



Lidar Measurements of Atmospheric CO₂

Bing Lin

NASA Langley Research Center

Bing.Lin@nasa.gov

Contributors: Michael Obland¹, Edward Browell², F. Wallace Harrison¹, Joel Campbell¹, Jeremy Dobler³, Amin Nehrir¹, Byron Meadows¹, Susan Kooi⁴, Tai-Fang Fan⁴, Zhaoyan Liu⁴, and ASCENDS Team

¹NASA Langley Research Center, ²NASA Langley/STARSS II Affiliate,

³Harris Corp, ⁴Science System and Application, Inc

Hampton University

27 January 2016, Hampton, VA



Outline

❖ Introduction

- Carbon science and measurement requirements
- Lidar CO₂ measurement approach

❖ Instrumentation and Measurements

- Airborne system & its CO₂ measurements
 - In-situ measurements: AVOCET
 - Ranging, accuracy & precision
 - CO₂ variability: seasonal, interannual, spatial; urban impact
 - Advanced capabilities for cloudy conditions
- Space lidar applications

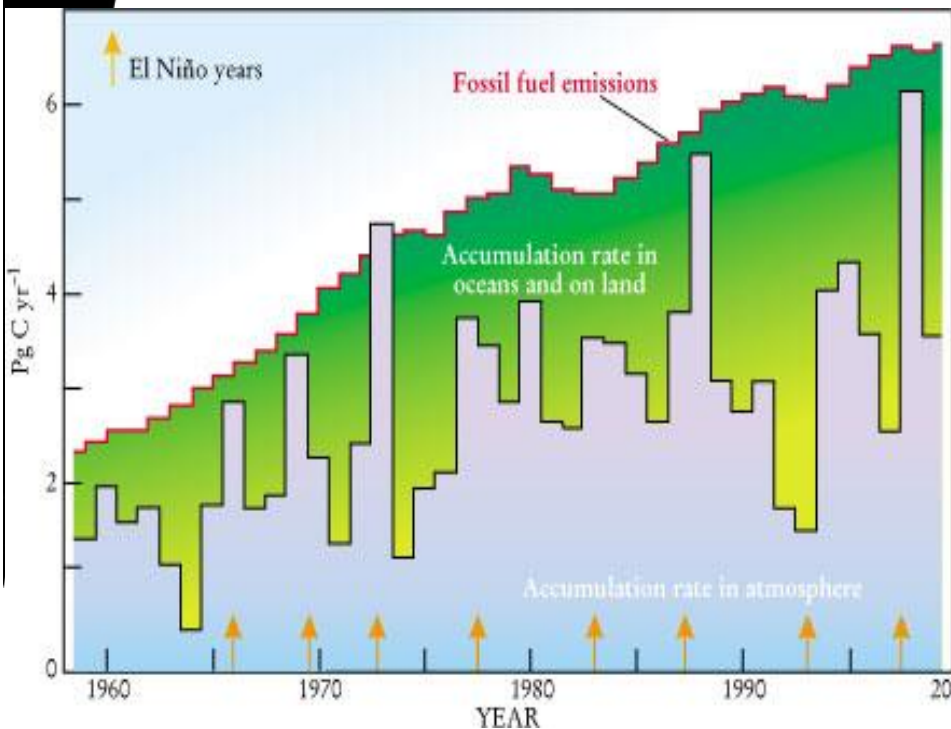
❖ Current & Future Campaigns

- ASCENDS & ACT – America

❖ Summary



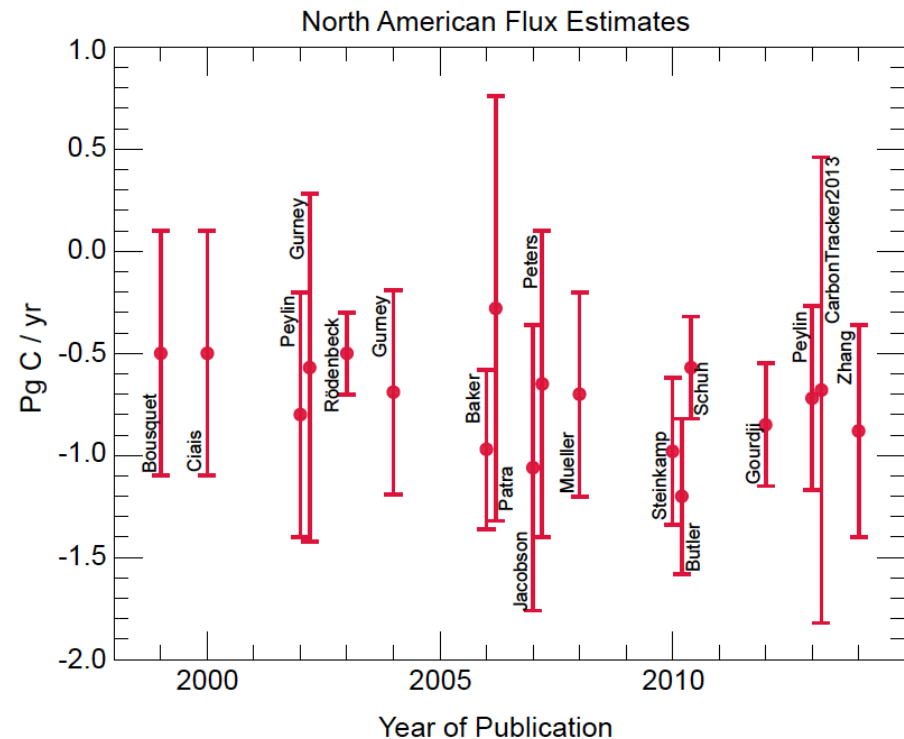
Terrestrial ecosystems are removing large quantities of CO_2 from the atmosphere, but regional fluxes are highly uncertain.



Terrestrial biosphere and marine CO_2 sinks are large.

Sarmiento and Gruber, 2002

We have poor skill in determining North American biogenic CO_2 fluxes.
Butler, Davis et al, AGU 2014





Prediction of future biogenic CO₂ fluxes is highly uncertain: This is a major source of uncertainty in climate model projections

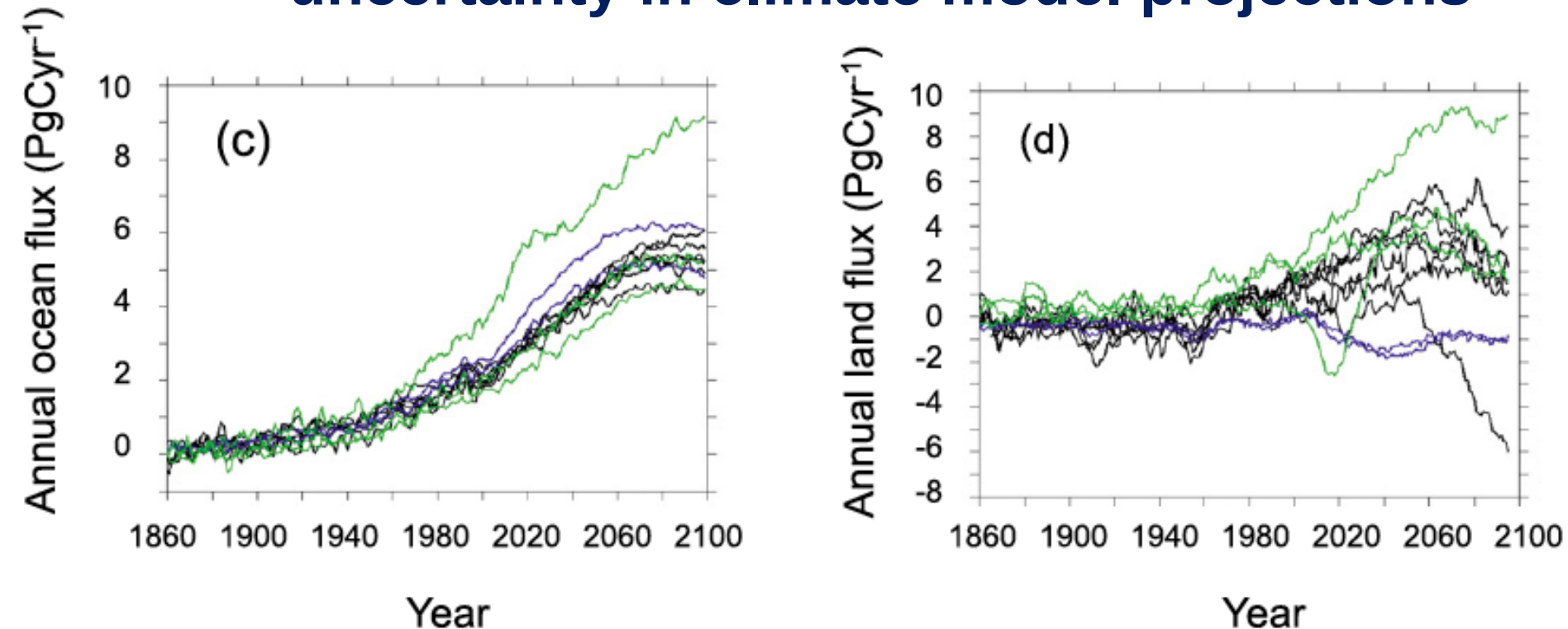


FIG. 4. Range of (a) cumulative global air to ocean carbon flux (PgC), (b) cumulative global air to land carbon flux (PgC) from the 11 ESMs E-driven simulations, (c) the annual global air to ocean carbon flux, and (d) annual global air to land carbon flux. Color code for model types is as in Fig. 1.

Friedlingstein et al., 2014

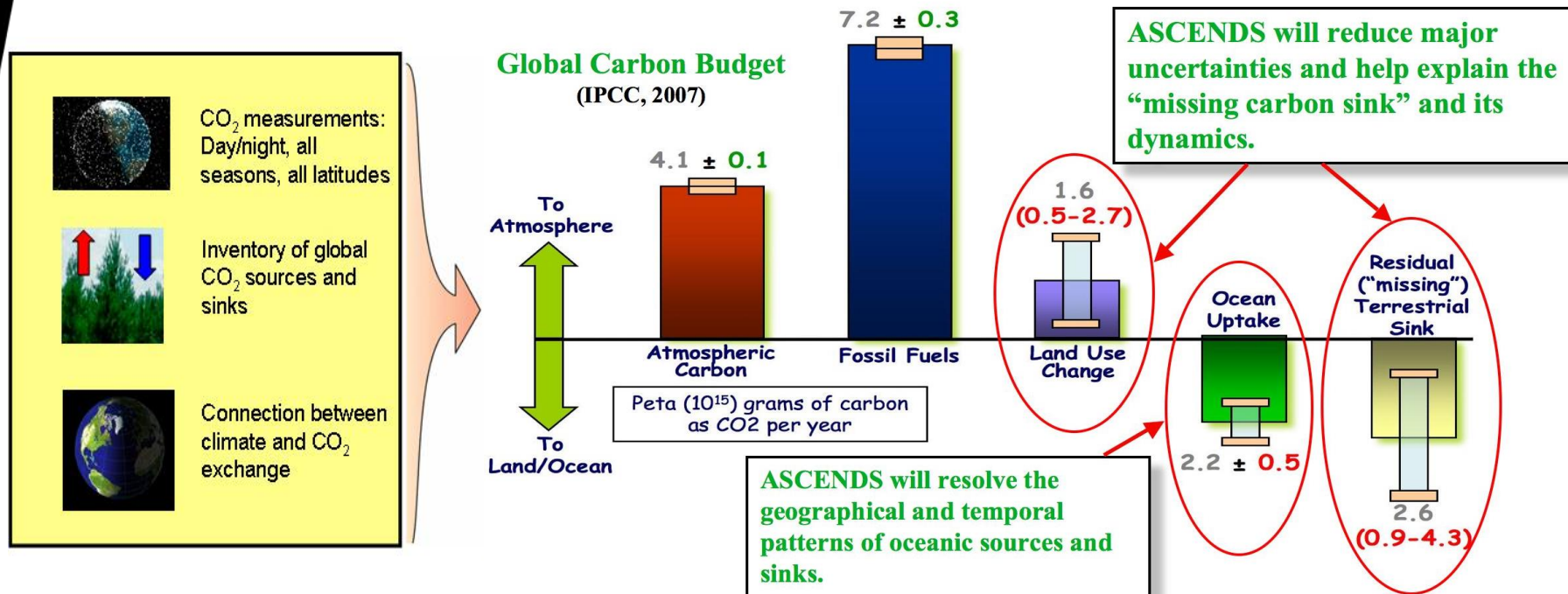
Observations needed to evaluate and improve these models are lacking.



Needs for Active Sensing of CO₂ Emissions over Nights, Days, and Seasons (ASCENDS)

2007 NRC Decadal Survey:

Earth Science & Applications from Space; Tier II Mission



- ASCENDS will provide an accurate global dataset of atmospheric CO₂ column measurements without seasonal, latitudinal, or diurnal bias.
- These measurements will be used in retrieval of CO₂ fluxes to estimate *regional* carbon sources/sinks and thereby improve understanding of underlying mechanisms to improve climate predictions.



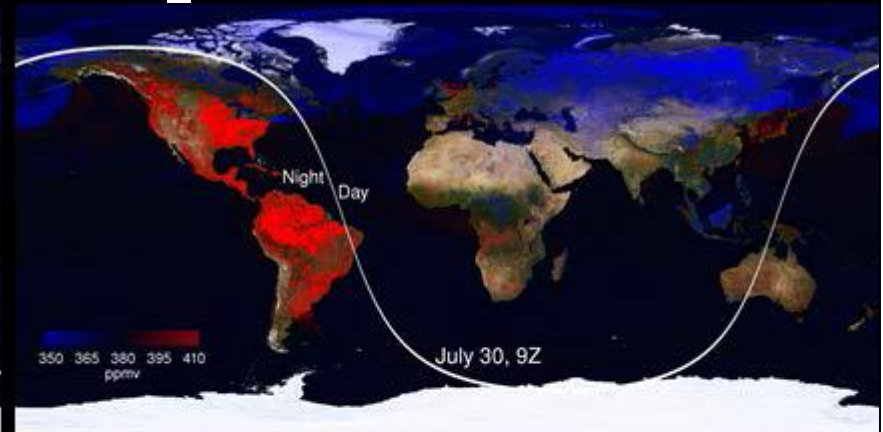
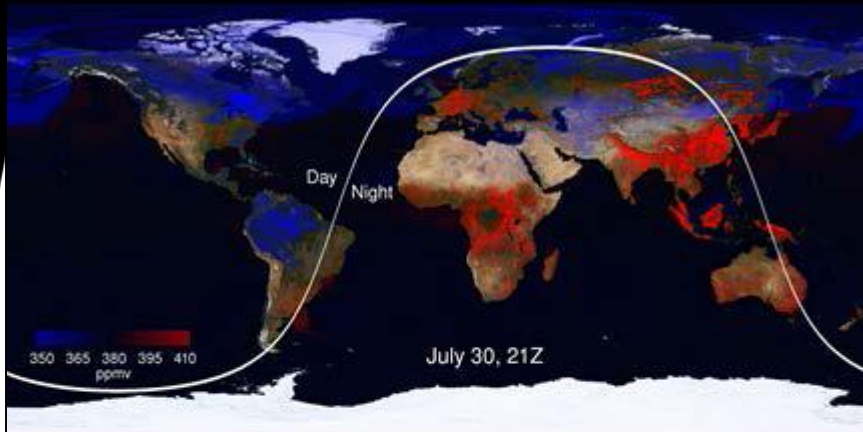
Lidar Measurement Challenge: Detection of Small Changes in Global CO₂

(GEOS-5 Simulated CO₂ : Day vs Night; main signals in PBL)

21 Z, 30 July

Surface CO₂

9 Z, 30 July



Column Averaged CO₂





CO₂ Science Objectives and Lidar Measurement Requirements

Science Objectives:

- 1. Quantify global distributions of atmospheric CO₂**
- 2. Quantify terrestrial and oceanic CO₂ sources and sinks**
- 3. Provide a basis for projections of future CO₂ sources and sinks**

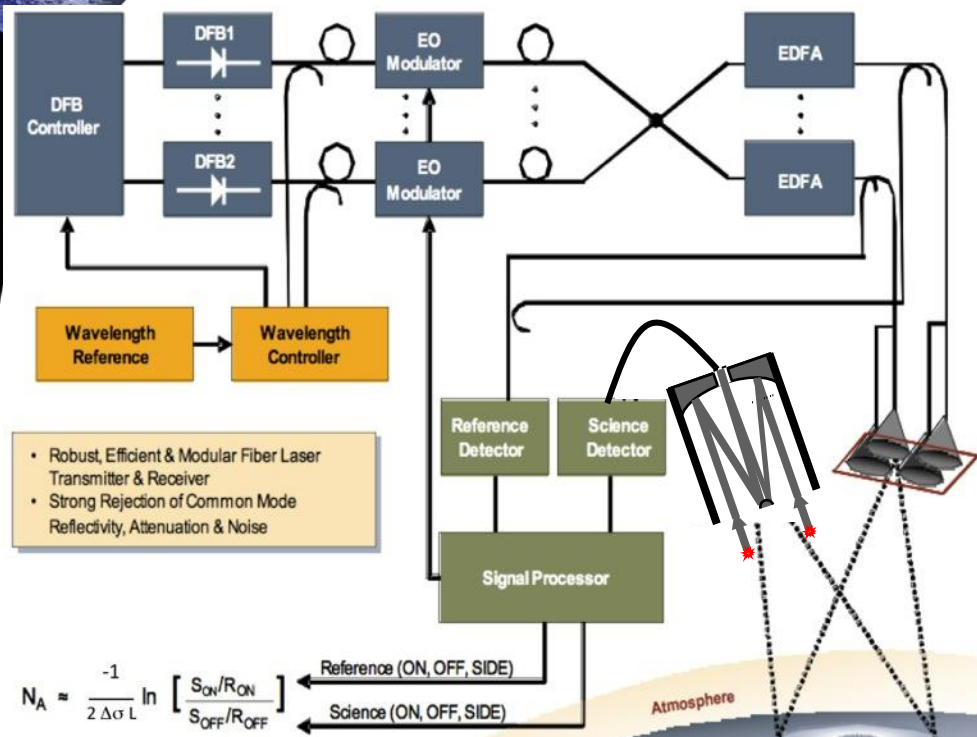
Measurement Requirements:

- 1. Measurements of column CO₂ differential absorption optical depth (DAOD), O₂ DAOD, range and range spreading requirements: weighted toward lower troposphere; ≥ 50 Hz sampling rate; clear sky and low OD cloudy conditions**
- 2. Precision: ≤ 0.5 ppm for clear sky with 10-s averaging**
- 3. Bias: < 0.5 ppm within 1 year after launch.**

CO₂ Measurement Architecture: laser absorption lidar

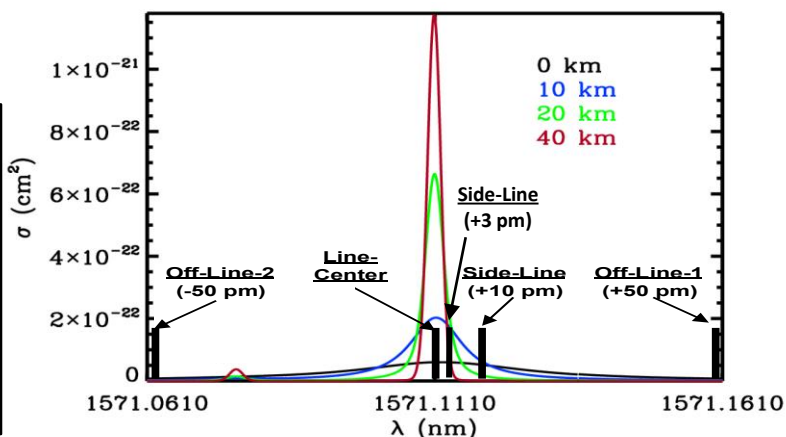
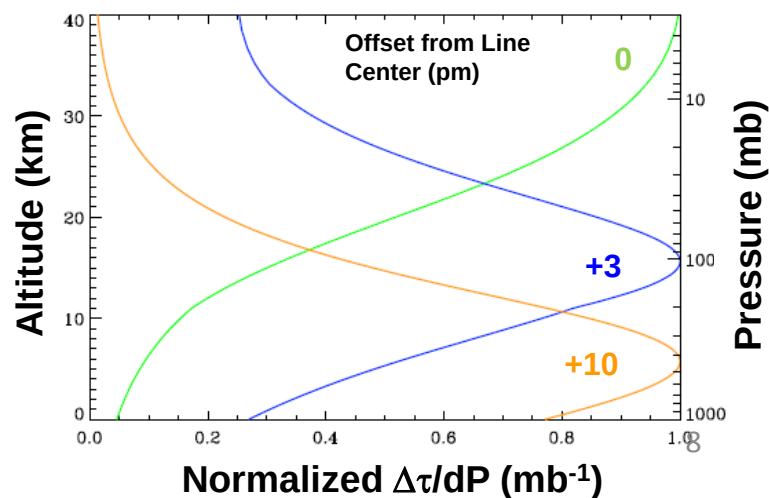
Integrated Path Differential Absorption (IPDA)

Intensity Modulated Continuous Wave (IM-CW)



- Simultaneously transmits λ_{on} and λ_{off} reducing noise from the atmosphere and eliminating surface reflectance variations.
- Approach is independent of system wavelength and allows simultaneous CO₂ (1.57 μm) & O₂ (1.26 μm) number density measurements to derive XCO₂.

Weighting Functions



Dobler et al., and Lin et al.
Applied Optics, 2013



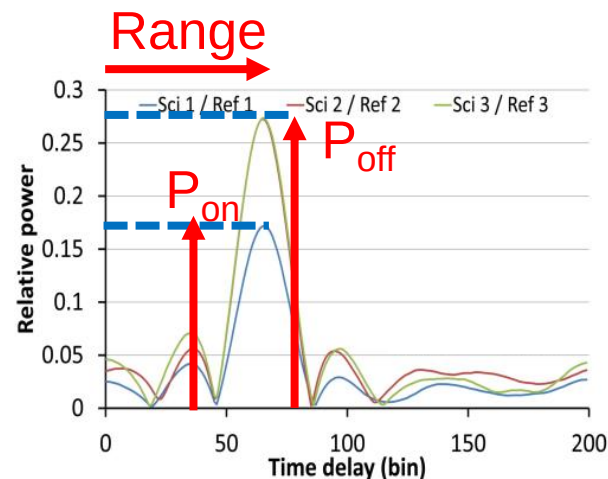
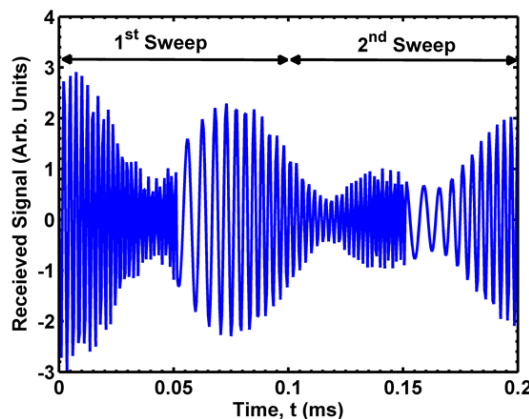
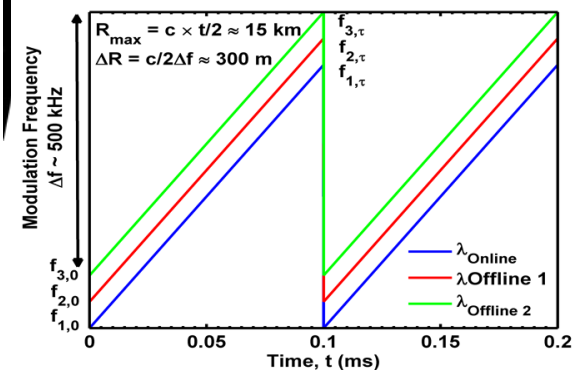
IM-CW Laser Absorption Lidar 1.57- μm CO₂ Measurement Technique

Progression of Transmitted/Received Intensity-Modulated Waveforms

Simultaneously
transmitted Intensity
modulated range
encoded waveforms

Simultaneously
received Online
and Offline IPDA
returns

Measurement: Output
of correlation between
transmitted and
received waveforms



Range encoded approach for detection and ranging is analogous to mature FM-CW Radar and GPS measurement techniques

$$DAOD = \frac{1}{2} \ln \left(\frac{P_{\text{off}} * E_{\text{on}}}{P_{\text{on}} * E_{\text{off}}} \right)$$



Instrument Development

(joint effort between LaRC and Harris)

**Multifunctional Fiber
Laser Lidar (MFL)**
(developed by Harris in 2004;
Harris and Langley since 2005)

ASCENDS CarbonHawk
Experiment Simulator
(ACES developed at Langley
with support from Harris)



Instrument-aircraft integration



Advancing key technologies for
spaceborne measurements of
 CO_2 column mixing ratio



In situ sensors



Atmospheric Vertical Observations of CO₂ in the Earth's Troposphere (AVOCET): shown here integrated on the NASA DC-8 aircraft.

In-situ sensors provide continuous measurements of CO₂, CH₄, and CO mole fractions and p/T/q/wind meteorological conditions.



Development & Demonstration

21-25 May 2005, Ponca City, OK (DOE ARM)

5 Lear Flts: Land, Day & Night (D&N)

20-26 June 2006, Alpena, MI

6 Lear Flts: Land & Water (L&W), D&N

20-24 October 2006, Portsmouth, NH

4 Lear Flts: L&W, D&N

20-24 May 2007, Newport News, VA

8 Lear Flts: L&W, D&N

17-22 October 2007, Newport News, VA

9 Lear Flts: L&W, D&N, Clear & Cloudy

22 Sept. – 30 Oct. 2008, Newport News, VA

10 UC-12 Flts: L&W, D&N, Rural & Urban

10-16 July 2009, Newport News, VA

5 UC-12 Flts: L&W

31 July – 7 Aug. 2009, Ponca City, OK

5 UC-12 Flts: L&W, D&N

10-20 May 2010, Hampton, VA

6 UC-12 Flts: L&W, D&N

5-11 May 2011, Hampton, VA

5 UC-12 Flts: L&W, D&N, Clear and Cloudy

6-18 July 2010, Palmdale CA

6 DC-8 Flts: L&W, D

28 July – 11 Aug. 2011, Palmdale CA

8 DC-8 Flts: L&W, D

February 19 – March 9, 2013, Palmdale CA

7 DC-8 Flts: L&W, D&N

August 13 – September 3, 2014, Palmdale CA

5 DC-8 Flts: L&W, D



MFLL on
Lear-25



MFLL on
UC-12



MFLL on
DC-8

various
lab,
ground
range,
and
flight
tests

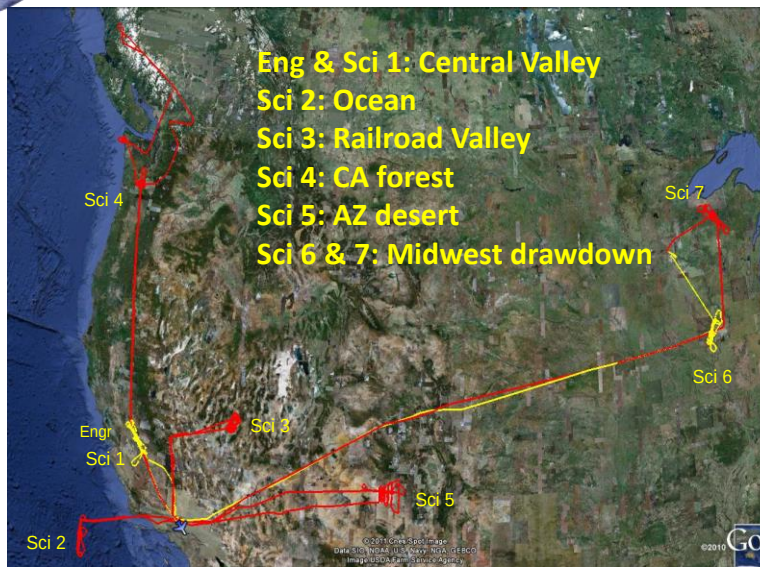
ranging
capability
enabled

Total of 14 MFLL flight campaigns since 2005

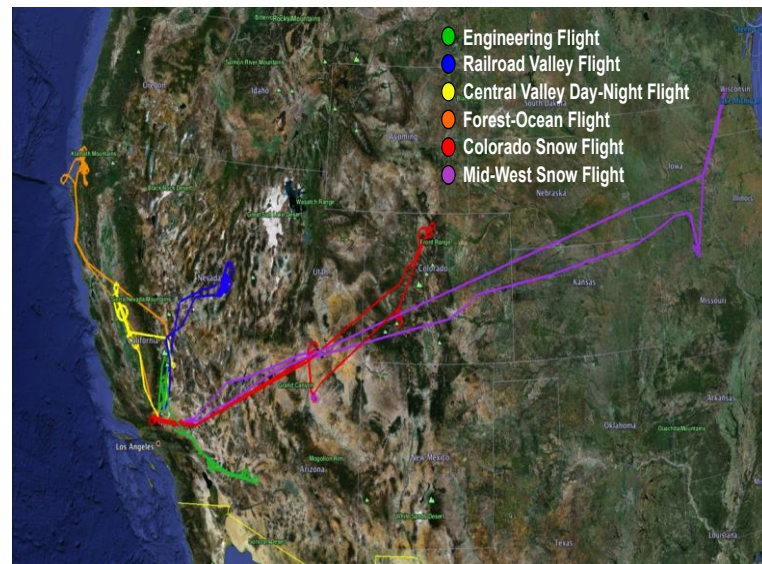
Total of 2 ACES test flight campaigns in Hampton, 2014-2015



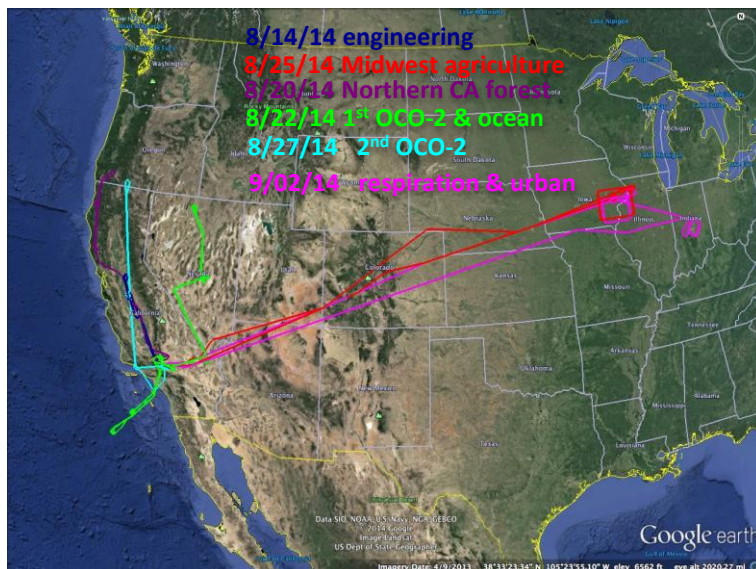
Recent DC-8 Flight Campaigns



2011 Summer



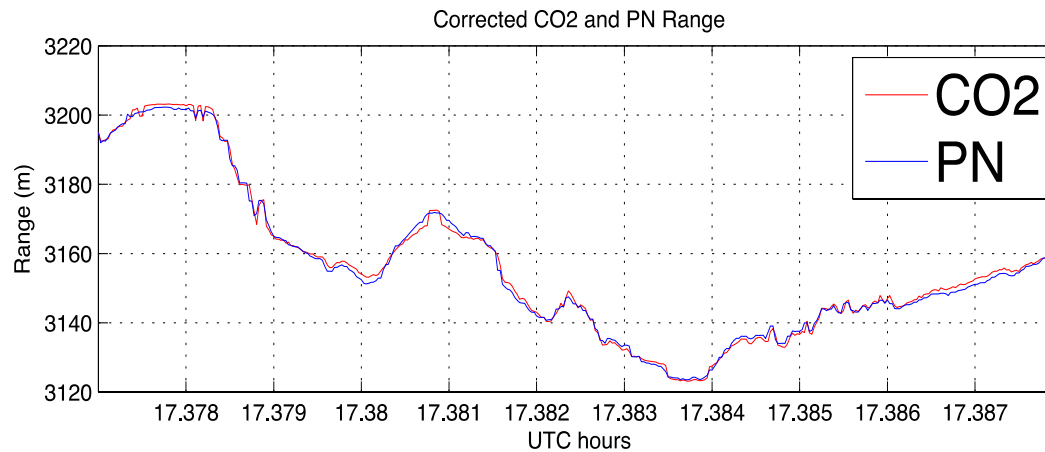
2013 Winter



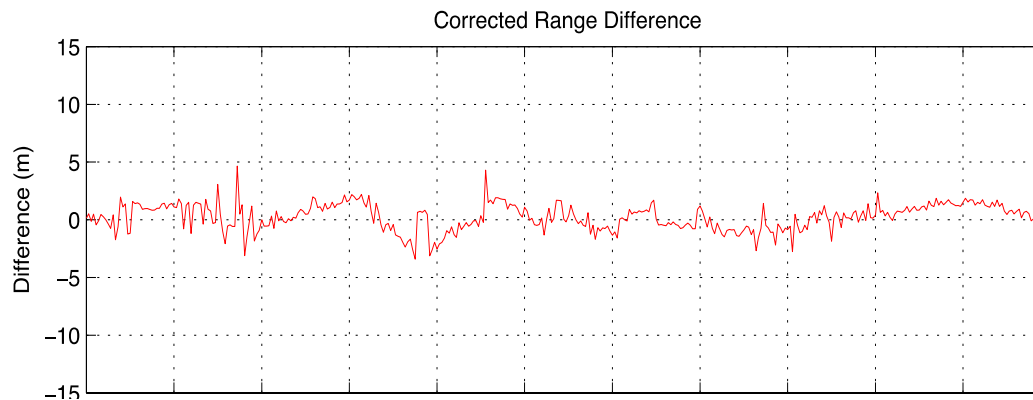
2014 Summer



Comparison of Range Determination from PN Altimeter and Off-line CO₂ Signal



MFL



RMS errors < 3 m

Range estimates obtained from the off-line CO₂ return and time-coincident returns from the onboard PN altimeter over the region of Four Corners, NM from the DC-8 flight on 7 August 2011.

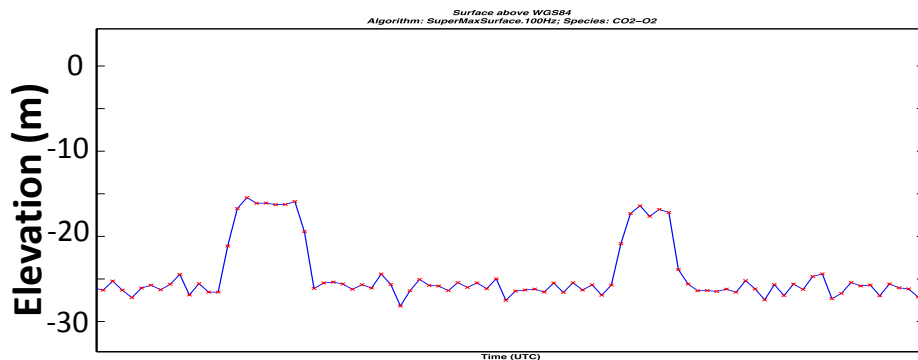
Dobler et al.,
Applied Optics,
2013



Ranging over Hampton Roads (June 2014)



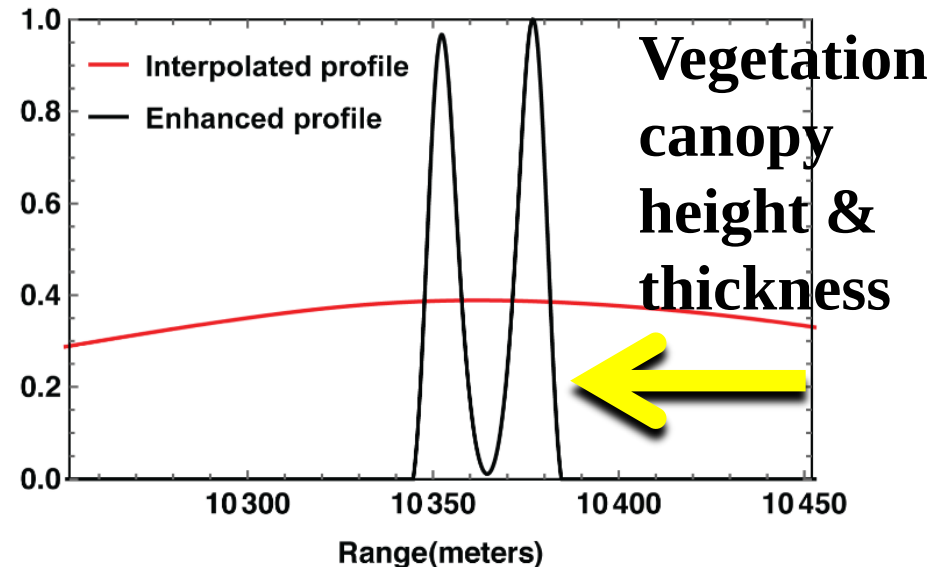
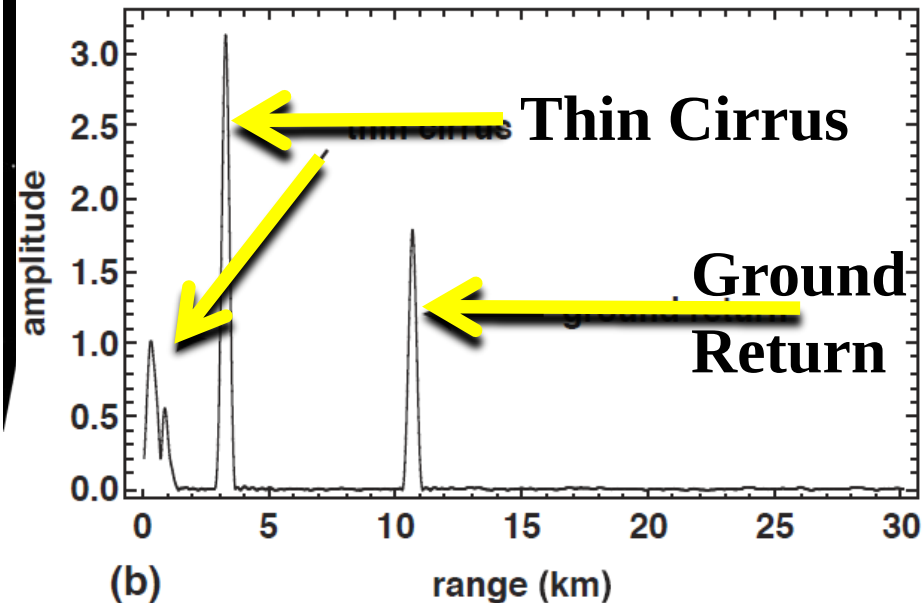
Chesapeake Bay Bridge





Results: Ranging

Flight campaign within Hampton Roads
Summer 2014 over thin cirrus and forest



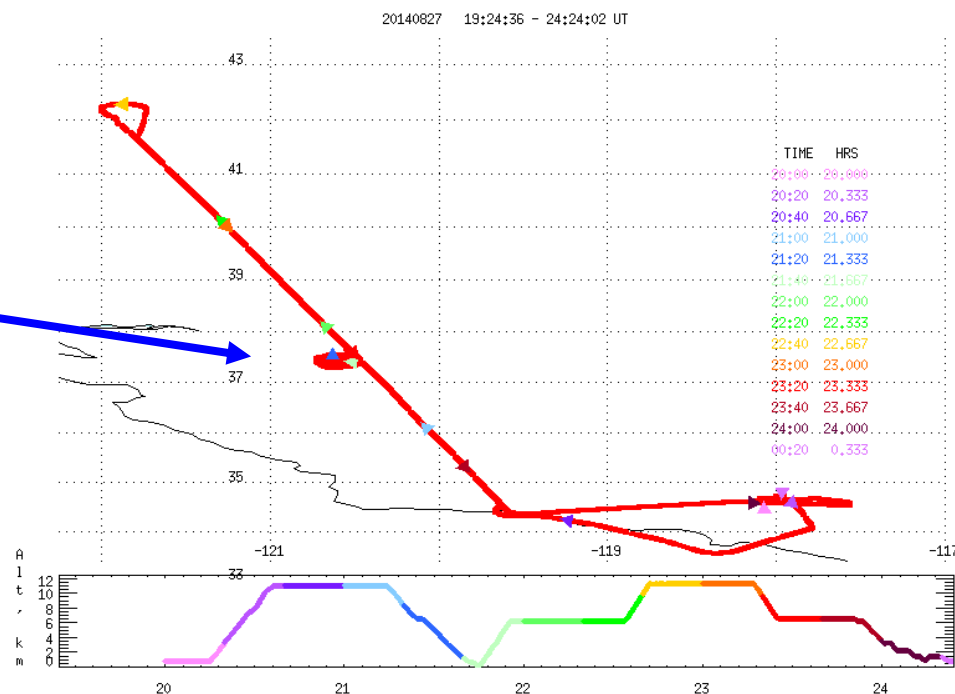
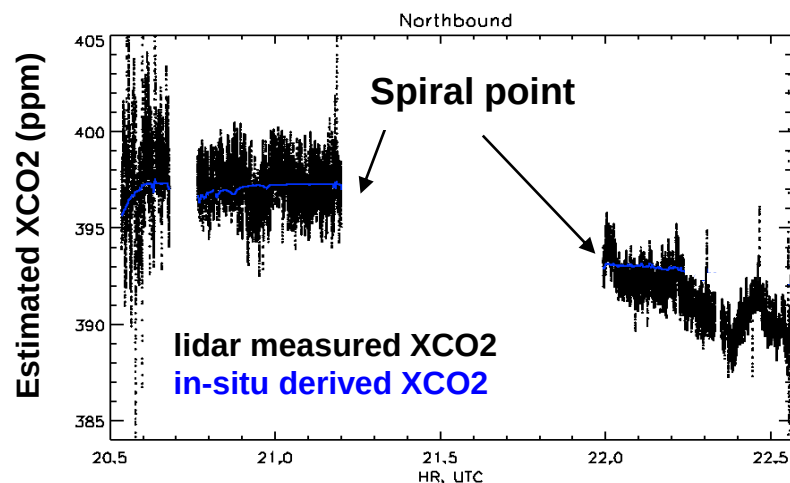
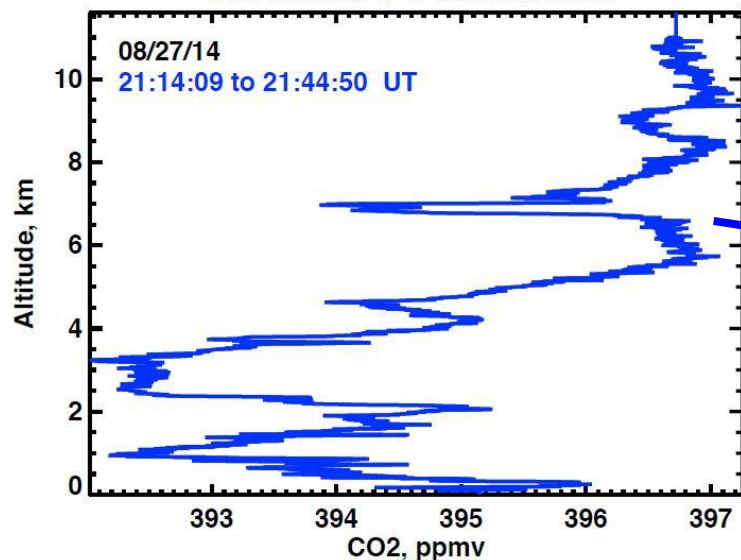
- Advanced deconvolution techniques resolve cloud and forest features:
 - Fourier transform reordering (**Interpolated** profile)
 - Richardson-Lucy deconvolution (**Enhanced** profile)

Campbell et al. *Optics Express and Optics Letters*, 2014



In Situ and Lidar Comparison (MFL OCO-2 Under Flight: 20140827)

2014 AVOCET In Situ CO₂



In-situ derived (or modeled) Value

- In-situ from Spiral: CO₂, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) XCO₂

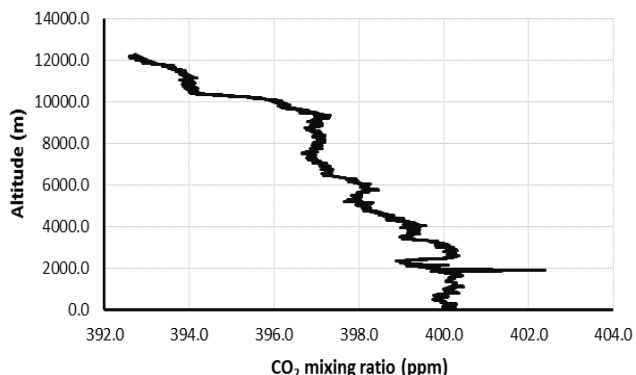
difference (ppm): 0.18



Winter 2013 Flight Campaign

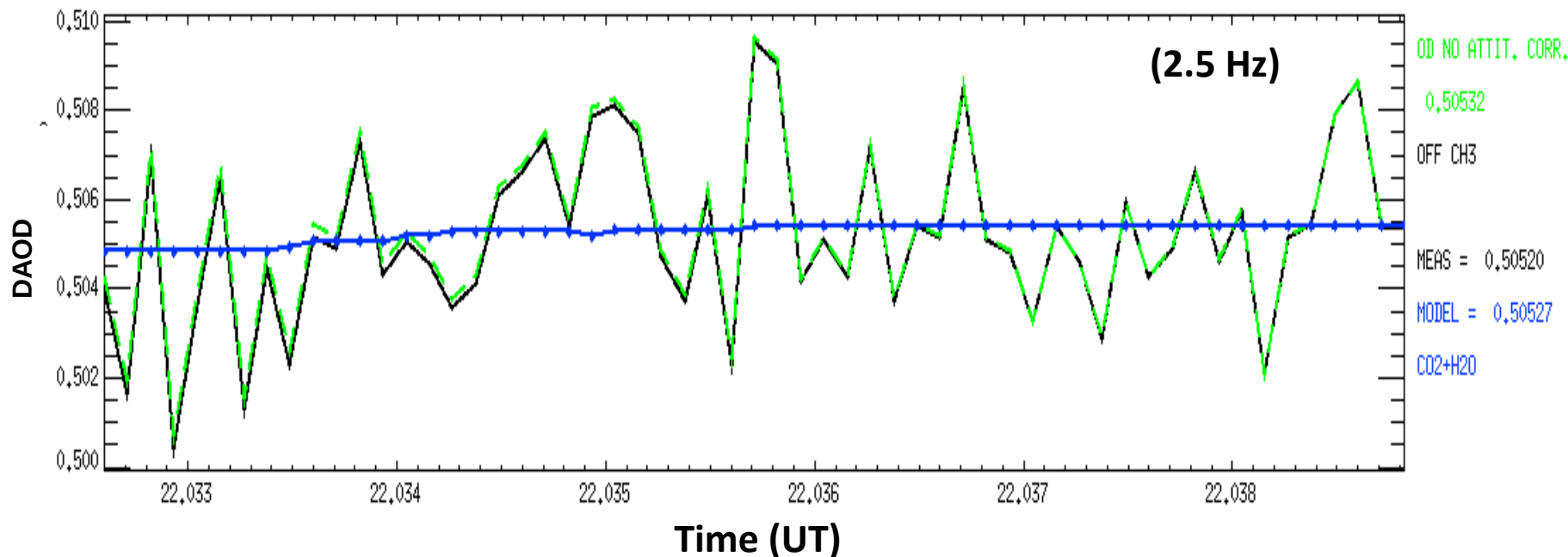
(22 Feb. 2013 Flight: Blythe, CA)

CO₂ concentration (22-Feb-2013)



Comparison of CO₂ columns from
MFL measurements
and in situ derived values

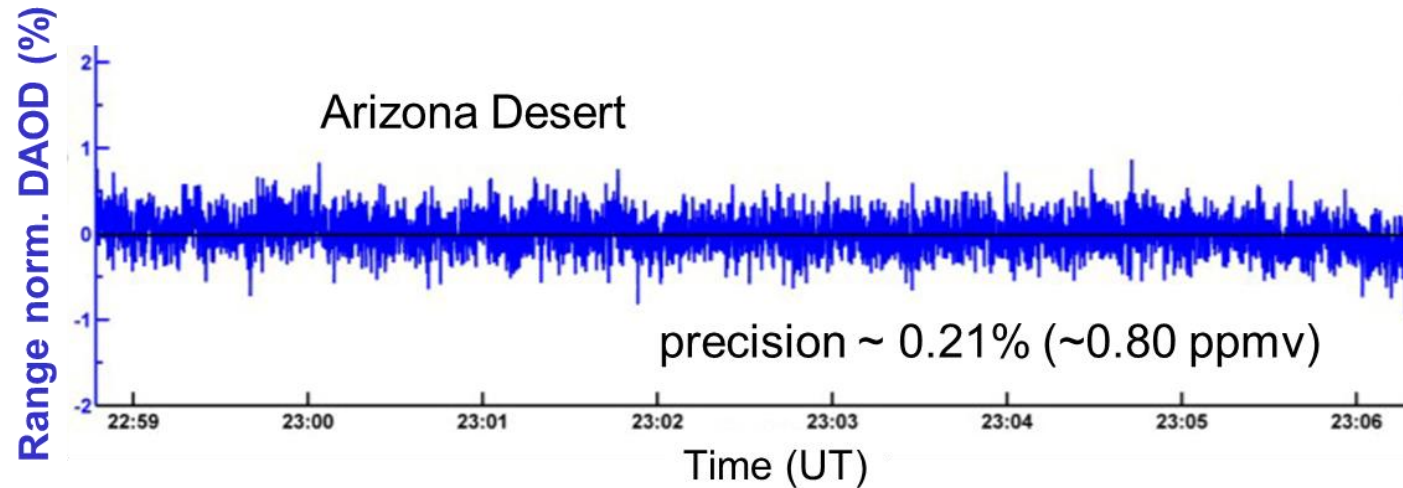
$$(\text{DAOD}_{\text{mea}} - \text{DAOD}_{\text{mod}}) / \text{DAOD}_{\text{mod}} = -0.01\% \text{ (or within 0.04 ppm)}$$



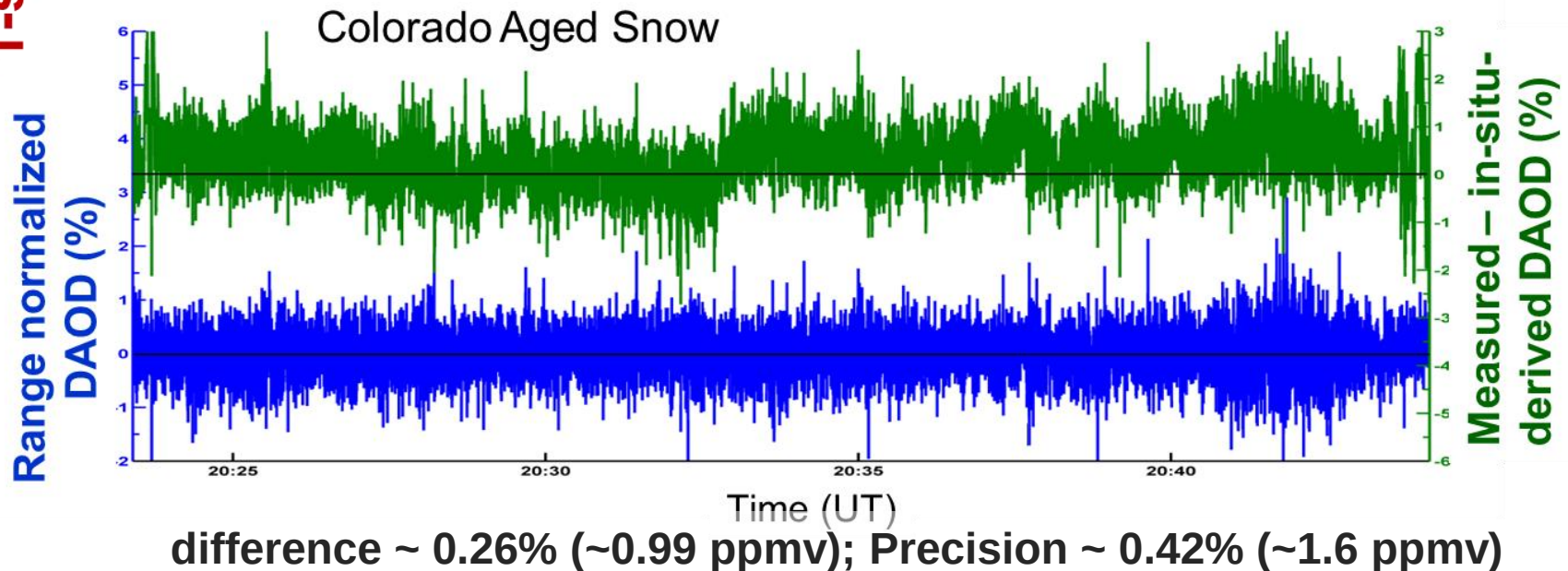


2013 ASCENDS Campaign: Measurements over varying terrain

1-s average



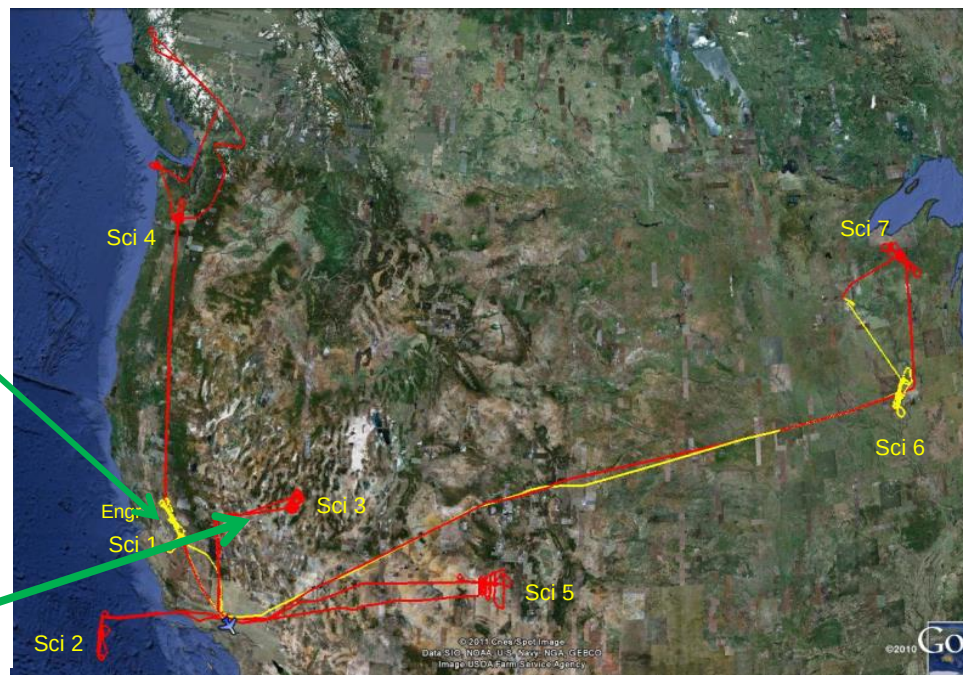
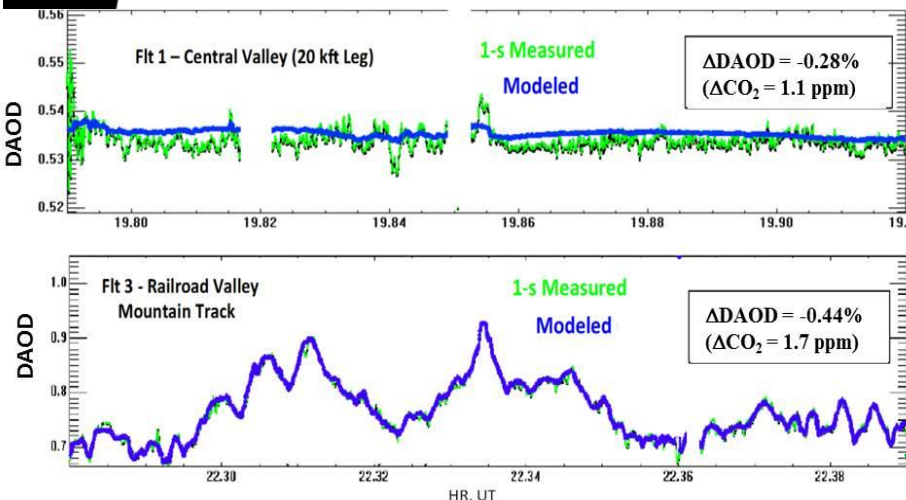
MFL





2011 ASCENDS DC-8 Flight Campaign (MFLC during 28 July – 11 August)

Differential Absorption Optical Depth (DAOD) Comparisons



SNR Comparisons

Flight #	Start Hour	End Hour	Delta Time, sec	Nadir Range, m	Optical Depth	CO ₂ , ppmv	1-s SNR	1-s !, ppmv	10-s SNR	10-s !, ppmv
1	20.07	20.08	198.0	6406	0.708	389.7	433	0.90	1264	0.31
3	20.03	20.06	211.0	6593	0.755	394.5	517	0.76	1510	0.26
4	15.63	15.70	396.0	6360	0.704	387.1	460	0.84	1325	0.29
5	20.00	20.02	180.0	8063	0.924	391.8	418	0.94	1274	0.31
7	17.21	17.23	79.2	5805	0.632	379.2	396	0.96	1237	0.31

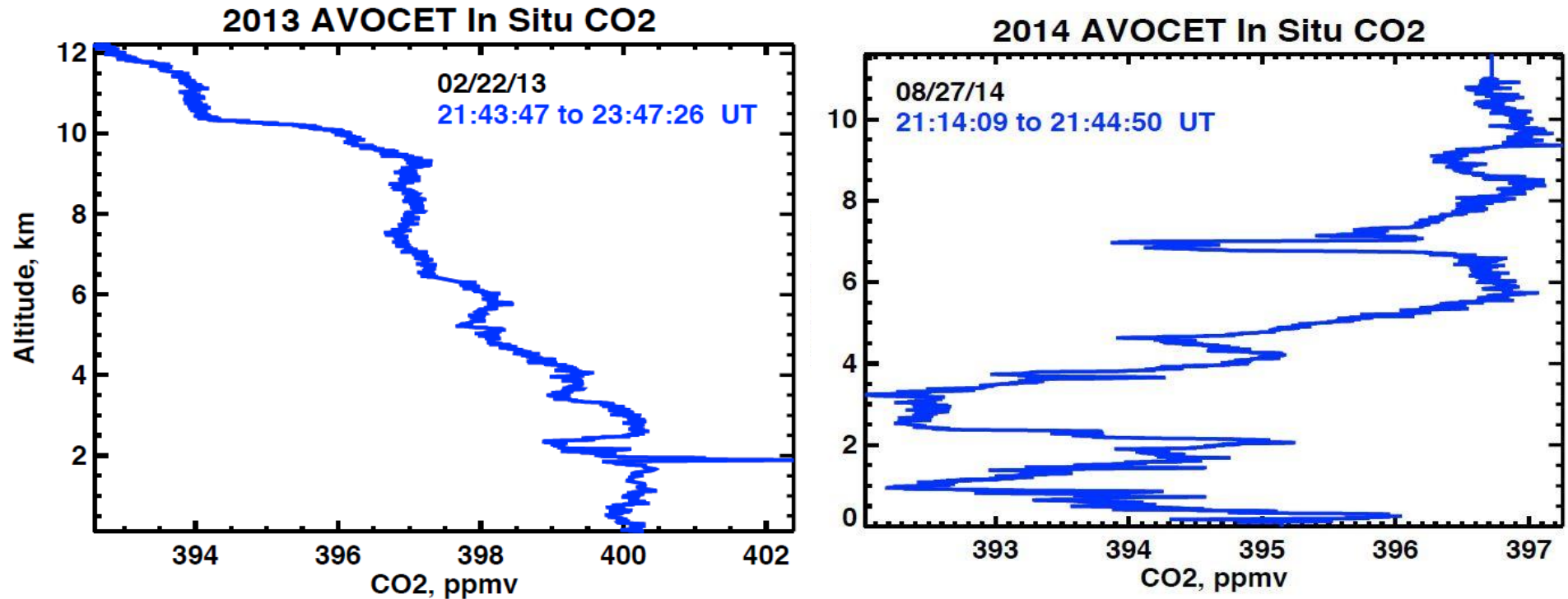
Avg:	6645	0.745	388.5	445	0.88	1322	0.29
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Modeled DAOD: in-situ XCO₂ measurements + radiative transfer model to calculate CO₂ absorption optical depth



Seasonal variations of atmospheric CO₂

Vertical profiles: CA



Winter buildup and summer drawdown of CO₂ around 3 ~ 5 ppm within low atmosphere were observed.



Agricultural CO₂ Drawdown (interannual changes)

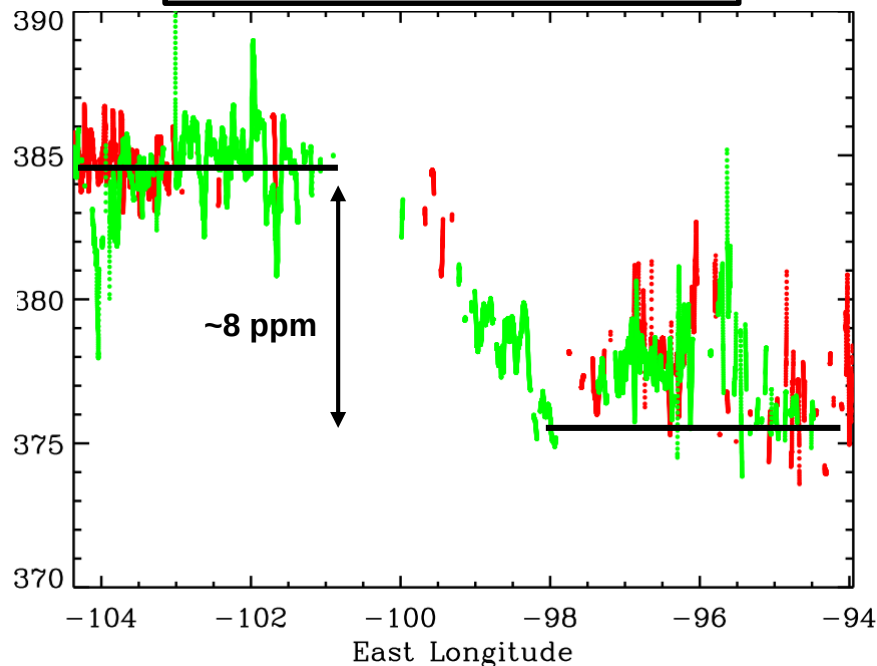
Column CO₂ measurements over Midwestern farm fields showed much larger drawdown signal in 2011 (~8 ppm) compared with measurements in 2014 (~3 ppm)

- Resulting from differences in meteorological states and phases of growing season
- Interannual changes in climate conditions

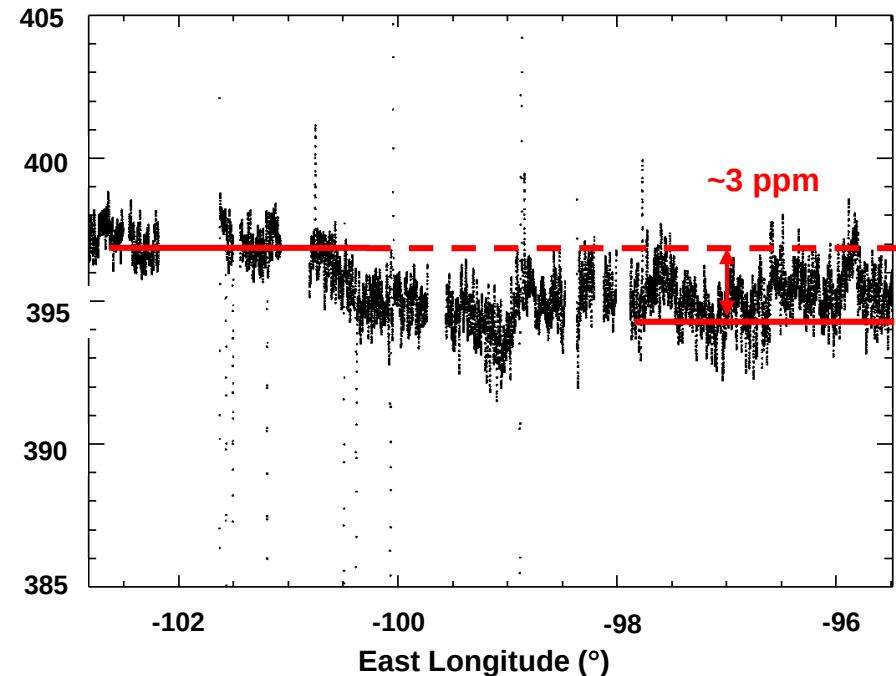
2011 Midwest Flights

Flight 6, 10 August

Flight 7, 11 August

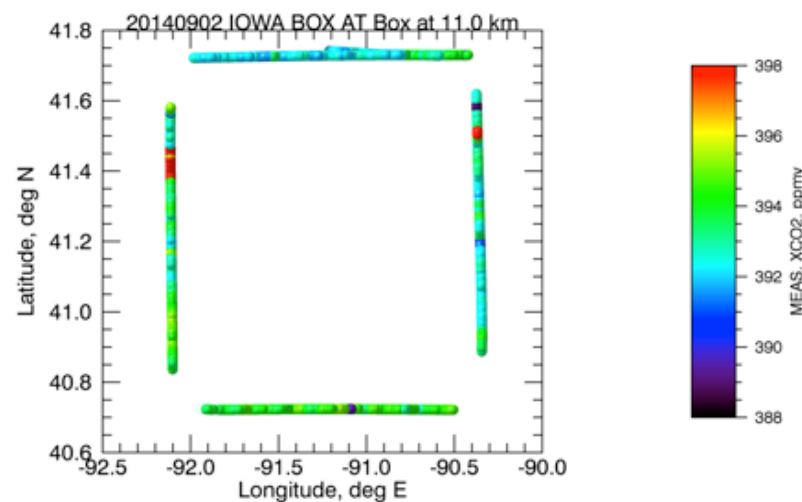
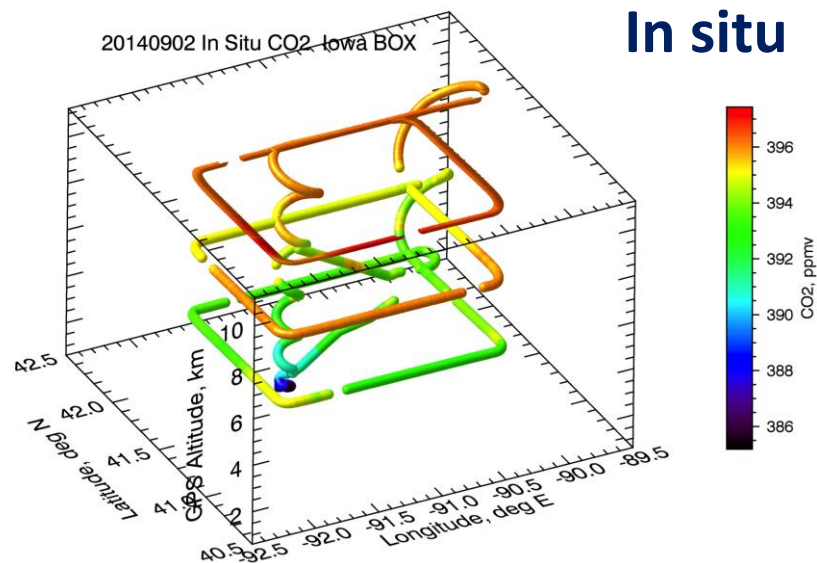
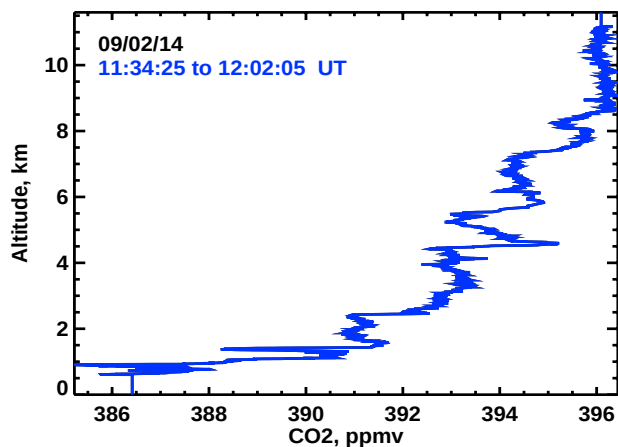
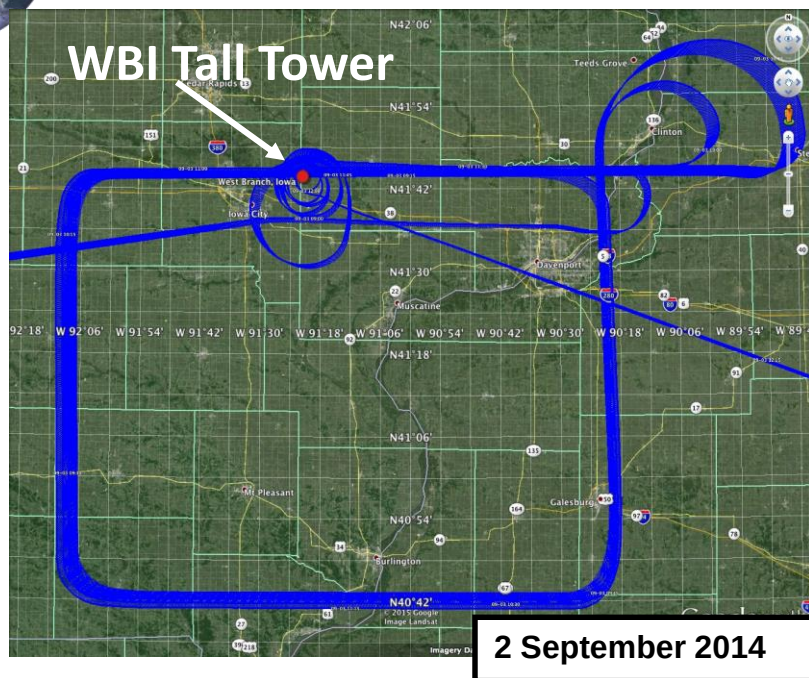


25 August 2014 Midwest Flight



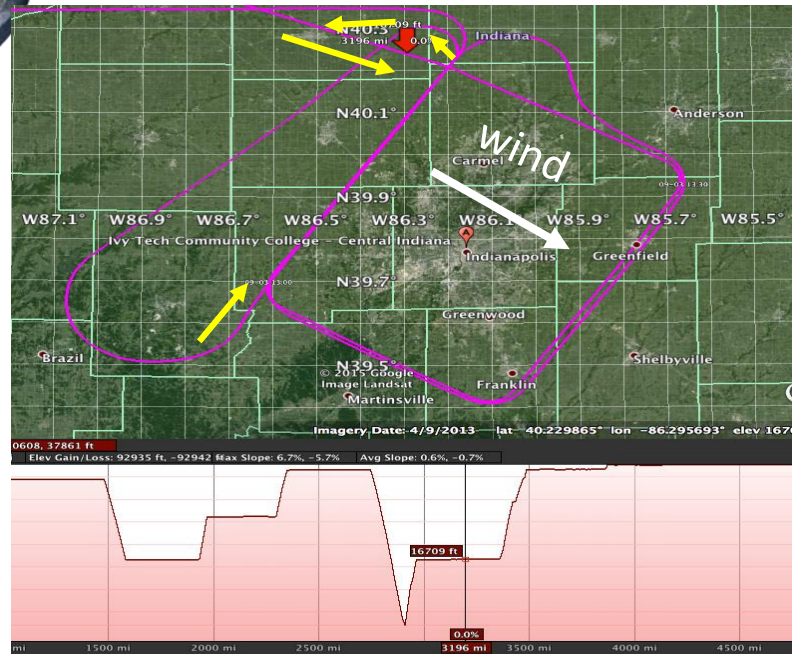


Spatial variability of atmospheric CO₂

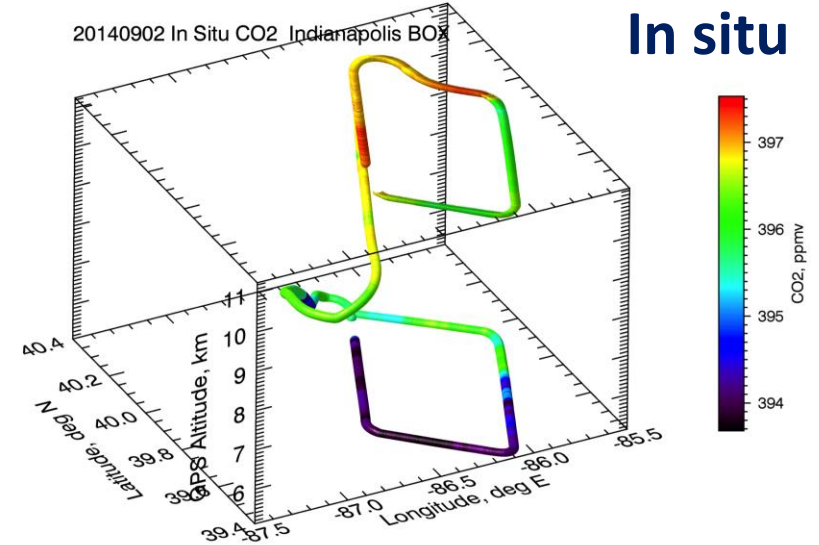




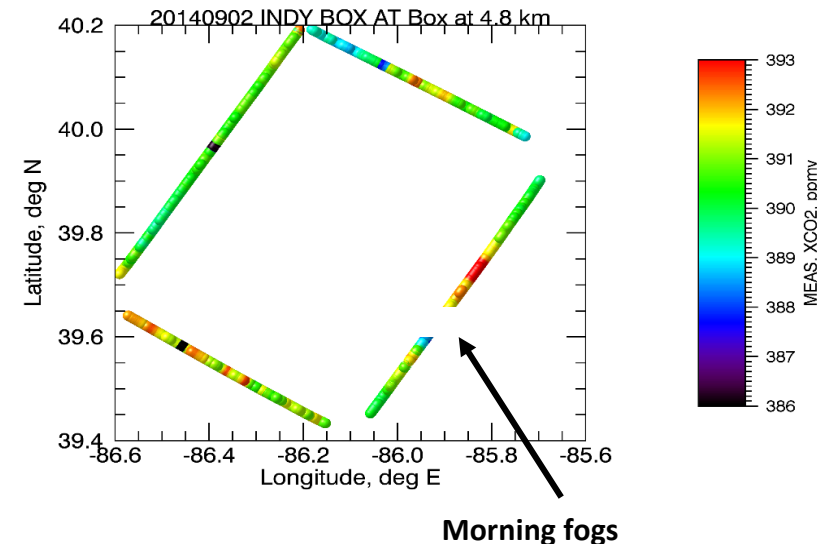
Urban impact on atmospheric CO₂



Time: 7:42 to 8:46 CDT



Lidar



Measurements over Indianapolis, IN on 2 Sept 2014. Significant CO₂ variability was observed by both in situ and lidar instruments. Lidar also observed high CO₂ values in downwind direction likely a result of anthropogenic activities during morning rush hours.

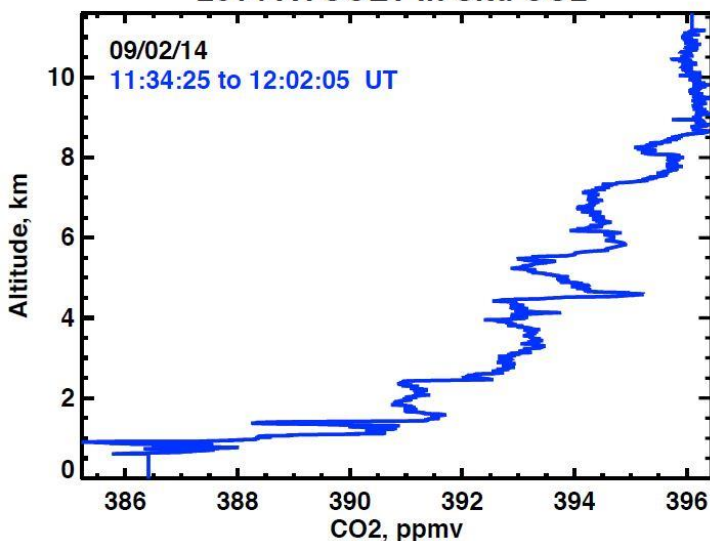


Natural Variability

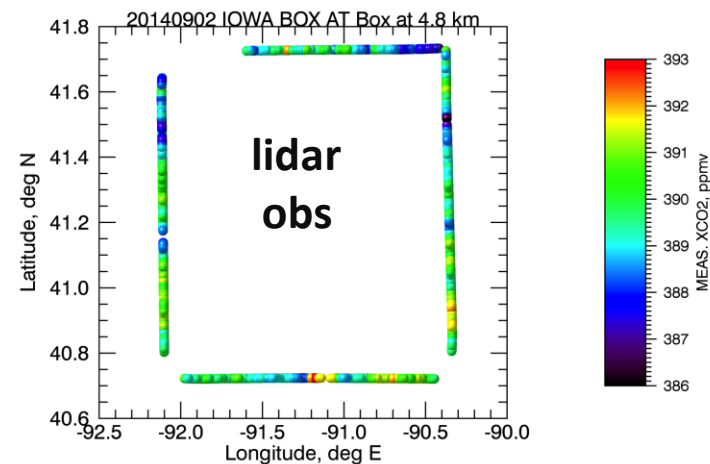
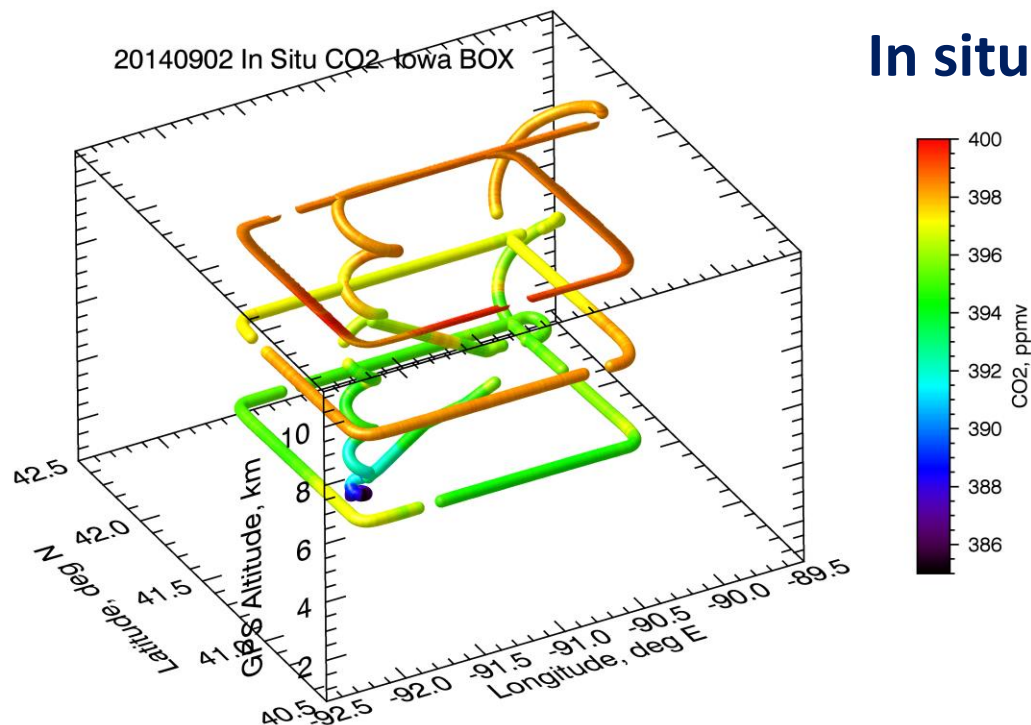
(lidar and in-situ measurements)

(Mid-West Flight: Iowa Box; 02 Sept 2014)

2014 AVOCET In Situ CO₂



20140902 In Situ CO₂ Iowa BOX



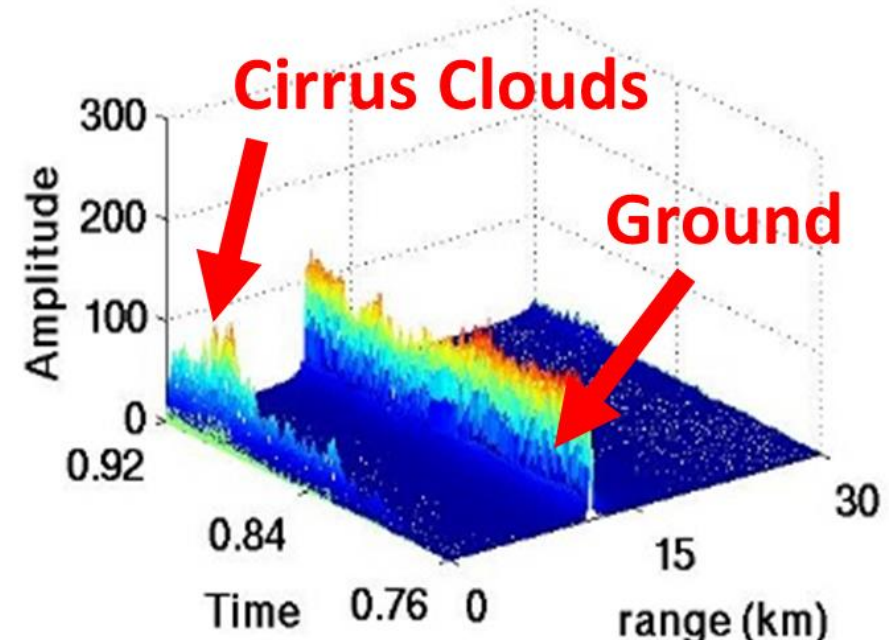
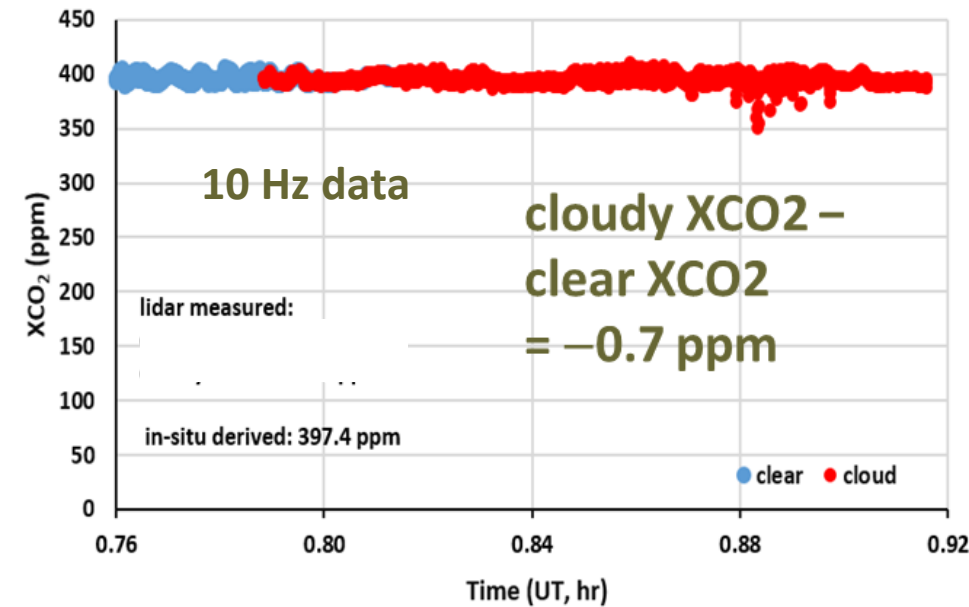
Significant spatiotemporal variations (a few ppm) found from both lidar observations and when comparing spiral with non-spiral in-situ observational data



Demonstration of CO₂ Column Measurements Through Thin Cirrus (Blythe, CA, 22 Feb 2013)

On

MFL

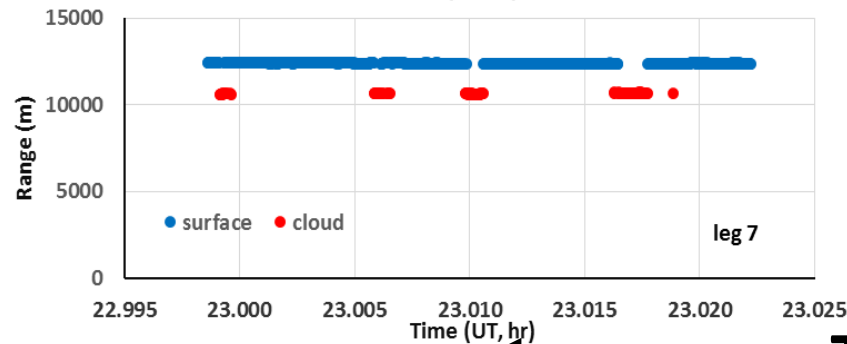
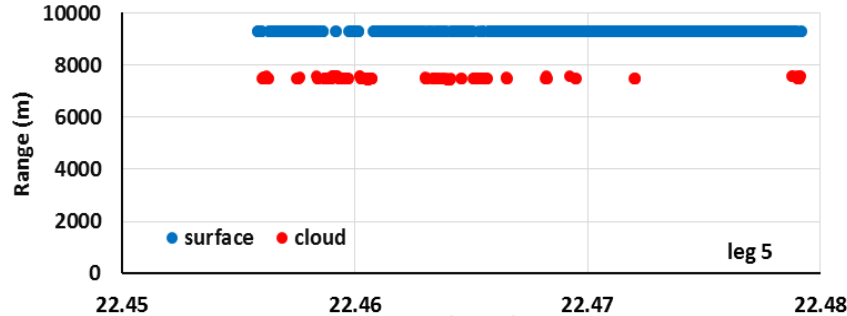
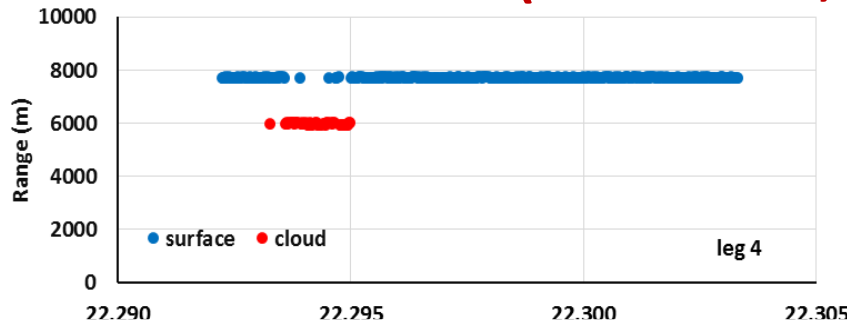


- No observable bias in transition from clear to cloudy conditions
- Increasing cloud OD results in lower SNR and higher standard deviation, but no bias
- Precise ranging capability allows retrievals in presence of tenuous clouds

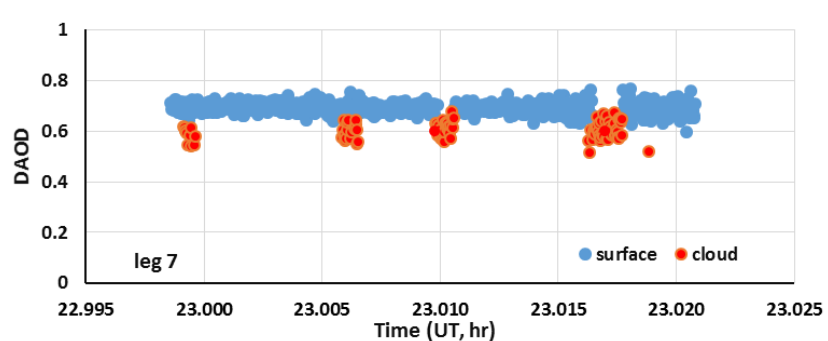
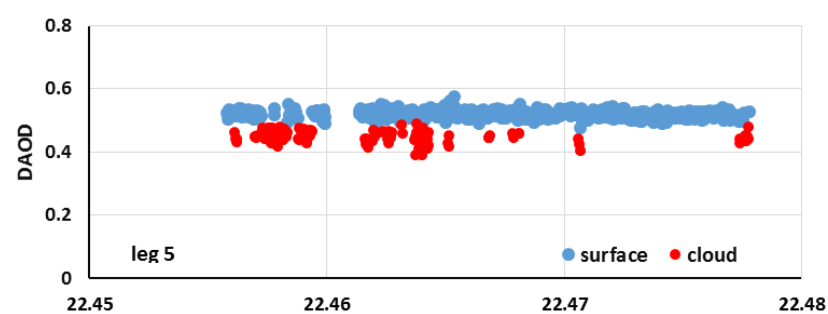
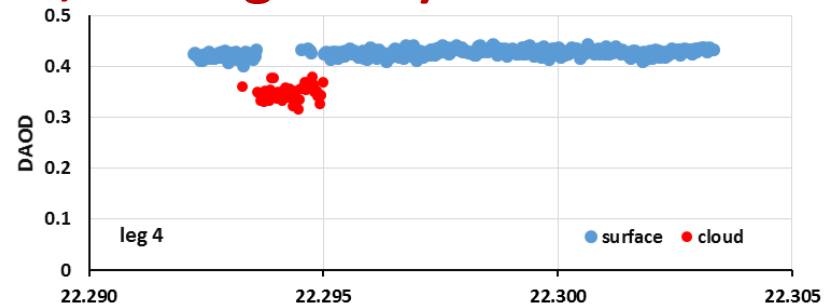


Range and Column CO₂ to Surface and Thick Cloud Tops (West Bank, Iowa; 10 Aug 2011)

Range (m)



DAOD



Time

CO₂ column observations to ground, cloud tops and
within boundary layer; consistent PBL measurements

MFL

10 Hz data



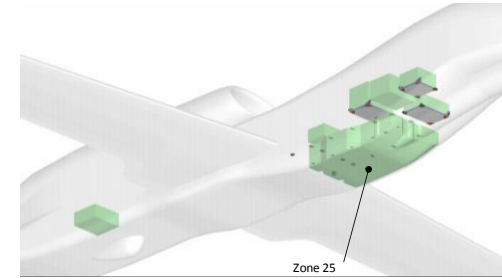
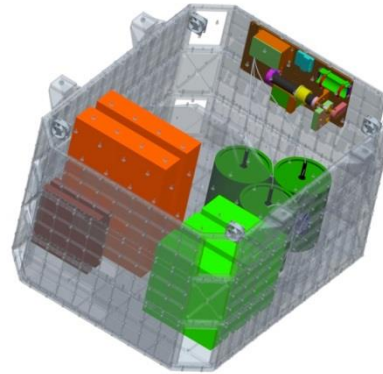
Column CO₂ Measurements to Surface and Thick Cloud Tops

	Leg 4	Leg 5	Leg 7
Lidar DAOD _{surface}	0.4271 ± 0.0056	0.5196 ± 0.0093	0.6902 ± 0.0155
Lidar DAOD _{cloud}	0.3480 ± 0.0143	0.4368 ± 0.0243	0.6007 ± 0.0339
Lidar DAOD _{bndryl_{yr}}	0.0791 ± 0.0154	0.0828 ± 0.0260	0.0895 ± 0.0373
In-situ DAOD _{surface}	0.4243	0.5160	0.6939
In-situ DAOD _{cloud}	0.3417	0.4334	0.6075
In-situ DAOD _{bndryl_{yr}}	0.0826	0.0826	0.0826
Lidar XCO2 _{surface}	383.2 ± 5.02	384.3 ± 6.88	381.6 ± 8.57
Lidar XCO2 _{cloud}	391.5 ± 16.09	387.7 ± 21.31	382.0 ± 21.56
In-situ XCO2 _{surface}	380.8	381.7	383.8
In-situ XCO2 _{cloud}	384.6	384.9	386.4
Lin et al. <i>Optics Express</i> , 2015	10 Hz data		

ASCENDS Mission Development



Current



High-altitude aircraft



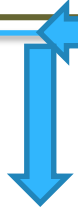
Today: MFL

&

ACES

Size = 100" x 43" x 24"
Mass = 787.2 lb.

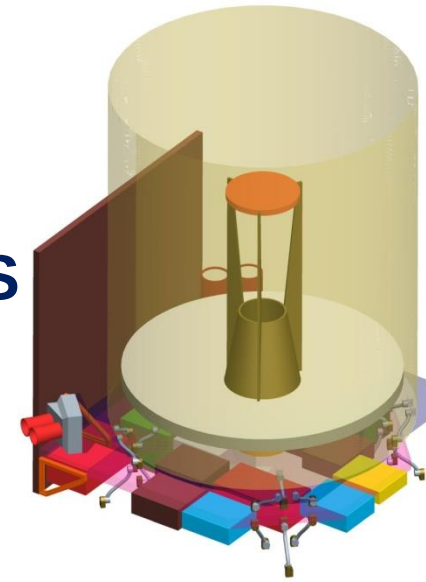
Size = 44" x 34" x 24"
Mass = 317.1 lb



TBD:
ISS Tech
Demo?



TBD:
ASCENDS
mission



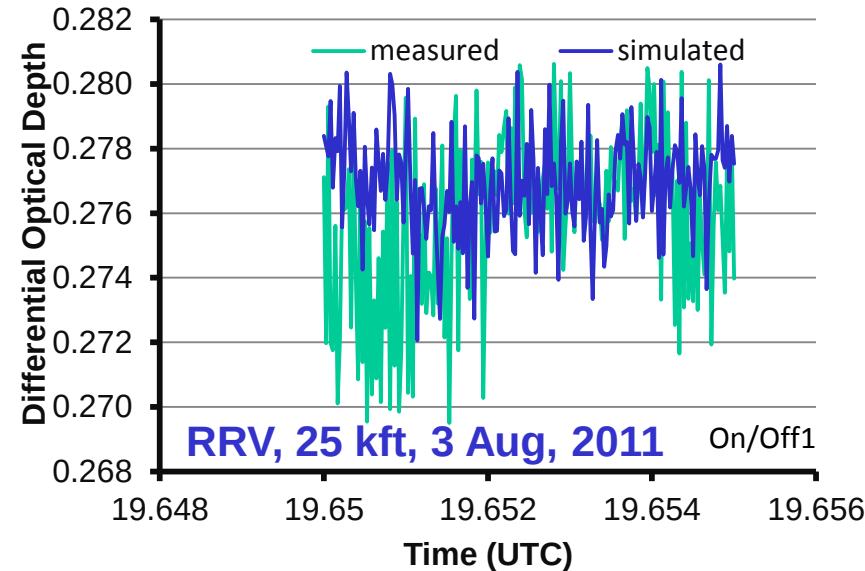
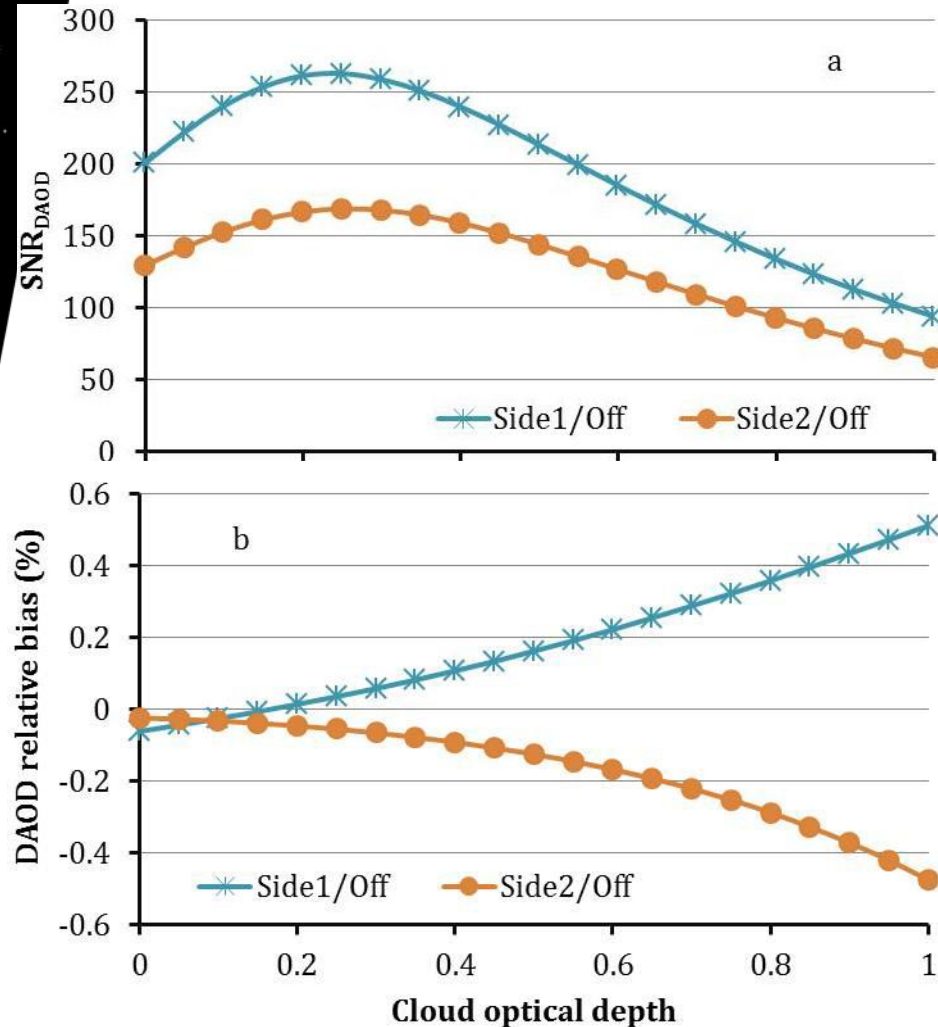
Future



Space CO₂ Lidar Modeling and Measurement

Same instrument architecture: increased power and telescope

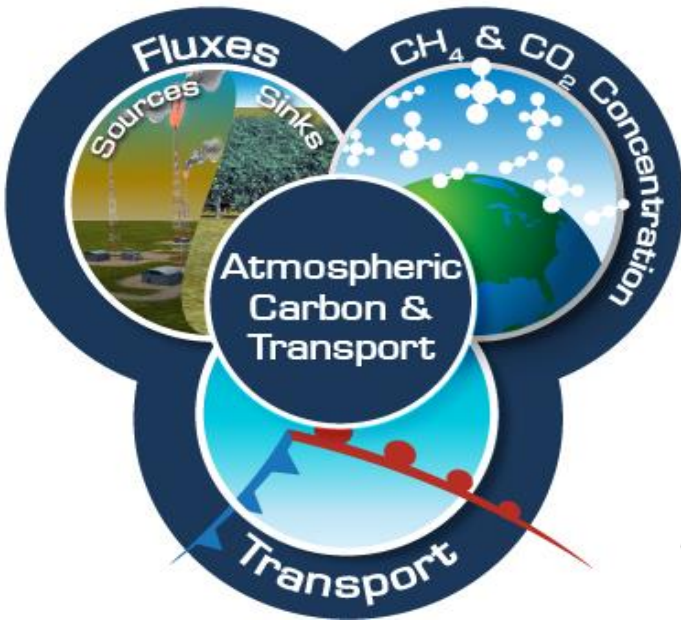
Lin et al. *Applied Optics*, 2013



- Cloud height: 9 km
- 0.1-s integration time
- High SNR & small bias (< 0.1%)
- Cloud OD < ~0.4
- Dawn/dusk orbit, 42W power
- Other LEO orbits are also applicable

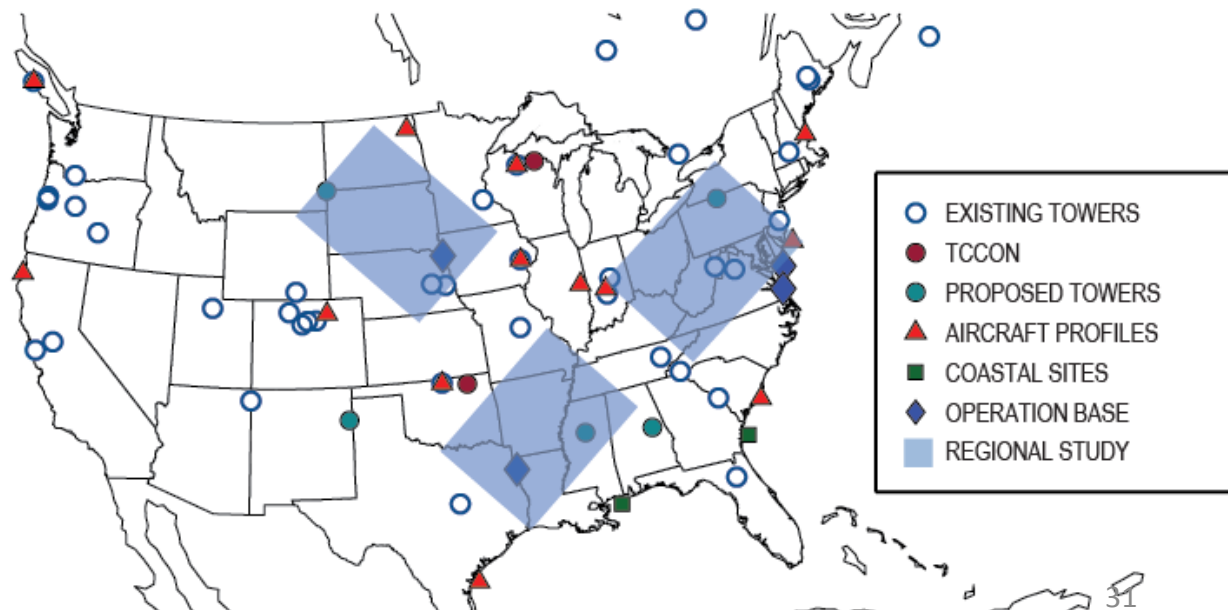


Atmospheric Carbon & Transport (ACT) – America



The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric carbon inversions: transport error, prior flux uncertainty and limited data density.

PI: Ken Davis, Penn State
NASA LaRC, WFF, GSFC, JPL
Harris Corp., Colorado State
NOAA ESRL/U Colorado
DOE Oak Ridge, U Oklahoma
Carnegie Inst. Stanford





ACT-America data are collected by remote and in situ sensors on two aircraft

Remote Sensors (C-130): In-Situ Sensors (C-130 and UC-12):

L (Exelis, Inc.):

- Column CO₂ number density
- Range to ground

PL (NASA Goddard):

- Atmospheric boundary Layer height
- Aerosol/Cloud optical depth

Picarro and Ozone (NASA Langley):

- In situ measurements of CO₂, CH₄, CO, H₂O, and O₃ number density

Flasks (NOAA):

- In situ samples of CO₂, CH₄, CO, ¹⁴CO₂, COS

In-Situ Sensors (Ground Towers):

Picarro (Penn State):

- In situ measurements of CO₂ and CH₄







Future Efforts

❖ Technology Maturation

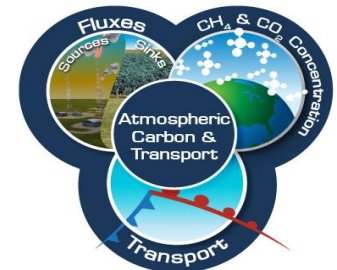
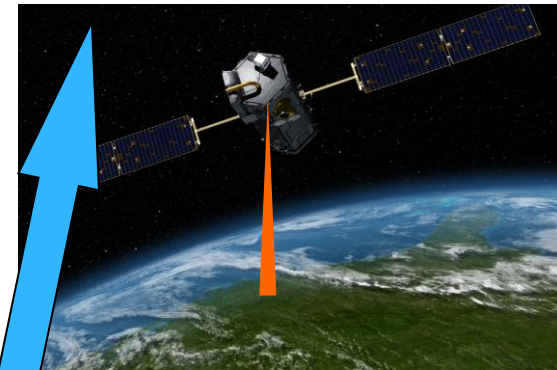
- Space qualified high power high efficiency 1.57 μm CO_2 laser amplifier
- ASCENDS airborne tech demonstration and development
- Tech demo: ISS?

❖ CO_2 Science Applications

- ACT-America science missions

❖ Active atmospheric carbon measurement mission: ASCENDS

Space mission



CO_2 science application

Technology maturation



ASCENDS



Mission preparation



Summary

- ❖ Carbon science requires high accuracy and precision CO₂ measurements.
- ❖ Laser absorption lidar approach provides advanced capabilities in ranging and CO₂ column measurements and even can take measurements through thin cirrus clouds and to thick cloud tops.
- ❖ IM-CW lidar at 1.57 μm has demonstrated precise CO₂ measurements through many airborne flight campaigns under variety of environment conditions.
- ❖ Significant CO₂ variations in different spatiotemporal scales have been observed through multiple airborne flight campaigns.
- ❖ Analysis shows that current IM-CW lidar approach will meet space CO₂ observation requirements.
- ❖ Future work: technology maturation, ASCENDS DC-8 campaign, ACT-America suborbital mission, space mission preparation



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