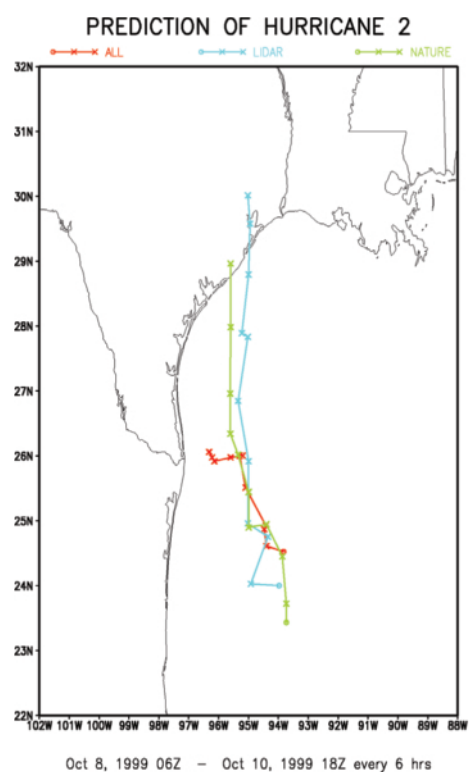
- Primary call for winds from the weather forecasting community
- Number 1 unaccommodated EDR for NPOESS
- On NASA's roadmap: cross-cutting with water cycle, climate, weather and atmospheric chemistry
- Value consistently revealed with the use of OSSEs (NOAA and NASA) since late 80's
- WMO call for global wind observations answered (partially) by ESA with its ADM

DWLs greatly improve hurricane track predictions

Potential Impact of new space-based observations on Hurricane Track Prediction

Based on OSSEs at NASA Laboratory for Atmospheres

- Tracks
  - Green: actual track
  - Red: forecast
  - Blue: improved forecast for same time period with simulated wind lidar
- Lidar in this one case
  - Indicates the hurricane will make landfall
  - Savings of 10's of millions $$ in avoided evacuation costs

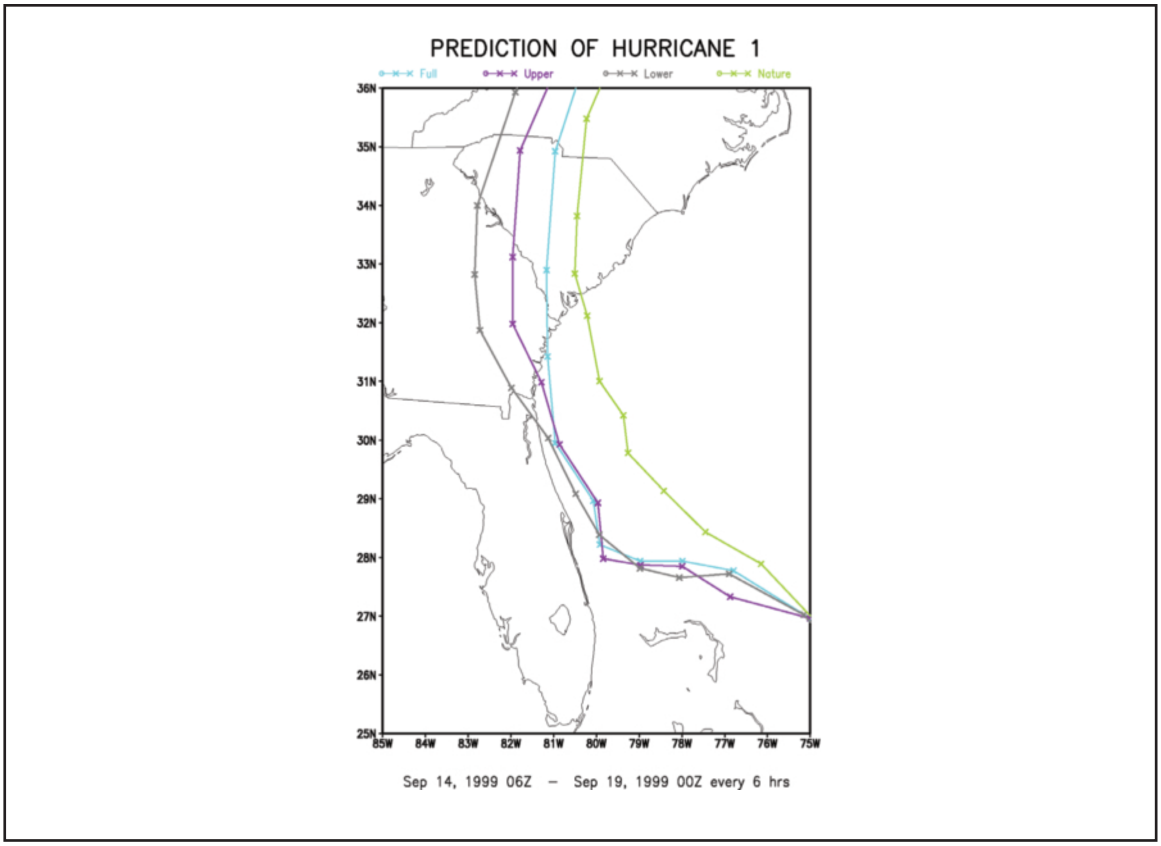


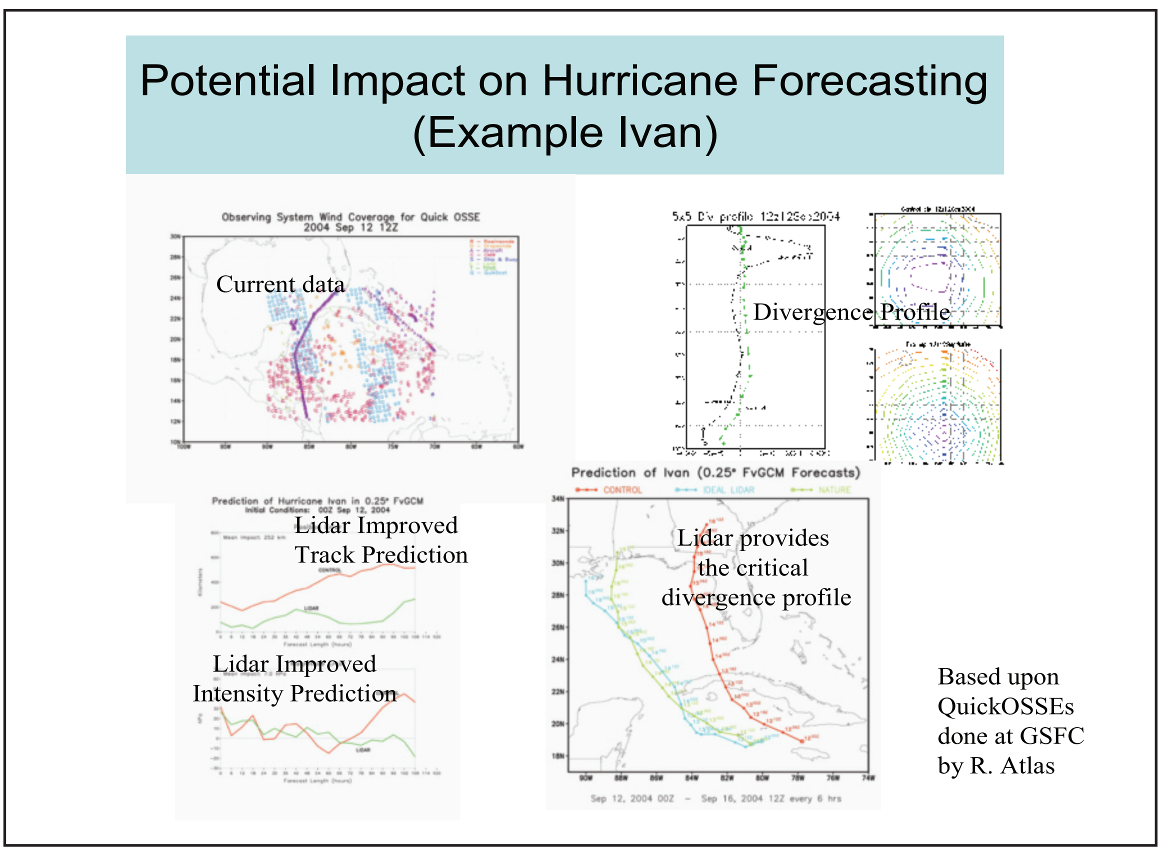
Data utility issue: accuracy

- To compete in the data assimilation schemes, wind accuracy must be better than model's background errors or first guesses.
- Accuracy in upper troposphere needs to be better than 3 m/s (HLOS)
- Accuracy in lower troposphere, 1-2 m/s (HLOS)

Data utility issue: vertical coverage

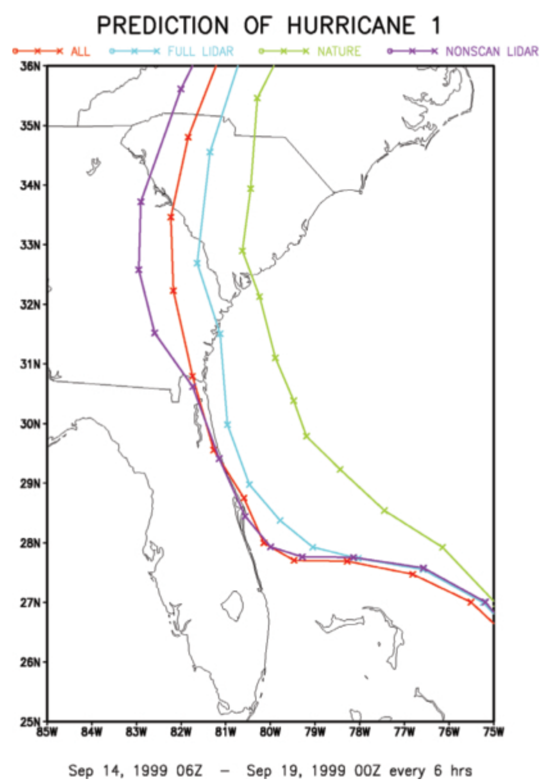
- OSSEs reveal need for full profile, especially for impacts in hurricane track prediction
- Response of the joint science/technology studies (e.g. ISAL/IMDC at NASA/GSFC) regarding the design of a space-based DWL was to propose a dual lidar technology approach to full wind soundings (multi-spectral DWL)
  - Direct detection molecular for mid/upper troposphere and lower stratosphere
  - Coherent detection for cloudy regions and lower troposphere (ESTO funded GLAS data analyses of cloud penetration statistics and system trades)


PREDICTION OF HURRICANE 1
Full
Upper
Lower
Nature
36N
35N
34N
33N
32N
31N
30N
29N
28N
27N
26N
25N
85W
84W
83W
82W
81W
80W
79W
78W
77W
76W
75W
Sep 14, 1999 06Z – Sep 19, 1999 00Z every 6 hrs


Potential Impact on Hurricane Forecasting
(Example Ivan)
Observing System Wind Coverage for Quick OSSE
2004 Sep 12 12Z
Current data
Divergence Profile
Prediction of Ivan (0.25° FvGCM Forecasts)
CONTROL
IDEAL LIDAR
NATURE
Prediction of Hurricane Ivan in 0.25° FvGCM
Lidar Improved
Track Prediction
Lidar provides
the critical
divergence profile
Lidar Improved
Intensity Prediction
Sep 12, 2004 00Z – Sep 16, 2004 12Z every 6 hrs
Based upon
QuickOSSEs
done at GSFC
by R. Atlas

Data utility issue: scanning

- Several studies have shown that bi-perspective sampling of the winds is critical to advancing forecasting skills
  - OSSEs at NCEP
  - OSSEs at GSFC
  - Simulations by Riishojgaard, Atlas and Emmitt
  - Current OSEs at GSFC



Data utility issue: adaptive targeting

- Research is showing that ~ 10% of a set of global wind observations can be responsible for ~ 90% of the impacts on analyses and forecast skill.
- OSSEs are being used to develop optimal target selection schemes
  - NASA/GSFC (primarily for tropical disturbances)
  - NOAA/NCEP (global perspective)
  - IPO/NPOESS (platform resource management)

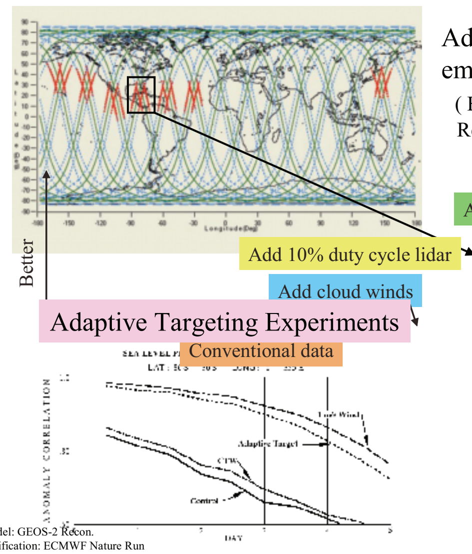
Primary Targets for Multi-spectral/AT*

- Significant Shear regions
  - Requires contiguous observations in the vertical. Thus both direct and coherent detection technologies are needed.
- Divergent regions
  - Requires some cross track coverage. Identified by NCEP adaptive targeting scheme(s)
- Partly cloudy regions
  - Requires measurement accuracy weakly dependent upon shot integration (i.e., coherent detection).
- Tropics
  - Tropical cyclones (in particular, hurricanes & typhoons). Requires penetration of high clouds and partly cloudy scenes.

*AT: Adaptive Targeting

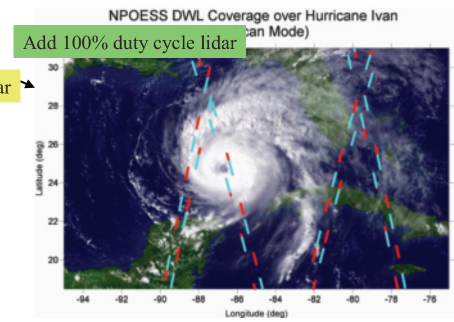
Adaptive Targeting

Adaptive targeting with emphasis on CONUS interests
(Blue is coherent coverage
Red is both coherent and direct)



Model: GEOS-2 Recon.
Verification: ECMWF Nature Run

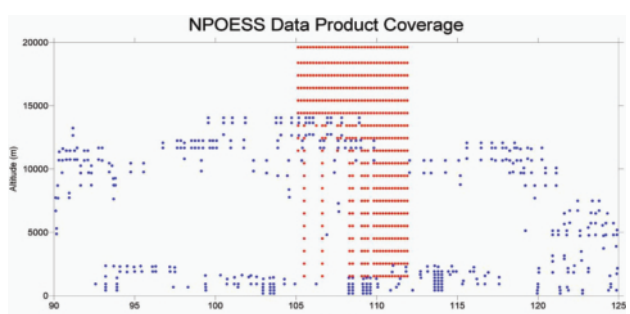
Control: - Conventional Data + Perfect TOVS
CTW - Control + Cloud Tracked Winds
1 m/s Wind - Control + Doppler Wind Lidar (RMSE = 1 m/s)
Adaptive Targeting - Control + Adaptive Targeting of DWL Observations (~10% duty cycle)



Example of targeting a hurricane as it approaches the Gulf coast.
(blue segments: forward looks;
Red segments: aft looks; Blue plus red
Provide full horizontal wind vector)

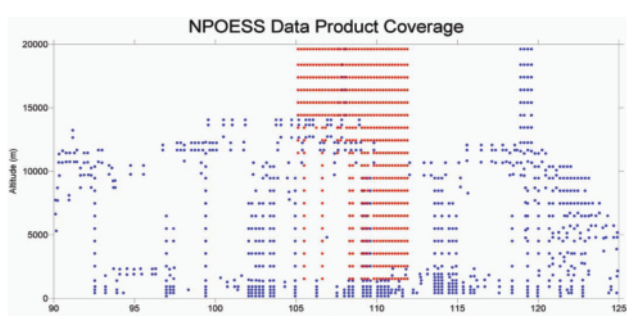
Example of vertical AT coverage

With background aerosol distribution



Red: < 4 m/s error
Blue: < 1.5 m/s error

With convectively pumped aerosol distribution



Concept for initial global tropospheric wind sounder

- Combined direct and coherent lidars meets coverage and accuracy goals with lowest platform resource requirements
- Operated with a step stare scanner for bi-perspective view and cross-tract divergence observations
- Operated in adaptive targeting mode to reduce platform power demand with minimal degradation of data impacts

Technology Issues

- Optimal design of multi-spectral approach; identification of shared sub-systems
- Scanning implications for telescope dimensions and momentum compensation
- Laser stability/lifetime implications of turning laser on/off in Adaptive Targeting mode

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Progress in Laser Transmitters for Direct Detection Wind Lidar

Floyd Hovis, Fibertek, Inc.
Jinxue Wang, Raytheon Space and Airborne Systems
Michael Dehring, Michigan Aerospace Corp.

January 10, 2005

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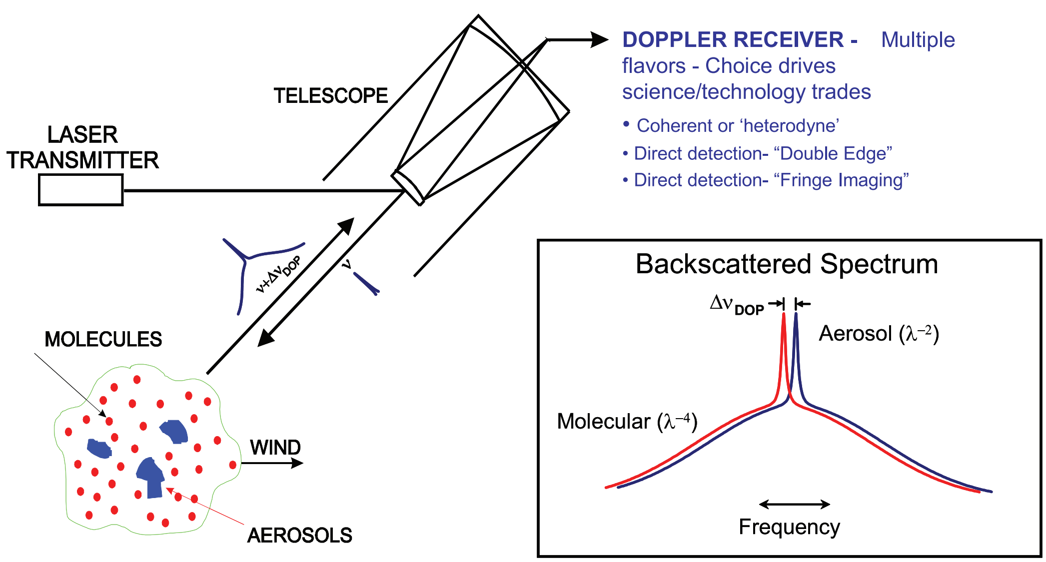
Doppler Wind Lidar Measurement Concept



Global tropospheric wind profiles are the #1 unmet Environmental Data Record (EDR) for the National Polar Orbiting Environmental Satellite Systems (NPOESS)

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Laser Requirements for Direct Detection Doppler Wind Lidar

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- Wavelength in the ultraviolet to take advantage of larger molecular backscattering
  - The 355 nm third harmonic of Nd:YAG meets this requirement
  - Diode-pumped Nd:YAG is a mature, space-qualified technology
- Single frequency operation
  - The Doppler shifts are small - a meter/second wind introduces a Doppler shift which is only a few parts per billion the laser frequency
  - Laser frequency, pulse width, and stability must be correspondingly well defined
- Pulse width greater than ~20 ns
  - Allows achieving a linewidth of <50 MHz
- Frequency drift of only a few Mhz/min
  - A 1 m/s wind velocity gives a Doppler shift of only ~ 3 MHz at 355 nm
- 50 Hz or higher operation
  - Speeds up signal averaged data acquisition

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Program Overview

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Fibertek Laser/LIDAR Expertise
- Many NASA and DOD SBIRS
- CALIPSO laser transmitter experience

Raytheon Laser/LIDAR Expertise
- Over 30,000 laser/lidar systems for DOD
- Leader in engineering & packaging rugged laser/LIDAR systems for air and space
- Significant IRAD investment

Develop a robust, single frequency 355 nm laser for airborne and space-based direct detection wind lidar systems
- All solid-state, diode pumped
- Robust packaging
- Tolerant of moderate vibration levels during operation
- Space-qualifiable design

A space-qualifiable laser in the same form and factor as the flight laser!

Incorporate first generation laser transmitters into ground-based and airborne field systems to demonstrate and evaluate designs
- Goddard Lidar Observatory for Winds (GLOW)
- Balloon based Doppler wind lidar being developed by Michigan Aerospace and the University of New Hampshire for NOAA

Develop scaling to higher powers and pulse energies
- Raytheon funded Risk Reduction Laser
- Air Force SBIR to develop a 1 J, 100 Hz 1064 nm pump source

Iterate designs for improved compatibility with a space-based mission
- Lighter and smaller
- Radiation hardened electronics

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Airborne vs. Space-Based Direct Detection Wind Lidar Requirements

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	Airborne	Space-based
Wavelength	UV (355 nm)	UV (355 nm)
Pulse energy	5 - 200 mJ	150 - 600 mJ
Repetition rate	50 – 2000 Hz	50 –200 Hz
Vibration environment	Operate in 0.3 g_{rms}	Survive 10 g_{rms}
Lifetime	2 x 10^8 shots	5 x 10^9 shots
Cooling	Conductive to liquid or air cooled heat exchanger	Pure conductive cooling
Thermal environment	Spec energy in ±5°C band	Spec energy in ± 5°C band
	Survive 0° to 50°C cycling	Survive –30° to70°C cycling

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Laser Transmitter Overview

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Summary of Approach

An all solid-state diode-pumped laser transmitter featuring:

? Injection seeded ring laser	Improves emission brightness (M^2)
? Diode-pumped zigzag slab amplifiers	Robust and efficient design for use in space
? Advanced E-O phase modulator material	Allows high frequency cavity modulation for improved stability injection seeding
? Alignment insensitive / boresight stable 1.0 µm cavity and optical bench	Stable and reliable operation over environment
? Conduction cooled	Eliminates circulating liquids w/in cavity
? High efficiency third harmonic generation	Reduces on orbit power requirements
? Space-qualifiable electrical design	Reduces cost and schedule risk for a future space-based mission

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Single Frequency Oscillator

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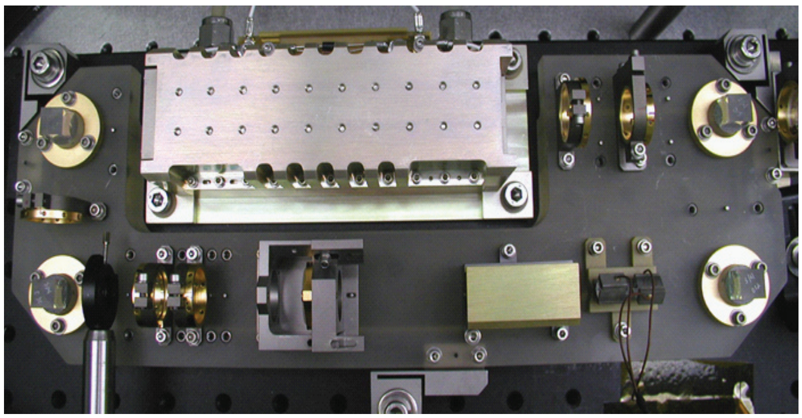
Mature oscillator design

- High beam quality demonstrated at up to 100 Hz
  - –30 mJ TEM_{00}, M^2 =1.2 at 50 Hz
  - –30 mJ TEM_{00}, M^2 =1.3 at 100 Hz
  - –50 mJ square supergaussian, M^2 = 1.2 at 50 Hz
- Injection seeding using an RTP phase modulator provides reduced sensitivity to high frequency vibration
- Zerodur optical bench results in high alignment and boresight stability



Final Zerodur Optical Bench (12cm x 32cm)

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Power Amplifier

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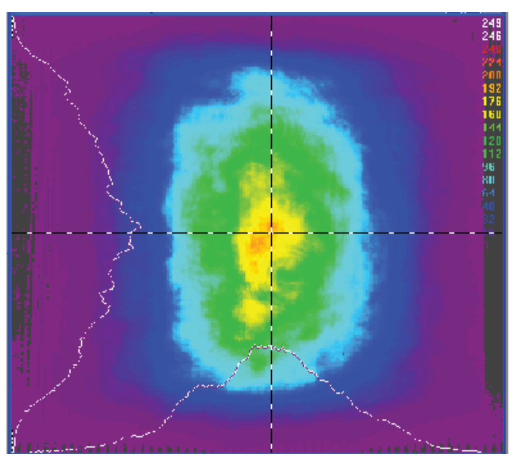
Recent Test Results

? **Pulse energy of > 700 mJ at 50 Hz in a conductively cooled design**

? **Preliminary M^2 measurements found a value of ~2 for final amplifier output**

? **Near field spatial is a rectangular super gaussian**

? **Beam asymmetry in final system will be reduced by fine tuning the cylindrical compensating lens values**



Near field beam profile

***Final amplifier electrical to optical efficiency for 700 mJ output was over 11%.
Full system electrical to optical efficiency was over 7%.***

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BalloonWinds Laser Transmitter Integrated and Tested

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Injection seeded single frequency ring oscillator

Key mechanical design features

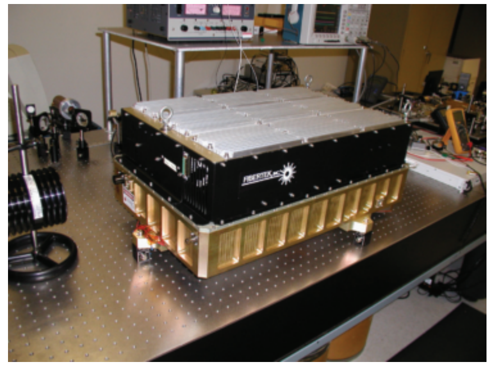
High voltage power supply design

Diode drive electronics

Control electronics printed circuit boards and software

User interface

Thermal control through conductive cooling



Completion of integrated laser and electronics modules for the BalloonWinds System in 2005 has validated many key elements of the Raytheon design in a packaged unit

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Direct Detection Winds LIDAR Laser Transmitter Status in 2006

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? Demonstration of 1 J/pulse from a single frequency 1064 nm pump laser operating at 50 Hz

? Demonstration of greater than 45% conversion to 355 nm to achieve 450 mJ/pulse at 50 Hz

- Completion of a risk reduction engineering model in space qualifiable, conductively cooled package with the performance given above

? Improved first stage amplifier efficiency to bring the system electrical to optical efficiency to >8%

- Amplifier tests to demonstrate scaling to 100 Hz
- Life-testing and field demonstration to demonstrate TRL 5 in 2006

Yb:YAG MOPA System and Non-linear Frequency Conversion Module for Remote Wind Sensing and DIAL based Atmospheric Ozone
Concentration Measurements

Arun Kumar Sridharan,
R. Roussev, K. Urbanek, Y.W. Lee, S.Sinha
Prof. M. M. Fejer, Prof. Robert L. Byer
Stanford University
Prof. S. Saraf
Rochester Institute of Technology

Sponsors: NASA (ATIP Program)
DARPA (MURI Program)

NASA/ESTO LIDAR Community Forum, January 10, 2006

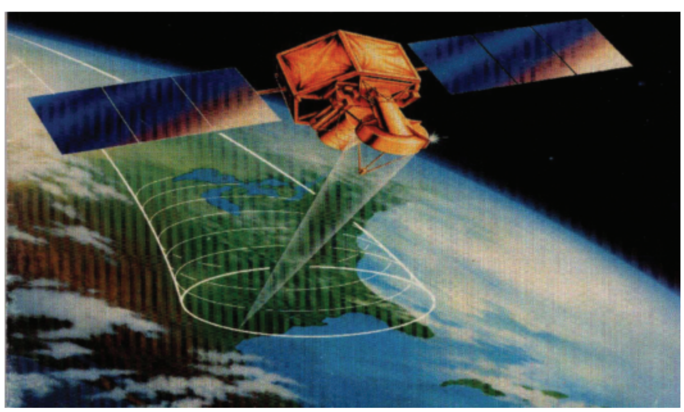
Stanford University 1

Global wind velocity sensing

- **Measurement specifications**
  - 100 km hor. res., 1 km ver. res. , 1 m/s velocity accuracy, eye safety.

Laser transmitter specifications for wind sensor

- Energy: 2J/pulse
- Repetition rate: 10 Hz
- Pulse width: ~ 1μs
- Linewidth : 1 MHz
- Satellite altitude :400 km
- $\lambda > 1.4$ μm



•Currently 2 μm sources developed by NASA/Langley are most advanced in development

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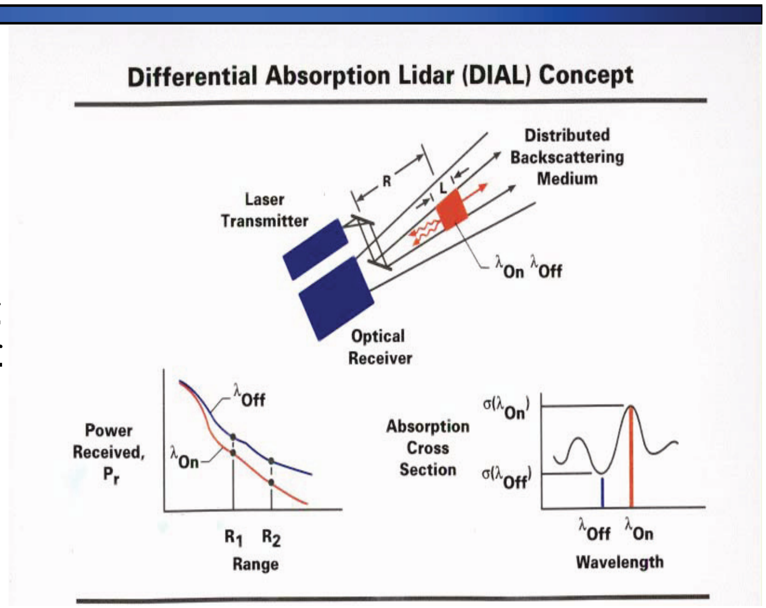
DIAL based ozone detection

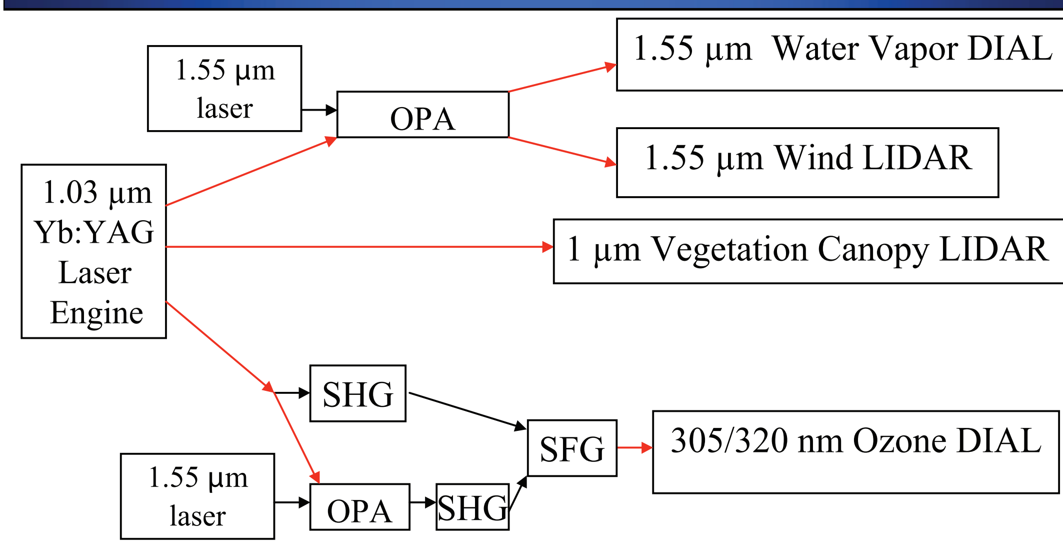
- **Tropospheric Ozone(O_3), NO_2, SO_2 detection**
  - 1-2 km vertical resolution.

Laser transmitter specifications for Ozone detector

- Energy: 0.5 J/pulse
- Repetition rate: 10 Hz
- Pulse width: ~ 1µs
- λ = 305 nm, 320 nm



Stanford Approach: Yb:YAG Laser + Non-linear Frequency Conversion



Outline

- Yb:YAG Laser Engine
  - Choice of gain media, pulse format, design and experimental results
- Nonlinear Frequency Conversion Module
  - Nd:YAG MOPA Testbed
  - Waveguide PPLN OPA
  - Bulk PPLN OPA
  - Future directions for pulse energy scaling
- Conclusion

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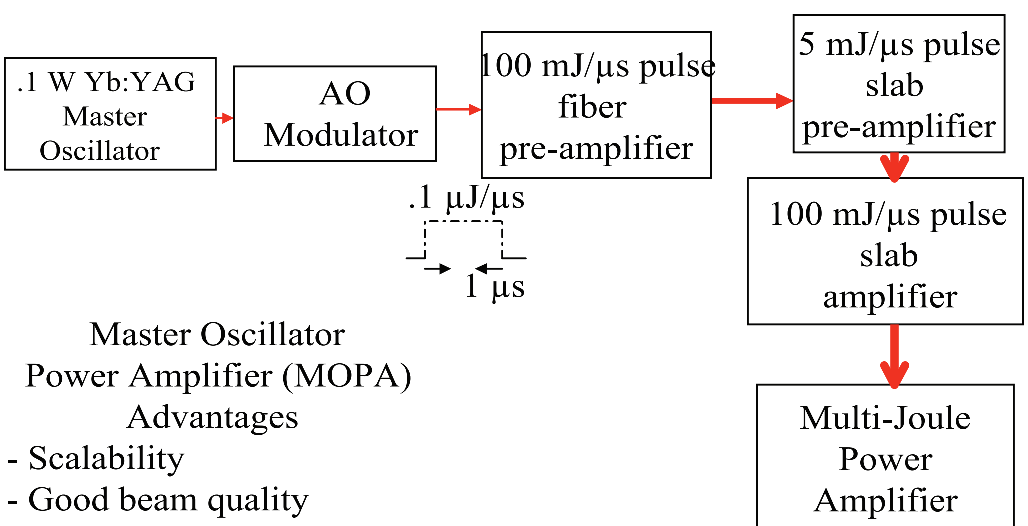
1.03 µm Yb:YAG Laser Engine

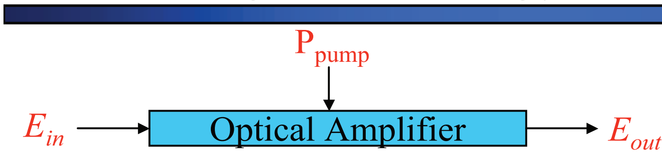


Master Oscillator
Power Amplifier (MOPA)
Advantages

- Scalability
- Good beam quality
- Coherence

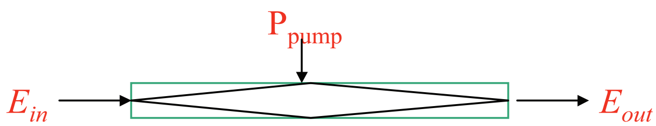
Stanford University 6

Challenges to Energy Storage/Extraction



$$E_{out} = E_{in} e^{g_0 l}$$

(small-signal limit)

- $E_{stored} = g_0 l \, F_{sat} \, A$ → High $g_0 l$ is needed for energy storage.
- $F_{sat} < F_{input} < F_{damage}$ → Needed for efficient extraction in power amplifiers
- 

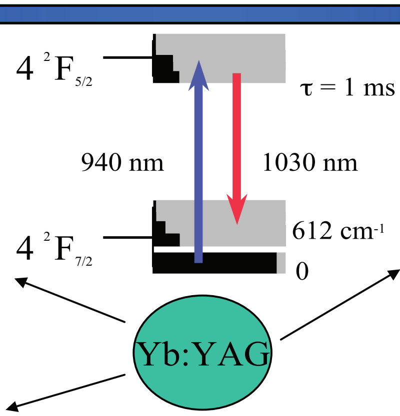
Closed loop parasitic oscillation reduces amplifier gain

Steps need to be taken to prevent loss of stored energy.

Why Yb:YAG ?

$$\frac{\lambda_{p\_940nm}}{\lambda_{l\_1030nm}} < 9\%$$

means high efficiencies are possible.



Energy stored ∝ P_{pump} τ

Long τ means, fewer diodes are required and lower costs

$$g_0 l = \Delta N \sigma_e l < 3$$

Parasitic oscillation limit

- $E_{stored} = g_0 l \, F_{sat} \, A$

→ 10 × smaller σ_e compared to Nd:YAG leads to 10 × higher energy storage

Why 1 μs Pulses?

1. Transform limited 1 MHz line-width, required for 1 m/s global wind velocity resolution.

2. Surface damage fluence (*J*) of YAG and PPLN* scales as $t^{1/2}$

$$J_{damage\_1\mu s} > 10\, J_{damage\_10ns}$$

10 J/cm²

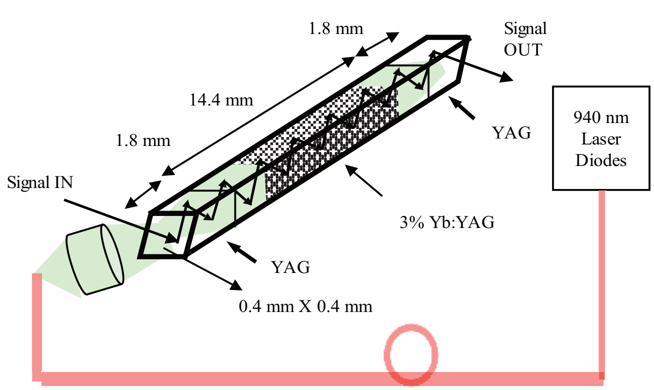
Available from traditional Q-switched lasers

$$F_{sat} < F_{input\_1\,\mu s} < F_{damage\_1\mu s}$$

Enables high-pulsed energy non-linear frequency conversion

*** AR coated PPLN crystals show J_{damage} = 10 - 15 J/cm² for 20 ns pulses**

End pumped slab geometry*



- Nearly complete absorption of pump light.
- Better mode overlap => Higher gain & efficiency
- Uniform gain across beam => better mode quality

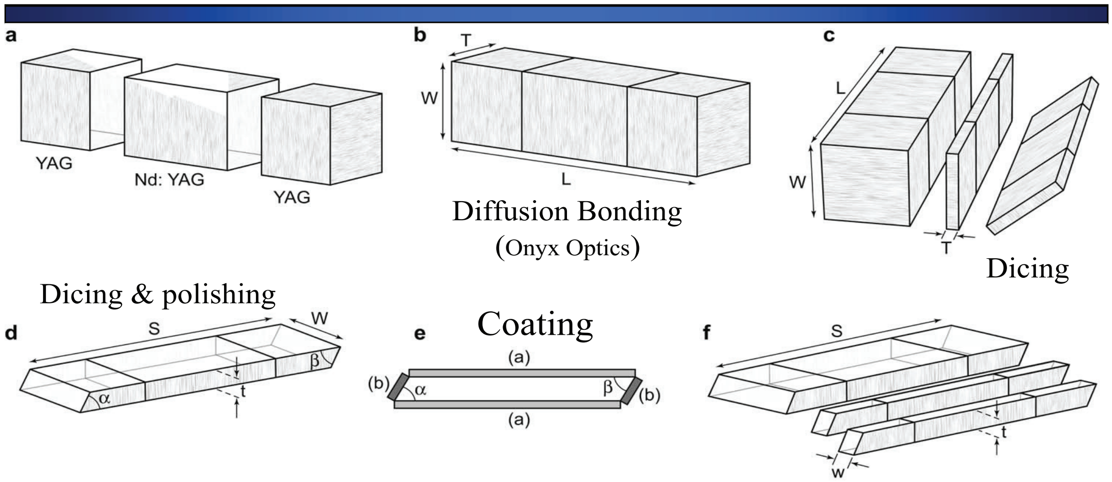
Slab Design Issues

1. Pump light coupling and absorption
2. Minimizing spatial distortion of signal beam
3. ASE & Parasitic Oscillation suppression

Parasitic suppression is accomplished by special cladding on all four large surfaces

 *Similar to TRW's end-pumped design,Hagop Injeyan

Slab Batch Fabrication Procedure

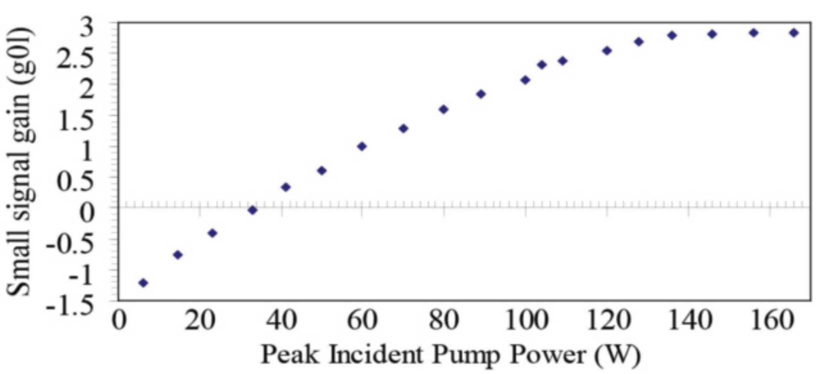


Cost/slab < $ 2000

Should enable wider use of slabs in commercial systems

Yb:YAG slab amplifier gain

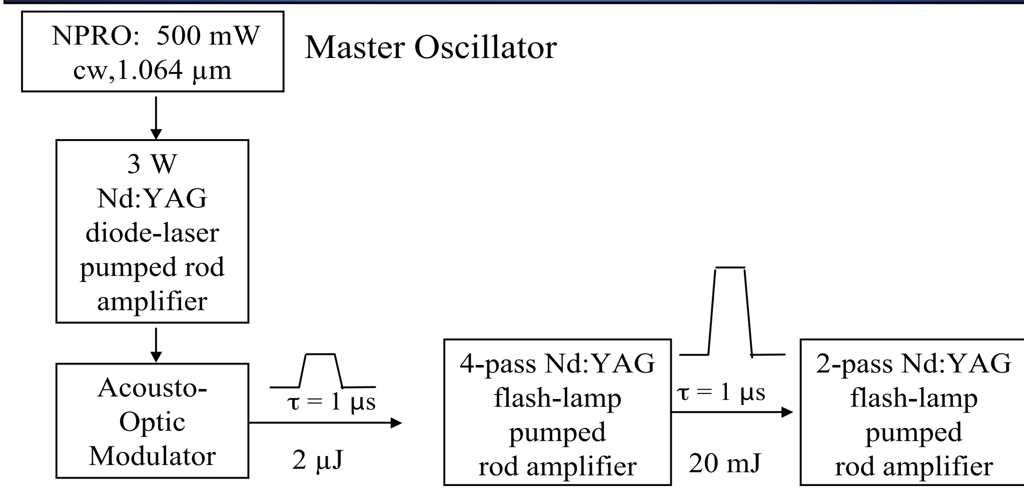
Koheras Fiber Laser 100 mW cw,1.030 µm → Acousto-Optic Modulator → Single-pass, laser-diode end-pumped, Yb:YAG slab pre-amplifier



This key result should enable an efficient high pulse energy Yb:YAG MOPA

Nd:YAG MOPA Test-bed

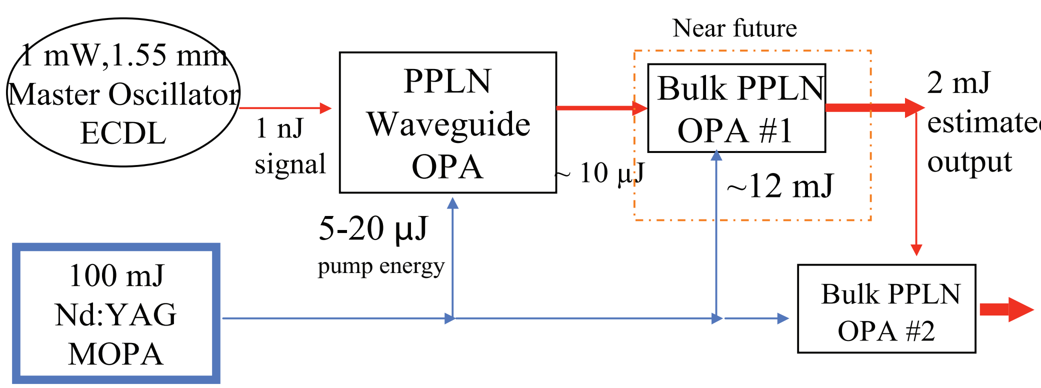
for Nonlinear Frequency Conversion: Experimental Setup



AOM can generate pulses with τ ≥ 200 ns

Output: >100 mJ, 1 μs pulses @ 1.064 μm

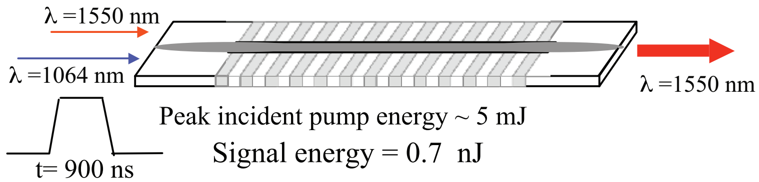
PPLN based Optical Parametric Amplifier (OPA) System Schematic



Conversion efficiency in waveguides 2-3 orders of magnitude higher than in bulk mixing

High gains in waveguide pre-amplifier offers potential for easier depletion of pump energy in bulk OPAs, and minimizes # of components.

Waveguide OPA:Results



Peak incident pump energy ~ 5 mJ

Signal energy = 0.7 nJ

Experimental result: 45 dB gain

Propagation loss at 1.55 µm- ~0.14 dB/cm

MF length=1.2mm, MF width=2.5 µm

Quadratic taper length=4.5mm

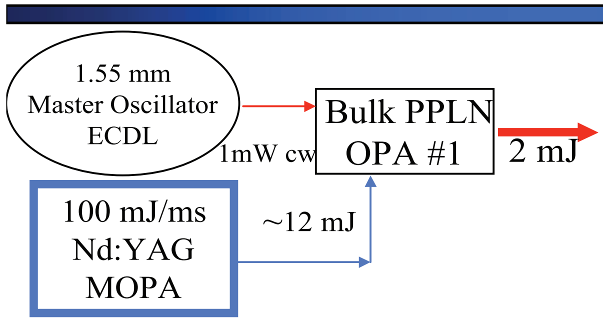
QPM length=56 mm

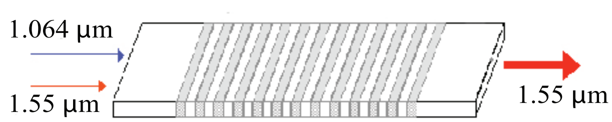
normalized efficiency ~10 %/Wcm^2

Theoretical expectation: 14%/Wcm^2

Tuning curve FWHM ~ 1 nm

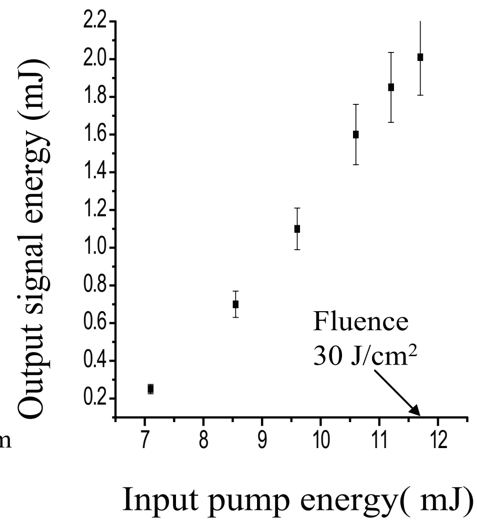
Bulk PPLN OPA





L = 29.9 µm, l = 8.4 cm, t = 0.7 mm

w_{p_x} = 180 µm, w_{p_y} = 140 µm, w_s = 130 µm



Future potential scaling of OPA

Stoichiometric PPLN

Low coercive electic field → 3-4 mm thick crystals → Increased pump spot size prevents surface damage

Low defect concentration → Photorefractive damage threshold increased → Room temperature operation possible

Negligible Green-Induced IR Absorption

Target→ 2 J, 1.55 mm, µs pulses possible with 5 J pump energy

Conclusion

Key Laser Engine Achievements

- Demonstrated record 12 dB ($g_0l = 2.84$) gain in end-pumped zig-zag slab amplifier.
- Scaling of aperture size and available pump power should enable efficient scaling of Yb:YAG MOPA to Joule energy levels

Non-linear frequency conversion module developments

- 100 mJ/ms Nd:YAG Testbed MOPA enabled
  - Testing of PPLN RPE waveguide OPA's with 45 dB gain.
  - Testing of first Bulk PPLN OPA with 2 mJ pulses at 1.55 mm
- Pulse energy scaling of OPA's by increasing aperture size (PPSLT,PPSLN ?) will be key to meeting end remote sensing requirements.

Space-based Ozone Lidar

Global Investigations of Tropospheric and Stratospheric Ozone, Aerosols, and Clouds

Builds on over two decades of technique/technology development and atmospheric science research with ground-based and airborne lidar systems

Edward V. Browell
(Presented by Johnathan W. Hair)
NASA Langley Research Center

ESTO Lidar Forum - 1/10/06

Science Objectives

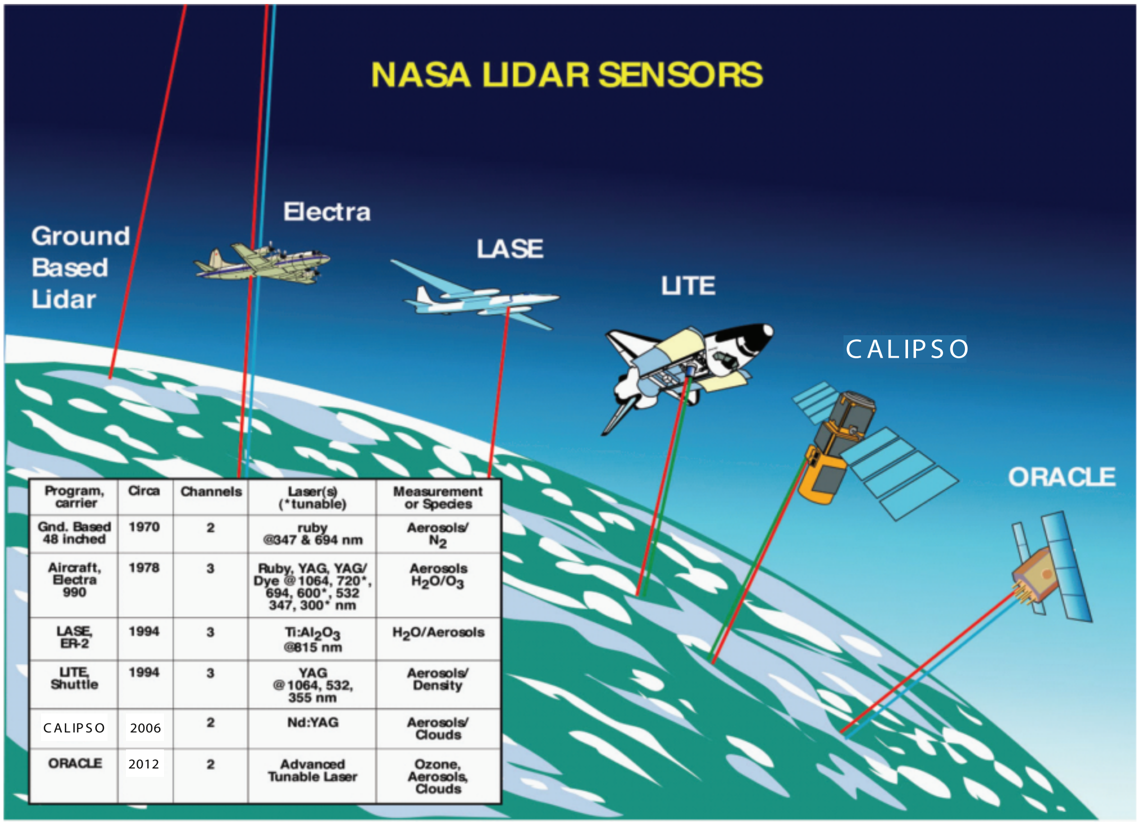
Understanding Global Atmospheric Composition and Predicting Future Evolution

Key Environmental Issues:

- Global Air Quality
- Climate Forcing by Radiatively Active Gases & Aerosols

Specific Science Questions:

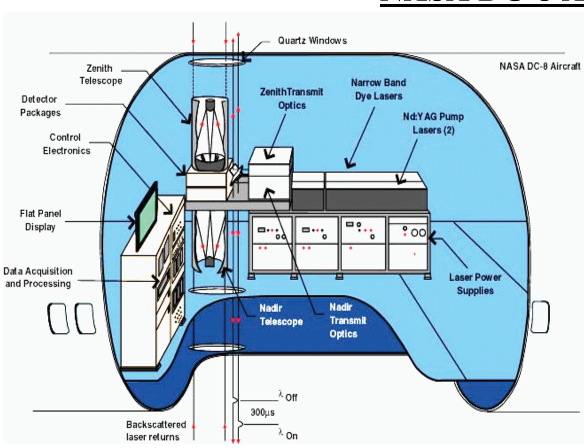
- What is global distribution of tropospheric ozone and how does it change seasonally and interannually?
- What is the relative contribution of photochemical and dynamical processes in determining the distribution of tropospheric ozone?
- What is the impact of ozone on global tropospheric chemistry and climate?

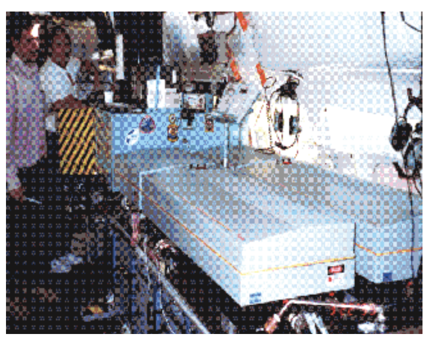


Program, carrier	Circa	Channels	Laser(s) (*tunable)	Measurement or Species
Gnd. Based 48 inched	1970	2	ruby @347 & 694 nm	Aerosols/ N_2
Aircraft, Electra 990	1978	3	Ruby, YAG, YAG/ Dye @1064, 720*, 694, 600*, 532 347, 300* nm	Aerosols H_2O/O_3
LASE, ER-2	1994	3	Ti:Al_2O_3 @815 nm	H_2O/Aerosols
LITE, Shuttle	1994	3	YAG @1064, 532, 355 nm	Aerosols/ Density
CALIPSO	2006	2	Nd:YAG	Aerosols/ Clouds
ORACLE	2012	2	Advanced Tunable Laser	Ozone, Aerosols, Clouds

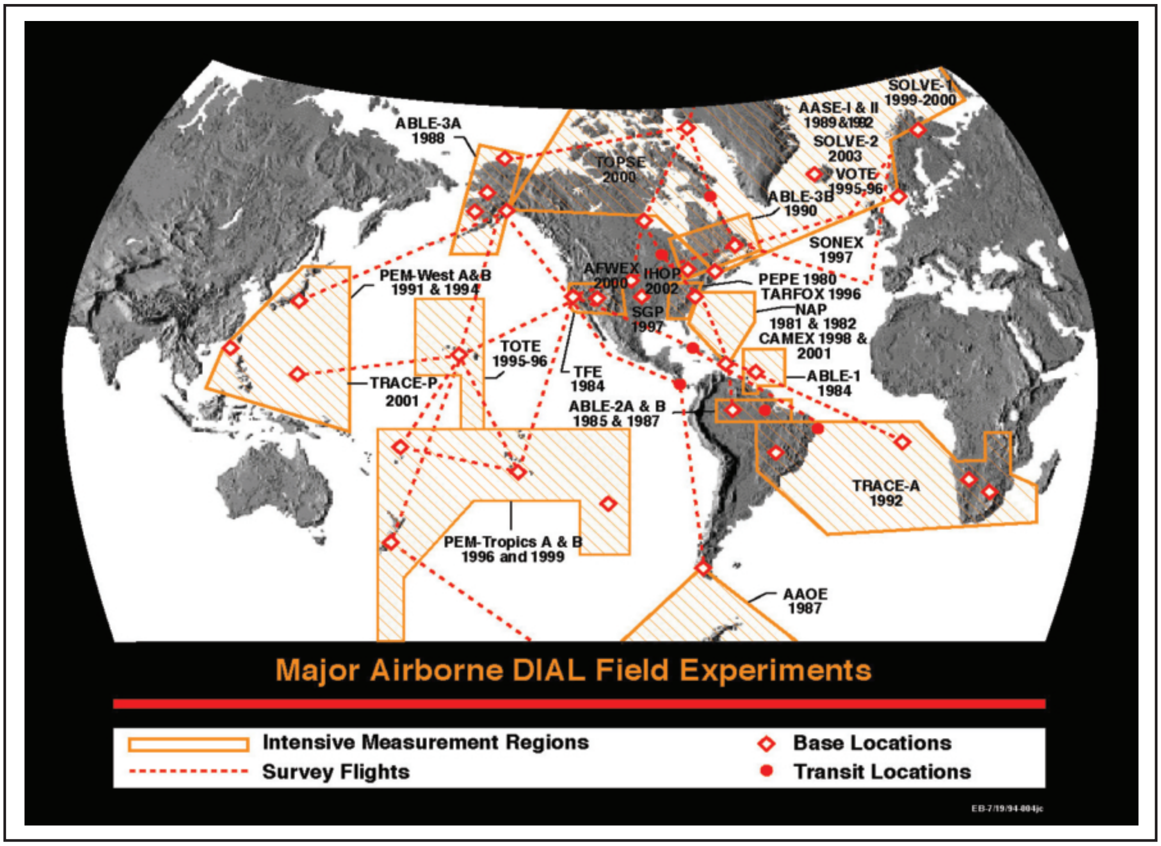
Remote Ozone, Aerosol, & Cloud Measurements

Airborne Ozone & Aerosol Lidar (UV DIAL) on NASA DC-8 Aircraft

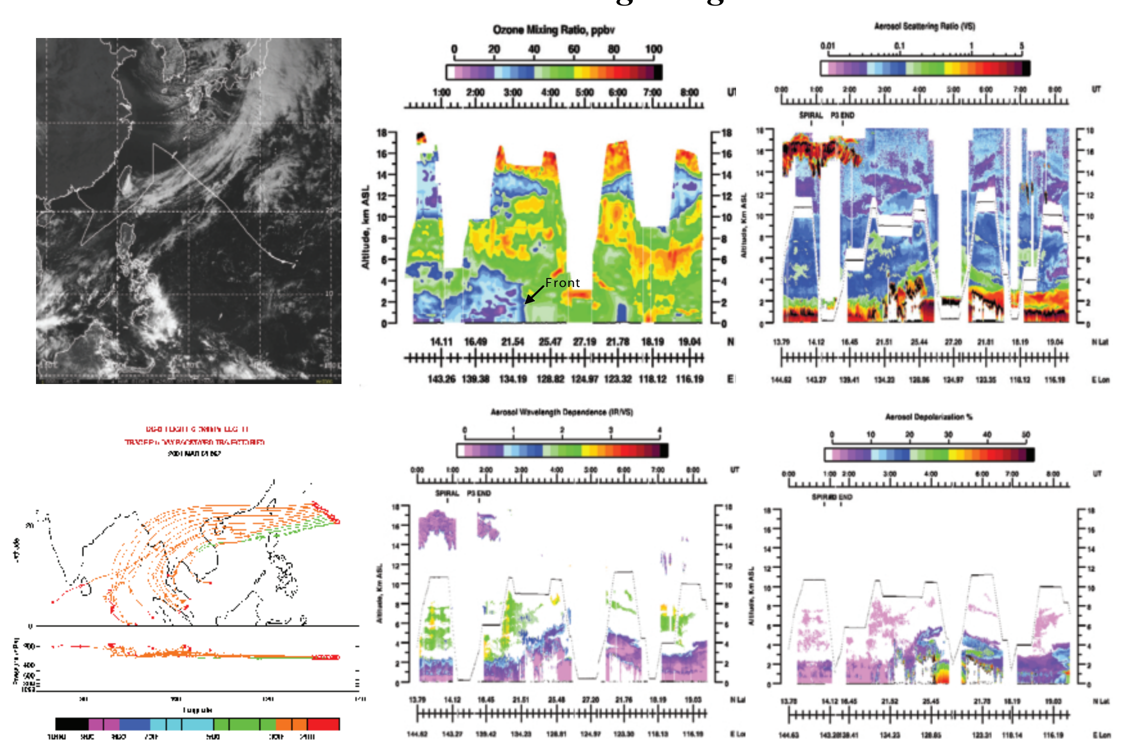


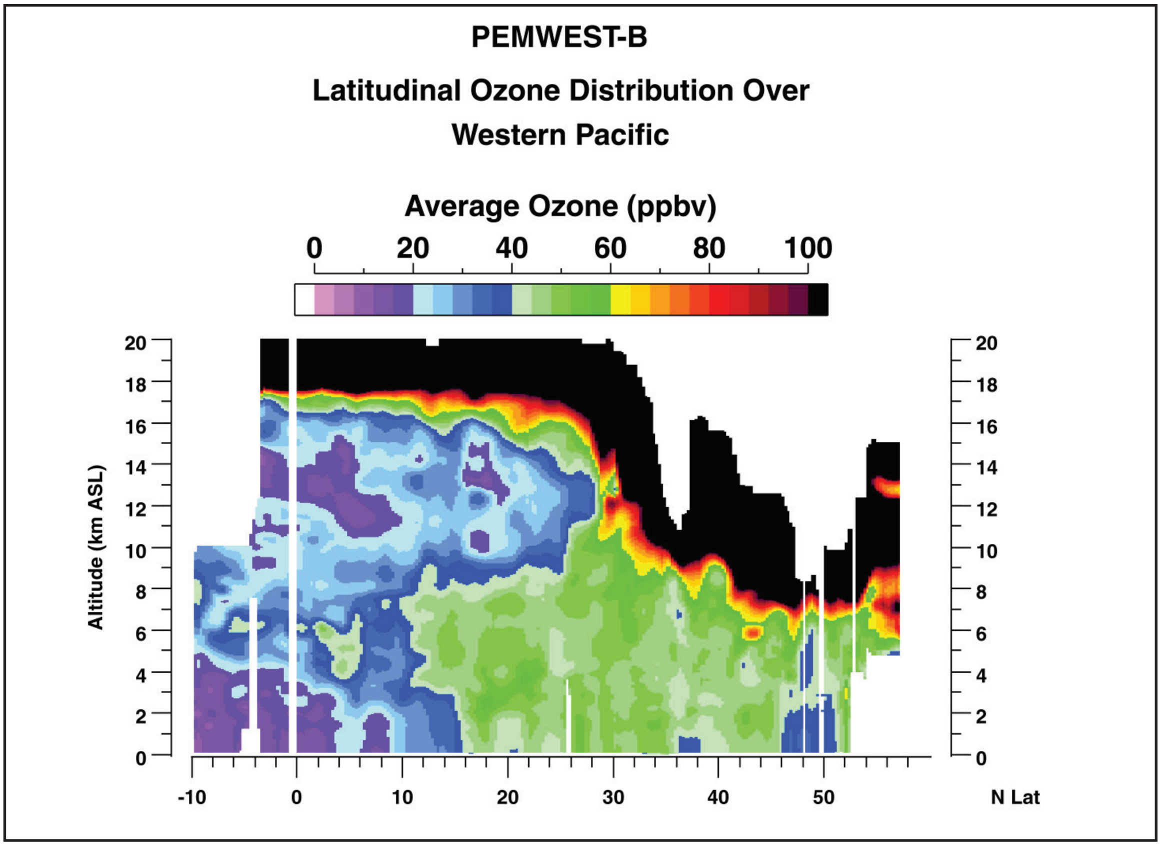


- **Ozone Differential Absorption Lidar (DIAL) Profiles (l_{on}=289 nm & l_{off} =300 nm)**
- **Aerosol & Cloud Profiles (600 & 1064 nm)**
- **Simultaneous Nadir and Zenith Profiling**



TRACE-P Flt. 6 Guam to Hong Kong 3-4 March 2001





Spaceborne Lidar Ozone & Aerosol Mission

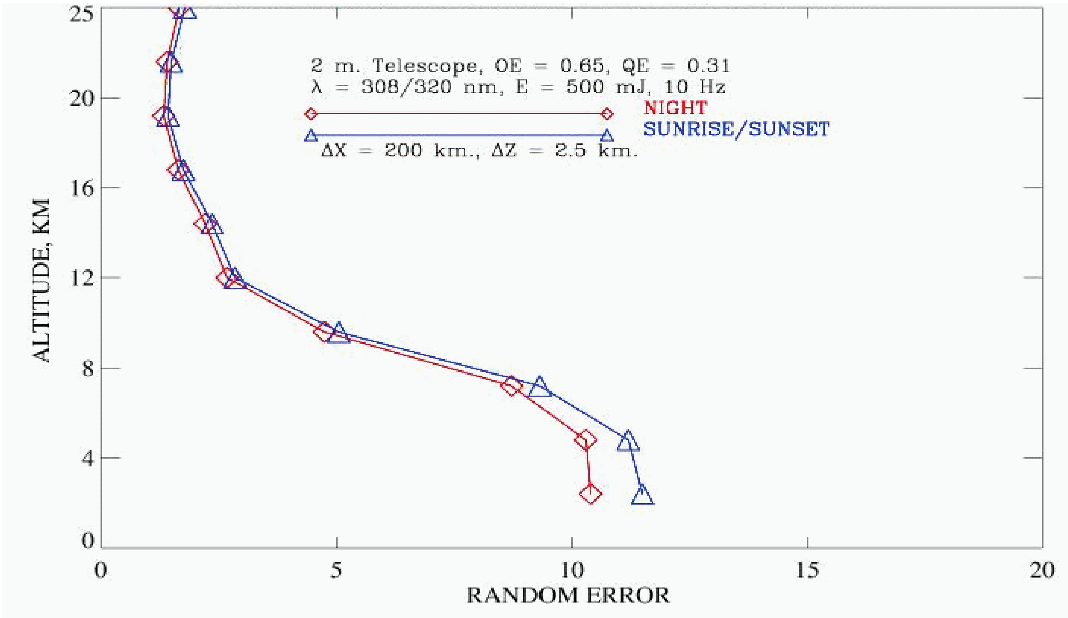
- Simultaneous tropospheric and stratospheric ozone profiles and column measurements with simultaneous aerosol & cloud profiles.
- Will address key global environmental issues including trop. and strat. chemistry & dynamics (trop. ozone production & transport, strat./trop. exchange, strat. ozone depletion & dynamics, meteorology, & weather forecasting), climate & radiation budgets, & biogeochemical cycles.
- Measurement resolutions and accuracy goals:

Ozone -	Trop.:	Night: ≤2.5 km x 200 km (10%)
		Day: ≤3.0 km x 300 km (10%)
	Strat.:	≤1 km x 100 km (10%)
Aerosols -	Trop.:	60 m x 1 km (10%) at 2l
	Strat.:	100 m x 10 km (10%) at 2l

- Spectral Regions: 305-320 nm with 10-12 nm Dl DIAL with two aerosol/cloud channels (l_{off} & visible/near IR) & one with depolarization.
- Deployment: Small satellite in polar, low Earth orbit with 2-3 year life.

Spaceborne Ozone DIAL Simulations

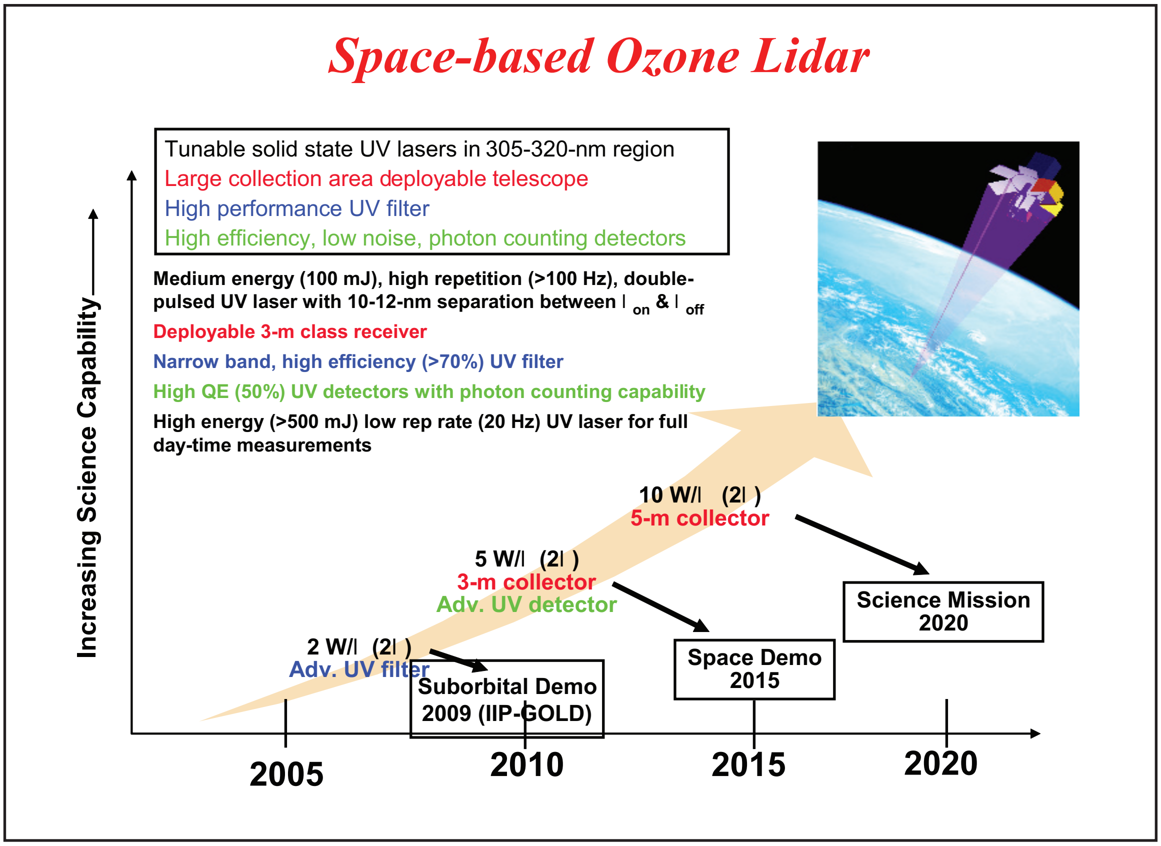
Night vs Sunrise/Sunset Day Background, 400 km Altitude



Space-based Ozone Lidar

Major Technological Challenges:

- Transmitter
  - Wavelengths: on-line: 305-308 nm; off-line: 315-320 nm; aerosol wavelength: visible or near IR
  - High-power: >10 W/wavelength with pulse energies of 10 mJ-1 J at pulse rep rates 1 kHz-10 Hz)
  - Lifetime: >2 year
- Receiver
  - Large-effective aperture telescope with area >4 m^2
  - High-performance UV filters: T >70% with narrow bandwidth
  - High-efficiency (QE >50%), low noise, photon counting detectors


Space-based Ozone Lidar
Tunable solid state UV lasers in 305-320-nm region
Large collection area deployable telescope
High performance UV filter
High efficiency, low noise, photon counting detectors
Medium energy (100 mJ), high repetition (>100 Hz), double-pulsed UV laser with 10-12-nm separation between l on & l off
Deployable 3-m class receiver
Narrow band, high efficiency (>70%) UV filter
High QE (50%) UV detectors with photon counting capability
High energy (>500 mJ) low rep rate (20 Hz) UV laser for full day-time measurements
Increasing Science Capability
10 W/l (2l)
5-m collector
5 W/l (2l)
3-m collector
Adv. UV detector
2 W/l (2l)
Adv. UV filter
Suborbital Demo 2009 (IIP-GOLD)
Space Demo 2015
Science Mission 2020
2005
2010
2015
2020

Global Carbon Dioxide Measurements with Space-Based Laser Absorption Spectrometer

Edward Browell, NASA LaRC
Berrien Moore III, Un. New Hampshire
Michael Dobbs and William E. Sharp, ITT-Space
Peter Rayner, CEA-CNRS
Syed Ismail and Stephanie Vay, NASA LaRC
T. Scott Zaccheo, AER

CO_2 Significance

- Important component of Carbon Cycle
- Major cause of climate change
- Global distribution of sources/sinks is uncertain

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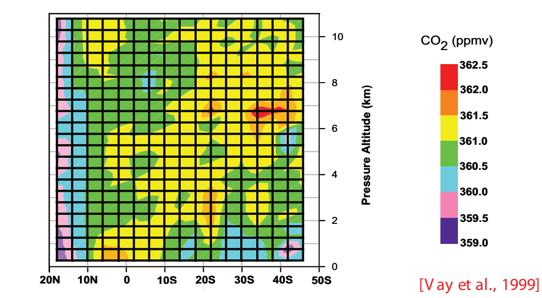
1/10/06

Atmospheric CO_2 Variations

South Pacific Basin



[Vay et al., 1999]

Figure 3. Mean concentration of CO2 at 107.5°W to 152.5°E longitude, as a function of latitude and altitude.

Lake Superior and Inland in Northern Wisconsin

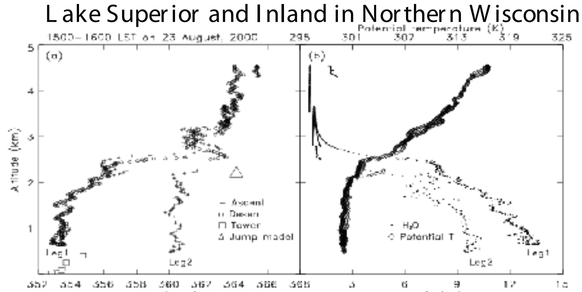
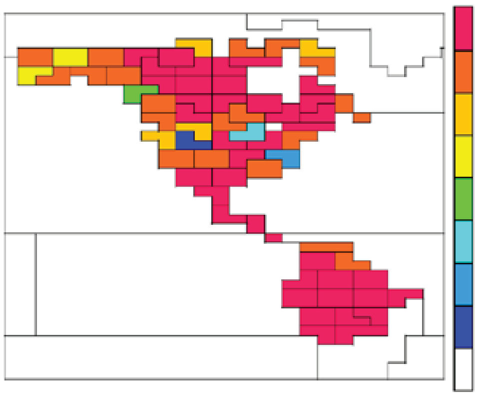


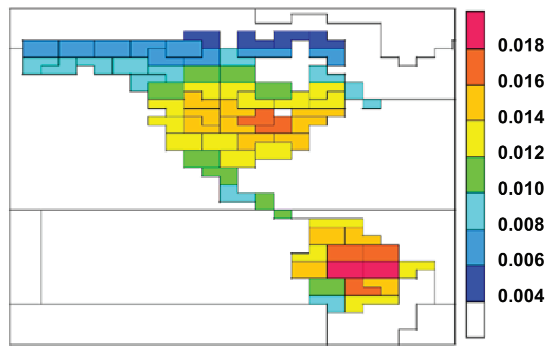
Figure 4. Mean CO2 concentration at 0 to 35°S latitude, as a function of longitude and altitude.

[Yi et al., 2004]

Surface CO_2 Flux Uncertainties



Surface Flux Uncertainties
GtC/Mo Using
Current (2001) Observational Network



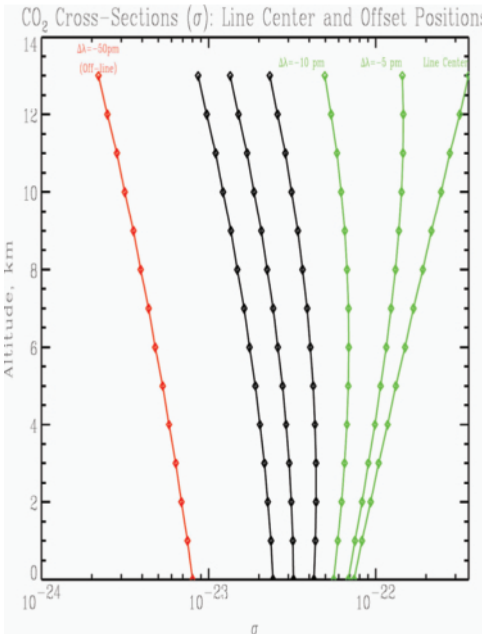
Surface Flux Uncertainties
GtC/Mo Using
Simulated Satellite Data

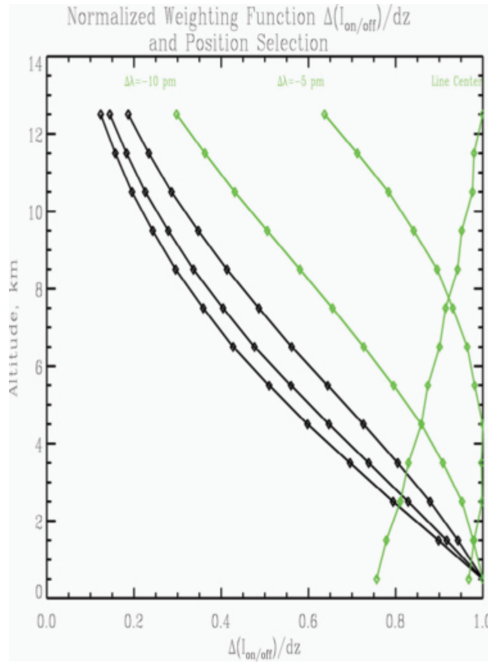
Source: Peter Rayner

Active Mission for Global CO_2 Measurements

- **Mission Objectives:**
  - **Quantify and understand the global distribution of CO_2, aerosols, and clouds and to improve forecasting of climate change.**
  - **Obtain global coverage of lower tropospheric CO_2 distributions during both day and night conditions.**
  - **Obtain simultaneous measurements of cloud and aerosol distributions for CO_2 interpretation and advanced climate-related investigations.**
  - **Quantify the global spatial distribution of terrestrial and oceanic sources and sinks of CO_2.**
  - **Provide enhanced observations for accurate prediction of future atmospheric CO_2 concentrations and climate change.**
- **Approach**
  - **Advanced communications-based continuous wave (CW) laser absorption technique in 1.57-μm region using surface/cloud top scattering for column CO_2 measurements.**
  - **Three CW laser wavelengths across CO_2 absorption line with advanced detector technology and modulated transmitter and detector technique for high precision CO_2 measurements.**
  - **Simultaneous measurements of aerosol, cloud, and surface elevation distributions for CO_2 measurement interpretation and climate applications.**

CO_2 Cross Sections and Weighting Functions

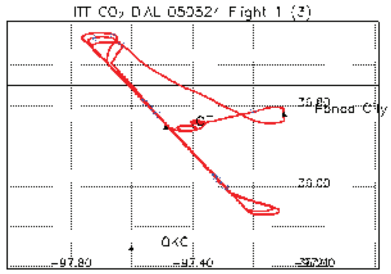




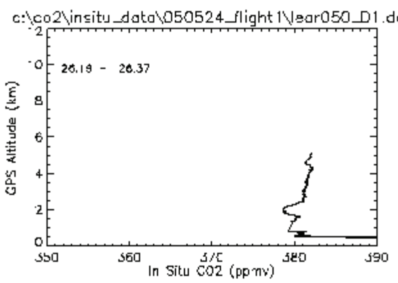
Airborne CO_2 Lidar Flight Tests

ITT Engineering Development Unit used to validate end-end system performance and demonstrate technology robustness for space mission.

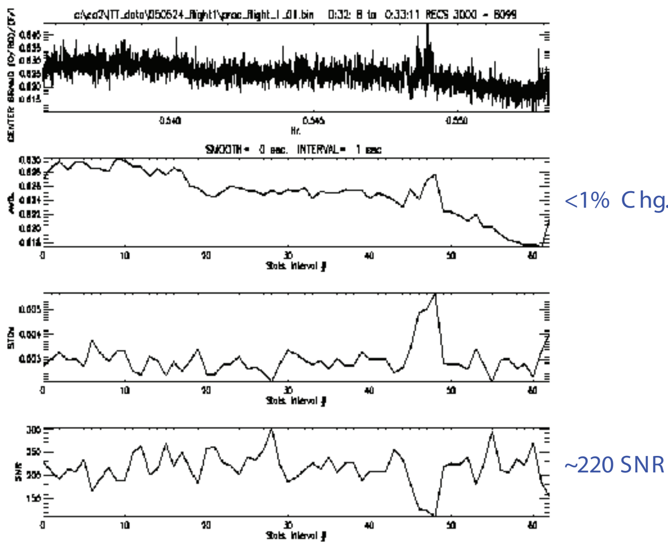
Initial Flight Testing of Active CO_2 Instrument Over Oklahoma on May 21-25, 2005



Lear Flight Track



In Situ CO_2 Profile



Active CO_2 Column Measurement
(1-min data interval; 1-s average time)

First Test Flight Series Results

- **Successful integration and operation of CO_2 lidar, pulsed laser altimeter, and in situ CO_2 system coupled with aircraft avionics, power, structure, and thermal systems.**
- **Developed and demonstrated flight procedures for combining remote and in situ CO_2 measurements.**
- **Successful operation of automatic CO_2 lidar transmitter-receiver alignment algorithm.**
- **Successful operation of automatic data collection systems for CO_2 lidar and in situ measurements.**
- **Obtained high-quality remote and in situ data. Initial results indicate that the remote CO_2 measurements are within 2.5% of modeled optical depths from the in situ data.**
- **Radiometric performance of CO_2 lidar instrument model compares well with observed measurements.**

Objectives for Future Test Flights

(Next Series Planned for Feb. 2006)

- **Demonstrate measurement accuracy of column CO_2 densities across the full troposphere and across the lower troposphere evaluated in comparison with *in situ* CO_2 measurements.**
- **Evaluate off-line, side-line and on-line laser wavelengths for CO_2 measurements in different altitude regions.**
- **Demonstrate measurement of surface height variations and evaluate impact on CO_2 column measurements.**
- **Examine observed surface reflectance variations and influence on CO_2 measurements**
- **Demonstrate measurement of atmospheric surface pressure and derived atmospheric density column amounts to convert CO_2 column densities to average mixing ratios.**
- **Examine the influence of aerosols and clouds on CO_2 column measurement uncertainties.**

Technology Development Needs

- **Support for flight testing of advance EDU from high altitude and under a range of surface and atmospheric conditions.**
- **Support for high-power, tunable fiber lasers operating in the 1.57-micron region.**
- **Development of high-efficiency detectors in 1.57-micron region.**
- **Development of large aperture receivers that can be efficiently packaged for space deployment.**
- **Support for laser technology for surface pressure measurement.**

Spaceborne High Spectral Resolution Lidar for Measurements of Aerosols and Clouds

Chris Hostetler
John Hair
Rich Ferrare
NASA Langley Research Center

Detlef Müller
Institute for Tropospheric Research, Leipzig

David Diner
Jet Propulsion Laboratory

Floyd Hovis
Fibertek, Inc.

Mission concept described in NRC Decadal Survey White Paper (Diner et al.)

Aerosol Global Interactions Satellite (AEGIS)

Multi-wavelength HSRL

Vertically resolved measurements:

- Extinction
- Backscatter
- Concentration
- Effective radius
- Index of refraction
- Single scatter albedo

Multiangle Spectro-Polarimetric Imager

2-D, column-averaged measurements:

- Aerosol optical depth
- Particle size distribution
- Non-spherical fraction
- Refractive index
- Single scatter albedo

- Application Areas: Atmospheric Composition, Climate Variability and Change, Water and Energy Cycle
- Aerosol measurements called for in NASA Roadmaps for Climate Variability and Change and Weather
- Science Objectives
  - Improve our understanding of aerosol effects on climate, chemistry, air quality, and precipitation.
  - Improve the predictive capability of climate models.

Disadvantage of backscatter lidar: 1 equation, 2 unknowns

Measured Signal; Range from Instrument; Calibration Constant; Molecular Backscatter Coefficient; Molecular Extinction Coefficient ← **Known**

Determined from measured signals and meteorological data

$$P(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\exp\left\{-2\int_0^r \left[\sigma_m(r') + \sigma_p(r')\right]dr'\right\}$$

Particulate Backscatter Coefficient; Particulate Extinction Coefficient ← **Retrieved Parameters**

$$\frac{s_P(r)}{b_p(r)} = S_p$$

← Assumption of value for extinction-to-backscatter (S_p) ratio required for backscatter lidar retrieval

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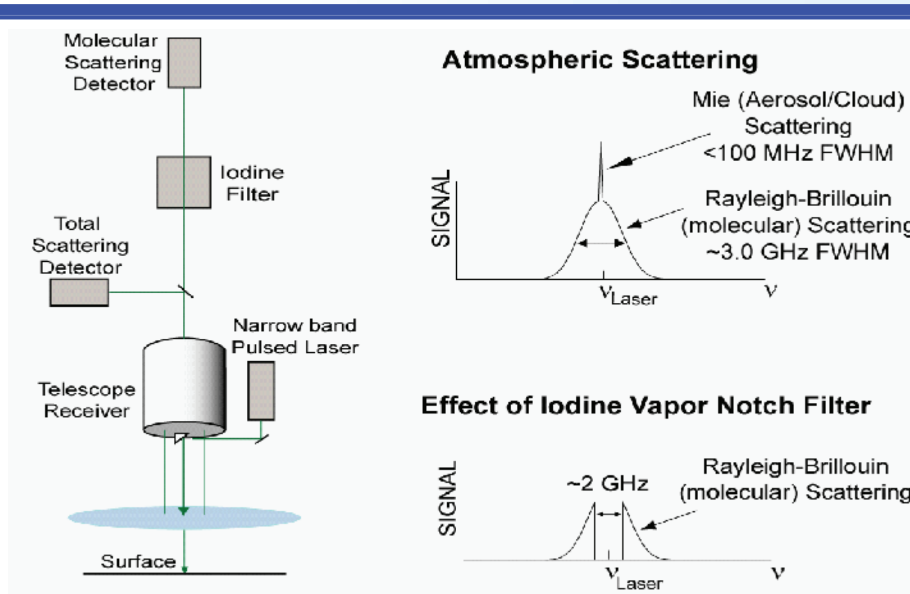
HSRL measurement concept



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HSRL: 2 equations, 2 unknowns

Measured Signal on Molecular Scatter (MS) Channel:

$$P_{MS}(r) = \frac{C_{MS}}{r^2} F(r)\, b_m(r) \exp\left\{-2\int_0^r \left[s_m(r') + \underline{s_p(r')}\right] dr'\right\}$$

Particulate Extinction

Measured Signal on Total Scatter (TS) Channel:

$$P_{TS}(r) = \frac{C_{TS}}{r^2}\left[b_m(r) + \underline{b_p(r)}\right] \exp\left\{-2\int_0^r \left[s_m(r') + s_p(r')\right] dr'\right\}$$

$$\frac{s_P(r)}{b_p(r)} = \underline{S_p}$$

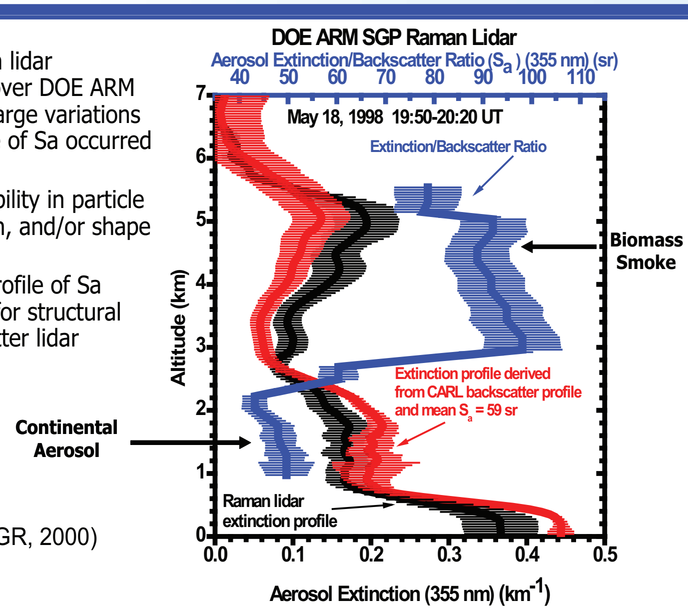
Ext/Backscatter

Particulate Backscatter

Retrieved Parameters

Extinction-to-backscatter ratio variability

- Multiyear Raman lidar measurements over DOE ARM SGP site found large variations in vertical profile of Sa occurred 30% of time
- Significant variability in particle size, composition, and/or shape often occurs
- Uncertainty in profile of Sa raises potential for structural error in backscatter lidar retrieval



(Ferrare et al.,JGR, 2000)

Heritage

U. Wisc.- Eloranta 1977 – …	Operating ground-based systems for decades; first etalon-based system; first 532 nm iodine vapor filter system;
Colo. St. - She 1983 – 1998	First vapor filter systems, various wavelengths; first demonstration of temperature measurements
NIES - Liu 1997 – 2001	Ground-based system; 532 nm iodine vapor filter technique and Mach Zehnder interferometric technique
DLR 1998 – 2000	First practical aircraft-based system (no longer functional); 532 nm using iodine vapor filter technique
LaRC 2004 – …	Developed aircraft-based system 532 nm HSRL (iodine filter), 1064 backscatter, and depolarization at both wavelengths. Funded to add 355 nm HSRL channels plus ozone DIAL through IIP (to be completed by 2008).
CNES 2006 ? – …	"LNG" -- Leandre upgrade; 355 nm HSRL (Mach Zehnder), 1064 backscatter
ATLID/Earthcare 2012 ? – …	Spaceborne system; etalon-based interferometric receiver; 355 nm

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3β+2α HSRL: the Über Lidar for Aerosols

- Fundamental data products
  - Backscatter at 3 wavelengths (3β) : 355, 532, 1064 nm
  - Extinction at 2 wavelengths (2α) : 355, 532 nm
  - Depolarization at 355, 532, and 1064 (dust and contrails/cirrus applications)
- Retrieved, layer-resolved, aerosol microphysical/macrophysical parameters (Müller et al., 1999, 2000, 2001; Veselovskii et al.,2002,2004)
  - Effective and mean particle radius (errors < 30-50%)
  - Concentration (volume, surface) (errors < 50%)
  - Complex index of refraction
    - real (±0.05 to 0.1)
    - imaginary (order of magnitude if < 0.01; <50% if > 0.01)
  - Single scatter albedo (±0.05)

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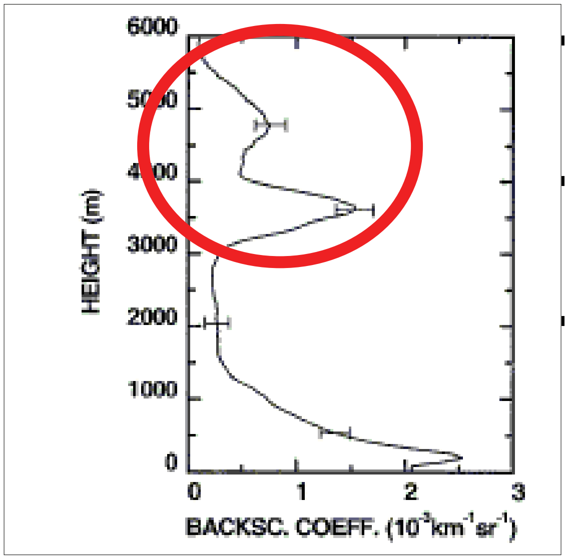
Example microphysical retrieval



- From Müller et al., Appl. Opt., 2001
- Data from LACE 98 campaign over Lindenberg, Germany
- Microphysical retrieval performed for upper layer (3-6 km) and compared to in situ aircraft measurements

Ex. #1- Müller et al. (2001) case study using 3-backsatter and 2-extinction wavelengths

Retrieval results compared to in situ measurements for biomass plume.

Parameter	Lidar Retrieval	Aircraft, in situ r>1.5 nm	Aircraft, in situ r>50 nm
r_{eff}, μm	0.27 ±0.04	0.24±0.06	0.25±0.07
Number concentration, cm^{-3}	305±120	640±174	271±74
Surface concentration, $\mu m^2 cm^{-3}$	145±8	110±50	95±55
Volume concentration, $\mu m^3 cm^{-3}$	13±3	9±5	8±5
m_R	1.63±0.09	1.56	1.56
m_I	0.048±0.017	0.07	0.07
SSA (532 nm)	0.81±0.03	0.78±0.02	0.79±0.02
SSA (355 nm)	0.76±0.06	–	–
S_a (532 nm) sr^{-1}	73±4 (75)	–	–
S_a (355 nm) sr^{-1}	51±4 (45)	–	–

Lidar Data Product Wish List

- Backscatter Lidar
- Backscatter Lidar + Passive
- 3β+2α Advanced HSRL

- Aerosol layer heights
- Qualitative vertical distribution (backscatter profile)
- Aerosol type vs. altitude
- Extinction profile from backscatter
- Extinction profile with column constraint
- Fine-coarse mode fraction vs. altitude
- Extinction profile
- Complex refractive index vs. altitude
- Aerosol size vs. altitude
- SSA vs. altitude
- Concentration vs. altitude

Further enhanced by addition of passive sensors

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Measurement Requirements

- Requirements below are minimums we are currently considering and are driven by
  - 15% accuracy on backscatter and extinction for microphysical retrievals
  - Horizontal and vertical resolutions required to capture relevant aerosol features. Will learn more about relevant aerosol scales with launch of CALIPSO.

Parameter	Resolution	Relative Error
Backscatter	$\Delta x < 150$ m $\Delta z < 50$ km	< 15%
Extinction	$\Delta x < 1$ km $\Delta z < 50$ km	< 15%

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Technology Requirements

- Transmitter
  - SLM, frequency agile Nd:YAG operating at 1064, 532, and 355 nm
    - Average output power > 50W
    - Rep rates 50-200 Hz
      - higher rep rates are acceptable, but puts more stringent requirement on receiver in terms of solar background rejection.
    - High electrical-to-optical efficiency
  - Issues
    - Lifetime
      - Pump diodes
        - Need quantitative database on lifetime vs. diode drive current: determine how derating drive current from nominal specs increase lifetime.
      - UV operation
        - Expect contamination to be a bigger problem in UV than in visible and near IR. Long-term degradation of coatings due to high power UV exposure should be studied. Contamination and contamination control processes should be studied: absorption by trace organic contaminants more of a problem in the UV.

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Technology Requirements

- Receiver
  - Interferometric receiver required for 355 nm HSRL measurement (may also be used at 532 if shows merit over iodine vapor filter technique)
    - Spectral resolution ~ 1 GHz
    - Photon efficient
    - Good rejection of solar background
    - High stability/calibration accuracy
      - Accurate calibration of throughput vs. wavelength critical to HSRL application
  - Detectors
    - High QE: >50%
    - Low dark noise
    - Gain sufficient to make amplification noise insignificant
    - Low excess noise factor
  - Telescope
    - Large area: > 1.5 m diameter

Earth Science Lidar Community Forum, January 10, 2006, Washington, DC

Aerosol/Cloud Lidar for Global Monitoring of Climate, Air Quality, and the Ocean

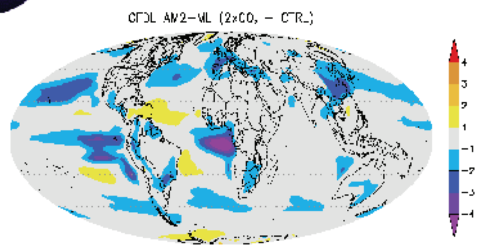
Dave Winker
NASA LaRC, Hampton, VA

Motivation

- Nadir-viewing lidar fills many measurement needs, but the coverage is too sparse for many applications
- Simple backscatter lidar *with cross-track coverage* would allow significant advances in critical Science Focus Areas. Three examples:
  - Acquisition of cloud climate data records for climate trends
    - > *Climate, Weather, Water and Energy Cycle*
  - Monitoring ocean ecosystems and carbon cycling
    - > *Carbon Cycle*
  - Air quality monitoring and forecasting
    - > *Atmospheric Composition, Public Health*

1) Climate-quality Observations from Satellite Lidar

Submitted in response to Decadal Survey RFI



Change in low cloud amount w/ 2X CO_2 (%/K)

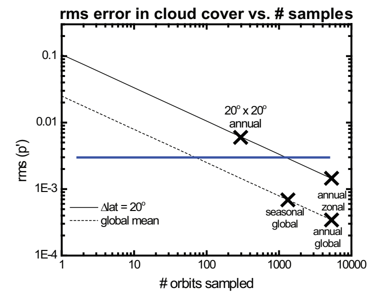
DT ~ 0.2 K/decade, so cloud 'signal' ~ 0.2-0.4%/decade

Objective

To directly observe climate change, stable and accurate cloud measurements are necessary:

	accuracy / stability
Cloud cover	1% / 0.3%
Cloud height	150 m / 30 m
Ice/water phase	

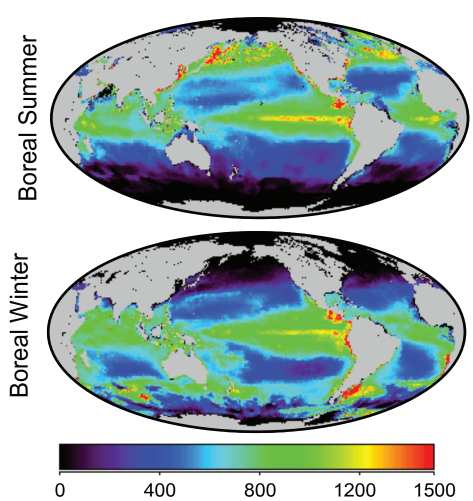
Lidar is uniquely qualified to meet these requirements



- **Nadir-pointing lidar can achieve required accuracies at seasonal-zonal scales**
- **But need cross-track sampling to monitor at regional scales**

2) Atmospheric Correction for Ocean Color

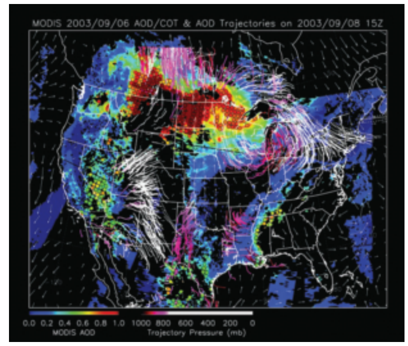
- **Next-generation ocean color sensors* will provide satellite measurements of biomass amount and production rate**
  - **Reduced uncertainties in ocean carbon fluxes**
  - **Monitoring of marine ecosystem health, even in coastal zones**
- **However, aerosol profile measurements are necessary for the high accuracy atmospheric corrections required**



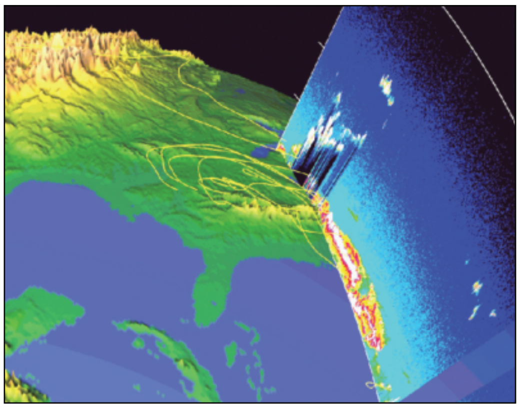
*** "The Ocean Carbon, Ecosystem and Near-shore (OCEaNS) Mission Concept", Behrenfeld, McClain, and Herman, submitted in response to Decadal Survey RFI**

3) Improving Air Quality Forecasts

- NOAA and the EPA now have a mandate to provide forecasts of air quality, including aerosols
- Current air quality forecast models use MODIS AOD, but could be greatly improved by adding profile information

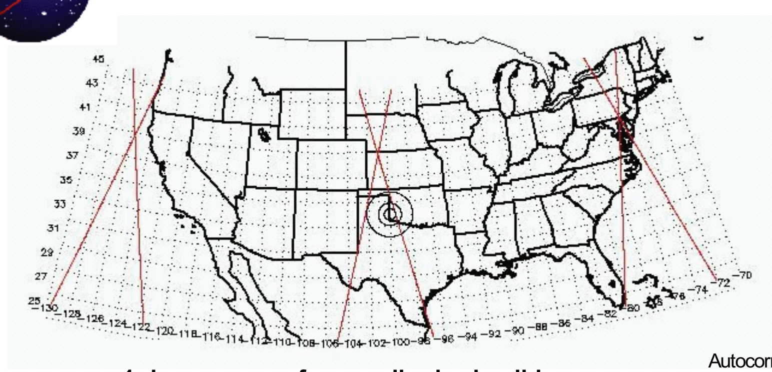


Single frame from a forecast animation of aerosol trajectories. Initialized with MODIS aerosol optical depth map.



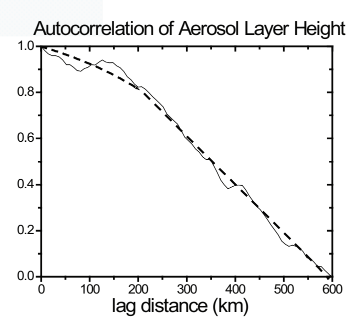
Profile data allows more accurate forecasts, as well as backtrajectories to emission sources

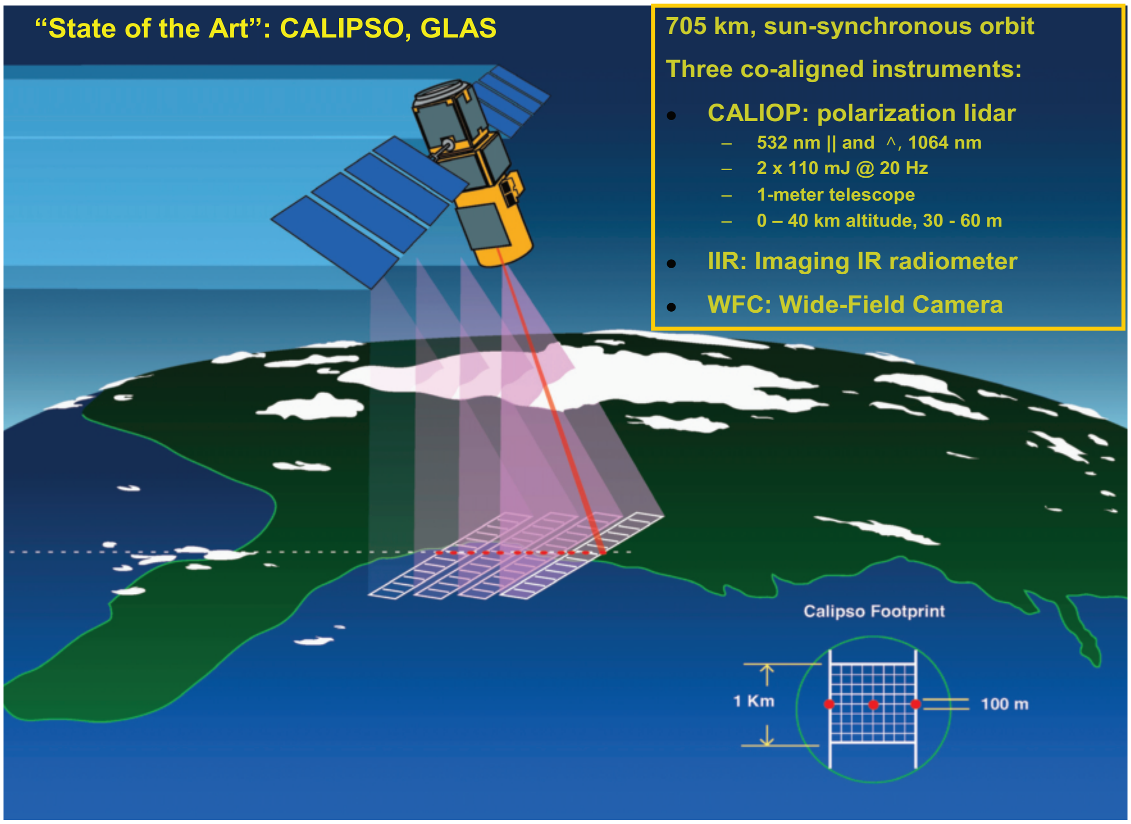
1-day nadir-viewing coverage



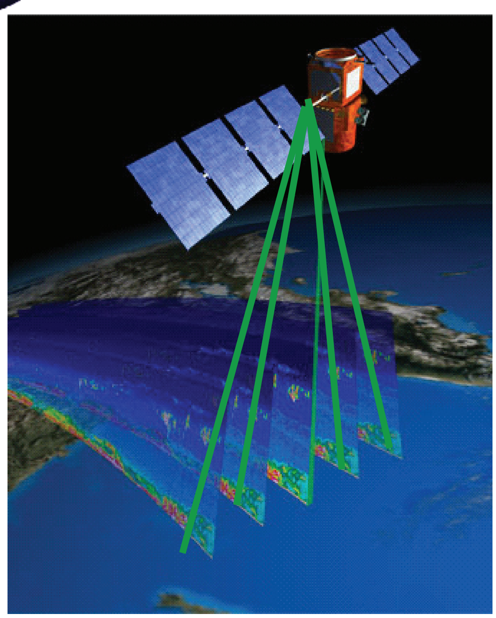
1-day coverage from nadir-viewing lidar

- Nadir-viewing coverage is very sparse (> 2000 km path separation)
- Nadir measurement accounts for only 50% of the height variation 200 km away
- Aerosol height is essentially uncorrelated beyond 400 km





Notional Instrument Concept

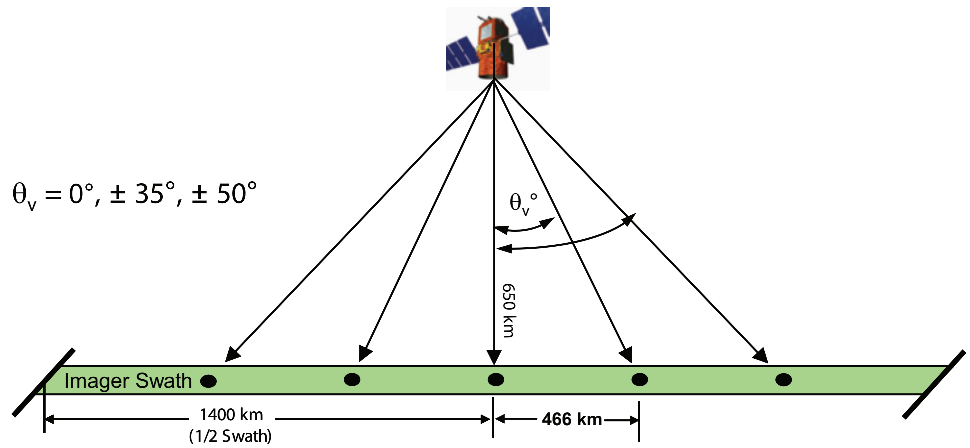


- "Simple" backscatter lidar and passive imager(s)
  - Same platform or in formation
- All 3 applications aided by adding multi-beam lidar with cross-track coverage
- For cloud monitoring, want independent samples
  - Widely spaced measurements are more efficient
  - Uncertainty of cloud fraction reduced by factor of 3
- Due to spatial correlations, aerosol measurements can also be sparse (Dx ~ 200 km)

ESTO Lidar Workshop, Washington DC
10 January 2006

Cross-track requirements

- Continuous cross-track coverage is not required (or desirable)
- Beams are spaced by 233 km, providing 1-day "coverage" of the US
- Central 3 beams provide 2-day global coverage
- R^2 losses are about 1.5 and 2.5 for the off-nadir beams



Concept Details

- Many system requirements are driven by the need to perform along-track cloud clearing at 100 m spatial resolution (or on single shots)
  - At ~7 km/sec, travel 100 m in 14 msec
- Require 2 wavelengths (for cloud/aerosol identification)
  - 532/1064 is fine, but not the only option
- Require depolarization measurements for at least 1 wavelength (for cloud ice/water discrimination)
- Wide detector dynamic range (10^6:1) required
  - Climate accuracies require calibration from stratospheric molecular returns as well as unsaturated cloud returns
- Good solar rejection
  - Implies narrow linewidth lasers (< 10 pm) and matching filters
  - If linewidth is narrow enough (£ 1 pm), can use low-pulse energy/high rep rate lasers without penalty

Technology Needs

- Primary issue is transmit/receive optics to span wide swath (30° – 50°)
  - Small apertures desirable
  - Increased laser energy or detector efficiency allows smaller receiver optics
- However, power requirements are a large multiple of nadir-only instrument:
  - Need high efficiency lasers, satellite power systems, detectors
  - Large apertures desirable
- Laser reliability/lifetime is an issue: goal of 7-year mission life
- Faster, more reliable photon-counting APD's would help

ESTO Earth Science Lidar Community Forum:

Dual wavelength, depolarization backscatter satellite lidar with novel cross-track scanning

Judd Welton, NASA GSFC
Matthew McGill, NASA GSFC
Peter Colarco, NASA GSFC

Cross-track Backscatter Lidar:

Science Objectives

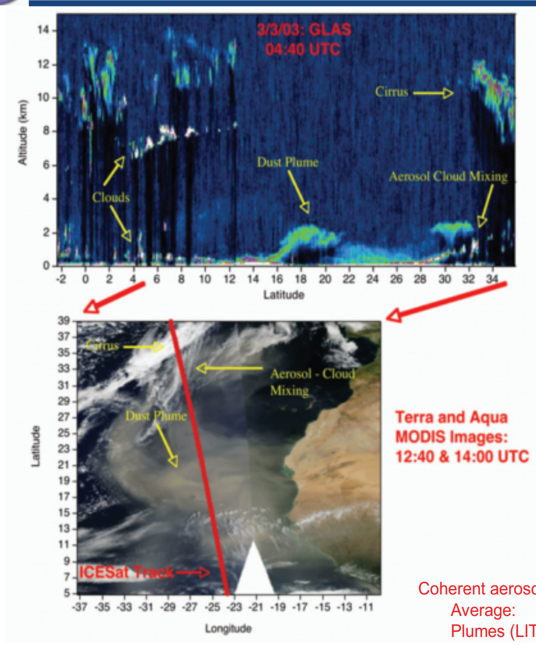
1. Continue basic aerosol and cloud vertical structure observations after the CALIPSO mission ends. Long-term data are required for climate assessments.

2. Use cross-track observations to improve aerosol and cloud parameterization in mesoscale and global transport models by providing sub-grid and multi-grid vertical profile data. Develop model assimilation schemes to provide better aerosol & cloud forecasting and Decision support framework.

3. Provide increased swath coverage for formation flight missions relying on combined lidar and imager observations.

Cross-track Backscatter Lidar:

Science Objectives, cont



Why cross-track observations?

Existing backsatter lidars only provide nadir profiles, producing a "curtain" of data along the ground track.

Lidar curtain is miniscule compared to typical imager swaths.

Successive orbits are separated by 1000s of km.

Result:

- true global & regional coverage is poor, weekly or monthly averages are required
- mismatch between lidar & imager swaths makes combined data analysis difficult
- limited lidar coverage for model assimilation & Decision support

Coherent aerosol time and space scales (Anderson et al., JGR, 2003):

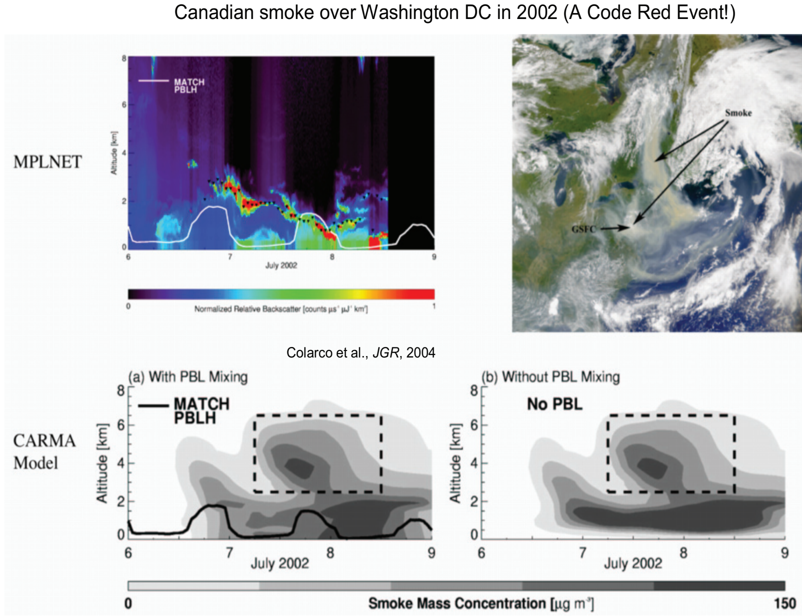
Average:	3 - 6.5 hrs,	60 - 130 km
Plumes (LITE):	0.8 - 2.1 hrs,	16 - 41 km

Judd Welton et al., GSFC 613.1 Slide 3 of 7

Cross-track Backscatter Lidar:

Science Objectives, cont

Using Lidar to help constrain aerosol transport models:
Canadian smoke over Washington DC in 2002 (A Code Red Event!)



In this real-life scenario, what help would a nadir only lidar provide for aerosol and air quality forecasting? Decision support?

Judd Welton et al., GSFC 613.1 Slide 4 of 7

Cross-track Backscatter Lidar:

Science Objectives, cont

NASA Roadmap Objectives:

Continuation of Backscatter Lidar Observations (GLAS/CALIPSO)

Atmospheric Composition
• Tropospheric/Stratospheric Aerosol Mapping & Profiles
• High latitude aerosols & PSC

Water and Energy Cycle
• Cloud structure and properties (water/ice phase, etc)
• Aerosol/Cloud interactions
  • 2nd indirect effect - modification of precipitation
  • semi-direct effect - cloud evaporation

Climate Variability and Change
• Long-term consistent climate change record required
• Global aerosol & cloud properties/structure
• No lidar missions in NPP or NPOESS

Basic lidar observations such as those from GLAS & CALIPSO must continue for long term climate studies. The next mission should not be so technologically advanced that its launch is many years after CALIPSO, or a large data gap will occur.

Addition of Cross-track Coverage:

Atmospheric Composition
• Global High Temporal & Spatial observations
• Assimilation of constituents in models, improved representations of aerosols & emissions

Carbon Cycle and Ecosystems
• Global Ocean & Coastal Carbon, Particle Abundance
• Ocean color requires correction for absorbing aerosol layers (height dependent), particularly coastal waters

Weather
• Global monitoring of water, energy, clouds, & air quality - operational prototype mission
• Steady improvements in weather prediction (including air quality) - Decision support

Cross-track coverage will benefit & enable model assimilation (a focus of every roadmap), Decision support, and improve co-located swath coverage between satellite lidar & imager data (ocean color correction). Potential benefit to other lidar missions.

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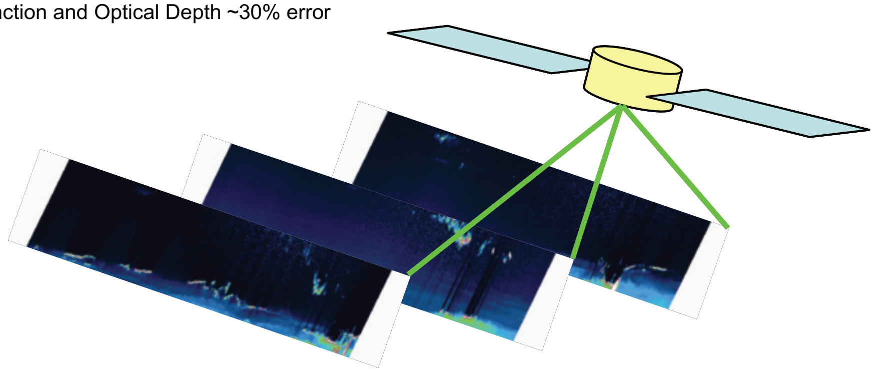
Cross-track Backscatter Lidar:

Measurement Concept

Orbital dual wavelength (1064 and 532 nm) backscatter lidar with depolarization. Utilize novel cross-track coverage technology to extend proven nadir observations to off nadir paths without using a moveable mirror. Cross-track observations using 3 to 6 fixed beams for coverage of 100 – 500 km +/- of nadir track. Similar orbit as CALIPSO is ideal, particularly formation flight with imager.

Observations:
• Cross-track coverage within 100 – 500 km +/- of nadir track
• Vertical resolution < 500 m
• Horizontal resolution: ~10 km along track (aerosol), ~5 km along track (clouds)
• Cloud phase at ~5 km along track
• Extinction and Optical Depth ~30% error



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Cross-track Backscatter Lidar:

Current State of the Art & Technology Requirements

Current State of the Art:

- GLAS - dual wavelength (1064 & 532 nm)
- CALIPSO - dual wavelength (1064 & 532 nm), depolarization capability
- No current plan exists to incorporate cross-track coverage with such lidars
  - Altimetry applications are already investing in this area

Technology Requirements:

- Laser transmitters, particularly fiber lasers, with improved efficiency and $\leq$ 10 W output power per beam at 1064 nm
- telescope receiver, or telescope array, providing bigger FOV and larger aperture
  - 1 - 2 m effective aperture
  - total FOV: ~ 10º (+- 100 km) or ~ 40º (+- 500 km) assuming ~ 600 km orbit
  - multiple IFOV ~ 200 μrad

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Solid State Frequency Conversion Technology Development for Atmospheric Measurements

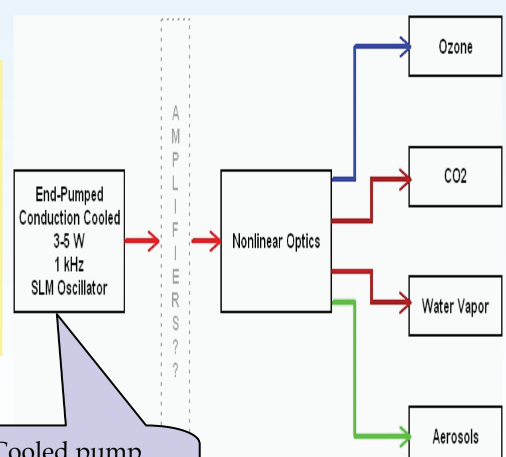
Thomas McGee
NASA Goddard Space Flight Center
Dale Richter
ITT Industries

ITT Industries
Advanced Engineering & Sciences Division

Remote Sensing Applications for End Pumped Configuration

Four different tasks to continue and expand LRRP work on frequency conversion:

- End-pumped oscillator (All)
- Green-pumped UV OPO (O_3 DIAL)
- 100 W pumped OPO transmitter (O_3)
- 100 W pumped OPA transmitter (CO_2)



TEC Cooled pump diodes will improve electrical efficiency 3-5X!

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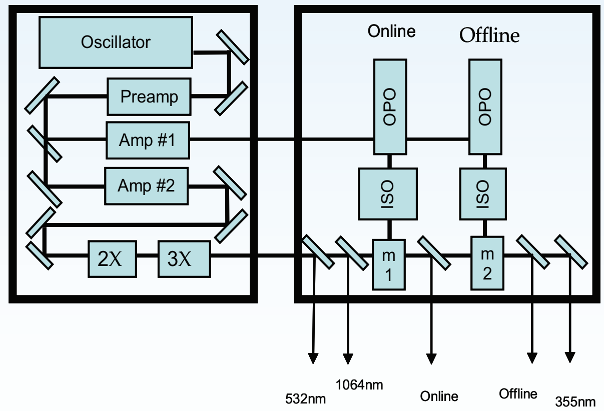
UV Generation Schematic

- Continuation and expansion of effort begun under LRRP
- Oscillator development will increase efficiency and robustness; current side-pumped osc. is water cooled
- Technology applicable to trop. ozone, CO_2, H_2O, measurements
- OPO development increases efficiency, demonstrates packaging for vibration and thermal stability; reduces risk for IIP instruments; increases efficiency for offline ozone DIAL
- OPA development for CO_2 DIAL will demonstrate transmitter power for space measurement
- Space and UAV compatible



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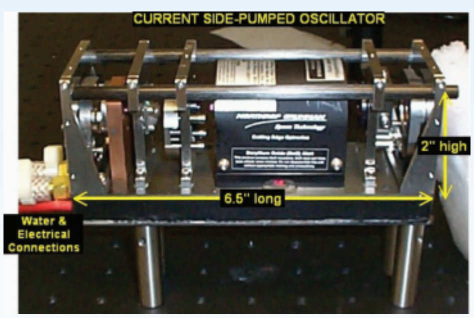
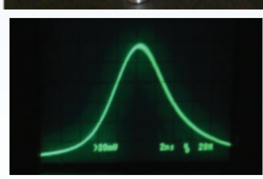
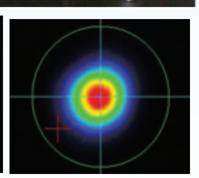
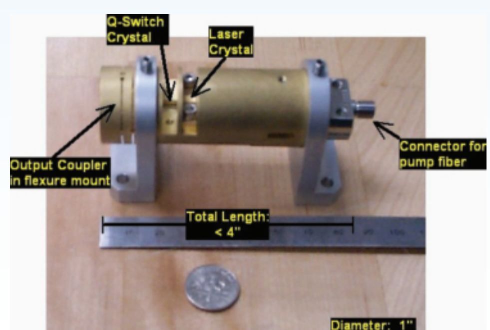
Concept: Efficient End-Pumping







8X Volume Reduction



END-PUMPED OSCILLATOR DESIGN

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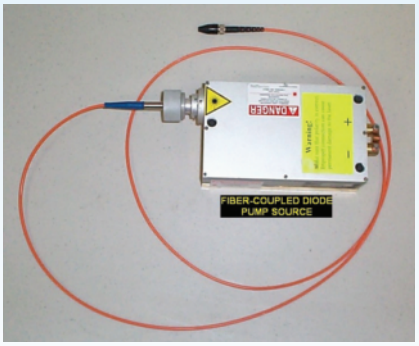
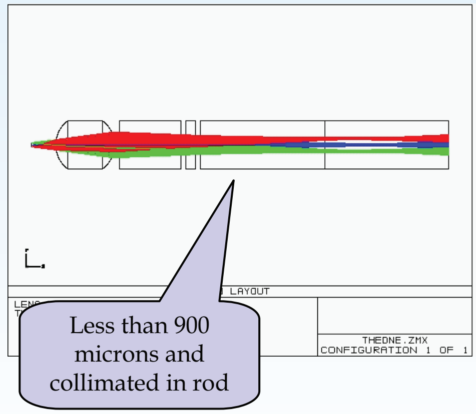
End Pumped Oscillator Performance Goals





- 3-5 mJ at 1 kHz (3-5 W)
  - SLM performance
  - 2-3 KHz may be achievable
- TEC cooled fiber coupled pump diode source
- Conductively cooled laser head
- Leveraging known parameters of side-pumped oscillator to predict and scale the performance of the end-pumped laser design

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End pumped Summary

- ITT Industries has been very successful in developing a KHZ SLM oscillator using off-the-shelf water cooled pump laser heads. *- This design can be leveraged into an end pumped configuration.*
- 3-5 X improvement in the efficiency will be realized for a TE cooled end pumped design. *– Future efficiency improvements can be made through passive cooling.*
- 8X Volume Reduction readily achievable. *– Mechanical stability will increase as well.*

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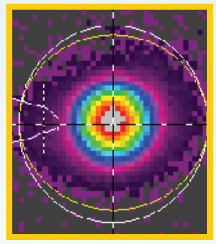
History of Green-Pumped OPO



Beam Quality at >55% CE from pump to signal + idler

- Numerous groups have built green-pumped OPOs but achieved marginal CE results due to properties inherent to the pump beam doubling process
- We propose to improve the green-pumped OPO conversion to match the performance of NIR OPOs demonstrated at ITT
  - Potential to surpass current OPO technology performance when converting to UV wavelengths for space based ozone measurements (one less NLO stage)
  - A key to the technique is the use of Quadrature doubling

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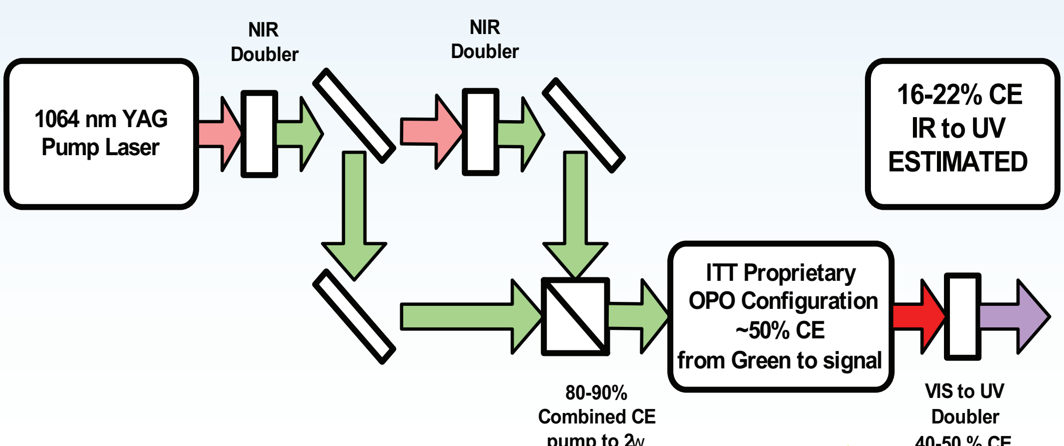
Green-Pumped OPO Concept



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Green-Pumped OPO Summary

- ITT has demonstrated the capability to produce efficient and compact nonlinear conversion modules for UV generation – ***This experience can be leveraged into the development of the green-pumped OPO technology to further the overall optical to optical conversion efficiency***.
- The green-pumped OPO is expected to increase the overall UV conversion efficiency into the 15% to 22% range (single stage) using this technology and possibly over 30% using UV Quadrature as well – ***Enhanced UV generation is important to the future of ozone measurement from space-borne platforms.***
- ITT can use the existing LRRP laser to test and evaluate the green pumped technology at a high repetition rate (1 kHz) with pulse energies of 50 or 100 mJ of pump – ***Direct compatibility with the high repetition rate, high pulse energy LRRP pump laser can be demonstrated.***

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Pump Laser/OPO –LRRP Extension

Calendar 07 begins	1/01/07	Jan-07
Design 100W dual wavelength flight-unit	03/31/07	Mar-07
Perform vibration and thermal analysis	03/31/07	Mar-07
Correct design deficiencies	04/30/07	Apr-07
Build and test flight-unit	07/31/07	Jul-07
Create environmental test plan	07/31/07	Jul-07
Perform thermal and vibration tests	09/30/07	Sep-07
Correct physical deficiencies found during testing, and retest	11/30/07	Nov-07
Integrate and perform engineering test flights (aircraft)	01/01/08	Jan-08

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OPA Development Summary

FY07 Begins	10/01/06	Oct-06
Perform trade of pump energy and rep-rate for CO2 DIAL	11/30/06	Nov-06
Down select bulk versus poled OPA crystals	12/31/06	Dec-06
Demonstrate optimized OPA at 100 mJ and 10 Hz	04/30/07	Apr-07
Design 100W pumped OPA demonstration at 1 kHz	06/01/07	Jun-07
Demonstrate optimized OPA with LRRP 100W pump laser	08/01/07	Aug-07
Perform CO2 DIAL demo using ITT aerosol lidar cart / NASA DAQ	09/30/07	Sep-07
Annual report	09/30/07	Sep-07

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SDCL

Technologies for Deployable Lidar Telescope Receivers

Prof. Lee D. Peterson
Dr. Jason D. Hinkle (presenting)
University of Colorado

Dr. Syed Ismail
NASA Langley Research Center

Presented at the
NASA/ESTO Lidar Community Forum
Washington, DC
10 January 2006

Research Sponsored by
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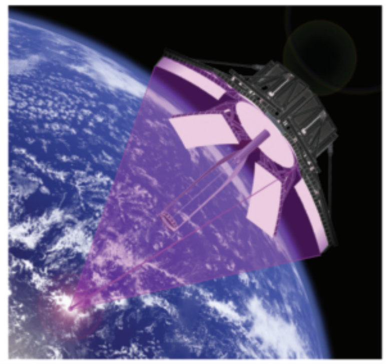
Advanced Component Technology Program
Contract No. NAS1-03009



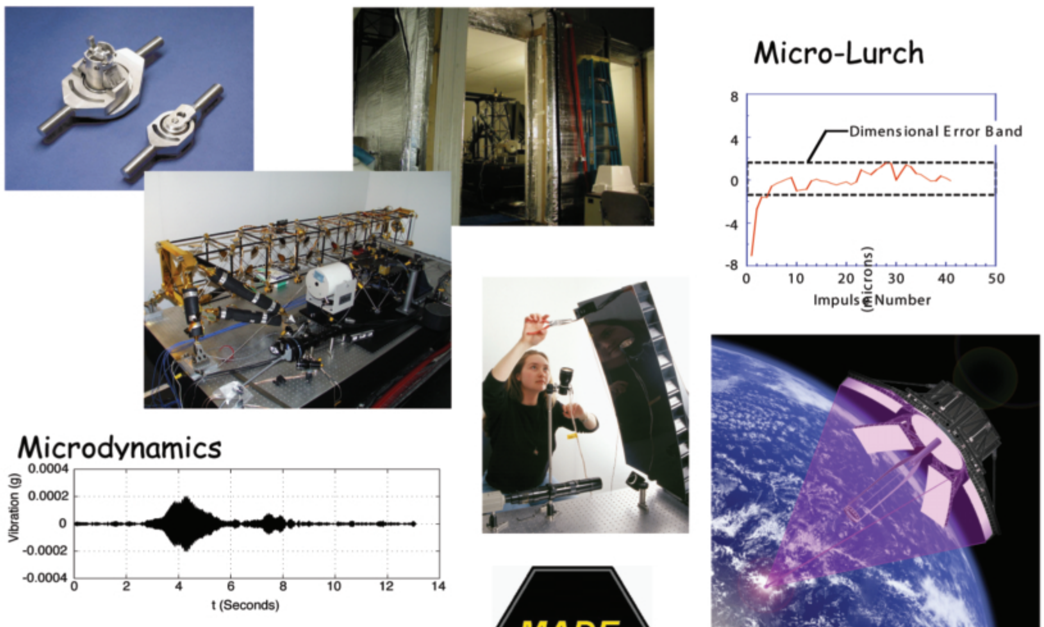
Earth science focus areas of NASA's Earth-Sun System

Climate | Carbon | Surface | Atmosphere | Weather | Water

'NASA's goal in Earth science is to observe, understand, and model the Earth system to discover how it is changing, to better predict change, and to understand the consequences for life on Earth. We do so by characterizing, understanding, and predicting change in major Earth system processes and by linking our models of these processes together in an increasingly integrated way.'

- Active remote sensing by lidar has application in all Earth science focus areas
- Deployable telescope technology development enhances space-based lidar remote sensing in all Earth science focus areas
- This technology is applicable to all classes of direct detection lidar missions including: aerosol, cloud, DIAL, wind, surface, and biospheric lidar systems

Some Background, History and Perspective



MADE

Structural Models at Nanometer Scale

http://sdcl.colorado.edu

Where is the state of the art in precision deployable optics?

- **What we know …**

  Structural depth will strongly affect the stability of any large space telescope. Deployed depth for optical precision therefore remains a key technical challenge.

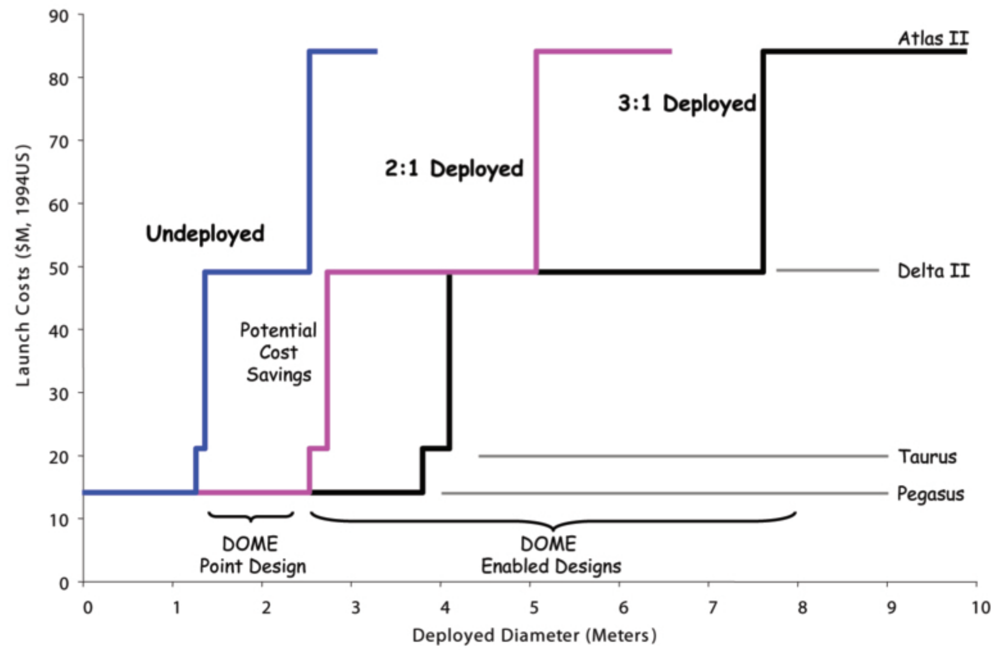
- **What we think we know …**

  System-wide static, dynamic, and microdynamic stability can be achieved through balanced passive structural performance and active structural/wavefront control.

- **What we think …**

  10-meter class optical telescopes are structurally feasible today, while 30-meter class (and above) involve substantial challenges.

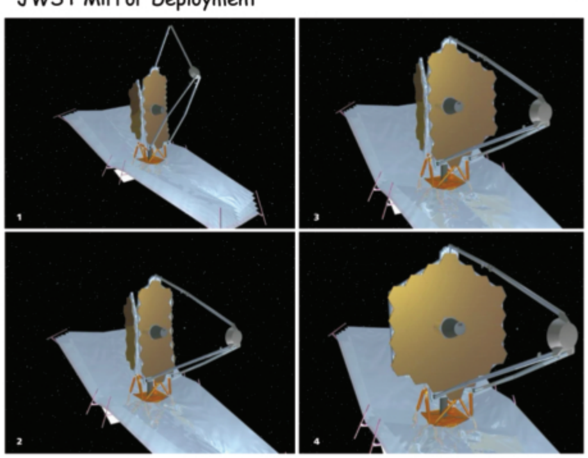
Deployment Substantially Reduces Launch Costs



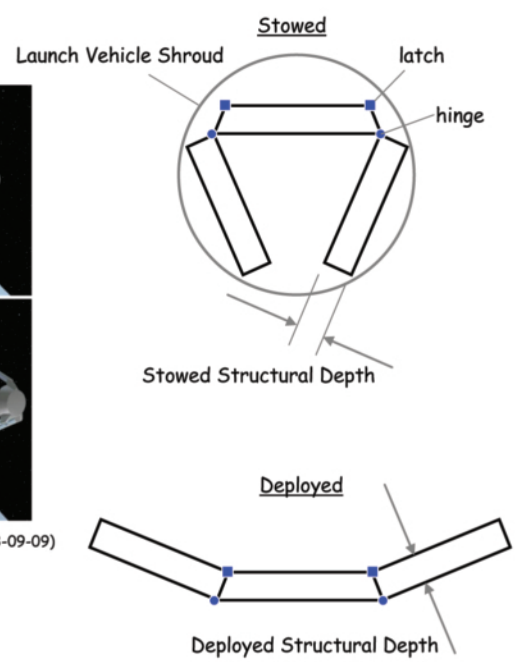
Cost and Diameter Data Source: http://www.jsc.nasa.gov/bu2/ELV_US.html (2003-09-09)

Structural "depth" or "thickness" is a key to overall structural stability

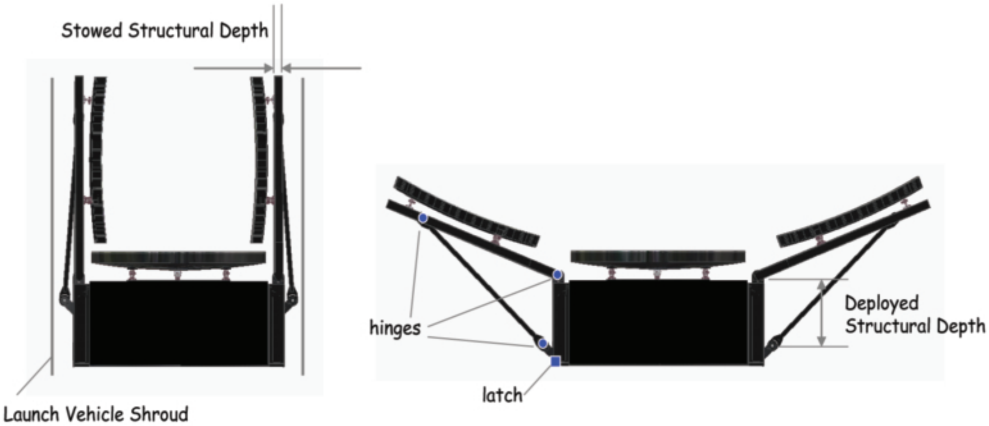
JWST Mirror Deployment



http://jwstsite.stsci.edu/gallery/deploy_graphics/lg_mirror_deploy.tif (2003-09-09)

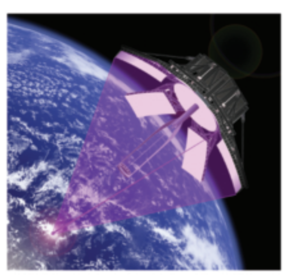


DOME will enable a folding scheme with deployed structural depth



Key to deployed depth: More degrees of freedom ➞ More mechanisms

DOME Project Develops Component Technology Leading to a Flight-Ready Instrument Concept



Flight-Ready Concept

- Low cost deployed lidar telescope mirror
  - Pegasus-size package (2:1 deployed diameter)
  - Equivalent to Delta-II-size undeployed mirror
- Eliminates need for figure control of deployed petals
  - 50:1 improvement in structural performance through deployed depth reaction structure
- Mitigates higher power laser issues:
  - 4-10 times improvement in sensitivity
  - Power, size, cost, and risk
  - Heat dissipation
  - Eye-safety

Enables

- Global tropospheric DIAL profiling of O_3, H_2O and CO_2 with day or night coverage, absolute measurements and direct inversion capability

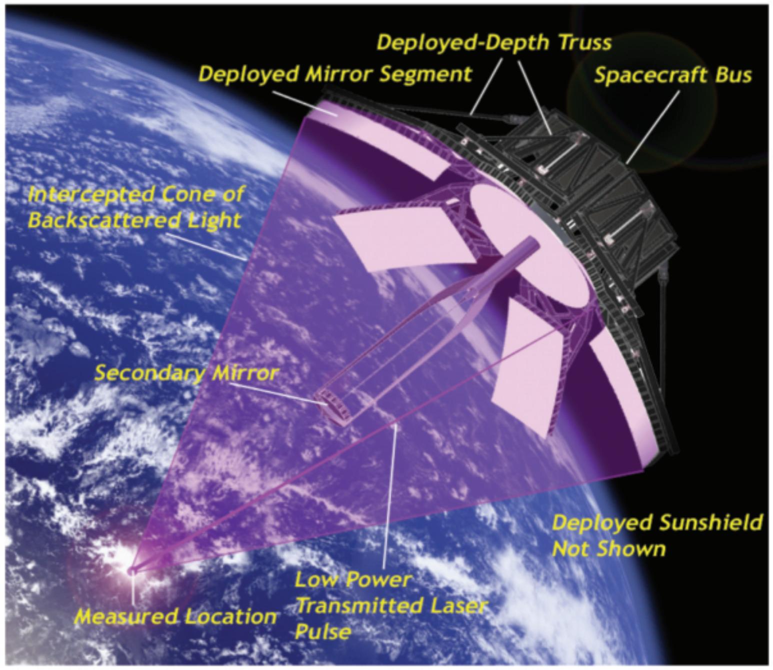
Enhances

- Global scale lidar profiles of aerosol and cloud optical and microphysical properties
- Global wind (direct detection)
- Global oceanographic lidar

Applications

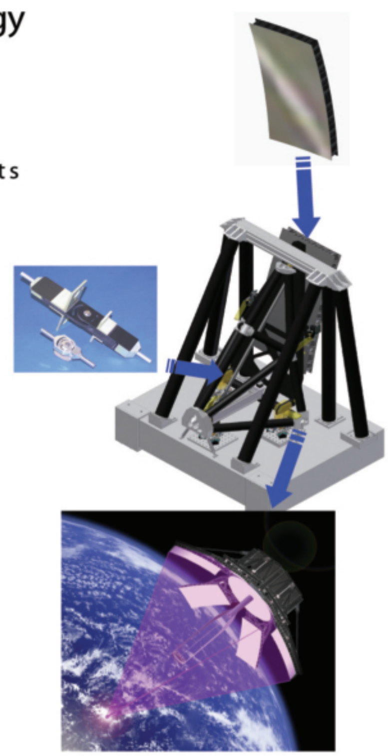
- Better understanding of Earth's atmospheric system
- Improves capability for predicting climate and weather
- Atmospheric composition and dynamics, and air quality
- Water and energy cycle
- Global carbon cycle

DOME- Derived Flight System Concept

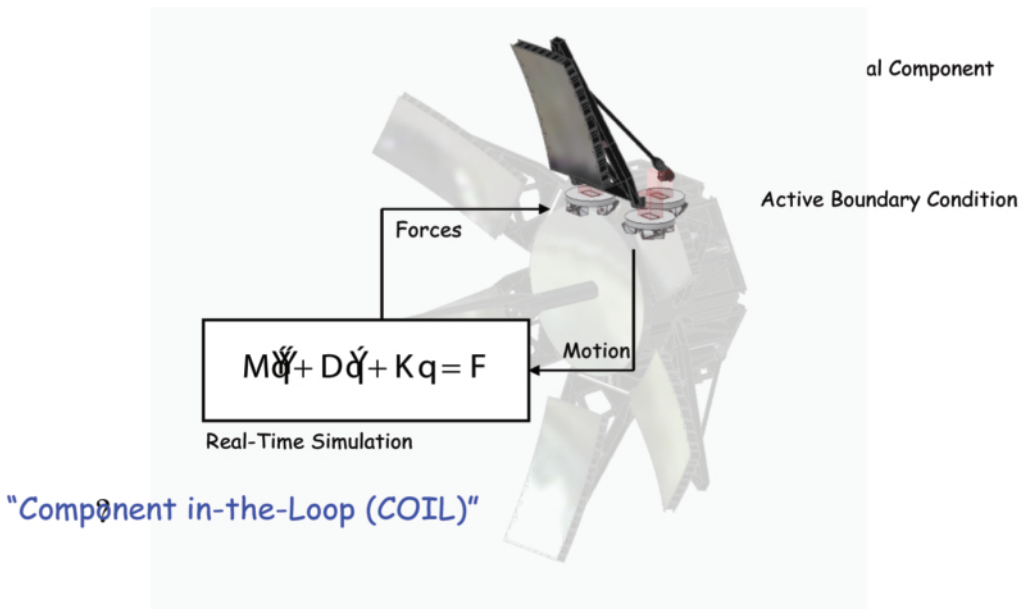


Elements of DOME Technology

- Hardware
  - Replication molded composite mirror segments
  - Precision mechanisms (hinges and latches)
  - Single-petal test article
- Models
  - Integrated structural-optical models
  - Nonlinear models of the mechanisms
  - Model tolerances
- Verification
  - Models correlated with test data
  - Innovative virtual boundary condition test methodology
  - Extrapolate performance of flight system concept



Virtual Spacecraft Test Method Enables High Fidelity Component Testing



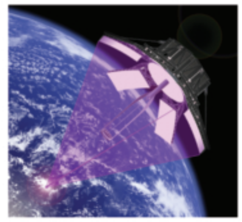
Summary

- DOME is developing and verifying key technology for deployable optics
  - Low cost, low mass mechanisms with predictable behavior
    Behave as though the frictional interfaces were absent
  - Methods for progressing from component to sub-system to system models
  - Verified models of components and sub-systems
- Focus is on a concept for deployed, 2.5 meter lidar receiver
  - Technology applies to any deployed optic
- DOME technology essential to the "virtual verification" of large optical systems
  - Nonlinear mechanical models (using "predictable" mechanisms)
  - Model and experiment uncertainty quantification
  - Verification of deployment repeatability and post-deployment stability
  - Predict on-orbit performance from 1-g experiments

DOME Overall Objective: Low Cost High Performance LIDAR through Telescope Deployment

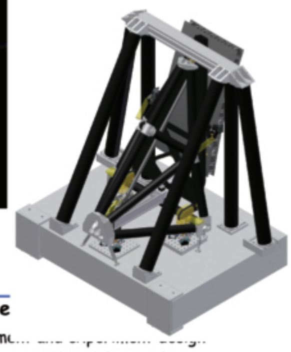
Objectives

- Develop and validate precision deployment technology for low-cost, optical-UV Lidar telescopes
  - Develop new optical precision deployment technology
    - 50:1 improvement in structural performance
    - Minimize need for active optical figure control
  - Validate technology in a sub-system test
    - Single petal and mirror segment
  - Use integrated structural-optical models to extrapolate to full system flight behavior



System Concept

Sub-System Experiment



Technical Elements

- Segmented mirror with a deployed depth reaction structure
- New components with sub-micron deployment repeatability and microdynamic stability
- Sub-system deployment and microdynamic experiments on a single-petal prototype hardware
- Innovative virtual boundary condition sub-system test methodology
- Component, sub-system and system level models updated and validated including uncertainty tolerances

Impact

- 4-10 times improvement in sensitivity
- Delta-II diameter mirror in a Pegasus-size package
- Enables UV, VIS, and IR Lidar/DIAL systems for O_3, H_2O, CO_2, aerosol, and cloud measurements from space

Schedule and Deliverable

- 03-04 Component developm
- 04-05 Component experiments and models complete
- 05-06 Sub-system experiments and models complete
- Final Report: March 2006

Co-I's/Partners

- Co-I: Dr. Syed Ismail, NASA LaRC
- Co-I: Dr. Mark Lake, Consultant
- Co-I: Dr. Jason Hinkle, CU
- Science Advisor: Dr. Ed Browell, NASA LaRC
- Technical Advisor: Tim Collins, NASA LaRC
- Partner: Dr. Ed Friedman, Boeing-SVS

$TRL_{In} = 2$

Measurement of offbeam lidar returns for cloud thickness retrievals

Tamás Várnai[1,2] Robert Cahalan[2]

[1]UMBC JCET, [2]NASA GSFC Code 613.2

Outline:

- Science objectives
- Measurement concept
- Current state of the art
- Technology requirements

Science Objectives

- **Cloud thickness**

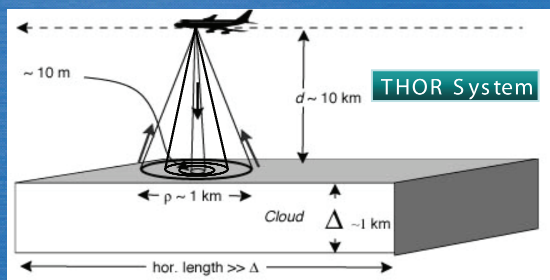
  Needed for:
  - Vertical profile of radiative and condensational heating
  - Surface greenhouse effect
  - Cloud dynamics & microphysics

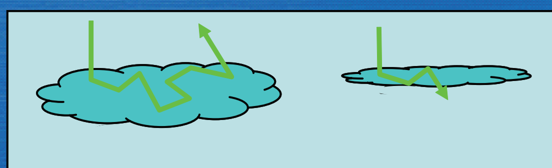
  Current methods cannot measure well the thickness of opaque clouds:
  - Lidars give thickness only for semi-transparent clouds
  - Radar not sensitive to small droplets, cannot separate drizzle from cloud

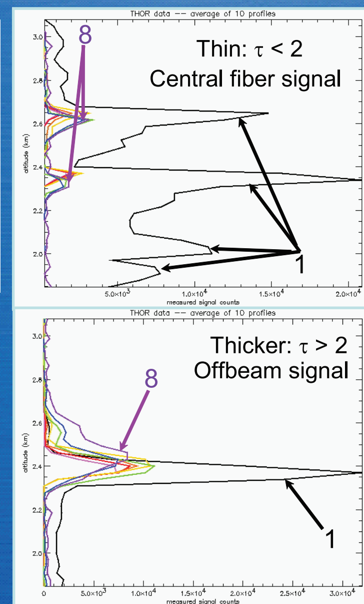
- **Vertical profiles of cloud extinction coefficient, water content, droplet size**

  Synergy with radar data would be helpful for water content & droplet size

Measurement concept



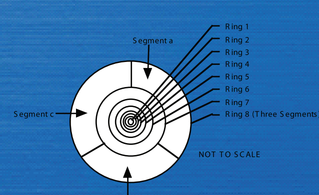


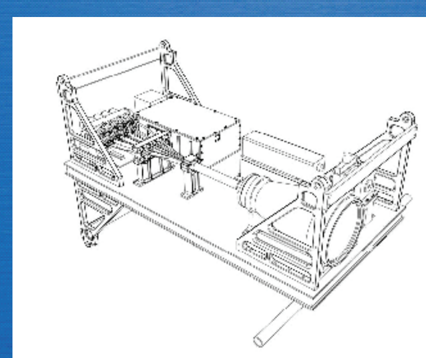


Current state of the art

Airborne instrument: THOR (THickness from Offbeam Returns)
Measured cloud thickness (500 m - 1 km) at 30 m accuracy for τ > 25

- Telescope primary: 19 cm
- Optical fiber bundle at focal plane,
  8 annular fields of view, full angles (mrad):
  106.7 (0.1 rad ~ 6°), 53.4, 26.72,
  13.4, ...0.84 (~0.05°)
- 7 nm wide spectral filter, neutral density filters
- Photon counting PMTs for each FOV





Technical requirements

Transmitter:

•Visible or NIR wavelength (e.g., 532 nm or 1064 nm)
•Beam divergence: 50-100 mrad
•Power: ?100 mJ and/or ?20 Hz

Receiver:

•PMT or APD at central field-of-view (FOV), photon counting PMT for outer FOVs
•Range resolution ~30 m
•Fiber bundle to channel photons from small focal plane to detectors
•5 FOVs, up to ~4 mrad (~2 km diameter)

Narrow-band spectral filtering for multiple field-of-views

Spectral filters need quasi-normal incidence angle

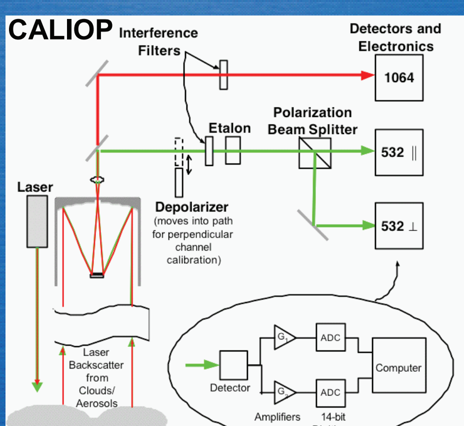


Figure from a paper by Winker et al. at SPIE

Problem with multiple FOVs:

•Incidence angles large behind fiber bundle (airborne THOR: 7nm vs. Caliop: <0.05 nm)

Some possibilities:

•Spectral filters with new optics, perhaps in front of focal plane and fiber bundle

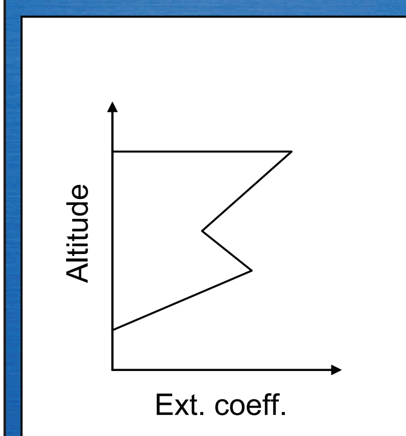
•Atomic line filters

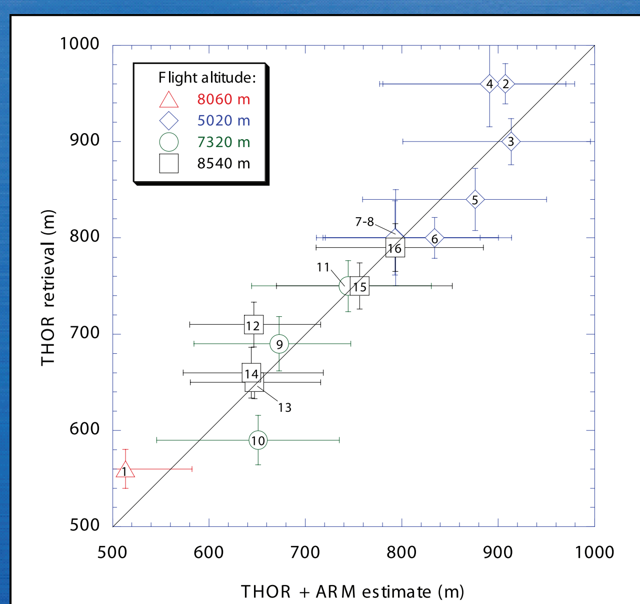
Measurement of offbeam lidar returns for cloud thickness retrievals

Tamás Várnai[1,2] Robert Cahalan[2]

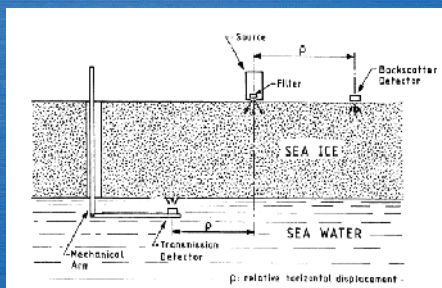
[1]UMBC JCET, [2]NASA GSFC Code 613.2

THOR cloud thickness retrievals

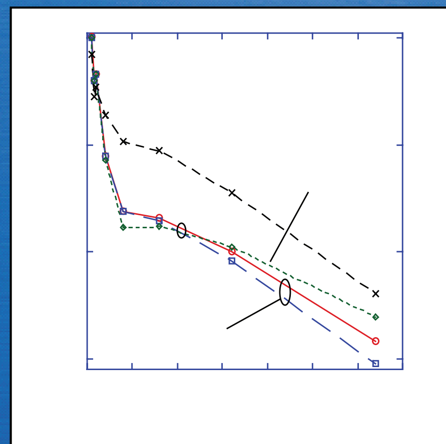




Sea ice observations



From Haines et al. (1997)



Challenge: 100X smaller scale (FOV < 10 m)

Advantage: slowly varying target

Topographic Mapping and Monitoring of Hazardous Geologic Processes

Jordan Muller and Jeanne Sauber, NASA GSFC

Science Objectives

- To better understand the physics of geologically hazardous processes, predict their onset, and respond to their hazardous effects

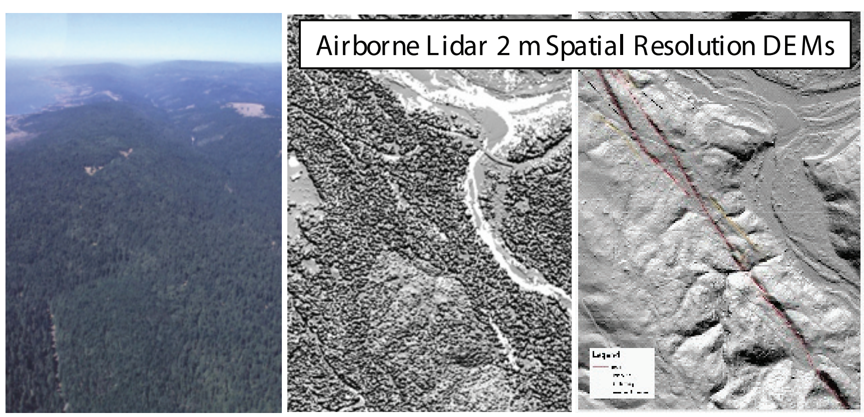
Motivation

- Monitoring topographic changes through time has dramatically improved the science of hazard detection, but repeat high-resolution data are not available for many regions of the world, particularly in vegetated regions

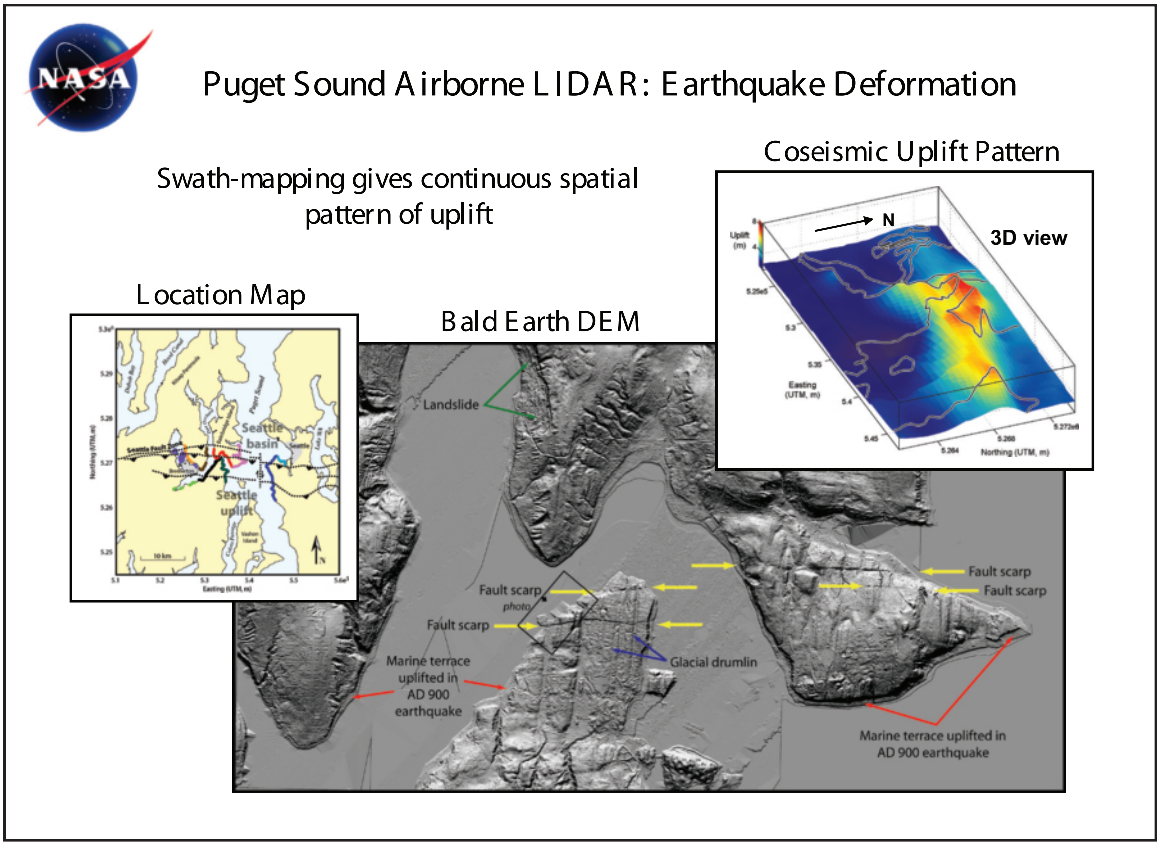
Earthquake Hazards:

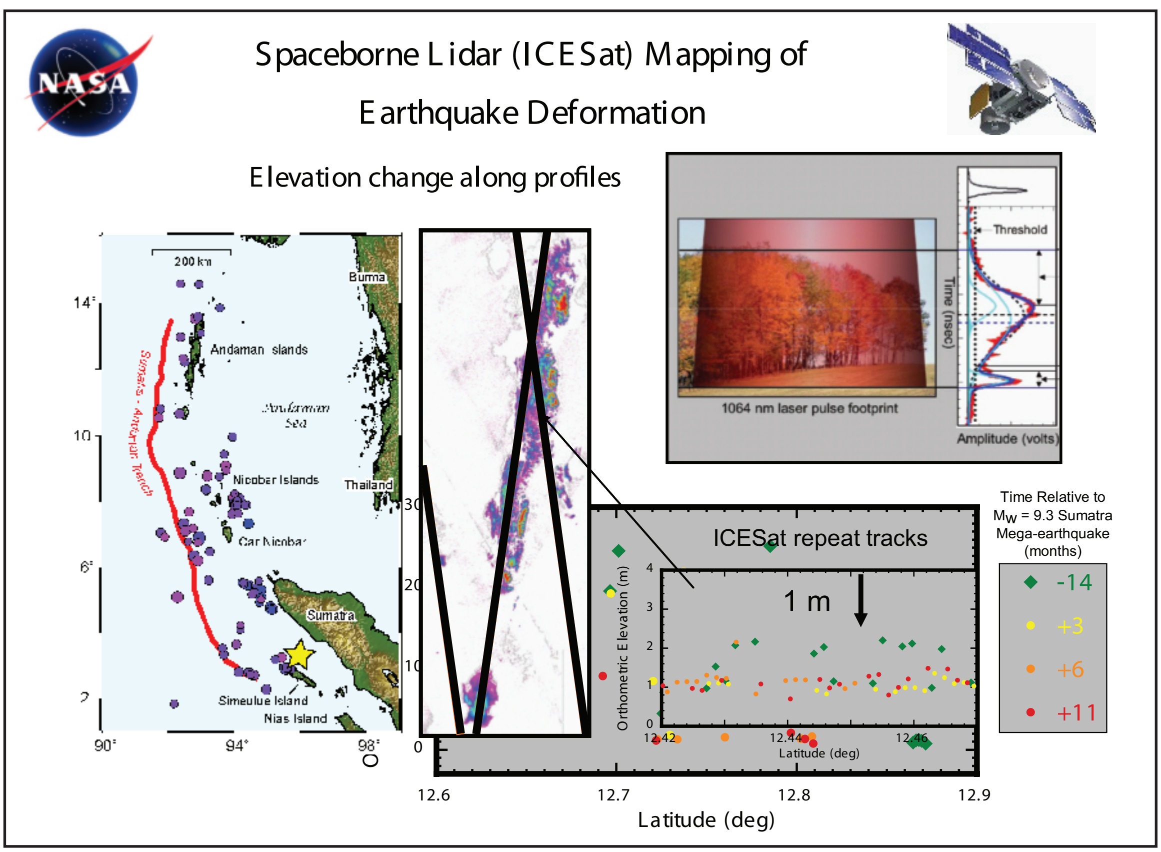
- Detection of active faults from geomorphology (e.g. scarps, terraces)
- Measurement of co-seismic surface deformation
- Input to models of slip direction and magnitude

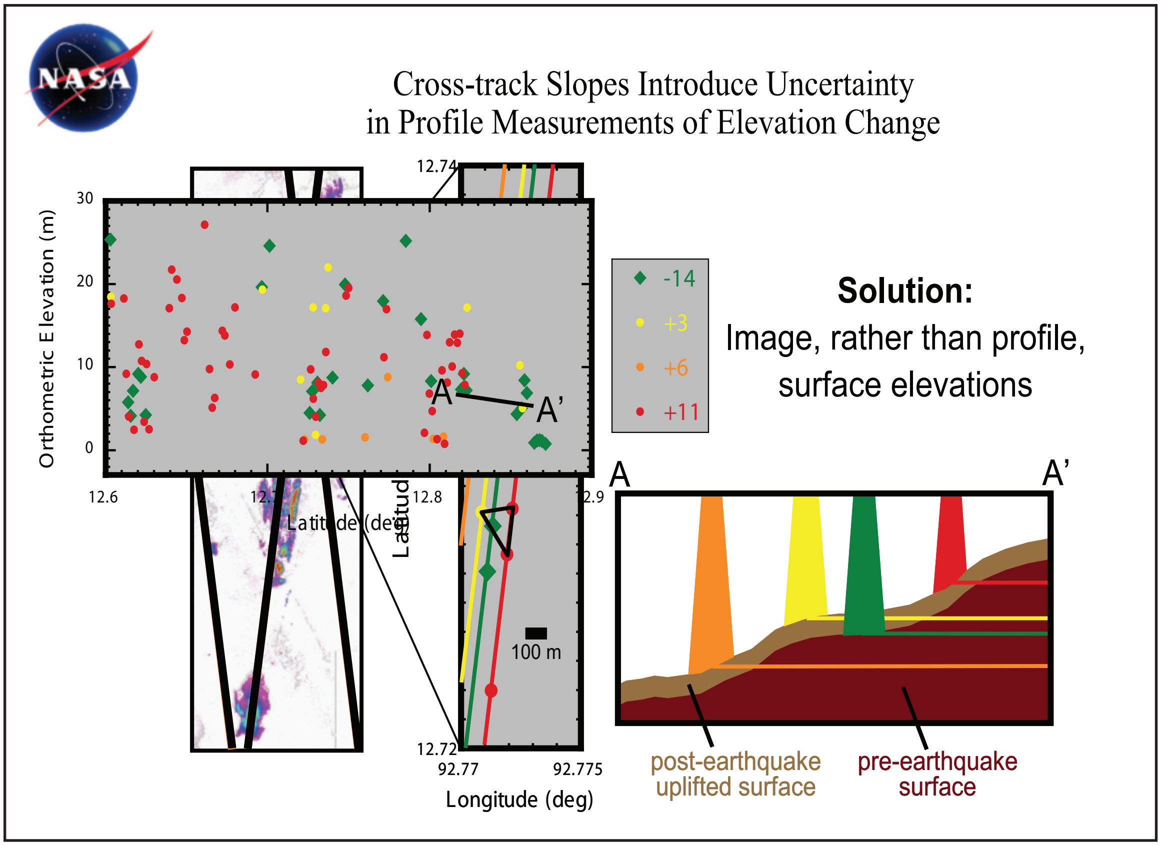
Northern San Andreas Airborne LIDAR: geomorphology beneath vegetation

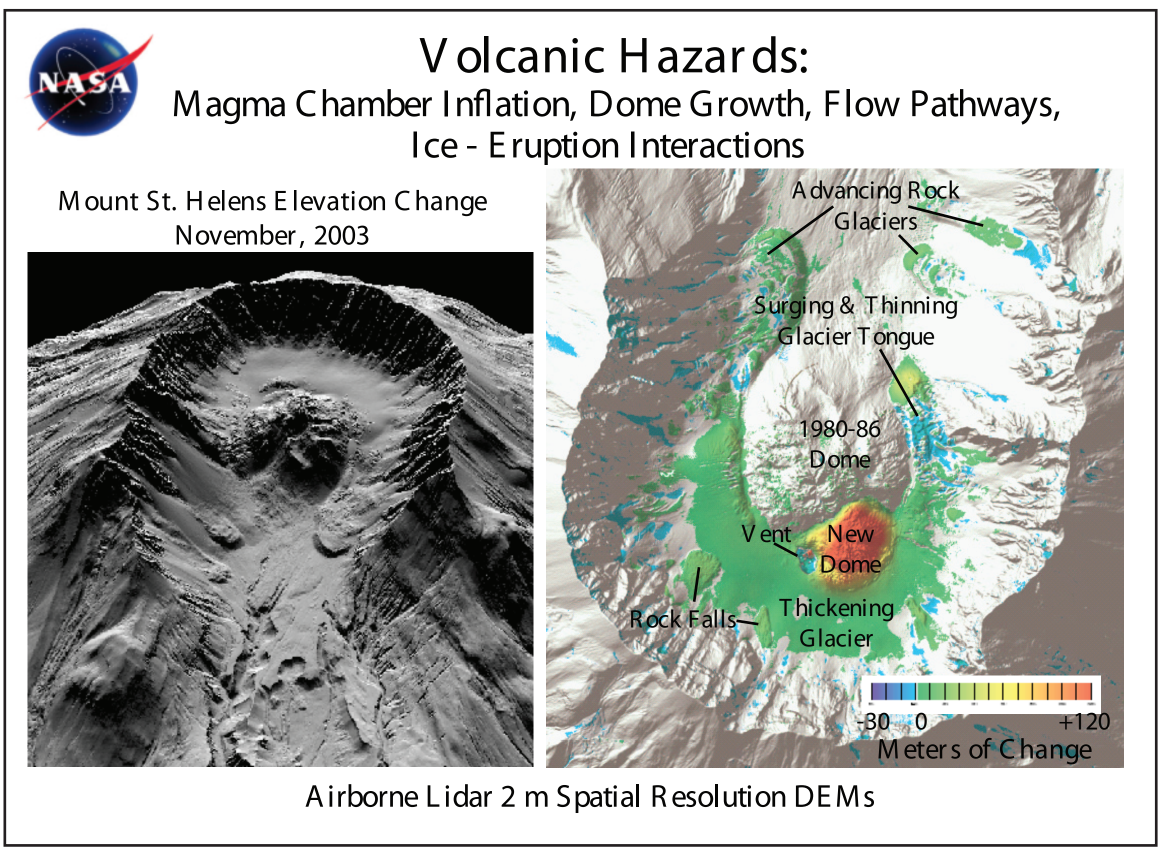


Oblique Aerial Photo | Highest Surface DEM canopy top and bare ground | Bald Earth DEM with fault interpretation


Puget Sound Airborne LIDAR: Earthquake Deformation
Swath-mapping gives continuous spatial pattern of uplift
Coseismic Uplift Pattern
3D view
N
Location Map
Seattle basin
Seattle uplift
Bald Earth DEM
Landslide
Fault scarp
Fault scarp
Fault scarp photo
Fault scarp
Marine terrace uplifted in AD 900 earthquake
Glacial drumlin
Marine terrace uplifted in AD 900 earthquake


Spaceborne Lidar (ICESat) Mapping of Earthquake Deformation
Elevation change along profiles
200 km
Burma
Andaman Islands
Andaman Sea
Nicobar Islands
Thailand
Car Nicobar
Sumatra
Simeulue Island
Nias Island
Sumatra - Andaman Trench
14°
10
6°
2
90°
94°
98°
Threshold
Time (nsec)
1064 nm laser pulse footprint
Amplitude (volts)
ICESat repeat tracks
1 m
Orthometric Elevation (m)
Latitude (deg)
Time Relative to M_W = 9.3 Sumatra Mega-earthquake (months)
-14
+3
+6
+11
12.6
12.7
12.8
12.9
Latitude (deg)

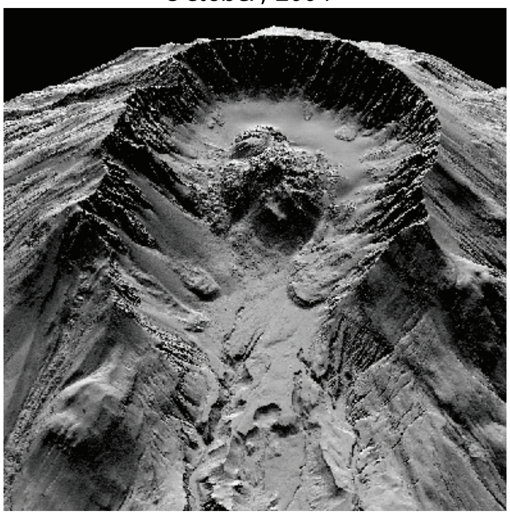

Cross-track Slopes Introduce Uncertainty
in Profile Measurements of Elevation Change
Orthometric Elevation (m)
30
20
10
0
12.6
12.8
12.9
Latitude (deg)
12.74
12.72
A
A'
-14
+3
+6
+11
100 m
92.77
92.775
Longitude (deg)
Solution:
Image, rather than profile,
surface elevations
A
A'
post-earthquake
uplifted surface
pre-earthquake
surface

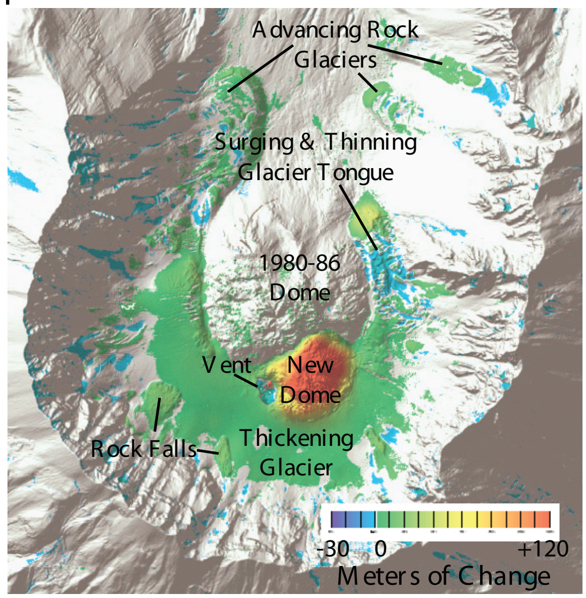

Volcanic Hazards:
Magma Chamber Inflation, Dome Growth, Flow Pathways,
Ice - Eruption Interactions
Mount St. Helens Elevation Change
November, 2003
Advancing Rock
Glaciers
Surging & Thinning
Glacier Tongue
1980-86
Dome
Vent
New
Dome
Rock Falls
Thickening
Glacier
-30
0
+120
Meters of Change
Airborne Lidar 2 m Spatial Resolution DEMs

Volcanic Hazards:

Magma Chamber Inflation, Dome Growth, Flow Pathways, Ice - Eruption Interactions

Mount St. Helens Elevation Change
October, 2004

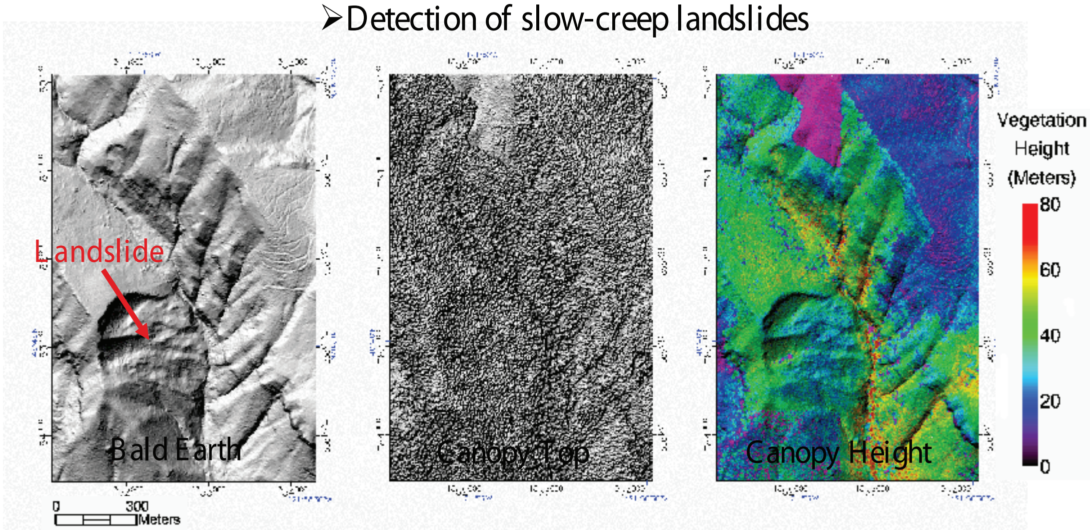




Airborne Lidar 2 m Spatial Resolution DEMs

Landslide Hazards:

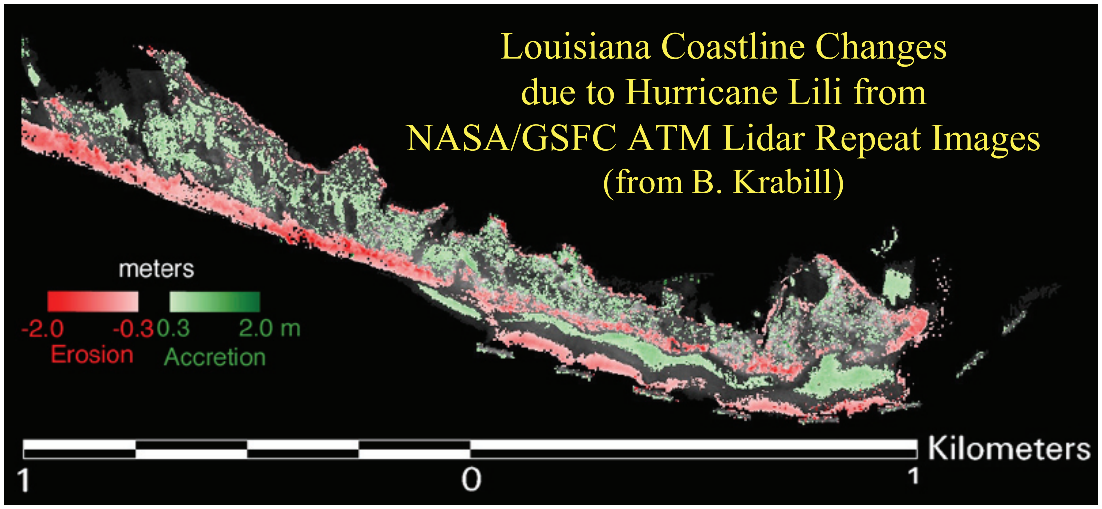
- Improved landslide inventory and process studies from bald Earth topo
- Canopy cover input to precipitation infiltration and surface runoff modeling
- Detection of slow-creep landslides



Airborne Lidar 2 m Spatial Resolution DEMs

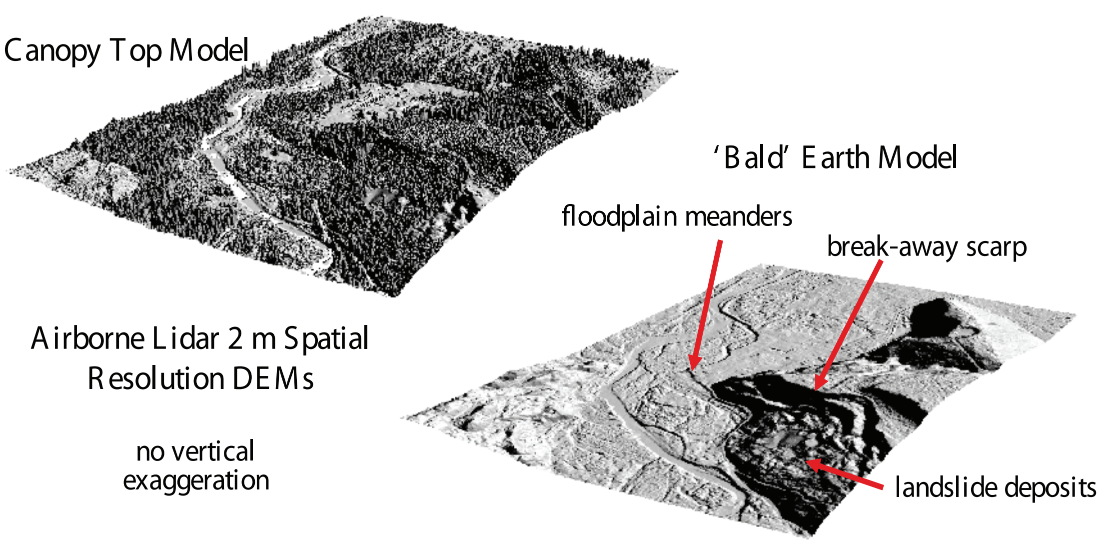
Coastal and River Shoreline Hazards:

- Storm surge and tsunami inundation modelling (topography & veg. cover)
- Environmental and infrastructure impacts of sea level rise



Coastal and River Shoreline Hazards:

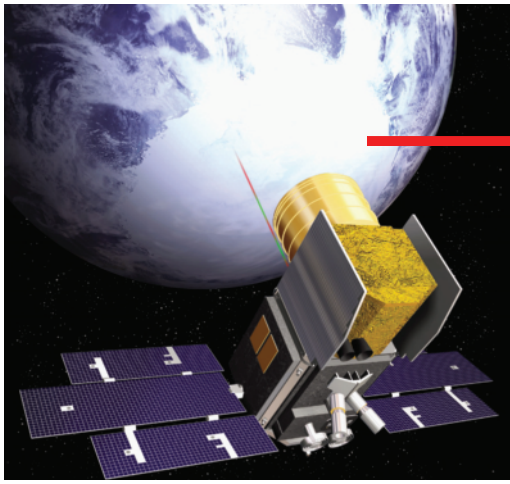
- Stream channel migration and flooding
- Erosion, sediment redistribution and storage

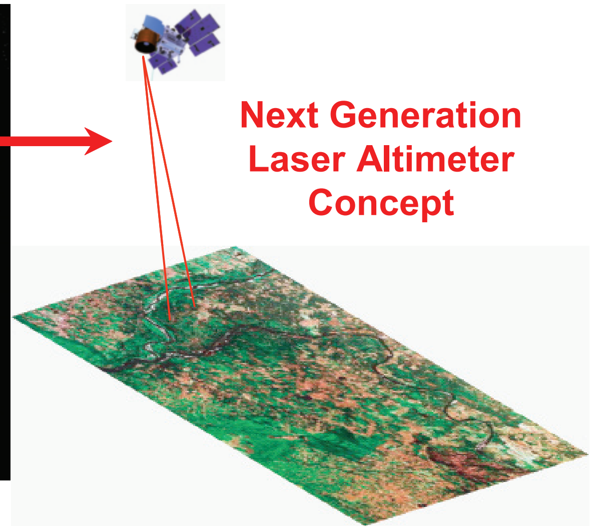


Measurement Requirements for Space-based Solid Earth Science Imaging LIDAR

- Targeted Ground Surface Elevation Mapping
  - ✓ 2 to 5 m spatial resolution
  - ✓ 5 cm (1σ) pixel-to-pixel relative vertical accuracy
  - ✓ 10 cm (1σ) absolute vertical accuracy where sparsely vegetated
  - ✓ 50 cm (1σ) absolute vertical accuracy beneath dense vegetation
  - ✓ elevation image swath width of ≥ 100's of meters
  - ✓ repeat imaging of elevation for change detection
  - ✓ repeat frequency of days to years depending on frequency of events and rate of change

Swath Mapping Laser Altimeter for Cryospheric Change



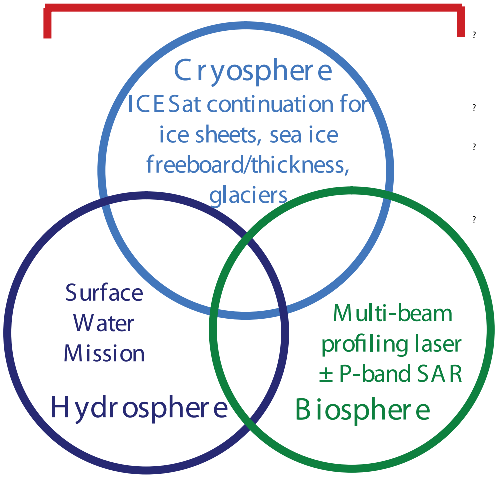


Advanced capability mission to follow ICESat

Christopher Shuman, David Harding, James Abshire, Xiaoli Sun, Michael Krainak, Phil Dabney, NASA Goddard Space Flight Center
Christopher.A.Shuman@nasa.gov

SMLA - Global Science Objectives

Capability simultaneously addresses 3 science areas:

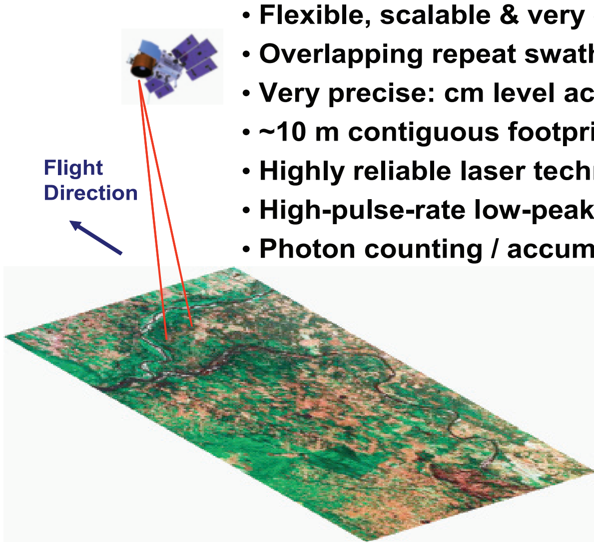


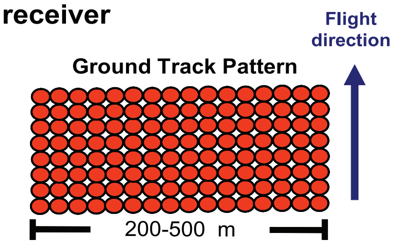
Measurements help determine responses and forcing feedbacks at high latitudes and elevations related to climate change:

- **Glacier and ice sheet mass balance**
- **Sea ice thickness and extent**
- **Snow cover depth, and implications for continental water storage and melt runoff**
- **Timing and volume of river discharge**
- **Quantifying inputs to sea level rise, freshening and warming of arctic ocean surface waters**
- **Modification of carbon source and sink dynamics**
  - **Adaptation of vegetation canopy to**
    - **Permafrost melting**
    - **Increased length of growing season**
    - **Alteration of fire cycles**

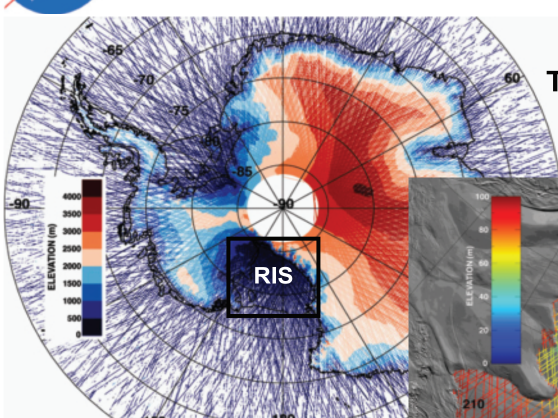
Swath Mapping Laser Altimeter - Summary

- Swath-mapping laser altimeter for cryospheric change
- > 7 year lifetime to build on ICESat pathfinder
- Configured to address multiple/global science disciplines
- Swath mapping instead of along track 'sampling'
- Flexible, scalable & very efficient architecture
- Overlapping repeat swaths for change detection along track
- Very precise: cm level accuracies over ice and flat topography
- ~10 m contiguous footprint spots form the swath
- Highly reliable laser technology from industry
- High-pulse-rate low-peak power measurements
- Photon counting / accumulation receiver

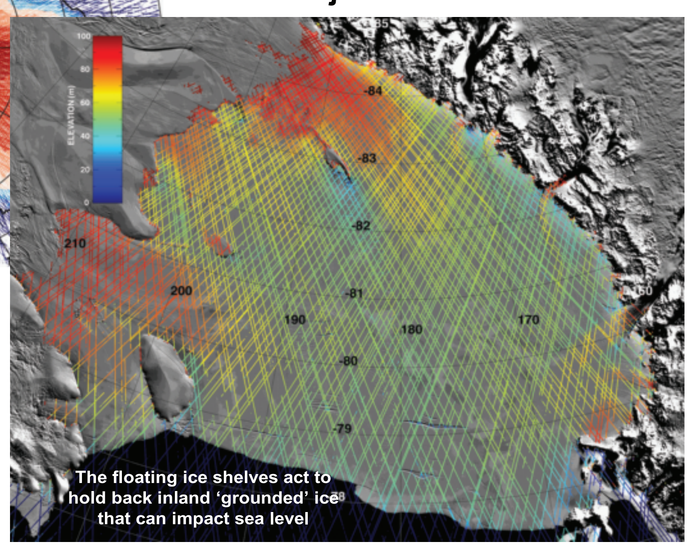




Laser Altimetry Details the Ross Ice Shelf



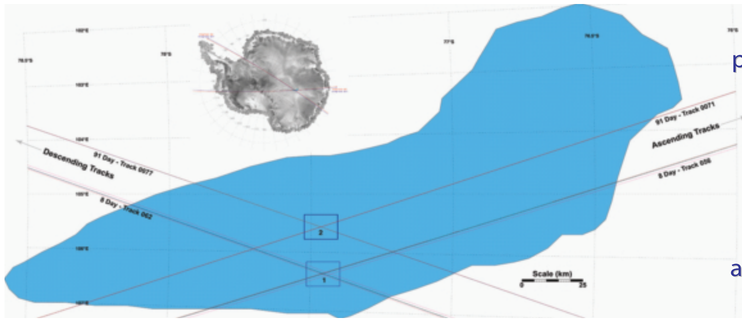
The Ross Ice Shelf from ICESat and MODIS - the altimetry and imagery reveal major ice flow features



In 2003-2005, over eight operation periods, GLAS has emitted > 1 Billion shots

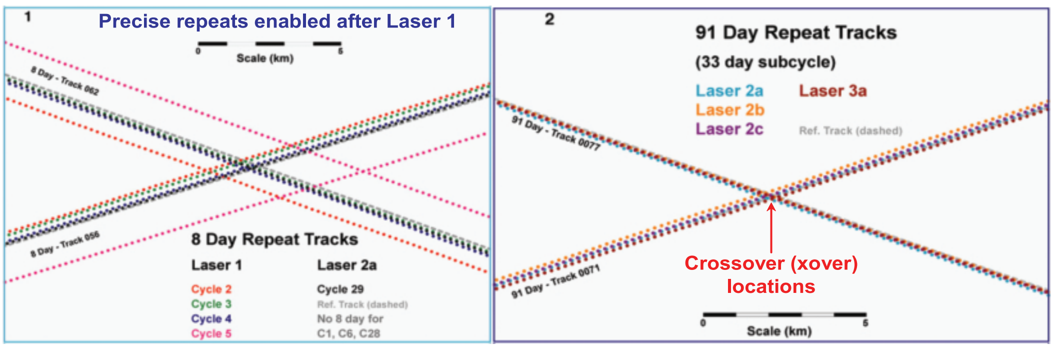
Over Antarctica, during Laser 2a operations ~20,000,000 pulses were emitted and ~17,000,000 were returned.

Repeat Track Overlap Issues - Lake Vostok



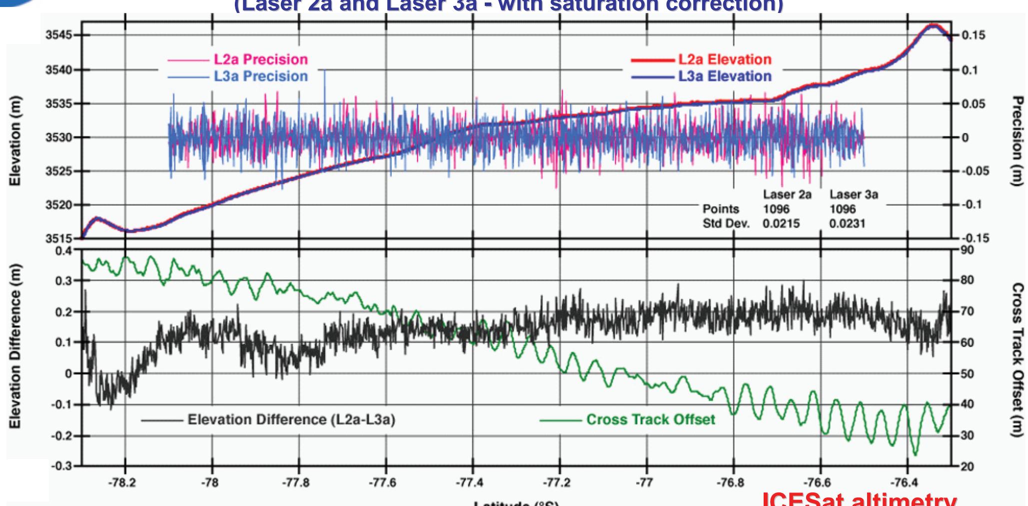
ICESat repeat track pointing is good to ~100 m level from Laser 2a operations onward

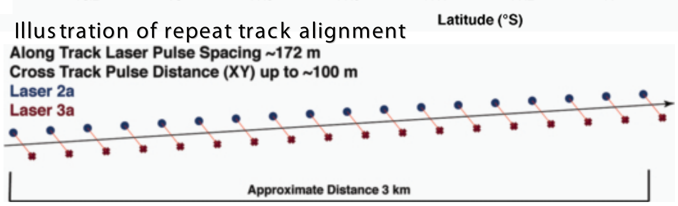
Note the grey reference track and the ~1Hz oscillation along track, altimetry data have ~170 m spacing along track)



Repeat Track Change - Lake Vostok Track 0071

(Laser 2a and Laser 3a - with saturation correction)





ICESat altimetry precision is near 2 cm

Repeat track elevation difference is ~30 cm

Cross-track slope impact negligible here

Laser Altimetry Accuracy - ICESat L2a Data

Laser 2a Release 21 Ascending-Descending Crossover Statistics

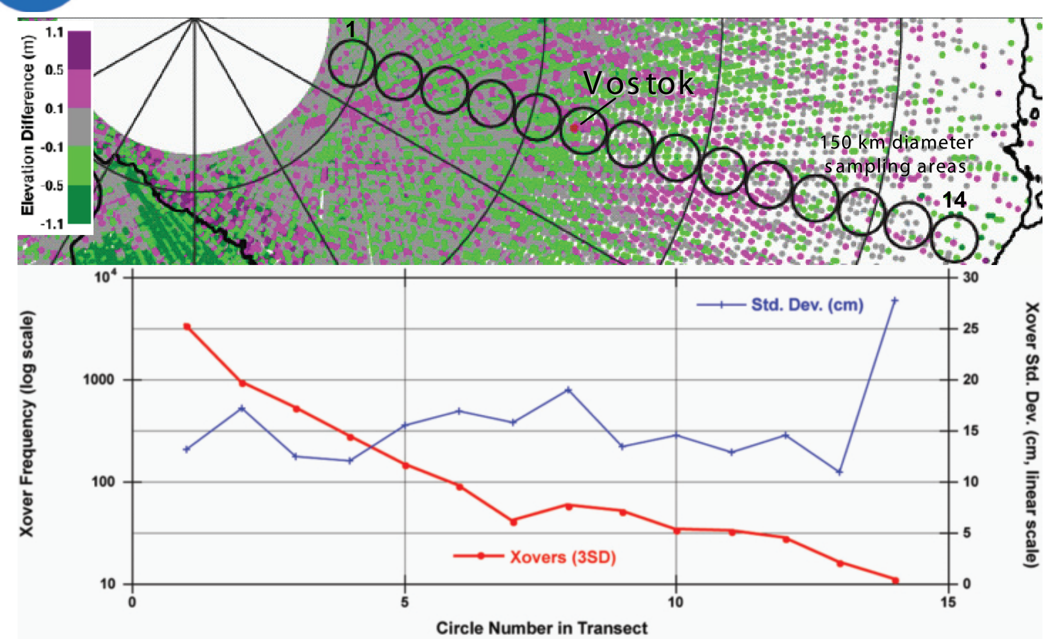
Area	Points (3SD)	Mean Slope (°)	Mean (cm)	SD (cm)
Antarctica	160740	0.202	-0.097	14.44
0 to 0.25°	127538	0.108	-0.173	13.85
0.25 to 0.5°	19731	0.318	0.288	16.46
0.5 to 0.75°	7038	0.567	0.141	19.57
0.75 to 1.0°	3363	0.924	-0.986	21.32
1.0 to 1.25°	1988	1.024	-1.969	23.88
1.25 to 1.5°	1228	1.290	-0.294	26.54
1.5 to 2.0°	867	1.560	-1.818	25.26

The best (so far) operational period has a relative accuracy (i.e. ICESat to ICESat) of ~±14 cm based on crossover standard deviations after 3 sigma editing of 'best' data (i.e. no off-nadir data and no tidal areas).

This plus/minus range is close to the Vostok repeat track comparison example (i.e. knowledge of the surface is currently at the several decimeter level with low slopes).

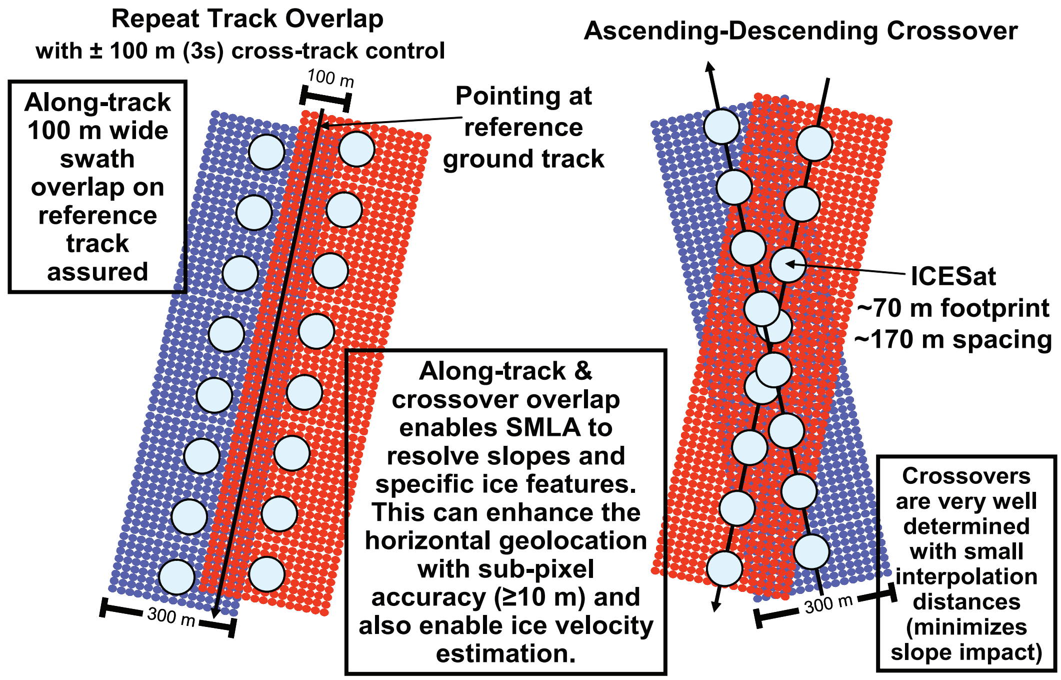
Note that accuracy declines as slope increases (5km DEM slope data used here) but statistics are much better than current radar altimetry.

Crossover Frequency For Change Detection



Near the coasts, ice sheet slopes get steeper and changes are likely, xover frequency is low and repeat track comparisons (with correction for cross track slope) become essential.

Swath Mapping Enhances Change Detection

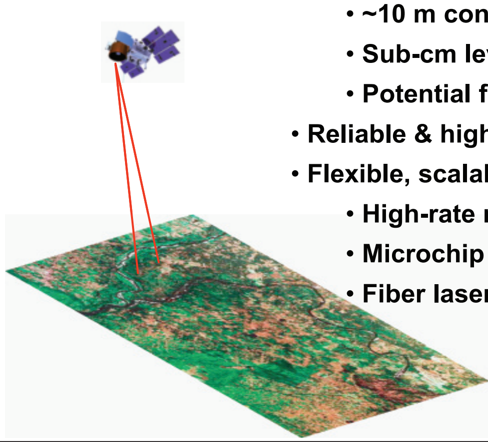


SMLA Concept - Status/Summary

- Swath-Mapping Laser Altimeter mission being studied (Harding et al., IIP Project)
- Has potential to address multiple science disciplines
- > 7 year mission lifetime goal

Study Results to date:

- Swath mapping has many benefits over line profiling altimetry
  - Overlapped repeat swaths allow precise change detection
  - ~10 m contiguous footprint spots (spatial resolution)
  - Sub-cm level accuracies over flat ice & topography
  - Potential for ice velocity through feature tracking
- Reliable & highly redundant laser technology
- Flexible, scalable & efficient architecture:
  - High-rate nJ - uJ laser pulses & photon counting receiver
  - Microchip lasers for near term
  - Fiber lasers for future



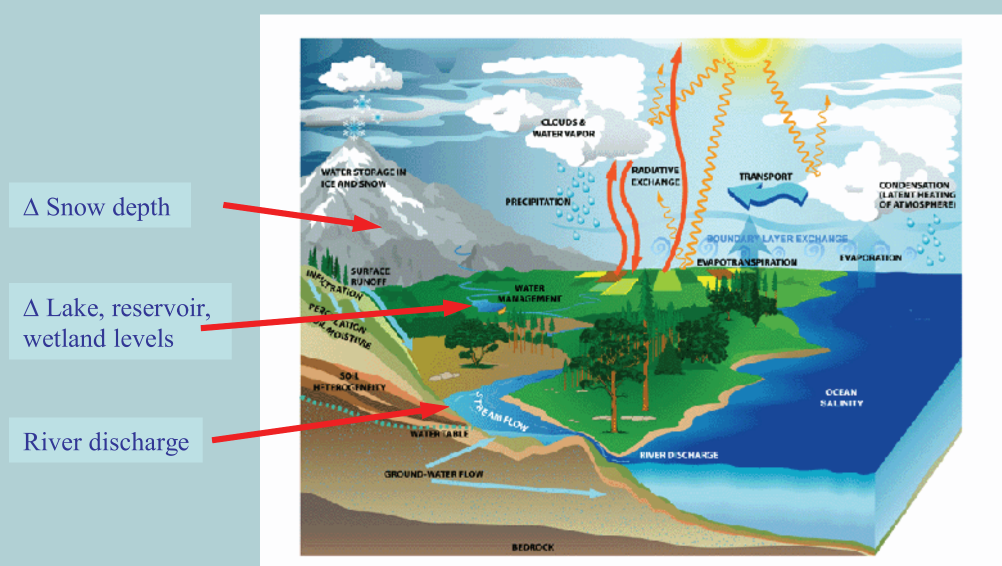
Concept appears viable in near term
Scalable to wider swaths in future

Use of Lidar Technology for Improved Surface Water Storage and River Discharge Dynamics

Michael F. Jasinski
Hydrological Sciences Branch
NASA Goddard Space Flight Center

NASA/ESTO Lidar Community Forum
January 10, 2006

Global Water and Energy Cycles

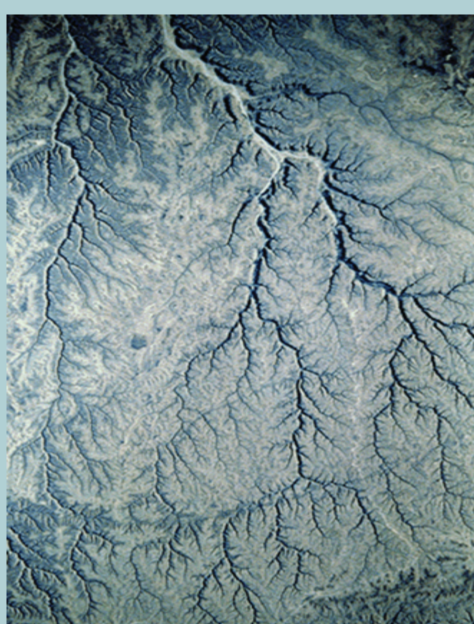


Δ Storage = Precipitation – Evaporation - Runoff

Need for Satellite Based Observations

- Insufficient and declining number of gauges, especially outside N. America and Europe
- Need global runoff and ΔStorage with GPM and other hydrologic quantities to
    1. close global hydrologic budget and validate models, and
    2. water resources planning (municipal and agricultural allocation, power, navigation, recreation, etc.)
    3. Relevance to other disciplines (e.g. biogeochemistry)

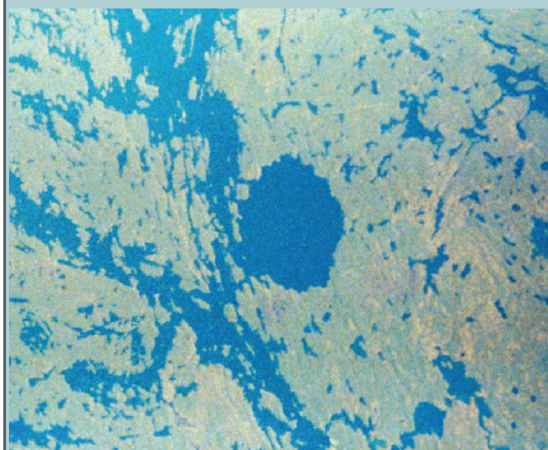
Sampling requirements not well established due to complex distribution of surface water



Yemen from NASA Shuttle

Western Plains, US

Complex distribution of stored surface water

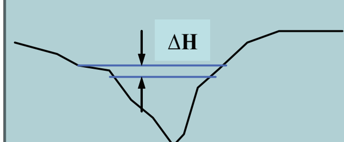


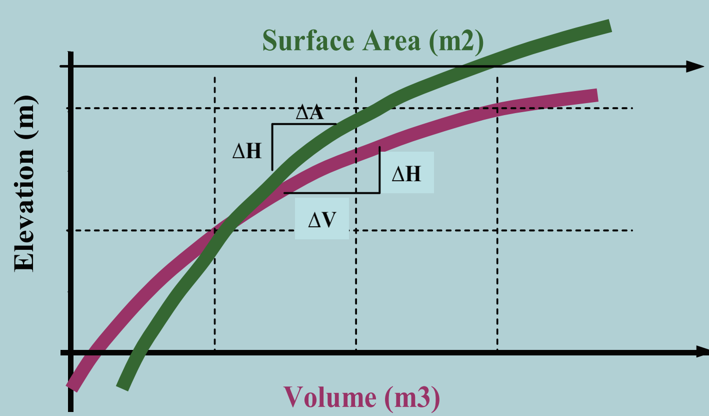
Deep Bay, Saskatchewan

Frasier Nat'l Park, CO

1. Lake, Reservoir, Wetland Storage

Empirical height–volume-area relation*





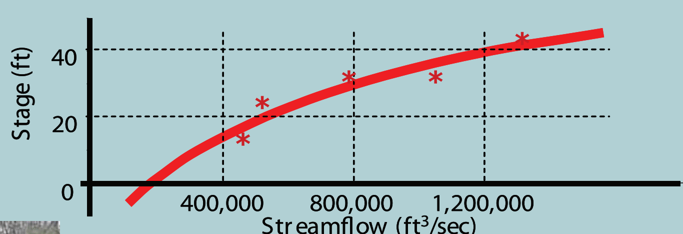
*Required vertical accuracy of water surface ~ 5 – 10 cm

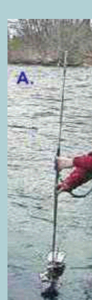
2. River Discharge

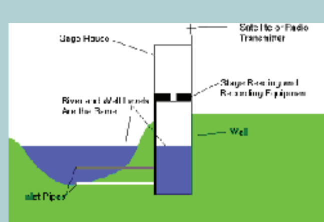
1. Water resources planning: repeat observations at days to weeks
2. Flood events: more frequent repeat observations

Current River Discharge Measurement Approach

"Stage – Discharge" Rating Curve
e.g. 2003 Mississippi River at Vicksburg, MS
(source, USGS)







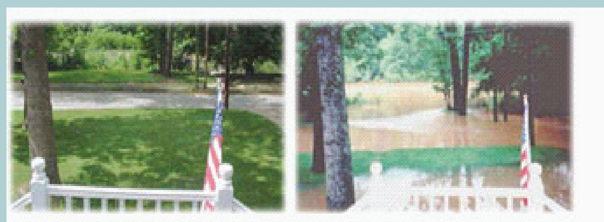
Manning's Equation

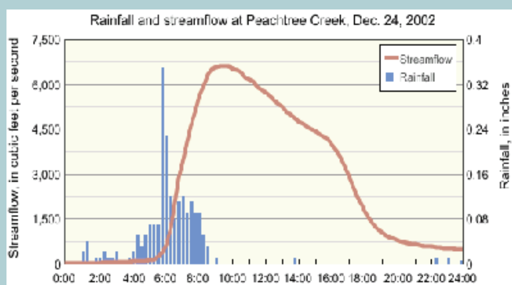
$$Q = \frac{1.49}{n} AR^{1/2} S_f^{\ 1/2}$$

where
A = stream cross-section
R = hydraulic radius
Q = flow rate
h = depth
S_f = friction slope ~ (bed slope – river surface slope)

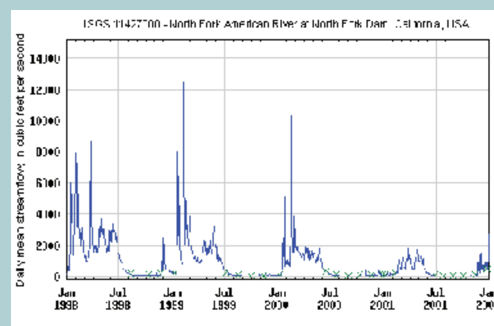
Jasinski/614.3

Passage of a Flood Wave





Influence of rainfall



Influence of snowmelt

Sampling Criteria for Water Resources and Water Budget Analysis

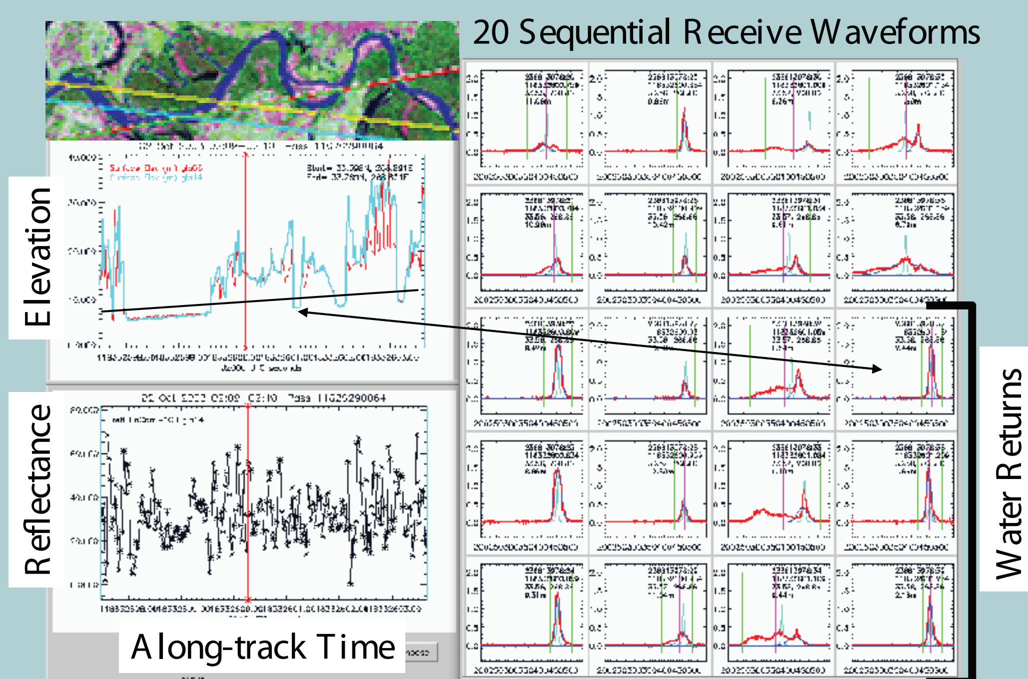
“What is the sampling frequency necessary to estimate daily, seasonal, or annual flow within a specified accuracy?”

Sampling Frequency for Flood Analysis

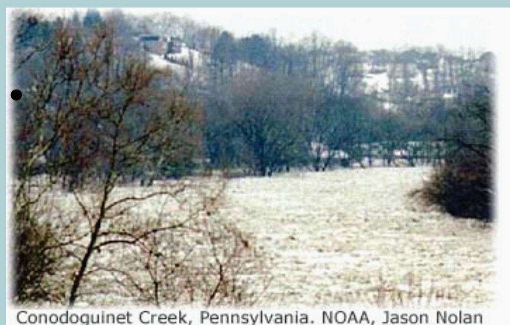
“What is the sensitivity of discharge to river stage and slope for various hydrologic regimes?”

“What are the theoretical and practical limitations for estimating global stream discharge in remote regions with little or no ancillary data?”

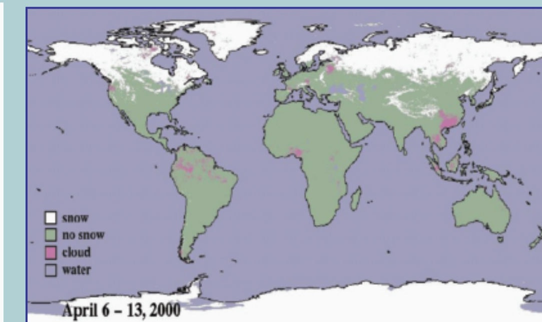
Along Channel Profile & Meander Crossings



3. Improved Snow Depth and Snowmelt Modeling of Using Satellite Products



Conodoguinet Creek, Pennsylvania. NOAA, Jason Nolan
1996



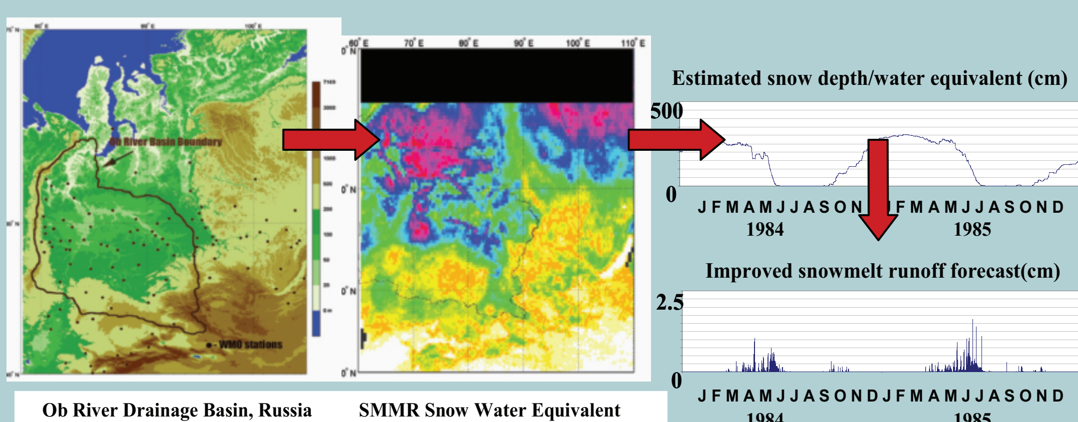
MODIS global snow cover map

Objective: Improve forecasting of snowpack and spring snowmelt runoff in high-latitude and high-elevation river basins

Justification:
- Approx. 75% of high latitude and alpine runoff comes from snowmelt
- Current snowpack estimates from SMMR, SSMI, AMSR-E possess low resolution and large errors.
- Improved snow will benefit navigation and water resources planning
- Biosphere sensitive to 0 degC.

Results of Ob River SMMR/hydrologic modeling study

1. Largest errors in snow depth observations (50-200%) occur in mountainous terrain
   large size of pixel (0.25 deg)
   complex topography
2. Great need for repeat Lidar over the same points (30-50m horizontal resolution)
3. Vertical accuracies ~ 10 cm
4. 100% coverage desirable but not necessary



Ob River Drainage Basin, Russia
2.4×10^6 km^2

SMMR Snow Water Equivalent
E.g. March 1-10, 1984

Summary – Potential Hydrologic Applications Using DELI Concept

Hydrologic Application	Advantages	Limitations
Lake and Reservoir Storage	No serious constraints for lakes and reservoirs	Need height-capacity relation, difficult in wetlands
Water Budget and Water Resources	Even low sampling rate (weekly) provides high accuracy in large basins Critical to water resources planners	Need Stage-Discharge Relations. Need to identify global distribution of catchments
River Discharge	Theoretical approach is clear Addressing flood issues may not be critical	Number of sites may be limited
Snow Depth	Critical for a variety of reasons. Clear advantages over radar technique in mountainous regions	Need consistent repeat paths

Surface Hydrology

Summary of Measurement Requirements

Altimetric laser altimeter

w/Repeat capability critical

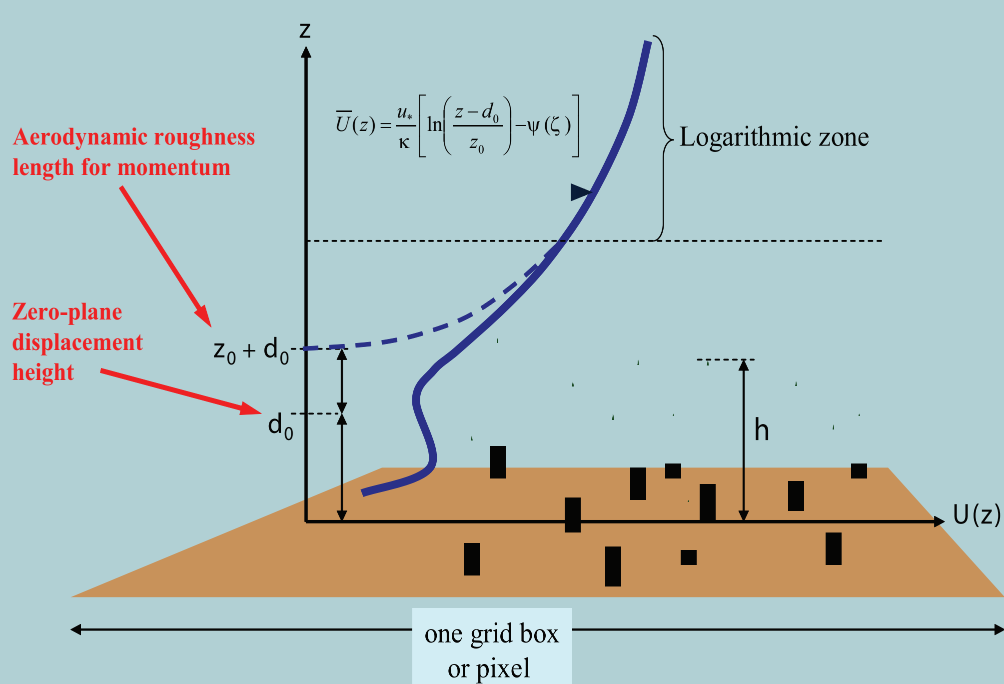
Observation Requirement	Horizontal resolution	Vertical resolution	Frequency
Lakes and Reservoirs	30 m	5 cm	Weekly to monthly
Rivers	10 m (TBD)	5 cm	Weekly, except for severe floods (TBD)
Snow	30-50 m	10 cm	Weekly

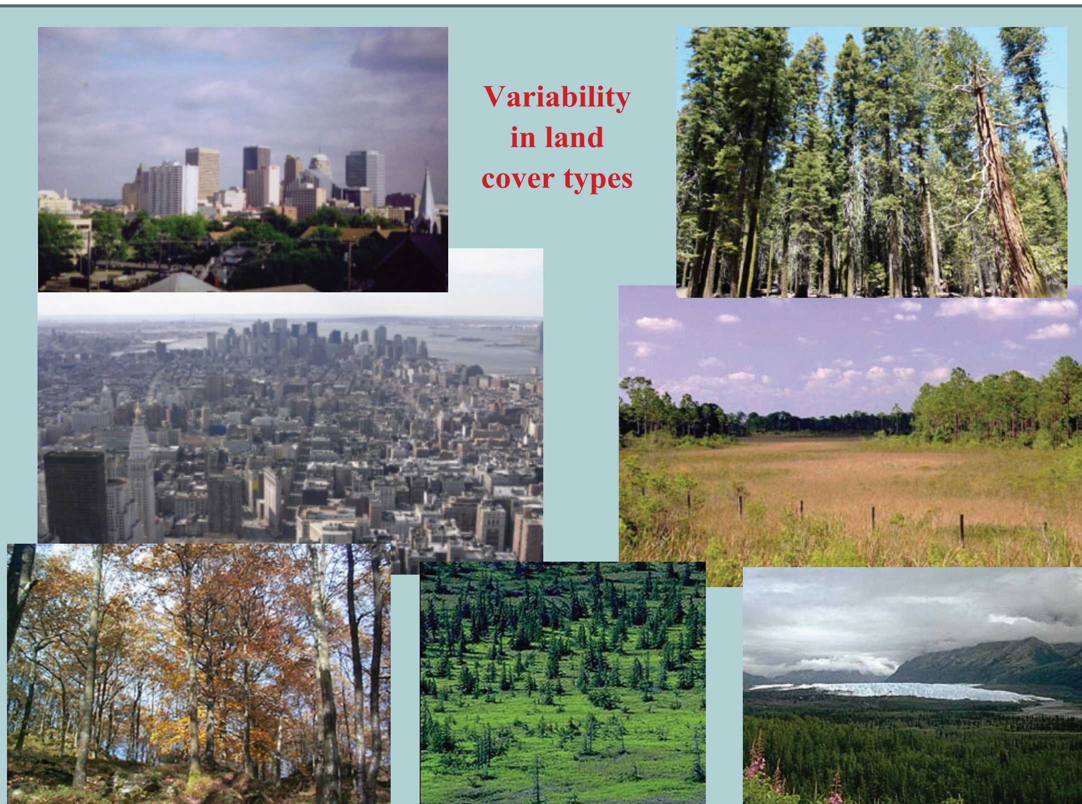
Global Aerodynamic Roughness for Climate Science and Regional/Urban Atmospheric Transport Science

Michael F. Jasinski
Hydrological Sciences Branch
NASA Goddard Space Flight Center

NASA/ESTO Lidar Community Forum
January 10, 2006

Vertical wind profile near land surface





Importance of Aerodynamic Roughness

1. Meteorology and Climate
   - Impacts on wind speed, shear stress, and growth of the boundary layer.
   - Affects energy and water exchanges bt/atmosphere and land surface (2nd order).
   - Required in almost all atmospheric and terrestrial hydrology models used today.

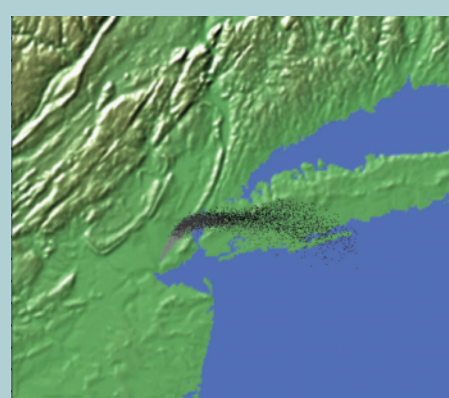
Importance of Aerodynamic Roughness

1. Meteorology and Climate
   - Impacts on wind speed, shear stress, and growth of the boundary layer.
   - Affects energy and water exchanges bt/atmosphere and land surface (2nd order).
   - Required in almost all atmospheric and terrestrial hydrology models used today.

2. Atmospheric Transport and Dispersion
   - Roughness is the principal surface parameter affecting plume dispersion
   - high roughness ? greater plume dispersion into the atmosphere
   - low roughness ? quicker dispersion over greater region

NARAC Prediction Compared with Satellite Photo for Staten Island Event of Feb. 21, 2003

Satellite image showing actual smoke plume



NARAC Plume Prediction

National Atmospheric Release Advisory Center,
Lawrence Livermore National Laboratory

Empirical Estimates of z_0 and d_0

1. **z_0 ~ vegetation height (h)**
   e.g. $z_0 = 0.13$ h; $d_0 = 0.7$h Brutsaert (1984)

2. **Look-up tables**
   e.g. 3D circulation models

MM5 z_0 Grell et al. (1994)	Summer (cm)	Winter (cm)
Urban land	50	50
Agriculture	15	5
Range-grassland	12	10
Deciduous forest	50	50
Coniferous forest	50	50
Mixed forest and wetland	40	40
Water	0.0001	0.0001
Marsh or wet land	20	20
Desert	10	10
Tundra	10	10
Permanent ice	5	5
Tropical or subtropical forest	50	50
Savannah	15	15

Physical Models of Momentum Roughness

E.g. Raupach's Roughness Sublayer Formulation

Roughness length for momentum:

$$\frac{z_0}{h} = \left(1 - \frac{d_0}{h}\right) \exp\left(-\kappa \frac{U_h}{u_*} + \psi_h\right)$$

$$\frac{u_*}{U_h} = \gamma^{-1} = \min\left[\left(C_S + \frac{\Lambda C_R}{2}\right)^{1/2} \exp\left(\frac{-c\Lambda\gamma}{4}\right), \left(\frac{u_*}{U_h}\right)_{\max}\right]$$

Displacement height:

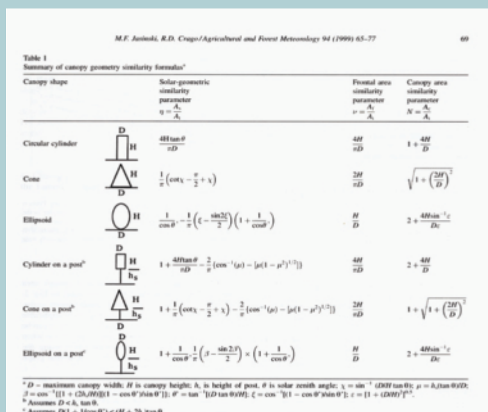
$$\frac{d_0}{h} = \left(\frac{\beta\Lambda}{2 + \beta\Lambda}\right)\left[1 - \alpha\gamma^{-1}\Lambda^{-1/2}\right]$$

where, Λ = **canopy area index variable = total canopy area/pixel area**
h = canopy height
C_S = surface drag coefficient,
C_R = bulk drag coefficient for canopy elements, $\beta = C_R/C_S$
c = empirical wake spreading coefficient,
α = empirical fitting coefficient,
ψ_h = **velocity profile adjustment based on canopy density profile**,
u_*/U_h = ratio of friction velocity to top of canopy wind speed.
$(u_*/U_h)_{max}$ = maximum ratio when the flow begins to skim over the canopy.

Potential lidar contribution

Canopy Area Index, Λ
Two categories

1. Urban Areas ~O(10 km²)
   Buildings ~ solid elements
   $\Lambda = - N \ln(1 - m)/2$



M.F. Jasinski, R.D. Crago / Agricultural and Forest Meteorology 94 (1999) 65–77 — 69

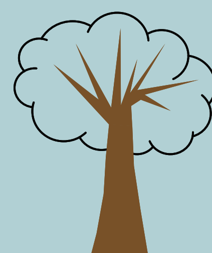
Table 1
Summary of canopy geometry similarity formulas[a]

Canopy shape	Solar-geometric similarity parameter $\eta = \frac{A_s}{A_t}$	Frontal area similarity parameter $\nu = \frac{A_f}{A_t}$	Canopy area similarity parameter $N = \frac{A_c}{A_t}$
Circular cylinder	$\frac{4H\tan\theta}{\pi D}$	$\frac{4H}{\pi D}$	$1 + \frac{4H}{D}$
Cone	$\frac{1}{\pi}\left(\cot\chi - \frac{\pi}{2} + \chi\right)$	$\frac{2H}{\pi D}$	$\sqrt{1 + \left(\frac{2H}{D}\right)^2}$
Ellipsoid	$\frac{1}{\cos\theta'} - \frac{1}{\pi}\left(\xi - \frac{\sin 2\xi}{2}\right)\left(1 + \frac{1}{\cos\theta'}\right)$	$\frac{H}{D}$	$2 + \frac{4H\sin^{-1}\varepsilon}{D\varepsilon}$
Cylinder on a post[b]	$1 + \frac{4H\tan\theta}{\pi D} - \frac{2}{\pi}[\cos^{-1}(\mu) - [\mu(1-\mu^2)^{1/2}]]$	$\frac{4H}{\pi D}$	$2 + \frac{4H}{D}$
Cone on a post[b]	$1 + \frac{1}{\pi}\left(\cot\chi - \frac{\pi}{2} + \chi\right) - \frac{2}{\pi}[\cos^{-1}(\mu) - [\mu(1-\mu^2)^{1/2}]]$	$\frac{2H}{\pi D}$	$1 + \sqrt{1 + \left(\frac{2H}{D}\right)^2}$
Ellipsoid on a post[c]	$1 + \frac{1}{\cos\theta'} \cdot \frac{1}{\pi}\left(\beta - \frac{\sin 2\beta}{2}\right) \times \left(1 + \frac{1}{\cos\theta'}\right)$	$\frac{H}{D}$	$2 + \frac{4H\sin^{-1}\varepsilon}{D\varepsilon}$

[a] D – maximum canopy width; H is canopy height; h_s is height of post, θ is solar zenith angle; $\chi = \sin^{-1}(D/H\tan\theta)$; $\mu = h_s(\tan\theta)/D$; $\beta = \cos^{-1}[[1 + (2h_s/H)][(1 - \cos\theta')/\sin\theta']]$; $\theta' = \tan^{-1}[(D\tan\theta)/H]$; $\xi = \cos^{-1}[(1 - \cos\theta')/\sin\theta']$; $\varepsilon = [1 + (D/H)^2]^{0.5}$.
[b] Assumes $D < h_s \tan\theta$.
[c] Assumes $D(1 + 1/\cos\theta') < (H + 2h_s)\tan\theta$.

(Jasinski and Crago, 1999)

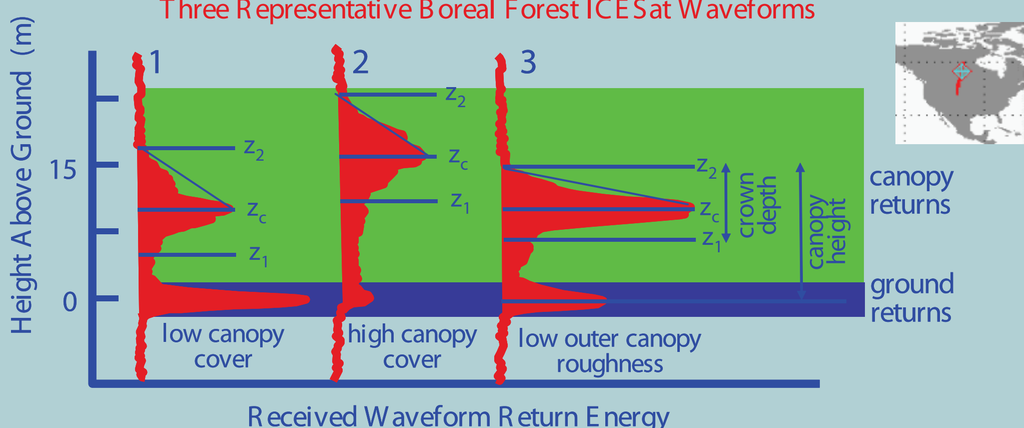
2. Regional Vegetation ~O(10²–10⁶ km²)
   Plant canopies ~ diffuse medium
   $\Lambda = LAI_g + LAI_d + LAI_s$.



(e.g. Raupach, BLM 1994; Zeng et al., J. Clim 2002)

Canopy Structure from LIDAR Waveform?

Three Representative Boreal Forest ICESat Waveforms



Canopy Height = Distance from Start of Signal to Last Peak, z_2
Crown Depth = Width of Upper Part of Canopy Return, $z_2 - z_1$
Roughness of Outer Canopy = Leading Edge Slope from z_2 to z_c

$$\text{Canopy Cover} \sim \frac{\text{Ground Return Energy}}{\text{Total Return Energy}}$$

Assumptions:
Ground return is detected
Ground relief across footprint is small fraction of canopy height
Canopy/ground 1064 nm reflectance ratio is constant

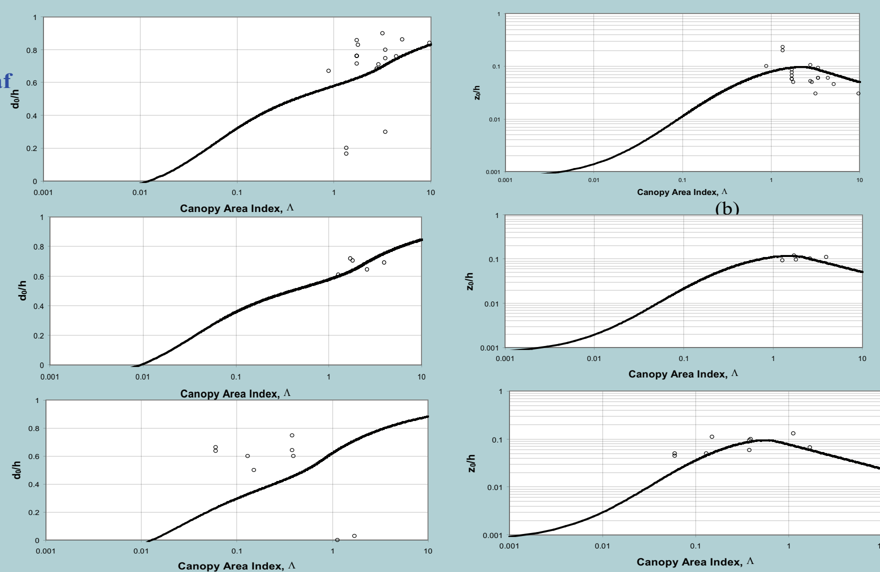
Roughness Graphs from Physical Model

IGBP Cover Type — d_0/h vs. Λ — z_0/h vs. Λ

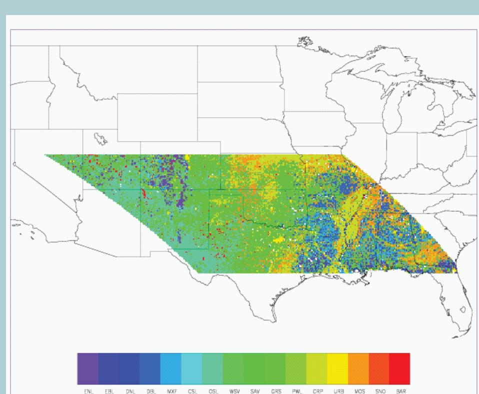
Evergreen Needleleaf Forests

Grassland

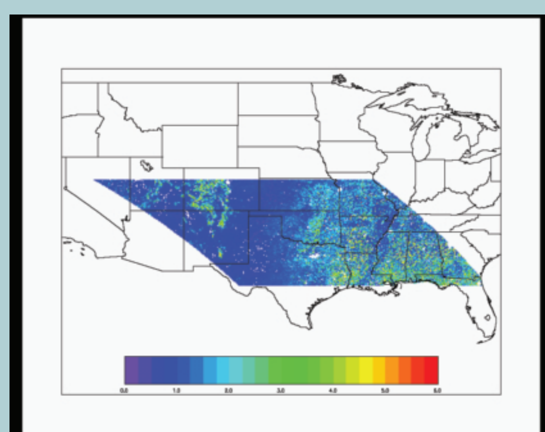
Open Shrubland



Regional scale application: U.S. Southern Great Plains



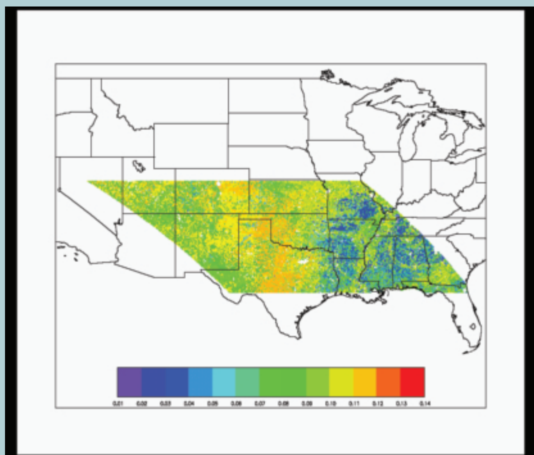
MODIS 2001 Land Cover Type of the U.S. Southern Great Plains



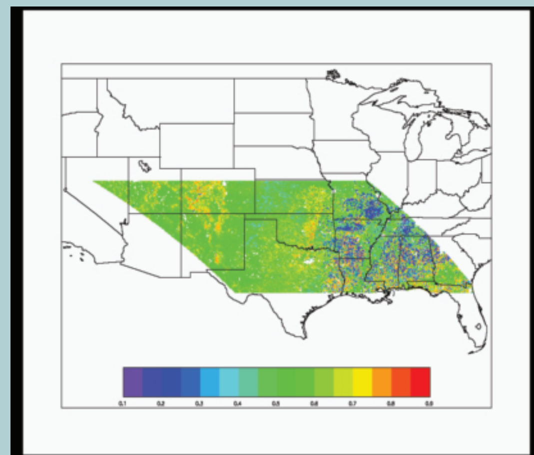
Map of Canopy Area Index, Λ, derived from MODIS data June 10, 2002.

where ENL = Evergreen Needleleaf Forest, EBL=Evergreen Broadleaf Forest, DNL = Deciduous Needleleaf Forest, DBL=Deciduous Broadleaf Forest, MXF=Mixed Forest, CSL=Closed Shrubland, OSL=Open Shrubland, WSV=Woody Savanna, SAV=Savanna, GRS=Grassland, PWL=Permanent Wetland, CRP=Cropland, URB=Urban and Built-up, MOS=Cropland Mosaic, SNO=Snow and ICE, and BAR=Barren

Normalized roughness maps derived from MODIS data products June 10, 2002.



d_0/h



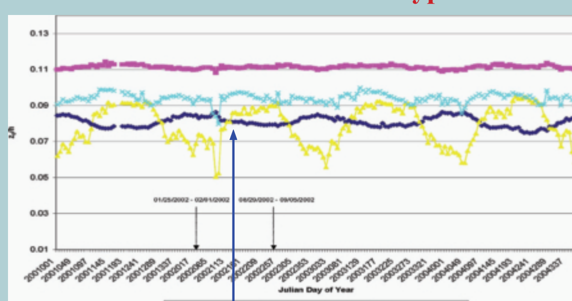
z_0/h

Jasinski et al., AFM, 2005

Time Series Normalized Roughness Length (2000-2004)

Mean for Each IGBP Land Cover Type in the Domain

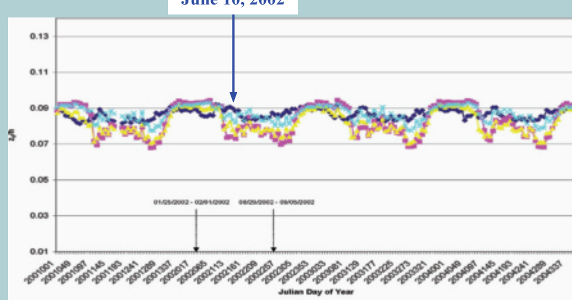
z_0/h



Forested IGBP cover types

June 10, 2002

z_0/h



Non- Forested IGBP cover types

Borak et al., AFM, 2006

Plan View of Central Oklahoma City Buildings

Aerial Photo

1.9 km

Derived from Lidar (2003)

Aerodynamic Roughness

Summary of Measurement Requirements

Altimetric laser altimeter w/seasonal repeat capability

Observation Requirement	Horizontal resolution	Vertical resolution	Frequency
Canopy top	30 m	20 cm	Seasonal or after significant change
Canopy distribution	30 m	20 cm	Seasonal or after significant change
Building top	5-10 m	20 cm	Once or after significant change
Ground surface topography	30 m	20 cm	Once

An Upward-Looking, Below-Canopy Lidar For Validation of Spaceborne Lidar Products

Alan Strahler, Boston University,
for
David L. B. Jupp
CSIRO Earth Observation Centre
Canberra, ACT, Australia

CSIRO Earth Observation Centre 1

CSIRO Canopy Lidar Initiative – Research Team

David Jupp	Earth Observation Centre
Darius Culvenor	Forests & Forest Products
Jenny Lovell	Earth Observation Centre
Glenn Newnham	Forests & Forest Products

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Ground Based Lidar

- ECHIDNA™ is ground based lidar technology designed by CSIRO specifically for forest and vegetation assessment
- CSIRO canopy Lidar Initiative (CLI) has patented ECHIDNA™ and aims to make it operational and commercial in Forestry and Environmental applications
- The ECHIDNA™ and the current prototype – the ECHIDNA™ Validation Instrument (or "EVI") has key differences to scanning rangefinders
  - Digitizes the full 'waveform'
  - Has variable beam divergence
  - Uses full hemispherical scanning
  - Linear response and calibration

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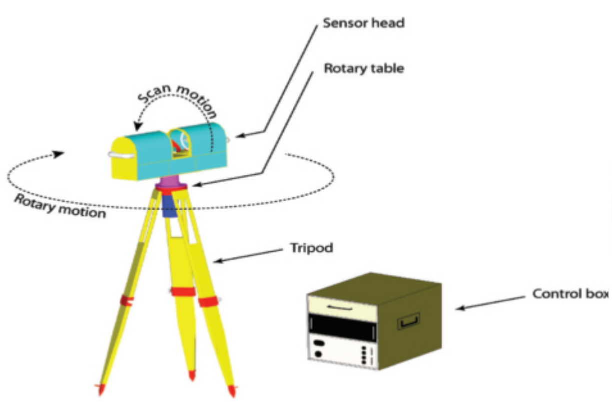
Ground Based Lidar (ECHIDNA™)



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A "Real" Echidna – in the forest

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EVI (The ECHIDNA™ Validation Instrument)

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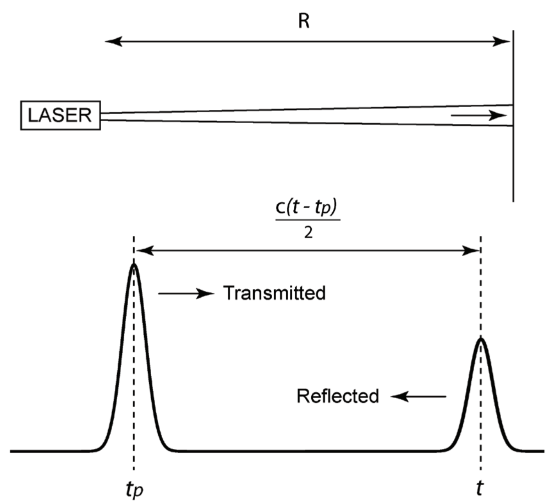
Principles of Lidar Ranging



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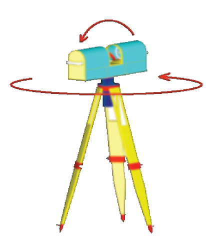
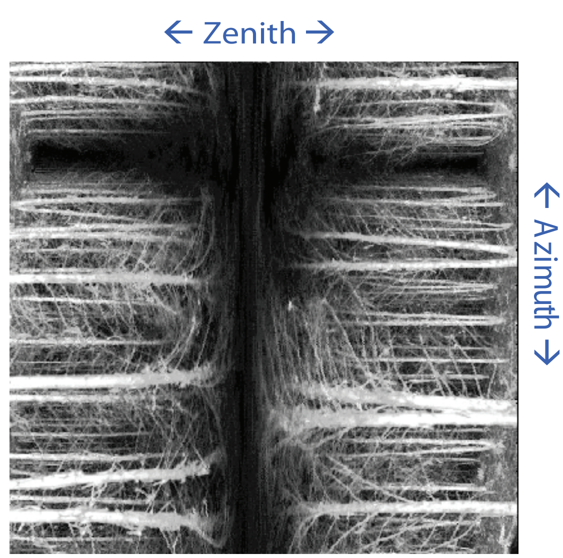
EVI data geometry

EVI provides returned Lidar power from all directions of the hemisphere as a function of time (range) following a laser pulse output with peak power at time tp.





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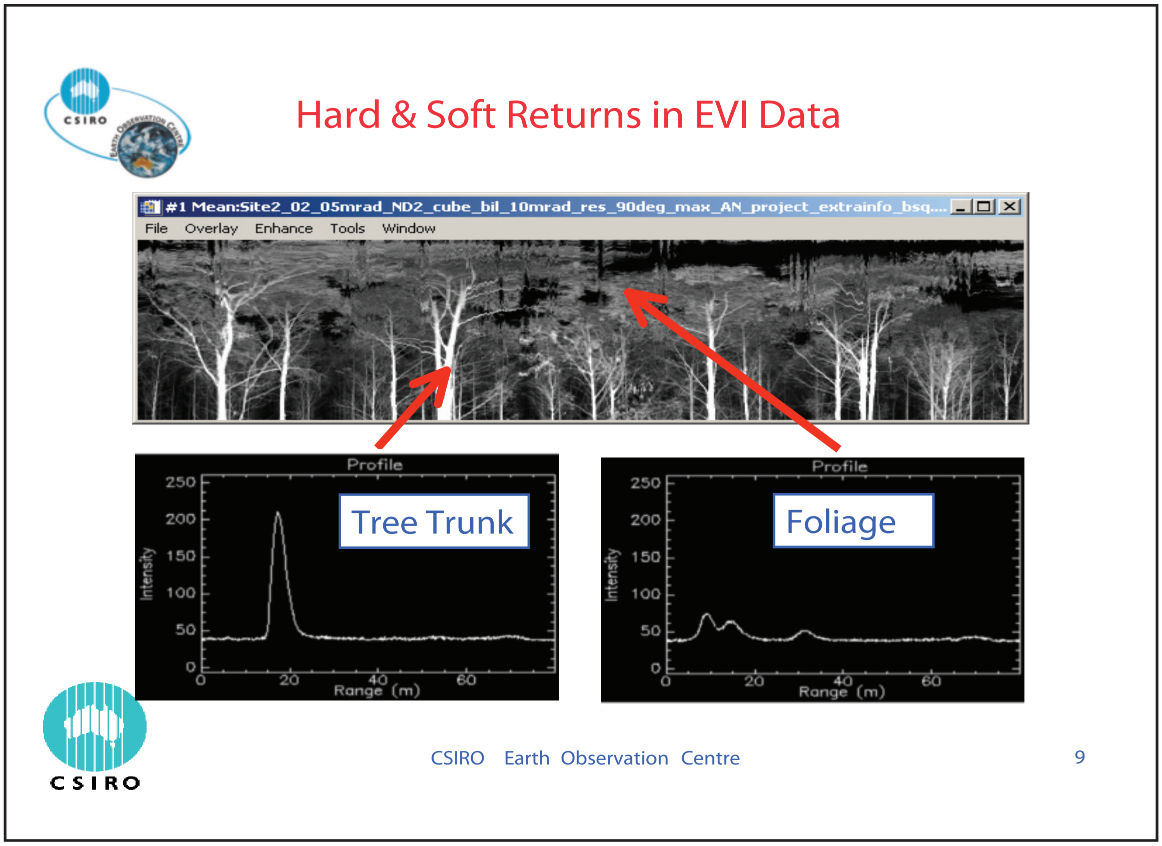
Hard & Soft Returns in EVI Data
#1 Mean:Site2_02_05mrad_ND2_cube_bil_10mrad_res_90deg_max_AN_project_extrainfo_bsq....
File Overlay Enhance Tools Window
Profile
Tree Trunk
Foliage
Intensity
Range (m)
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9
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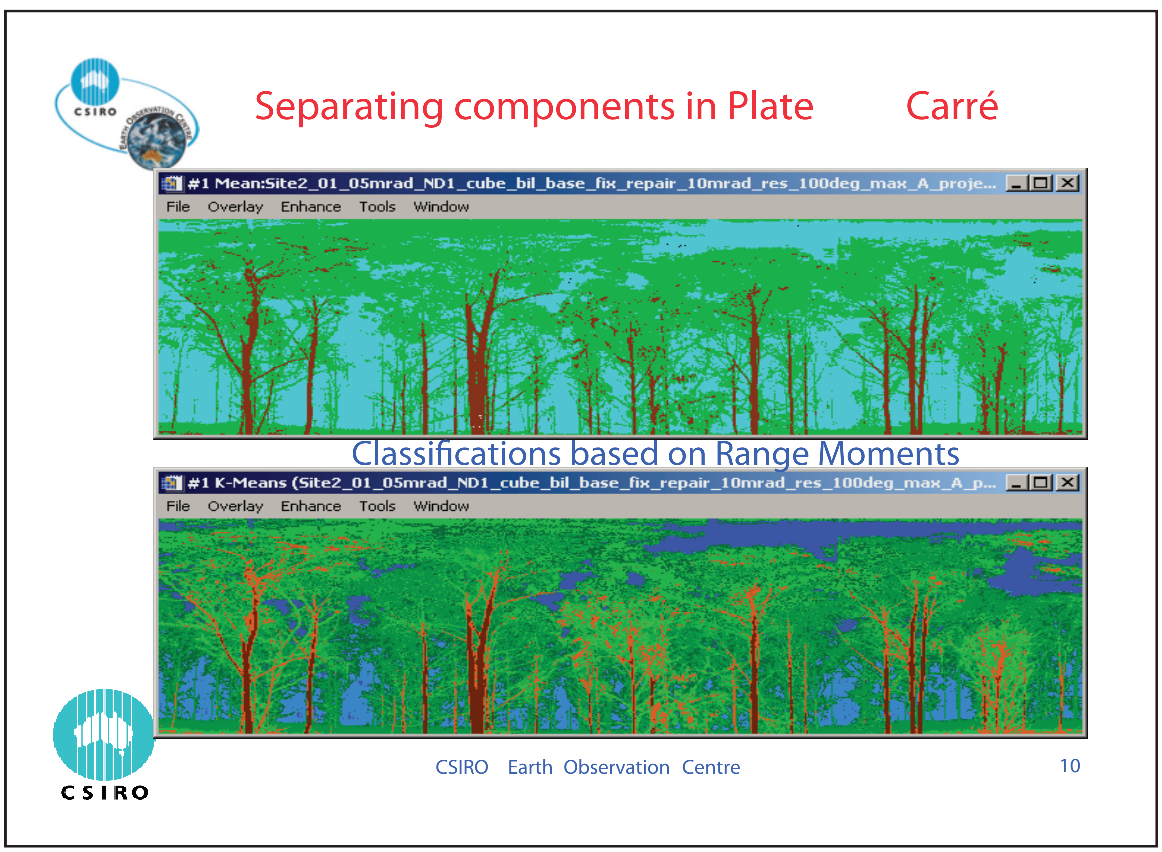
Separating components in Plate Carré
#1 Mean:Site2_01_05mrad_ND1_cube_bil_base_fix_repair_10mrad_res_100deg_max_A_proje...
File Overlay Enhance Tools Window
Classifications based on Range Moments
#1 K-Means (Site2_01_05mrad_ND1_cube_bil_base_fix_repair_10mrad_res_100deg_max_A_p...
File Overlay Enhance Tools Window
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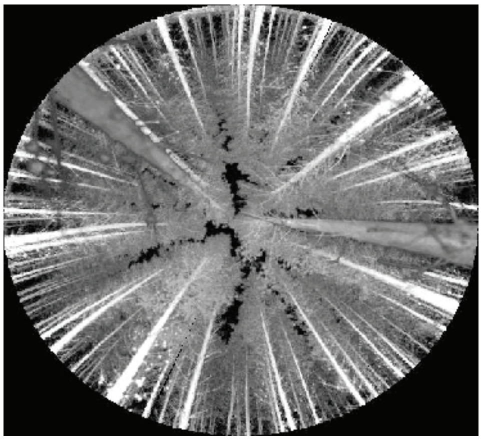
ECHIDNA ™ Data Projections



Hemispherical

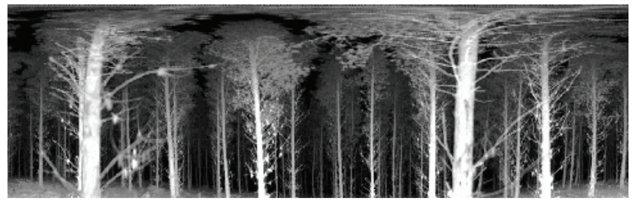
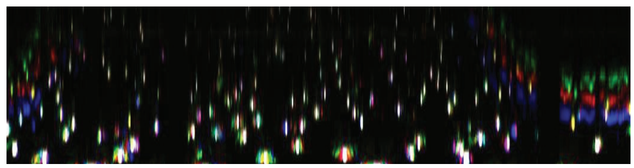


Plate Carré (simple cylindrical)



Horizontal & Radial Slices

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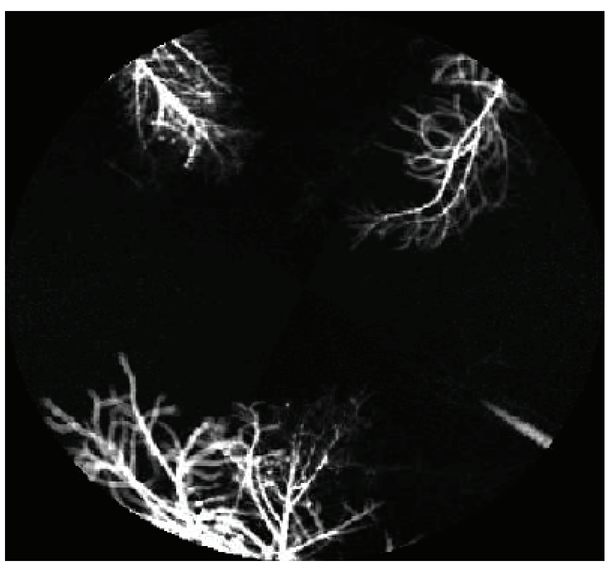
MPeg of Hemispherical Scan



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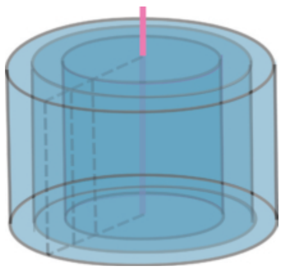
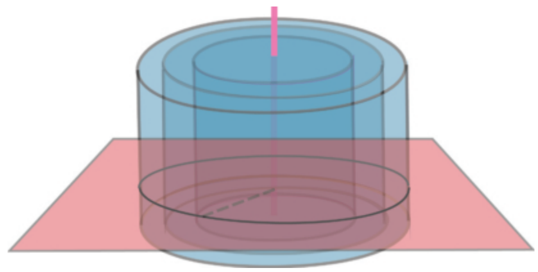
Cylindrical projection shows layers of uniform horizontal distance from the instrument



Cut vertical cylinders and unwrap: constant distance



Slice through cylinders: constant height

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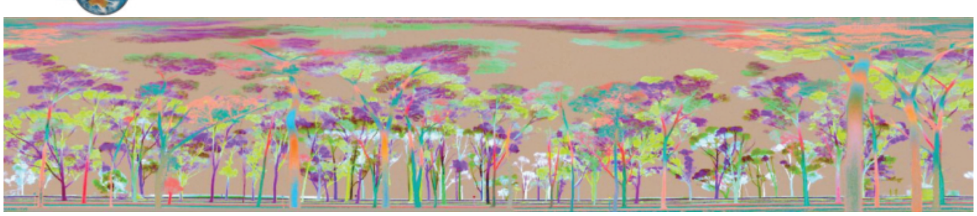
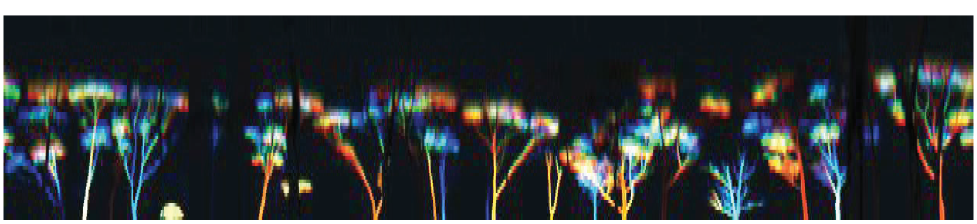
The data can be "sliced" by radial distance providing tree silhouettes



Range Moments 18, 20 & 22 (comparison)



Range Slice 15-17 m away from and above EVI for branching, defect and shape of stems

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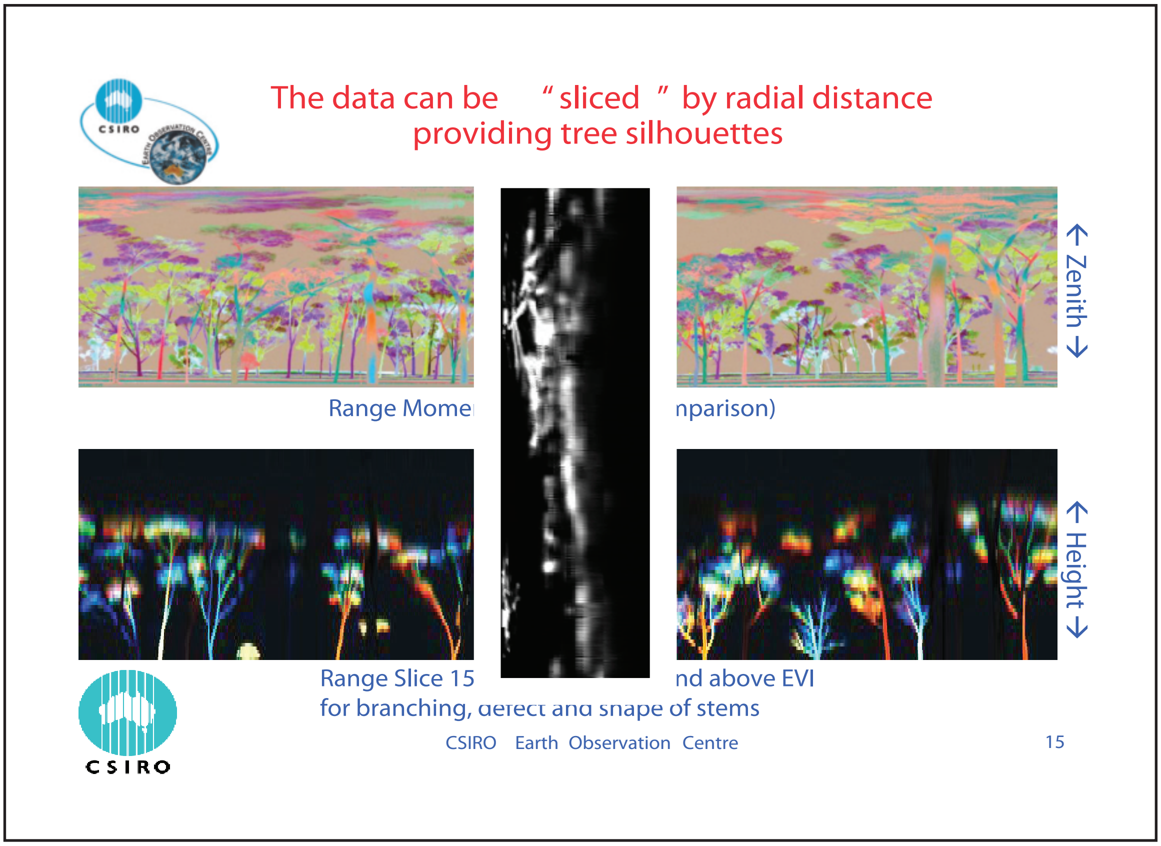
The data can be “sliced” by radial distance
providing tree silhouettes
Zenith
Range Mome
nparison)
Height
Range Slice 15
nd above EVI
for branching, defect and shape of stems
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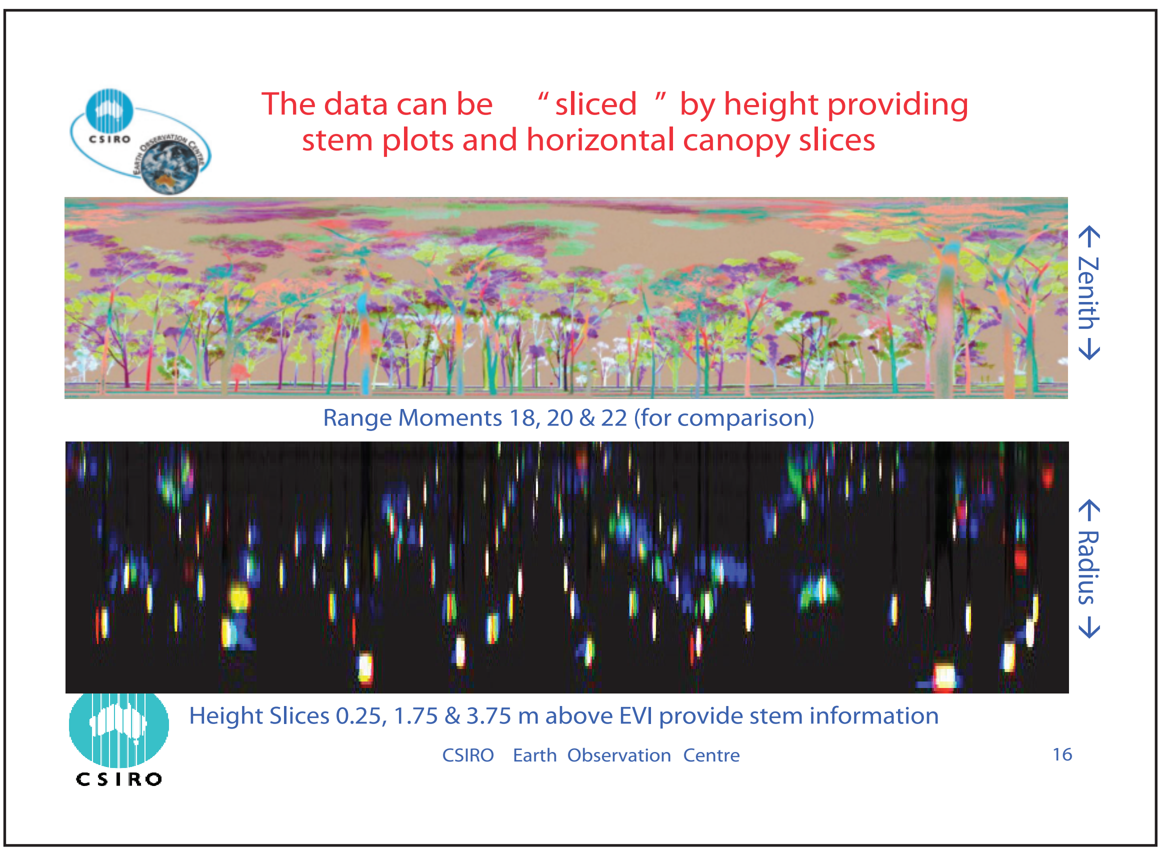
The data can be “sliced” by height providing
stem plots and horizontal canopy slices
Zenith
Range Moments 18, 20 & 22 (for comparison)
Radius
Height Slices 0.25, 1.75 & 3.75 m above EVI provide stem information
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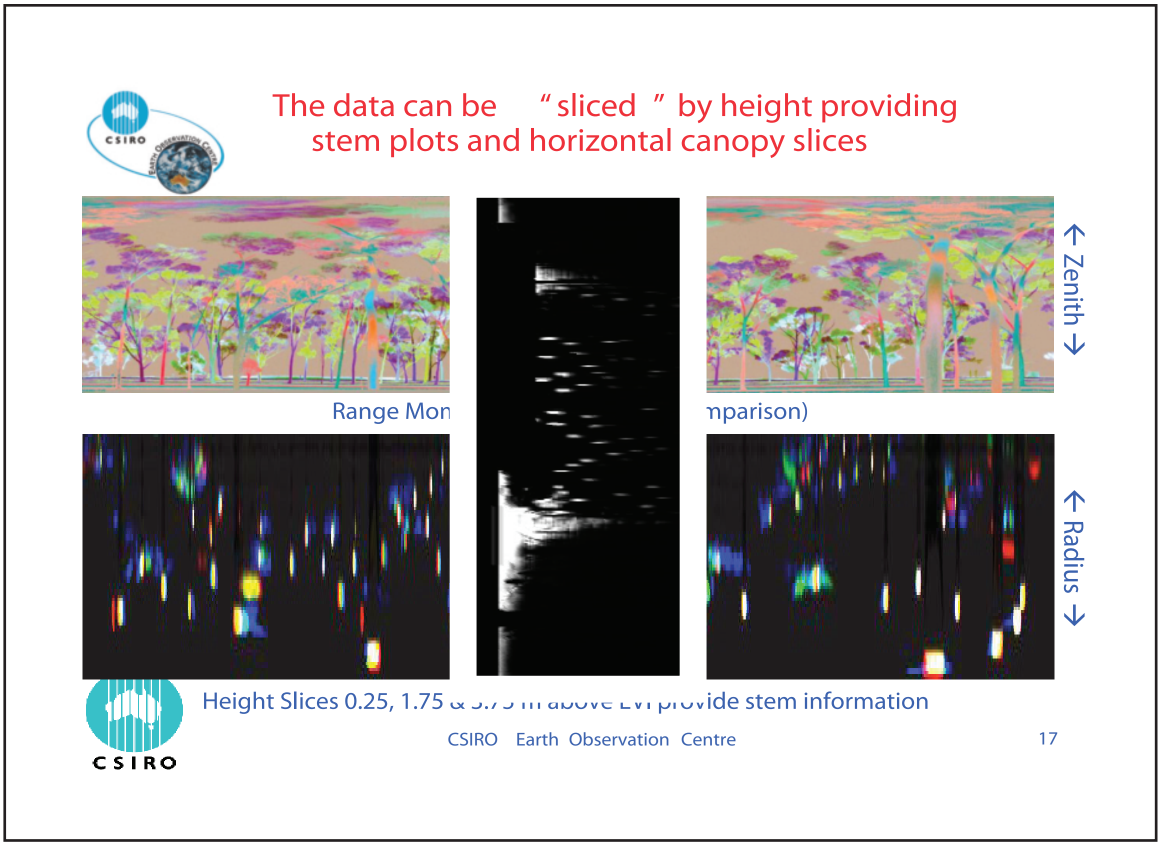
The data can be "sliced" by height providing stem plots and horizontal canopy slices
Range Mon
nparison)
Zenith
Radius
Height Slices 0.25, 1.75
vide stem information
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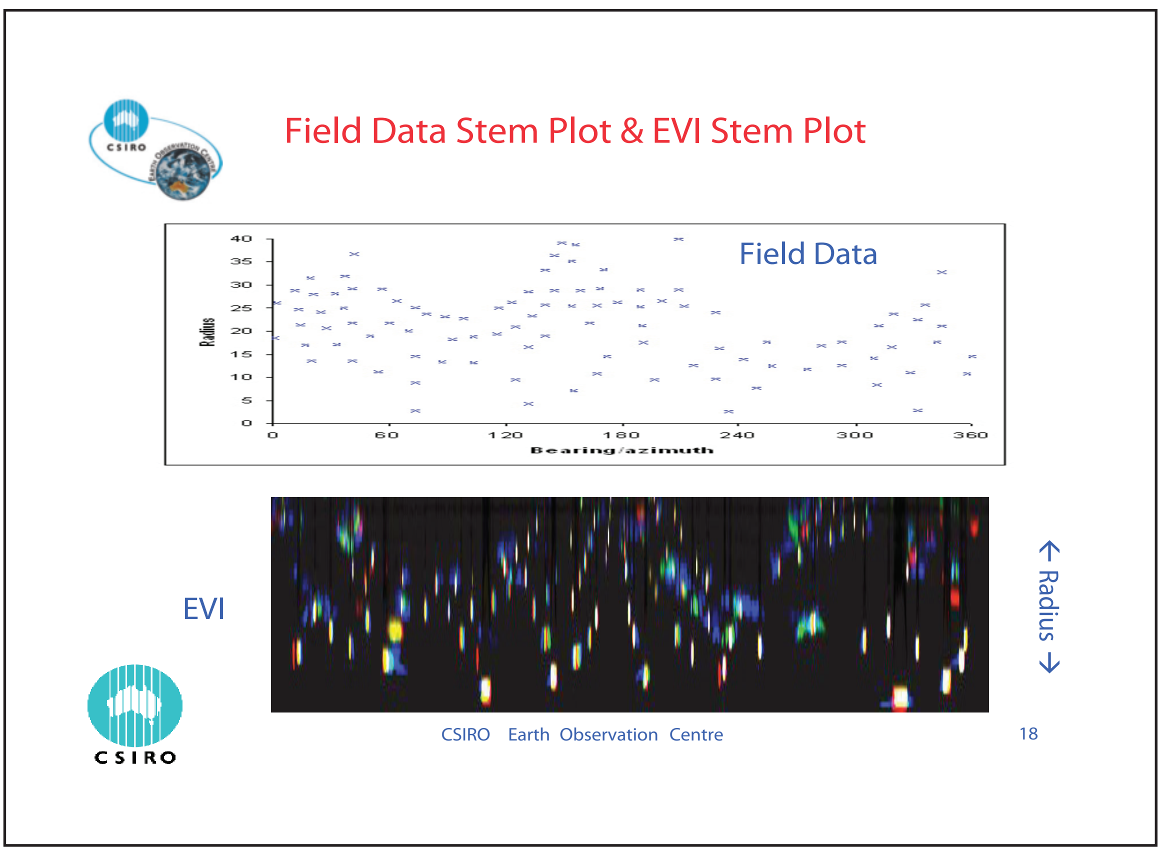
Field Data Stem Plot & EVI Stem Plot
Field Data
Radius
Bearing/azimuth
0 60 120 180 240 300 360
0 5 10 15 20 25 30 35 40
EVI
Radius
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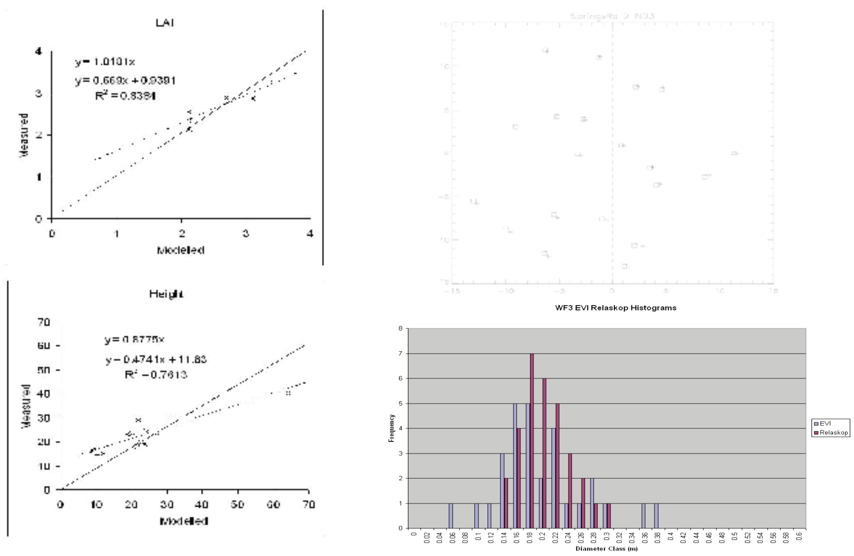
ECHIDNA ™ Products – height, LAI & stem location, size distribution, and density



Applications of ECHIDNA™

- Primary Information
  - Foliage profile & LAI
  - Stocking, Basal Area & DBH distribution
  - Stem maps and identification
  - Tree silhouettes
  - Bole height & branching
- In Progress
  - Stem form factor, taper and sweep (for volume by size class)
  - Separating branches and foliage
  - Allometry from ground to airborne data
- The potentials in forestry & ecology are almost unlimited

Guard Ring Protected InGaAs/InP IR APD Arrays

Feng Yan, Joseph S. Adams, Bing Guan, Meng P. Chiao and Peter K. Shu
Detector Systems Branch, GSFC, Greenbelt Road, Greenbelt, MD 20771
Xiucheng Wu
AdTech Optics, Inc., City of Industry, CA 91748

01/10/2006

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Motivations

- Current space-borne Lidar detectors are dominated by Si APDs, which:
  - Need ~200um absorbers for 60% Q.E. at 1.064 um
  - Large absorbers make arrays of Si APDs impractical for applications in the IR
  - Are completely insensitive to 1.1 um and beyond
- Why InGaAs/InP APDs
  - Feasibility of 32x32 InGaAs/InP photon-counting APD arrays for IR demonstrated
  - Good sensitivity from 800 nm to 1.6 um
  - Material science of InGaAs/InP has excellent industry base

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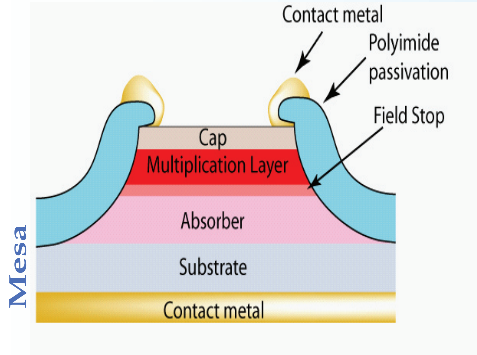
Mesa vs. Guard-Ring



- Mesa structure APDs are the current state-of-the-art

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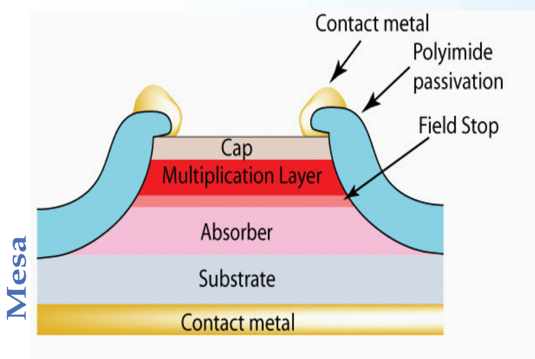
Mesa vs. Guard-Ring



- Mesa structure APDs are the current state-of-the-art
- Potential issues with mesa APDS for space applications:
  - Short lifetime from early breakdown
  - Dark current increases over time

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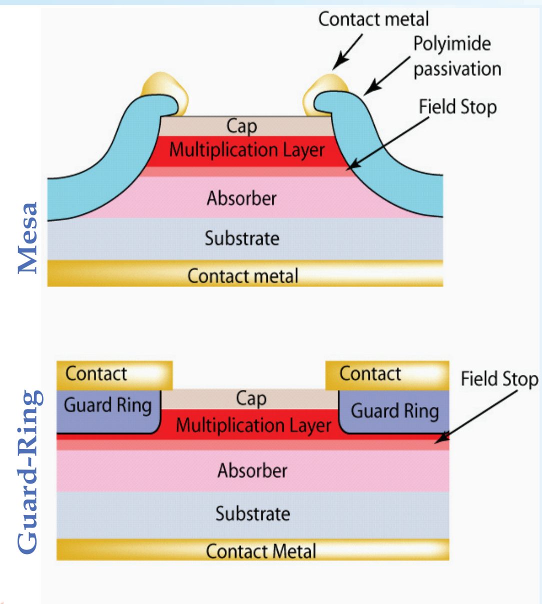
Mesa vs. Guard-Ring



- Mesa structure APDs are the current state-of-the-art
- Potential issues with mesa APDS for space applications:
  - Short lifetime from early breakdown
  - Dark current increases over time
- We are focusing on guard-ring designs to address the above issues

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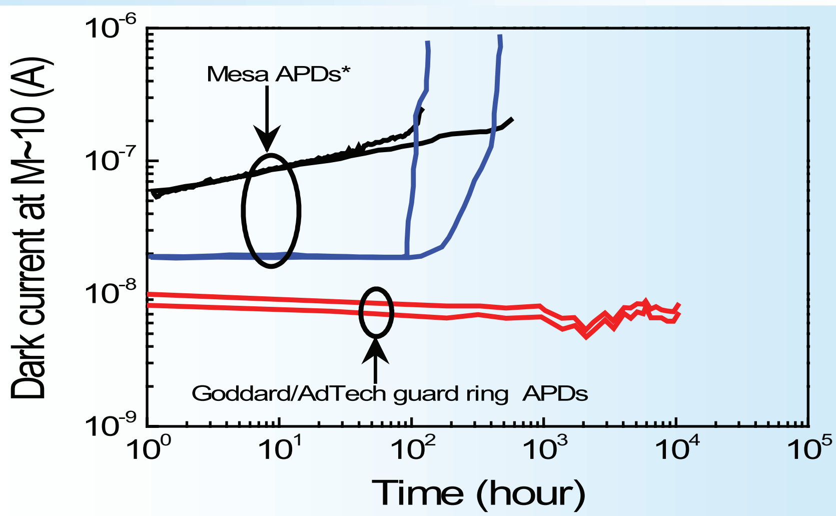
Reliability of Guard-Ring APDS



Aging test condition: 200°C/I=100µA Testing method: measure dark current at M~10 periodically

* S. Tanaka et al on OFC 2003

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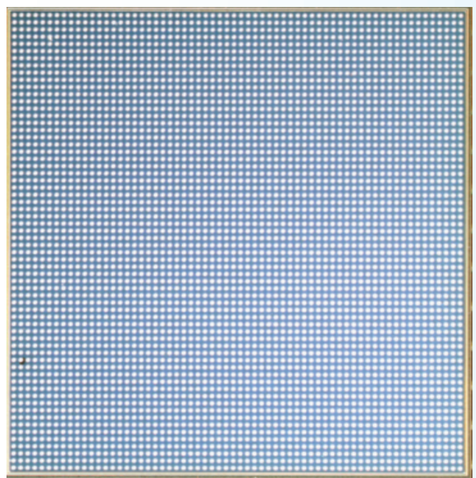
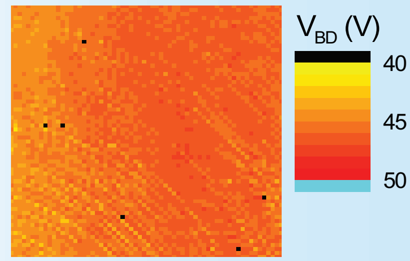
Recently fabricated 64x64 APD array

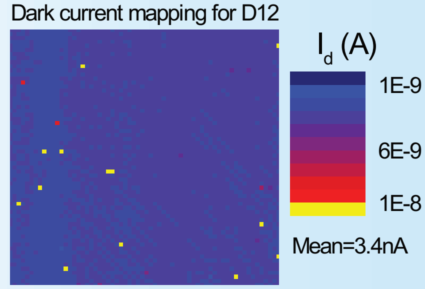
Guard-ring InGaAs/InP APD array



Breakdown voltage mapping for D12



Dark current mapping for D12



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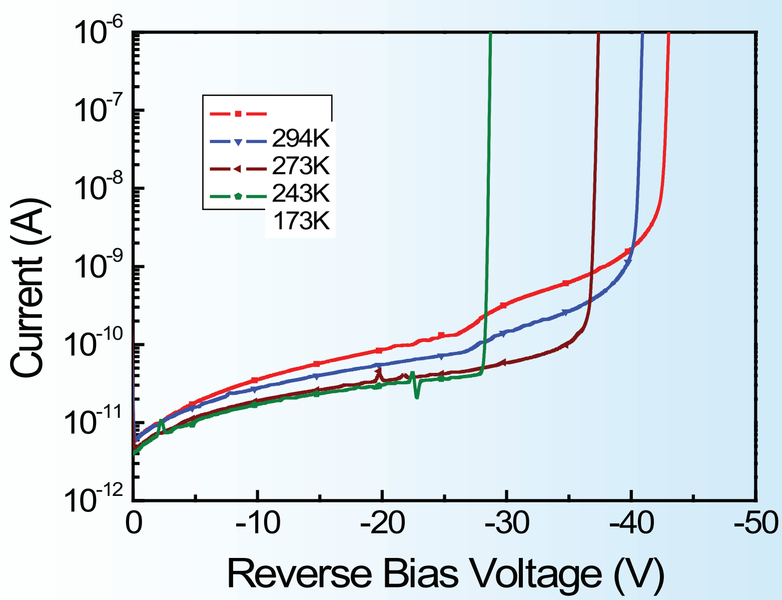
I-V Characteristics vs. Temperature



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Summary

Detector Systems Branch at Goddard is actively developing InGaAs/InP guard ring APD arrays for space applications

- We have fabricated 64x64 InGaAs/InP guard ring APD arrays with our collaborators
- We have measured performance on testing structures, devices show:
  - True avalanche breakdown
  - Dark current comparable to other devices
  - More tests are on going…
- Guard ring design promises outstanding reliability and long-term stability
- Future project goals
  - Develop complete IR APD array modules w/ integrated readout electronics for space applications (e.g for imaging lidars)
  - Build up capability to custom fabricate modules for specified Lidar instrument (e.g. array dimensions, pixel size etc..)

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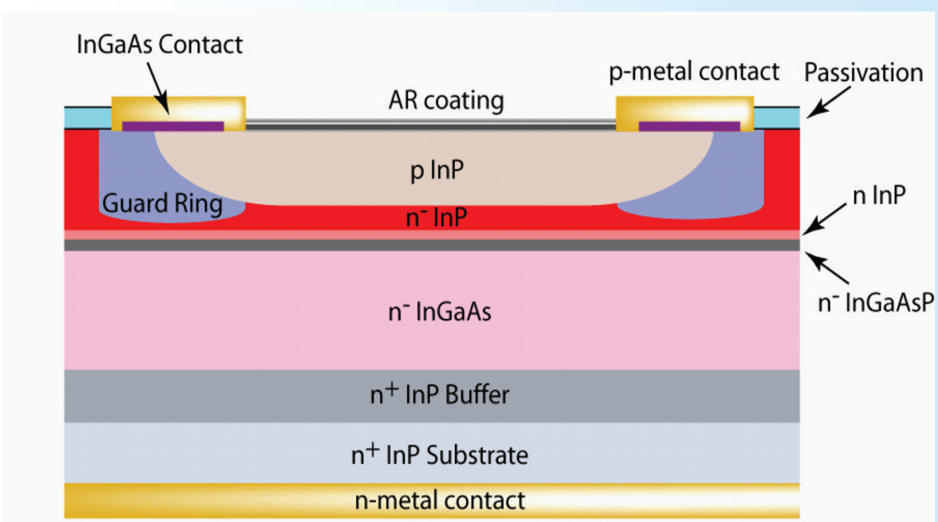
Detailed Mesa Cross Section



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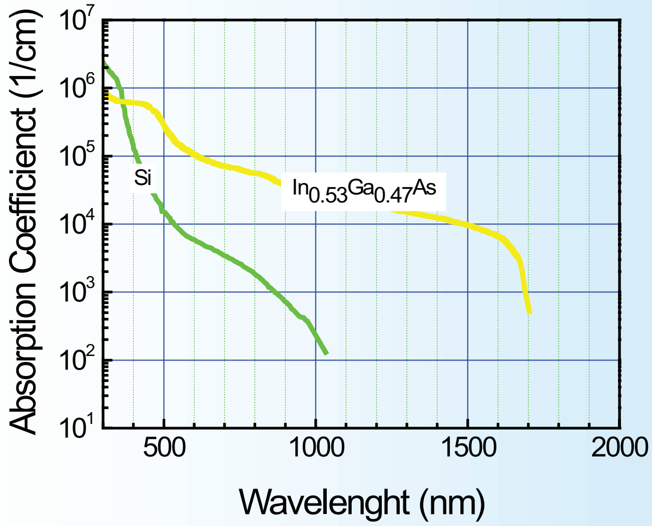
Absorption spectra of Si and InGaAs



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New Cost Models Are Needed for Fiber Laser Based Missions

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Fiber Amplifiers and Lasers are an Enabling Technology for next Generation of NASA Missions

- NASA's Science and Exploration objectives – as well as partners in NOAA, Homeland, etc - require affordable solutions to active remote sensing.
  - > Ex; NRC Decadal Survey, ESTO, ESTEC/ESA
- For a wide variety of objectives, lidars constructed using fiber amplifiers and lasers meet the mission requirements.
  - > Ex; Coyle, Application of Fiber Amplifiers for Space, ESTEC/ESA
- Mass produced fiber amplifiers and lasers, properly procured with up-screening, meet the mission reliability requirements - at considerable cost savings compared to one-off solutions.
  - > Ex; DoD Special Technology Area Review, 2001
- What is missing is an accepted cost model which differentiates between Fiber lasers and Diode Pumped Solid State lasers.

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Fiber Amplifiers-Lasers Offer Significant Advantages in Terms of Managing Program Risk, Cost, and Schedule.

- **Mass produced units offer many significant advantages:**
  - **Established Manufacturing Processes**
    - > Manufacturing and Testing Processes are de-bugged.
    - > Telecordia defines test procedures and pass/fail criteria.
    - > A ‘space’ unit build can and should occur using the same processes and production line as the COTS products.
      - » **Lot test data will be reviewed.**
      - » **Selected component up-screening may be deemed necessary; but that does not impact process.**
  - **Established Reliability**
    - > Large manufacturing volume provides more accurate estimate of MTBF
  - **Healthy Industrial Base**
    - > Multiple US and International suppliers
  - **Significant External Sources of Research and Development Funding**
    - > Multiple agencies funding fiber technologies
    - > Reduces cost to Science Community

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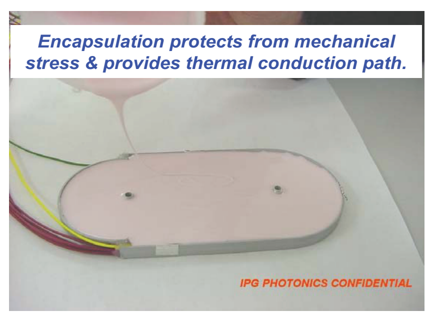
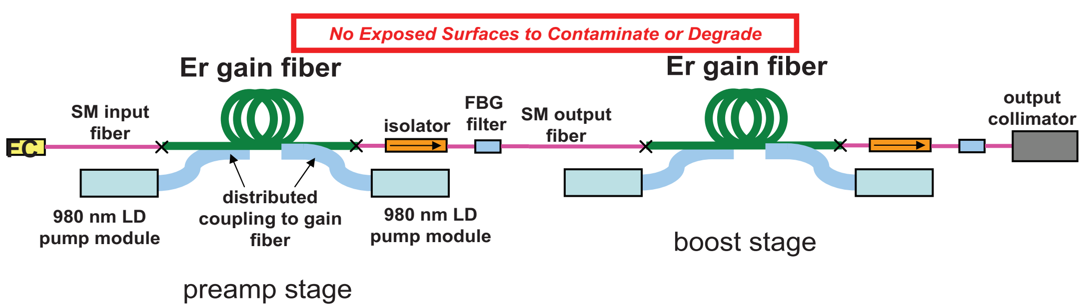
Components are robust, reliable and mass produced. Fiber Amplifiers are robust, reliable and mass produced.

- Two (2) gain stages
  - optical series
- Gain Stage
  - Fiber bragg grating
  - Yt/Eb doped gain fiber
  - Distributed optical pump
  - Pump String
  - Optical isolator
- Pump String
  - Many diodes
  - Optical parallel/electrical series





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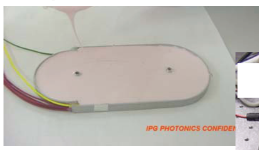
Fiber Amplifiers & Lasers have Lower Complexity and Risk compared to traditional DPSS lasers.

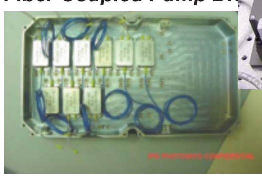
Fiber Amplifier	Classic Pulsed Laser
No cavity	Sensitive cavity in hostile environment
No surfaces	100's of sensitive surfaces
100X lower power density	High fluences destroy optics
No pump diode stress @ CW mode	High diode thermal cycle @ pulse mode

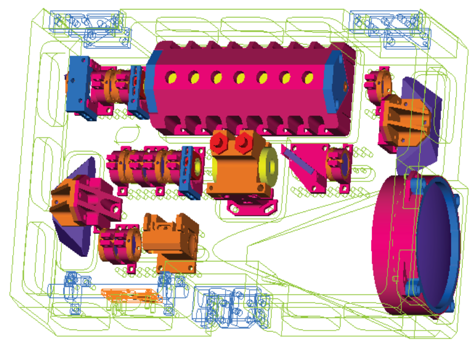
Encapsulated Gain Block



Compact, Rugged.

Fiber Coupled Pump Di





Old photos for example only.

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COTS Fiber Amplifiers are Readily Qualified.

- **In 2001, ITT ran a <u>complete LIDAR transmitter system</u>, including <u>off-the-shelf</u> DFB and Fiber Amplifiers through a limited qualification test program:**
  - Vibration
    - Tested to Acceptance Level 10gRMS
      - 3db below Qualification Level 0.15 g^2/Hz (10Grms)
  - Thermal Cycle
    - Tested to 12 cycles, +20°C to +60°C
      - ±20 around 40C design point
  - Radiation
    - The objective of the test was to determine the ability of the photonic components to withstand 2 years in a LEO orbit.
      - The commercial electronics were shielded.
- **The integrated transmitter system exhibited <u>no change in power or spectral characteristics</u> as a result of the qualification test program.**
- **ITT is preparing to thermal-vacuum test a Fiber Amplifier which leverages the lessons learned from MLCD.**
  - Hermetic (true) Pump Diodes.

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Comparison of Reliability Issues and Impact on Cost

Reliability Issues for Lasers for Space Flight Environment	Relative Weight	MOLA NEAR VCL Calipso	EDFA pulsed	EDFA cw	Impact on Manufacturability, Robustness, and Cost and Schedule (MRCS)
Surface Contamination (1)	High	Yes			Requires extremely high levels of cleanliness throughout lifetime of laser; construction, integration and test, launch, on-orbit. Sealed enclosures to reduce risk
Damage from High Fluences(1)	High	Yes	Yes		Contamination or poor quality coatings will result in degradation; which is a self accelerating process.
Laser Development Required(1)	High	Yes			Custom design significantly increases risk to MRCS
Laser LifeTime(1)	High	Yes	Yes		Pulsed Pump Diode Bars, Q-Switches have poor lifetime.
Pump Diode Availability(1)	Medium	Yes	No	No	Telecom pumps produced in volumes >500,000 year, multiple vendors, long term expanding market.
Complicated Optical Path(1)(2)	High	Yes			Large number of components, with complex alignment requirements increases risk to MRCS.
Modularity	Medium	Sort Of	Sort Of	Simple	Coupling/Ganging DPSS requires optical bench.
Scalability	Medium	No	Not Yet	Yes	Fiber Lidar can be scaled to higher power using multiple low power modules. • Ex; IPG 10Kwatt fiber laser Scaling DPSS has posed problems at high energy levels.
Established and Vetted Manufacturing Process (2)	High	No	Yes	Yes	Space qualified fiber laser have been made on same manufacturing line as commercial laser. Preserves the reliability gained from using a vetted process. Shorter, Predictable delivery times reduces schedule and cost. COTS for space costs ~10% of custom for space; • Ex; 5watt vacuum ready EDFA by IPG costs <$50K, versus 5watt EDFA by Lucent Gov Systems for $500K, versus many $M's for a GLAS-like laser. • 10X-20X reduction in cost through manufacturing process and use of CW (2)

(1) Earth Science Enterprise Independent Laser Assessment Report, 2000/2001
(2) DoD Special Technology Area review on Low Cost, Mass Producible Solid-State Lasers, Nov 2001

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New Cost Models Are Needed for Fiber Laser Based Missions

- What is missing is an accepted cost model which accounts for the significant differences in Manufacturability, Robustness, and Cost and Schedule (MRCS) between COTS Fiber Amplifiers Lasers and Diode Pumped Solid State lasers.

- Recommended Action
  - Joint effort by NASA, Industry and Aerospace Corp.
    - > NASA Electronics Parts and Packing program (NEPP)
      - » Identify qualification requirements over and above Telecordia
    - > Industry
      - » IPG Photonics & ITT Space Systems to update internal cost model based on most recent NEPP inputs using IPG established manufacturing processes and procedures. Provide validation data for cost model.
      - » Other suppliers to do same
    - > Aerospace Corp
      - » Develop and Validate common Parametric Cost Model

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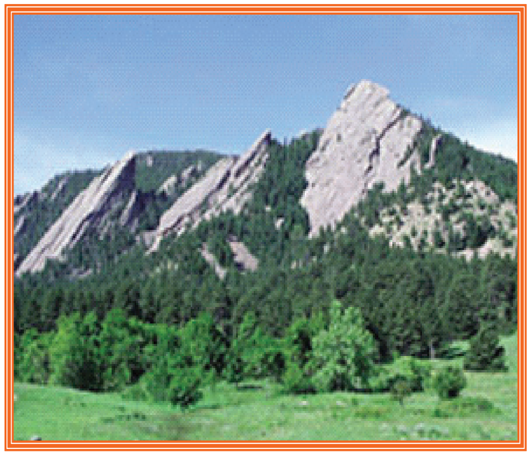
Boulder Nonlinear Systems



Outline

- Beam steering using Liquid Crystal on Silicon (LCoS) Optical Phased Arrays (OPAs)
- 1x12288 LCoS OPA Development
- OPA/System Enhancements – field of regard, aperture size, space qualification, power handling, etc

Motivation for effort

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- Eliminate gimbals (mechanical scanners)
  - Pointing accuracy, slewing & settling issues
  - Size, weight and power (SWaP) issues
- Bootstrap on large manufacturing infrastructures to reduce costs:
  - VLSI industry
  - Liquid crystal microdisplay industry
- Provide additional capabilities:
  - Multi-spot steering from single aperture
  - Dynamic beam shaping and pulse shaping
  - Adaptive wavefront correction

Nematic Liquid Crystals

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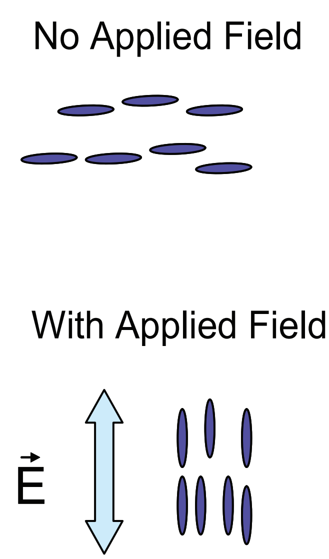
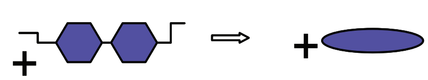
The “cigar-shaped” molecules of this fluid re-orient in an applied electric field. This results in changing the index of refraction encountered by incident light. Modulation of the refractive index changes the optical path. (recall the prism and blazed grating structures)



The dielectric anisotropy due to the physical-chemical structure



of the molecules causes them to re-align along the electric field lines.

Spatial effect

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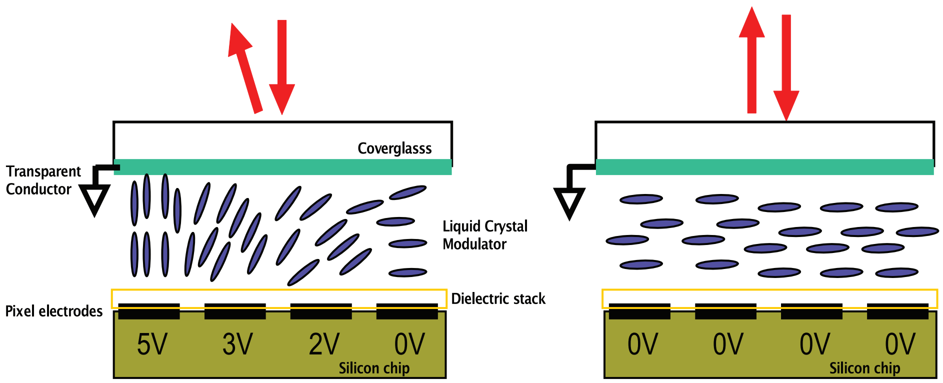
Beam deflection

Specular reflection



Applied Field

No Applied Field

Deflection Angle

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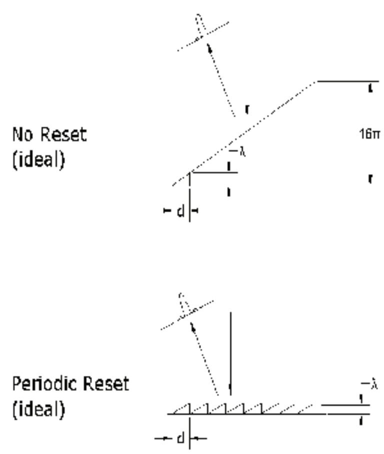
- Optical path difference controls steer angle:

$$\sin \theta = \lambda / d$$

- Since liquid crystal modulation is typically 10-20% of its average index, the prism approach gets to thick for angles larger than arc-seconds.
- For the grating structure, phase resets reduce the required thickness.
- The deflection angle is changed by changing the grating period, d.

Prism



Blazed Grating

Reducing higher-order diffraction

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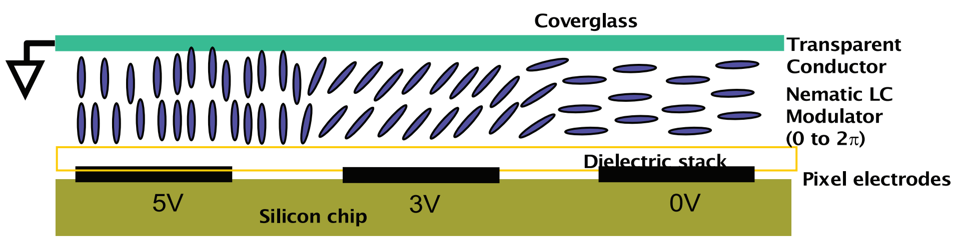
- Pixelated LCoS backplanes produce grating lobes due to amplitude variations
  - Loss in efficiency
  - Causes interference
- Steps to reduce higher-order diffraction are:
  - Blacken the pixels using anti-reflection coatings
  - Flatten the surface using chemical mechanical polishing (CMP)
  - Cover the active area with a continuous dielectric stack (i.e. increase fill factor to 100%)



LCoS OPA active-matrix addressing

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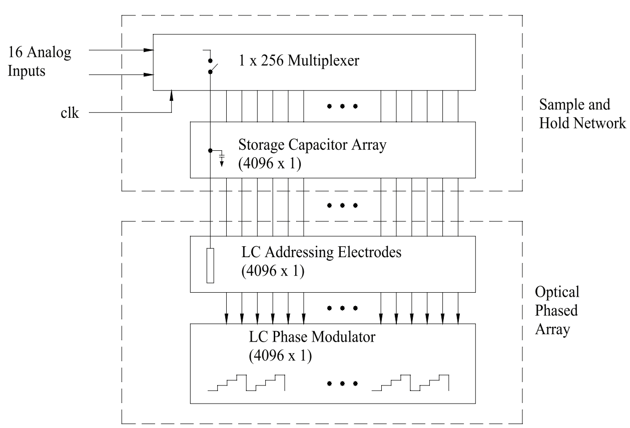
- Each pixel is individually addressed using a on-chip multiplexer
- Capacitive storage maintains the voltage across the LC as data is multiplexed into the array
- Fast load rates produce a static phase profile across the array



Optical Phased Array (OPA)

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Liquid Crystal on Silicon (LCoS)

Pixel array – 1 x 4096

Pixel pitch – 1.8 μm

Backplane Voltage – 5V

Aperture area – 44 mm^2

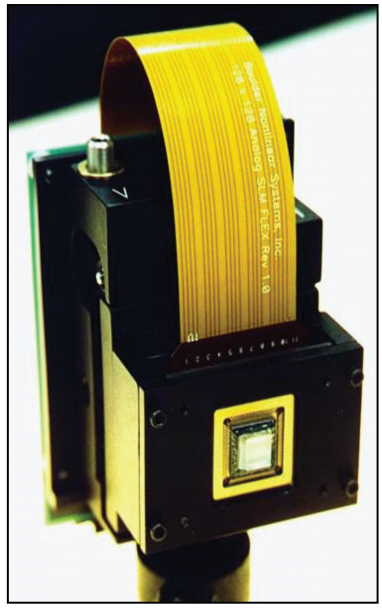
Load rate – 25 μs

LC – nematic

Modulation – 2π phase-only

Response rate – ~30 ms @ 1.5 μm

Efficiency – >80% @ small angles



Steered Order for Nematic Liquid Crystal Grating

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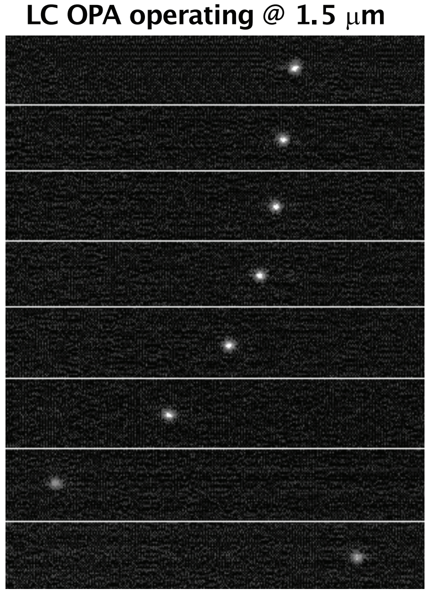
LC OPA operating @ 1.5 μm

Images from an infrared camera



0.00°

0.09°

0.19°

0.38°

0.75°

1.50°

3.00°

-.75°

Programmable FOV result

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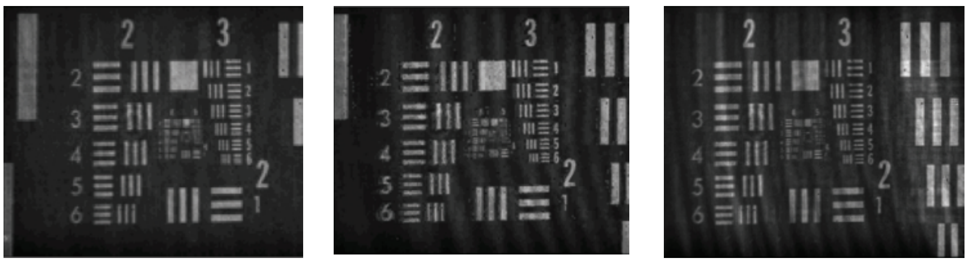
Field of View (FOV) Steering of a Monochromatic Image



Data using BNS' 1x4096 OPA, Courtesy of Air Force Research Laboratory (Scott Harris)

AFRL Tower Demonstration

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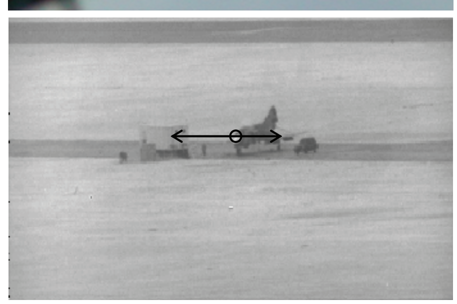
Demonstration Stats:
- Laser – YAG Raman Shifted to 1.5 µm
- Power on OPA – 12mJ/3ns (4 Megawatts)
- Range Distance – 1.7 km
- Camera – InGaAS (320x240)
- Telescope – 8 inch Cassegranian
- FOV – 3 degrees
- Max steer angle - ± 0.8 degrees



2D beam steering

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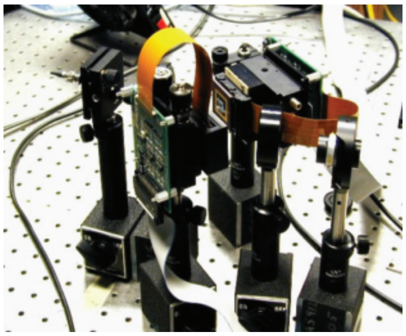
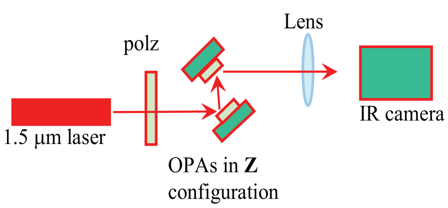
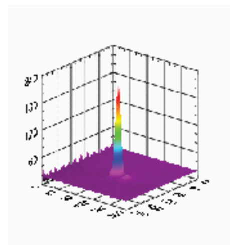
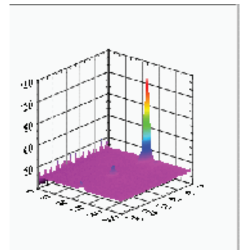


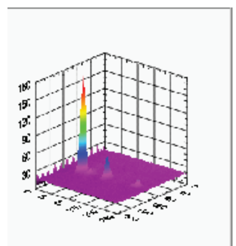




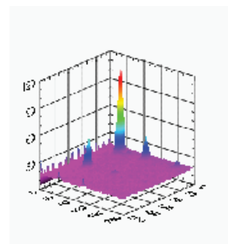
Zero order



1.0° up



0.75° left



0.75° left & 1.0° up

OPA improvements

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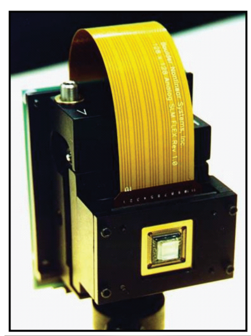
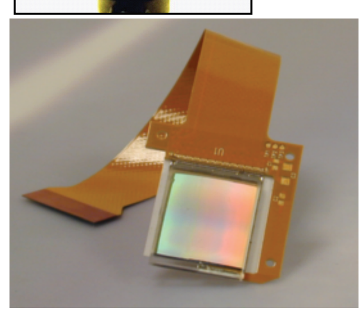
New OPA

- Larger OPA active area (2 cm x 2 cm)
- More phase control (12,288x8 degrees of freedom) which is useful for:
  - Improving angular resolution over field of regard
  - Applying wavefront correction across OPA aperture
  - Incorporating fine focus/defocus or other forms of beam shaping
- Increased addressing voltage (> 13 volts)
  - Drives faster liquid crystal modulators
  - Increases field of regard (from ±3° to ±7°)
- Maintains high-resolution addressing (1.6 µm pitch)
- Better planarization (flatter die)



1 x 4096 OPA



1 x 12,288 OPA

1x12288 OPA fabrication

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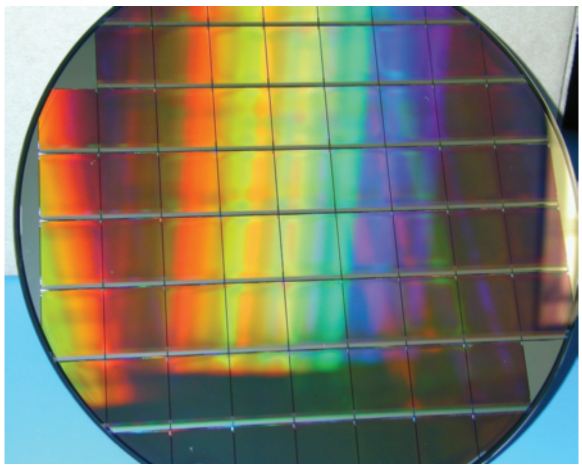

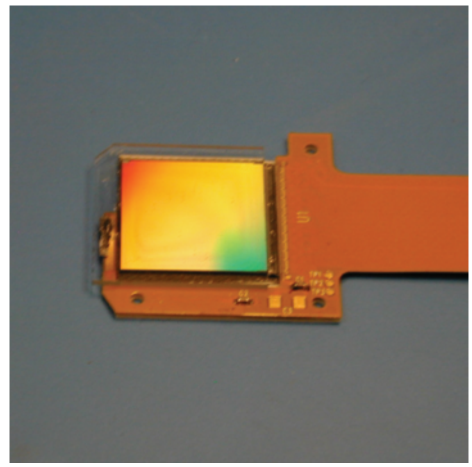

1x12288 OPA System

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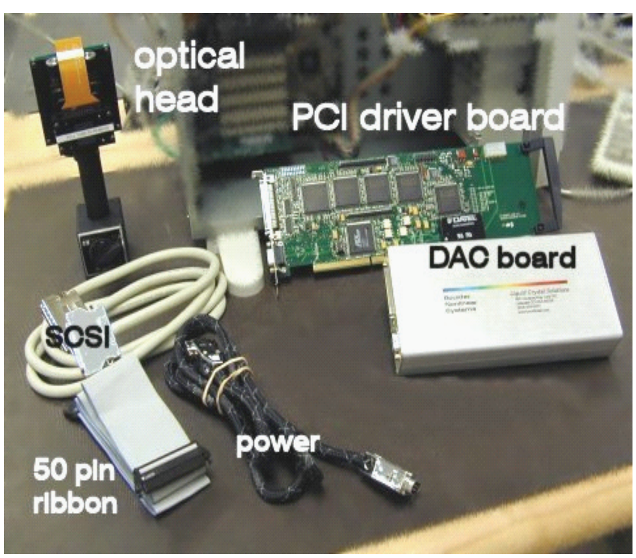
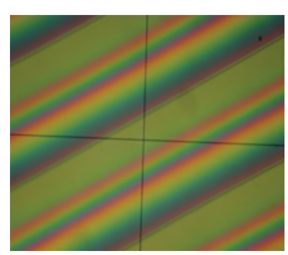


Full System

Optical phased array head



Wedge pattern on OPA

Wide field-of-regard (FOR) broadband beamsteering

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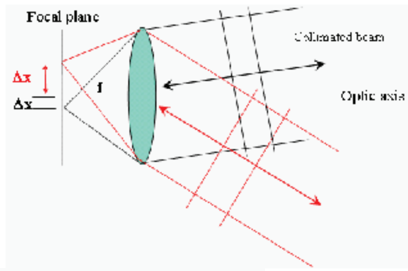
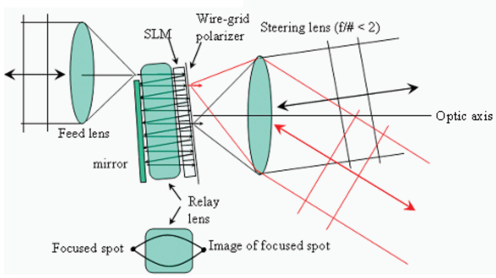
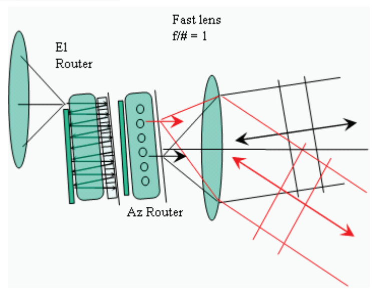


θ_{max} = tan-1 [1/(2 f/#)]



1-D Configuration



2-D Configuration

Steering with White cell

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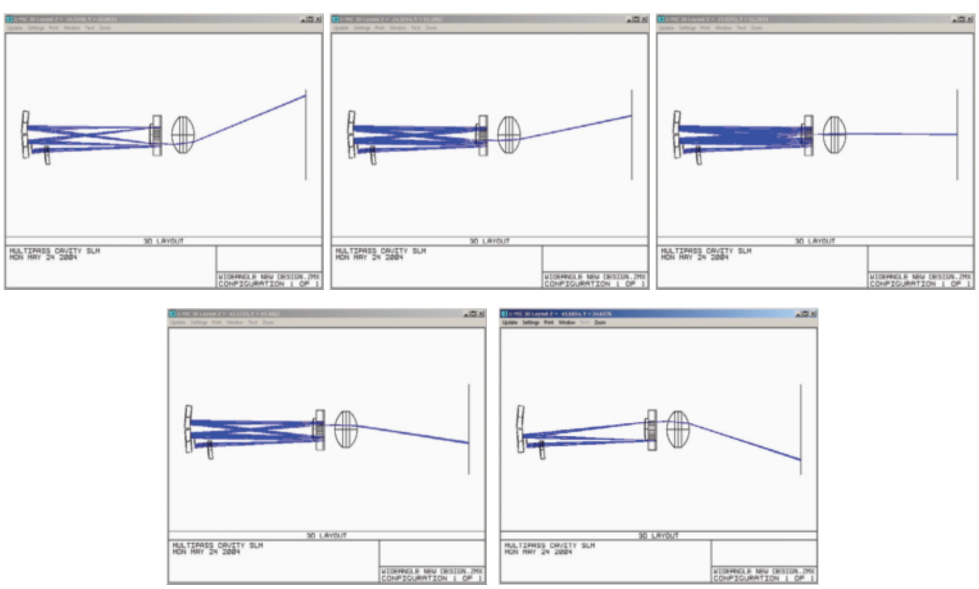
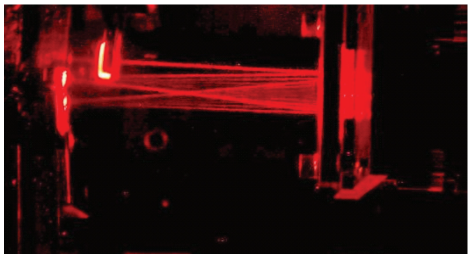
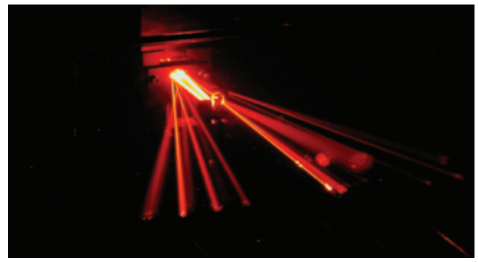


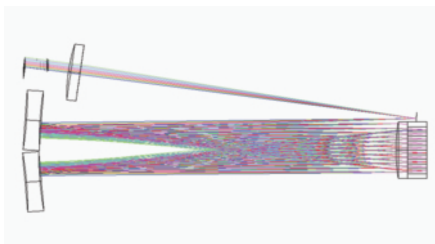
White cell operation



Top view



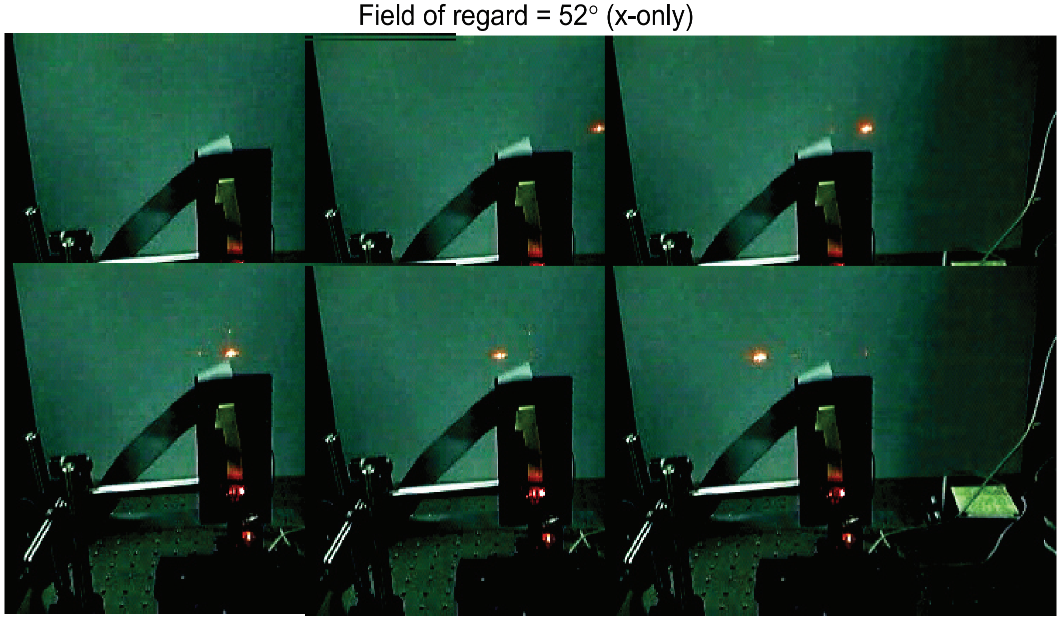
Back view



Ray trace from ZEMAX

Wide FOR beamsteering demo

F/# = 1
Step size = 5.2°
Field of regard = 52° (x-only)



Fine & coarse steering – high resolution over a wide FOR

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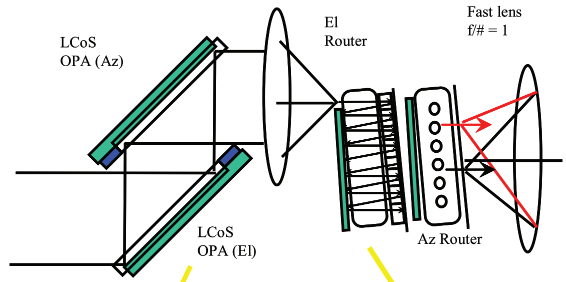
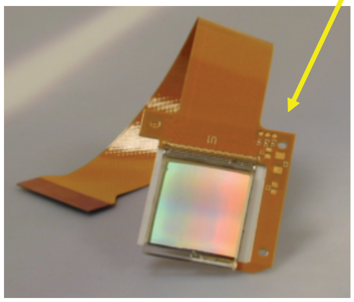
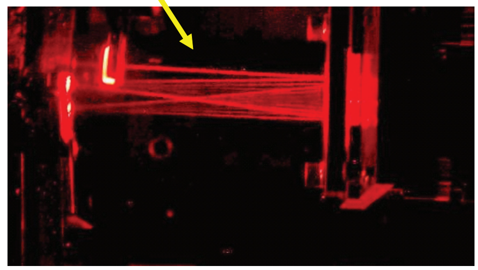




1x12,288 OPA on flex



1-D Demo using discrete components

Phased Array of Phased Arrays (PAPA)

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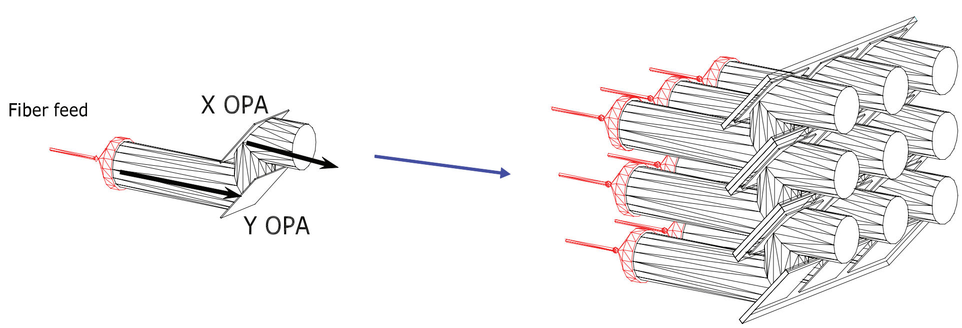
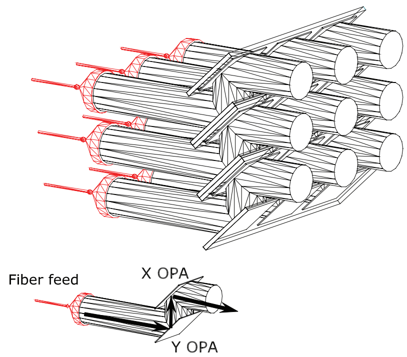
2-D crossed grating arrangement – single element

A conical-scanning phased array of phased arrays (PAPA) using an in-line “transmissive” architecture

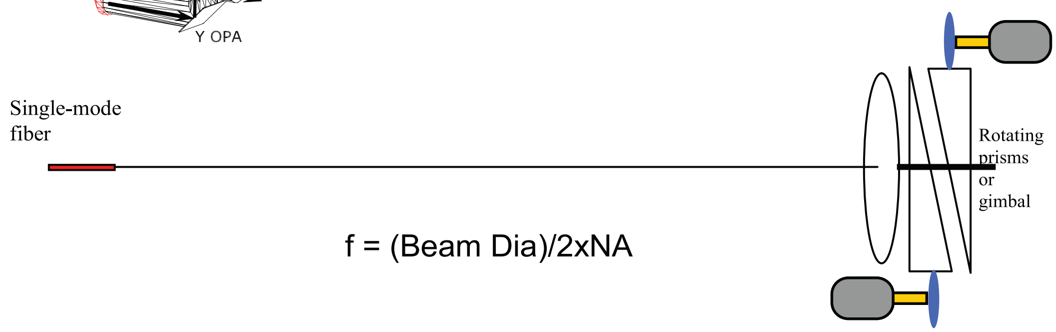


2-D in-line PAPA

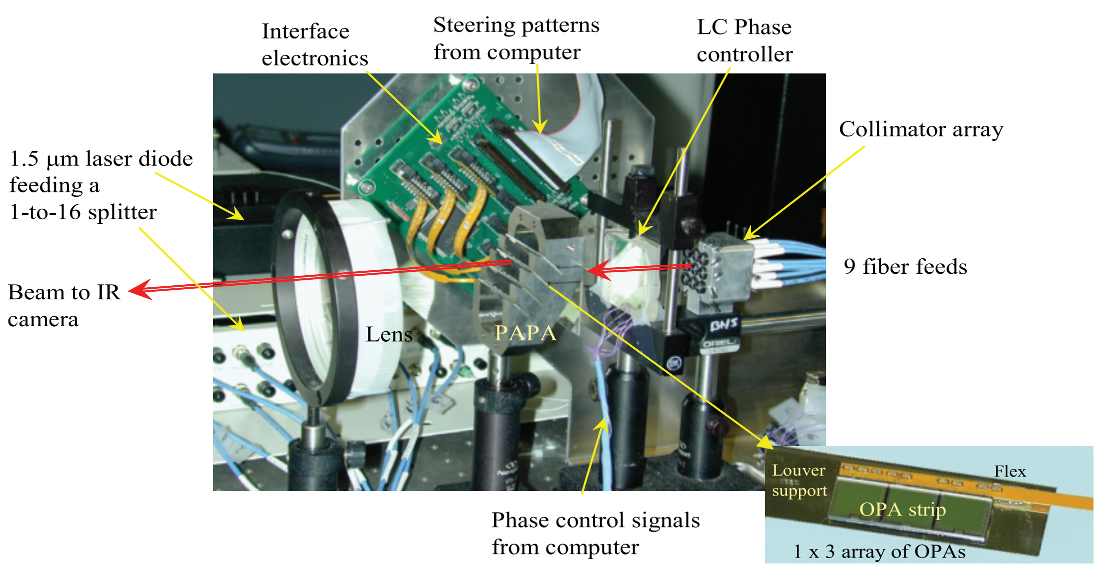


2-D Phased Array of Phased Arrays (PAPA) using reflective OPAs

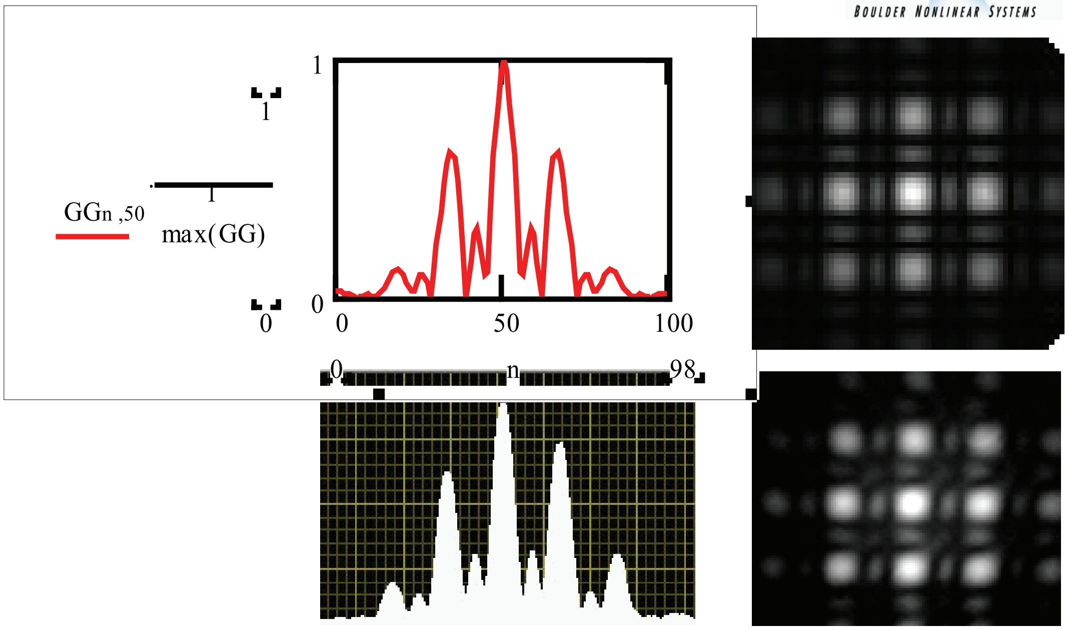
Per liquid crystal on silicon (LCoS) OPA:
- 1.9 cm x 1.9 cm active area
- 5 to 10 grams
- < 50 milliWatts
- Fully programmable (12,288 phase levels)



PAPA assembly with small OPAs



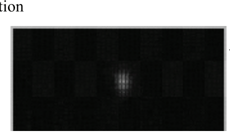
Modeled versus actual for small-aperture OPAs

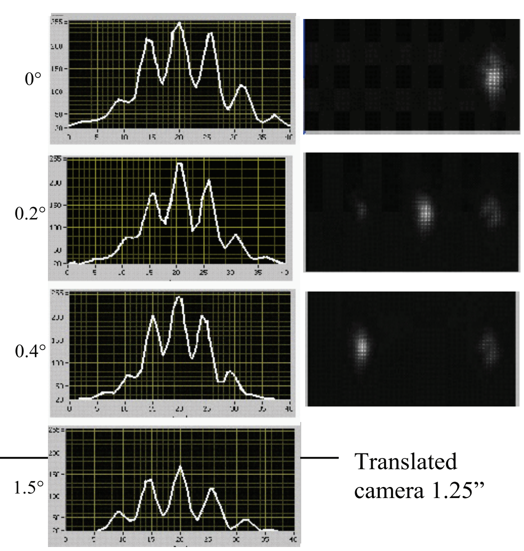


PAPA steering results using small-aperture OPAs

Angle	Peak Intensity (Normalized)	Peak Efficiency (Normalized*)
0°	1.0	0 dB
0.2°	0.91	-0.6 dB
0.4°	0.91	-0.6 dB
1.5°	0.63	-2.84 dB

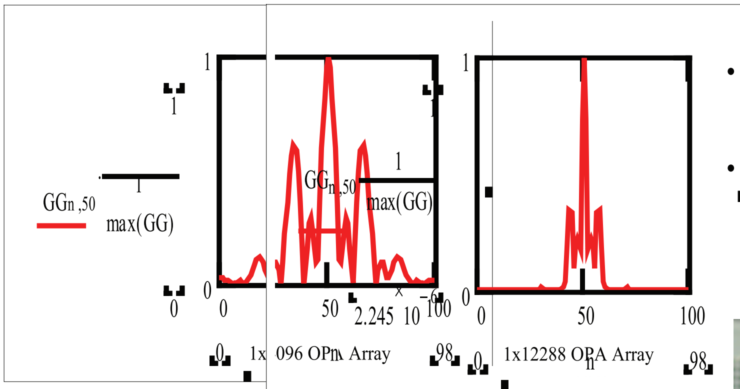
* Includes gamma correction



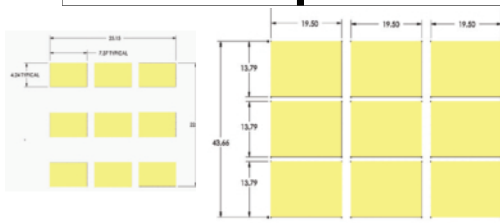


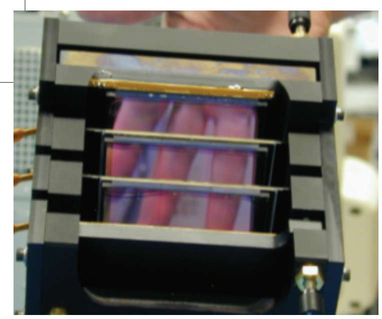
PAPA improvements

BNS
BOULDER NONLINEAR SYSTEMS



- Better array fill factor
  - 84% versus 51%
  - Lower sidelobes
- Larger aperture
  - 28 cm^2 versus 5.5 cm^2
  - 3x3 array of 1x12,288 OPAs

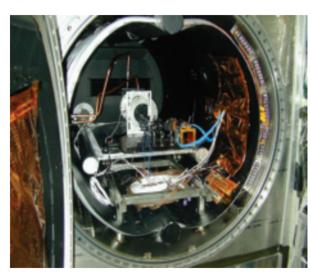




Environment

BNS
BOULDER NONLINEAR SYSTEMS

- Radiation: Operating OPAs have been tested to over 200 kRad (an ionizing γ radiation dose equivalent to 14 years Geo) without significant effects.
- Temperature and vacuum cycles: devices have survived temperatures from –25 C to +70 C and vacuum below 4 x 10 –7 Torr.
- Vibration: 4 Gs, 2-2000 Hz no effects
- Further testing is planned



OPA power handling

BNS
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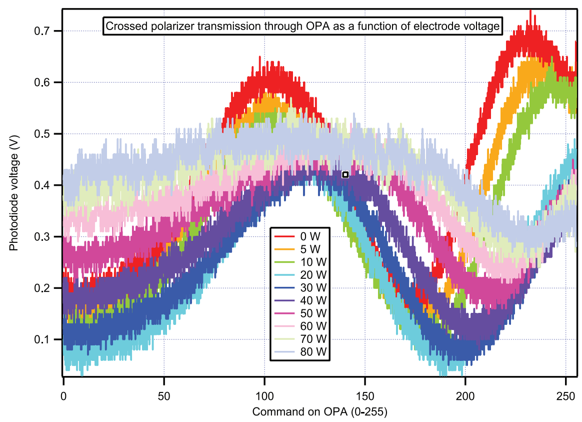


- Modulation versus laser power on 1 x 4096 OPA
  - 1064-nm laser
  - Laser output is CW
  - Beam diameter is 5 mm
- Loss of modulation with increase in power level
- Over 50 watts the LC appears to go isotropic
- Water cooling does not change outcome much
- Watts/cm^2 is ~ 4 times power level
  - assuming 1/e^2 points for beam diameter
  - average power exceeds 150W/cm^2

Polarization Independent Beam Steering

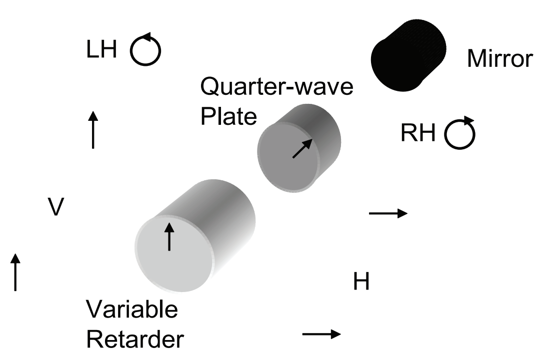
BNS
BOULDER NONLINEAR SYSTEMS

Requirements

A modulator that produces identical phase shifts for horizontal and vertical polarizations.

A compact aspect ratio to reduce diffractive effects on reflection(i.e. a thin quarter-wave retarder).

Polarization Independent Phase Modulator



Implementation

Incident polarization is converted to the orthogonal state on reflection by a quarter-wave-plate and mirror. Regardless of polarization, the light is modulated by the variable retarder on one of the two passes.

It is desirable that the quarter-wave plate be as thin as possible. The solution here is to use a polymer nematic quarter-wave plate.

Lidar System Development at Ball Aerospace

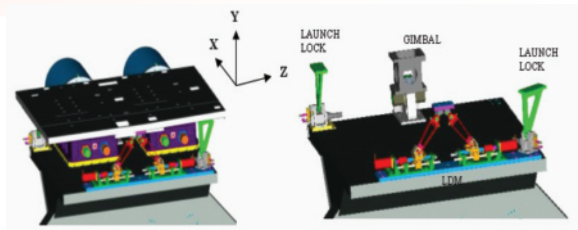
Carl Weimer, PhD
January 10, 2006

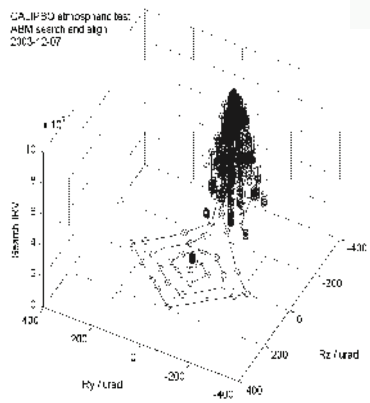
System Development at Ball supporting potential Lidar Systems

- Ball Aerospace will draw from its broad range of flight programs to support future Lidar Mission Development. For example:
  - CALIPSO/CALIOP – Lidar design, production and testing, Payload development, laser system development, flight software including lidar signal processing and control.
  - ICESAT – Spacecraft for lidar - precision pointing control for spacecraft, Lidar /spacecraft integration and test, ground operations support
  - Quickbird/ Worldview – High Precision optical structure design and test, agile high-precision pointing control.
  - LaserCom – Integrated laser transmitter/receiver systems with adaptive high-speed pointing capability
  - JWST – Deployable Large Aperture Optics, Beryllium telescope development
  - Deep Impact – mission-level design and development, Vis/IR science instrumentation, reduced-cost spacecraft, autonomous operation, mission ops

Precision Mechanical Subsystems: CALIPSO example

Example: Precision Pointing and Automated Alignment for CALIPSO lidar

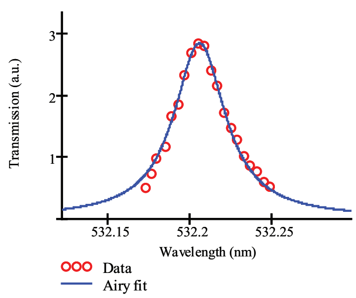


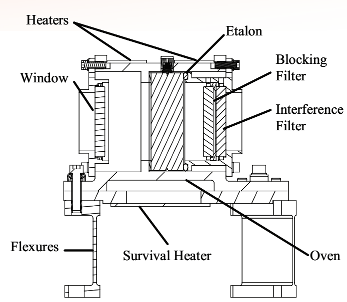


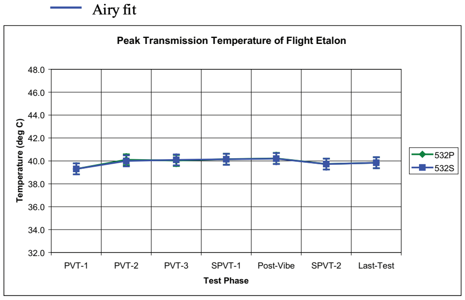
- -Ball has extensive background in space-qualified mechanisms including those for precision pointing of lasers
- -CALIPSO mechanism shown above
- -CALIPSO Flight software gives automated search and alignment capability using integrated lidar signal. Demonstration (left) shows results of an atmospheric test of the flight Payload as the system searches, aligns, and is repeatedly perturbed and autonomously realigns

Key Optical subsystems for Lidar: CALIPSO Etalon Example

Example - Space Qualified Etalon Filters for CALIPSO lidar – teamed with Coronado Tech.



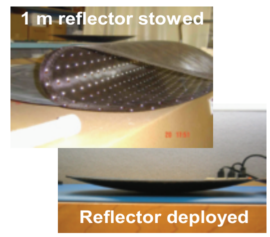




- -"Sandwich" Etalons matched to the CALIPSO Wavelength
- -Wavelength Tunable via temperature over a linewidth
- -Stability in peak transmission wavelength over past two years since integrated on Payload (left) (includes one satellite integration, two vibe tests, two T/V tests, three acoustic tests, and a trip to France and back)

Ball is developing large optical aperture systems and new test capabilities

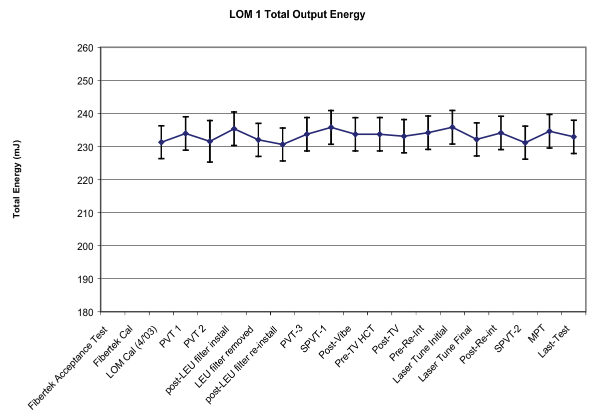
- James Webb Space Telescope
  - Scaled mirror alignment and control testbed complete, actuators align each segment
  - Beryllium petal blanks complete, now being lightweighted – 1.3 m minimum Aperture
- Deployable shape memory reflectors
  - Developed and tested for microwave applications
  - Areal density of < 1kg/m^2
- New Thermal Vacuum Optical Test Capability added
  - Horizontal 0.7 m aperture collimator complete
  - Vertical 1.4 m aperture collimator to be completed this year
  - Sized to handle up to full satellite systems and for cryogenic temperatures



Twenty 1.3 m diameter Beryllium Blanks Built for JWST Completed

Ball teams to Develop Flight Qualified Laser Systems

- CALIPSO Risk Reduction Laser - Fibertek/LaRC/Ball - Completed > 2billion shots and still running at Ball
- New Lasers for a broad range of applications are being worked
- Ball provides critical engineering support needed to qualify laser systems and meet NASA manufacturing and test standards.



CALIPSO Flight Laser #1 showing 80 million shots over 3.5 years of Laser/Payload/Satellite Testing.

Ball Spacecraft Development

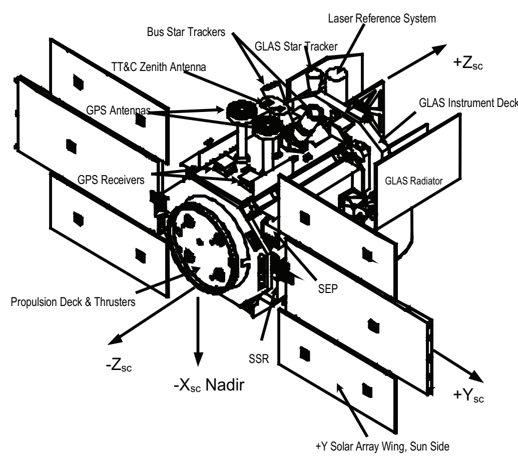
ICESat BCP 2000 Spacecraft:

- The ICESat bus supports the GLAS instrument system by providing a stable, thermally isolated platform, power, data services, spacecraft pointing control, orbit maintenance and propulsion, and space to ground communications.
- Spacecraft is meeting its requirements for pointing accuracy and knowledge (<50 urads rss each)

Ball has now developed a lower-cost alternative spacecraft

- Deep Impact Impactor, Orbital Express, WISE

ICESat - GLAS Laser Altimeter on Ball's BCP 2000 spacecraft

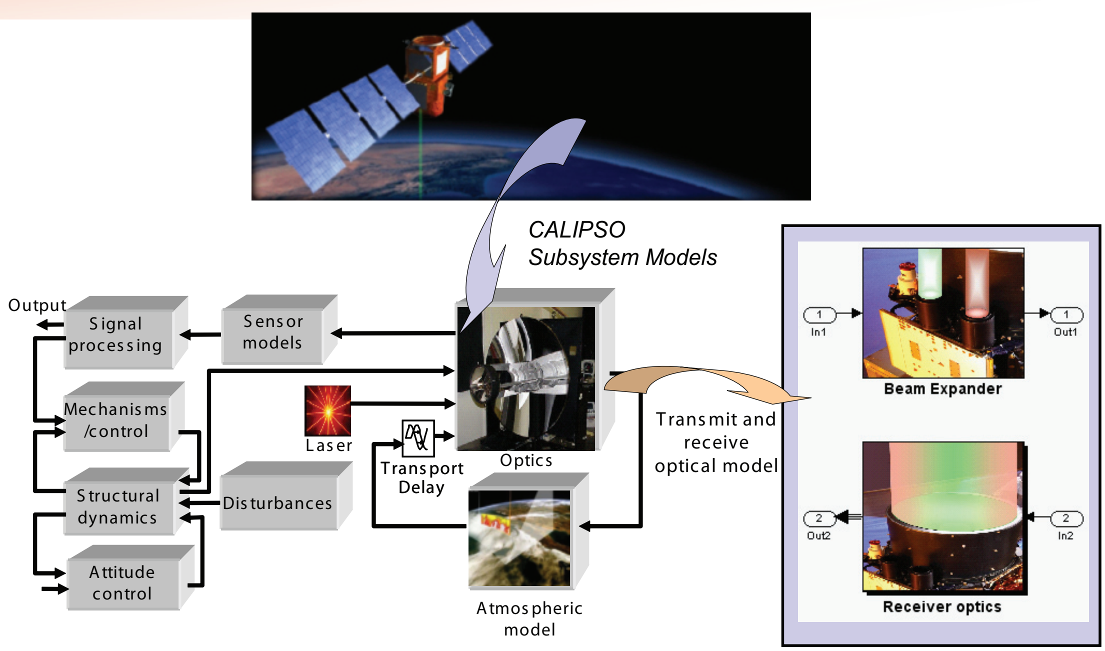


Internally Funded Technology Development

Examples from across Ball of ongoing internal development projects:

- 3-dimensional LADAR for Exploration
- Optical Autocovariance Receiver Development for Wind Lidar
- Space Qualified Laser Development for Civil & Defense
- Lightweight Deployable Apertures
- System Pointing and Scanning for Lidars
- Passive A-band Wind Sounder
- Lidar Integrated Modeling

Calipso Integrated Model as Implemented in Simulink/ MATLAB - EOSyM-L



Google Earth Applications to Lidar-Based and Remote Sensing Instrumentation

By Martín Cadirola, CEO
Ecotronics Ventures LLC

What is Google Earth

- An interactive 3D mapping software capable of displaying any geography-related data; Google calls it "A 3D interface to the planet"
- Users can place placemarks, tilt & rotate views, make annotations, etc
- Free version does most of what the scientific community needs

What is Google Earth

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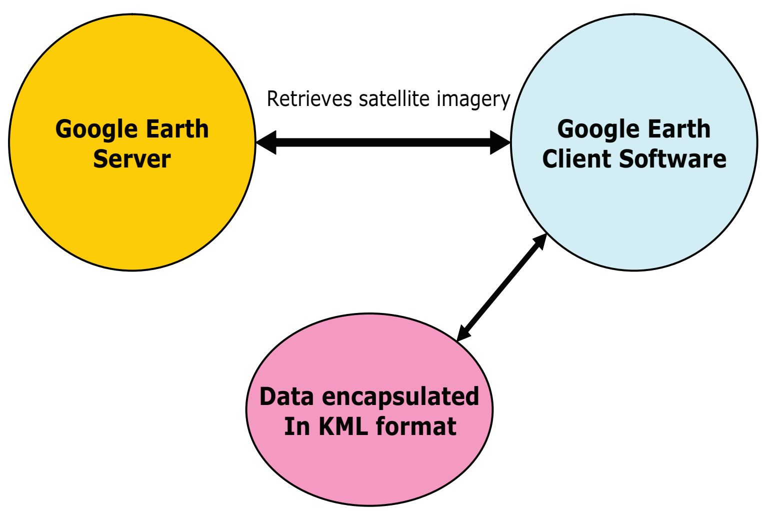
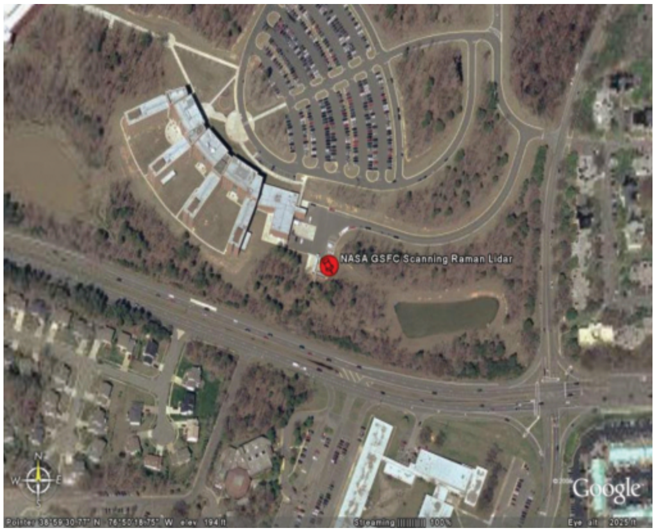
How does Google Earth work

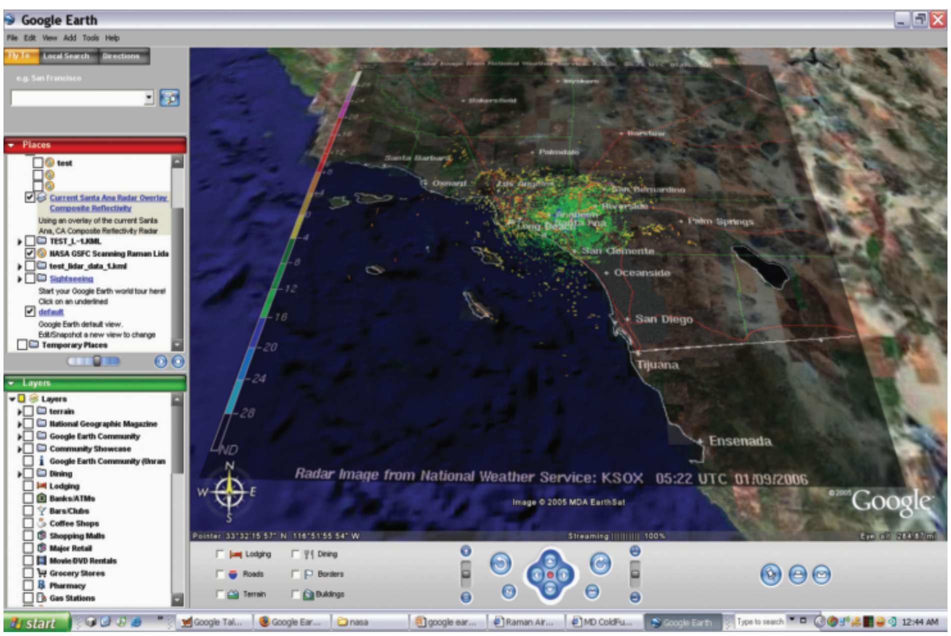


Some Google Earth Snapshots



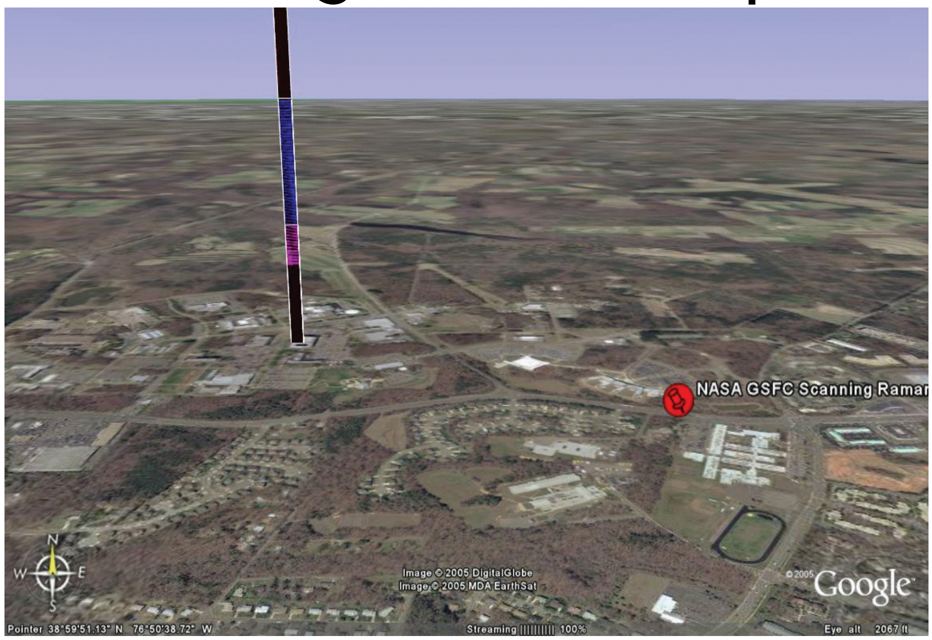
NASA Google Earth BETA ecotronics

Some Google Earth Snapshots

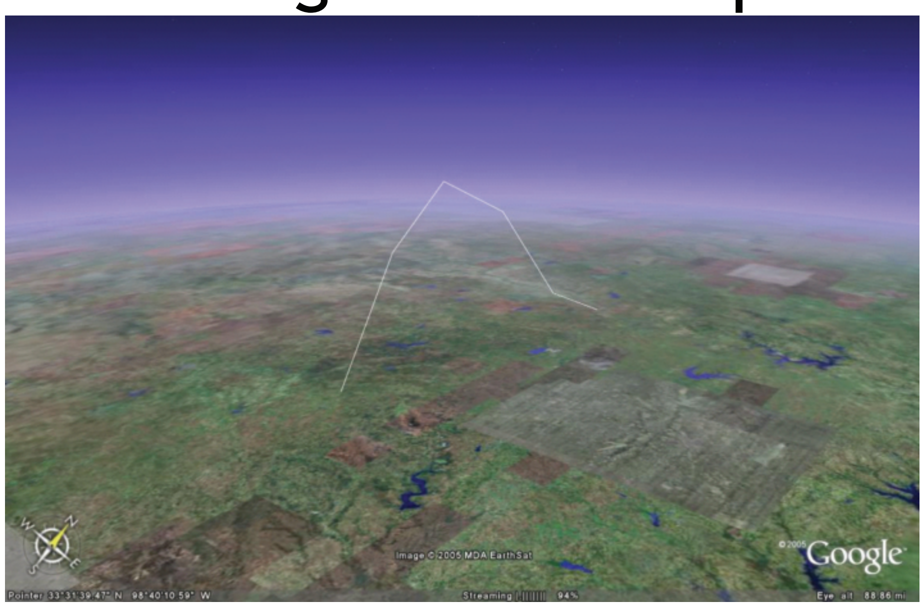


NASA Google Earth BETA ecotronics

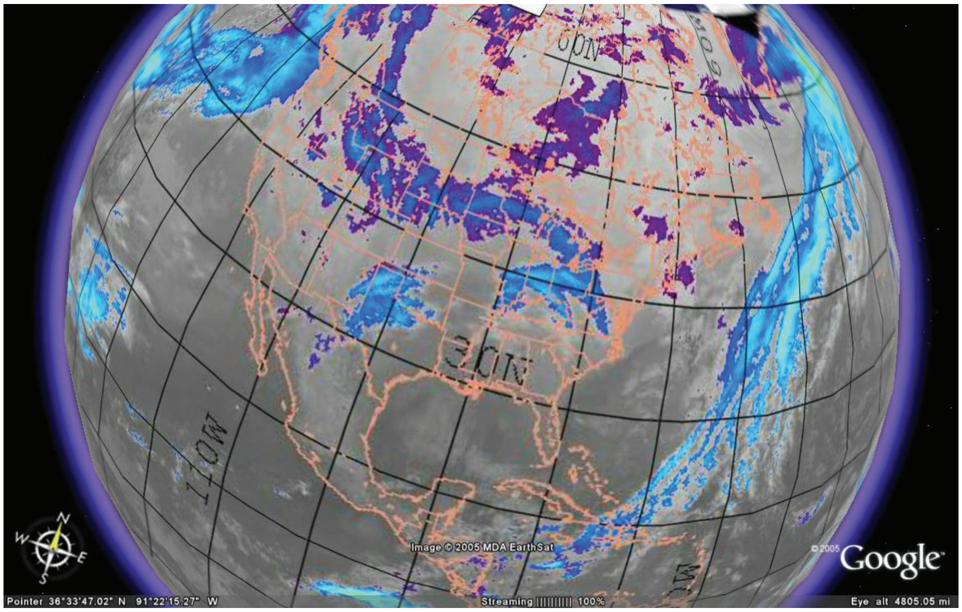
Some Google Earth Snapshots



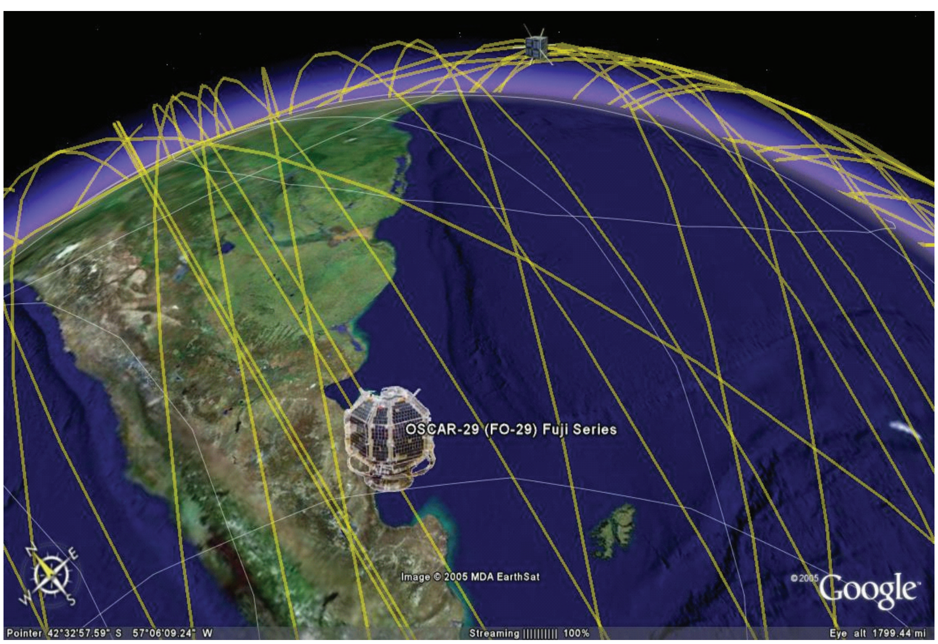
Some Google Earth Snapshots



Some Google Earth Snapshots



Some Google Earth Snapshots



Google Earth + Lidar Applications

- Atmospheric data visualization
  - Ground and airborne instrumentation
- Geographic data visualization
  - Rapid topographic mapping
- Demo

Google Earth + Remote Sensing Applications

- Integration of multiple sources in one place
  - Satellite/Ground/Airborne instruments
- Remote management of sensor network
  - MPLNet, Aeronet, etc
- Demo

Beyond Google Earth…

- Potential Uses:
  - Scientific collaboration
  - Real-time data visualization (field campaigns)
  - Interagency decision making (NASA, NOAA, DOE)
  - Conference presentations
  - Educational outreach
- Mars, Moon available in the short term

Google Earth Summary

- Integration+Visualization+Collaboration
- Low-cost, scalable publishing platform
- Tool that help us increase our knowledge and understanding of our world

What's next…

- Ecotronics Google Earth Solutions
  - Development of KML Conversion Software
  - Secure platforms for Collaboration
- Interested in working with NASA groups for beta testing

Try Google Earth!

- Download Google Earth
  - http://earth.google.com
- Download KML samples from Ecotronics site
  - http://www.ecotronics.com/google-earth
- Contact us with questions/comments!
  - By email: martin@ecotronics.com
  - By phone: 301-591-1706/301-614-6774

Ecotronics Background

- Currently providing electronics engineering support services for Goddard's Scanning Raman Lidar (SRL)and the Raman Airborne Spectroscopic Lidar (RASL) (Dr. David Whiteman)
- Developed a Raman Lidar at UMBC (aka ALEX, Atmospheric Lidar Experiment) with Dr. Harvey Melfi
- Since 2000, enabling commercial organizations with Internet-based back-end software solutions, engineered locally
- Steering committee member of the International Association of Space Entrepreneurs, a non-profit entrepreneurial organization dedicated to the promotion of business in space
- Manager of Adobe/Macromedia Coldfusion Users Group at GSFC

Q&A

- What challenges do you face today?
- How would Google Earth help you?

Data Acquisition Planning and Adaptive Control of Lidar Systems

Robert Morris, NASA ARC

Autonomous On-board Lidar Data Management

- On-board processing of laser data is required; it is not possible to telemeter the entire data stream.
- On-board data processing and compression techniques exist (GLAS).
- Quality and coverage can be improved by more informed on-board autonomous decision-making.

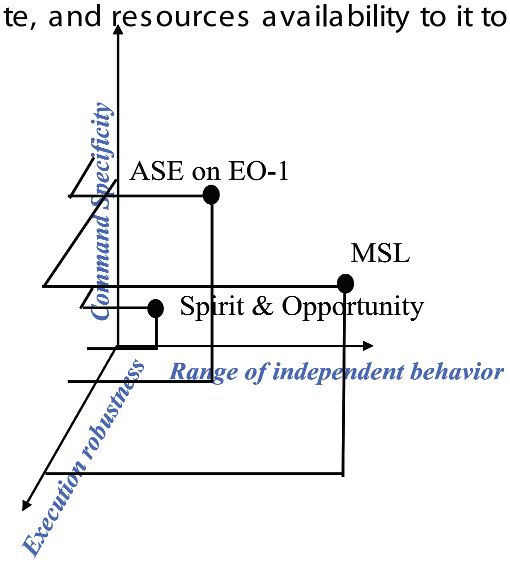
Autonomy Definition and Metrics

Autonomy describes a system's ability to exhibit goal directed behavior by making decisions in response to uncertainties within the external environment, its internal health state, and resources availability to it to accomplish its goals.

Range of Controllable Behavior: Range of capabilities that the system can exhibit (control authority).

Command Specificity: Level of abstraction in specification.

Execution Robustness: Envelope of conditions under which system can achieve its goals.



What does Autonomy buy you?

Increased mission assurance:

- Ability to respond to a wider range of environmental and system health conditions.

Improved performance:

- Increased science return and more efficient operations due to the systems ability to respond to opportunities.
- Attempts to narrow the gap between the scientist and the spacecraft.

Decreased cost:

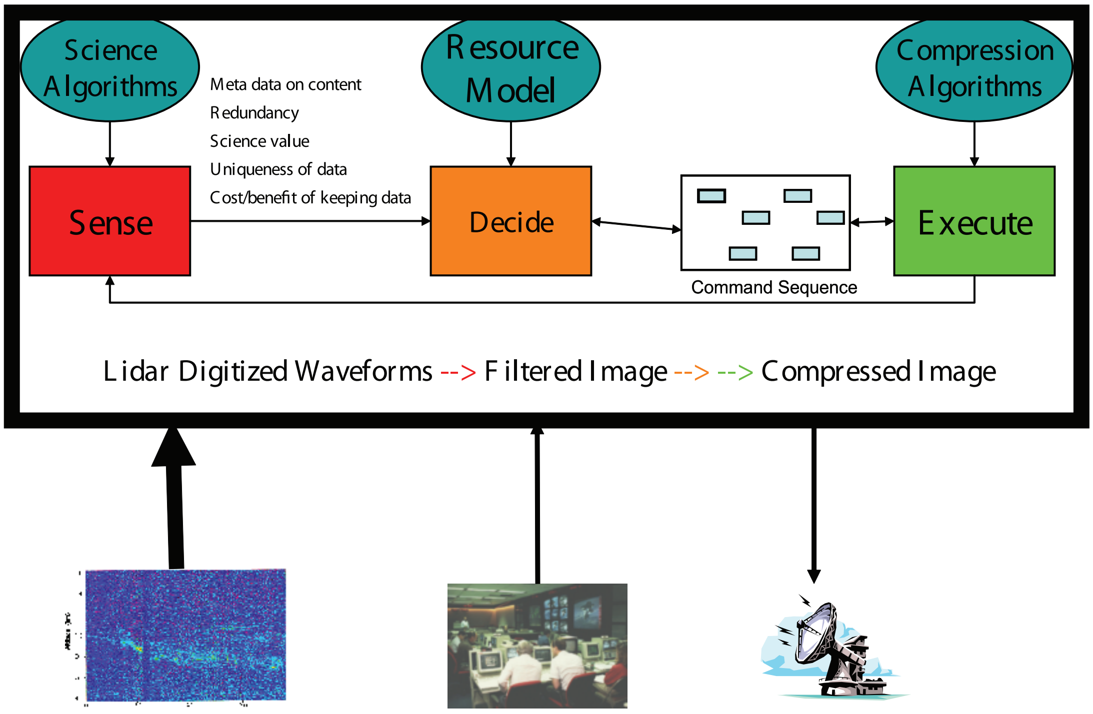
- Reduction in mission ops cost and potential decrease in mission development costs.

Key Components of Autonomy

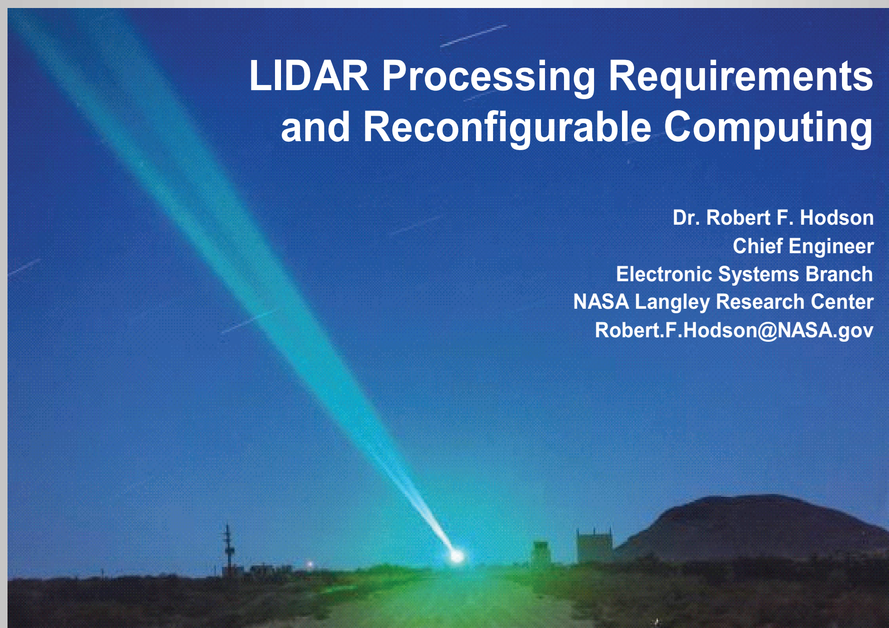
- Sensing
  - Where am I?
  - How am I doing?
  - What is that?
- Deciding
  - Explore?
  - Analyze some data?
  - Figure out what's wrong with me?
  - Figure out what to do later?
- Executing
  - Navigating over tough terrain
  - Extending arm
  - Taking pictures
  - "Phoning home"

Continuous Autonomous Decision Making for

- Interpreting Lidar data stream
  - Meta data on content
  - Redundancy
  - Science value
  - Uniqueness of data
  - Cost/benefit of keeping data
- Selecting optimal data compression algorithm to minimize science content loss
  - Reasoning with resource (SSR, power, CPU) constraints
  - Visibility into future observation schedule
- Execution of data compression tasks
  - Monitoring resource utilization
  - Invoking new data analysis tasks
  - Ensuring the system will not transition to an unsafe state



Autonomy for Integrated On-board Data Processing and Observation Planning and Execution



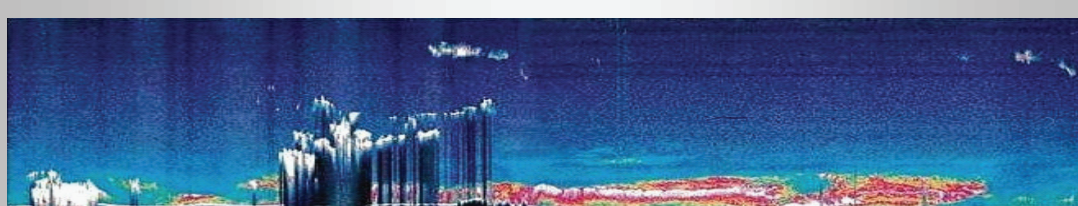
LIDAR Processing Requirements and Reconfigurable Computing

Dr. Robert F. Hodson
Chief Engineer
Electronic Systems Branch
NASA Langley Research Center
Robert.F.Hodson@NASA.gov

Explore. Discover. Understand.

Overview

- Understanding LIDAR processing requirements
- What is reconfigurable computing?
- When Reconfigurable Computing Works Best
- A case for reconfigurable computing for high-performance LIDAR applications (Examples)
- Solicit processing requirement



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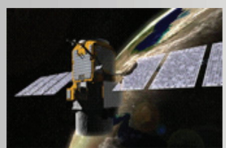
Processing Requirements Flow-Down



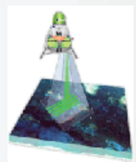
Science

Atmospheric Measurements of Cloud/Aerosols, Wind, Vapor

Exploration

Hazard Avoidance
Terrain Mapping
Altimetry
Autonomous Landing

Photon Counting
Scanning
3D Flash
Multi-Channel Scalers



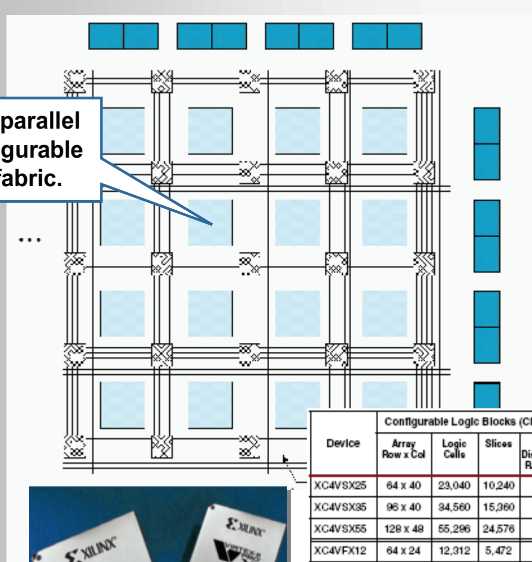
Precision Timing
Ray Tracing
Counting/Binning
Image Processing
Hazard Detection
Signal Processing
Communications
SEE Mitigation

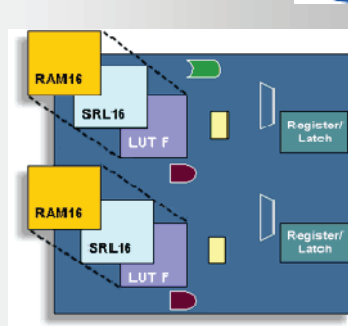
Mission Requirements, Measurement Requirement, Lidar Systems, Processing Requirements

Explore. Discover. Understand.

Reconfigurable Computing

Highly parallel reconfigurable FPGA fabric.





Device	Configurable Logic Blocks (CLBs)[1]				XtremeDSP Slices[2]	Block RAM		DCMs	PMCDs	PowerPC Processor Blocks	Ethernet MACs	RocketIO Transceiver Blocks	Total I/O Banks	Max User I/O
	Array Row x Col	Logic Cells	Slices	Max Distributed RAM (Kb)		18 Kb Blocks	Max Block RAM (Kb)							
XC4VSX25	64 x 40	23,040	10,240	160	128	128	2,304	4	0	N/A	N/A	N/A	9	320
XC4VSX35	96 x 40	34,560	15,360	240	192	192	3,456	8	4	N/A	N/A	N/A	11	448
XC4VSX55	128 x 48	55,296	24,576	384	512	320	5,760	8	4	N/A	N/A	N/A	13	640
XC4VFX12	64 x 24	12,312	5,472	86	32	36	648	4	0	1	2	N/A	9	320
XC4VFX20	64 x 36	19,224	8,544	134	32	68	1,224	4	0	1	2	8	9	320
XC4VFX40	96 x 44	41,904	15,552	243	48	144	2,592	8	4	2	4	12	11	448
XC4VFX60	128 x 52	56,880	25,280	395	128	232	4,176	12	8	2	4	16	13	576
XC4VFX100	160 x 68	94,896	42,176	659	160	376	6,768	12	8	2	4	20	15	768
XC4VFX140	192 x 84	142,128	63,168	987	192	552	9,936	20	8	2	4	24	17	896

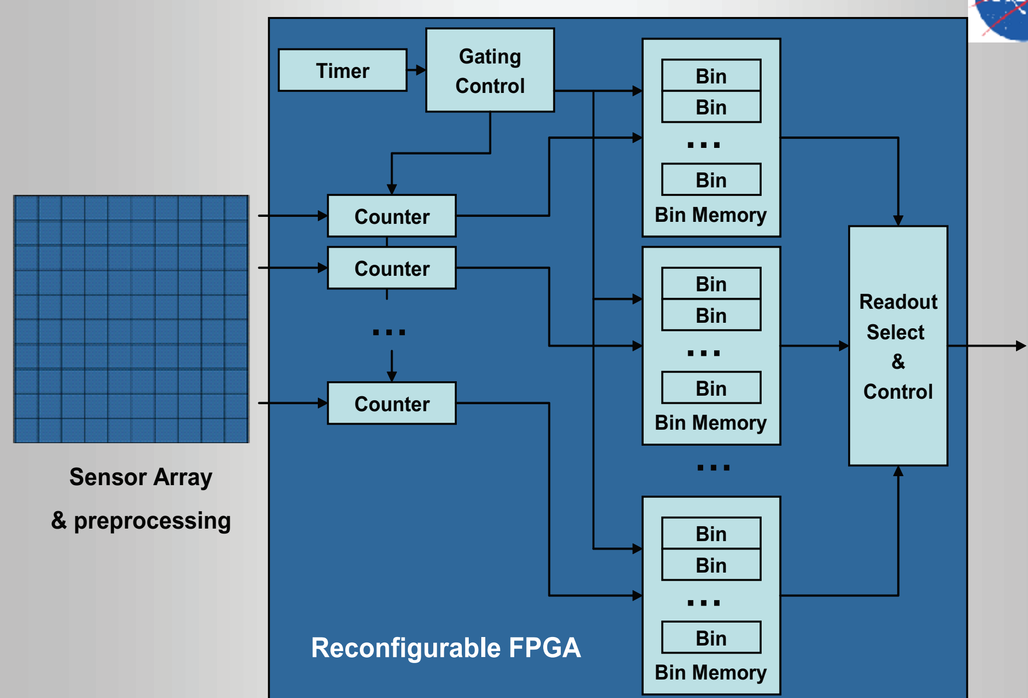
Explore. Discover. Understand.

When Reconfigurable Computing Works Best

- Multi-channel parallelizable dataflow architectures
  - Supported by high I/O counts
  - Ample memory, logic and routing resources
  - Can eliminate CPU and memory bottlenecks in applications
- DSP Applications
  - Special DSP slice supports
    - fast counters, multipliers, multiply-accumulates, …
    - thus efficient digital filters, signal transforms (FFT, Wavelet), etc.
- Imaging
  - Enhancement, fusion, feature extraction,…
- Performance
  - 8 to 800 speedup over an 800 MHz Pentium III processor *[Draper]*
  - 200M sample/sec/channel filters
  - 57% Power savings *[Lysecky]*

Explore. Discover. Understand.

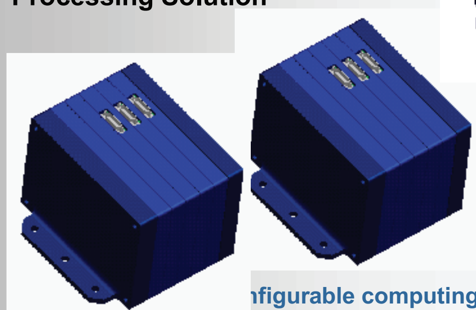
Example Lidar Counting/Binning Function

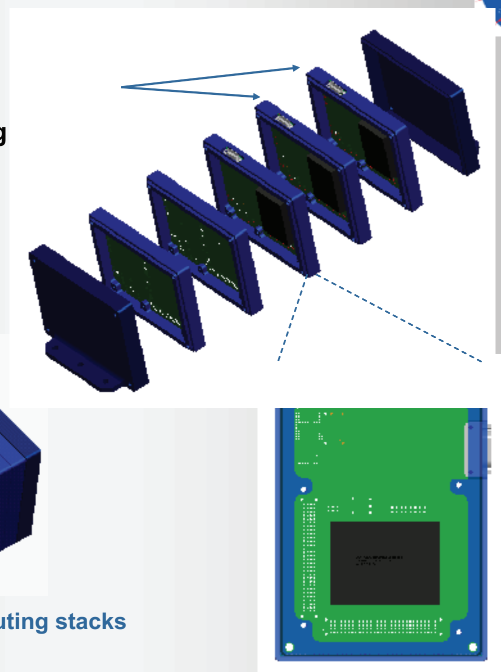


Explore. Discover. Understand.

Reconfigurable Computing for Space

- High Performance
  - -Highly parallel
  - -Optimized for signal processing
- Low power
- Flexible/Adaptable
- Modular
- Space Hardened
  Processing Solution

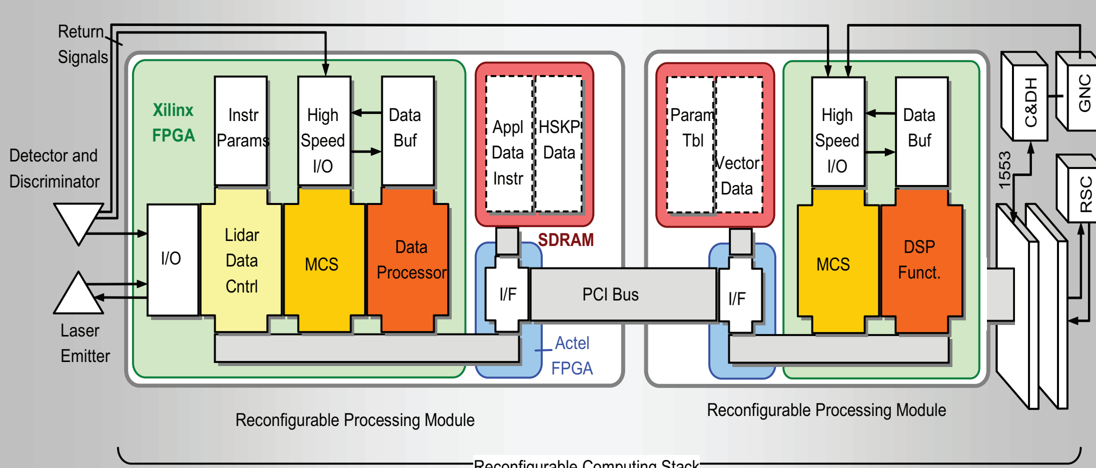




nfigurable computing stacks

Explore. Discover. Understand.

Example Lidar Application on a Reconfigurable System



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Summary

- Existing space computing systems will not meet the needs of some lidar applications
- Need to better understand lidar processing requirements and work towards a flexible processing solution that can meet future needs for many lidar systems
- Reconfigurable computing is a potential solution that offers advantages over existing space computing systems

Lidar processing white paper available for comment.

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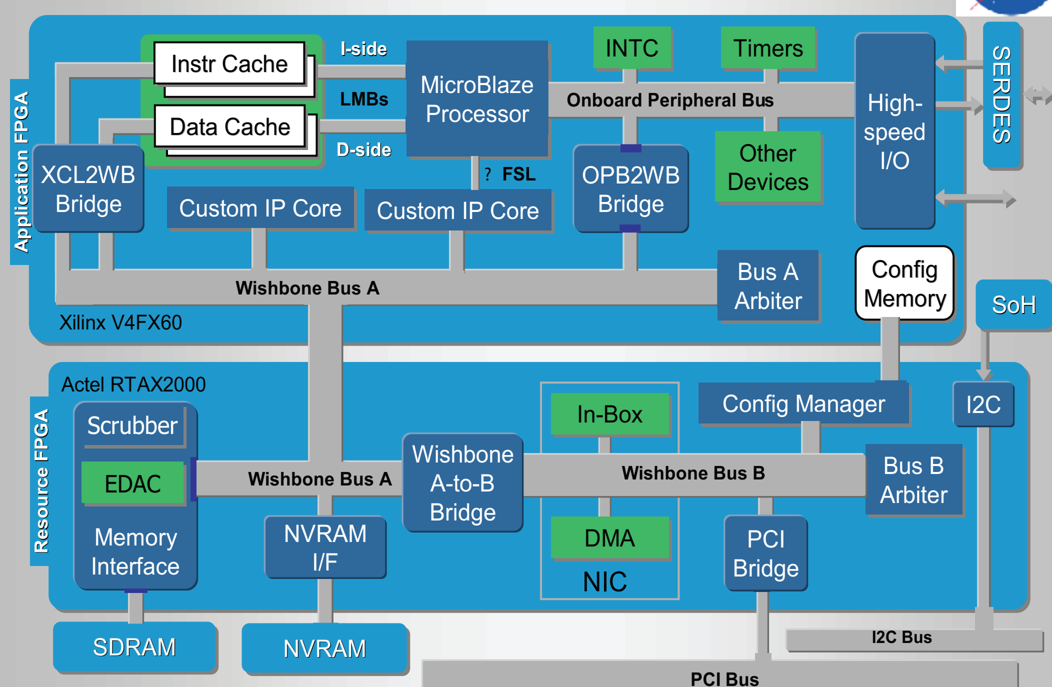
RPM – Reconfigurable Processing Module



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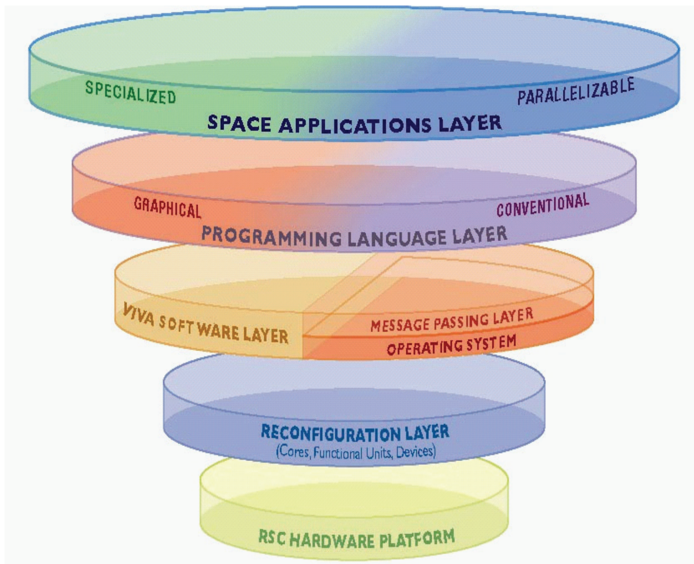
Software Architecture



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Performance/Power Benefits

- The *MicroBlaze Warp processor* eliminates the performance and energy overhead
- Improving performance on average by 5.8X
- Reducing energy consumption on average by 57%
- Making them competitive with current hard-core processors

Figure 6: Speedups of MicroBlaze-based warp processor and ARM7, ARM9, ARM10, and ARM11 (MHz in parentheses) processors compared to MicroBlaze processor alone for various Powerstone and EEMBC benchmark applications.

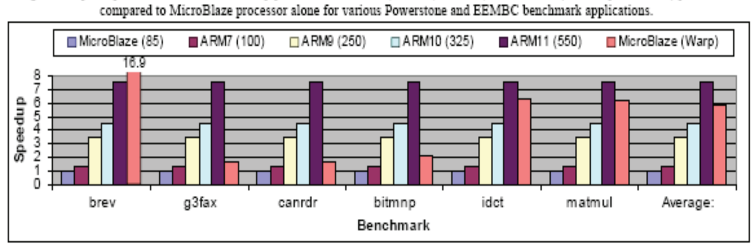
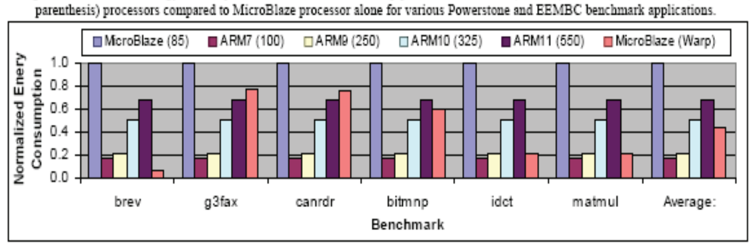


Figure 7: Normalized energy consumption of MicroBlaze-based warp processor and ARM7, ARM9, ARM10, and ARM11 (MHz in parenthesis) processors compared to MicroBlaze processor alone for various Powerstone and EEMBC benchmark applications.



Source: R. Lysecky and F. Vahid, "A Study of the Speedups and Competitiveness of FPGA Soft Processor Cores using Dynamic Hardware/Software Partitioning," Design Automation and Test in Europe (DATE), March 2005

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Maximizing lidar product information content for vegetation canopy structure

- Lidar data can be considered multi-valued, that is, multiple values exist at each location.
- To preserve information content and maximize flexibility for data analysis, data products should comprise multiple values for each raster, pixel or grid cell.

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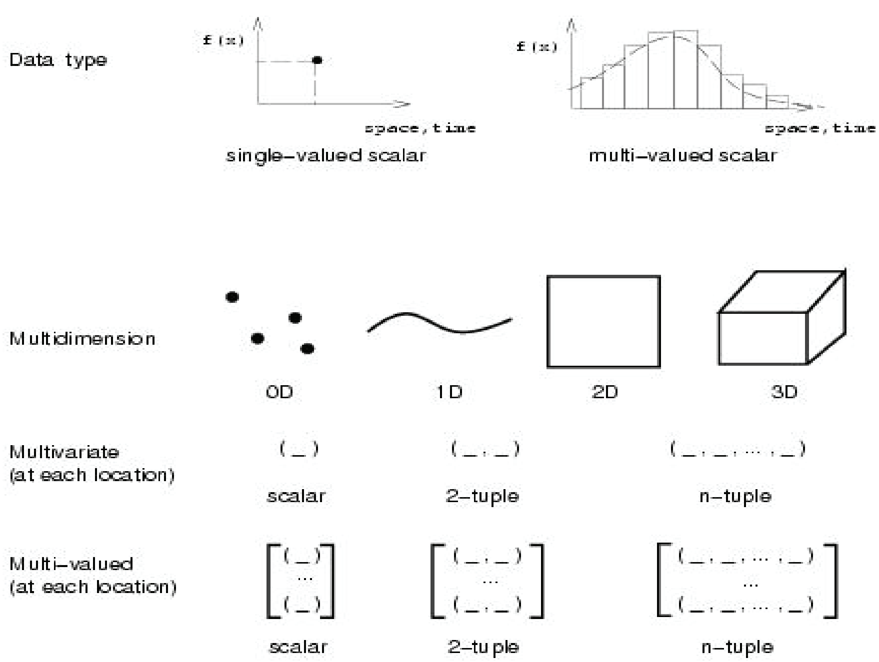
Multi-Valued Data



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Multi-valued data sets arise in many studies of bio and geo-physical phenomena

- A collection of values measured at a single location, such as those from a probabilistic model.
  - Several, alternative scenarios from different models or from different parameterizations of the same model
  - Multiple, conditionally simulated realizations from a spatial process
- A collection of values measured within an area.
  - Multiple returns of lidar pulses from each grid cell

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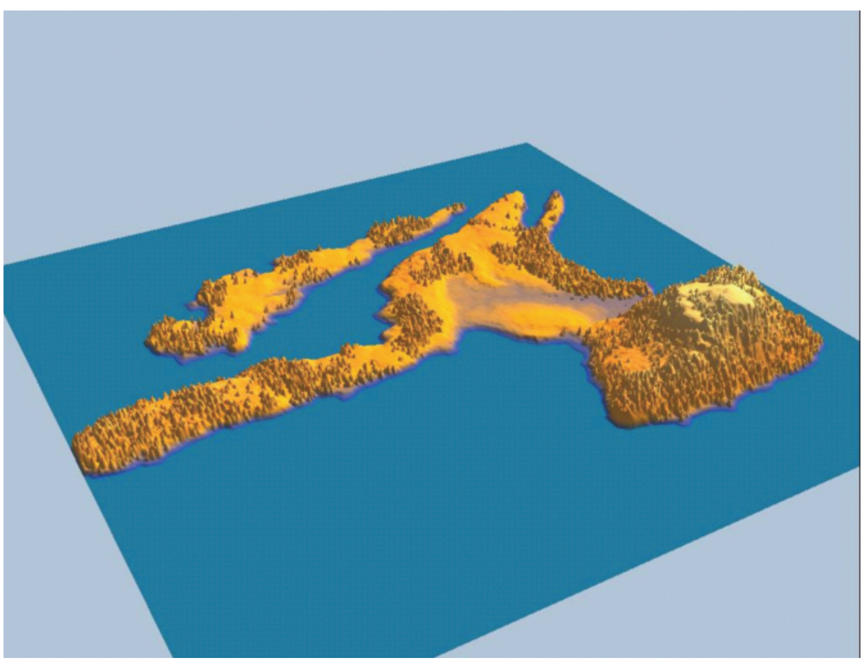

A graphical model of High Island forest, Alaska from airborne, multi-return lidar data (courtesy Marc Kramer).

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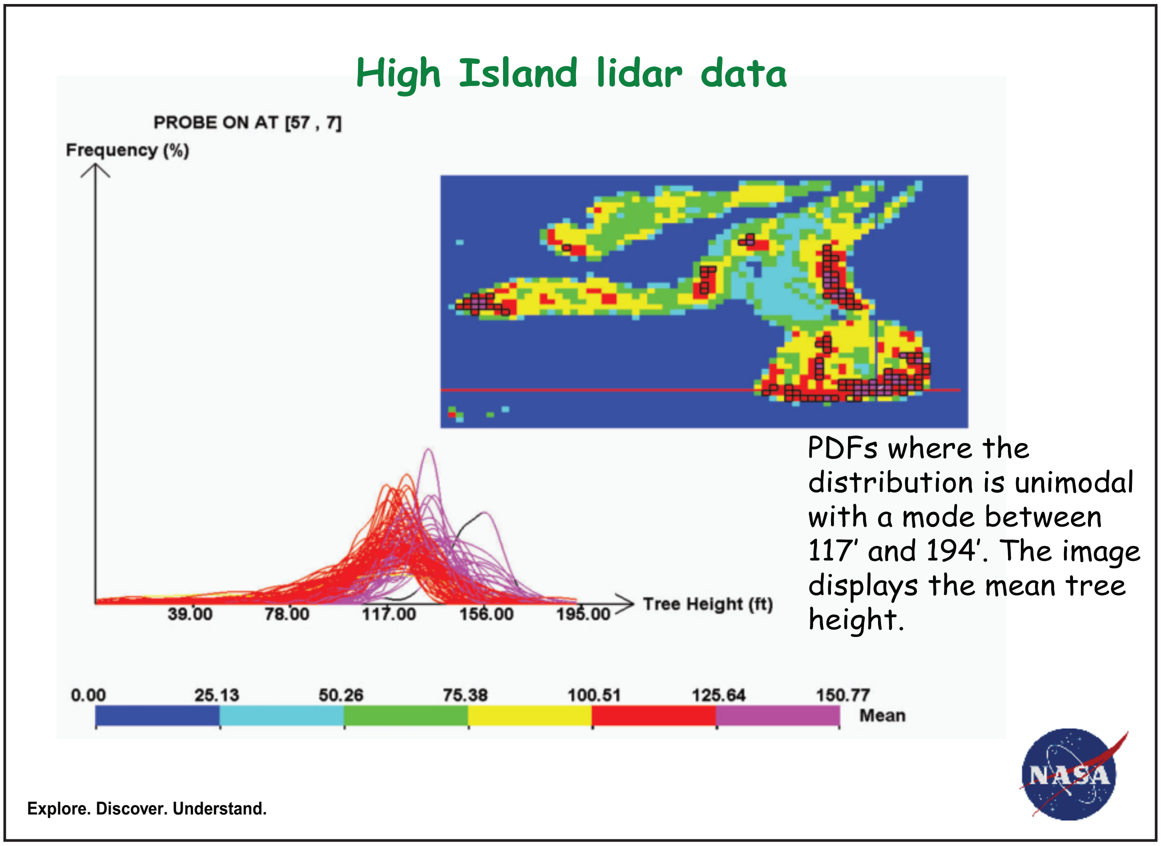
High Island lidar data
PROBE ON AT [57 , 7]
Frequency (%)
39.00
78.00
117.00
156.00
195.00
Tree Height (ft)
PDFs where the distribution is unimodal with a mode between 117' and 194'. The image displays the mean tree height.
0.00
25.13
50.26
75.38
100.51
125.64
150.77
Mean
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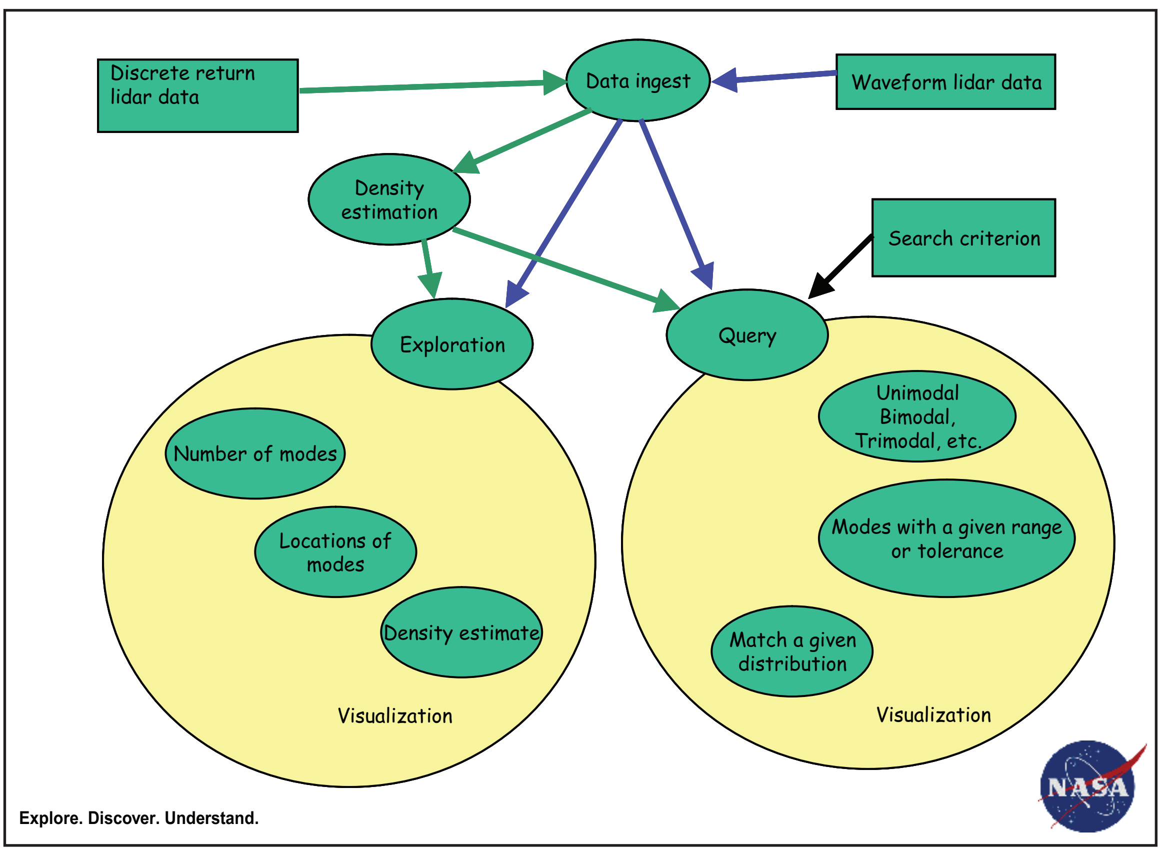
Discrete return lidar data
Data ingest
Waveform lidar data
Density estimation
Search criterion
Exploration
Query
Number of modes
Locations of modes
Density estimate
Visualization
Unimodal Bimodal, Trimodal, etc.
Modes with a given range or tolerance
Match a given distribution
Visualization
NASA
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The Biomass/Carbon Sampler –
A Small-Footprint Profiling Space LiDAR

January 10, 2006
Ross Nelson, Biospheric Sciences Branch, NASA-Goddard

Scientific Objective:

Measure forest height, height variability, and crown closure globally between ±70º latitude, without topographic constraints. Use these measurements to estimate above-ground forest biomass and carbon, by political unit (county, state, province, ecoregion, country, etc.) and land cover type on an annual basis for the entire globe.

Who Benefits?
- *global carbon modelers; may help us find the missing sink.*
- *Kyoto signatories and carbon traders.*
- *global climate modelers – characterization of surface roughness and spatial distribution of photosynthetically active vegetation.*

Why a small footprint LiDAR?

Given a flat, treeless surface, the following "apparent heights" will be generated due to topographic pulse spreading:

footprint size(m)	slope (deg)	height error(m)
1	20	0.4
	30	0.6
	45	1.0
2	20	0.7
	30	1.2
	45	2.0
***		
10	20	3.6
	30	5.7
	45	10.0
25	20	9.1
	30	14.4
	45	25.0

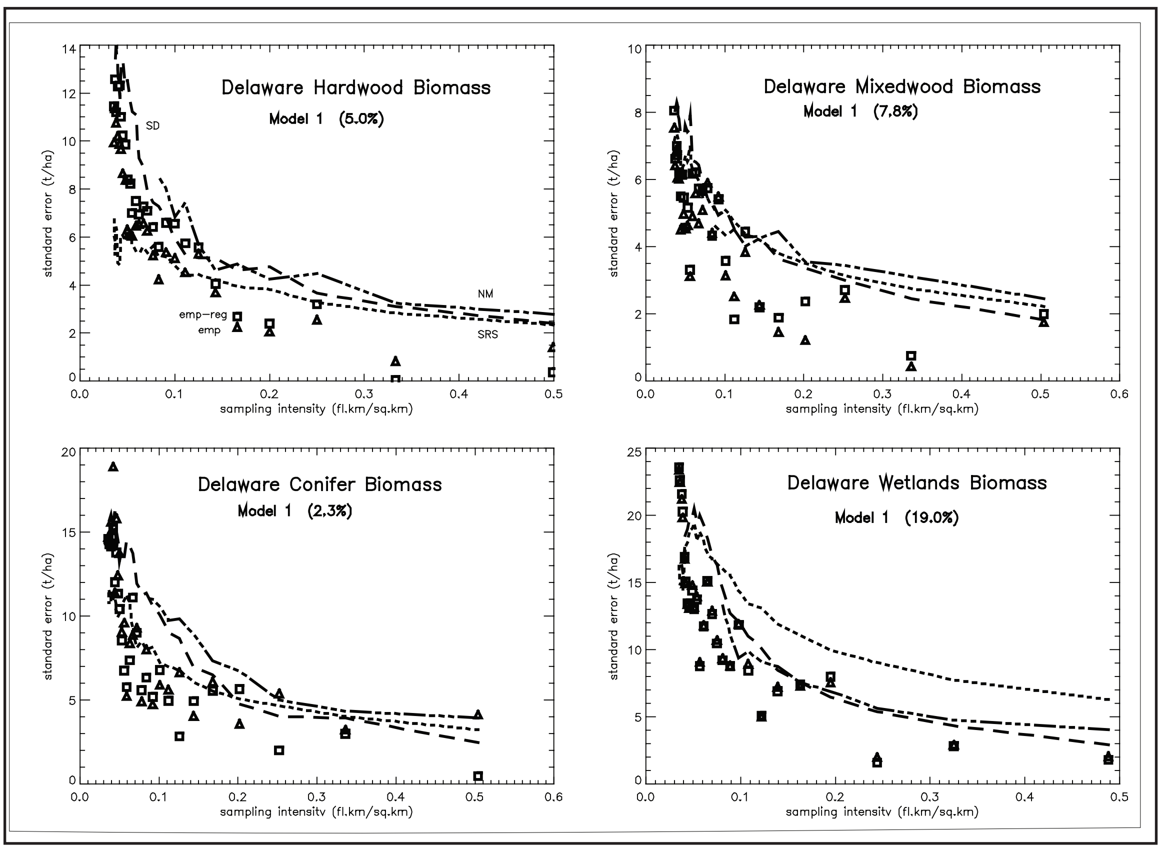
Science/Measurement Requirements:

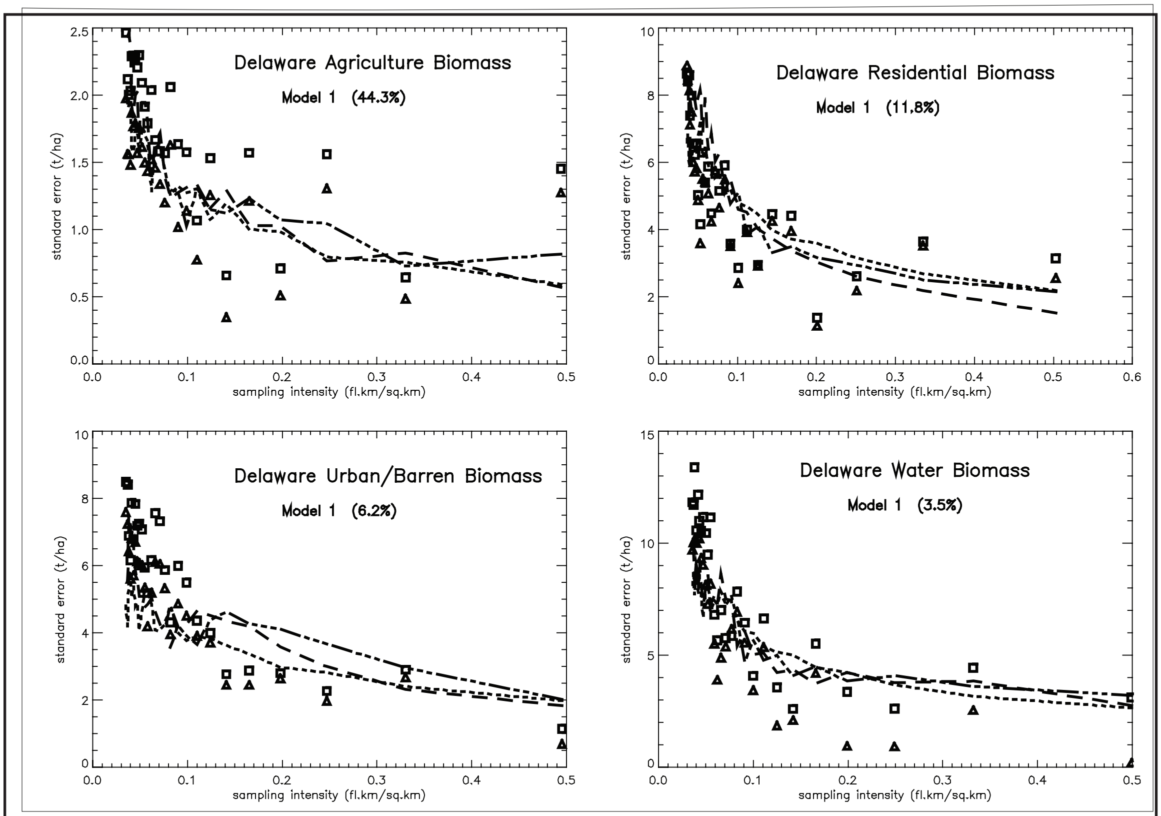
We want to estimate forests on all slopes globally.

- small footprint, 2m – profiling LiDAR (0.00334 mr divergence).
- post spacing (along-track), 2m, contiguous profiles.
- first/last return receiver. No waveform.
- 14.4 kHz transmitter, 0.8 kW power requirement w/3m mirror.
- 4 transects 4 km apart, global data collection in 83 days.
- multi-year mission, 3-5 years, with follow-ons to maintain C monitoring and vegetation migration (decades).
- repeat overpasses: tracking control within 20m at 95% LOC.
- geolocation accuracy of each pulse: within 5m at 95% LOC.
- ranging accuracy: <50 cm.

IT Requirement:

Data stream will be machine processed in conjunction with global GIS for county, state, province, country borders and LC types.
- automatically track ground, identify roofs, water crossings, and process height data to estimate biomass and carbon by political unit and land cover type.





The idea is, simply, to report AG C-stocks annually, globally, by land cover type, for areas as small as 2000 km^2. Use existing land cover maps to stratify.