

Solid-state 2-micron Laser Transmitter Advancement for Wind and Carbon Dioxide Measurements from Ground, Airborne, and Space-based Lidar Systems

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Abstract

NASA Langley Research Center has been developing 2-micron lidar technologies over a decade for wind measurements, utilizing coherent Doppler wind lidar technique and carbon dioxide measurements, utilizing Differential Absorption Lidar (DIAL) technique. Significant advancements have been made towards developing state-of-the-art technologies towards laser transmitters, detectors, and receiver systems. These efforts have led to the development of solid-state lasers with high pulse energy, tunability, wavelength-stability, and double-pulsed operation. This paper will present a review of these technological developments along with examples of high resolution wind and high precision CO₂ DIAL measurements in the atmosphere. Plans for the development of compact high power lasers for applications in airborne and future space platforms for wind and regional to global scale measurement of atmospheric CO₂ will also be discussed.



Solid-State 2-Micron Laser Transmitter Advancement for Wind and Carbon Dioxide Measurements From Ground, Airborne, and Space-Based Lidar Systems

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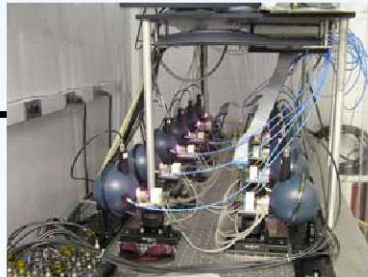
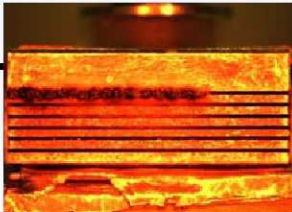
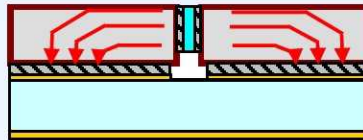
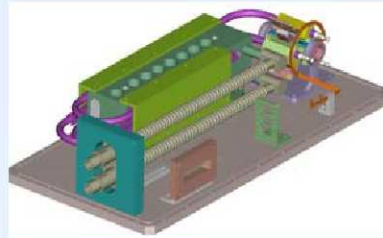
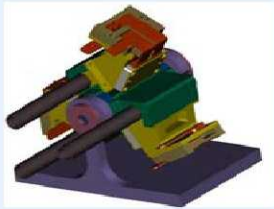
Outline

- Laser Risk Reduction Program
- Coherent Doppler Wind and CO₂ Lidar Transmitter and Field Measurements
- One Joule 2-micron Laser
- Conductively cooled Laser Development
- Conclusions



Laser Risk Reduction Program (LRRP)

Products



Approach & Partners

Upendra N. Singh, LaRC and William S. Heaps, GSFC – Co-PI

This is a joint LaRC-GSFC program. The primary output product is knowledge that will reduce risk of future NASA laser/lidar space missions. Investigations are primarily performed at the two Centers, with frequent inter-Center communication, collaboration, and review. Numerous partnerships with other agencies, academia, and industry have been initiated and are ongoing.

Description and Objectives

The objective is to reduce the risk of failure in future NASA laser/lidar space missions. Laboratory experiments will be conducted to gain understanding and demonstrate advancement of the high-energy, 1 and 2-micron laser; the laser diode arrays that pump the pulsed laser; wavelength conversion technologies to permit, wind, CO₂, and O₃ profiling; related detector and receiver technologies advancements; and lifetime effects from contamination, radiation, etc for space-based measurements.

Schedule & Deliverables

The LRRP began in FY02. It has already assisted the GLAS and CALIPSO lidar missions, and a RTF activity. Elements of LRRP should be continued since the knowledge is vital to the success of future multi-\$100M missions.

Applications/Mission

- Global tropospheric wind profile measurements
- Global CO₂ profile measurements
- Global O₃ profile measurements
- Global aerosol measurements
- Global cloud measurements
- Mars exploration



2-micron Wind/ CO₂ Lidar Transmitter

- **Coherent Wind Lidar**

- Choice of solid state 2-micron laser transmitter is attractive because of:
 - High energy, high efficiency, and long life time
 - Narrow linewidth gives high measurement accuracy
 - Eye safe wavelength allows global coverage

- **CO₂ DIAL Lidar**

- 2-micron solid state laser technology developed for wind detection is applicable for CO₂ detection
- Narrow spectral absorption lines near 2-micron
- 2-micron laser provides tunability needed for DIAL



Coherent Doppler Lidar

Measurements:

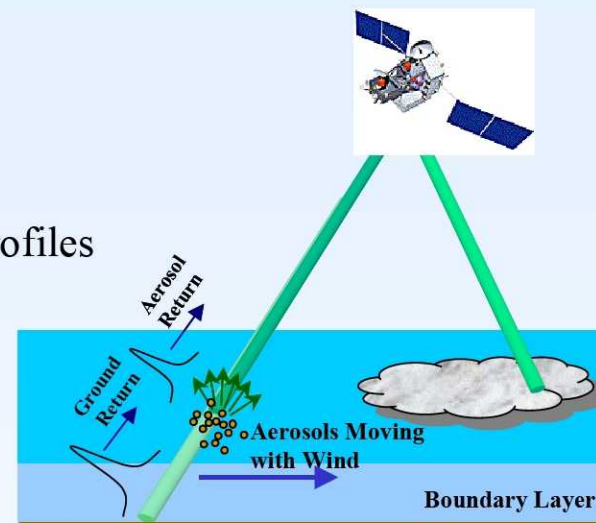
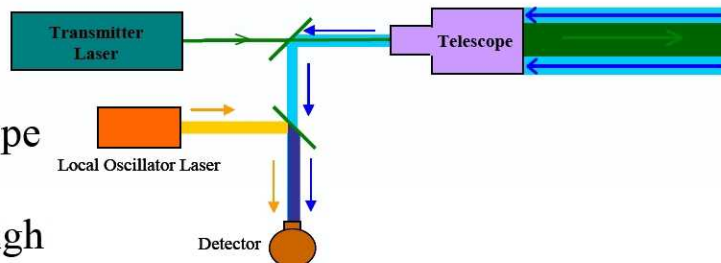
- Boundary Layer and Lower Troposphere Wind Velocity Profiles
- Cloud Height and Velocity
- Aerosol Concentration
- River Flow

Instrument Description:

- Transmit medium duration laser pulses ($\tau_p > 150$ nsec)
- Reflected photons from atmospheric aerosols are collected by a telescope
- Wavelength of the backscattered light is Doppler shifted by aerosols moving with wind
- Doppler shift is measured using heterodyne detection similar to FM radio

Instrument Attributes:

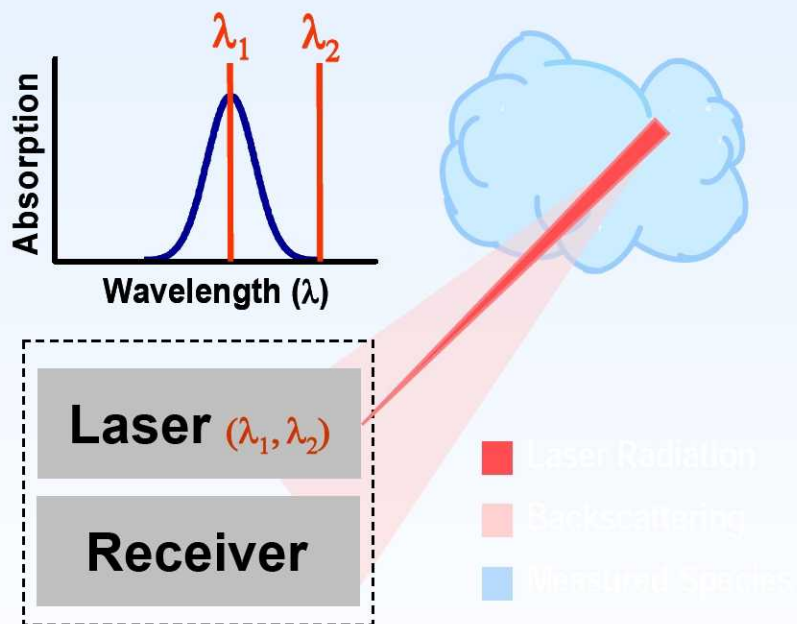
- Scanning
- Sub-Meter class Telescope
- 2-micron Laser
- Level of Complexity: High





Differential Absorption Lidar (DIAL) Technique and Advantages

DIAL Concept



Advantages:

- High vertical and horizontal resolution
- DIAL data permit direct inversion and absolute concentration measurements
- Simultaneous species and aerosol profiles, and cloud distributions
- Day and night coverage and no dependence on external radiation

DIAL technique for Atmospheric CO₂ measurements requires suitable absorption lines; narrow-band, tunable, and line locked lasers; high efficiency and low noise detectors



2.05-micron laser developments for DIAL profiling of CO₂

- Pulsed laser for range resolved profiling
- Double pulsed operation to sample the same air mass by on- and off-laser pulses
- Wavelength stability and spectrally narrow output
- Line-locking with respect to a selected CO₂ line
- Operation on a side of the line for optimum absorption cross-section selection



Why DIAL?

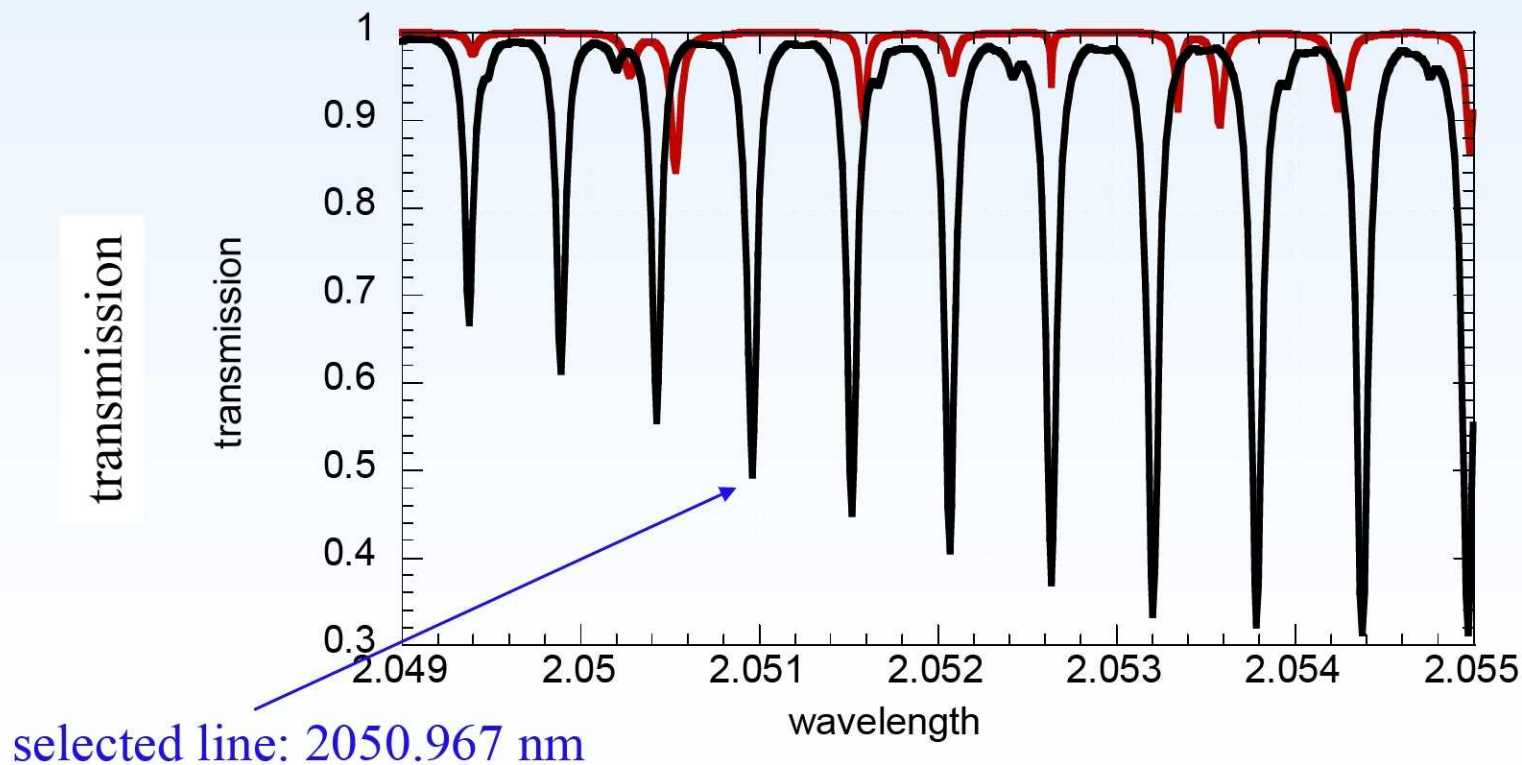
- Uncertainty in prediction of carbon cycle is one of the leading sources in climate projections
- Quantification and understanding of carbon sources and sinks is a major priority
- DIAL technique offers potential to provide tropospheric *profiles* of CO₂
- Sources and sinks of CO₂ are near surface
- Mixing ratio differences ~10 ppm between ABL and free troposphere, day night, and across weather fronts
- DIAL precision 1-2 ppm (<0.5%), with 0.5 to 1 km vertical resolution, near surface to free troposphere (4-5 km), and ~30 min time resolution data needed for ground-based DIAL systems
- Resolution of boundary layer, free-, mid- and upper-tropospheric CO₂ over regional scales (300-500 m) needed from space-based systems



Ho:Tm:YLF Tuning Range



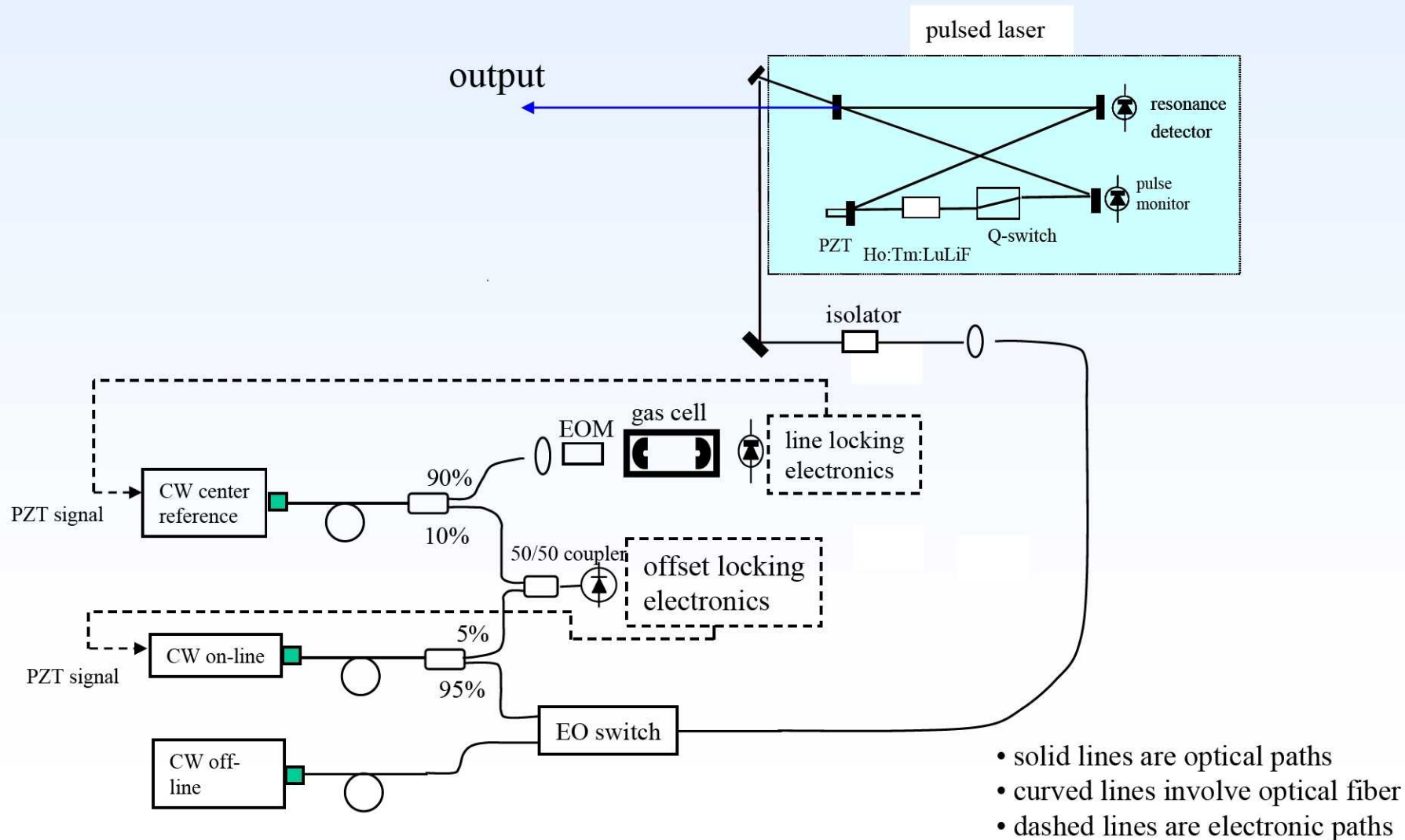
HITRAN data over 1 km vertical path at STP.



Lines: allow optimum sampling of low troposphere, low temperature sensitivity, and have minimum interference from other species

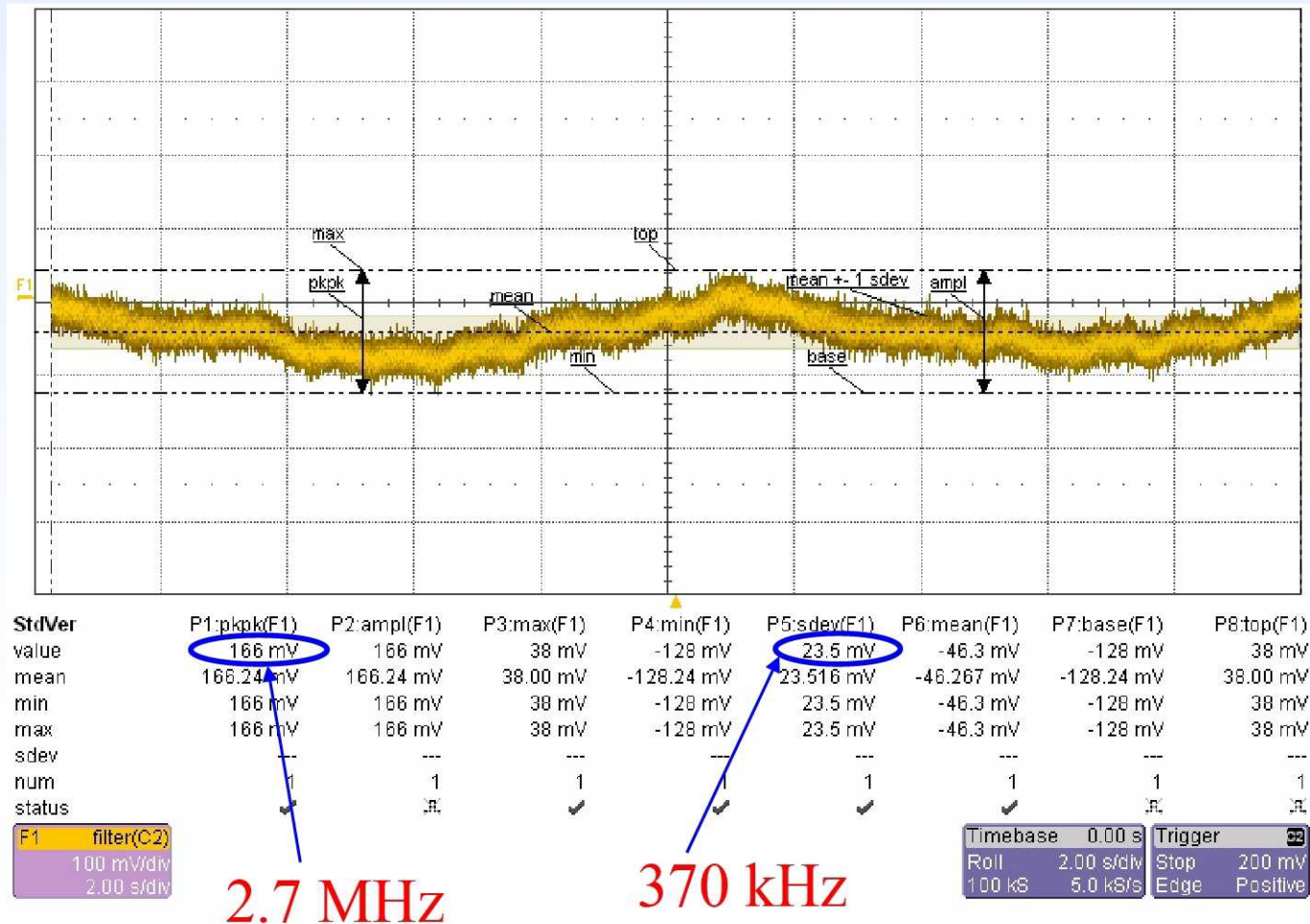


Transmitter System Architecture





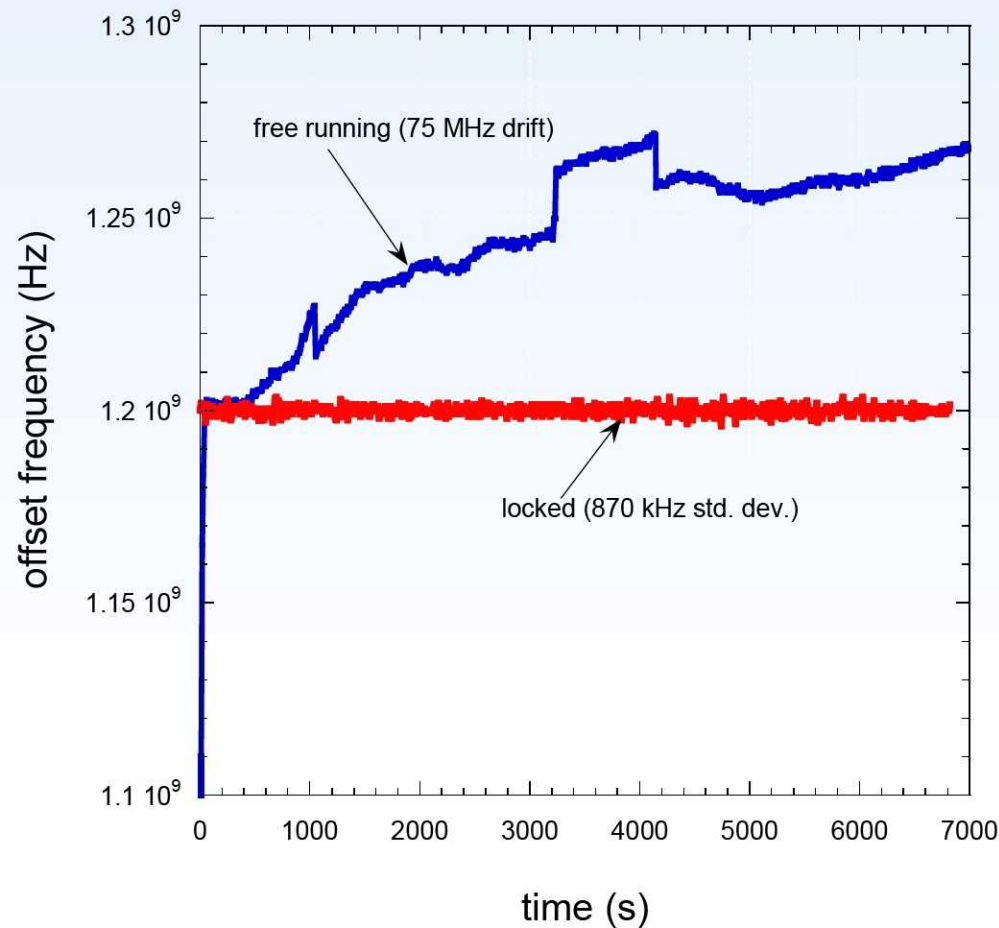
Line Center Lock Characterization



10 times tighter lock by new FM technique.



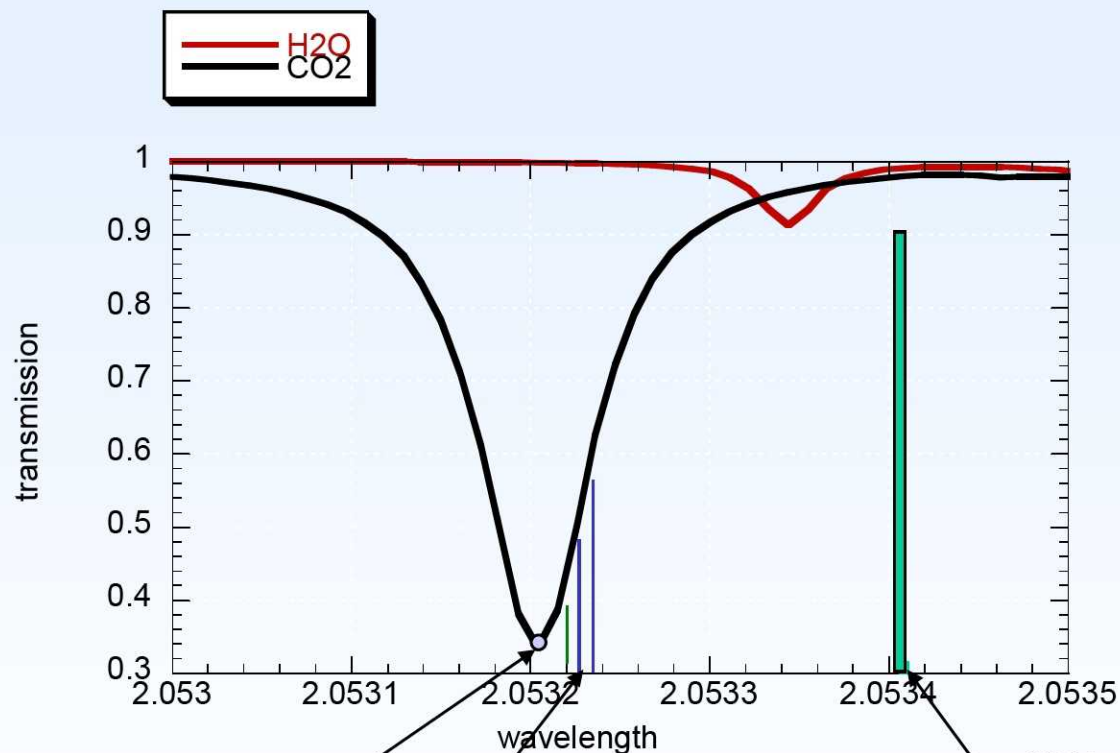
Side Line Offset Locking Characterization



- Electronic control holds an offset from center-line locked laser.
- Offset can be electronically programmed.
- Test here assesses quality of offset lock set for 1.2 GHz (37.3 pm).



Result: Fine Wavelength Control



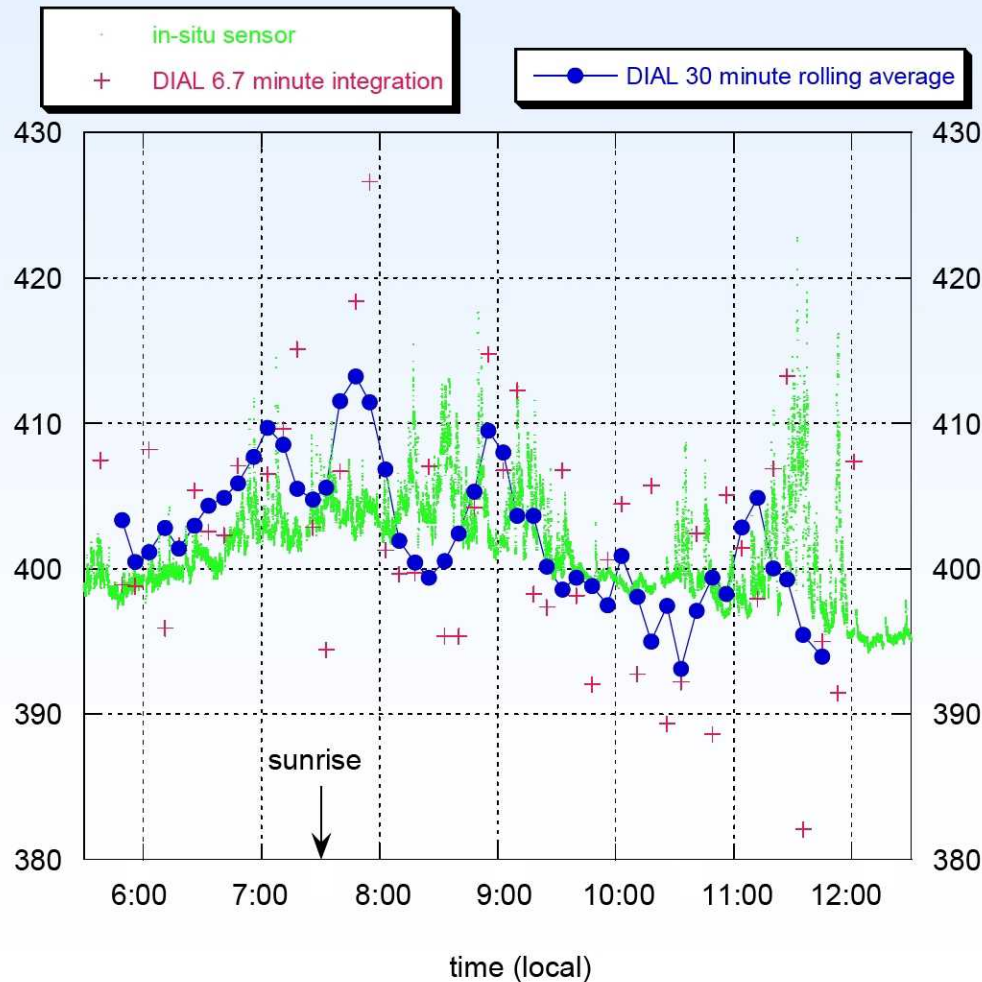
center line (locked):
2053.204 nm

side line (locked):
1) 2053.220 nm
2) 2053.227 nm
3) 2053.233 nm

off line (drifting):
2053.403—2053.410



Atmospheric Testing at LaRC—Horizontal Column



- DIAL at better than 0.7% precision for column over $\frac{1}{2}$ hour (9000 pulses).
- range-resolved at better than 2.4% on 500-m bins and 6.7 minutes (2000 pulses).
- Accuracy established by incorporating new spectroscopic data
- Two sensors show the same trend and occurrence of CO₂ perturbations.
- Excellent agreement between DIAL and *in-situ* sensor.



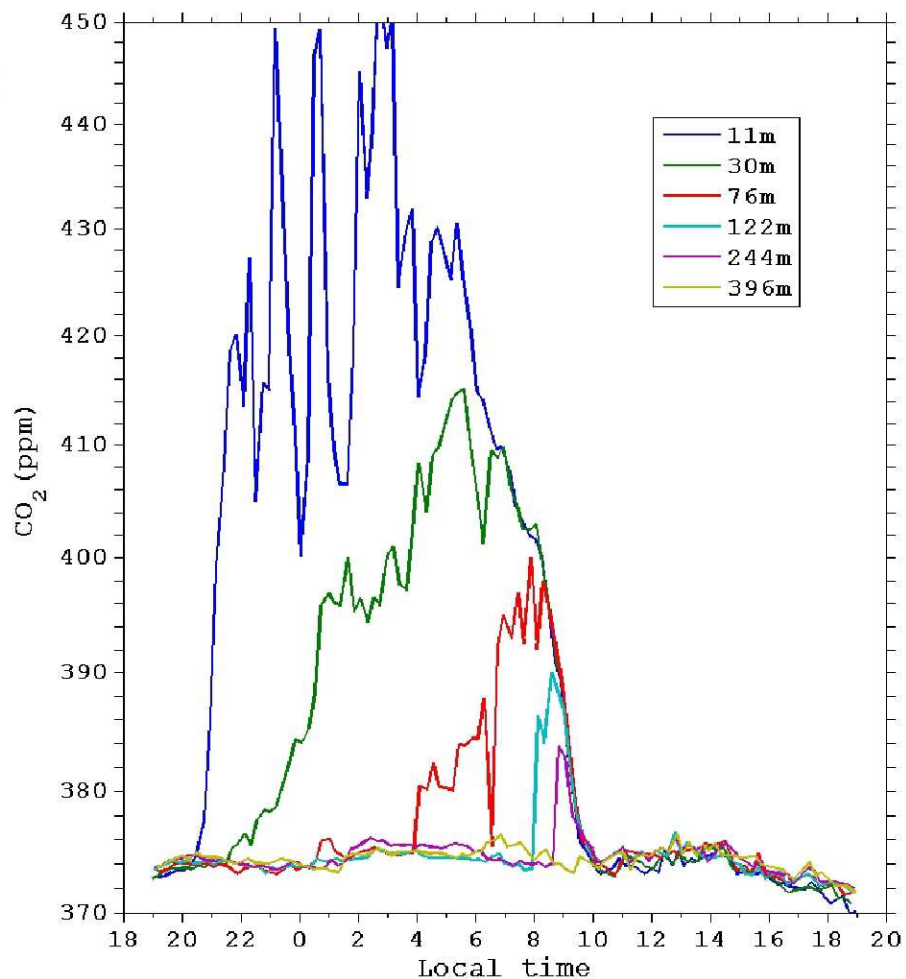
Field Testing



- Lidar setup in June 2007 at WLEF site in Wisconsin.
- Tower is outfitted with CO₂ and meteorological sensors for assessing lidar performance in profile measurements.
- Cooperative work with Penn State, State of Wisconsin, and NOAA.



WLEF Tower

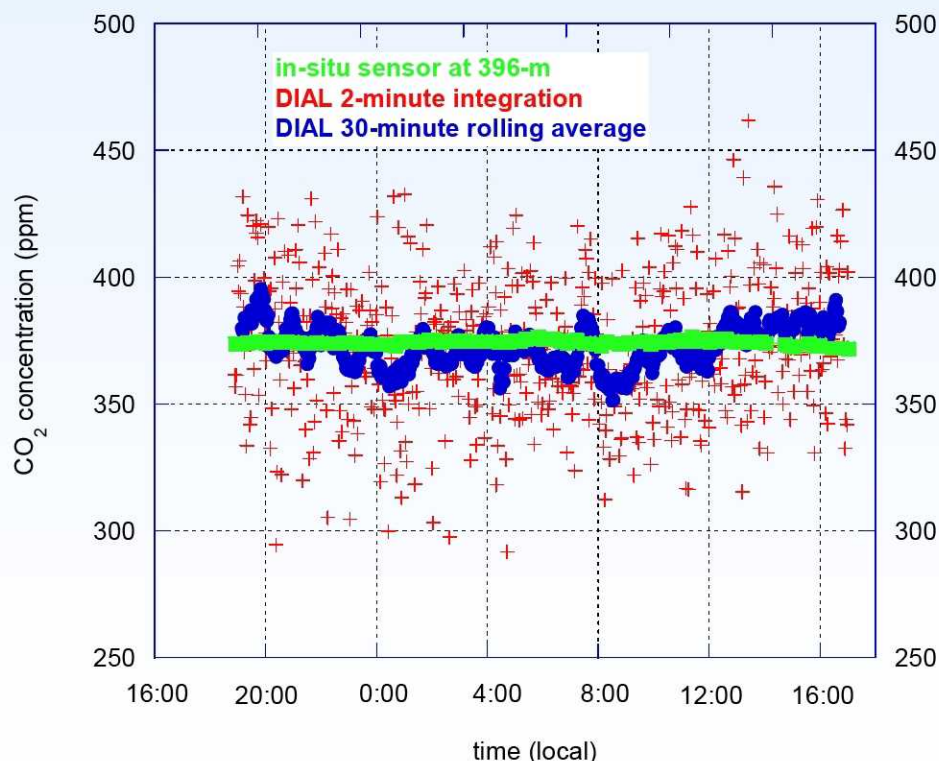


- data provided by Penn State and NOAA ESRL.
- diurnal variation can be quite large close to the ground.
- sensors at high altitudes useful for comparing with DIAL.



Atmospheric Testing at WLEF—Vertical Column

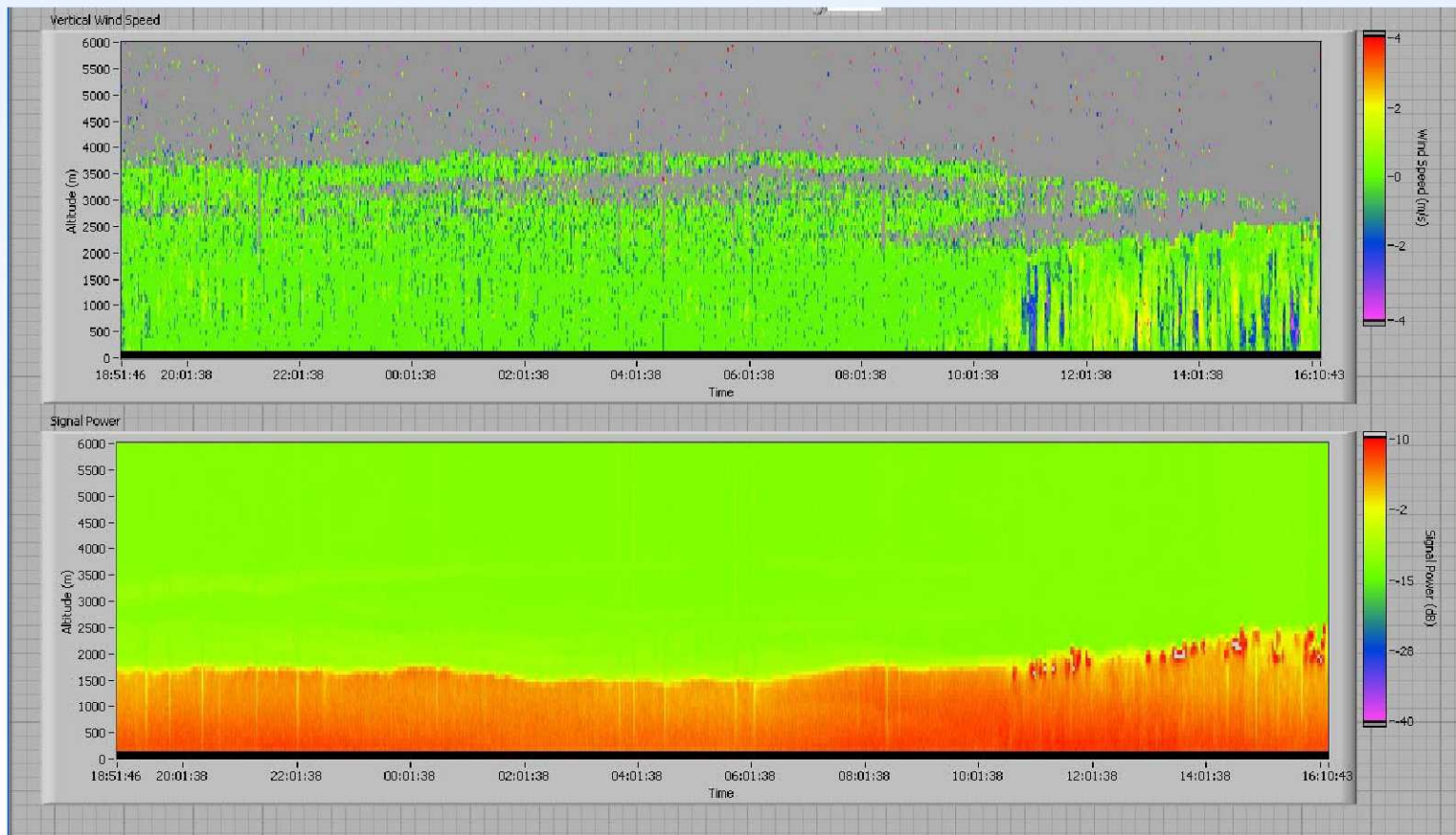
June 13-14, 2007



- DIAL pointed vertically.
- tower *in-situ* sensors show little CO₂ variation at 396-m and higher.
- DIAL vertical column expected to also measure little variation.
- 7.9 ppm RMS difference between two sensors.
- DIAL measurements interleaved with Doppler wind measurements.
- optimal processing still under development.



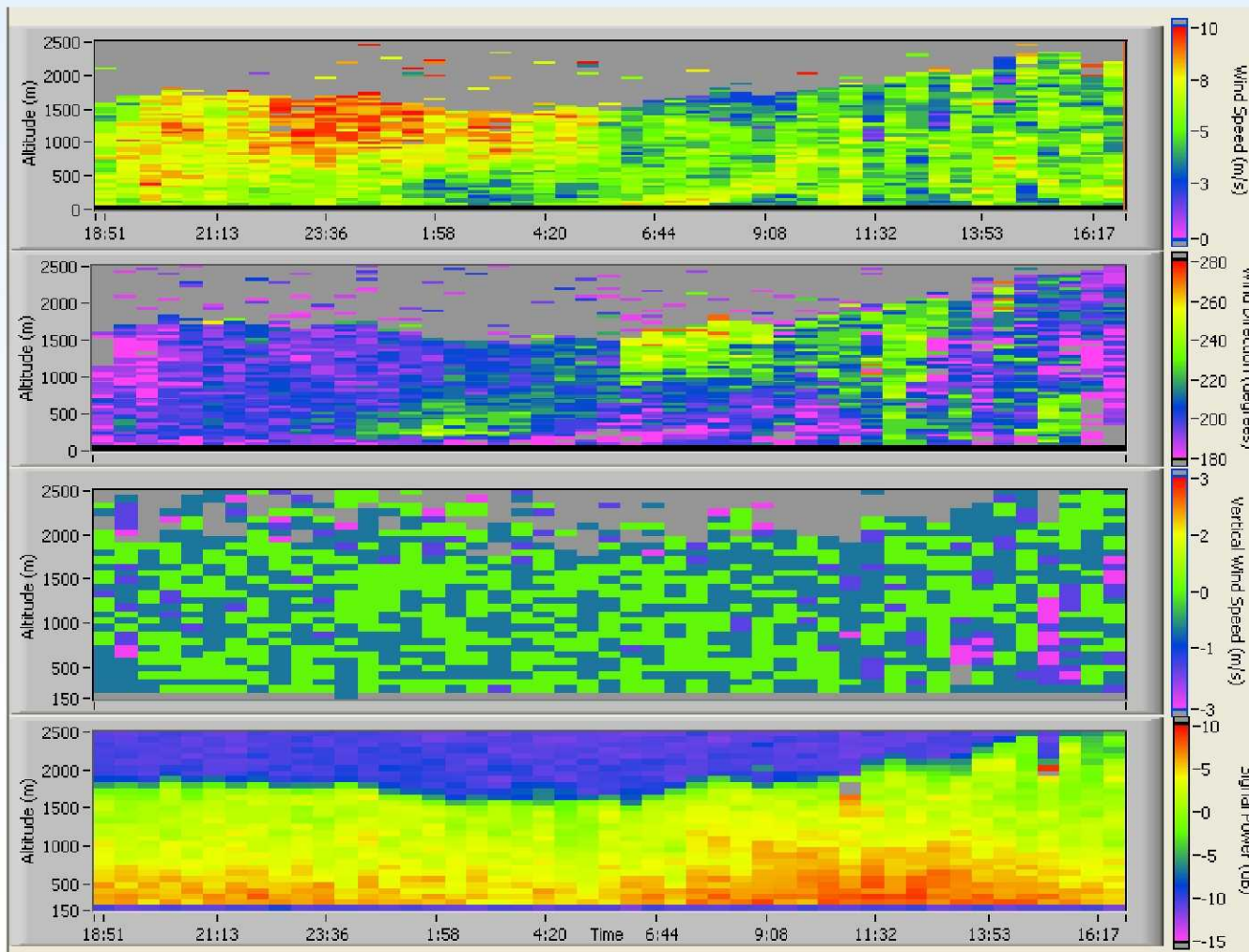
Simultaneous Vertical Wind



same time period of CO₂ measurements of previous slide



Horizontal Wind Profile



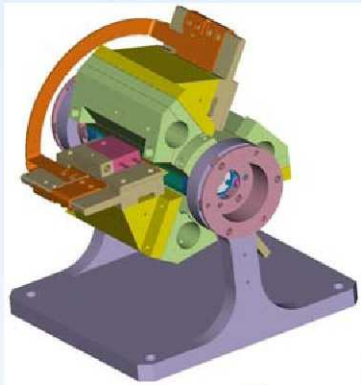
- 3D wind measured every $\frac{1}{2}$ hour.
- same time as previous 2 Slides.



Technology Maturation Example

Technology Enables: Measurement of global CO₂ and/or 3-D Winds from a space platform

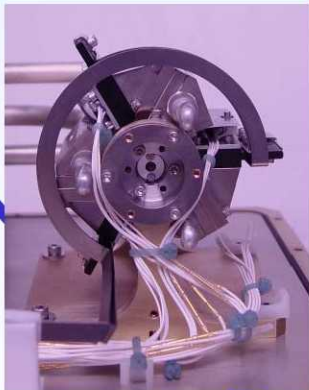
A fully conductively cooled 2-micron solid-state pulsed laser has been demonstrated for the first time.



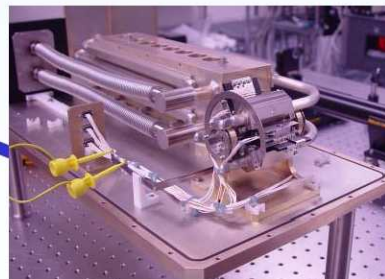
**Analysis &
Design**



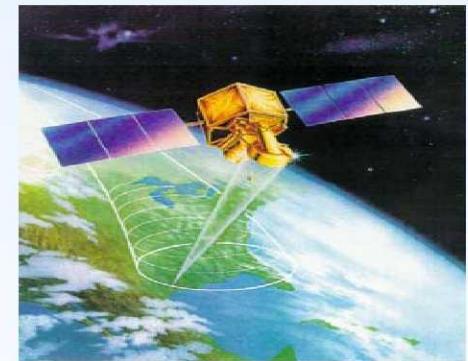
Quantum Mechanical Modeling



Fabrication



System Integration



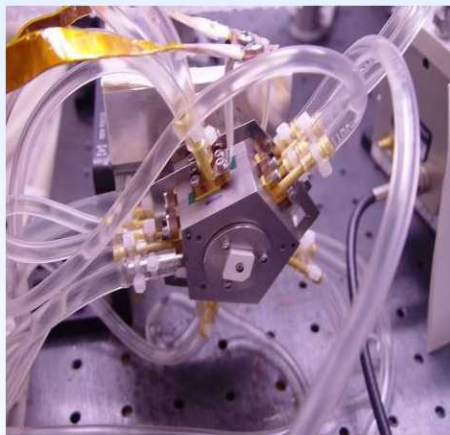
**Space Qualifiable
Design**



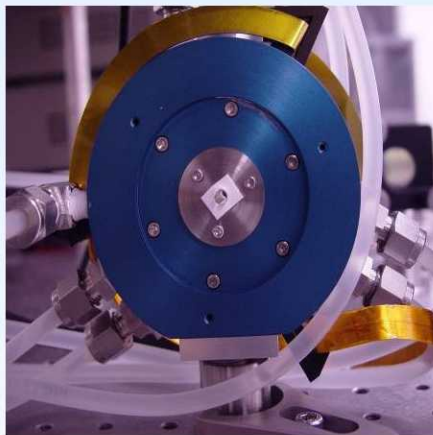
**Testing and
Model Verification**



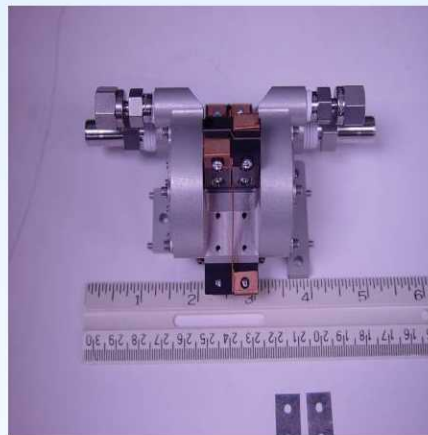
Laser Head Design Advancement



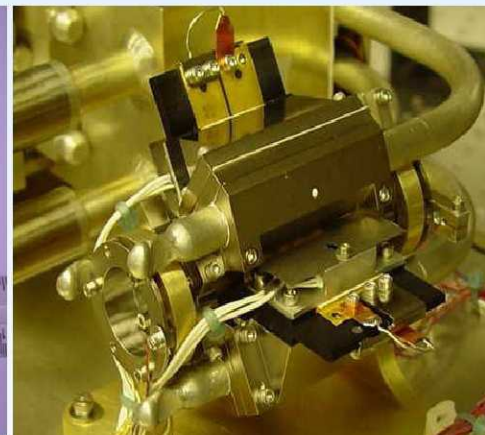
10 Diode Arrays
22 water channels



6 Diode Arrays
8 water channels



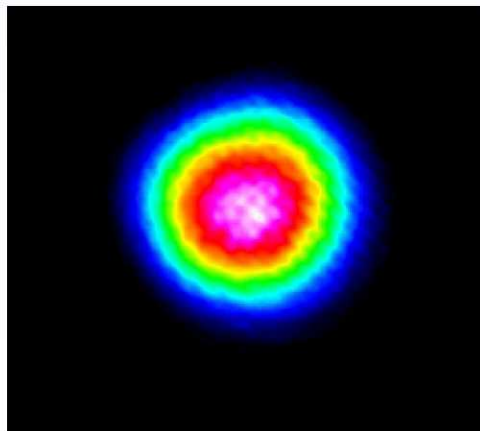
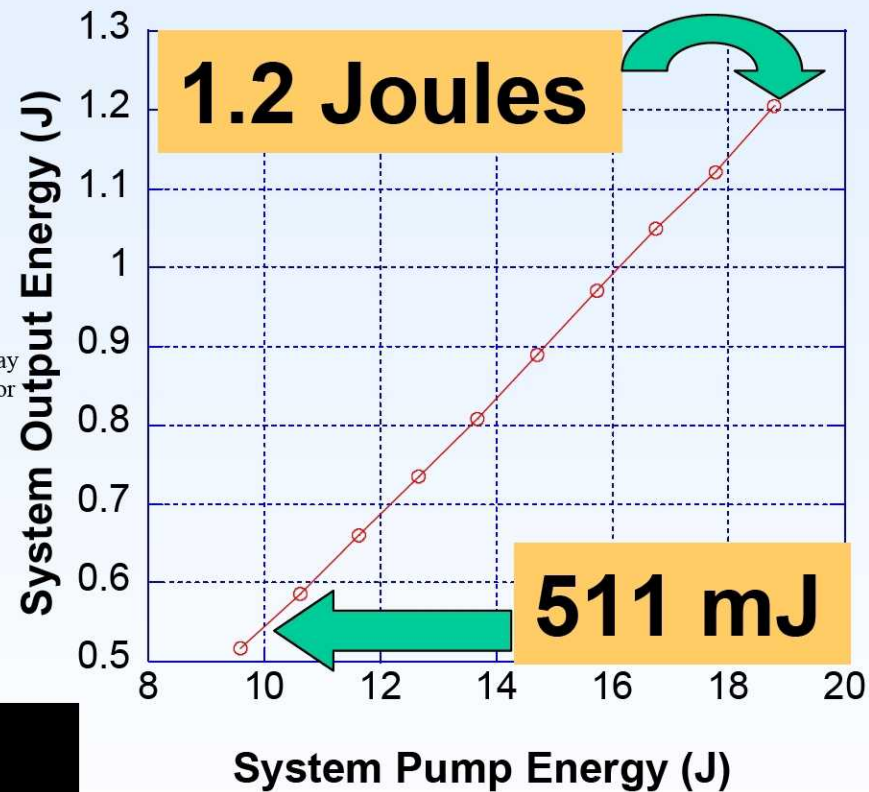
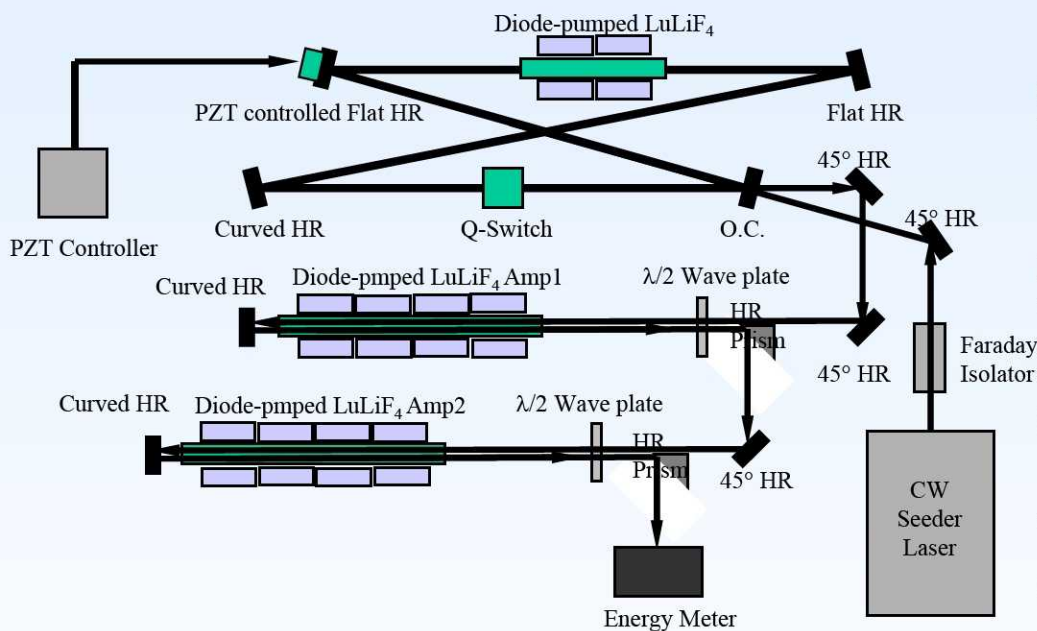
6 Diode Arrays
4 water channels



6 Diode Arrays
Conductive cooled



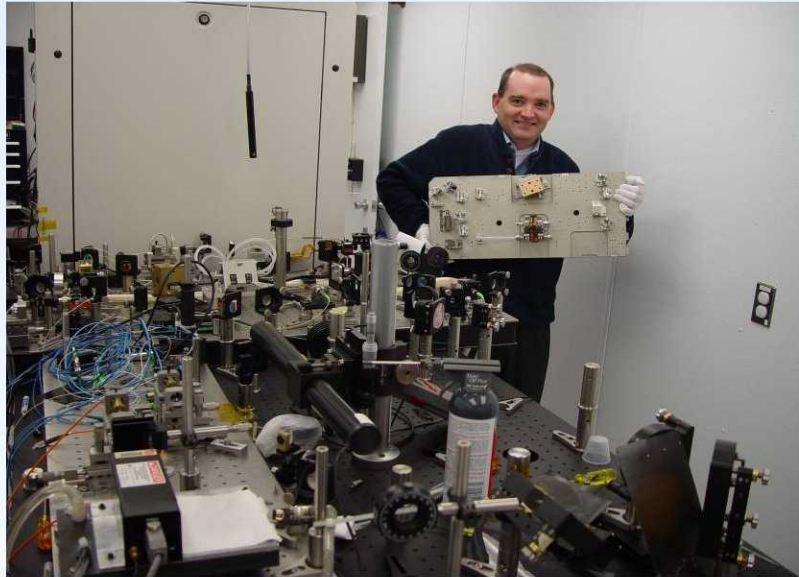
World Record 2-micron Laser





Hardware Size Reduction

Before & After



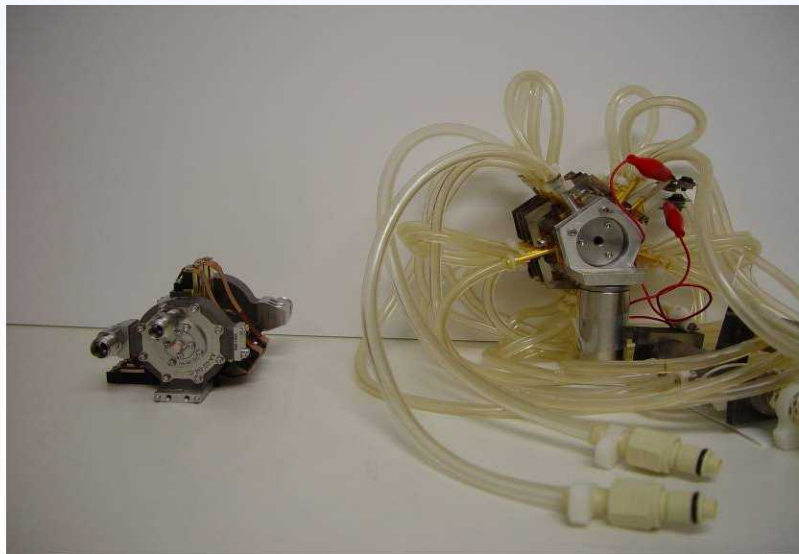
**2-Micron Coherent
Doppler Wind Lidar
Transceiver:**

**Footprint area
reduction = factor of 6**



Coherent Lidar System Electronics:

**8 separate electronic boxes to 1
electronic box with added capability**



**2-Micron Laser Oscillator
Module:**

**42 water connections
lowered to 4 water
connections**

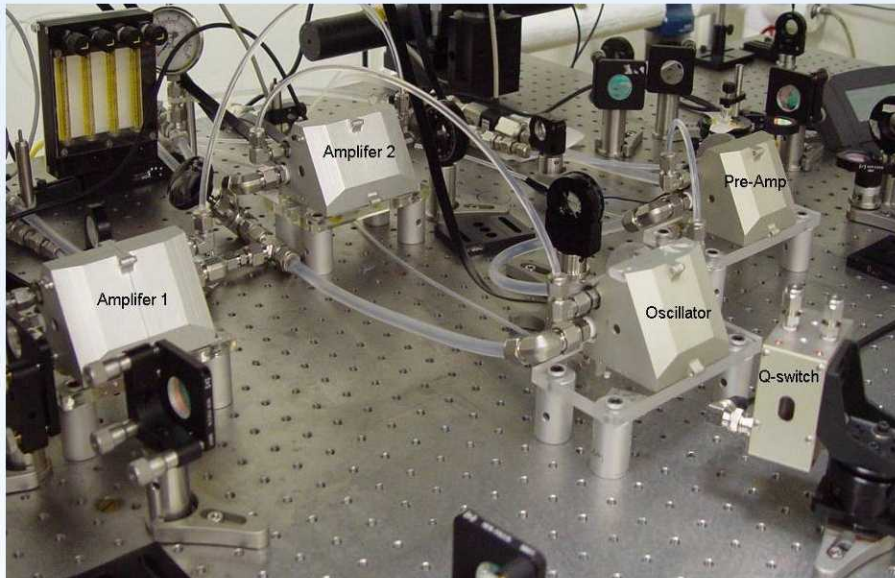
**Output power
improvement = factor of 9**



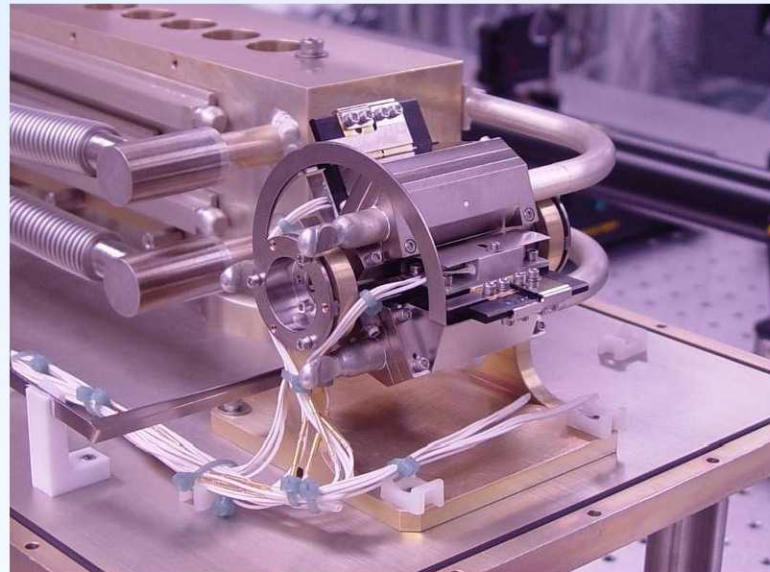


2-Micron Laser Development Enables 3-D Winds DS Mission

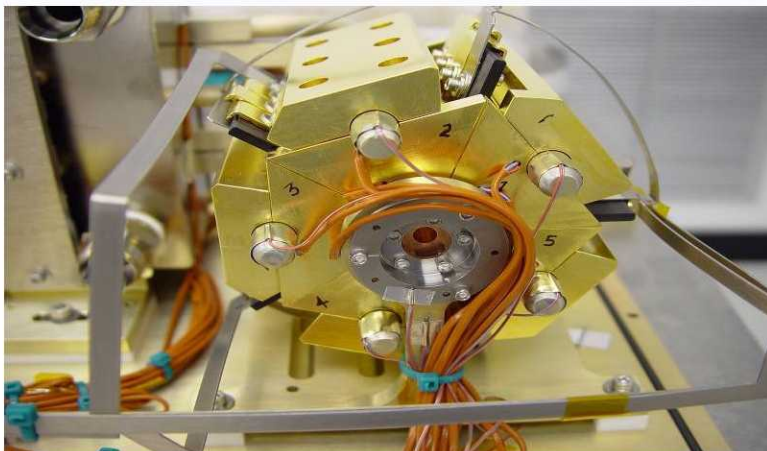
1-Joule System – World Record



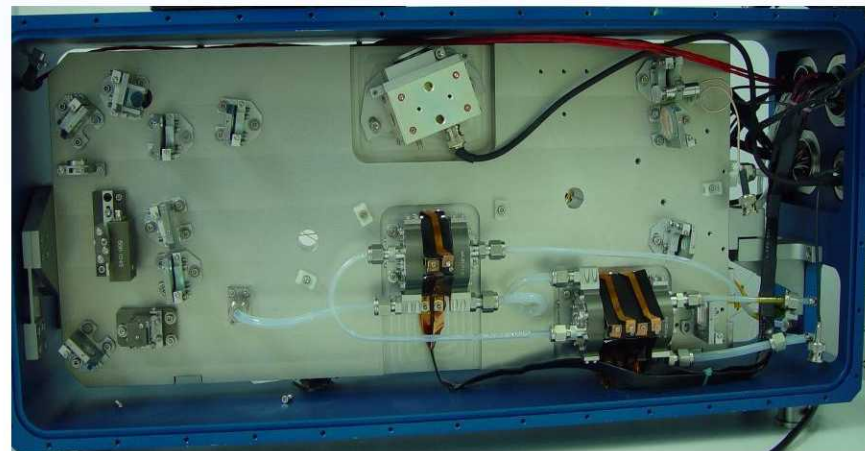
Conductive-Cooled Oscillator



Conductive-Cooled Amplifier



300 mJ Compact 2-Micron Laser





Conclusion

- Technologies developed for CO₂ DIAL
 - Tunable, lockable transmitter.
 - Direct-detection receiver (being integrated now)
 - Coherent heterodyne detection (used for atmospheric tests).
- Atmospheric testing progressing
 - Benefit of varying optical depth with side-line tuning.
 - **Less than** 0.7% precision measured.
 - Much characterization alongside *in-situ* sensors.
- Developed conductively cooled master oscillator and power amplifier (MOPA) system.
- Through better thermal management, demonstrated 200% improvement in amplifier gain
- Current performance indicates that conductively cooled power oscillator can deliver wind quality beam with energy of >250mJ at the repetition rate of 5-10 Hz.
- Also, in double-pass configuration LaRC developed conductively cooled amplifier can amplify the 250mJ pulses to 1J pulses for 3-D operational mission