Current Status of Active Remote Sensing of CO_2 & Applications to NACP Investigations

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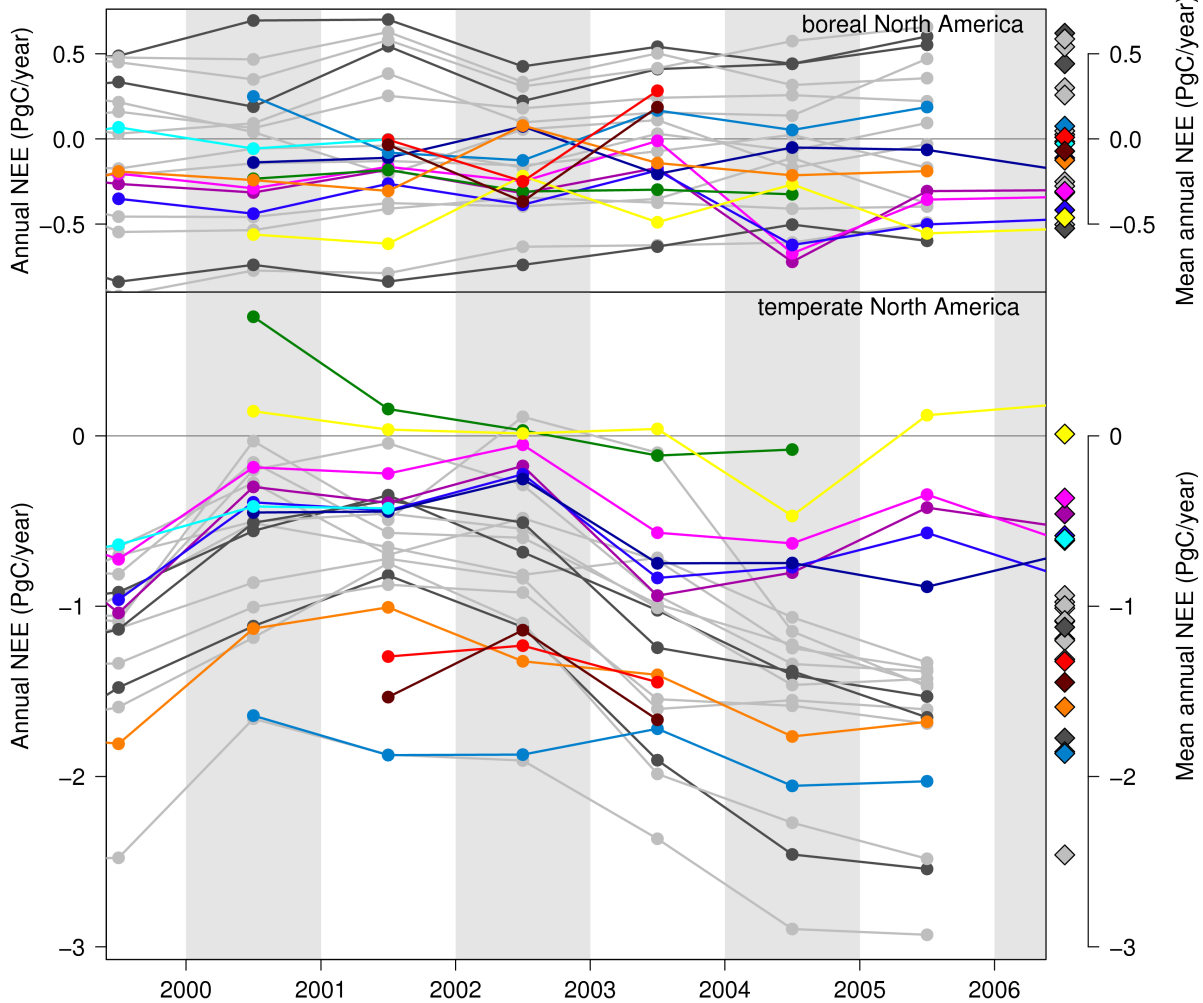
[7] JAXA, Japan; [8] JPL/Cal Tech

3rd North American Carbon Program Meeting
New Orleans, Louisiana
1-4 February 2011

NACP Needs

- Atmospheric inversions do not, to date, converge in their diagnosis of the carbon balance of North America.
- This is due both to a limited density of atmospheric data, and uncertainty in our simulations of atmospheric transport.

“Inverse” models - annual NEE for North America, 2000-2005



Large range of results for annual fluxes of CO_2.

Evidence of coherence in interannual variability.

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rayner.2008
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Figure courtesy A. Jacobson, NOAA

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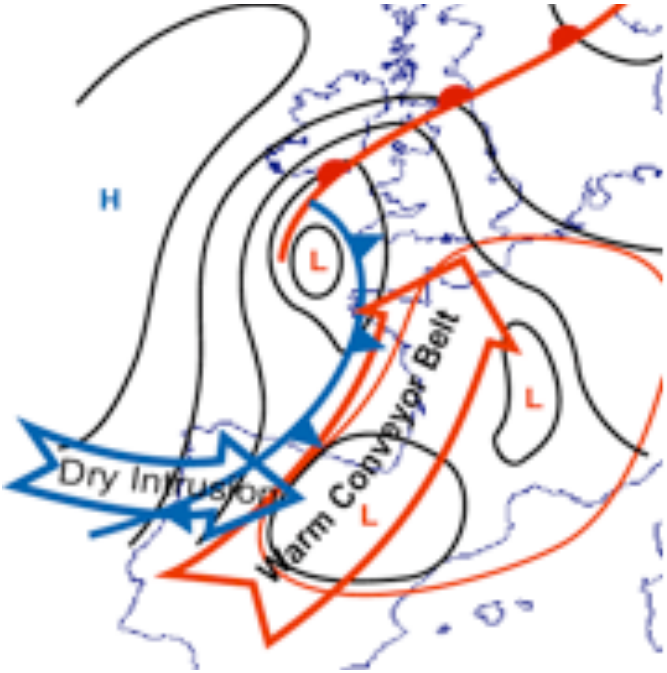
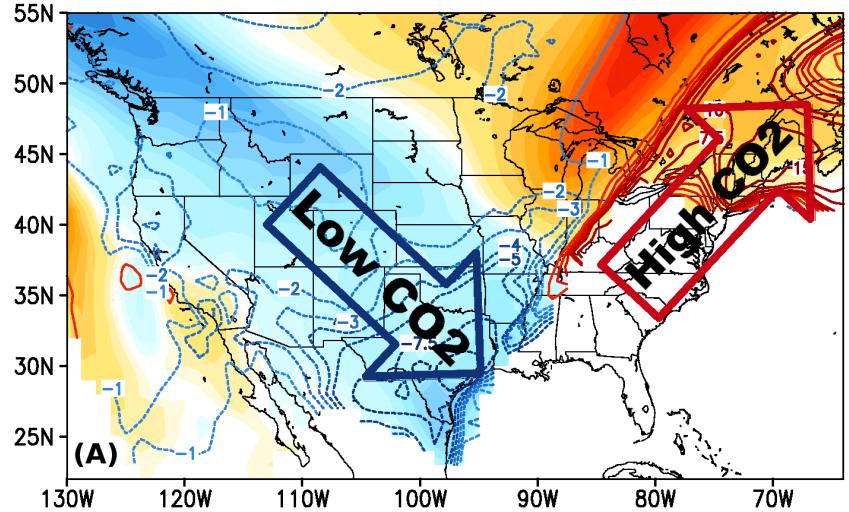
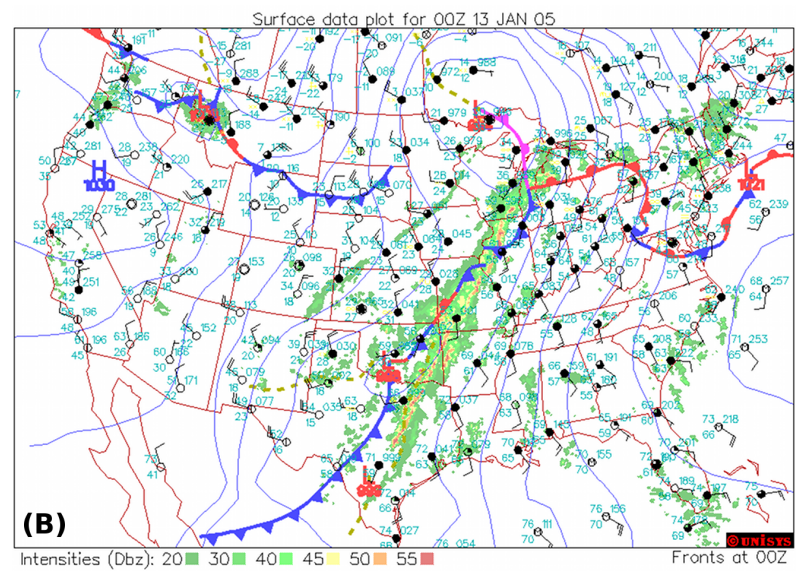
Simulations: Synoptic transport is central to the resulting seasonal, latitudinal CO_2 distribution







Parazoo et al, in preparation.
PCTM simulations.

Figures courtesy Nick Parazoo, CSU

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Potential Roles for Active Remote Sensing of Atmospheric CO_2

- **Data for evaluation of atmospheric transport and model results**

  (airborne sensors)
- **Direct flux measurements via eddy covariance**

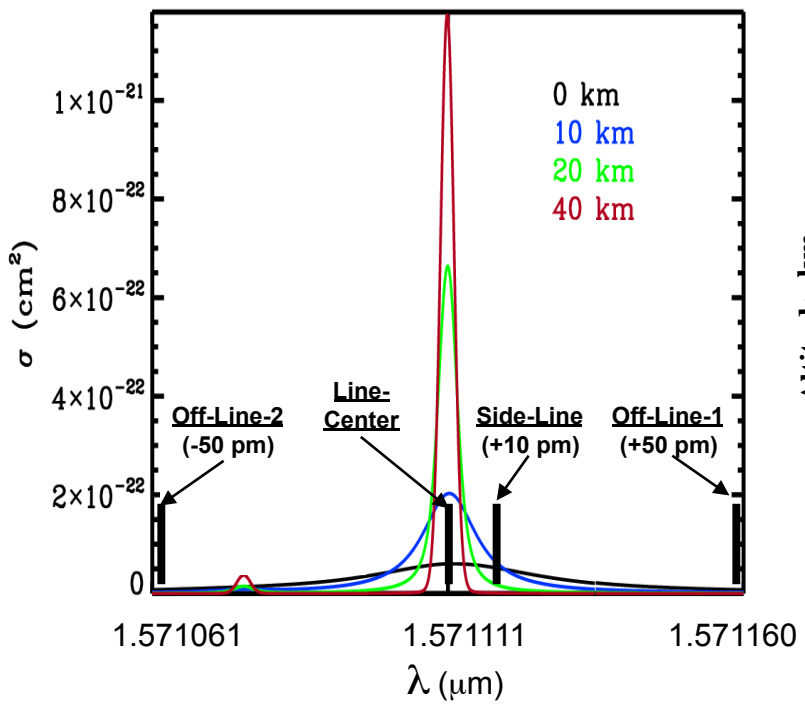
  (ground-based or airborne sensors)
- **Data for atmospheric inversions**

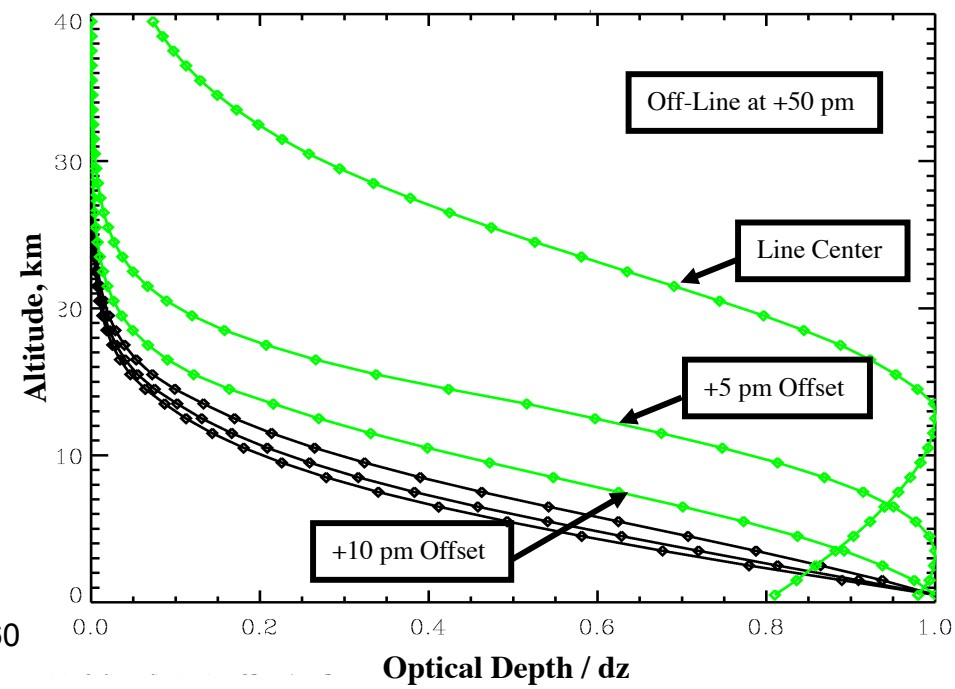
  (satellite based instruments)

General CO_2 Measurement Approach

Integrated Path Differential Absorption (IPDA)

CO_2 Absorption Line Regions 1.57 & 2.06 μm





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

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

Current Operational CO_2 Laser/ Lidar Approaches & Systems

Airborne: CO_2 columns with IPDA from aircraft to surface/cloud top

- Continuous wave (CW) laser transmitter with two/more CO_2 laser λ's
  - Intensity Modulated (IM) @ 1.57 μm with lock-in detection
    - NASA Langley/ITT Geospatial Systems (Browell/Dobler)
    - Japanese Space Agency (JAXA) (Sakaizawa)
  - Doppler shifted @ 2.06 μm with heterodyne detection
    - JPL/Cal Tech (Spiers/Menzies)
- Pulsed laser transmitter @ 1.57 μm with 10-20 laser λ's across CO_2 line
  - Photon counting detection
    - NASA Goddard (Abshire)

Ground: CO_2 profiling in lower troposphere with pulsed 2.06-μm Differential Absorption Lidar (DIAL) using atmospheric scattering

- Direct detection receiver
  - NASA Langley (Ismail/Singh)
- Coherent transmitter & heterodyne receiver
  - French LMD/IPSL (Gibert/Flamant)

Summer 2009 Coordinated Airborne Flight Tests in Support of ASCENDS Mission Definition

LaRC/ITT MFLL CO_2 Lidar Instrument in NASA UC-12

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

GSFC Airborne CO_2 Lidar Instrument in NASA Lear-25

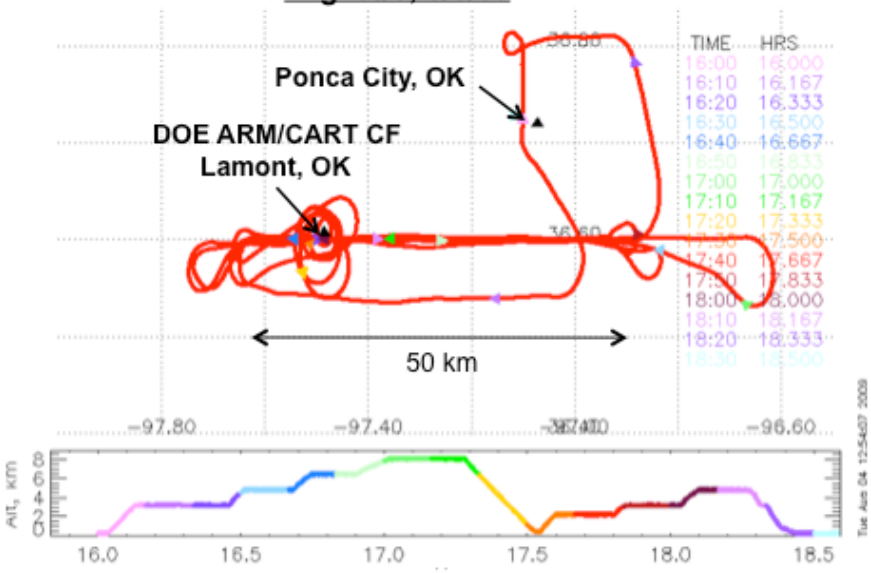
- GSFC team, NASA Glenn aircraft
- Jim Abshire/GSFC, Team Leader

JPL Airborne CO_2 Lidar Instrument in Twin Otter

- 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



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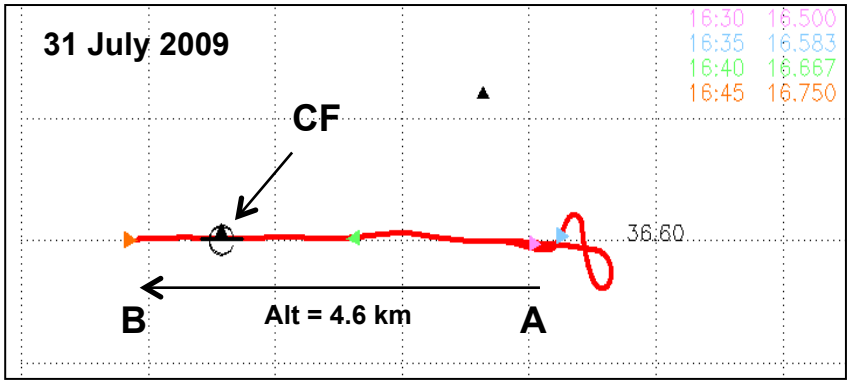
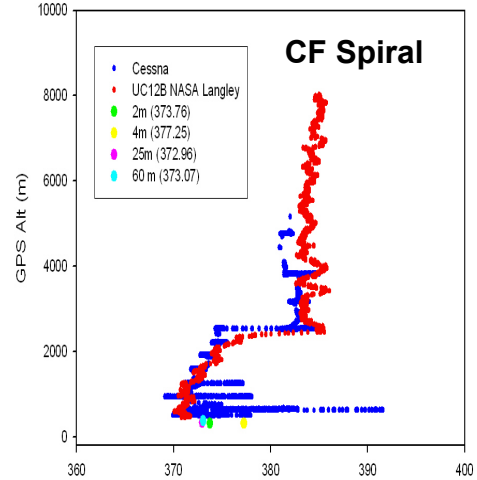
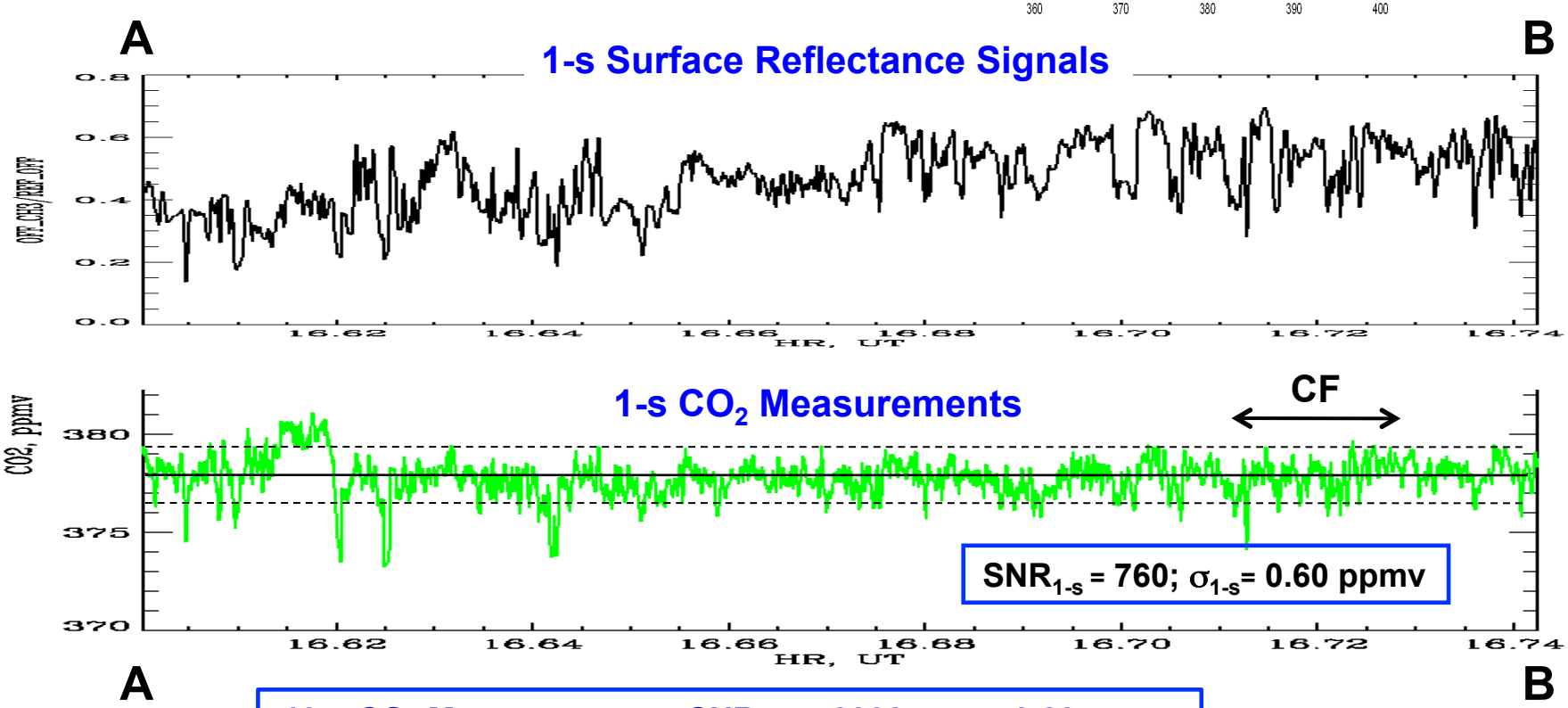
LaRC/ITT MFLL CO_2 Remote Measurements







10-s CO_2 Measurements: $SNR_{10\text{-}s} = 2002$; $\sigma_{10\text{-}s} = 0.20$ ppmv

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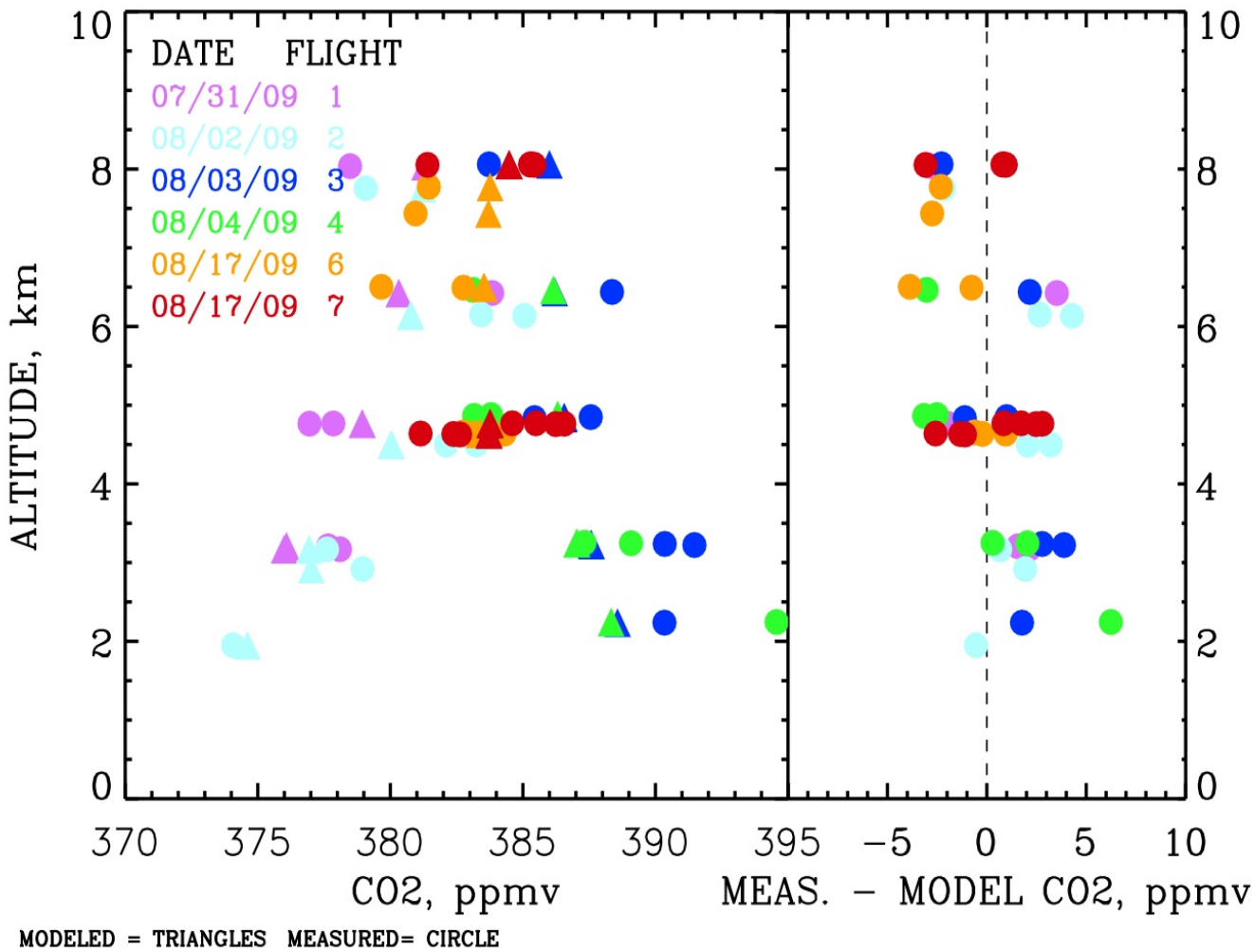
LaRC/ITT MFLL CO_2 Comparisons for All 2009 Coordinated Flights



Average ΔCO_2 = 0.32 ppmv with σ = 2.4 ppmv

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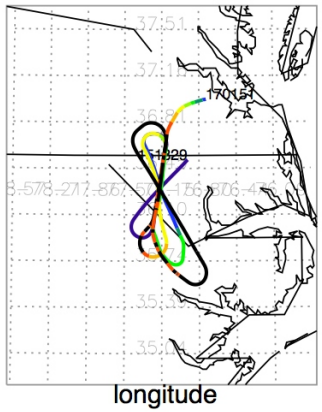
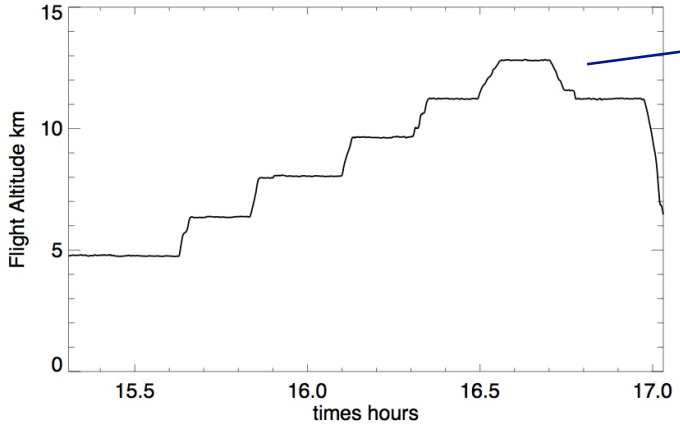
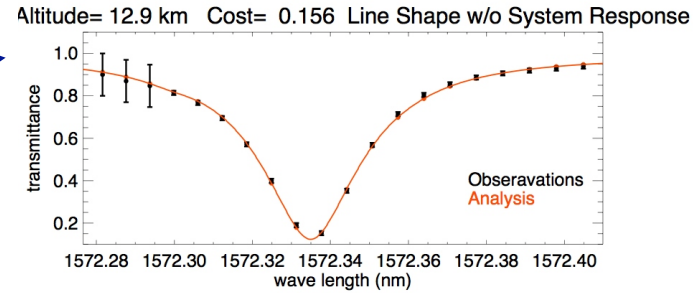
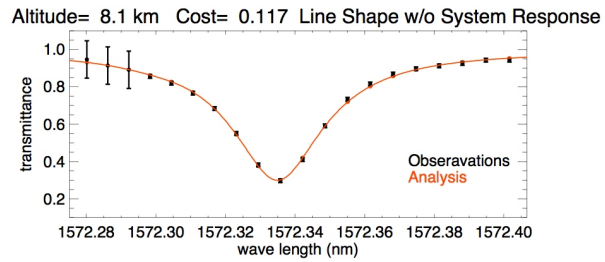
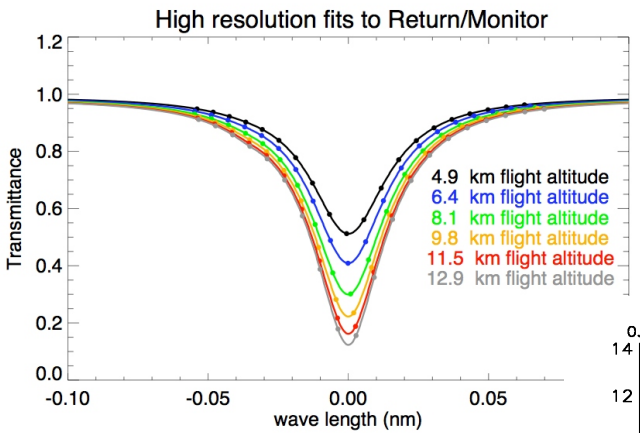
GSFC CO_2 Sounder: Line Optical Density & # Density vs Altitude
North Carolina Flight - August 17, 2009



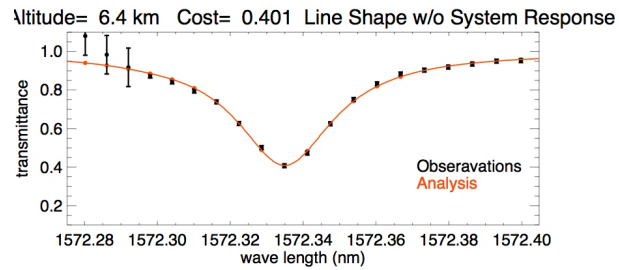


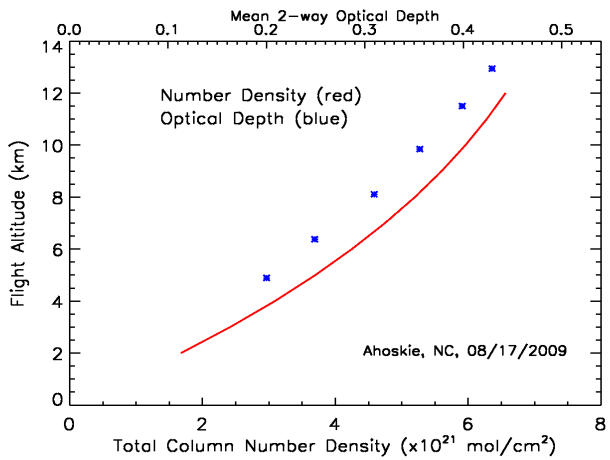


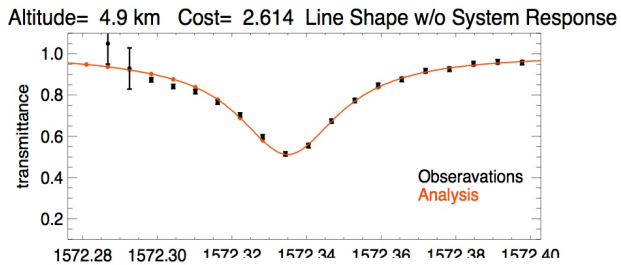




- Depth increases with altitude
- Smooth line shapes at all altitudes !







- Mean Optical Depths from line fits to CO_2 Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings

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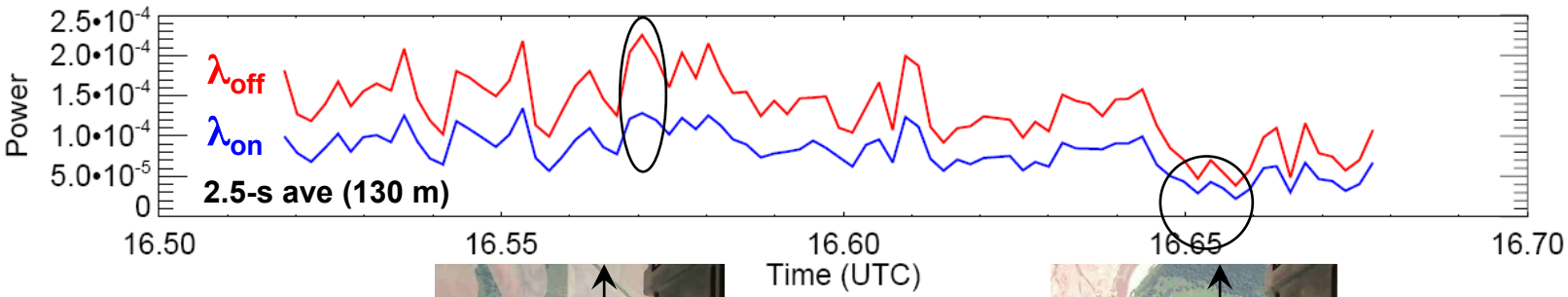
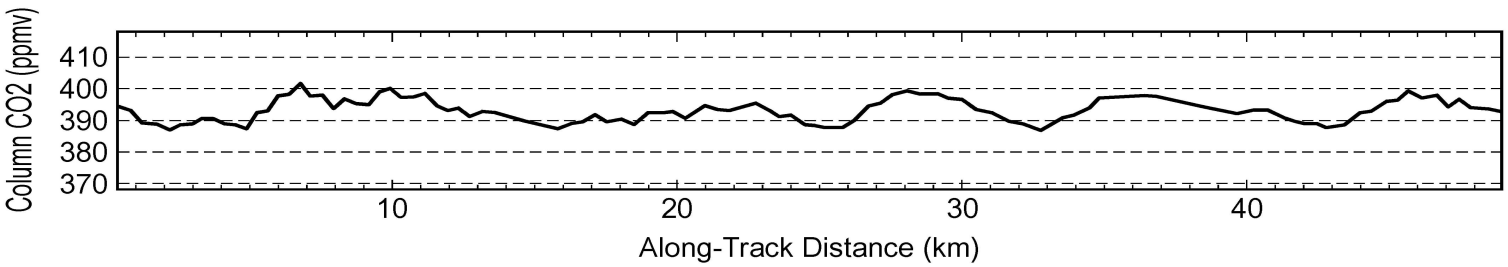
JPL 2-µm CO_2 LAS
Signals from 10 kft Pass over Oklahoma Site



Arrow shows flight track and direction

Retrieved CO2 – Oklahoma 8/4/2009 9 kft Overpass 2 (east to west)



CO_2 Ave. 393 ppmv

- **Std Dev due to speckle fluctuations for 600 m resolution: ~ 5 ppm.**
- **The same level of variability in the weighted CO_2 column seen on both days.**

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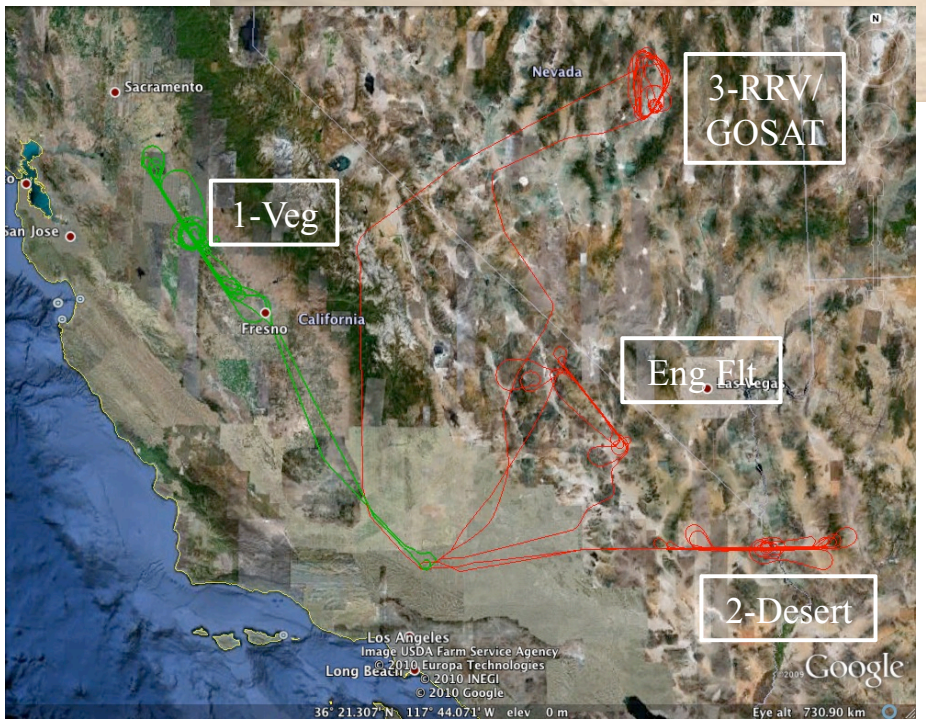
Airborne Experiments to Measure CO_2 Column Densities to Support ASCENDS Mission Definition – 6-18 July 2010

Instruments: ITT/LaRC MFLL (Dobler/Browell); GSFC CO2 Sounder (Abshire); JPL CO2 LAS (Spiers); LaRC In Situ Instrumentation (Vay/Choi)



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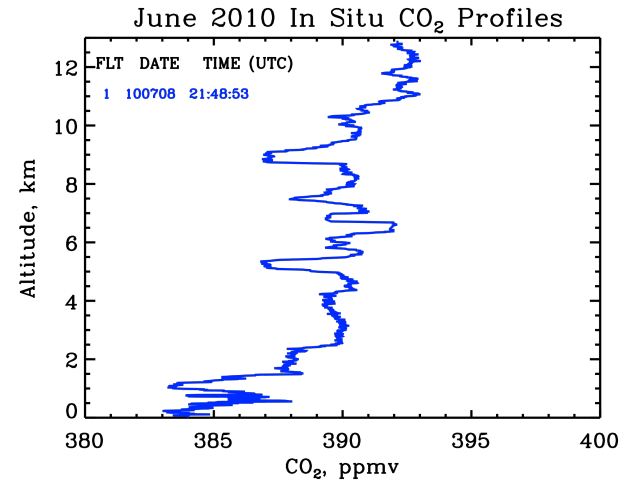
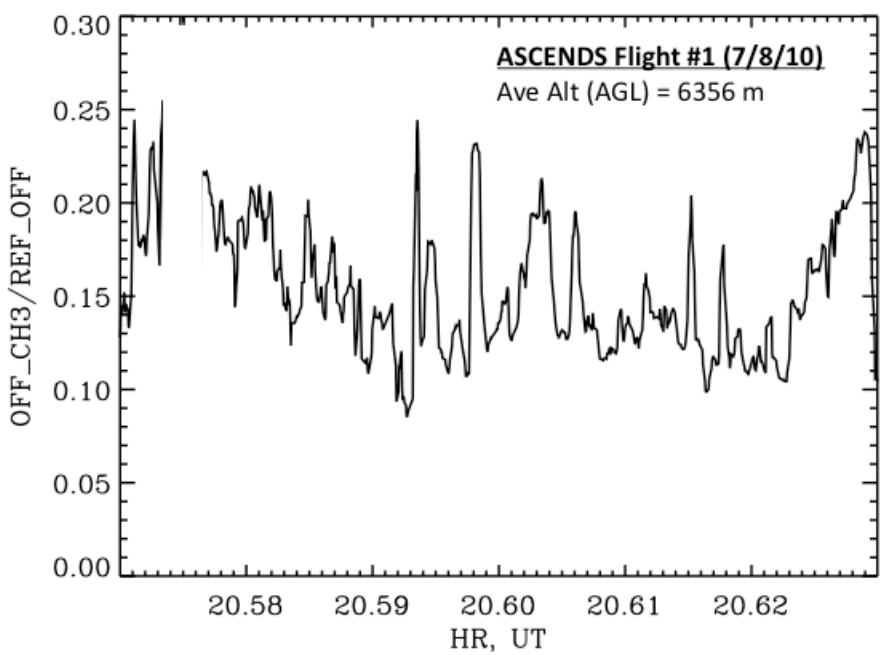
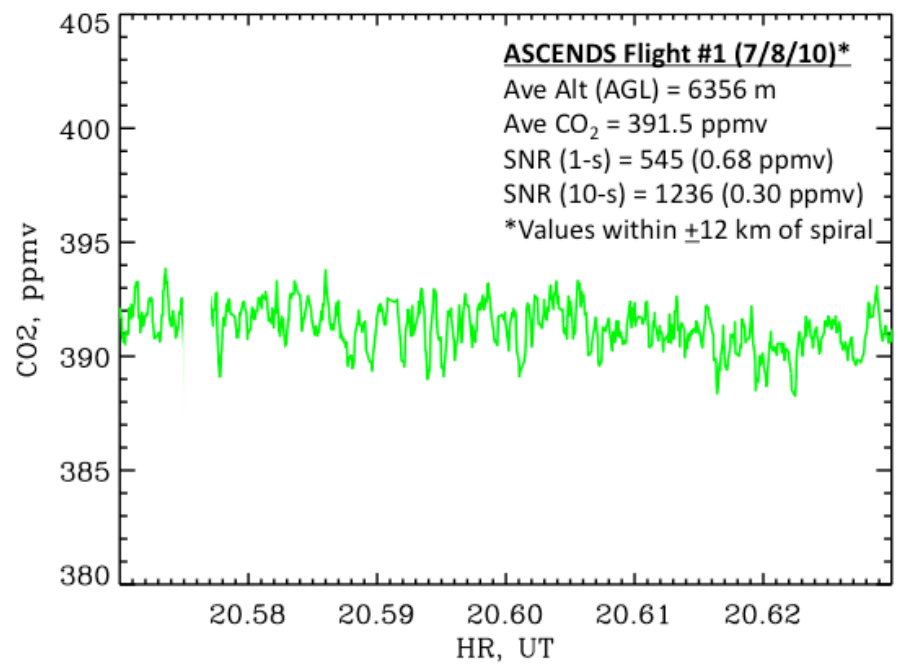
LaRC/ITT MFLL ASCENDS Flt #1, 8 July 2010

Vegetation #1: Central Valley, California







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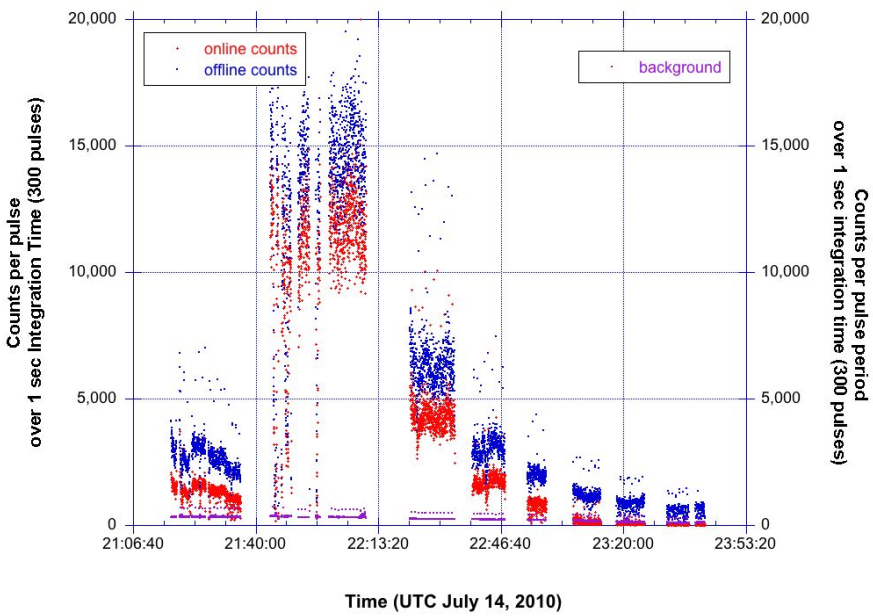
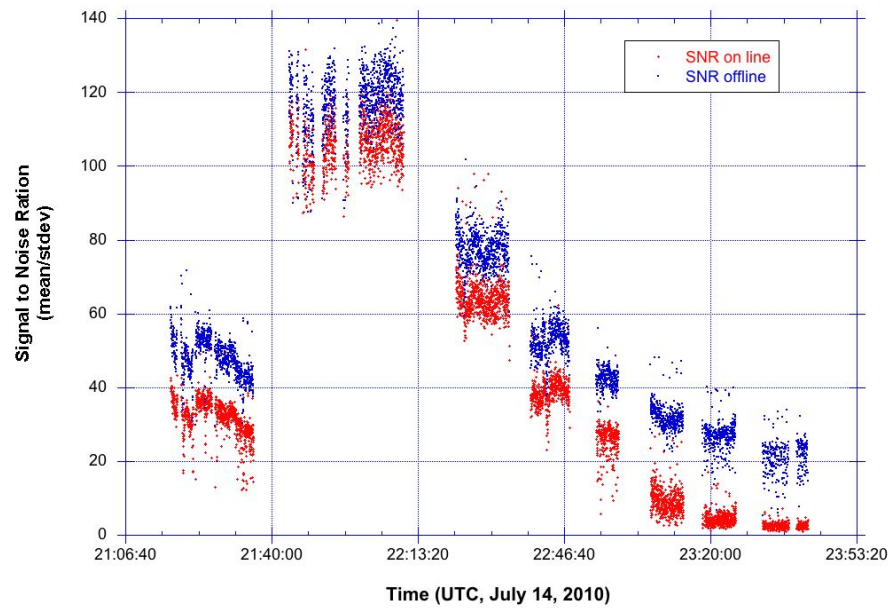
GFSC CO_2 Sounder Signal and Noise During Pacific Ocean Flight





Initial Estimate of Random error in 2010 Airborne measurements

- Over typical terrain have energy SNR for single pulse = 100:1 in a 1 sec measurement
- Have ~ 9 pulses measured across the mid-section of the CO2 line
- Can estimate the area of the line with SNR ~300:1 in 1 second
- Can estimate the area of the line with SNR ~1000:1 in 10 seconds
- Optical depth of midpoint of line is ~0.5
- SNR of the OD estimate (CO2 column density) is ~500:1 for 10 second average
- Is < 1 ppm in CO2 mixing ratio
- More averaging is required over darker surfaces

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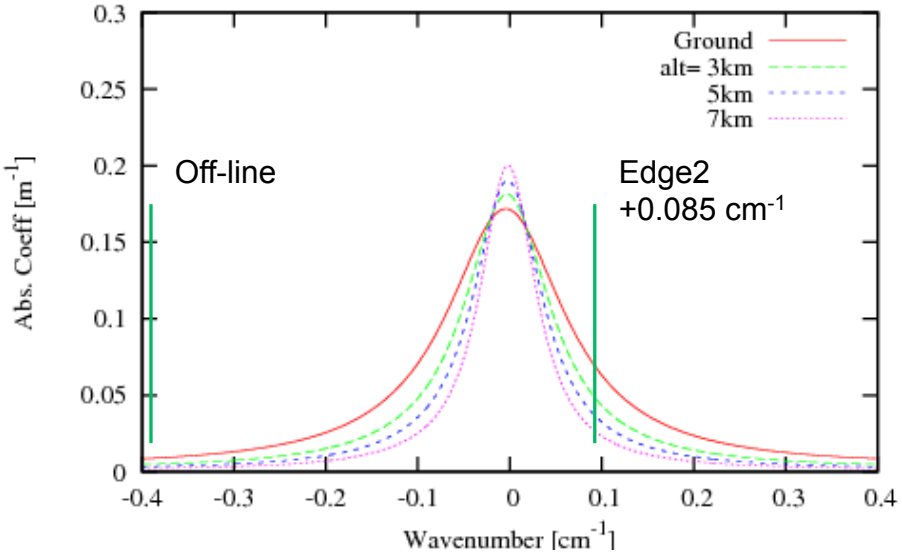
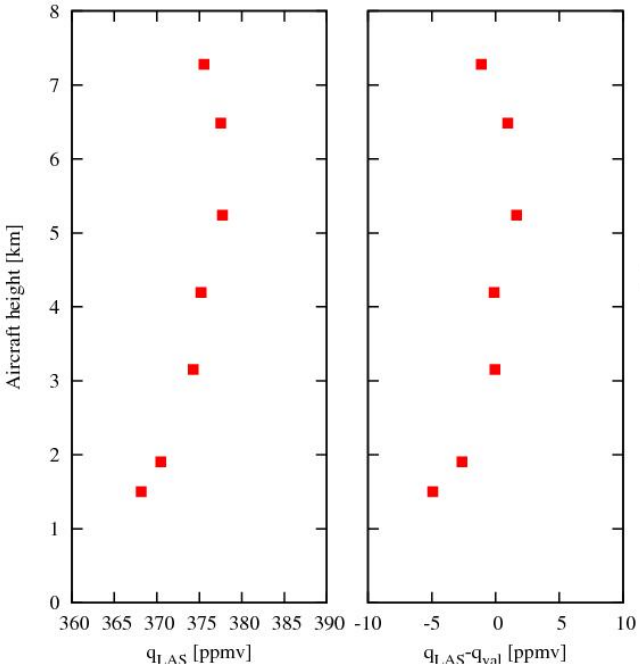
Airborne flight test using proto-type 1.57μm JAXA-LAS (Sakaizawa et al.)

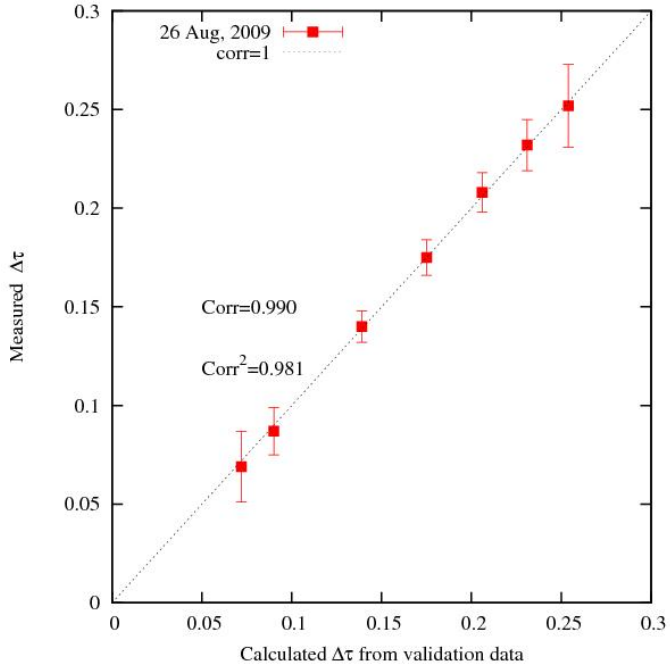


S. Kameyama et al. "1.6 micron continuous-wave modulation hard-target differential absorption lidar system for CO2 sensing," Opt. Lett. vol. 34, pp. 1513-1515 2009.

D. Sakaizawa et al. "Ground-based demonstration of a CO2 remote sensor using a 1.57μm differential laser absorption spectrometer with direct detection" J. Appl. Remote Sens. vol. 4 043548 2010

D. Sakaizawa "Feasibility Study for the Potential CO2 Measurement from Space using the 1.57-μm Differential Laser Absorption Mission", Proc. ICSO Rhodes Greece 2010





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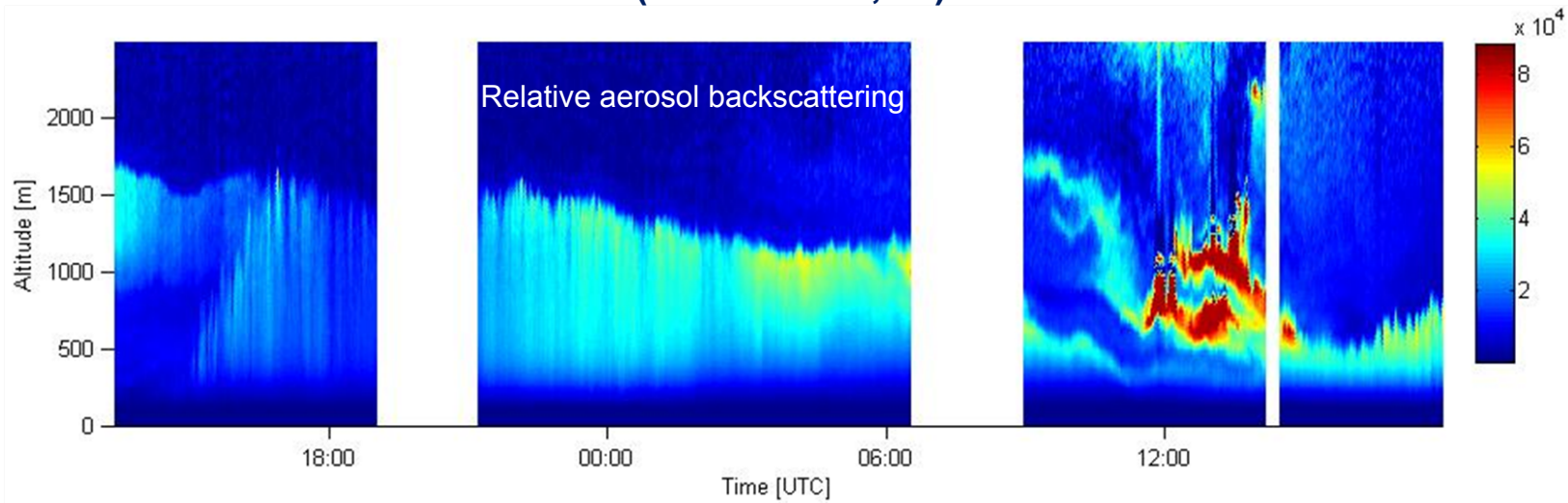
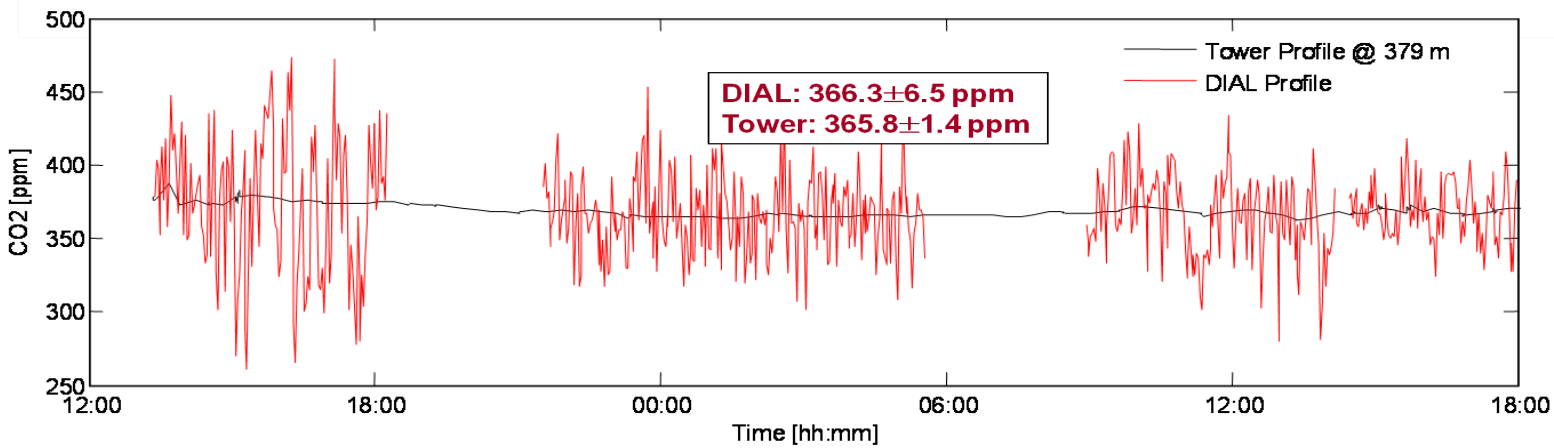
Development of a Pulsed Direct Detection 2.0-μm DIAL CO_2 Profiling System (Ismail et al. 2008)

Variations in boundary layer scattering at off-line and CO_2 during July 5-6, 2008 (West Brach, IA)





Goal: DIAL precision 1-2 ppm (<0.5%) with 0.5 to 1 km vertical resolution from 0.5 to 5 km with 30 min average.

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Vertical CO_2 & Wind Measurements of 2-µm Coherent DIAL (Gibert et al. 2008)

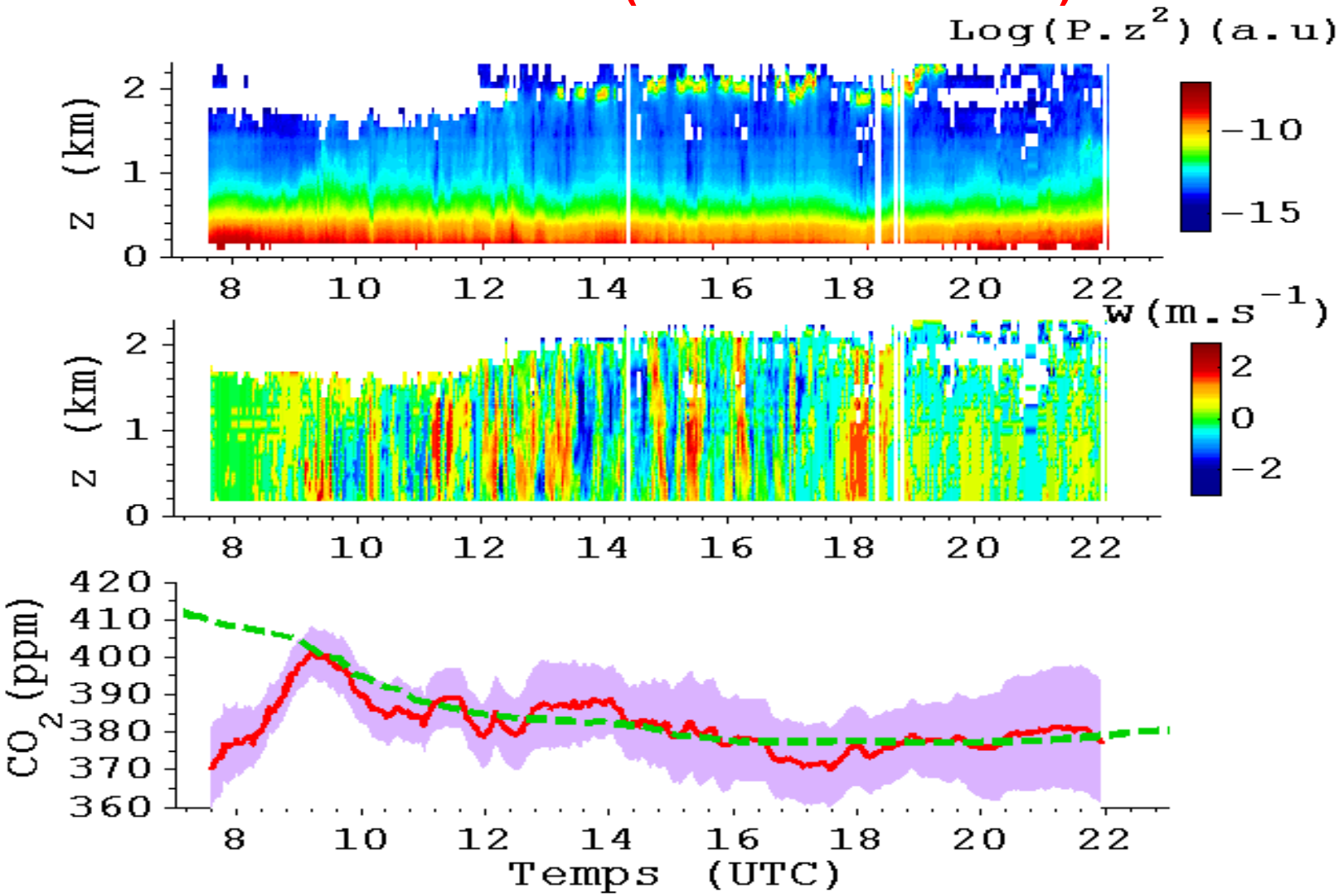

FIG 3: Vertical Doppler DIAL measurements: backscatter signal at 2-µm, vertical velocity and 1-km mean CO_2 mixing ratio in the ABL (red line) to be compared to ground-based in-situ sensor (dashed green line)

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CO_2 Laser/Lidar Systems Under Development or Planned

Airborne:

- Pulsed IPDA columns of O_2 @ 0.765 μm
  - NASA Goddard (Abshire) (2010)
- IM-CW IPDA columns of O_2 @ 1.26 μm
  - NASA Langley/ITT GS (Browell/Dobler) (2011)
- Pulsed IPDA columns of CO_2 @ 1.57 μm and CH_4 @ 1.65 μm
  - DLR, Germany (Ehret) (2012)
- Pulsed IPDA columns & coherent DIAL profiles of CO_2 at 2.06 μm
  - NASA Langley (Singh) (proposed)

Space:

- ISS IPDA columns of CO_2 using IM-CW @ 1.57 μm
  - JAXA (Sakaizawa) (2015)
- Global IPDA columns of CH_4 @ 1.65 μm
  - German-French Mission (MERLIN) (Ehret /Flamant) (2014)
- Global IPDA CO_2 columns weighted to lower atmos. (Approach TBD)
  - NASA ASCENDS Mission (ASCENDS) (Jucks) (2019/20)

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Conclusions

- Airborne lidars have demonstrated a CO_2 column measurement precision <0.5 ppmv with 10-s (~1-km) horizontal averaging with an absolute accuracy <2.5 ppmv.
- Airborne lidars have the potential to add high quality, spatially dense data that could improve understanding of regional CO_2 transport, thus improve continental inversions.
- Ground-based lidars have measured CO_2 profiles with 1-km vertical resolution and 30-min averaging to have a precision ~2 ppmv.
- Future space-based active remote sensing missions (e.g., ASCENDS) are being planned for global atmospheric inversions for CO_2 sources and sinks.