Collaborators

ITT

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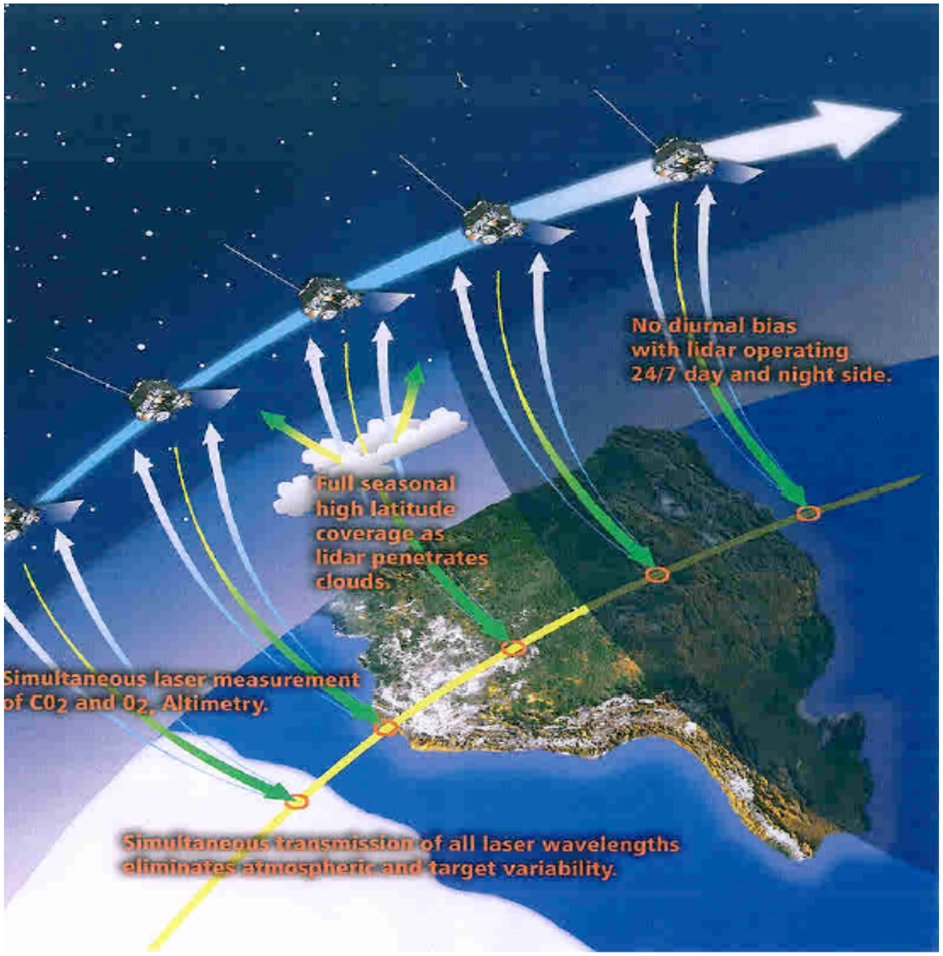
Outline

- ITT LAS overview
- ITT's flight validated CO_2 engineering development unit
- O_2 amplifier development overview
- First generation Raman amplifier
- Initial testing of first year amplifier
- Retrieval tools development for XO_2
- Initial results
- Current and future efforts
- Summary

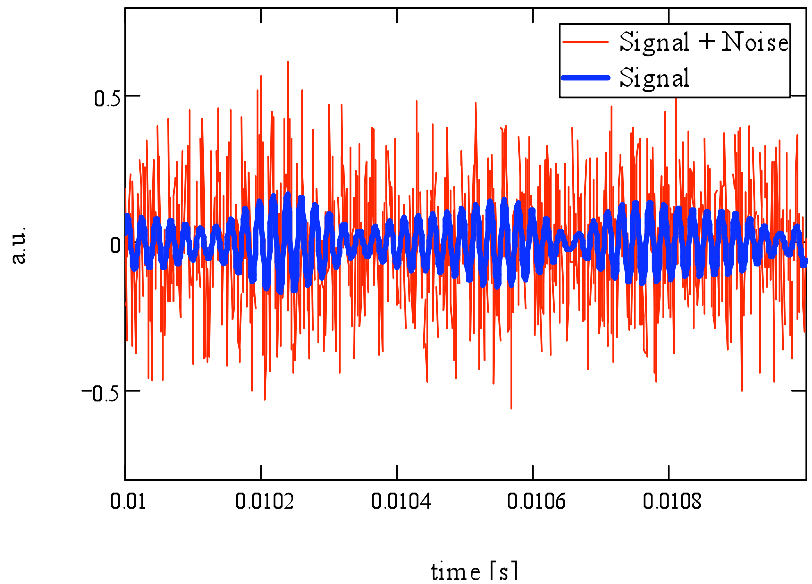
Active Sensing of CO_2 Emissions over Nights, Days and Seasons [ASCENDS]: A Multi-Functional Fiber Laser Lidar for Climate Variability and Atmosphere Composition

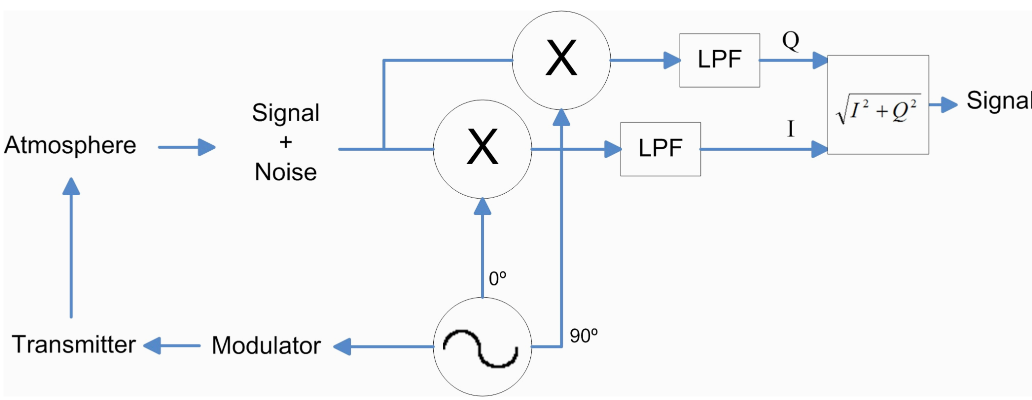
- Comprehensive Instrument Suite:
  - CO_2 Lidar
  - O_2 Lidar
  - PN Laser Ranger
  - Passive Temperature Sounder
  - Passive CO Sensor
  - Dedicated Payload



"Atmospheric pressure/density effects on deriving the CO2 mixing ratio columns can be addressed by a combination of simultaneous CO2 and O2 density column measurements to the surface/cloud tops, or possibly with surface/cloud top altimetry measurements from a lidar in conjunction with advanced meteorological analysis for determining the atmospheric pressure profile across the measured CO2 density column. The concurrent on-board O2 measurements are preferred and can be based on measurements using an O2 absorption line in the 0.76 or 1.27 μm band."
Quote From NRC Decadal Survey 2007

Synchronous/Lock-In Detection

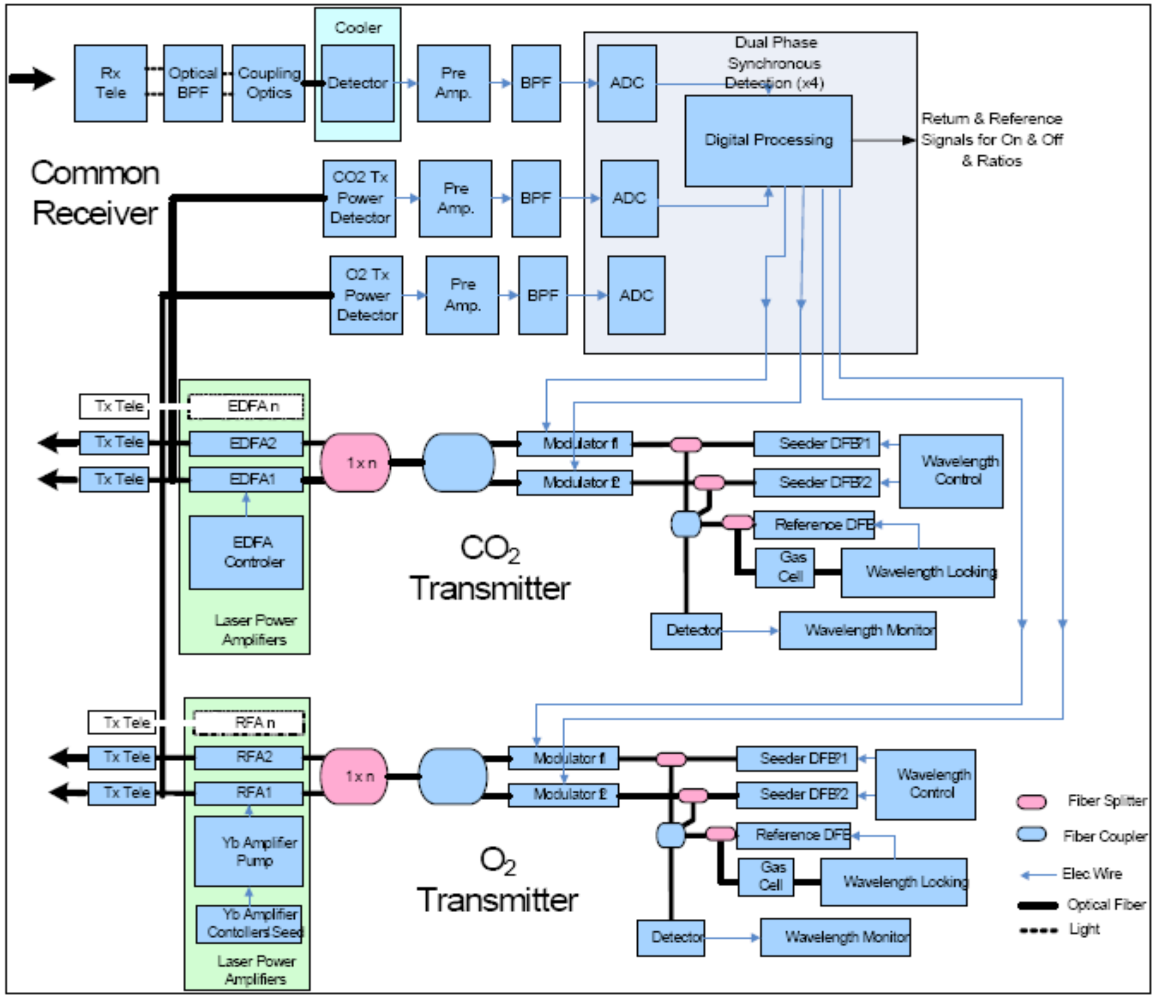




- The input consists of the N -modulated signals plus noise.
- The lock-in method multiplies the raw signal by pure sine and cosine waves at the n reference frequencies.
- The root sum squared of the product of these multiplications yields a DC output signal proportional to the components of the signal whose frequencies are exactly at the reference frequencies.
- This method provides significant rejection of the broad background noise and allows small signals to be picked out of a large background signal.
- This implementation is not sensitive to phase. This enables the use of multiple fiber amplifiers and renders the measurement insensitive to variations in topography.
- We are operating with modulation frequencies in the region of 50kHz with noise bandwidths of ~5Hz per lock-in signal.

Laser Absorption Spectrometer Functional Architecture

- **Simultaneous transmission of all wavelengths eliminates significant source of error from fast changes in target reflectivity, reduces pointing requirements, converts most noise to common mode**
- **Use of one receiver chain (for CO2 and O2) and modulation to separate on/off wavelengths eliminates bias and drift which arise with separate optical paths, detectors, and electronics**
- **Large-area HgCdTe APD provides gain of ~1000 with a near unity excess noise factor**
- **Non-diffraction limited, incoherent receiver enables fiber coupling and multiple low-cost collectors, which can provide several meters of area at low cost**
- **Multiple 5 watt EDFAs with independent, but co-aligned, Outputs can be used**



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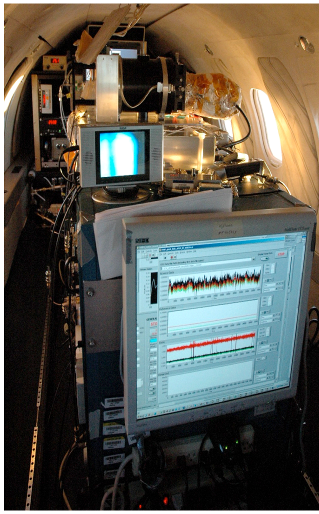
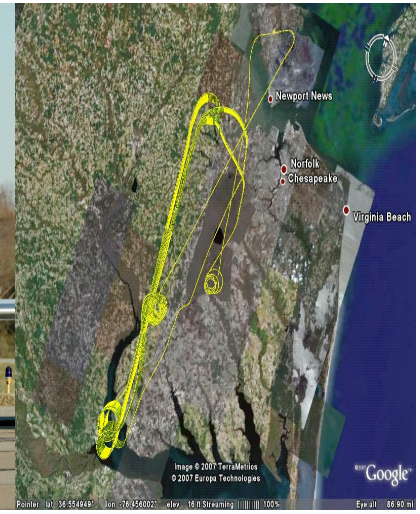
August 5, 2010

ESTO Earth Science Technology Office

Flight Demonstrated CO_2 EDU





Since 2004 the ITT CO_2 instrument has successfully completed over 50 sorties beginning with a balloon engineering test flight, then 5 campaigns in a Lear-25 and most recently on a NASA UC-12. Hundreds of hours of ground-based field testing have also been conducted.

Summer 2009 Coordinated Airborne Flight Tests

LaRC/ITT MFLL CO_2 Lidar Instrument in NASA UC-12	GSFC Airborne CO_2 Lidar Instrument in NASA Lear-25	JPL Airborne CO_2 Lidar Instrument in Twin Otter

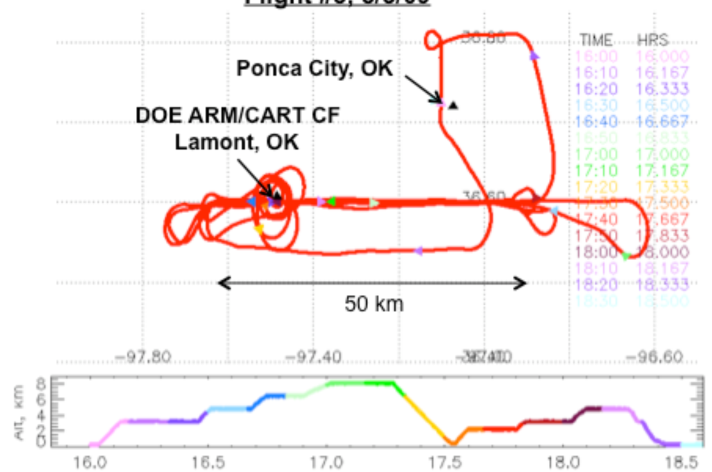
- LaRC & ITT team, LaRC aircraft
- Ed Browell/LaRC, Team Leader

- GSFC team, NASA Glenn aircraft
- Jim Abshire/GSFC, Team Leader

- JPL team, Twin Otter aircraft
- Gary Spiers/JPL, Team Leader

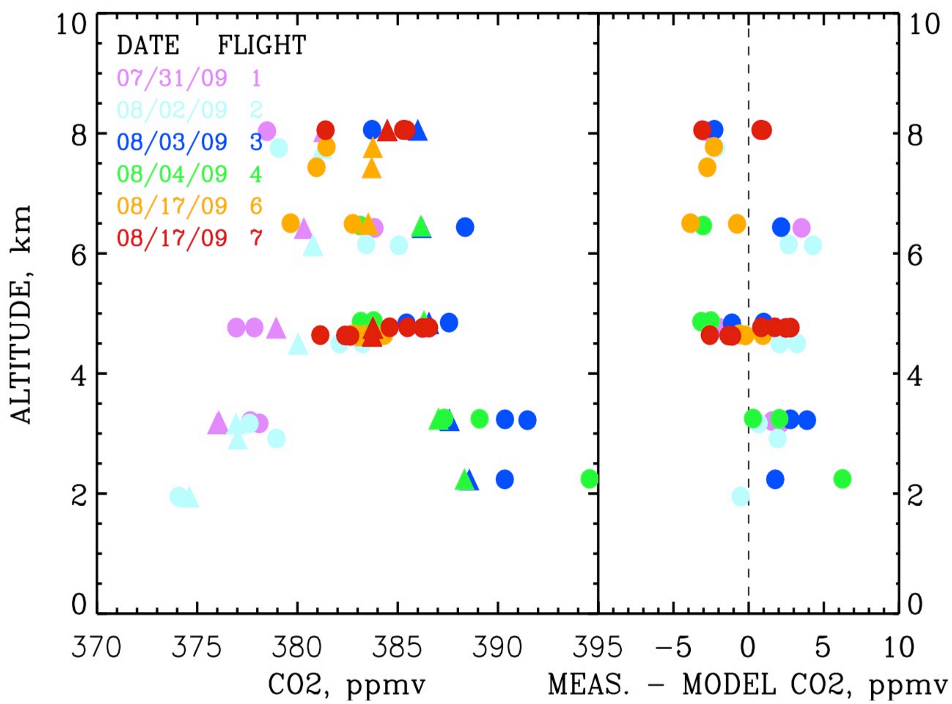
Flt #	Date (2009)	Flight Location	UC-12	Lear	Twin Otter	Cessna	Flt Time & Conditions
1	7/31	OK: ARM CF	X	X	X	X	Noon – Clear
2	8/2	OK: ARM CF	X	X	X	X	Noon – Clear
3	8/3	OK: ARM CF	X	X	X	X	Noon – S. Hazy
4	8/4	OK: ARM CF	X	X	X	X	Noon – V. Hazy
5	8/7	OK: ARM CF	X				Pre-Dawn - Variable
6	8/17	NC: Inland	X	X			Noon - Clear
7	8/17	VA: E. Shore & Chesapeake Bay	X	X			Late Afternoon – Clear

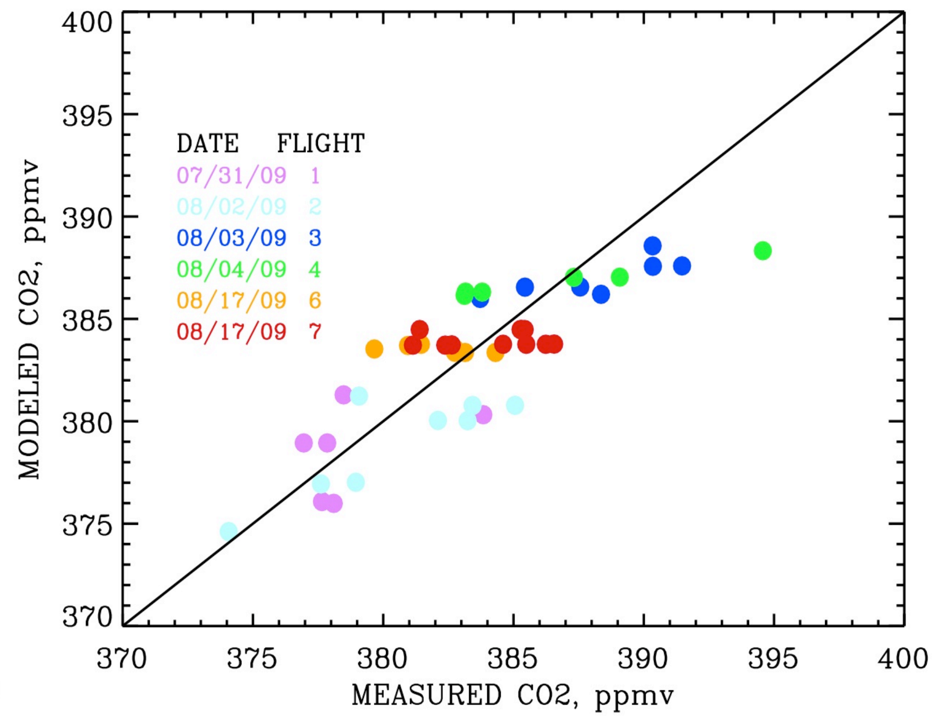
Flight #3, 8/3/09



Data provided courtesy of Dr. Ed Browell, LaRC

CO_2 Comparisons for All Coordinated Flights





Average DCO_2 = 0.32 ppmv and s_{DCO2} = 2.40 ppmv

We are currently in the process of integrating our instrument into the NASA DC-8 aircraft along with GSFC's and JPL's instruments to do inter-comparisons from the same aircraft at Dryden Aircraft Operations Facility in Palmdale, CA

Data provided courtesy of Dr. Ed Browell, LaRC

Fiber Raman Amplifier Development

- The development of optical Fiber Raman Amplifiers (FRA's) offers the remote sensing community access to wavelengths which are not presently available in conventional solid state lasers or fiber lasers/ amplifiers
- In nonlinear fiber optics, stimulated Brillouin scattering (SBS) has a much lower threshold power than stimulated Raman scattering (SRS) meaning that SBS is particularly a problem when designing a fiber Raman amplifier
- SBS can be suppressed by spectral broadening of pump and signal, application of heat and stress to the fiber, or fiber design (both material and waveguide design)
- For the ITT Raman amplifier, narrow spectral linewidths are preferred. The amplifier must also be robust for airborne or space environments. Therefore fiber design is the most viable option for suppressing SBS, to achieve a high power and high efficiency transmitter.

SBS Threshold

- SBS Threshold power is proportional to both waveguide and material parameters

$$P_{Th} \propto \frac{K A_{eff}}{g_{Bp} \bar{I}_u^{ao}}$$

  - K – A constant depending on polarization of pump and signal beams (1/2 for unpolarized pump and signals)
  - A_{eff} – Effective mode area of the optical field in the core
  - g_{Bp} – Peak effective Brillouin gain coefficient
  - $\bar{I}_u^{ao}$ – Normalized overlap integral between electric and acoustic fields

A_{eff} and $\bar{I}_u^{ao}$ are waveguide parameters, g_{Bp} is material dependent

SRS Threshold

- The forward SRS threshold can be approximated assuming a Lorentzian Raman-gain spectrum

$$P_{Th} \approx \frac{16 A_{eff}}{g_{Rp} L_{eff}} \qquad L_{eff} = \frac{1 - e^{-\alpha_P L}}{\alpha_P}$$

  - L_{eff} – Effective length (length before which pump absorption becomes important)
  - L – Fiber length
  - α_P – Pump absorption coefficient
  - A_{eff} – Effective mode area of the optical field in the core
  - g_{Rp} – Peak effective Raman gain coefficient

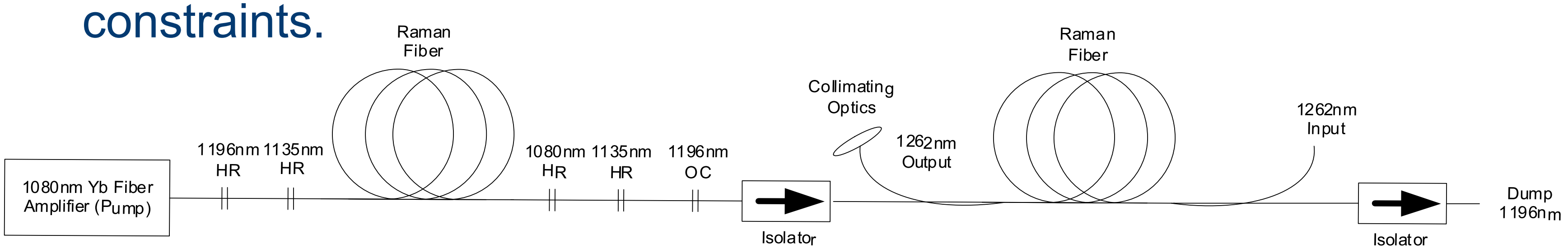
- To decrease the threshold power at which SRS begins, reduce A_{eff} (waveguide parameter) or increase g_{Rp} and/or L_{eff} (material parameters)

Objective

- The objective is to design a fiber such that SBS is minimized while maximizing the SRS efficiency
  - A_{eff} is common to both SRS and SBS processes
  - Determine the material dopants and concentrations that maximize g_{Rp} while minimizing g_{Bp}
  - Determine a fiber geometry that minimizes the acoustic phonon/photon interaction in the fiber core (minimize $\bar{I}_u^{ao}$)
  - Determine the best architecture for the overall fiber Raman amplifier based on the gain and losses from the fiber design

Initial Fiber Raman Amplifier Development (Pre ACT)

- Our initial attempt at a Fiber Raman amplifier was centered around an SBS suppressed design using GeO_2 as the primary dopant.
- The decision to use GeO_2 was mainly driven by manufacturing constraints.



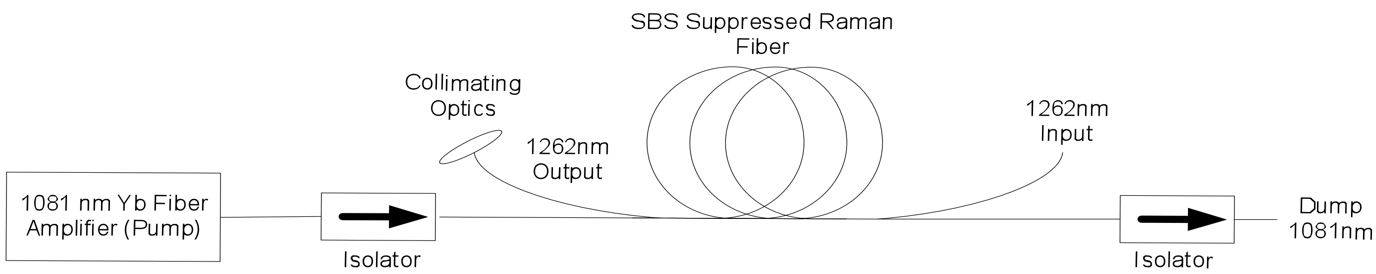
- The relatively small Stokes shift of GeO_2 doped fiber (~425 cm-1) requires three stage design, a cascaded Raman laser stage and the amplification stage
- Fiber was designed by the University of Arizona based on ITT's specs and manufactured by Corning Specialty Fiber

Gen I GeO_2 Fiber-Based Amplifier Results

- Initial fiber delivered from Corning based on ITT/UA design had very high losses >10 dB/km
- Re-cladding and a more controlled draw tension improved this slightly to ~6.5 dB/km
- Modified design was developed and a preform was made that matched design
- However high cost of initial development due to multiple iterations, left the initial effort with insufficient funding to have final preform pulled into fiber for further evaluation
- Decision was made to commit resources fully to exploring P_2O_5 as the primary dopant under the ACT program

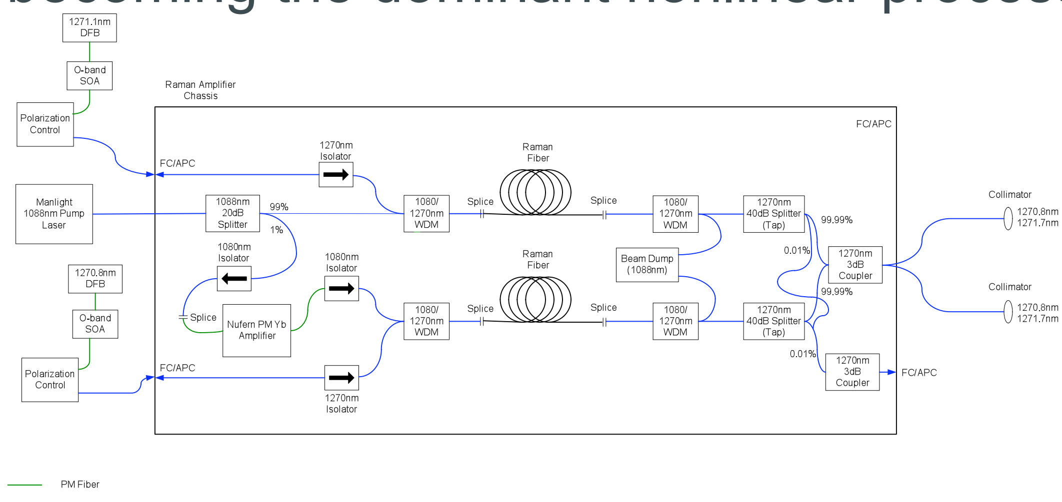
FRA Development Under NASA ACT

- Using $P_2 0_5$ as the fiber dopant results in a Stokes shift of ~1320 cm^{-1}
- This large Stokes shift allows for a single stage amplifier design
- Less stages results in fewer splices and increased efficiency
- Goal is to develop P_2O_5 based fiber amplifier which minimizes SBS while maximizing SRS



First Year Raman Amplifier Design

- Over the first year of this effort an amplifier was built using a fiber with P_2O_5 as the primary dopant
- The fiber achieved SBS suppression through varying the mode field diameter along the fiber length
- Modulated output power of 1.8 W average was achieved
- Design was forced to a two arm amplifier design due to 4 wave mixing becoming the dominant nonlinear process



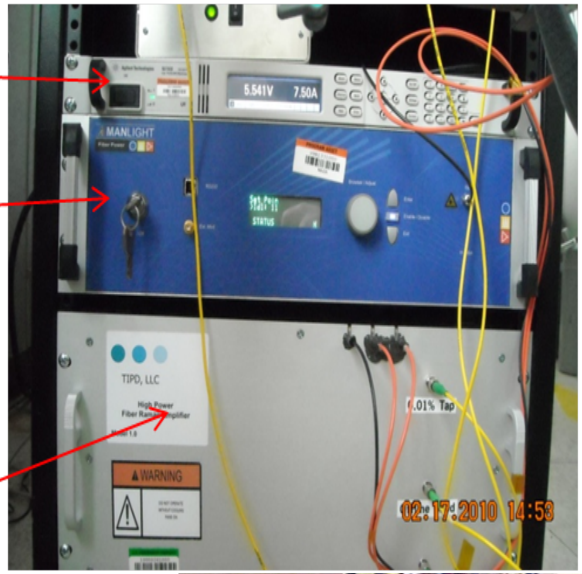
First Amplifier and Test Setup

The first amplifier was completed in late 2009 and was integrated with ITT's CO_2 EDU in Feb 2010

Nufern Amp PS

Pump laser and seed for Nufern amp

Raman Fiber Amplifier (80% of size is driven by Nufern Amp and heat sink

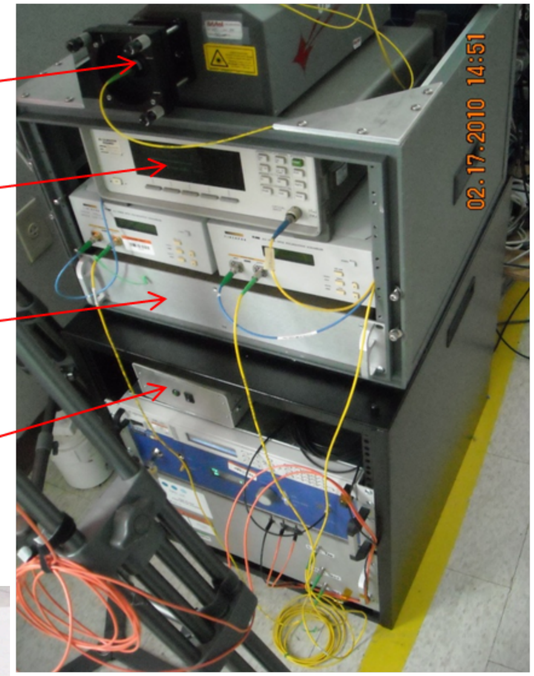


Online Wavemeter

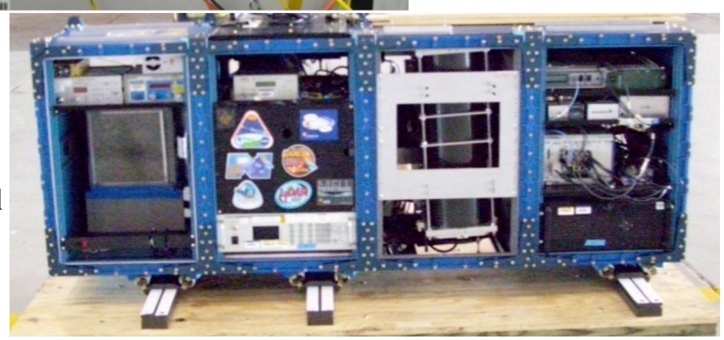
Offline Wavemeter

DFB's and SOA's

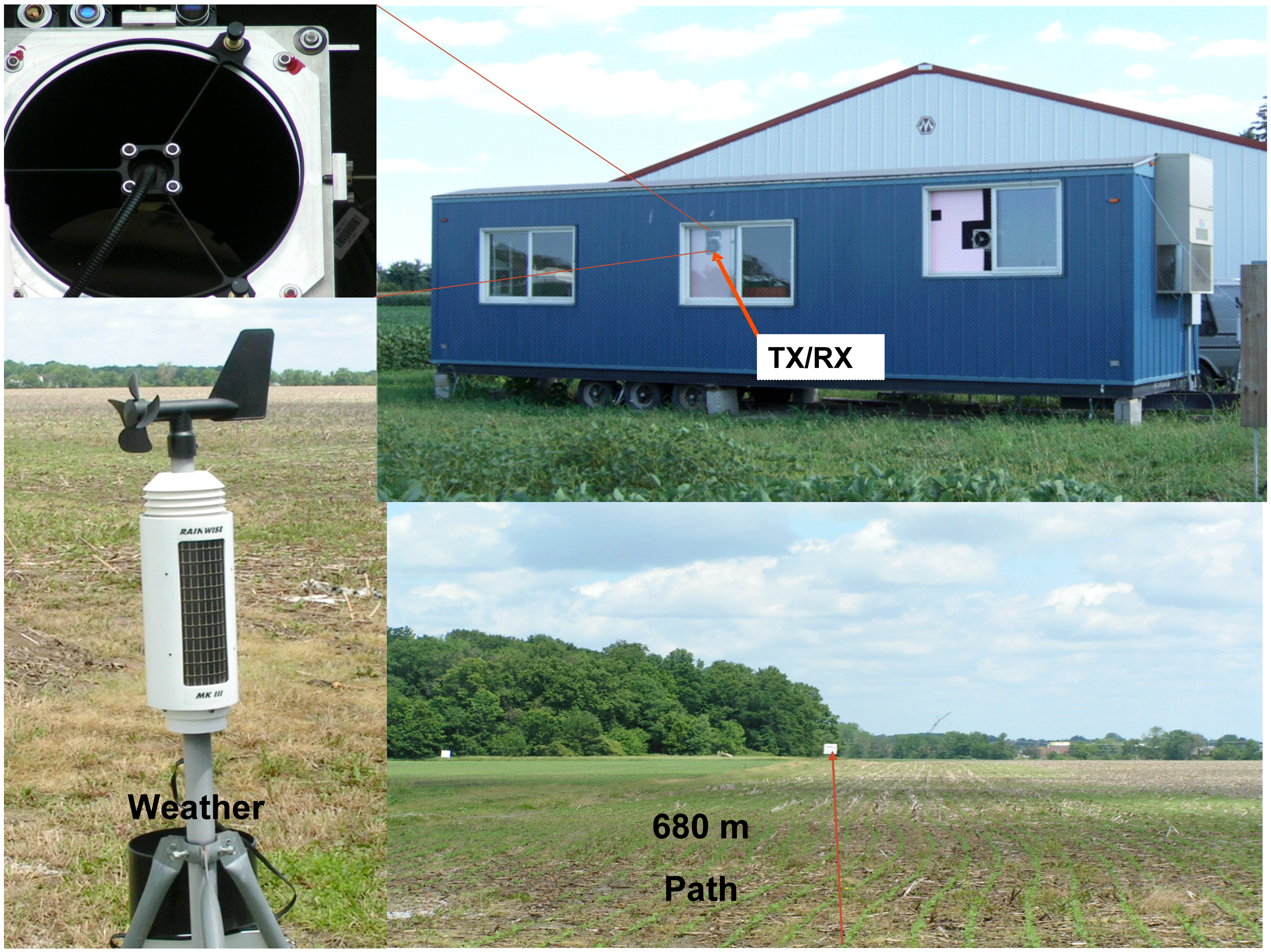
Custom modulator



Data acquisition and control done through integration with ITT CO_2 EDU



After integrating with the EDU tests were performed at ITT's ground test facility



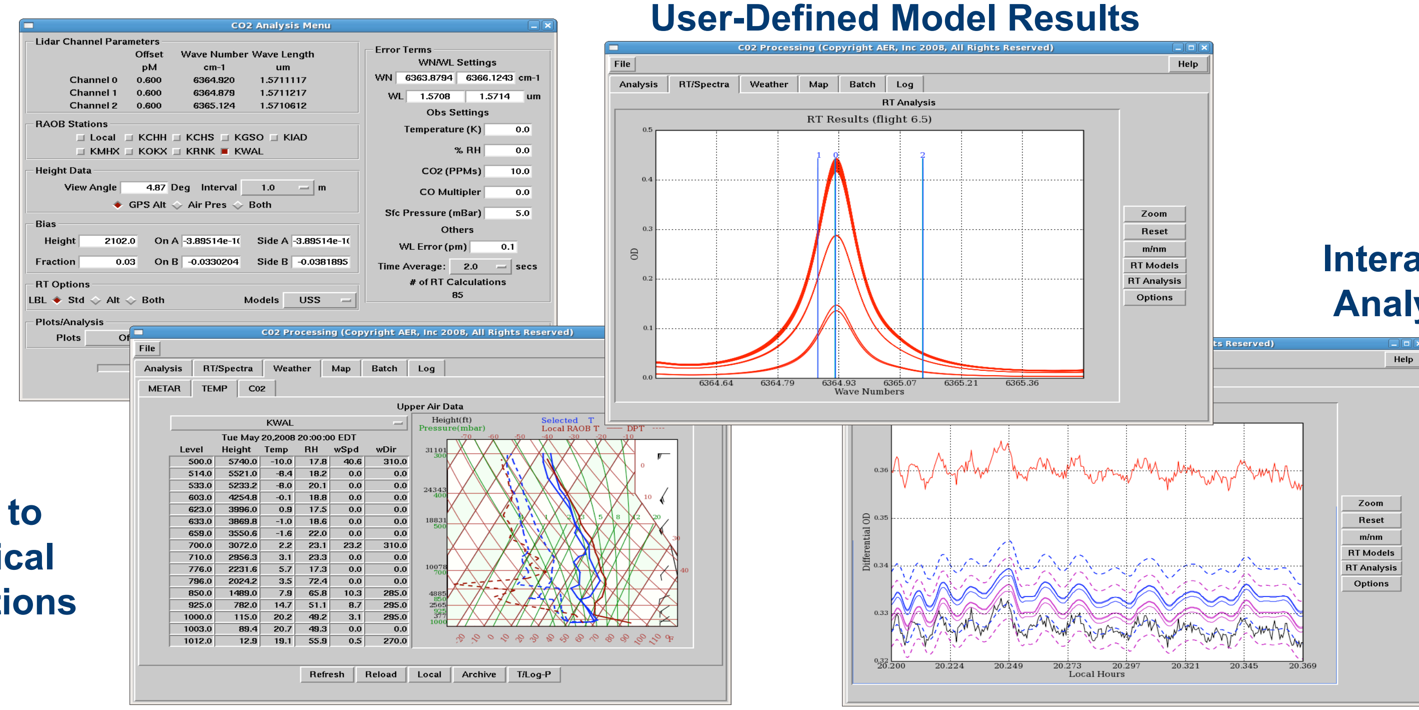
AER's End-to-End analysis software, previously developed for the CO_2 EDU was updated to include O_2

User-Defined Model Results

Ingest/Analysis Interface

Interactive Analyses

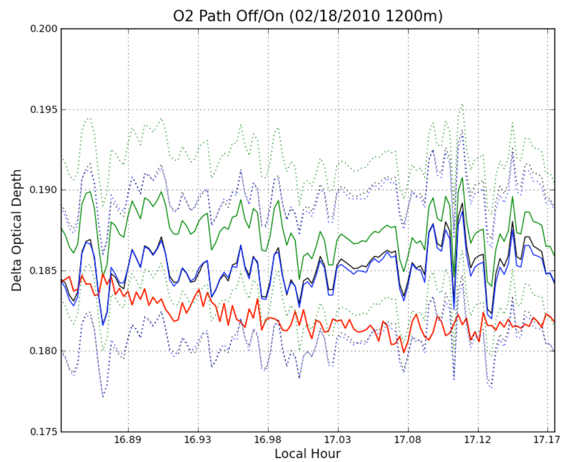
Web Interface to Current/Historical Weather Conditions

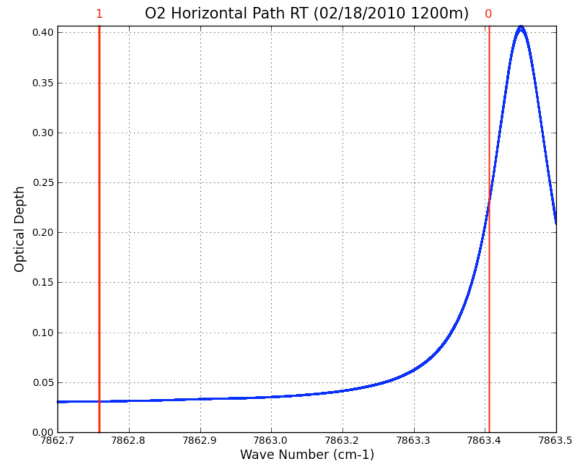


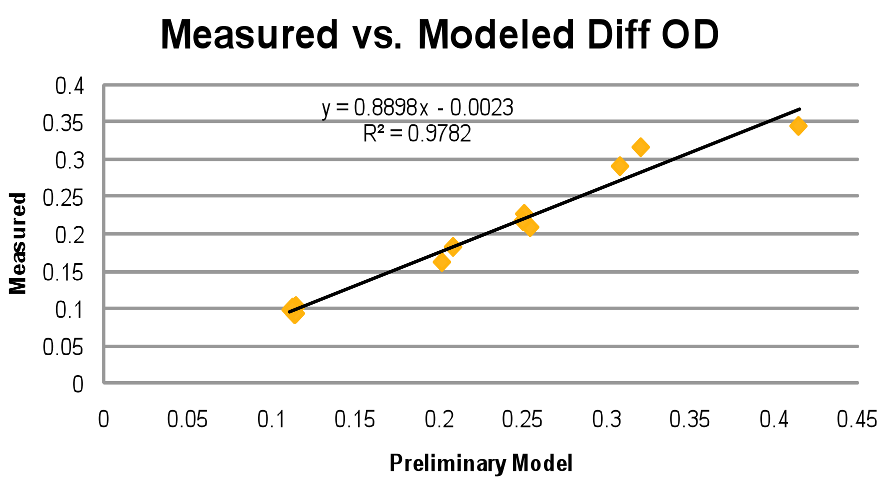
The data is fed into LBLRTM to generate values of optical depth for a given pressure, temperature, relative humidity, and distance to target. The values for optical depth are computed in wavelength range of the LAS, and values for online/offline optical depth are selected based upon the measured wavelengths provided by the LAS system. The difference between online and offline optical depths are taken to compare with measurements of differential optical depth taken with the LAS.

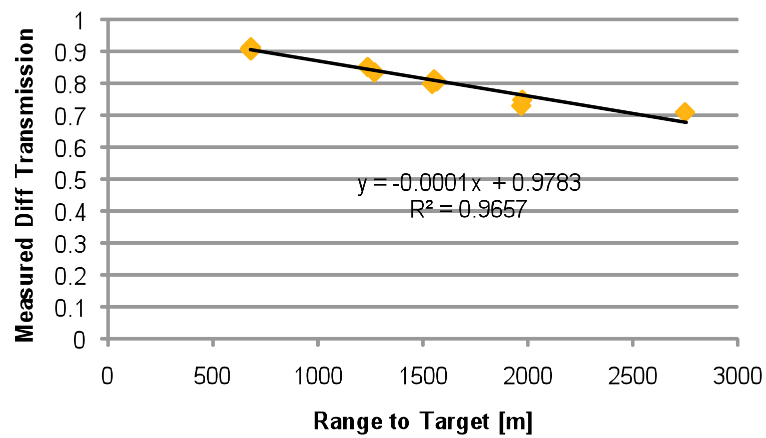
Initial Results

- The preliminary model comparisons completed to date show good correlation with the O_2 LAS measurements
- More detailed comparisons are on going



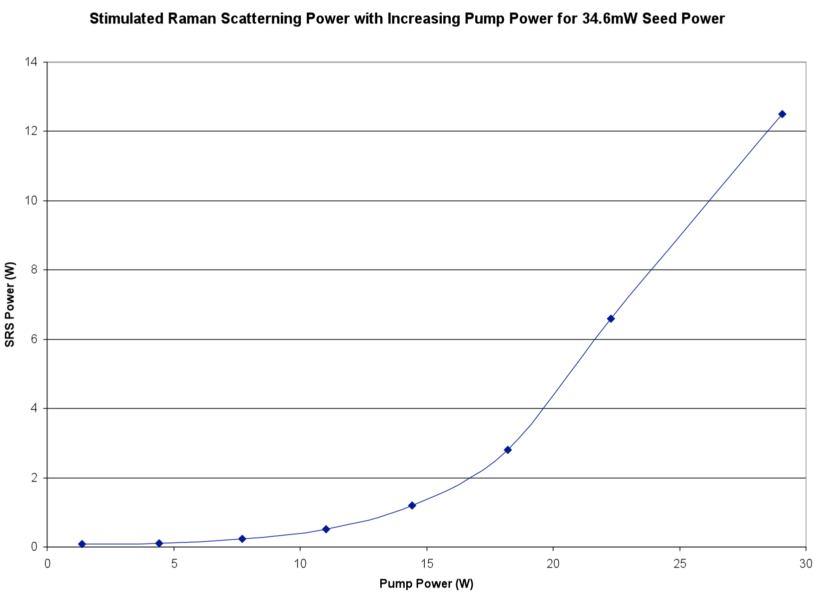


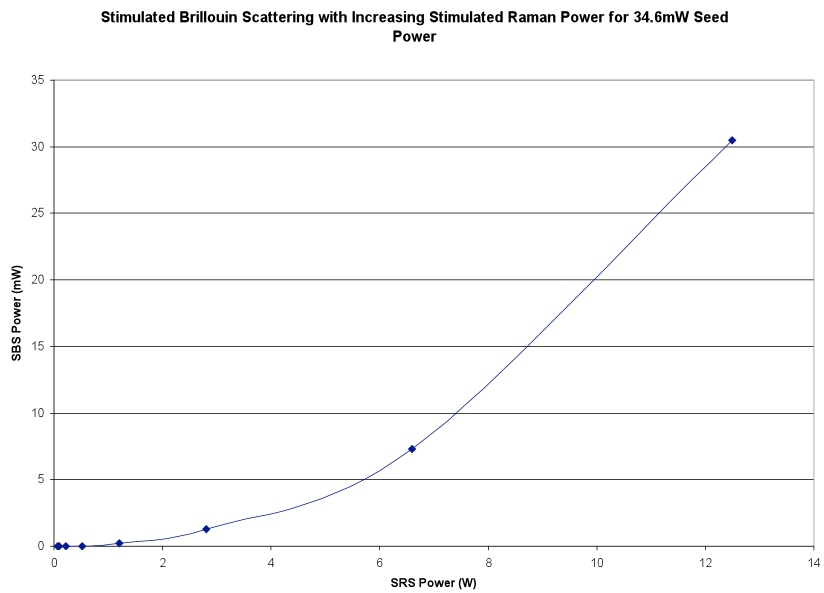




Current and Future Work

- Fiber from year 1 is being evaluated further using a higher power pump and has demonstrated the ability to produce ~12.5 W of peak power with <3 MHz linewidth
- Additional fiber designs are being manufactured which will result in increased SBS suppression through separation of the acoustic and optical modes
- Next amplifier scheduled to be assembled in July





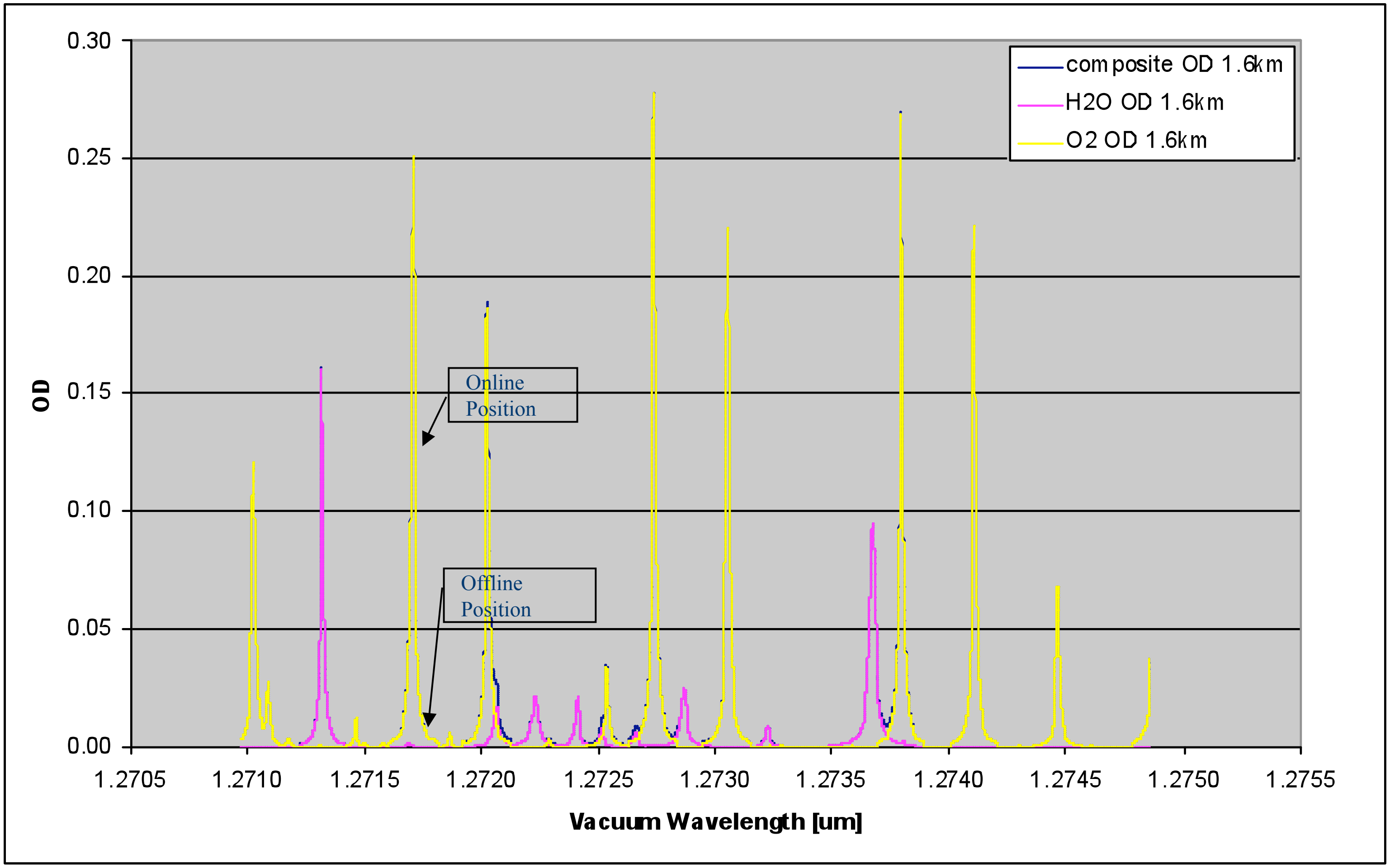
Summary

- In the first year of this ACT program we have built a Raman amplifier using P_2O_5 as the primary fiber dopant
- The amplifier demonstrated 1.5 W of narrow linewidth average power from the SBS suppressed fiber and the ability to be modulated in a manner consistent with ITT's measurement approach
- The amplifier was integrated with the ITT EDU and O_2 measurements were made at the ITT ground test site facility
- Tools were developed to allow detailed comparisons with predicted O_2 optical depth values and to do the inversion from the LAS measurement to pressure measurements
- Narrow linewidth power >12 W has been demonstrated with the same fiber used in the online channel for the first year effort
- Lessons learned during the first year effort are being applied toward the development of a second amplifier which will be integrated and tested later this summer.
- New fiber designs are being manufactured to further suppress SBS with the goal of achieving > 5 W average modulated power and improved amplifier efficiency

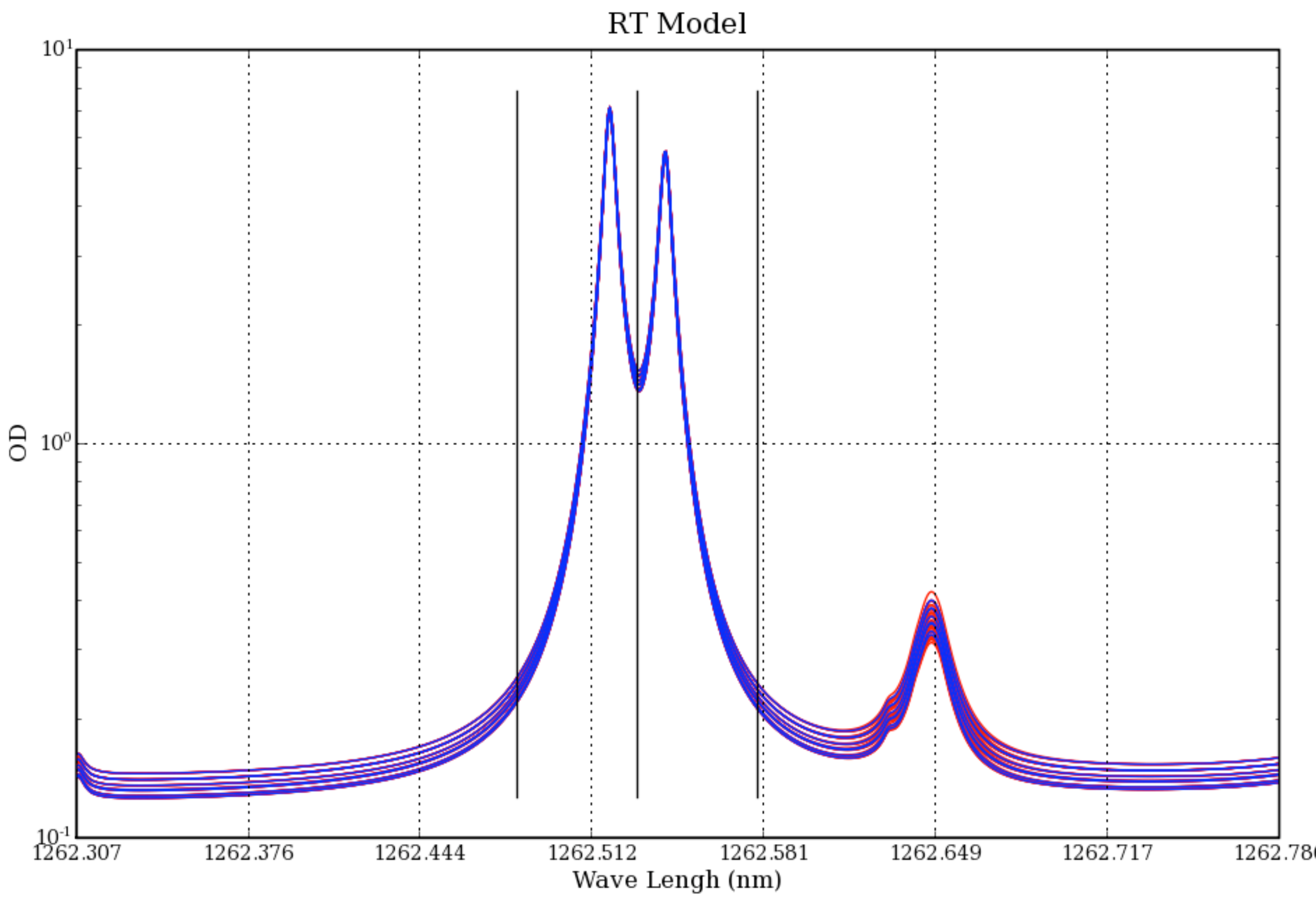
Questions?

Backup Slides

O_2 Line for Ground Tests



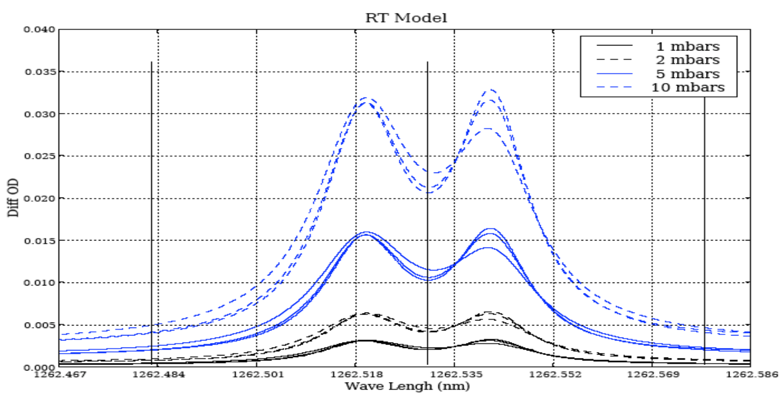
Trough for Space-Borne Measurements

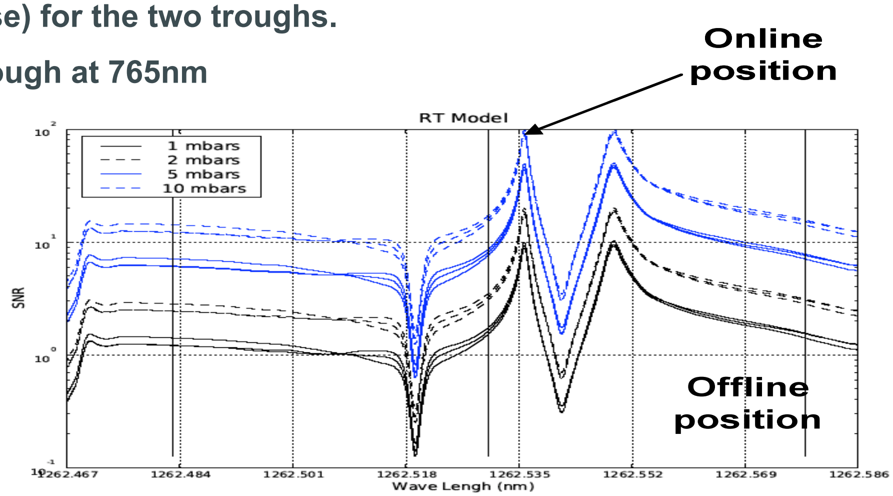


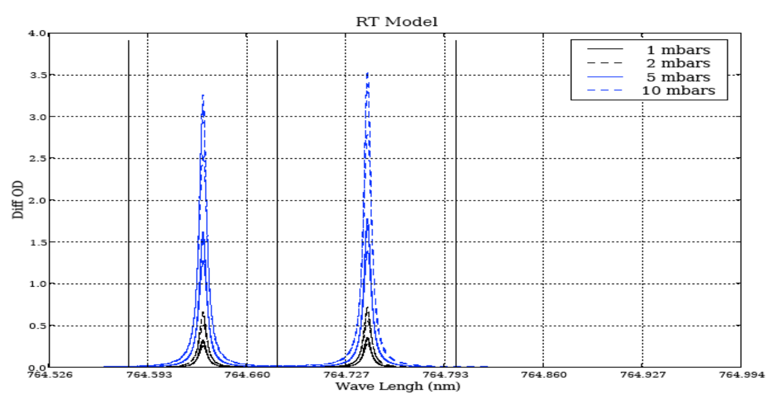
Use of this trough reduces sensitivity to laser jitter and drift by and order of magnitude

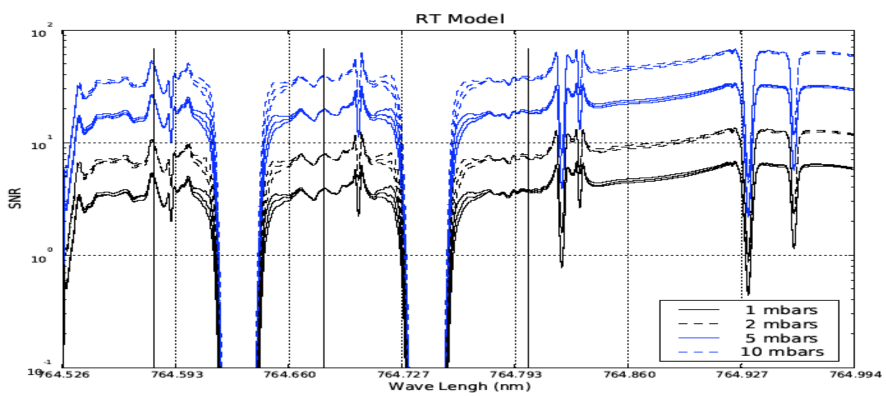
Comparison with Trough in Oxygen A-band

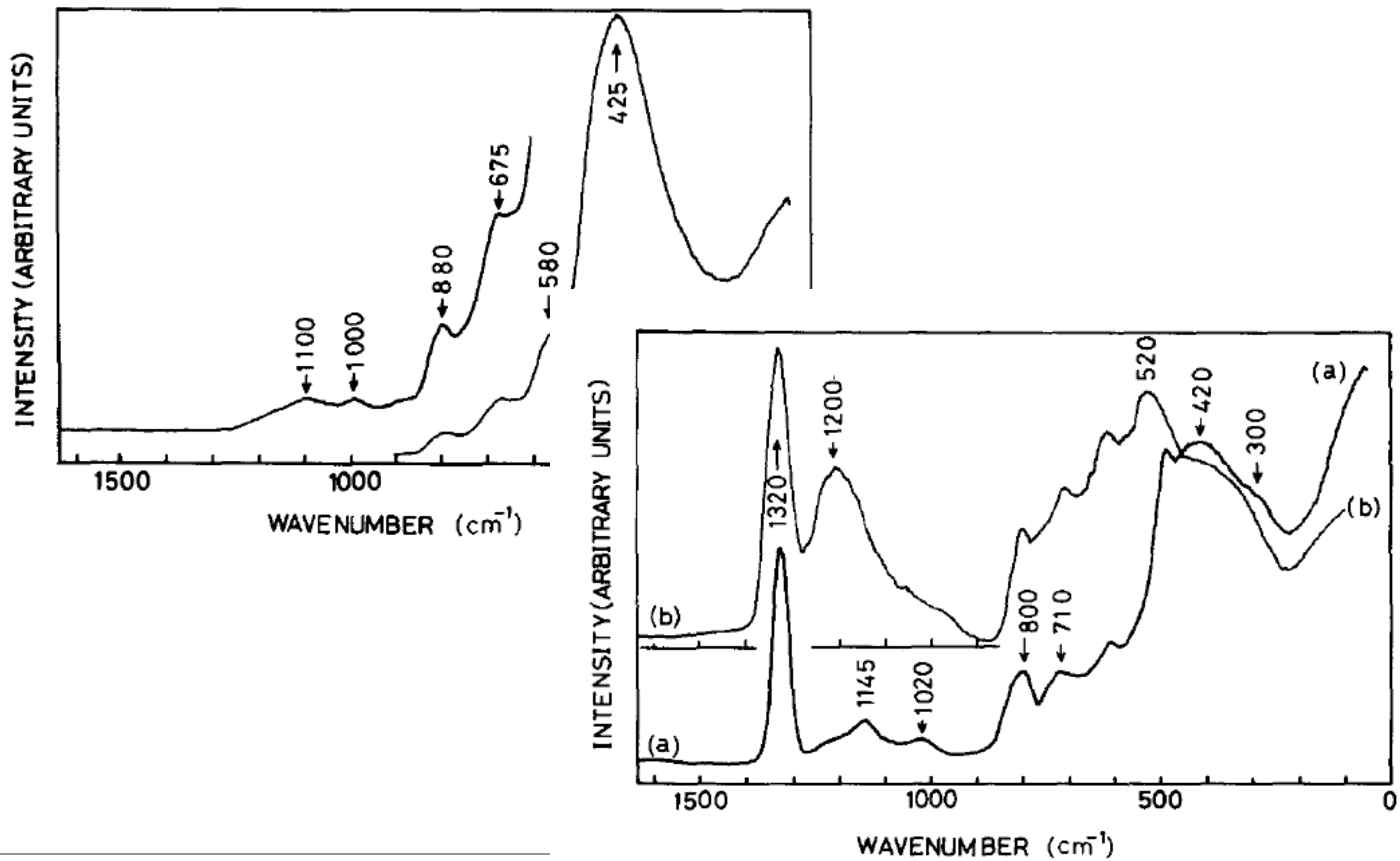
- The two plots on the left show the sensitivity of the OD to variations in pressure for a trough located near 1262nm and one near 764nm.
- The two plots to the right show a more complete picture that evaluates this sensitivity of the atmospheric transmission for a given pressure change (signal) versus the variability of the atmospheric transmission due to realistic temperature and RH variations (noise) for the two troughs.
- The trough at 1262nm has a higher SNR than the trough at 765nm










INTENSITY (ARBITRARY UNITS)
425
675
880
580
1100
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1000
WAVENUMBER (cm⁻¹)
INTENSITY (ARBITRARY UNITS)
1320
1200
520
420
300
(a)
(b)
(b)
800
710
1145
1020
(a)
1500
1000
500
0
WAVENUMBER (cm⁻¹)