LaRC-JPL Active Remote Sensing Concepts for ASCENDS

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Presenting for All

LaRC, JPL, ITT, UNH, and AER

Team Members

Carbon Cycle & Ecosystems Workshop

Adelphi, Maryland

28-30 April 2008

Outline

- Why active remote sensing of CO_2 ?
- How make active CO_2 measurements?
  - CO_2 spectroscopy and measurement approach
- Results from recent 1.57-μm airborne LAS validation experiments.
- Complementarity of 1.57- and 2.0-μm LAS measurements.
- Results from 2.0-μm LAS flight tests.
- ASCENDS mission study summary and near-term activities.

ASCENDS Measurement Approach & Why

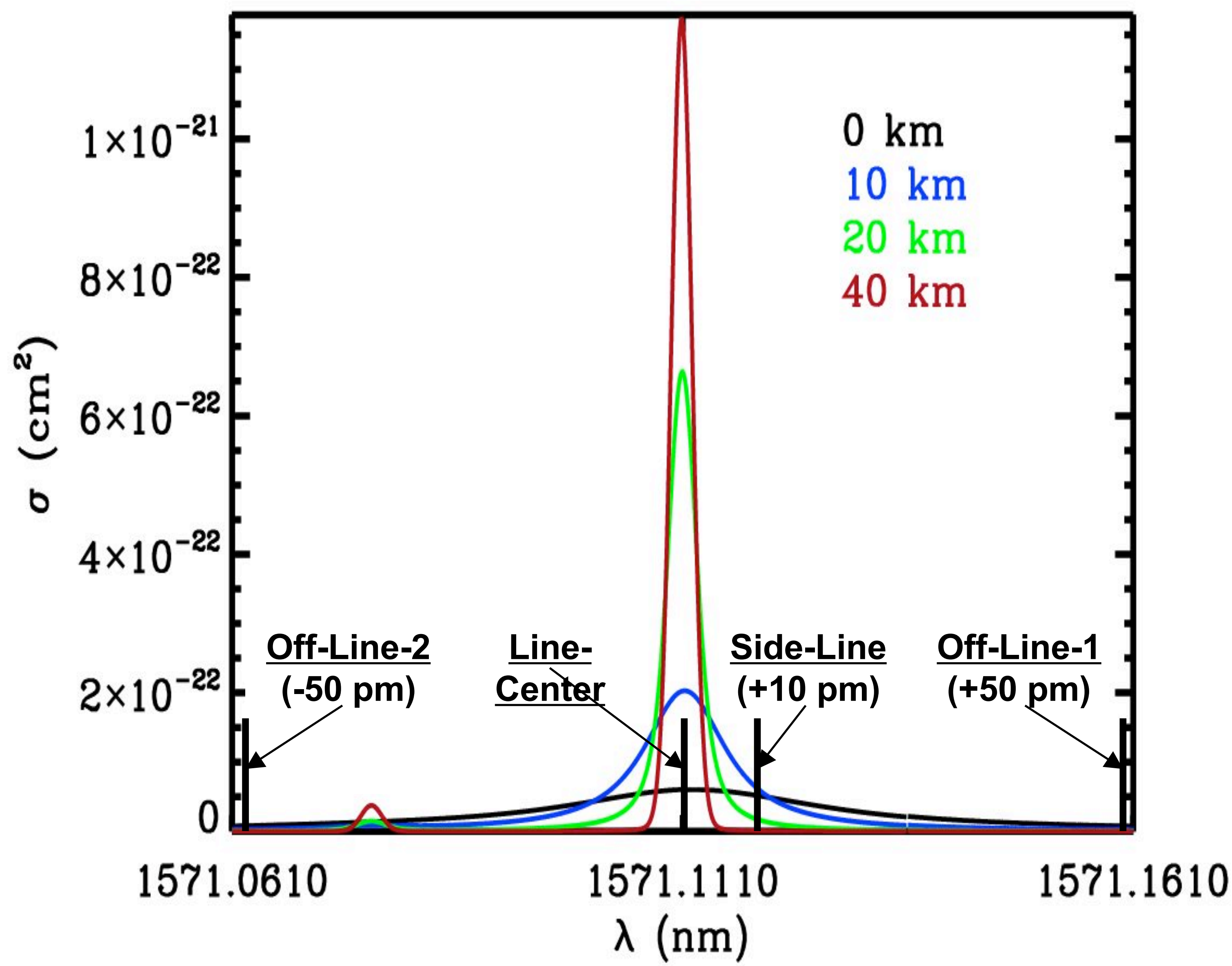
♦ASCENDS Measurement Approach

- **Laser Absorption Spectrometer (LAS) to provide column integrated measurements of CO_2**

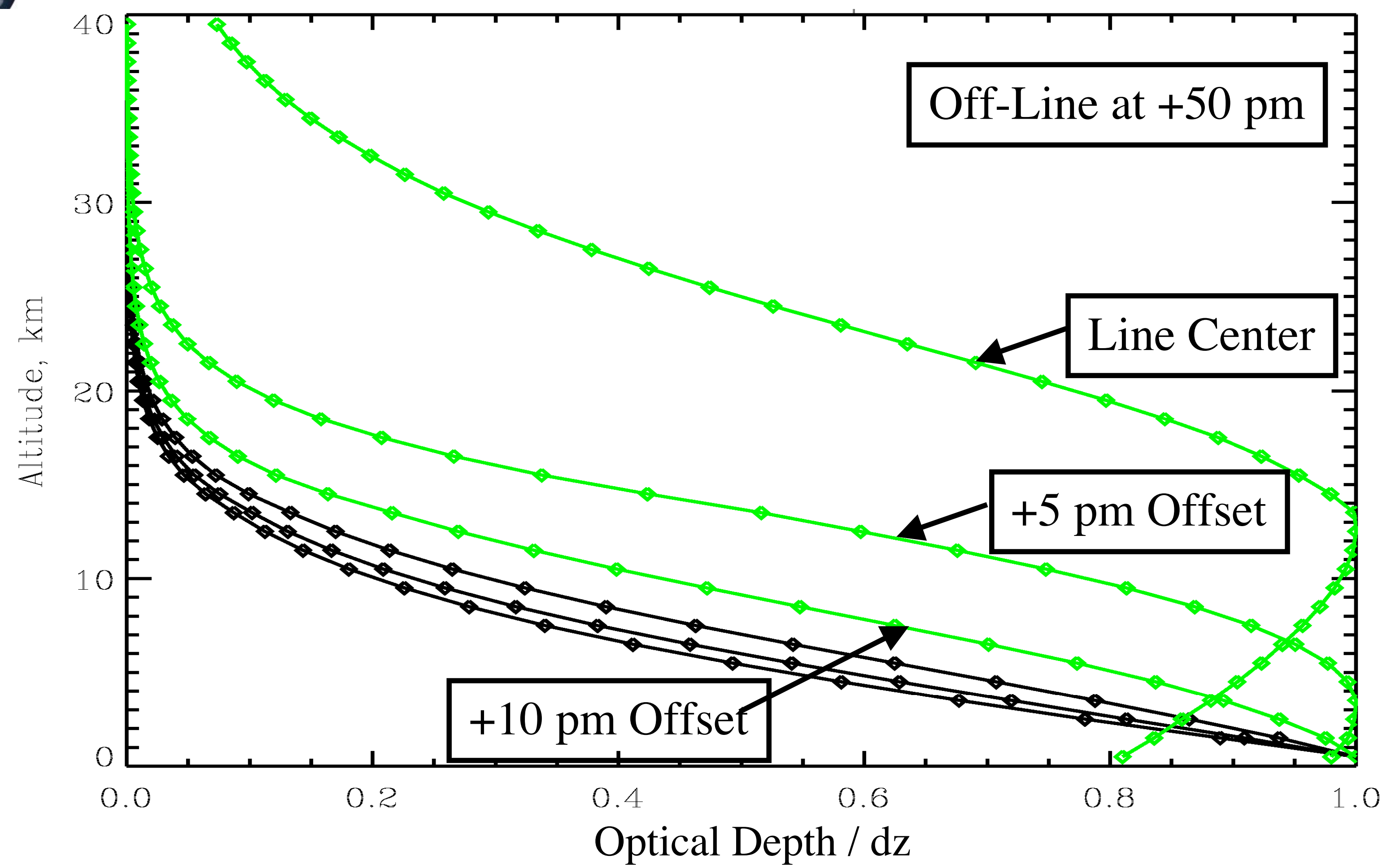
♦Why active remote sensing of CO_2?

- **Control of light source and detectors for precise wavelength control and background discrimination.**
- **Global CO_2 column measurements.**
- **Orders of magnitude higher density and coverage than ground networks.**
- **Measures at all times of day and night.**
- **Measures over land and water.**
- **Measures over all latitudes and surfaces on every orbit.**
- **Illumination path = observation path.**
- **Small measurement footprint measures to the top of thick clouds and between broken clouds.**
- **Measurement weighted to lower troposphere for enhanced CO_2 source/sink sensitivity.**

CO_2 Absorption & LAS Wavelengths



Normalized CO_2 Absorption Profiles



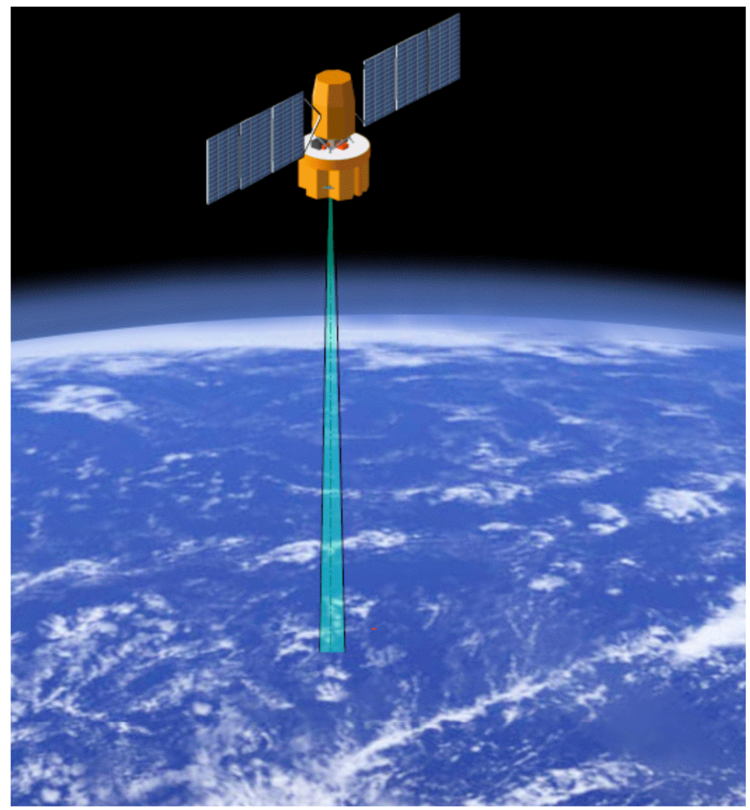
Optical Depth (OD) = n_{CO2} [cm^{-3}] x σ [cm^2] x dz [cm]

LAS CO_2 Measurement is two-way integration of OD from platform to surface.

ASCENDS Measurements

CO_2 column mixing ratio (XCO_2) measurement with Laser Absorption Spectrometer (LAS) technique requires the simultaneous measurement of the CO_2 column number density (CND); the O_2 column number density to converting the CND to XCO_2; and the path length of the measurement. A temperature profile measurement is also required to constrain the XCO_2 measurement. A column CO measurement over the same XCO_2 path is also recommended for interpreting sources and sinks of CO_2.

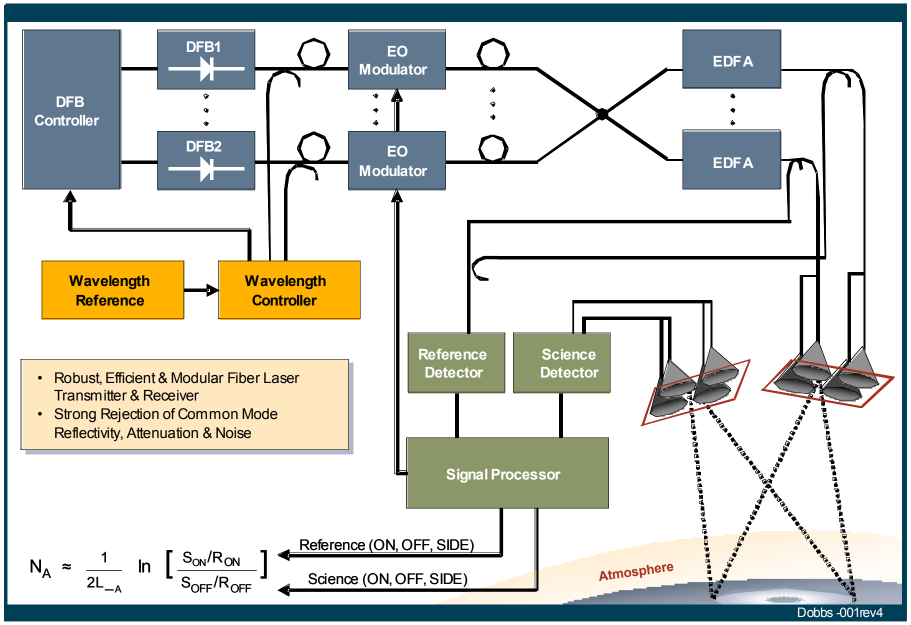
- **CO_2 column measurement**
  - **CO_2 Laser Absorption Spectrometer to resolve (or weight) the CO_2 altitude distribution, particularly across the mid to lower troposphere.**
  - **1.6-μm LAS only baseline or integrated 1.6-μm + 2.0-μm LAS option**
- **Surface pressure measurement**
  - **O_2 Laser Absorption Spectrometer to convert CO_2 number density to mixing ratio.**
- **Surface/cloud top altimeter**
  - **Laser altimeter to measure CO_2 column length.**
- **Temperature sounder**
  - **Six channel passive radiometer to provide temperature corrections.**
- **CO sensor**
  - **Gas Filter Correlation Radiometers (at 2.3 & 4.6 μm) to separate biogenetic fluxes from biomass burning and fossil fuel combustion.**
- **Imager**
  - **To provide cloud clearing for soundings.**



Multifunctional Fiber Measurement Architecture

♦ **The 1.57-μm LAS architecture**

1. simultaneously transmits online and offline wavelengths reducing noise from the atmosphere, target and sensor into a common-mode term which is readily removed,
2. is independent of the system wavelength, and
3. supports N+M redundancy.



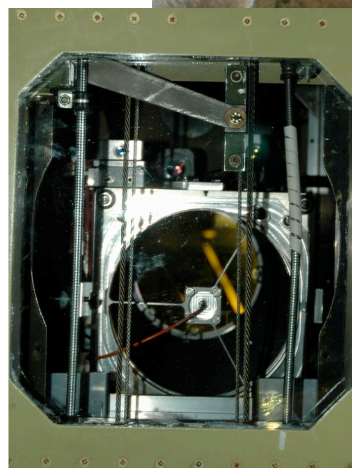
The LAS architecture supports the measurement of multiple species (i.e., CO_2 and O_2) and altitude simultaneously.

(See 1.57-μm LAS Poster by Dobbs et al. #62)

Advanced CO2 and Climate LAser International Mission (ACCLAIM)

(Active Laser System for ASCENDS)

ITT Engineering Development Unit used to validate end-end system performance model; technology readiness for ACCLAIM Mission; and capability for high precision CO_2 measurements.



ACCLAIM Flight Test Campaigns

May 21-25, 2005
Ponca City, Oklahoma (DOE ARM Site)
(5 Science Flights: Land, Day & Night,)

June 20-26, 2006
Alpena, Michigan
(6 Science Flights: Land & Water, Day & Night)

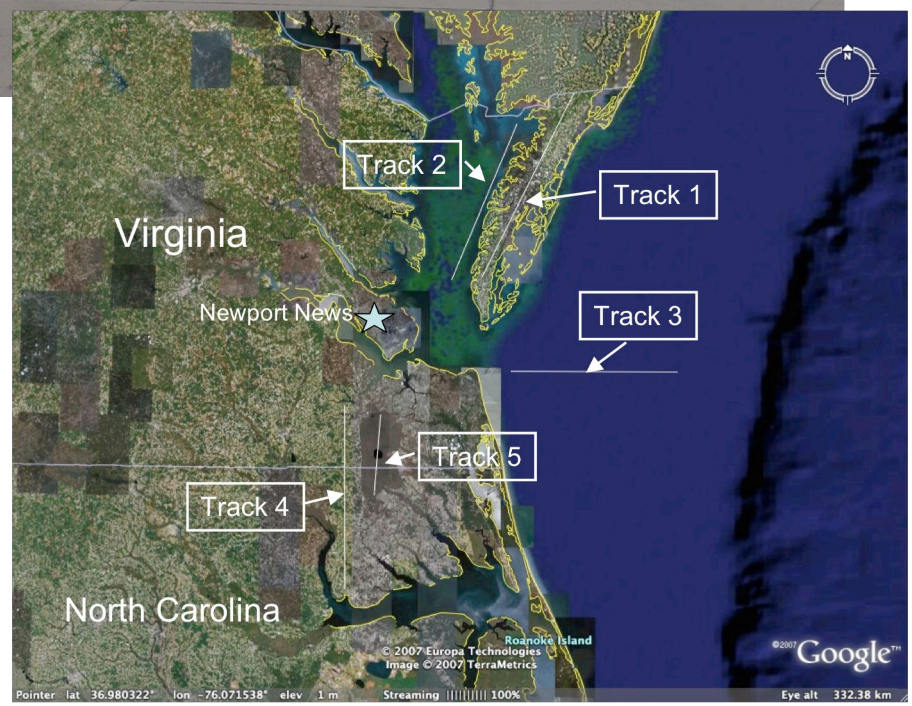
October 20-24, 2006
Portsmouth, New Hampshire
(4 Science Flights: Land (inc. mountains) & Water, Day & Night)

May 20-24, 2007
Newport News, Virginia
(8 Science Flights: Land & Water, Day & Night)

October 17-22, 2007
Newport News, Virginia
(9 Science Flights: Land & Water, Day & Night, Clear & Cloudy)

ACCLAIM & JPL LAS Flight Test Campaign

Newport News/ Williamsburg Airport, 17-23 October 2007

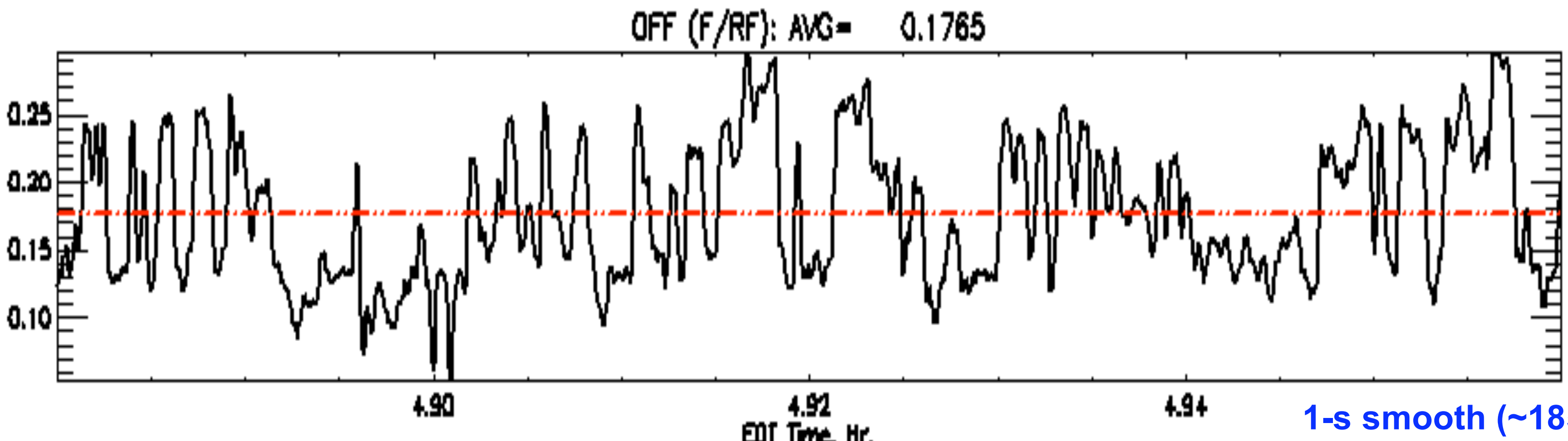


CO_2 Test Flight Campaign - October 17-23, 2007

Flight #	Date (2007)	Objectives	Track	Aircraft	TO Time (EDT)	Landing (EDT)	Comments
1	10/17	Inland, Afternoon	4	Lear	1541	1659	Mostly Clear
2	10/18	Coast, Mid-Day	1	Lear	1021	1242	Low & Mid Scat. Clds
				Twin Otter	1000	1305	
3	10/20	Inland, Mid-Day	4	Lear	1100	1320	Mid Clds on N Tk
4	10/20	Ocean, Afternoon	3	Lear	1550	~1800	Clear
5	10/21	Inland, Late-Morning	4	Lear	1008	1234	Clear
6	10/21	Inland, Night	4	Lear	1900	2030	Clear Below 20kft
				Twin Otter	1825	~2100	
7	10/22	Bay & Coast, Late-Morning	1 & 2	Lear	1005	1208	Mostly Clear
			2	Twin Otter	1010	~1230	
8	10/23	Inland, Pre-Dawn	4	Lear	431	645	Clear
				Twin Otter	441	706	
9	10/23	Ocean, Late-Morning	3	Lear	949	1217	Many Clds
				Twin Otter	1010	~1245	

ACCLAIM Off-Line Science Return & Reflectance Variations Along Track 4 on 23 Oct. 2007

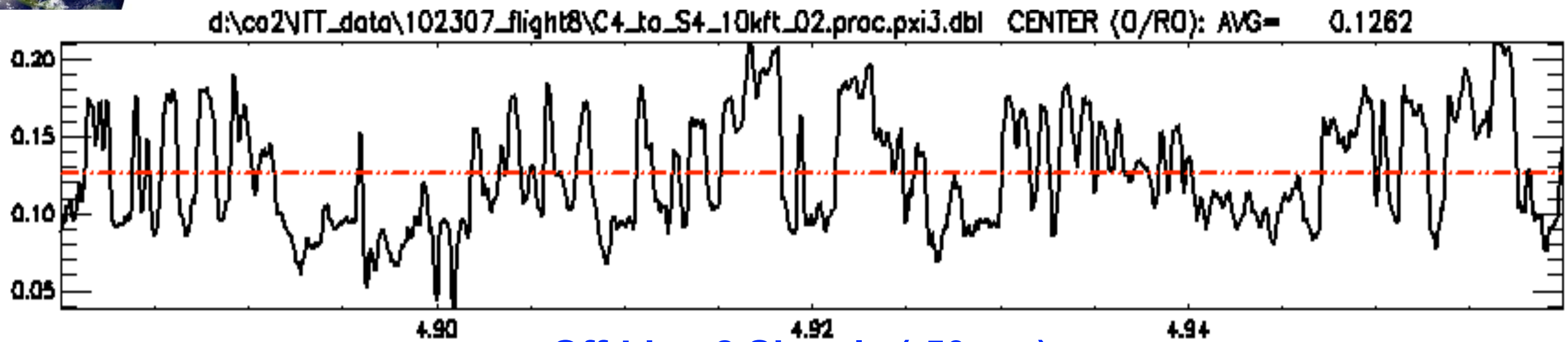
Off-Line Signal Variation



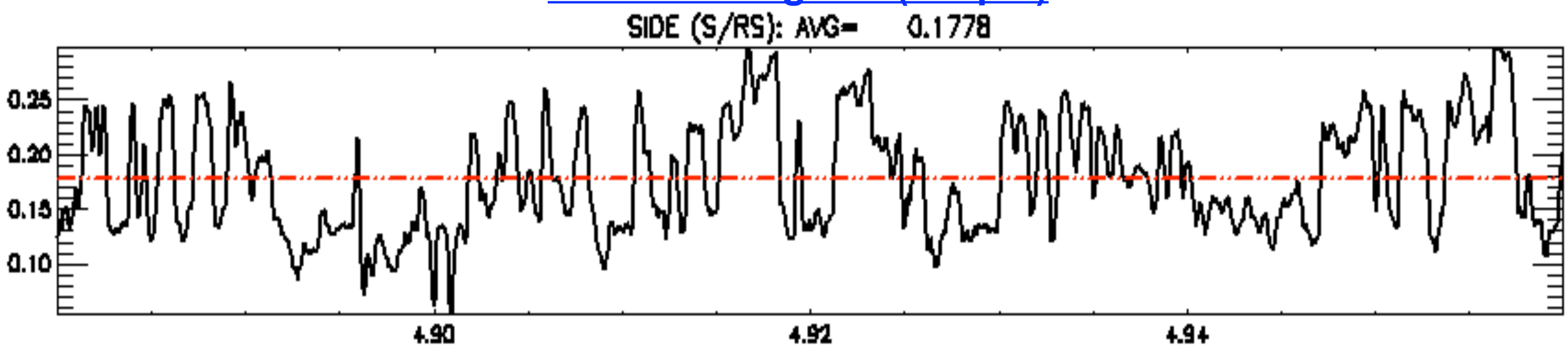
1-s smooth (~185 m)
(data: 50 Hz)

ACCLAIM DIAL Returns Along Track 4 on 23 Oct. 2007

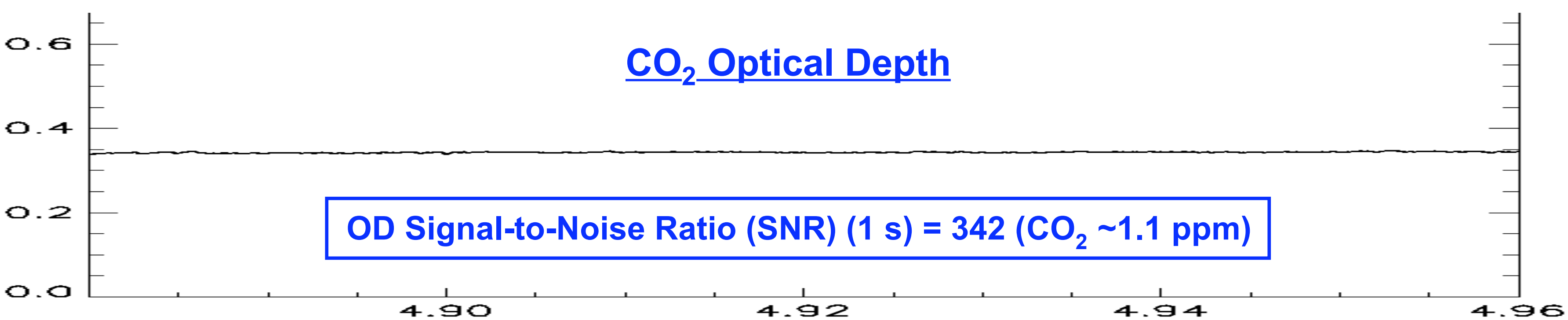
Center On-Line Signals



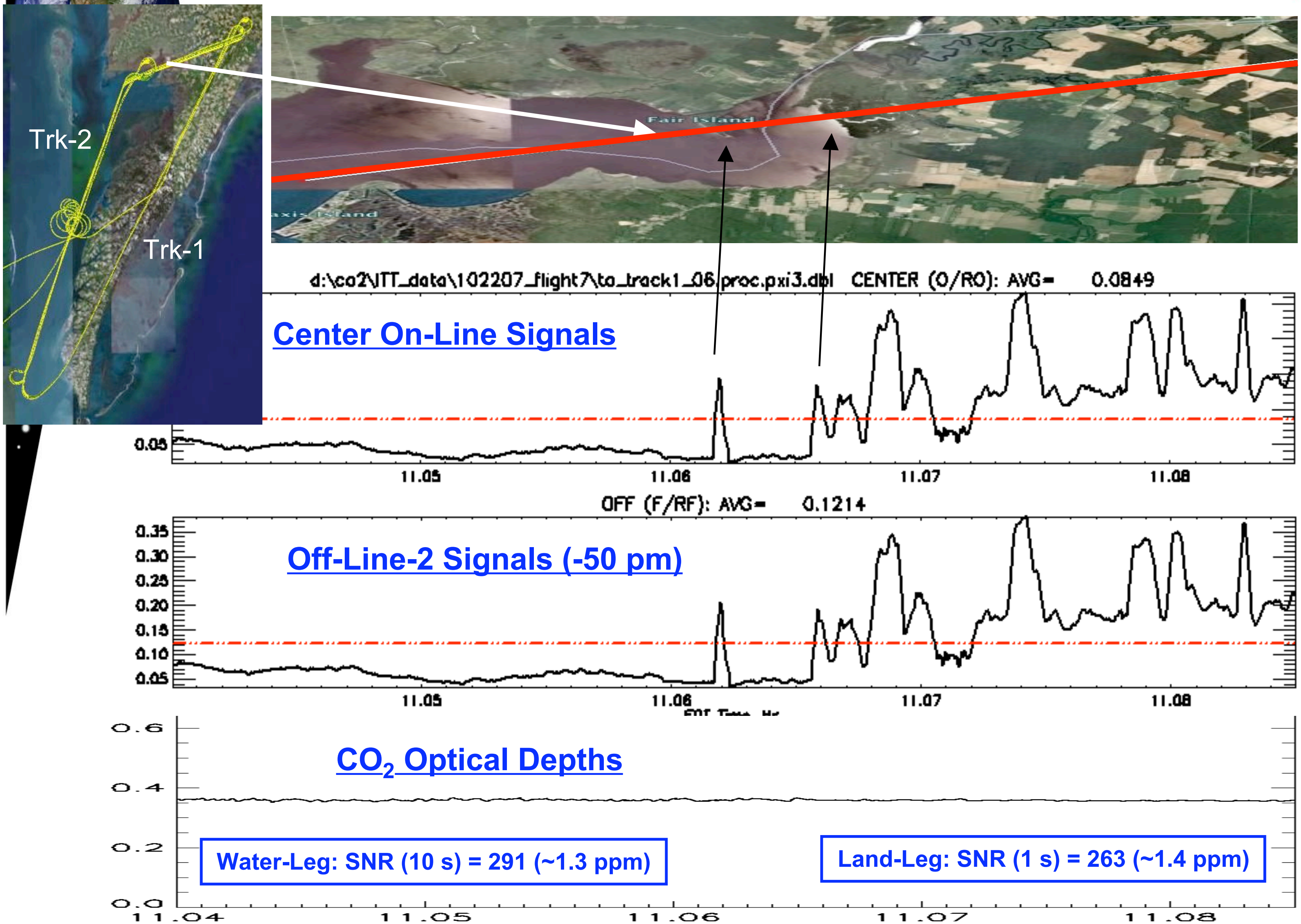
Off-Line-2 Signals (-50 pm)



CO_2 Optical Depth



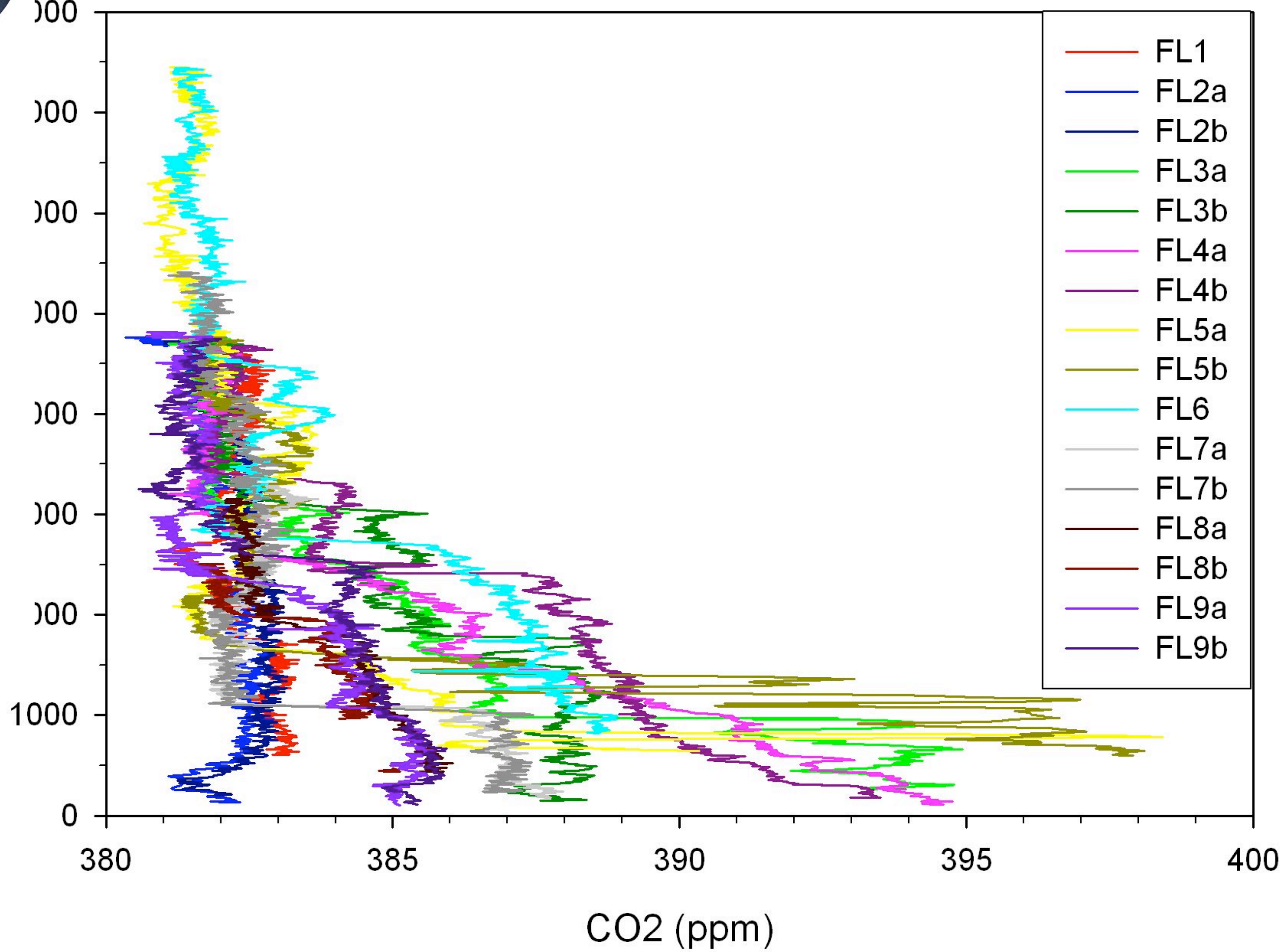
Water-Land Transition Between Tracks 2 & 1 on 22 Oct. 2007



CO_2 OD Measurement SNR

DATE	FLIGHT	FILE	Start Hour	End Hour	Delta Time, sec	ALT	OD	OD	OD	ON/OFF Ratio	OD	ON/OFF Ratio
LAND							MEAN-1s*	STDV-1s*	SNR-1s*	SNR-1s*	SNR-10s*	SNR-10s*
101807	2	7	11.505	11.515	36	3306	0.3579	0.0043	232.96	650.83		
102107	5	6	11.560	11.672	403	3126	0.3574	0.0040	252.89	707.60	324.85	908.95
102107	6	5	20.200	20.354	554	3141	0.3567	0.0047	212.79	596.61	272.71	764.61
102207	7	7-L	11.145	11.200	198	3132	0.3536	0.0038	263.06	743.86	395.89	1119.47
102307	8	2	4.880	4.960	288	3153	0.3392	0.0030	336.11	990.93	563.39	1661.01
102307	8	3	5.070	5.170	360	3144	0.3363	0.0034	291.73	867.54	393.05	1168.85
								Ave [SNR]	264.92	759.56	389.98	1124.58
								CO2 [ppm]	1.43	0.50	0.97	0.34
WATER												
102207	7	5-W	10.940	11.020	288	3127	0.3567	0.0076	131.09	367.50	290.54	814.52
								CO2 [ppm]	2.90	1.03	1.31	0.47

In situ CO_2 Spiral Measurements on All Flights



(See In Situ CO_2 Poster by Vay et al. #292)

ACCLAIM Versus In Situ CO2 Measurements

FLIGHT	FILE	Start Hour	End Hour	Altitude	CO2 Optical Depths (OD) & Mixing Ratios (MR)					
					OD MEASURED (M)	MR MEASURED (M)	OD MODELED (A)	MR MODELED (A)	OD DIFF (%)	MR DIFF (ppm)
1	2	16.213	16.325	4701	0.4955	378.6	0.5005	382.5	-1.01	-3.8
	3	16.383	16.445	4702	0.4934	376.7	0.5008	382.5	-1.49	-5.6
	4	16.585	16.634	4700	0.4909	374.8	0.5010	382.5	-2.00	-7.6
2	3	10.795	10.806	4725	0.5081	385.0	0.5045	382.3	0.70	2.7
	4	10.95	10.97	4715	0.4986	379.8	0.5032	382.3	-0.91	-3.5
	7	11.505	11.515	3306	0.3579	394.3	0.3474	382.4	3.05	11.6
	9	11.988	12.024	1720	0.1813	390.2	0.1778	382.4	1.98	7.5
5*	5	11.31	11.44	5382	0.6127	383.8	0.6142	384.7	-0.25	-0.9
	6	11.56	11.672	3126	0.3574	388.1	0.3560	386.6	0.39	1.5
	7	11.82	12	1526	0.1758	395.7	0.1737	391.2	1.19	4.5
	8	12.07	12.092	1524	0.1771	394.6	0.1755	391.2	0.90	3.4
6*	4	19.9	20	5398	0.6221	389.1	0.6154	385.0	1.07	4.1
	5	20.2	20.354	3141	0.3567	385.6	0.3579	386.9	-0.35	-1.3
7*	5-W	10.94	11.02	3127	0.3567	385.3	0.3554	383.9	0.37	1.4
	7-L	11.145	11.2	3132	0.3536	383.4	0.3541	383.9	-0.14	-0.5
8	2	4.88	4.96	3153	0.3392	391.6	0.3328	384.0	1.92	7.3
	3	5.07	5.17	3144	0.3363	390.2	0.3310	384.0	1.58	6.0
	4	5.28	5.44	1543	0.1631	393.4	0.1599	385.3	2.03	7.7
	5	5.52	5.67	599	0.0606	384.3	0.0608	386.0	-0.48	-1.8
	6	5.73	5.95	597	0.0605	386.2	0.0605	386.0	-0.01	0.0
	7	6.055	6.15	447	0.0444	379.9	0.0451	386.0	-1.62	-6.2

* Operational mode change, in-flight calibration on Flt 7, Leg 8, and altitudes limited to <5500 m.

Average	384.84	0.33	1.25
Std Dev	2.62	1.35	5.13

In situ profiles of CO_2 on each flight were used to determine in situ OD and comparisons with measured CO_2 OD showed high correlation under wide range of surface and background conditions.

Results from ACCLAIM Flight Tests in October 2007

- **Obtained EXTENSIVE data set for ACCLAIM instrument performance evaluation and CO_2 column measurement accuracy and precision.**
- **Flight tests conducted over wide range of surface reflectances, including measurements in presence of scattered clouds, and determined their effective backscatter reflectance at 1.57 micron.**
- **Obtained high signal-to-noise (SNR >250 or <1.5 ppm CO_2 uncertainty) for CO_2 column measurements with 1-s averaging times over land and 10-s averaging over water.**
- **Absolute comparisons show ACCLAIM CO_2 optical depths were within ~1.5% (~5 ppm) of the modeled optical depths with very small (<0.3% or <1.25 ppm) average offset calculated from in situ CO_2 profiles.**
- **October flight tests were coordinated with JPL 2-micron heterodyne laser system on Twin Otter aircraft - results to follow.**

(See Poster by Browell et al. #61)

IPDA Measurement of CO_2 in 2 Bands: Complementarity of 1.57 and 2.05 micron Soundings

- (**IPDA** = Integrated Path Differential Absorption)
- What is gained by having both 1.57 and 2.05 micron capability?
  - Altitude profiling capability in lower and middle troposphere (due to significant difference in 1.6 and 2 micron CO2 absorption band strengths)
  - Enhanced cloud detection and filtering capability
- Topics of presentation:
  - How IPDA soundings in the two CO2 bands can "weight" different altitude zones by tuning the transmitter frequencies appropriately
  - The JPL LAS aircraft instrument operating in the 2-micron CO2 absorption band
  - JPL LAS flights in Virginia (Oct. 2007) and sample of data
  - Aircraft instrument ops. – validation of key system performance elements

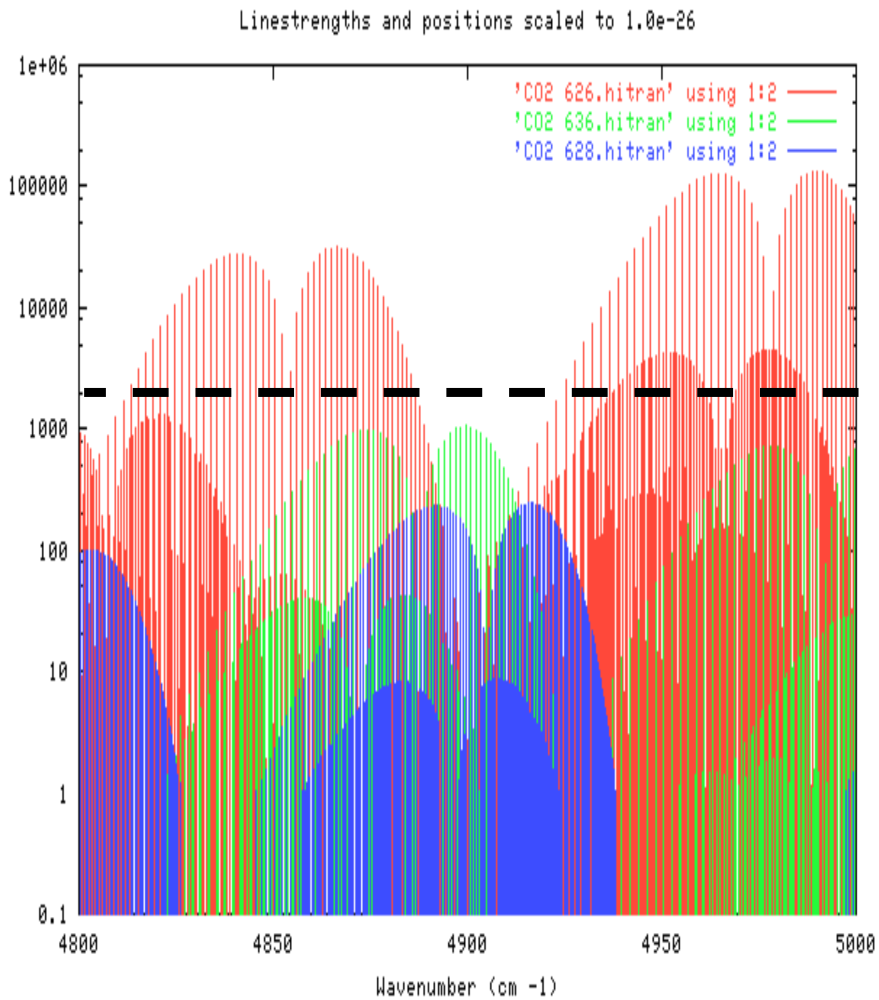
IPDA Measurement of CO_2 : Optimization

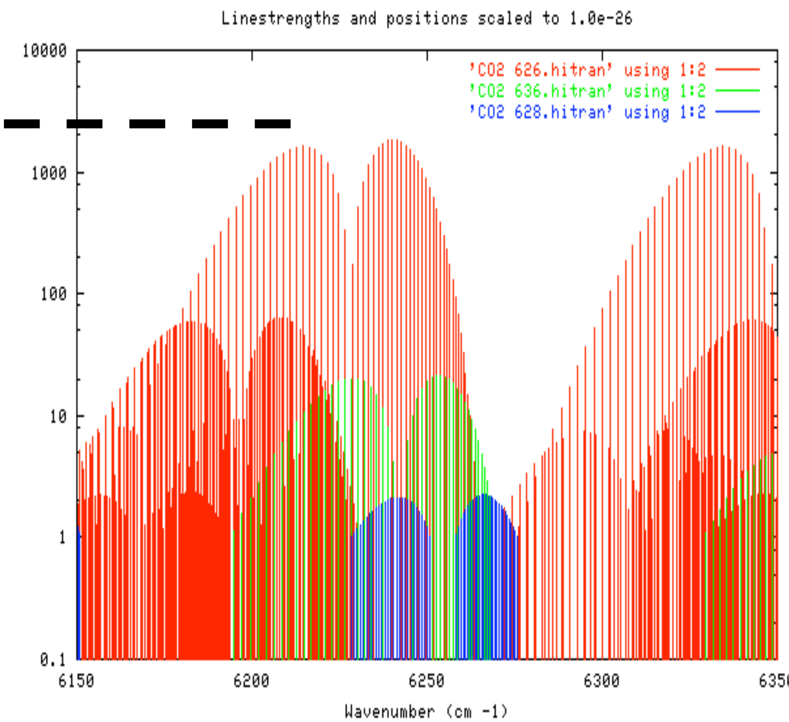
- There is an optimum on-line absorption optical depth (OD) for **IPDA**:
  - Absorption OD?? Transmittance through absorbing path = e^(-OD)
  - OD too small: not enough <u>differential</u> <u>absorption</u> – loss of sensitivity to the CO2 - can compensate by transmitting more power, increasing receiver telescope aperture size, or both;
  - OD too large: not enough <u>detected signal</u> – loss of sensitivity – can compensate as state above;
- What is the optimum?
  - Optimum optical depth ~ 1 (on-line/off-line transmittance ratio ~ 0.3)
- How does this affect the tuning of the LAS instrument to "weight" the lower or middle troposphere?
- With the LAS, the laser transmitter frequency can be tuned for strong interaction with lower or middle tropospheric CO2 molecules; however maintaining the "optimum optical depth" constrains the tuning;
- Use of (temperature insensitive) absorption lines with line strengths covering an order of magnitude in dynamic range greatly increases the flexibility

CO_2 Bands in 1.575 – 1.625 and 2.0 – 2.08 μm Regions

Laser sensing – can choose an optimum line in one or more of these bands for differential absorption measurements

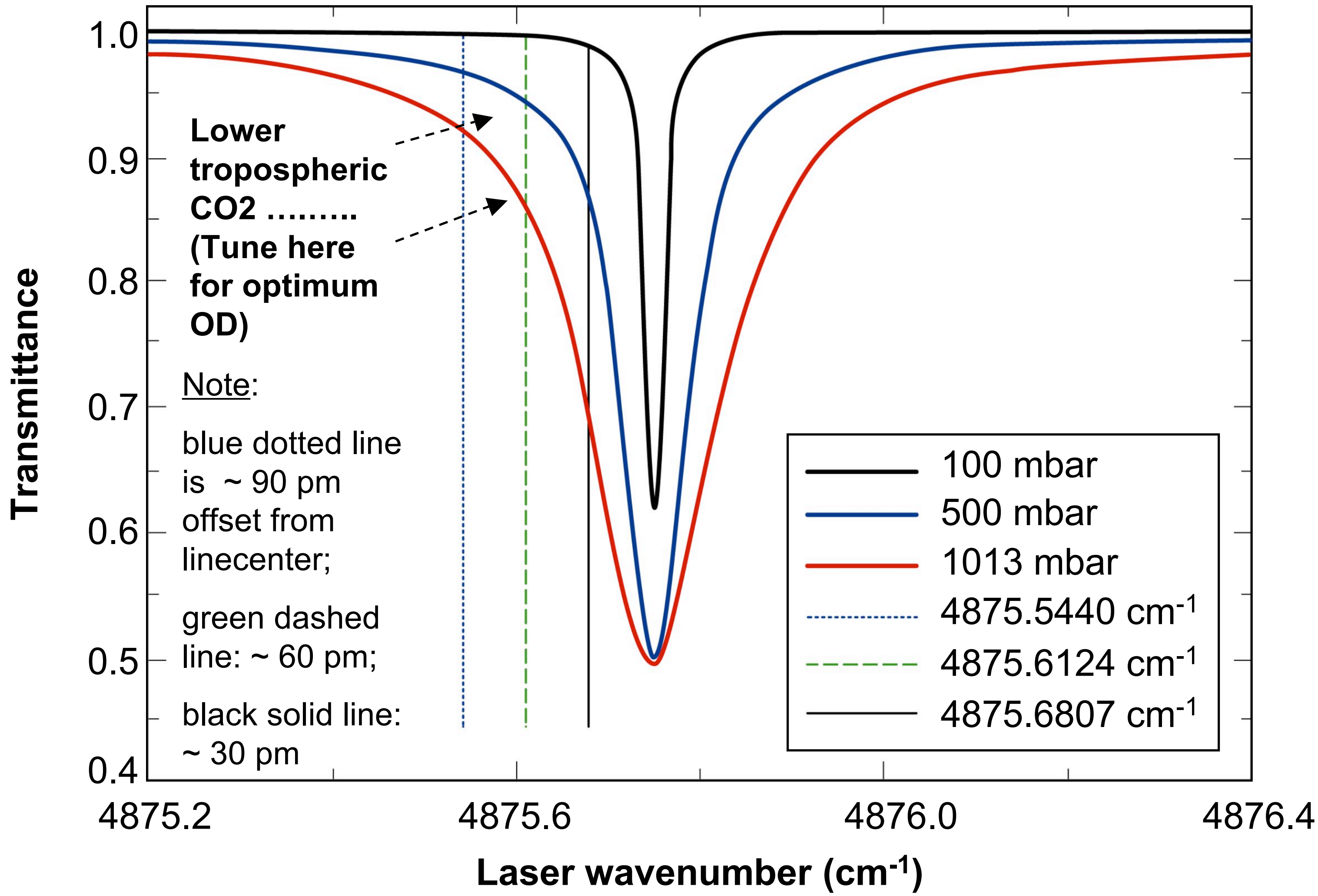
Linestrengths in 2.06 μm region are 10 times larger than in the 1.6 μm region





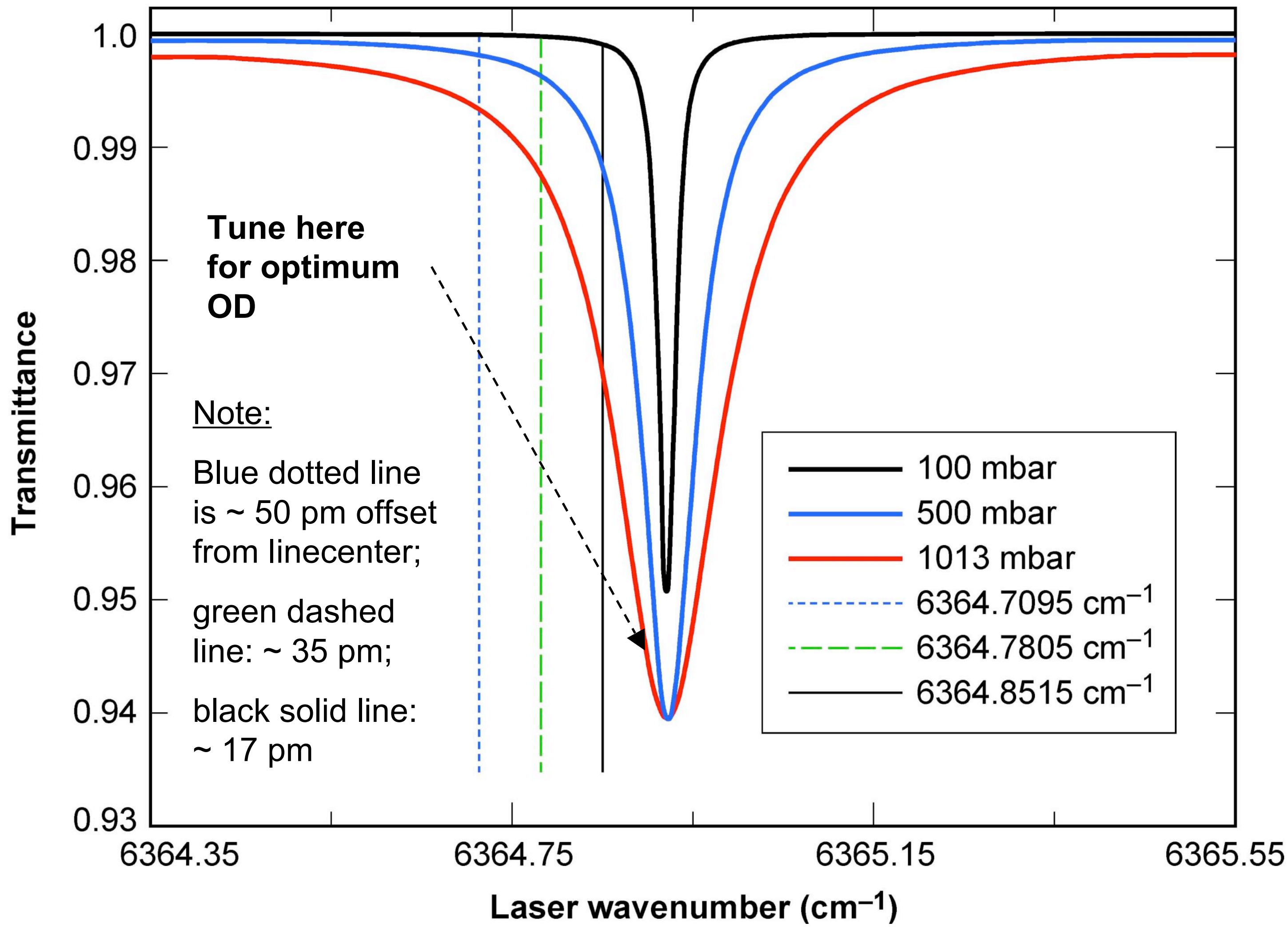
Atmospheric CO_2 Transmittance Near 2.05 μm

Laser Transmitter Offsets (vertical lines): 1,2,3 halfwidths from line center



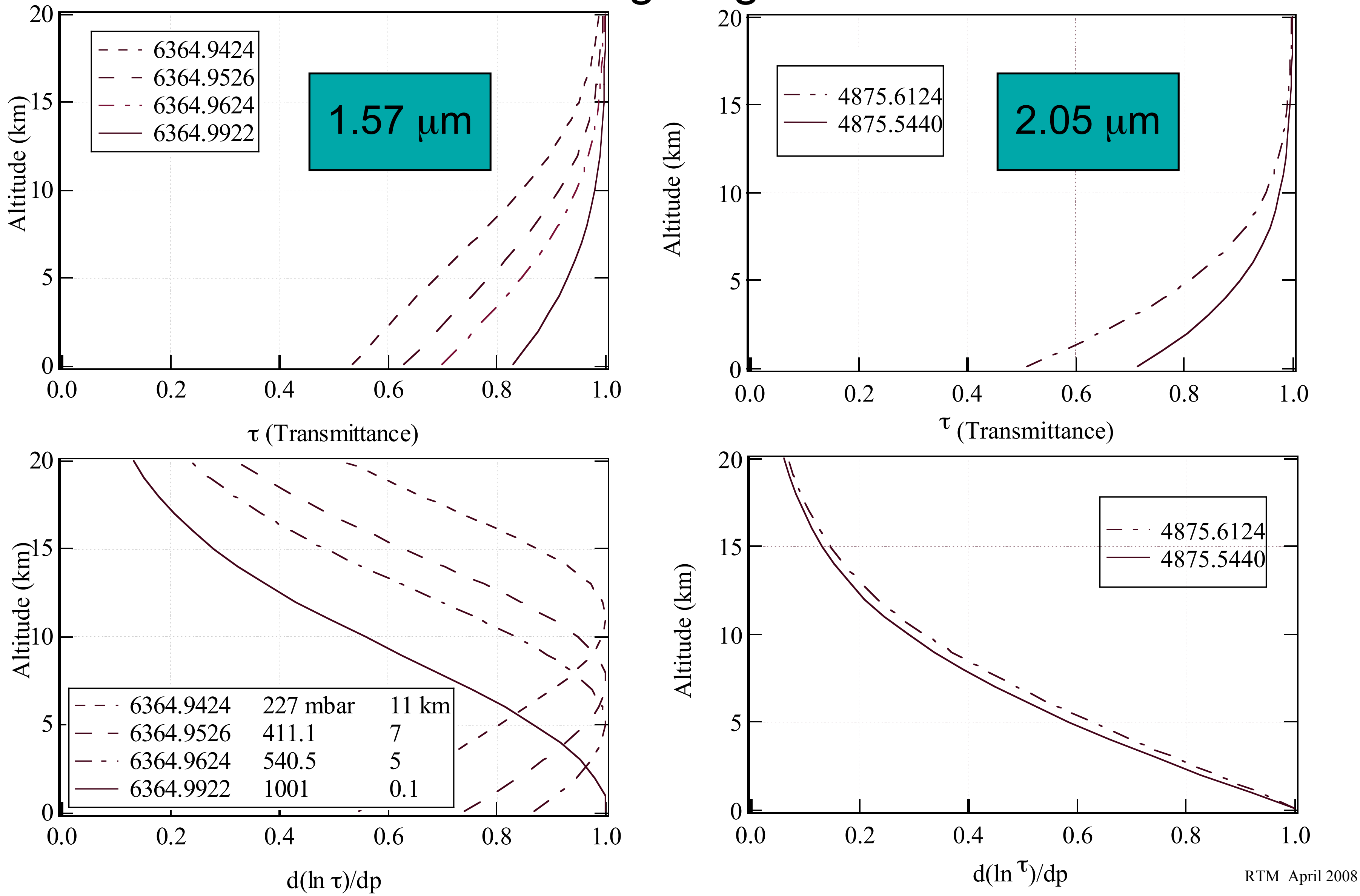
Simulated spectral transmittance near the 4875.7490 cm^{-1} line for a **1-km pathlength**

Atmospheric CO_2 Transmittance Near 1.57 μm



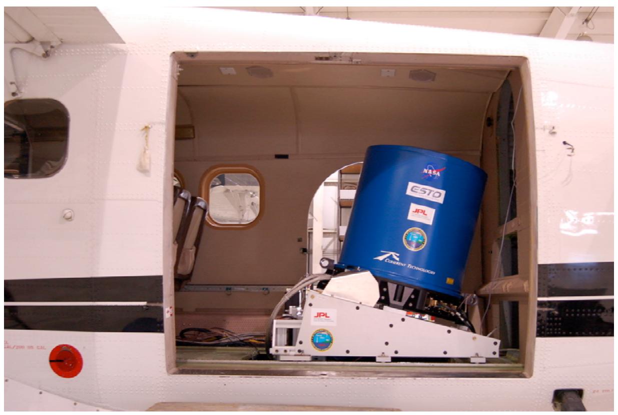
Simulated spectral transmittance near the 6364.9225 cm^{-1} line for a **1-km pathlength**

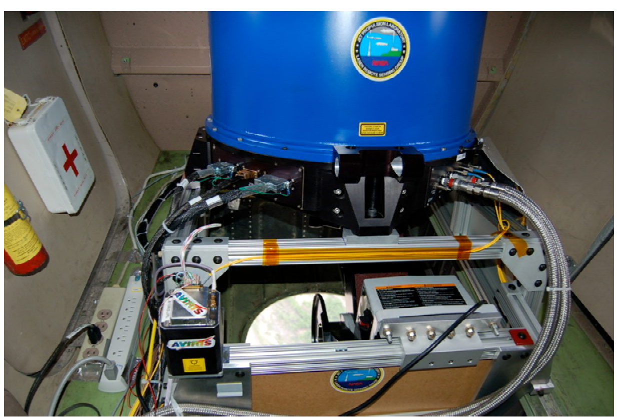
Transmittances and Weighting Functions from Orbit



RTM April 2008

JPL Airborne CO_2 Laser Absorption Spectrometer





Status

- Instrument built and tested in a laboratory environment with funding from NASA ESTO Instrument Incubator Program;
- Operates at 2.05 microns, employs heterodyne receiver;
- Initial measurement of differential CO2 concentration at the ~1% agreement demonstrated in the laboratory

- <u>Flights:</u>

  - <u>California:</u> engineering checkout flights were conducted over the Mojave desert and the Pacific Ocean during summer <u>2006</u>.

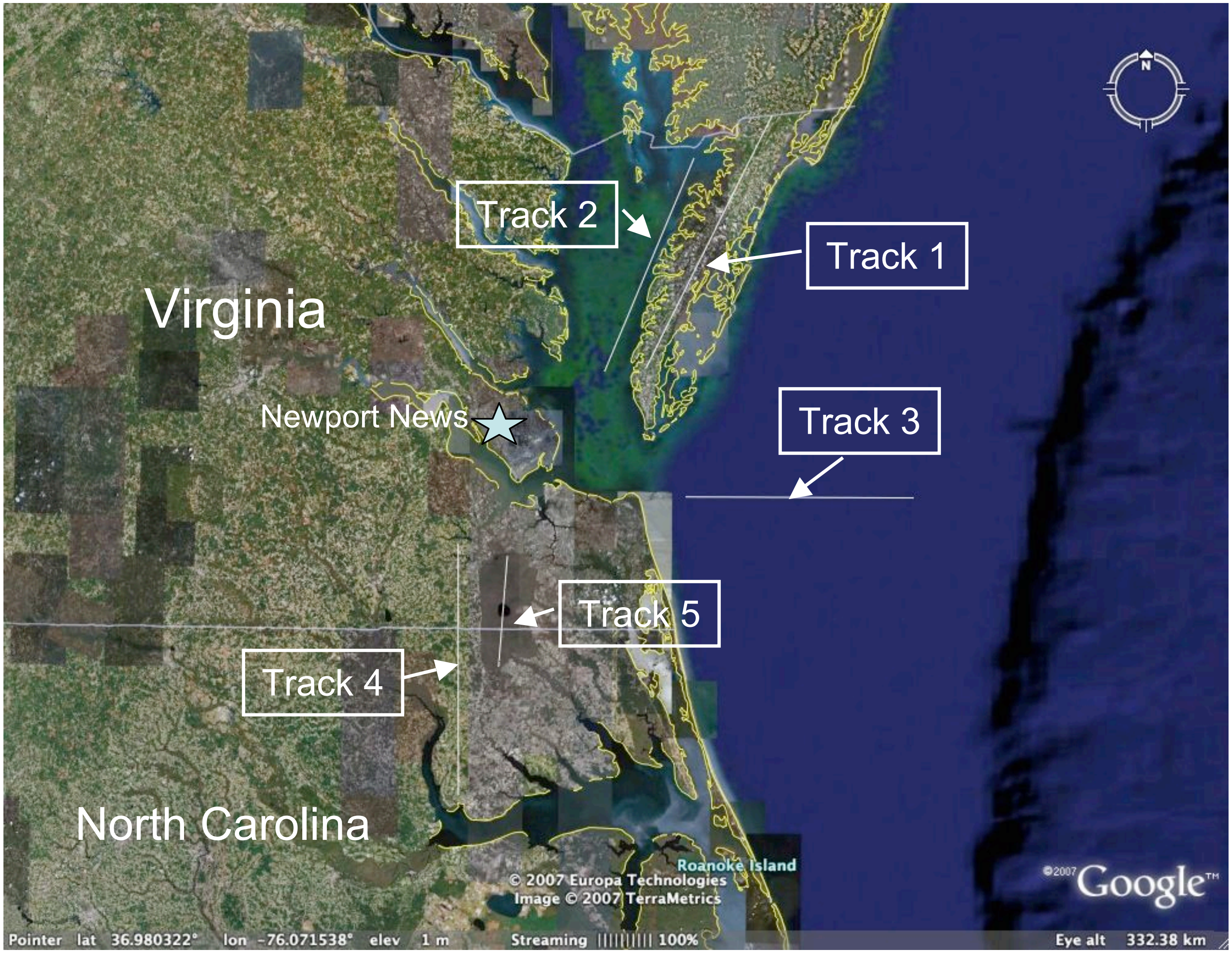
  - <u>Oklahoma:</u> 3 flights were conducted near the instrumented tower at the DOE Oklahoma ARM site during <u>September 2007</u>.

  - <u>Virginia;</u> 5 flights were conducted in Virginia in <u>October 2007</u> under the joint campaign with the ACLAIM instrument.

- See poster paper (Gary Spiers / Bob Menzies)

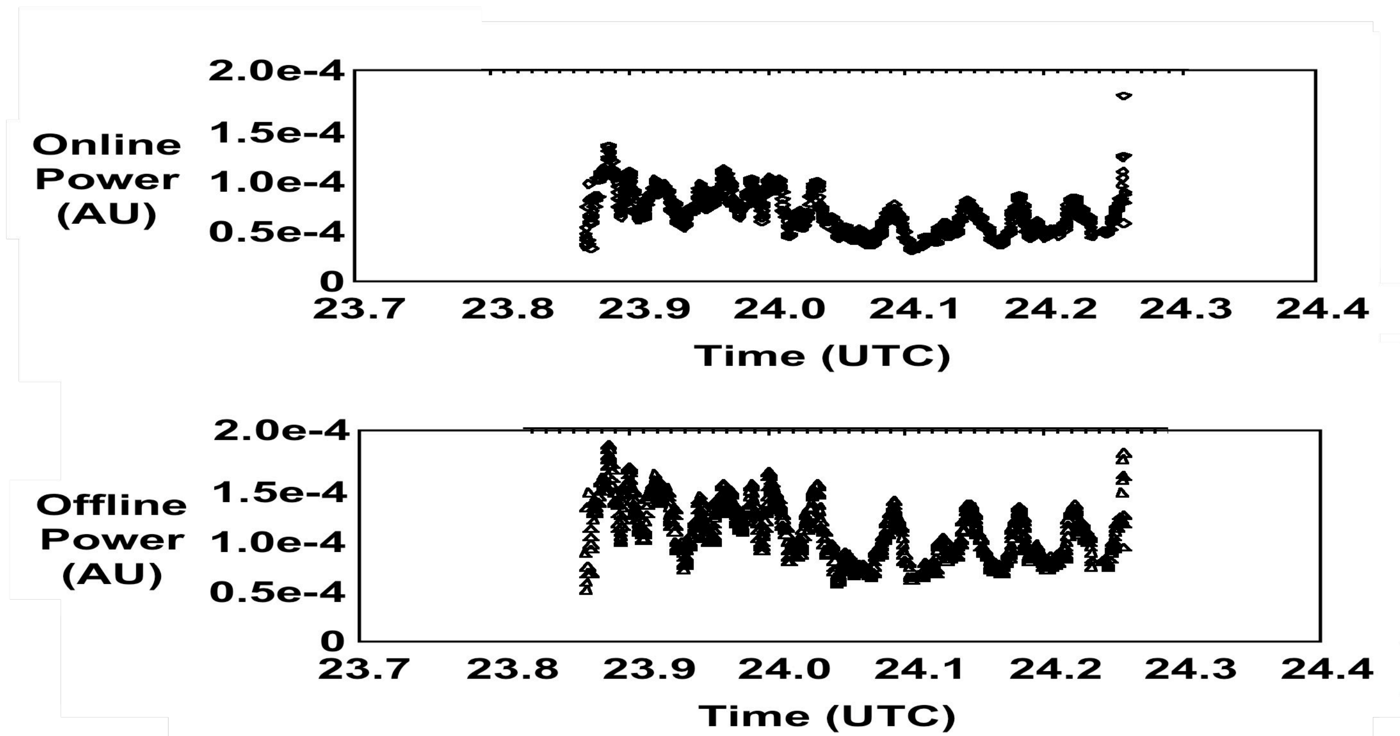
CO_2 Flights - October 2007

Flight Tracks



RTM April 2008

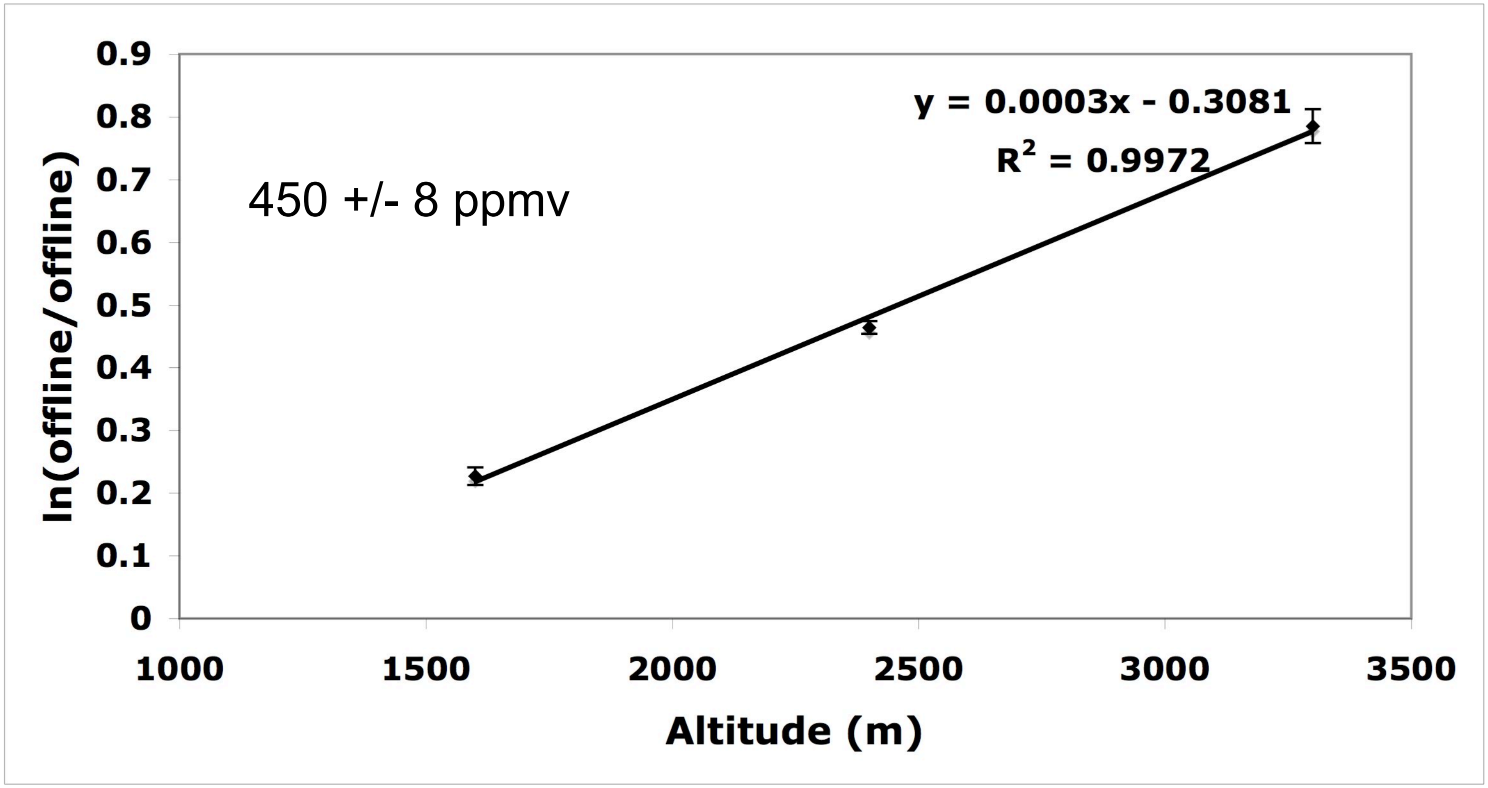
Example of Data from Oct. 21 Virginia Flight



- Online and Offline return signal powers are highly correlated along Track 4, as expected when primary fluctuation source is due to surface reflectance variability
- We achieved a differential absorption precision of ~2%. This is consistent with speckle-limited fluctuation amplitudes for the data averaging time (~ 1 s). Faster data transfer electronics will reduce speckle effect for a given data averaging time.

Column CO_2 Retrieved from Flight Data

10/21/2007 Flight Track 4, Night Time



Slope corresponds to a CO_2 concentration of 450 +/- 8 ppmv

In-situ measured CO_2 concentration varied between 392 and 396 ppmv as a function of altitude

- The measurement bias is being investigated through further analysis of the data

Summary

- With LAS soundings of CO_2 at 1.57 and 2.05 microns, we can probe the lower and middle troposphere independently, while optimizing the IPDA sensitivity for each channel
- Airborne 2.05 micron LAS instrument status
  - Demonstrated CO_2 retrievals with 2% precision over ~ 5 second time increments from multiple flight legs
  - Continuing data analysis
  - Resolving bias
  - Next steps:
    - Incorporate higher-speed data transfer/storage capability for increased throughput – can increase precision by factor of 2 for the same time average (same spatial resolution)
- With both 1.57 and 2.05 micron LAS instruments – have demonstrated precision levels that validate system performance predictions in varied atmospheric conditions over diverse terrain

Summary of ASCENDS Mission Study

- **ASCENDS mission has been defined that can meet the science objectives defined in the NRC decadal survey (DS).**
  - CO_2 column mixing ratios over day/night, all latitudes, all seasons with high precision.
  - Global coverage to surface/cloud tops and to surface between broken clouds.
  - Mission data will permit significant improvements in source/sink estimates on regional scales.
- **ASCENDS mission approach utilizes mature instrument technologies that could support an LRD as early as 2014.**
  - Architecture based on advanced telecom technologies mitigates risk associated with early launch option.
  - Mission design utilizes mature SC and launch capabilities.
- **Baseline ASCENDS mission cost within DS estimate uncertainty.**
  - Cost for enhanced science options evaluated.
- **ASCENDS mission includes all required measurements.**
  - Minimizes risk from dependencies on other missions and external data sets.

(See ASCENDS Poster by Harrison et al. #66)

ASCENDS Near-Term Activities

- **Science**
  - ASCENDS Workshop - July 2008
  - Continue impact studies of ASCENDS measurements
  - Continue LaRC-JPL flights in preparation for OCO validation
  - Apply airborne CO_2 LAS systems to regional to continental scale CO_2 investigations
- **Active Instrument Development**
  - Extend ground-based 1.26-micron O_2 LAS pressure measurements to flight experiments (July 2008)
  - Combine 1.6 & 2.0 CO_2 LAS systems with 1.26 O_2 LAS and laser altimeter for ASCENDS Airborne Flight Simulator on NASA P-3 (available by Dec. 2009)
- **Mission Development**
  - Begin life tests of laser transmitters
  - Conduct study of passive instrument for T & CO
  - Conduct Independent Cost Estimate of ASCENDS mission
  - Examine potential national/international collaborations

(See CO_2/O_2 Poster by Dobbs et al. #62; CO Poster by Cook et al. #37)