Regional and Global Atmospheric CO_2 Measurements Using 1.57 Micron IM-CW Lidar

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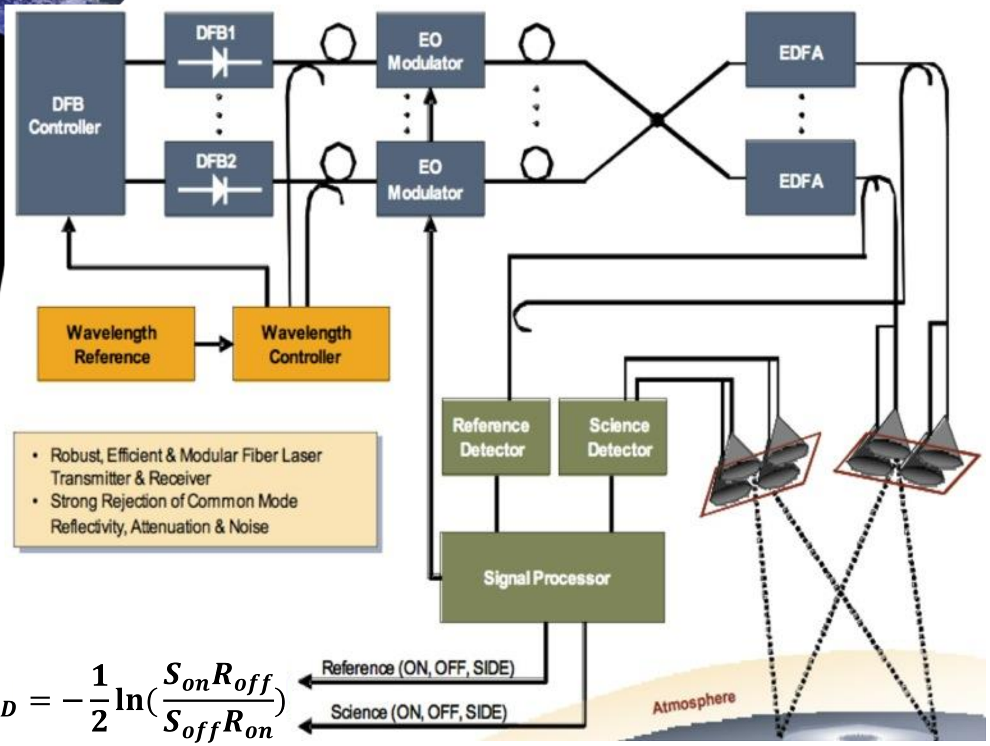
13-17 September, 2015, La Jolla, California, USA

Outline

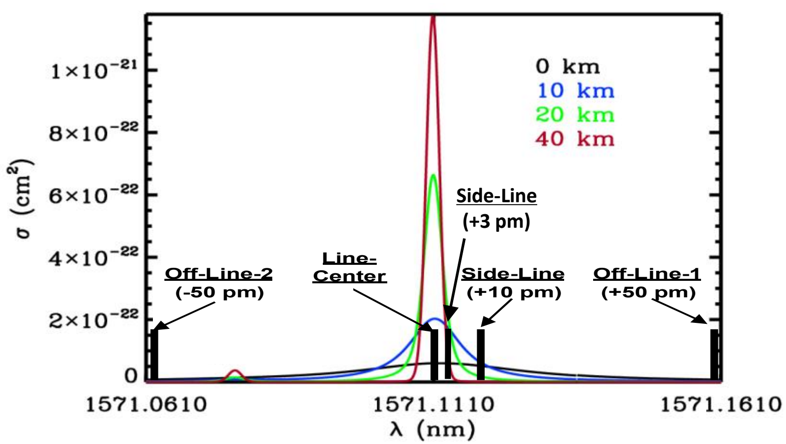
- **Introduction**
  - **Lidar approach for CO_2 measurement**
  - **CO_2 lidar instrumentation**
- **Lidar Measurements**
  - **CO_2 column measurements**
  - **Ranging capability**
  - **Accuracy and precision**
  - **CO_2 column measurements with clouds**
  - **Space application**
- **Summary**

CO_2 Measurement Architecture IM-CW Laser Absorption Lidar

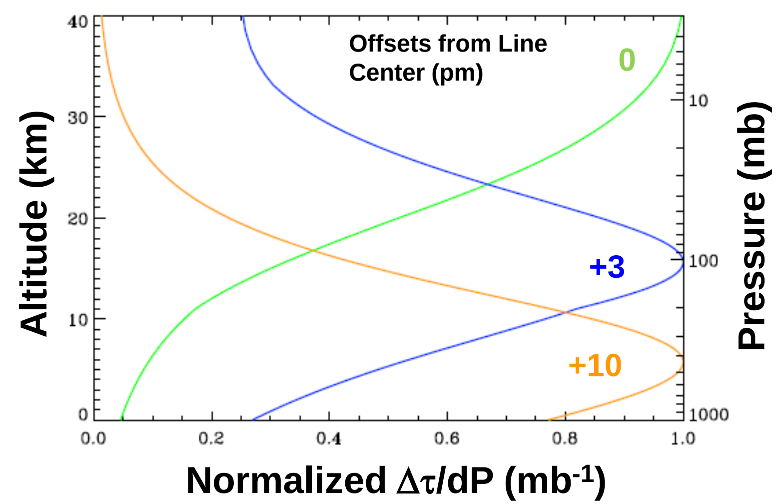


$$\tau_{DAOD} = -\frac{1}{2}\ln\left(\frac{S_{on}R_{off}}{S_{off}R_{on}}\right)$$

- Precise CO_2 measurements using the Integrated Path Differential Absorption (IPDA) technique with a range-encoded intensity-modulated continuous-wave lidar.
- Simultaneously transmits l_{on} and l_{off} reducing noise from the atmosphere and eliminating surface reflectance variations.



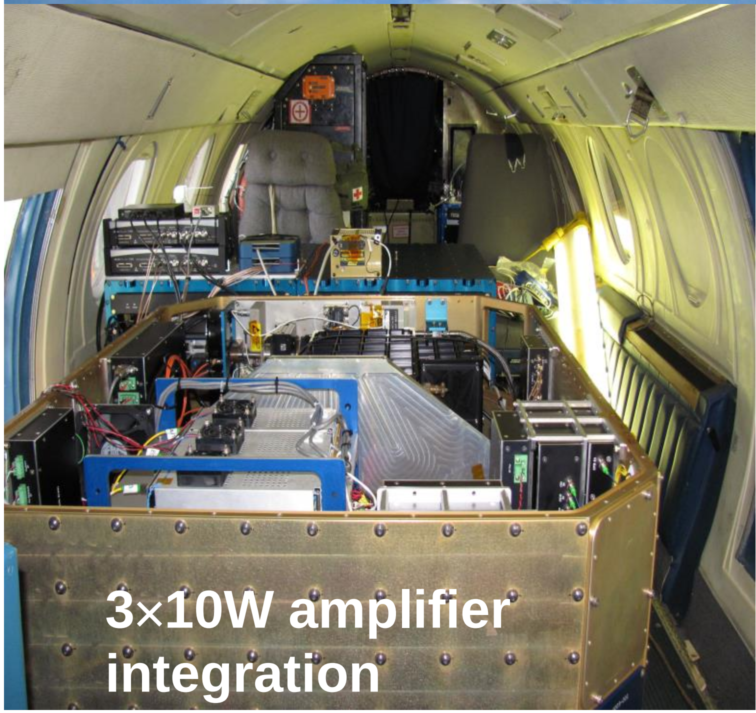
Weighting Functions



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

Instrument Development
(joint effort of LaRC and Exelis)

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



Multifunctional Fiber Laser Lidar (MFLL) (developed by Exelis in 2004 Exelis and Langley since 2005)

advancing key technologies for spaceborne measurements of CO_2 column mixing ratio

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

ranging capability enabled

various lab, ground range, and flight tests

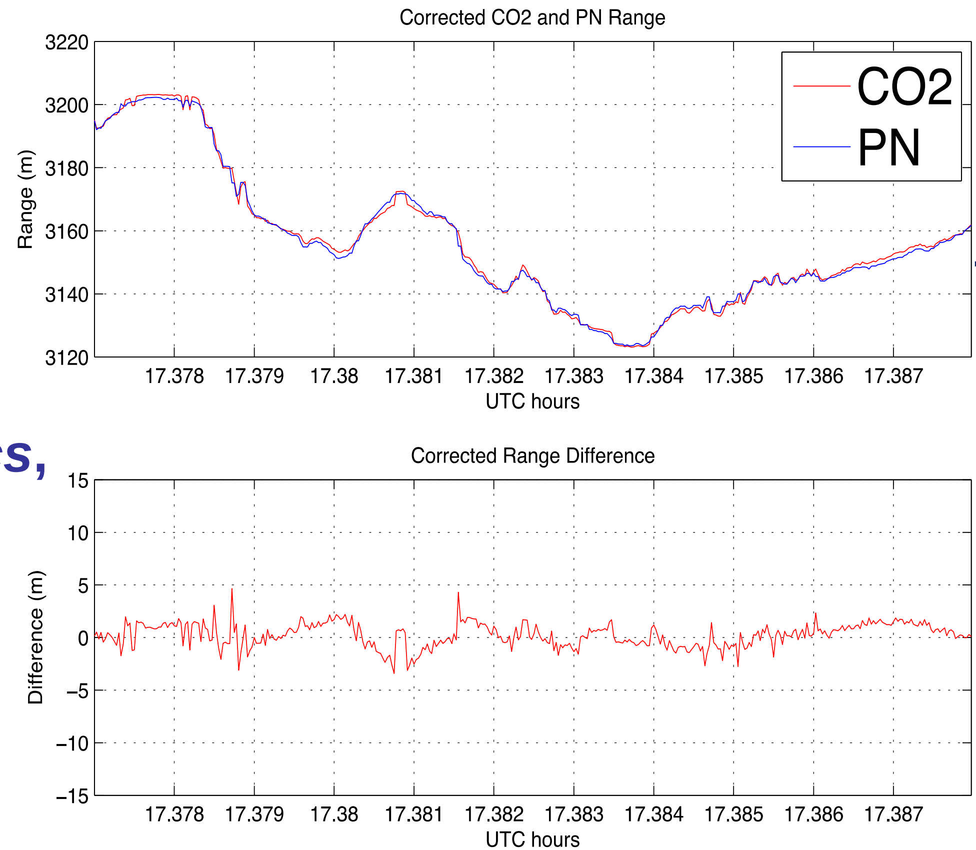
Total of 14 MFLL flight campaigns since 2005
Total of 2 ACES test flight campaigns in Hampton, 2014-2015

Comparison of Range Determination from PN Altimeter and Off-line CO_2 Signal

ASCENDS

MFLL

Dobler et al., *Applied Optics*, 2013

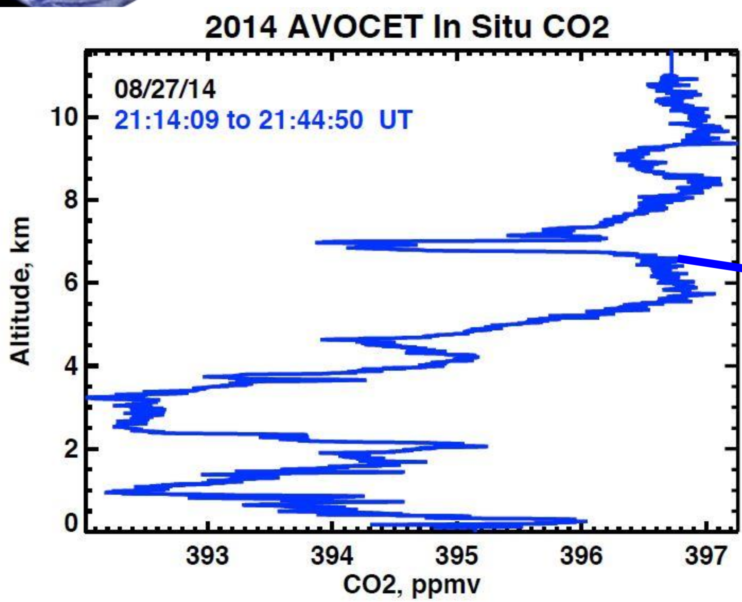


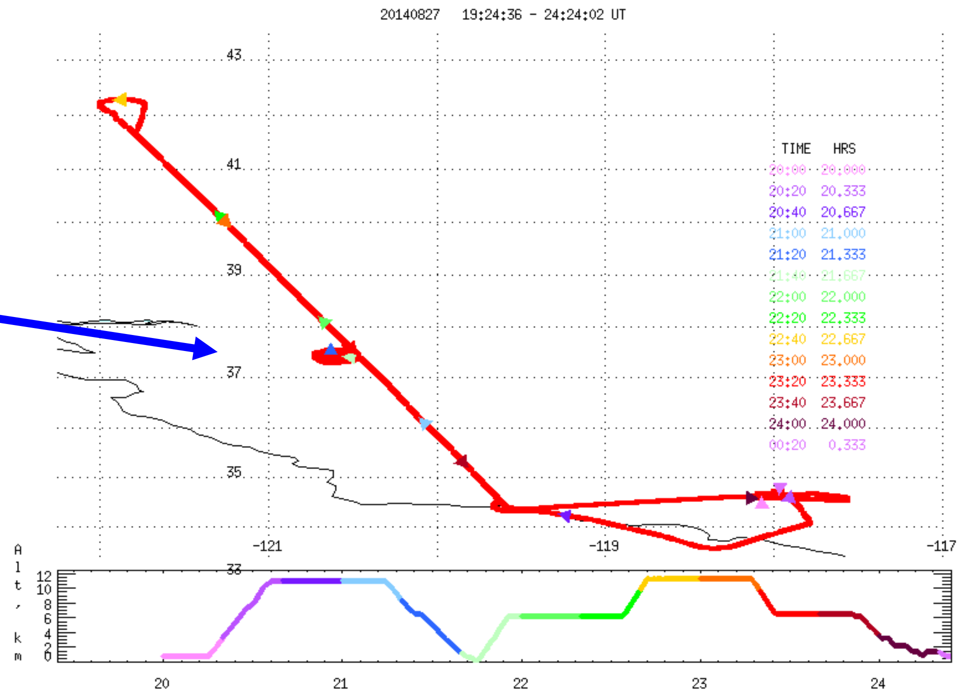
Simultaneously transmitted Intensity modulated range encoded waveforms

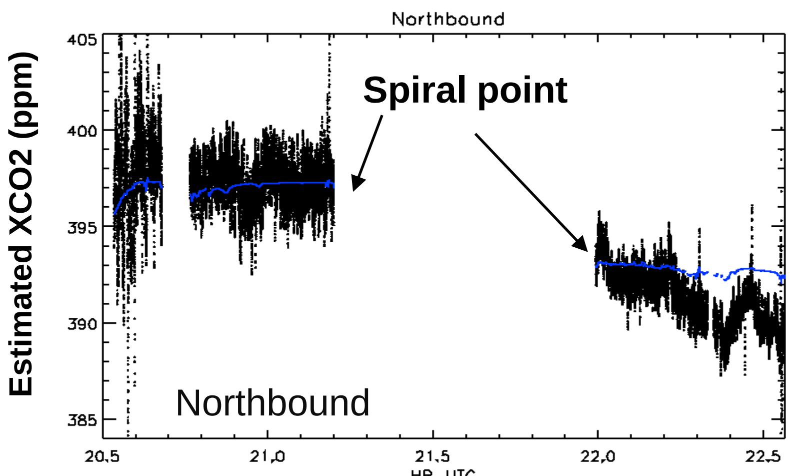
RMS errors < 3 m

Range estimates obtained from the off-line CO_2 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.

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







Black curves: lidar measured XCO2
Blue curves: in-situ derived XCO2

In-situ derived (or modeled) Value

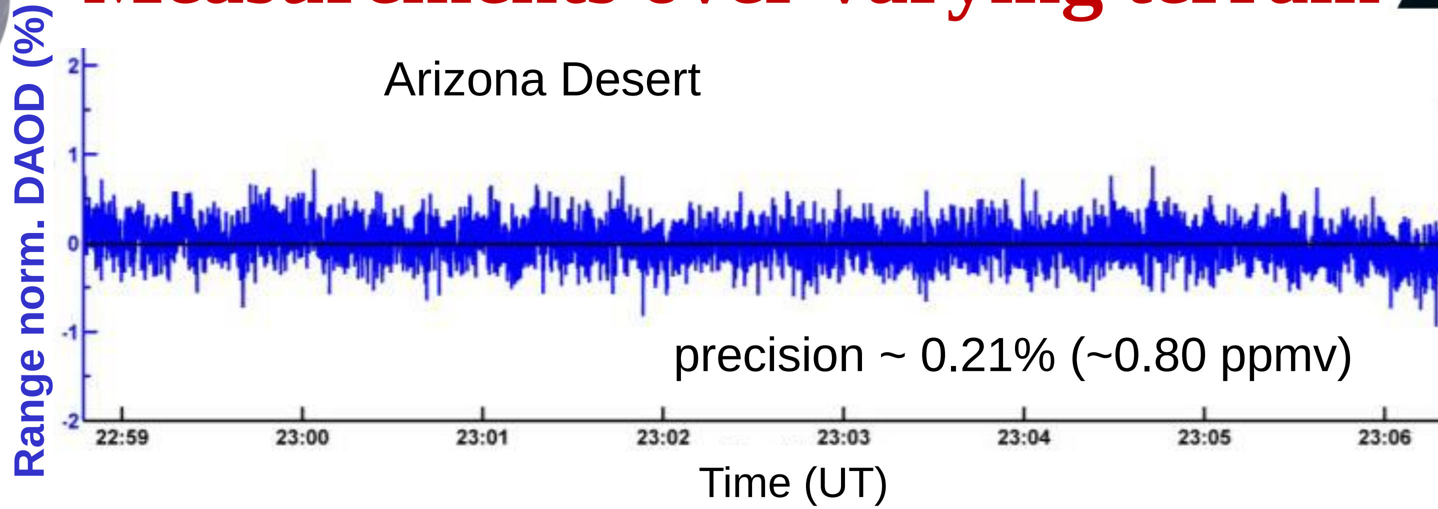
- In-situ from Spiral: CO_2, T/p/q profiles
- Radiative transfer model
- Ranging correction with lidar range data
- In-situ derived (or modeled) DAOD
- In-situ derived (or modeled) XCO_2

difference (ppm): 0.18

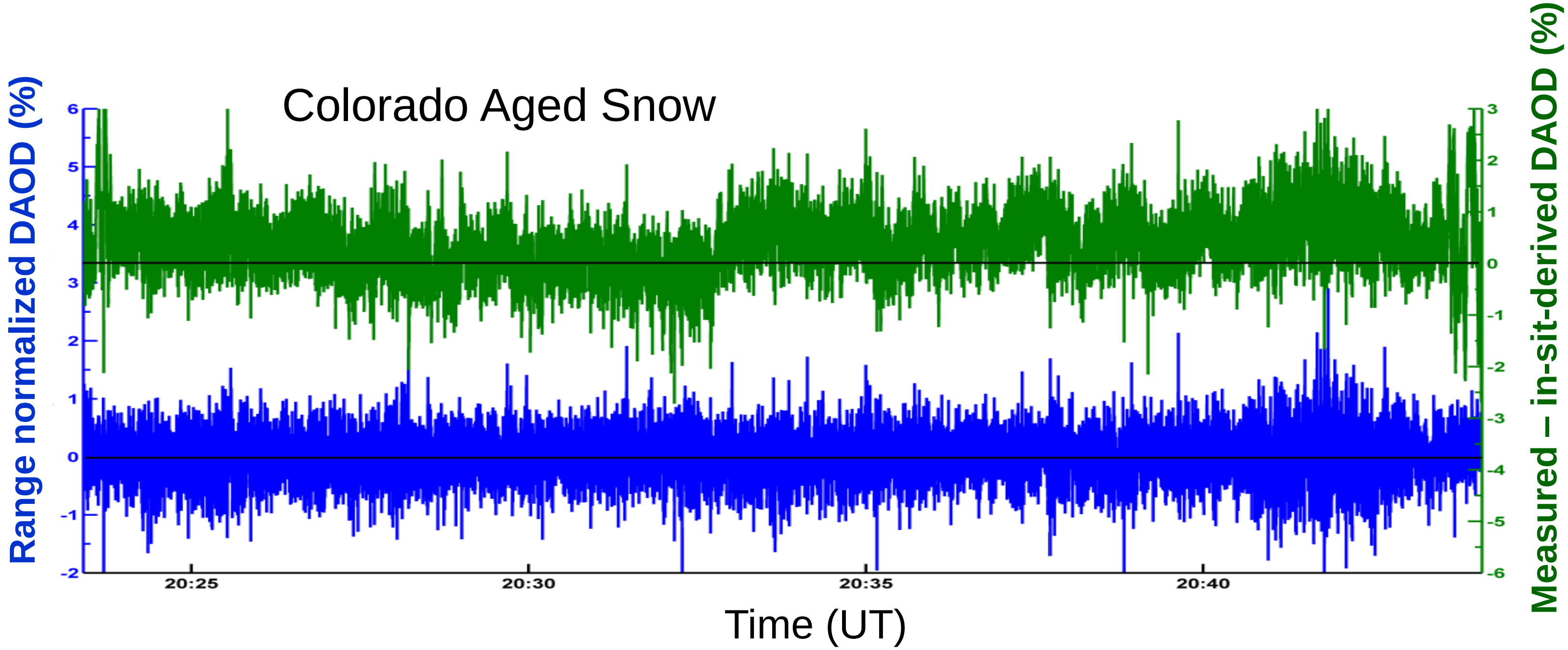
2013 ASCENDS Campaign: Measurements over varying terrain

ASCENDS

1-s average



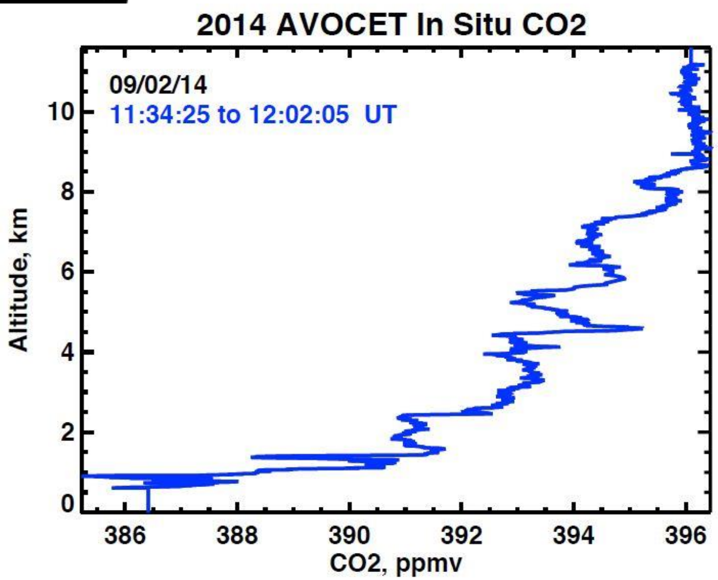
MFLL

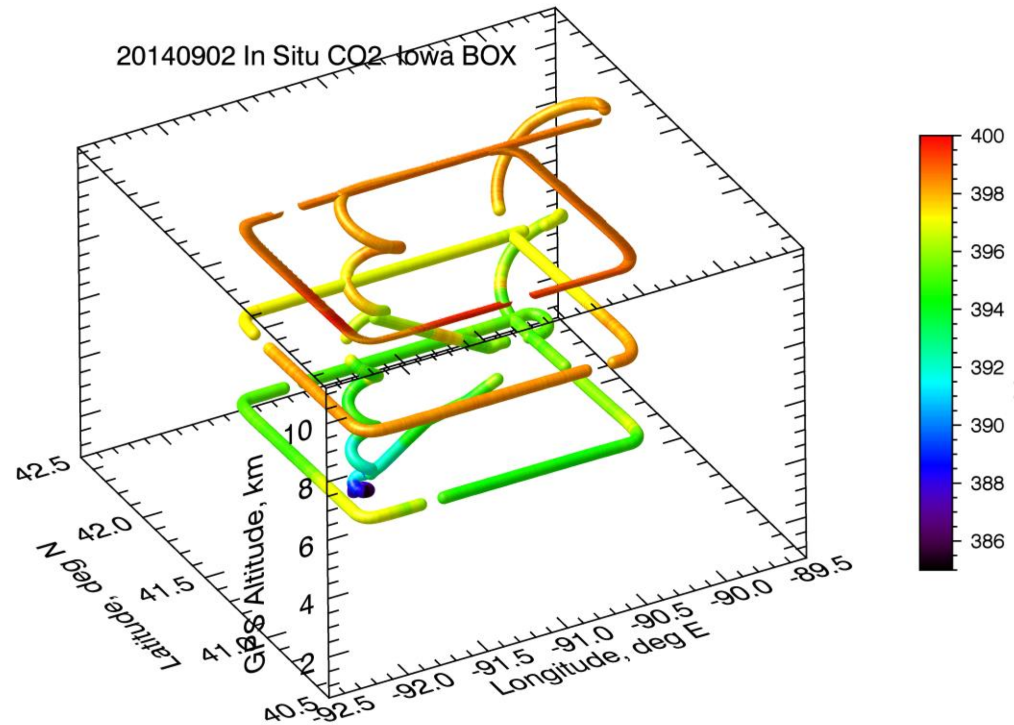


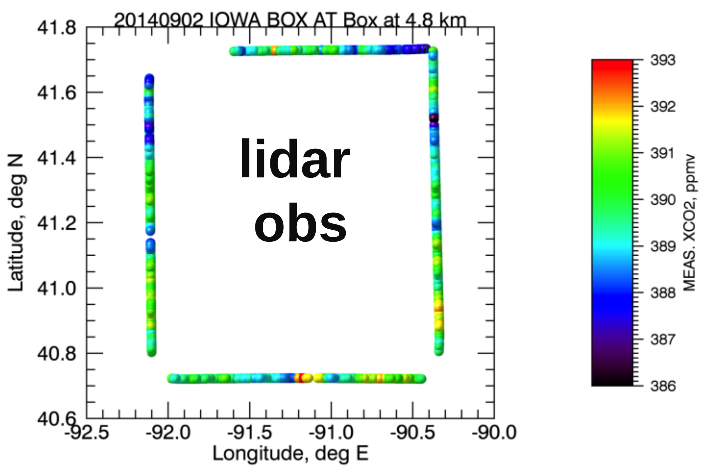
difference ~ 0.26% (~0.99 ppmv); Precision ~ 0.42% (~1.6 ppmv)

Natural Variability
(lidar and in-situ measurements)

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

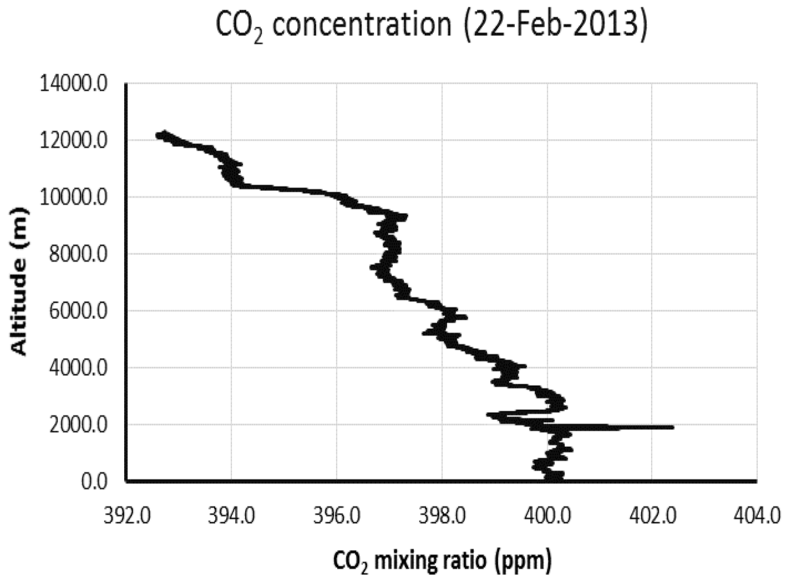


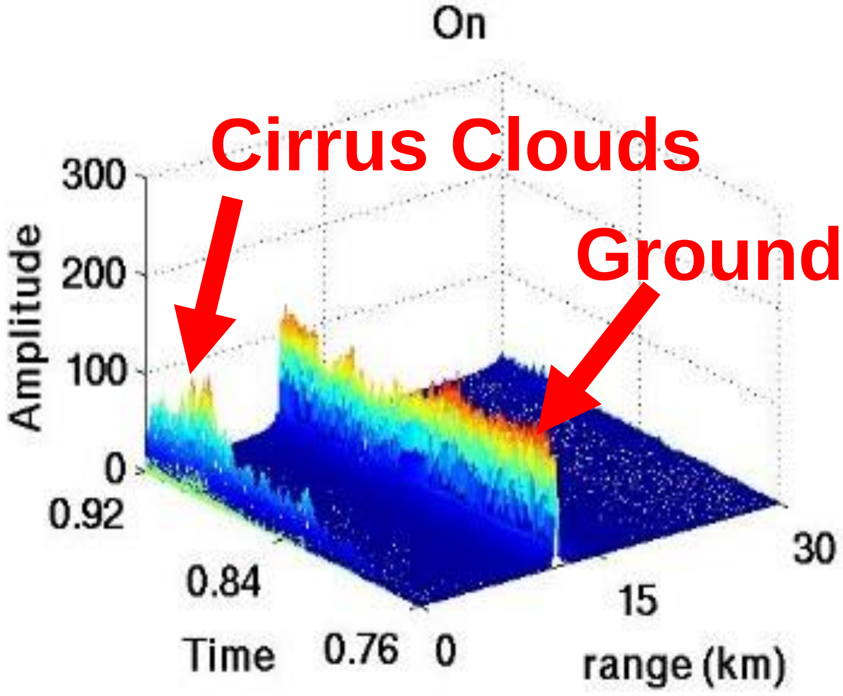


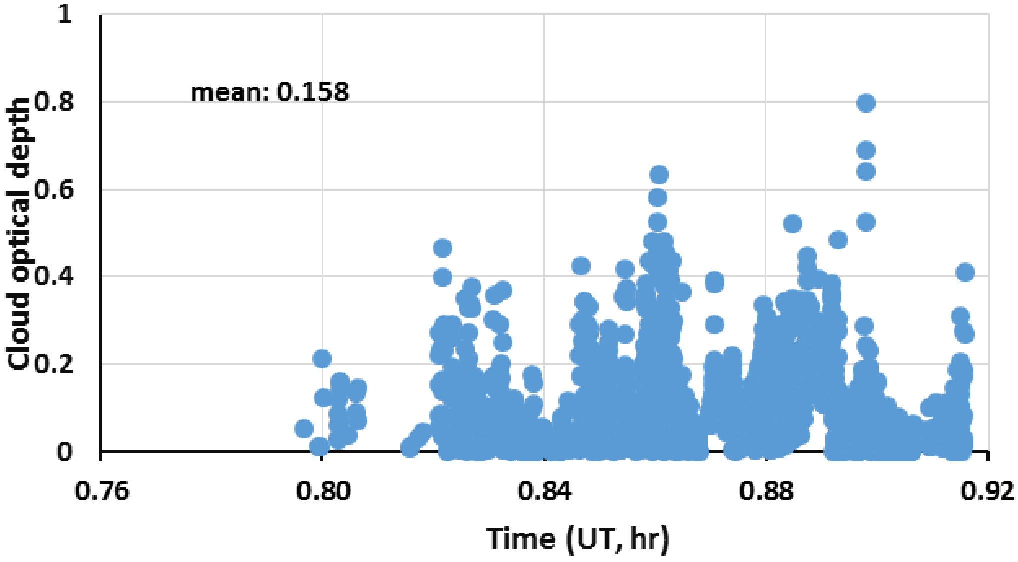


Significant spatiotemporal variations (a few ppm) found from lidar observations and when comparing spiral with non-spiral in-situ observational data

CO_2 Column Measurements Through Thin Cirrus (22 Feb 2013)





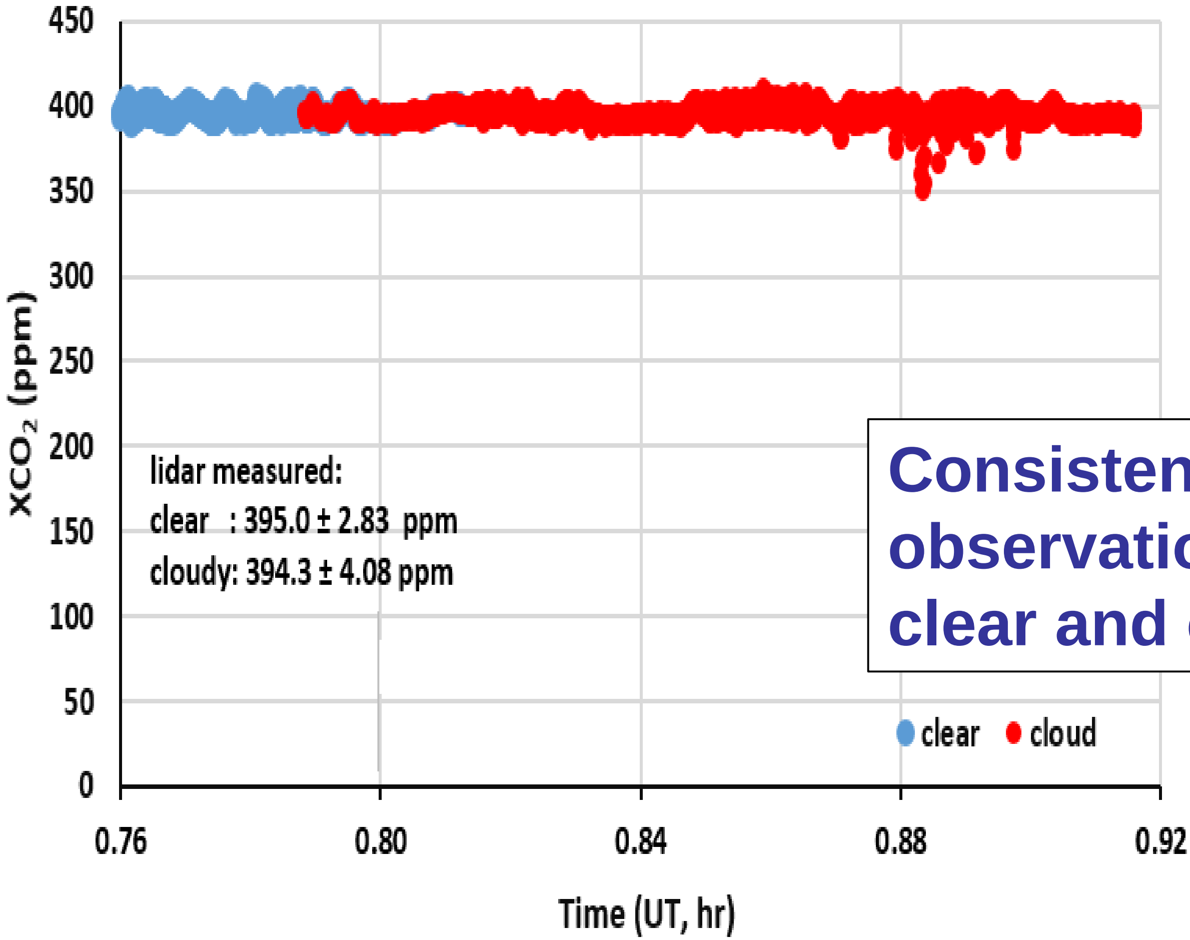


Blythe, CA

10 Hz data

Lin et al., *Optics Express*, 2015

Derived XCO_2 Column Measurements to the Surface Under Clear and Cloudy Conditions



cloudy XCO_2 – clear XCO_2 = –0.7 ppm

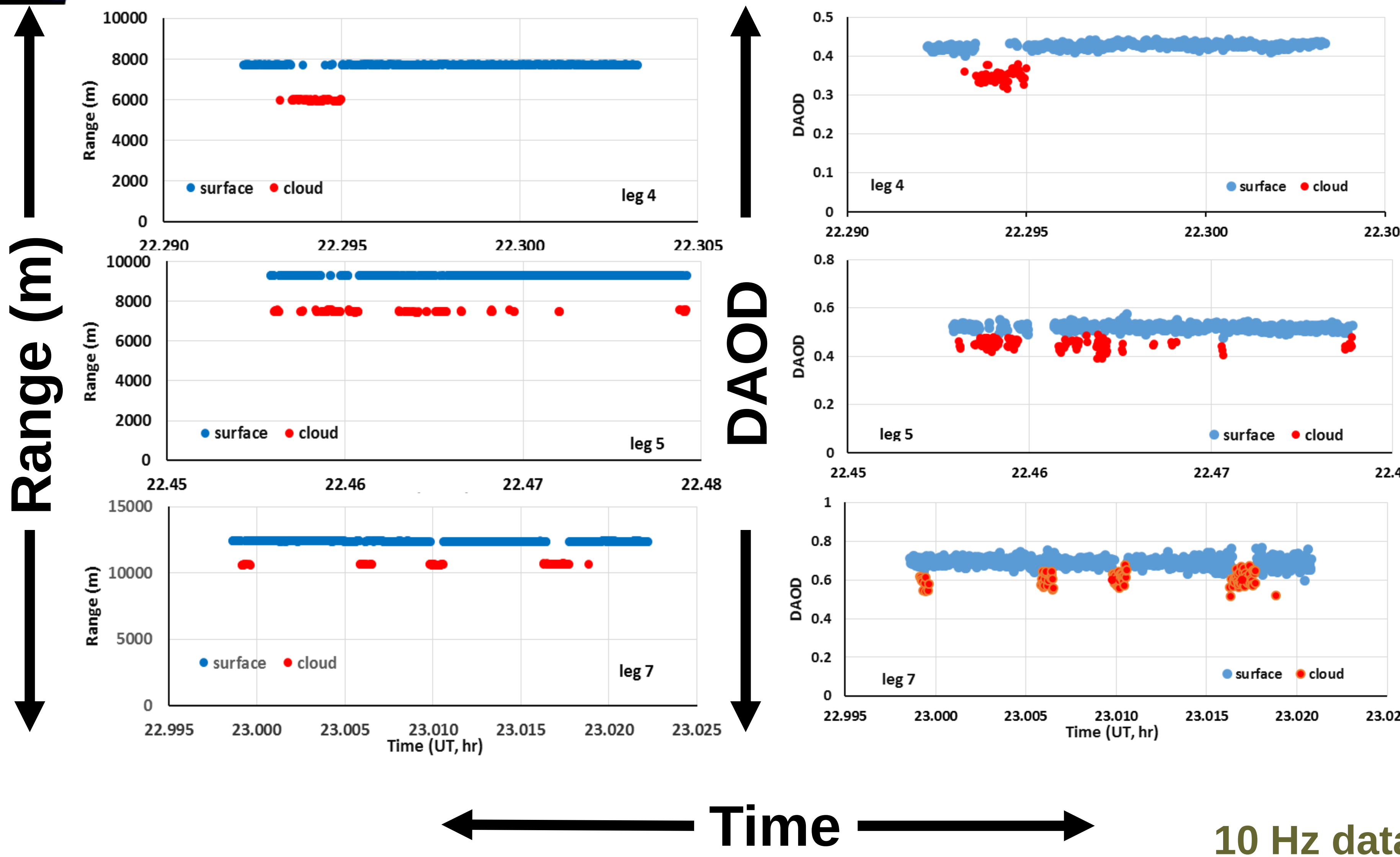
Consistent CO_2 column observations obtained for clear and cloudy conditions

Lin et al., *Optics Express*, 2015

10 Hz data

Range and Column CO_2 to Surface and Thick Cloud Tops

(West Bank, Iowa; 10 Aug 2011)



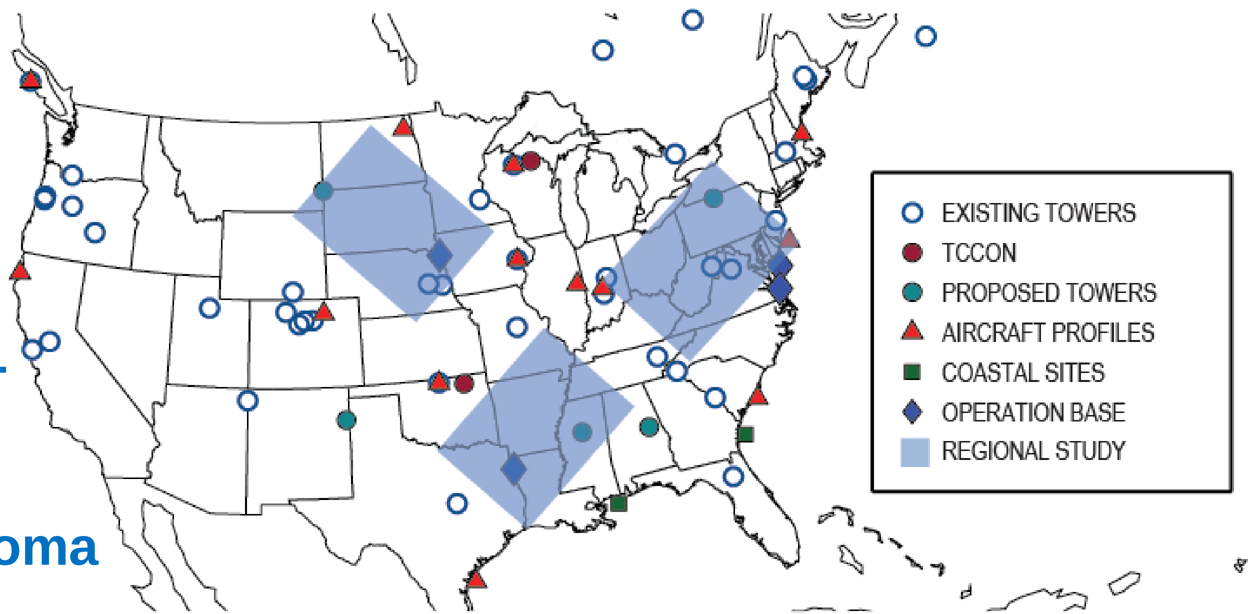
Lin et al., *Optics Express*, 2015

10 Hz data

Atmospheric Carbon & Transport (ACT) – America

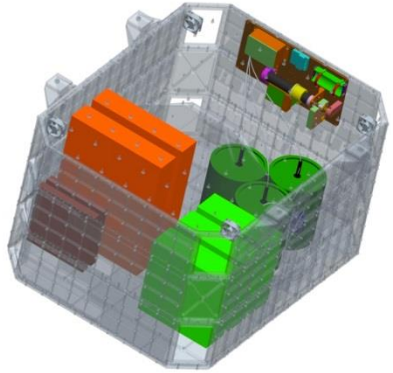
The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric carbon inversions: transport error, prior flux uncertainty and limited data density.

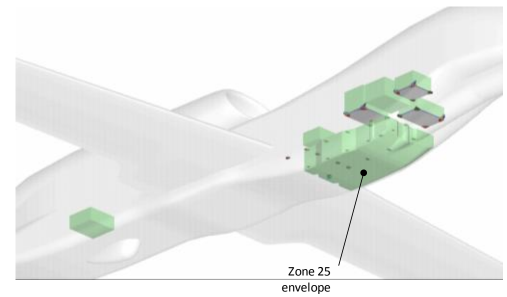
Penn State
NASA
LaRC, WFF, GSFC, JPL
Exelis, Colorado State
NOAA ESRL/U Colorado
DOE Oak Ridge, U Oklahoma
Carnegie Inst. Stanford



ASCENDS Mission Development

Current





Today: MFLL and ACES instruments in DC-8 racks

Global Hawk

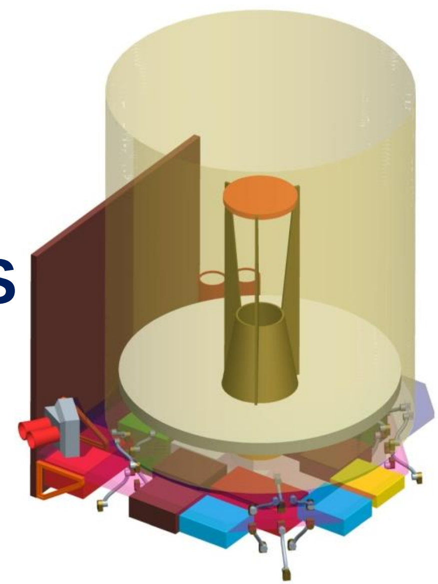
Size = 100” x 43” x 24”
Mass = 787.2 lb.

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

Future

TBD: ISS Tech Demo?

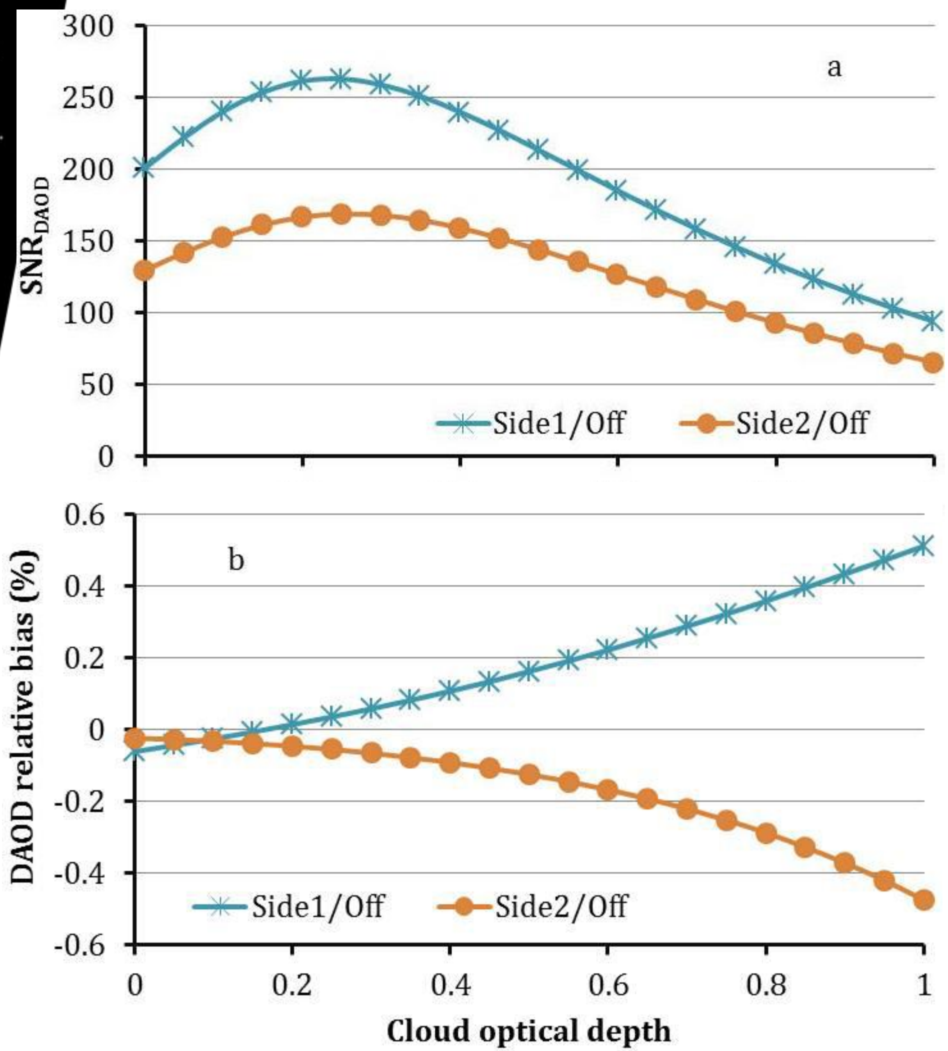
TBD: ASCENDS mission

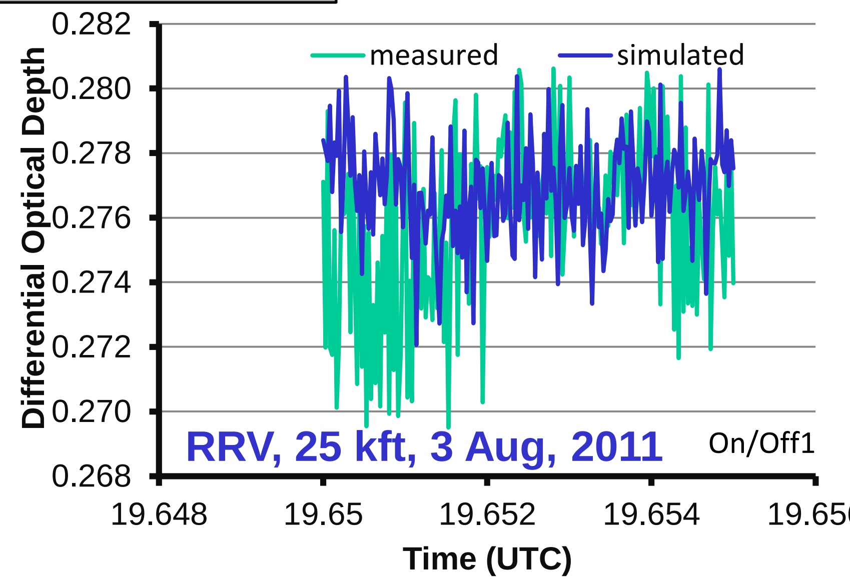


Space CO_2 Lidar Modeling and Measurement

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**

Summary

- IM-CW lidar at 1.57μm with ranging-encoded IM has demonstrated the capability of precise CO_2 measurements through many airborne flight campaigns under variety of environment conditions, including CO_2 column measurements through thin cirrus clouds and to thick clouds.
- Over land, clear-sky lidar CO_2 measurements with 1-s integration reach a precision as high as within 1 ppm; these measurements are also consistent with coincident in situ measurements with mean bias much smaller.
- Ranging uncertainties are shown to be at sub-meter level.
- Analysis shows that current IM-CW lidar approach will meet space CO_2 observation requirements and provide precise CO_2 measurements for carbon transport, sink and source studies.

Column CO_2 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 $DAOD_{bndrylyr}$	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 $DAOD_{bndrylyr}$	0.0826	0.0826	0.0826

Lin et al., *Optics Express*, 2015

10 Hz data