Advancements for Active Remote Sensing of Carbon Dioxide from Space

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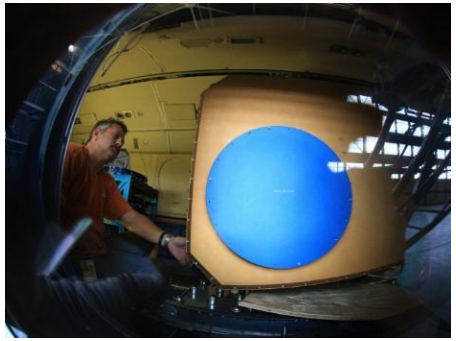
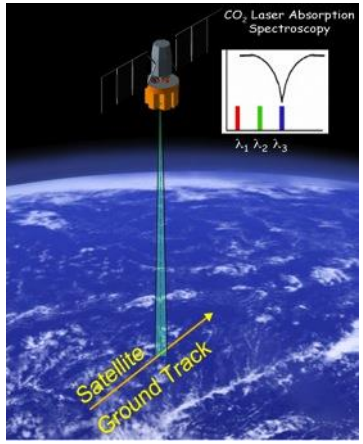
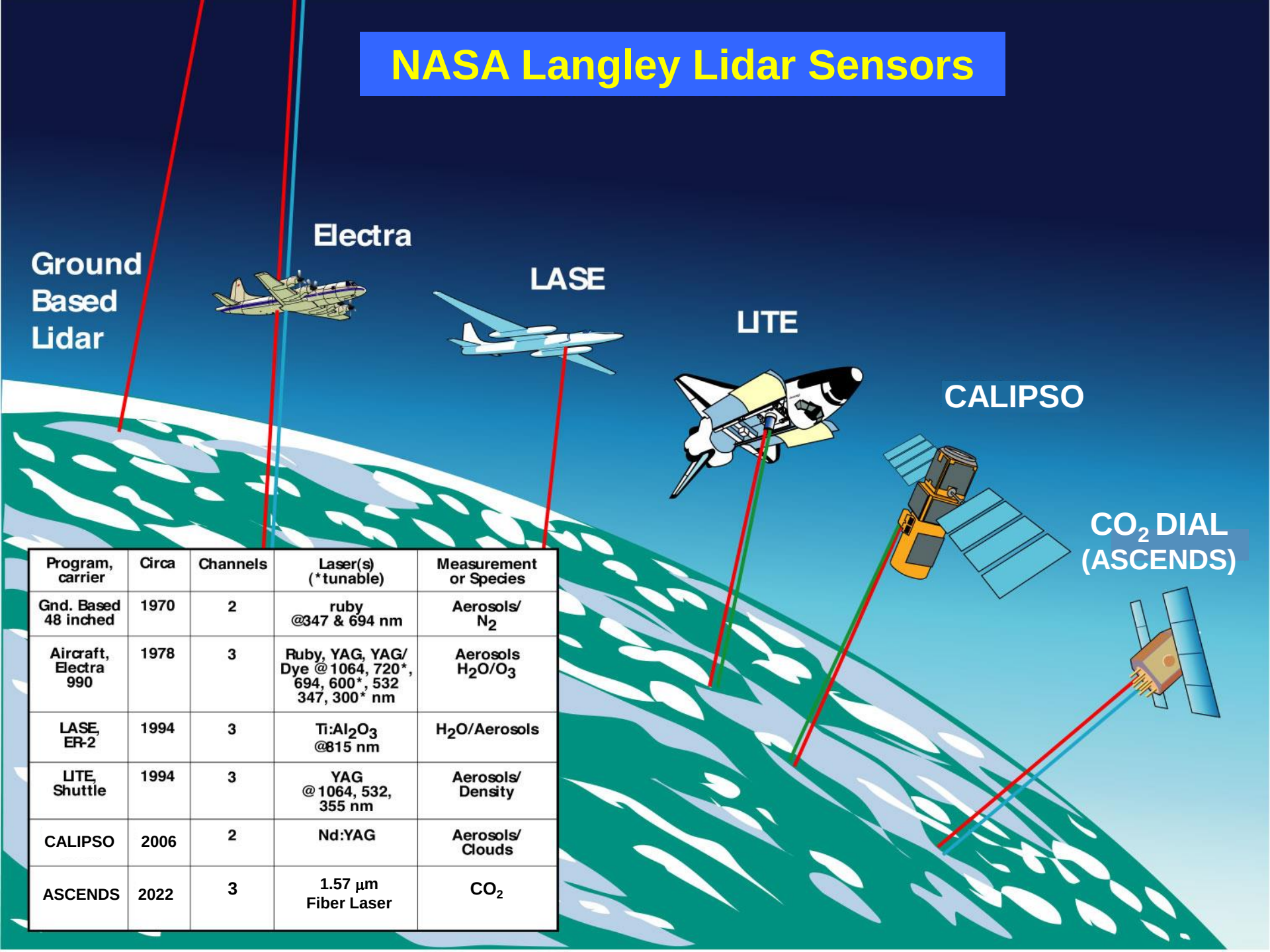




4th International Symposium on Atmospheric Light Scattering and Remote Sensing

June 3, 2015

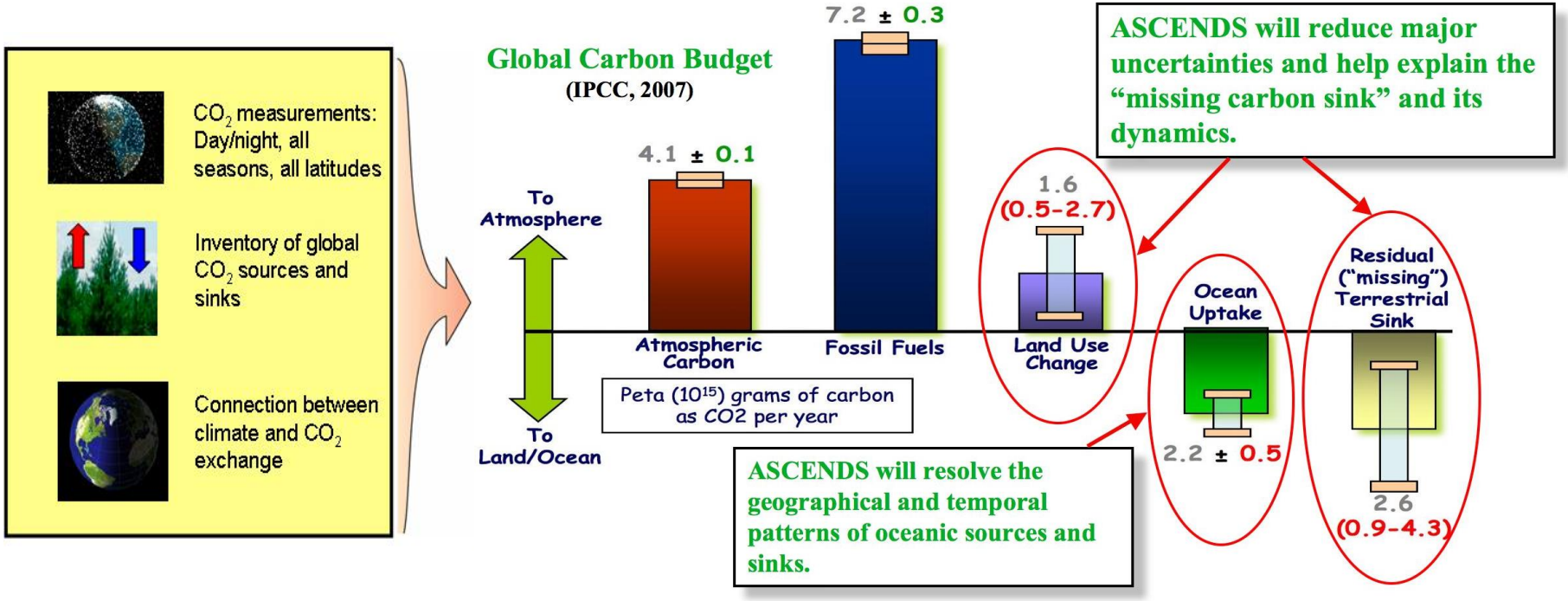
NASA Langley Lidar Sensors



Program, carrier	Circa	Channels	Laser(s) (*tunable)	Measurement or Species
Gnd. Based 48 inched	1970	2	ruby @347 & 694 nm	Aerosols/ N_2
Aircraft, Electra 990	1978	3	Ruby, YAG, YAG/ Dye @1064, 720*, 694, 600*, 532 347, 300* nm	Aerosols H_2O/O_3
LASE, ER-2	1994	3	Ti:Al_2O_3 @815 nm	H_2O/Aerosols
LITE, Shuttle	1994	3	YAG @1064, 532, 355 nm	Aerosols/ Density
CALIPSO	2006	2	Nd:YAG	Aerosols/ Clouds
ASCENDS	2022	3	1.57 μm Fiber Laser	CO_2

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

2007 NRC Decadal Survey:
Earth Science & Applications from Space; Tier II Mission



- **ASCENDS provides a accurate global dataset of atmospheric CO_2 column measurements without seasonal, latitudinal, or diurnal bias.**

- **These measurements will be used in retrieval of CO_2 fluxes to estimate *regional* carbon sources/sinks and thereby improve understanding of underlying mechanisms to improve climate predictions.**

Instrument Development: Langley and Exelis, Inc.
14 MFLL + 1 ACES flight campaigns

Multifunctional Fiber Laser Lidar (MFLL)

- **Developed by ITT/Exelis in 2004, and advanced by Exelis and Langley since 2005**
- **14 proof-of-concept field campaigns**

ASCENDS CarbonHawk Experiment Simulator (ACES)

- **Developed at Langley with technical support from Exelis**
- **Advancing key technologies for spaceborne measurements of average CO_2 column mixing ratio**

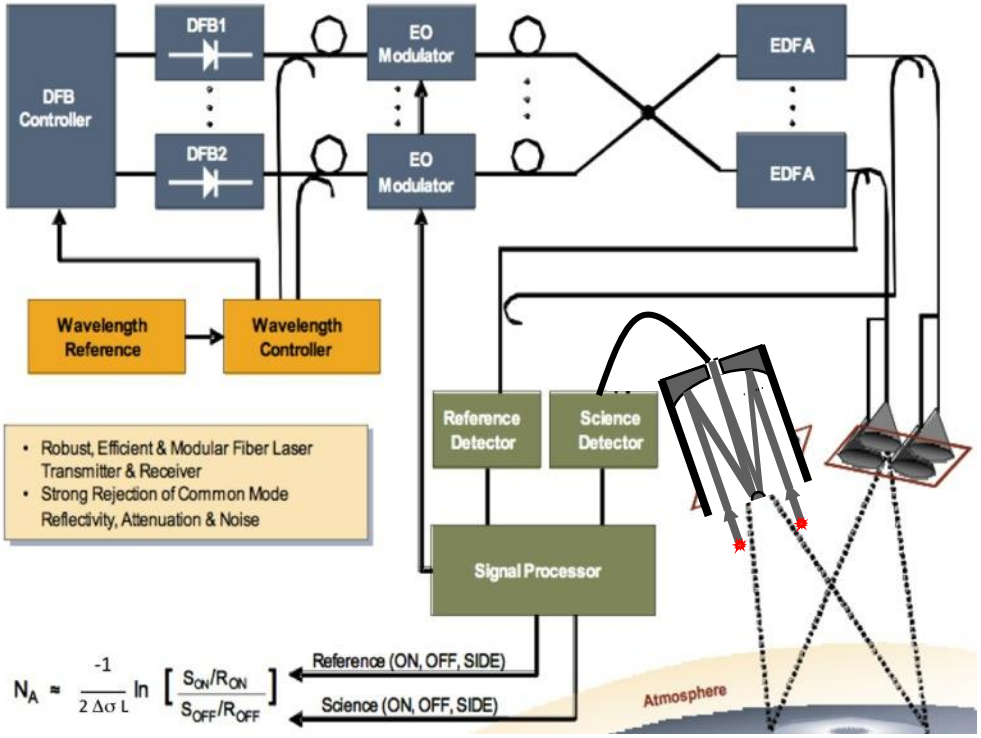
MFLL integrated on DC-8

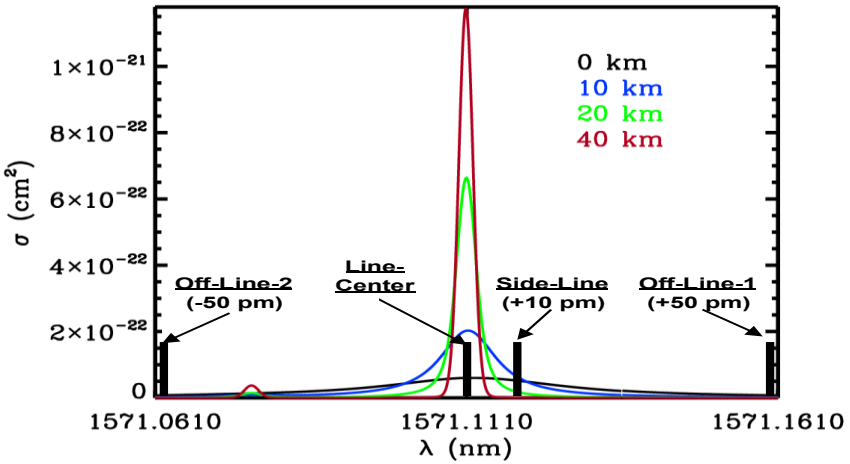
ACES integrated on HU-25

CO_2 Measurement Architecture

ACES architecture based on Exelis Multi-functional Fiber Laser Lidar (MFLL):

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





- Simultaneously transmits multiple λ_{on} and λ_{off} wavelengths reducing atmospheric noise & eliminating surface reflectance variations.
- Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 μm) measurements for deriving mixing ratio (XCO_2).

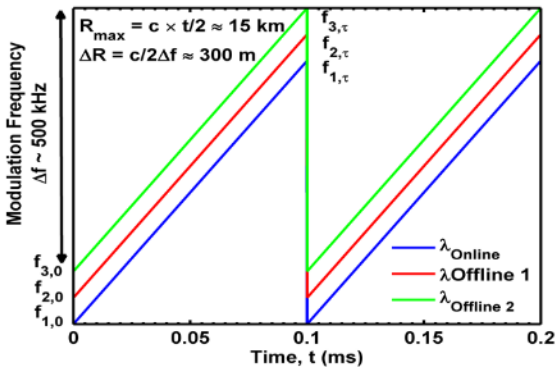
Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

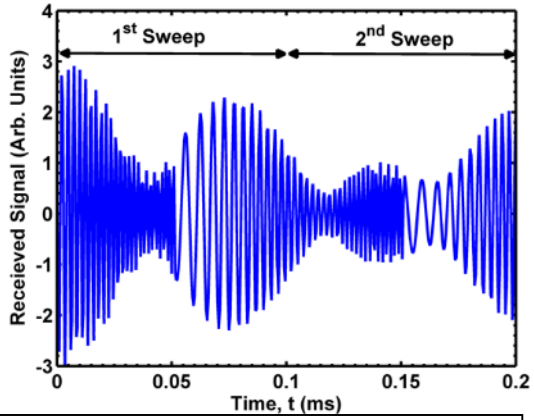
Progression of Transmitted and Received Intensity-Modulated Waveforms

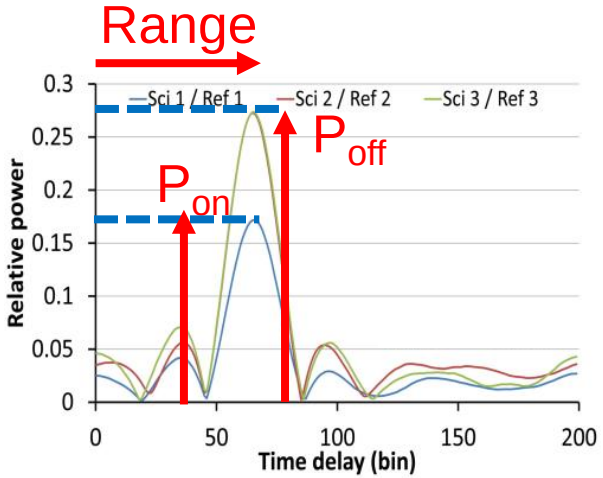
Simultaneously-transmitted intensity modulated range encoded waveforms

Simultaneously-received Online and Offline IPDA returns

Measurement: Output of correlation between transmitted and received waveforms



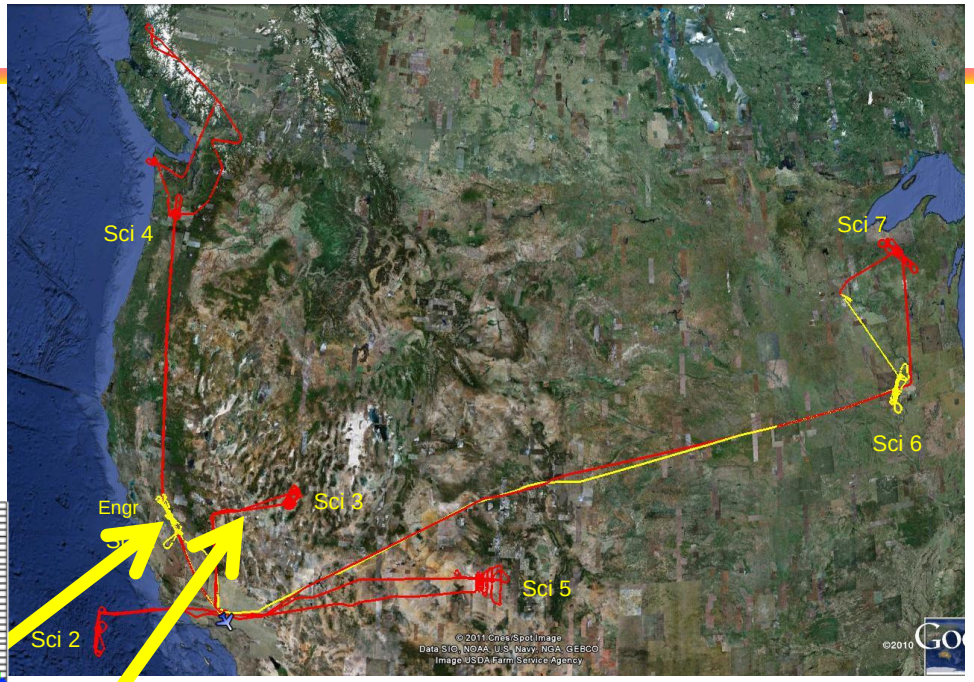




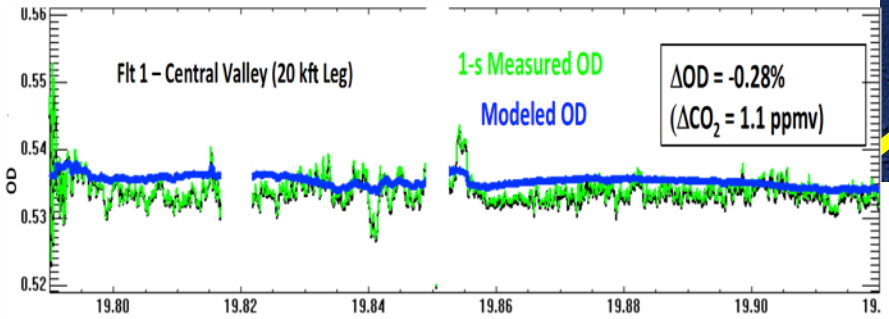
Range-encoded approach for detection and ranging is analogous to mature Frequency-Modulated Continuous Wave (FM-CW) Radar and GPS measurement techniques

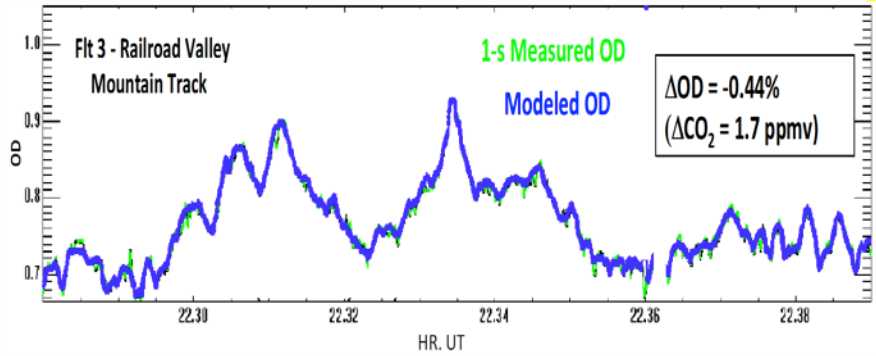
$$DAOD = \frac{1}{2} ln\left(\frac{P_{off} * E_{on}}{P_{on} * E_{off}}\right)$$

MFLL Optical Depth Comparisons: ASCENDS DC-8 Campaign 28 July – 11 August, 2011

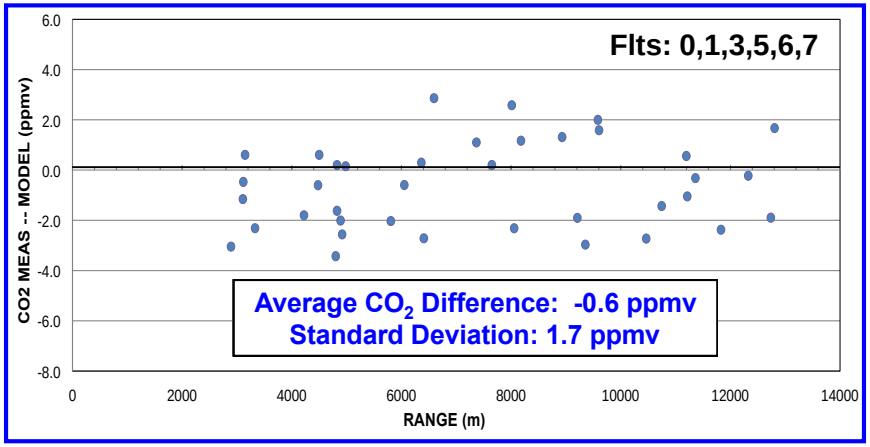


Optical Depth (OD) Comparisons



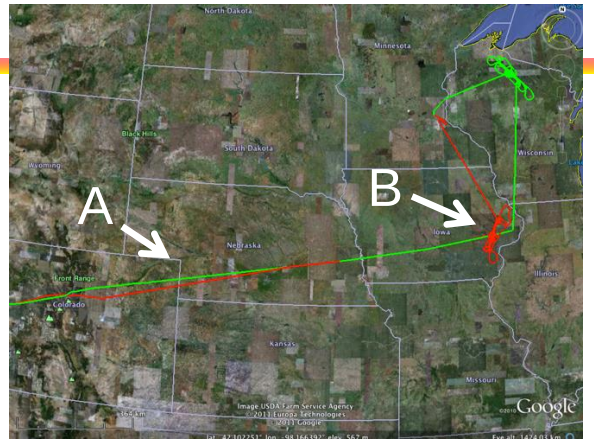


All OD Comparison Differences (Measured – Modeled)



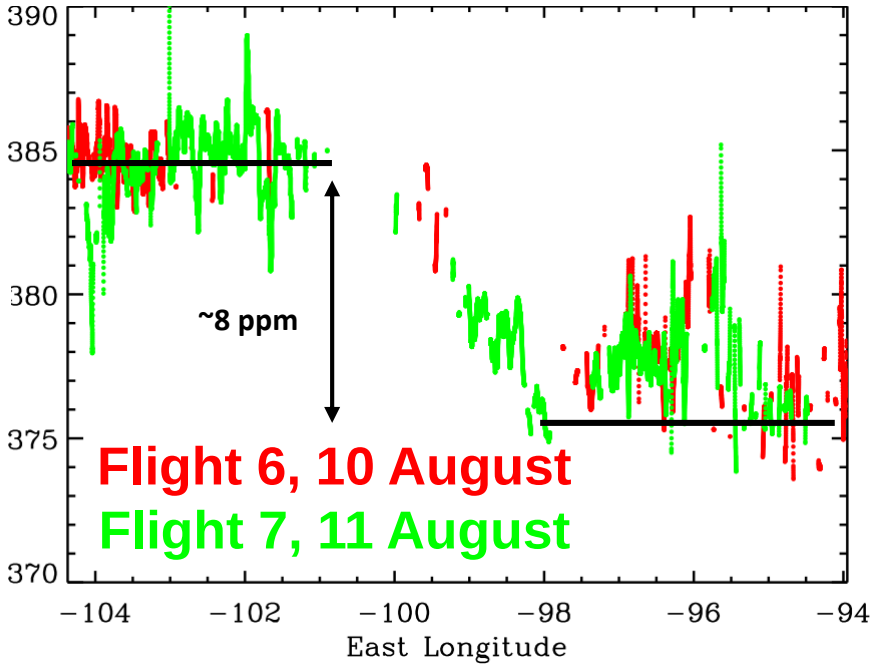
Dobler, et al., *Applied Optics*, 2013

MFLL 2011 and 2014 measurements: Agricultural Respiration

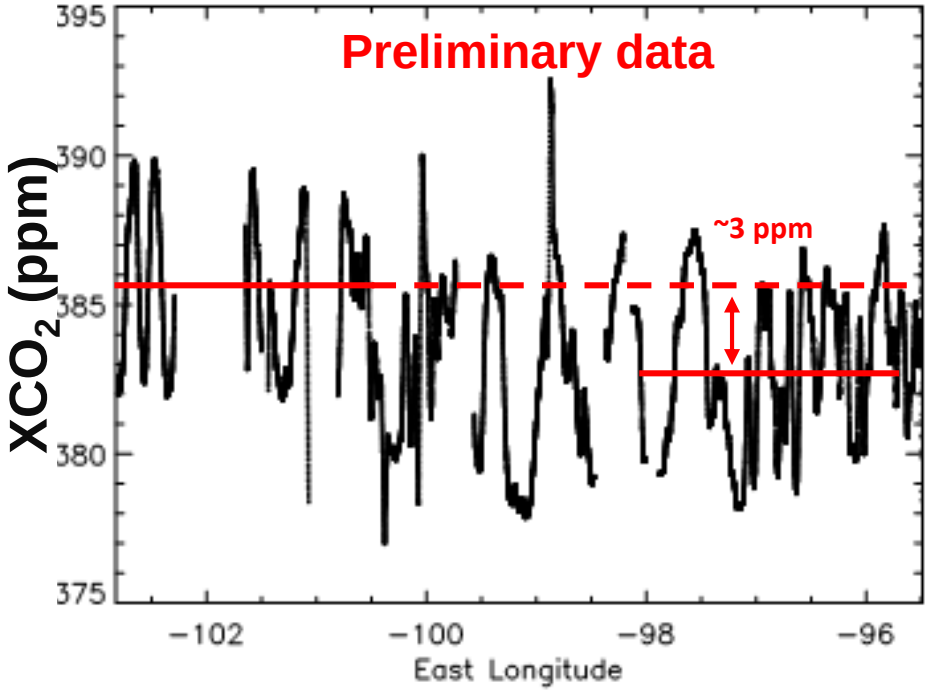


- Column CO_2 measurements over Midwestern US farm fields showed much larger drawdown signal in 2011 campaign (~8 ppm) compared with measurements in 2014 (~3 ppm)
  - Resulting from different corn growth periods and meteorological states

2011 Midwest Flights

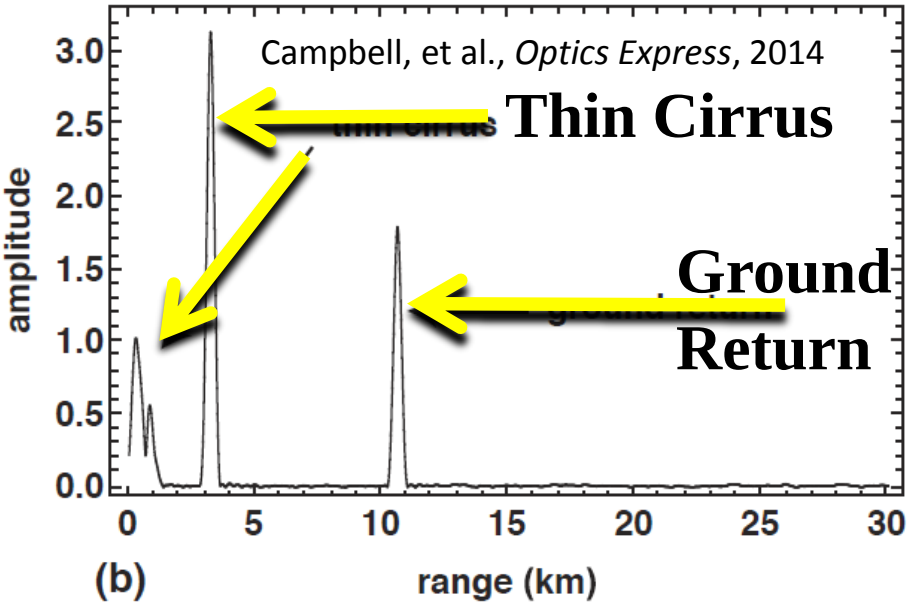


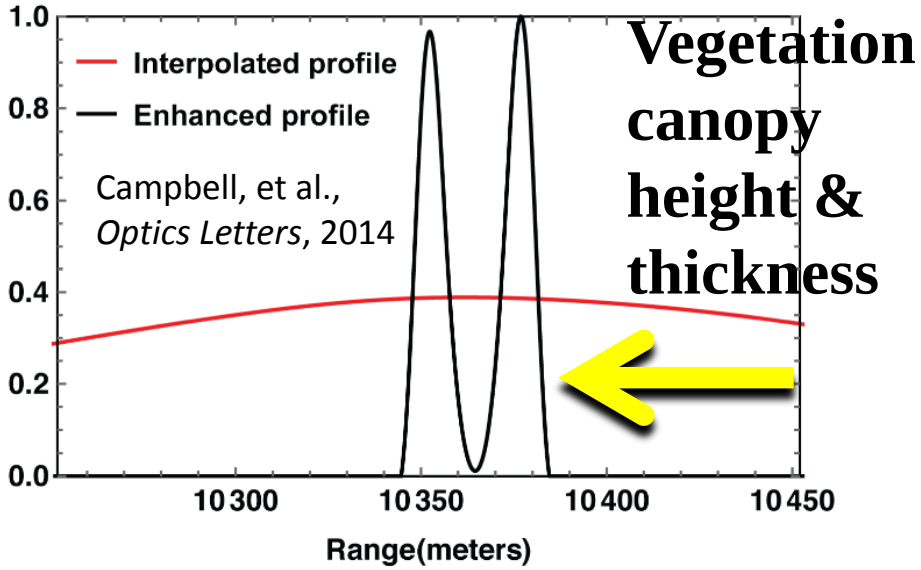
25 August 2014 Midwest Flight



ACES 2014 Test Flights: Preliminary Ranging Results

IM-CW technique accurately retrieves range over a variety of surfaces and in the presence of optically thin clouds allowing for retrievals of column CO_2 mixing ratios to surface and cloud tops.



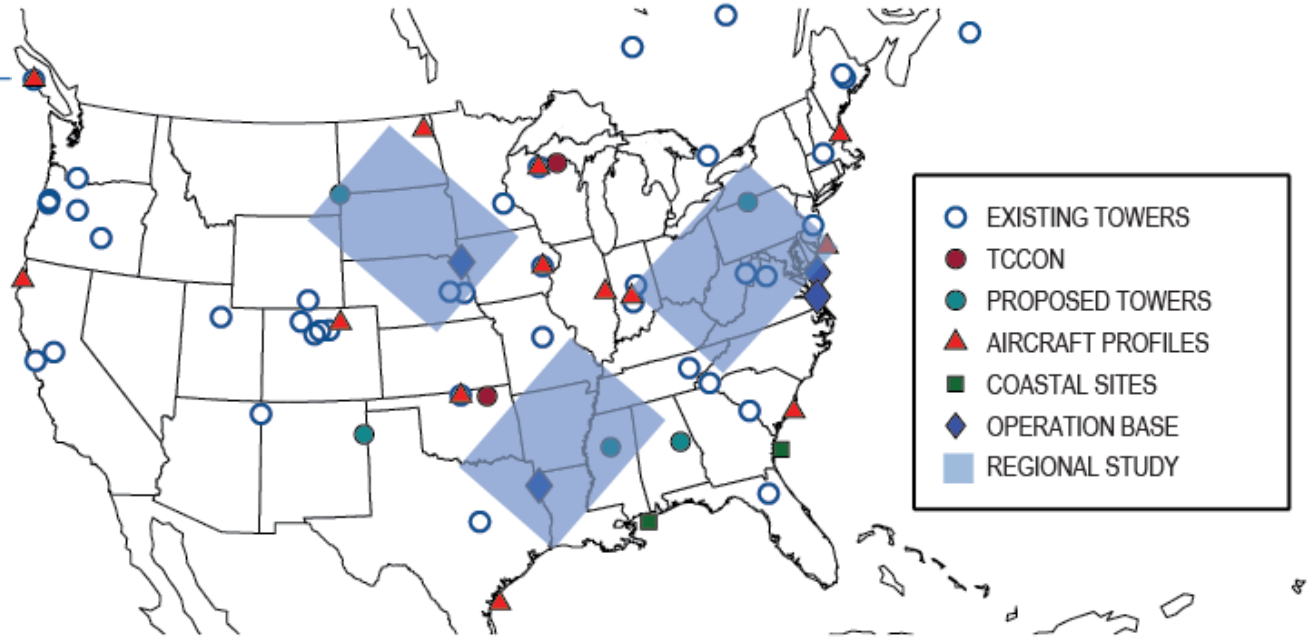


- Advanced deconvolution techniques resolve cloud and forest features

Atmospheric Carbon and Transport - America (ACT-America)

PI: Ken Davis, Pennsylvania State University

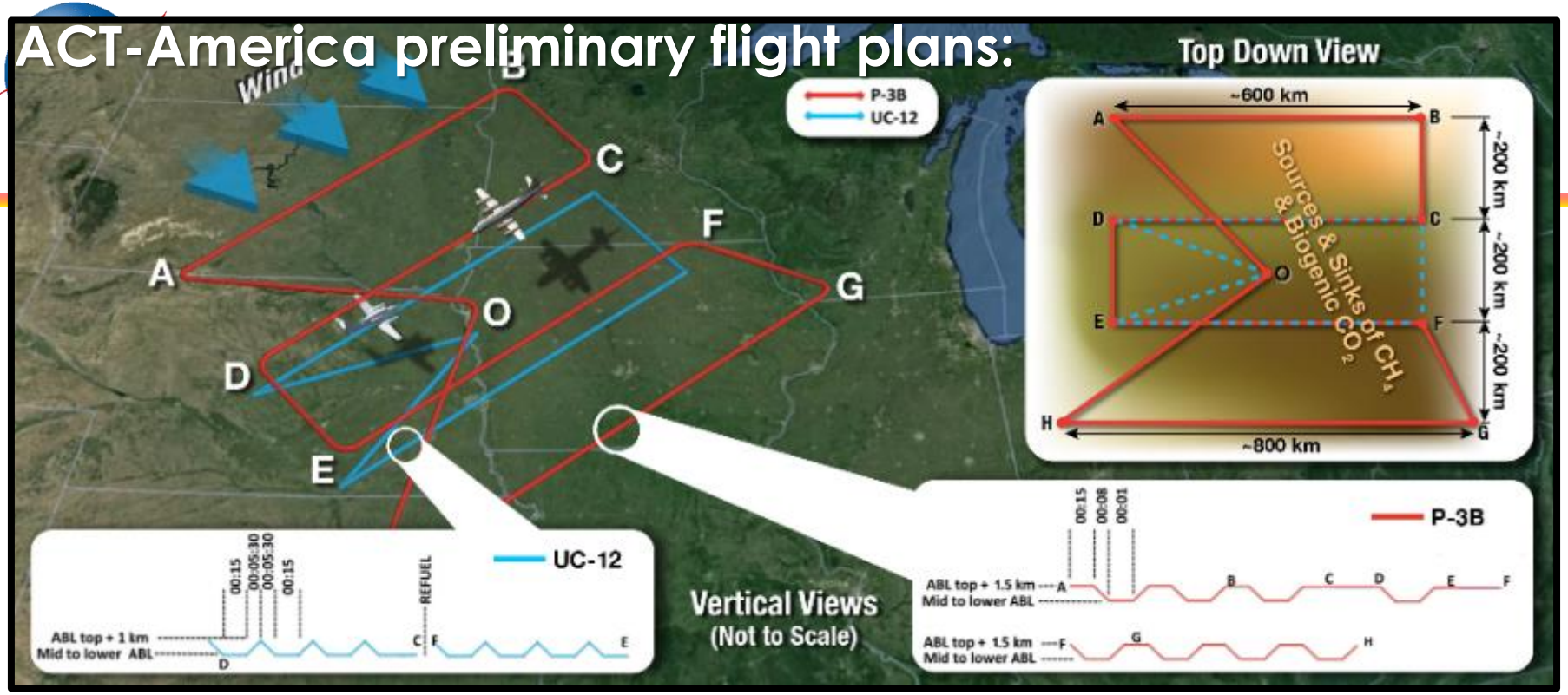
Our goals address the three primary sources of uncertainty in atmospheric inversions – transport error, prior flux uncertainty and limited data density

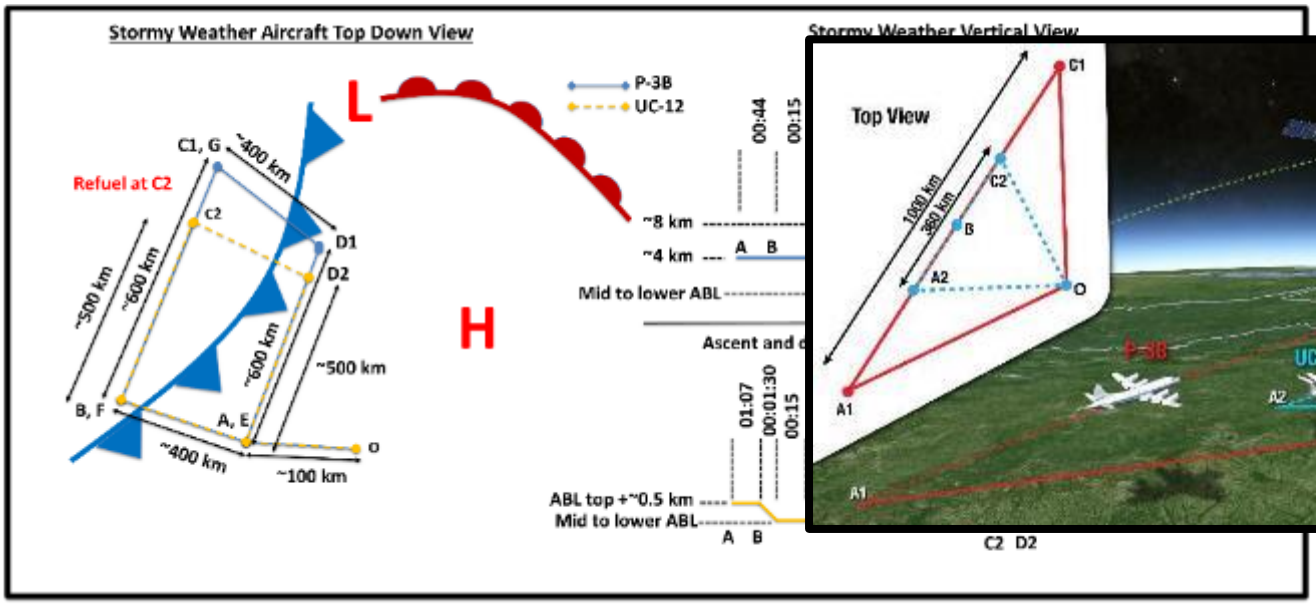


- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft: C-130 (MFLL, Cloud Physics Lidar, in situ instruments) & UC-12 (in situ instr.)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)

Fall 2015	Win 2016	Spr 2016	Sum 2016	Fall 2016	Win 2017	Spr 2017	Sum 2017	Fall 2017	Win 2018	Spr 2018	Sum 2018	Fall 2018
	X		X			X		X			X	

ACT-America preliminary flight plans:





Summary

- NASA Langley Research Center has a long history of successfully designing and implementing airborne and spaceborne lidar systems.
- The Exelis MFLL instrument has collected airborne CO_2 column measurements in 14 campaigns since 2005 and is now preparing for the ACT-America Earth Venture Suborbital campaign.
- The ACES instrument successfully completed its first test flights in 2014, and will continue technology advancement efforts during test flights in August 2015 and January 2016.
  - HgCdTe detector/TIA bandwidth increased to ~4.9 MHz for advanced modulation waveforms
  - Increased transmitter power and receiver aperture yielding high precision measurements over varying surfaces
- Our team is continuing to advance technologies and measurement techniques critical for column CO_2 measurements from space.

Future Directions

- The ACT-America mission has begun, with five airborne campaigns planned for 2016-2018.
- Continue data analysis to fully quantify MFLL and ACES instrument performances
- Continue flight testing of new modulation algorithms and hardware improvements
  - Deconvolution techniques for clouds and forest canopies
  - Operational tests of retrievals with sideline wavelengths
  - Instrument automation for UAV operations
- Continue Technology Readiness Level (TRL) advancement and space qualification of ASCENDS technologies

Acknowledgements

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Thank you to the NASA Science Mission Directorate, the NASA Earth Science Technology Office (ESTO), the NASA Headquarters ASCENDS program, and NASA Langley Research Center for supporting these projects. The authors wish to thank the many contributions to this work from the rest of our teams at Exelis, Welch Mechanical Designs, the University of Melbourne, NP Photonics, NASA Langley, Pennsylvania State University, and the DC-8 and HU-25 aircraft support teams.

Backup Slides

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

Remote Sensors (C-130):

MFLL (Exelis, Inc.):

- Column CO_2 number density
- Range to ground

Cloud Physics Lidar (NASA Goddard):

- Atmospheric boundary Layer height
- Aerosol/Cloud optical depth

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

Picarro and Ozone (NASA Langley):

- In situ measurements of CO_2, CH_4, CO, H_20, and O_3 number density

Flasks (NOAA):

- In situ samples of CO_2, CH_4, CO, $^{14}CO_2$, COS

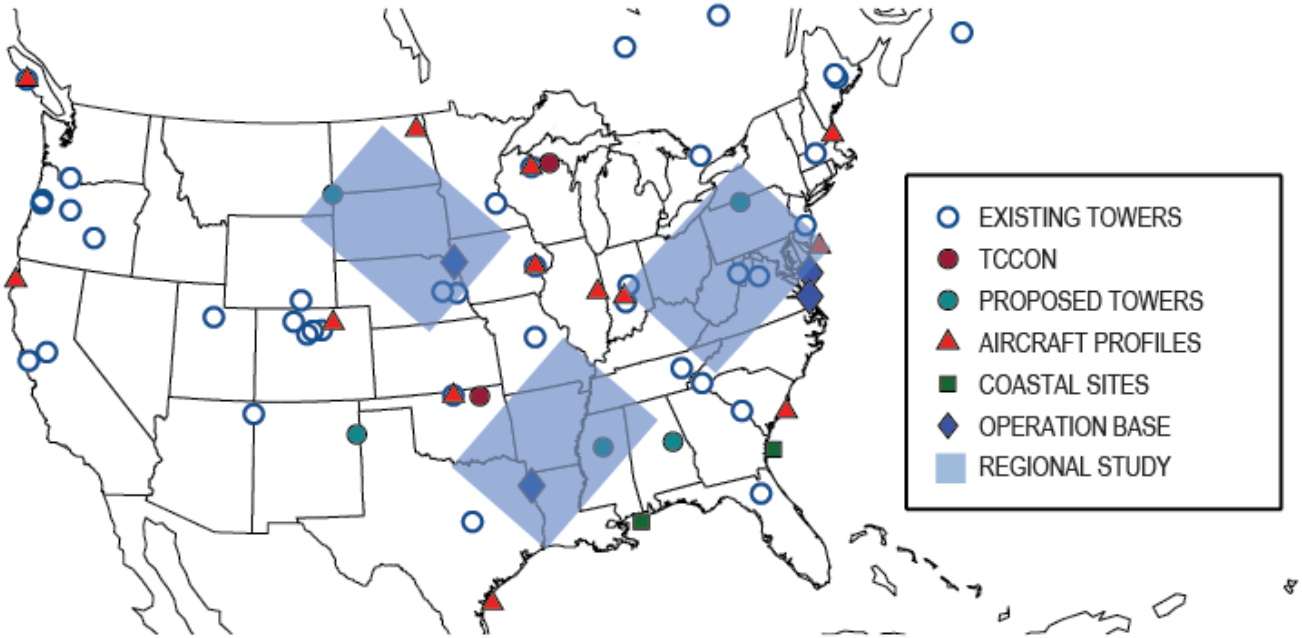
In-Situ Sensors (Ground Towers):

Picarro (Pennsylvania State University):

- In situ measurements of CO_2 and CH_4

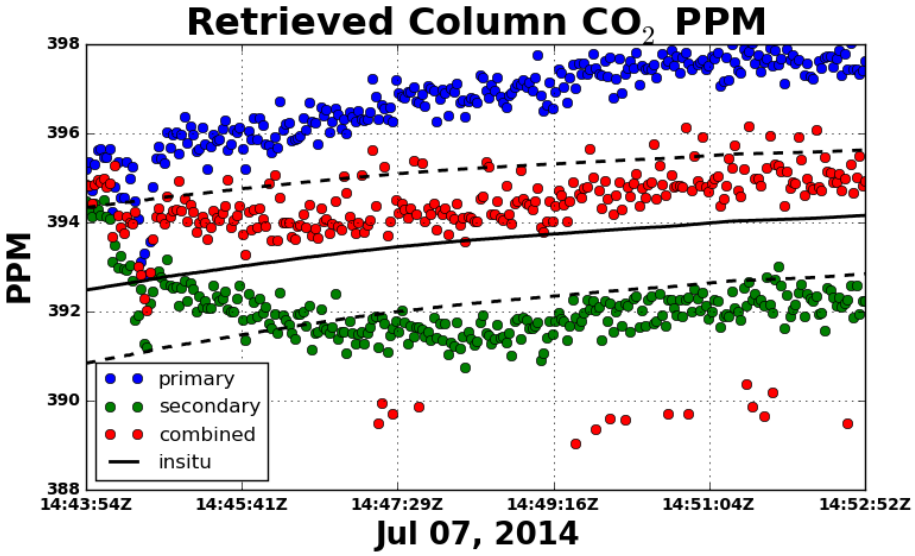
ACT-America data are collected in three regions across the eastern United States:

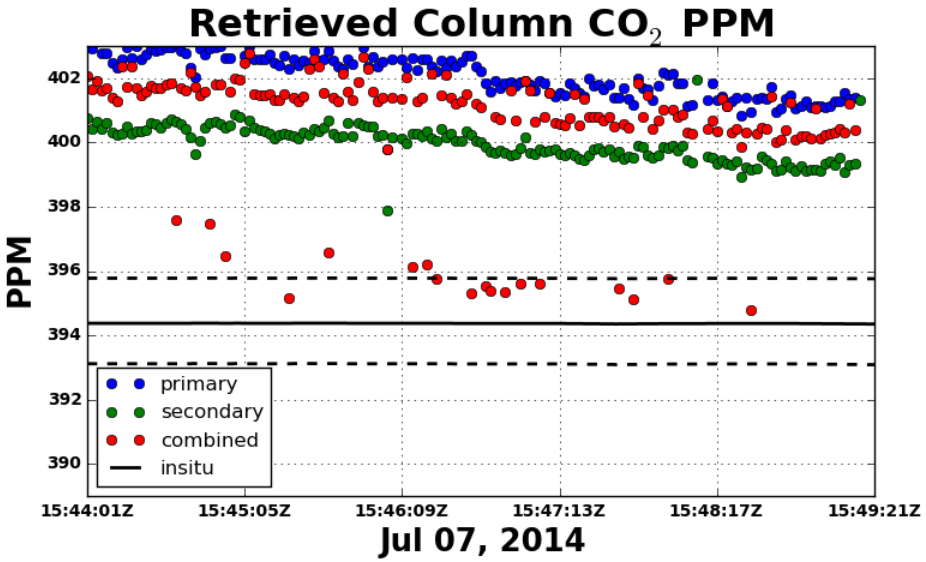
- Five, six-week campaigns over 3 years, covering each season and summer twice
- 2 aircraft:
  - C-130 (Wallops)
  - UC-12 (Langley)
- 2 weeks in each region (Wallops/Langley, Sioux City, and Shreveport)

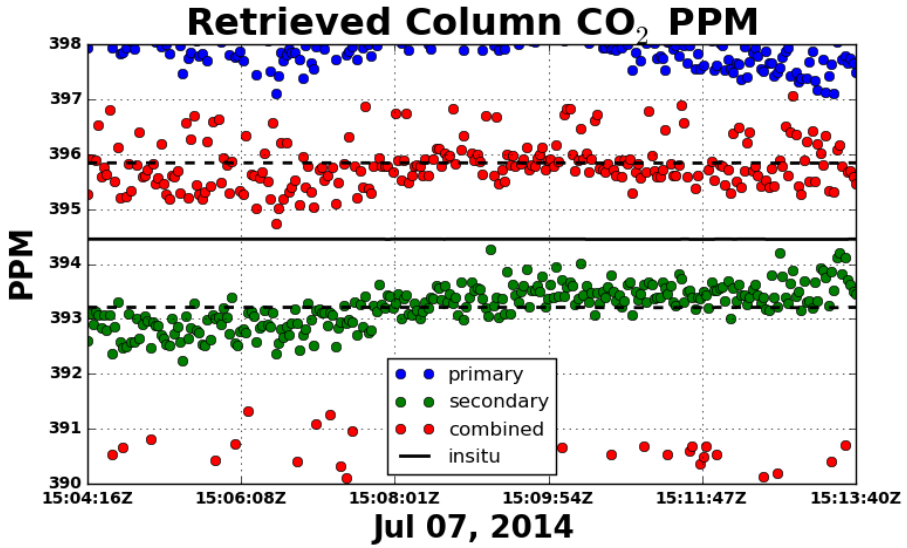


Fall 2015	Win 2016	Spr 2016	Sum 2016	Fall 2016	Win 2017	Spr 2017	Sum 2017	Fall 2017	Win 2018	Spr 2018	Sum 2018	Fall 2018
	X		X			X		X			X	

ACES 2014 Test Flights: Preliminary CO_2 Retrievals over Ocean and Land:

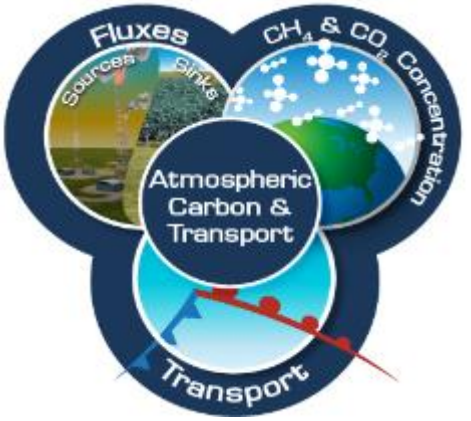






- CO_2 retrieval values (2-s average) are calibrated using primary and secondary offline wavelengths
- Average of in situ data across entire flight (binned by altitude) used for comparisons
- Actual CO_2 number densities likely different far away from spiral point and airport
- Further work is needed to compare directly with data from in situ spirals

Atmospheric Carbon and Transport - Ameri
(ACT-America



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Colorado State University

NASA

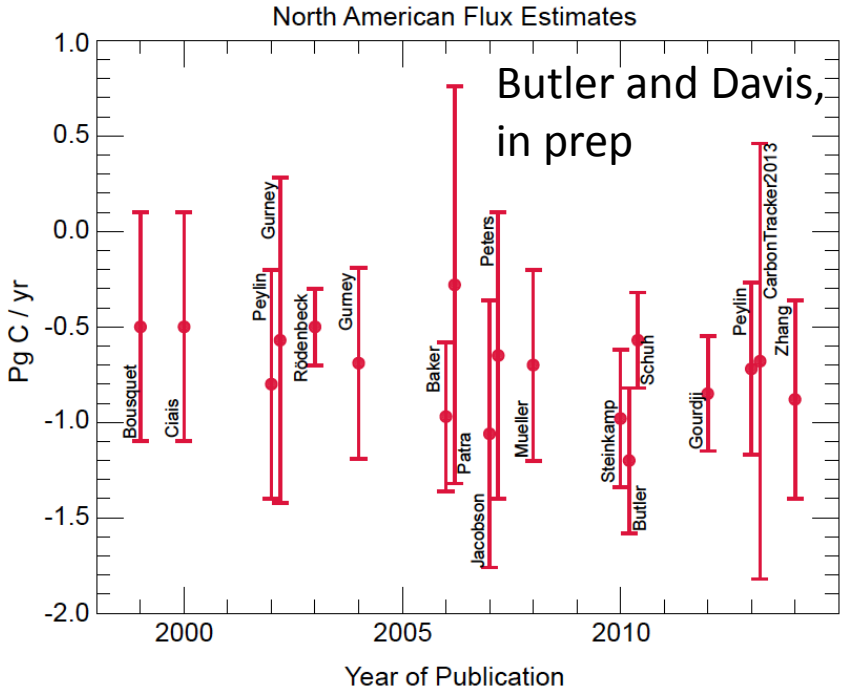
April 2015 SD All-Hands Meeting

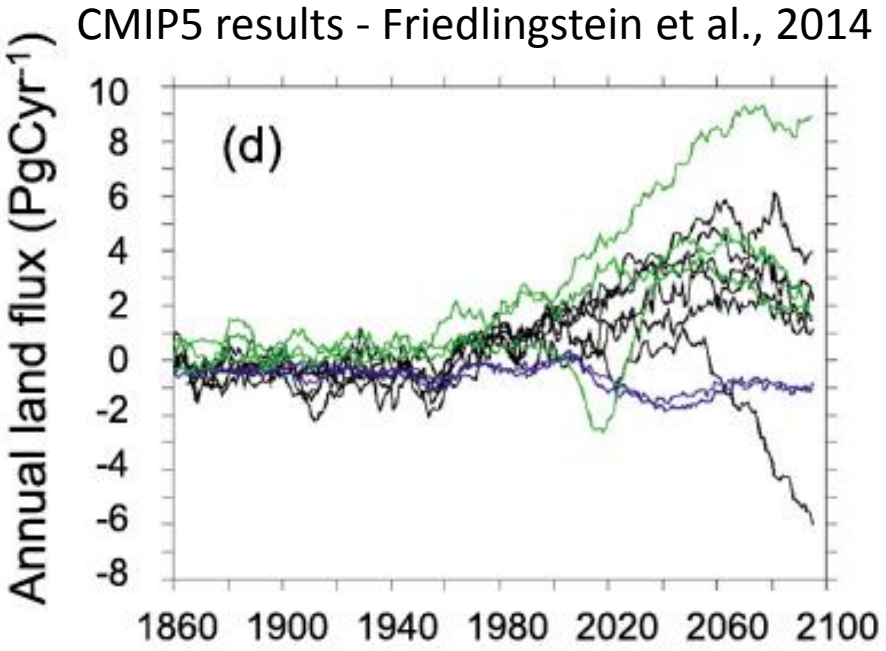
Ken Davis, Principal Investigator
Thomas Lauvaux, Deputy PI
Chris O'Dell, Deputy PI

Bing Lin, Project Scientist
Mike Obland, Project Manager
Byron Meadows, Aircraft Integration/Logistics Manager
Gao Chen, Data Manager
Amin Nehrir, Instrument Scientist
…and many others

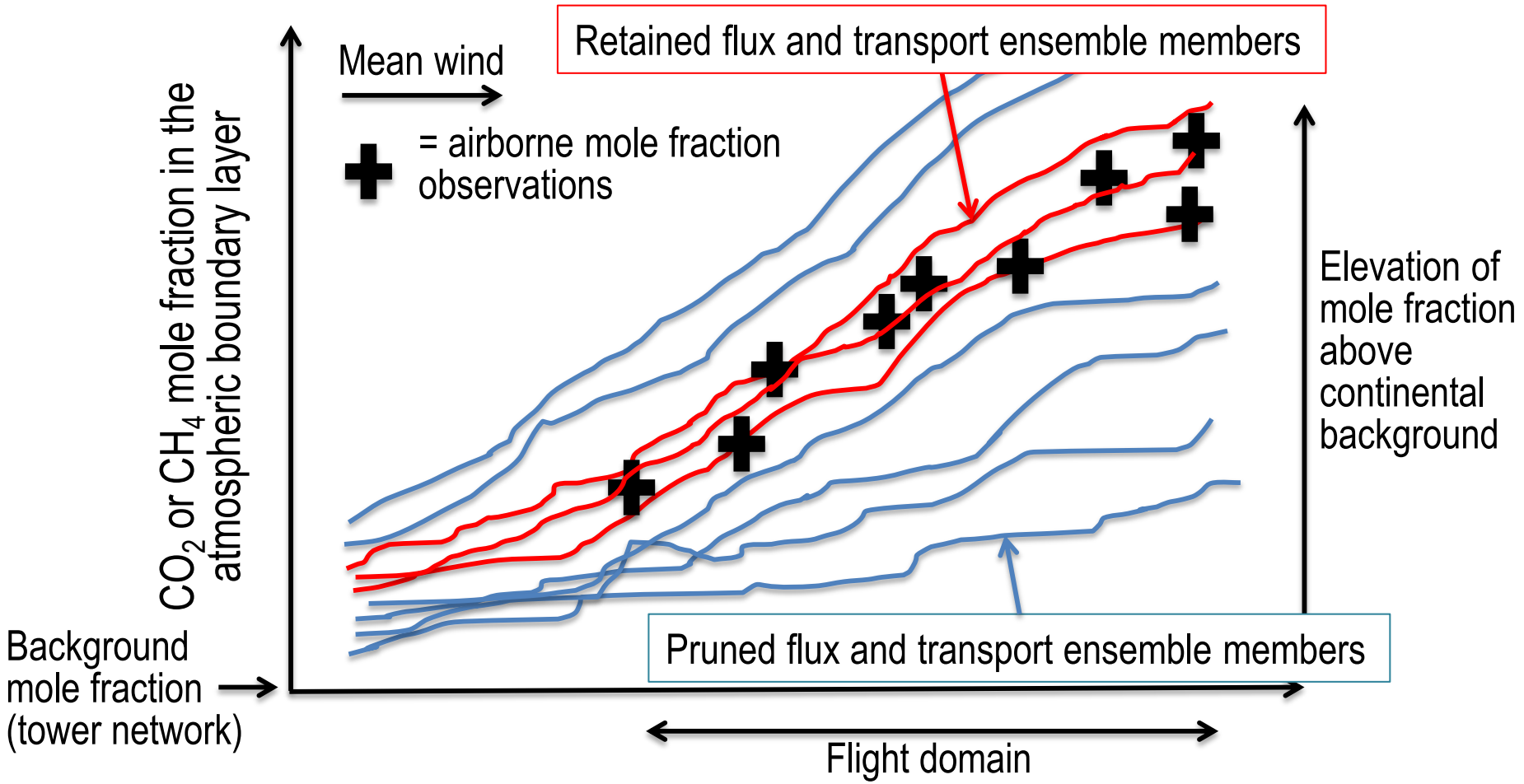
The challenge we are addressing:

- Assertion: Our inability to quantify carbon fluxes with "good" accuracy and precision across regional (larger than a flux tower footprint and smaller than the globe) domains is a *primary* methodological challenge in carbon cycle science today. It hamstrings our ability to address *all other* terrestrial carbon cycle science questions.





Simplified vision of model (flux and transport) ensemble pruning using airborne observations:



Pruned ensembles lead to more accurate and precise flux inversions using long-term GHG data (towers, flasks, satellite, NOAA airborne profiling.

ACES Scientific Motivation

The **ASCENDS CarbonHawk Experiment Simulator (ACES)** is an Instrument Incubator Program (IIP) project that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios from space in support of the ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons) Decadal Survey mission:

- Passive satellite measurements cannot make retrievals of CO_2 column densities to the surface at night, at high latitudes (i.e. northern Europe during winter and over the poles), and through cirrus clouds, high optical depth aerosols, or in presence of scattered clouds.
- Active measurements using lidars do not have these limitations, and they can therefore fill these data gaps and aid in the refinement and understanding of the global carbon cycle budget.

Technology Challenges

ACES is advancing 4 key technology areas:

(1) Enable development of more advanced modulation waveforms with improved detector subsystem

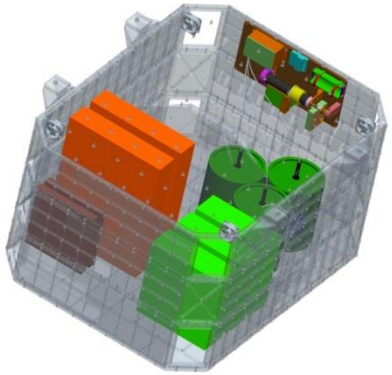
(2) Increase transmit power and efficiency for CO_2 measurements at 1.57 microns using commercial amplifiers with stable, tunable laser-line locking system

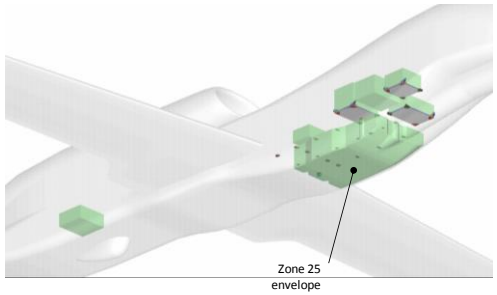
(3) Demonstrate column CO_2 retrievals with alignment of multiple laser beams transmitting simultaneously in the far-field for scalability to space

(4) Continue refining CO_2 column retrieval algorithms in the presence of low optical depth clouds and distributed scattering layers (i.e. aerosol layers)

ASCENDS Mission Development

Current





Today: MFLL and ACES instruments in DC-8 racks

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

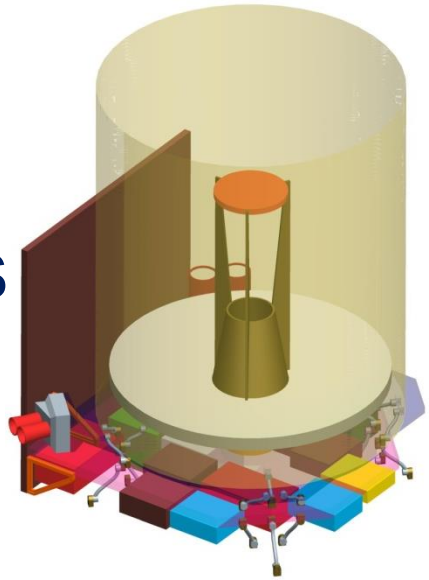
Size = 44” x 34” x 24”
Mass = 317.1 lb

Global Hawk

Future

TBD: ISS Tech Demo?

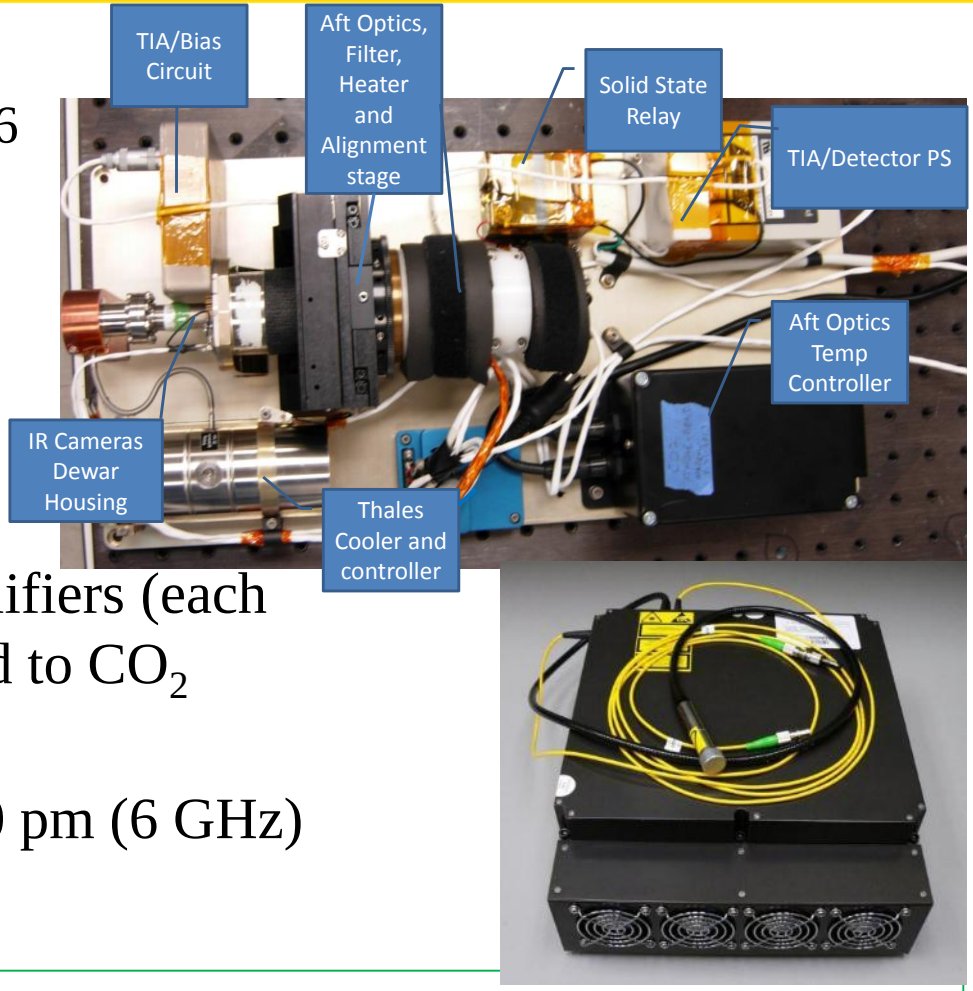
TBD: ASCENDS mission



Transmitters and Telescopes

DRS Technologies HgCdTe array

- ~4.9 MHz bandwidth @ gain of 10^6
- Continuously cooled at 77 K
- NEP: 2.4 fW/Hz$^{1/2}$
- Excess Noise Factor: ~1.1
- Tested with MFLL on DC-8 in 2013

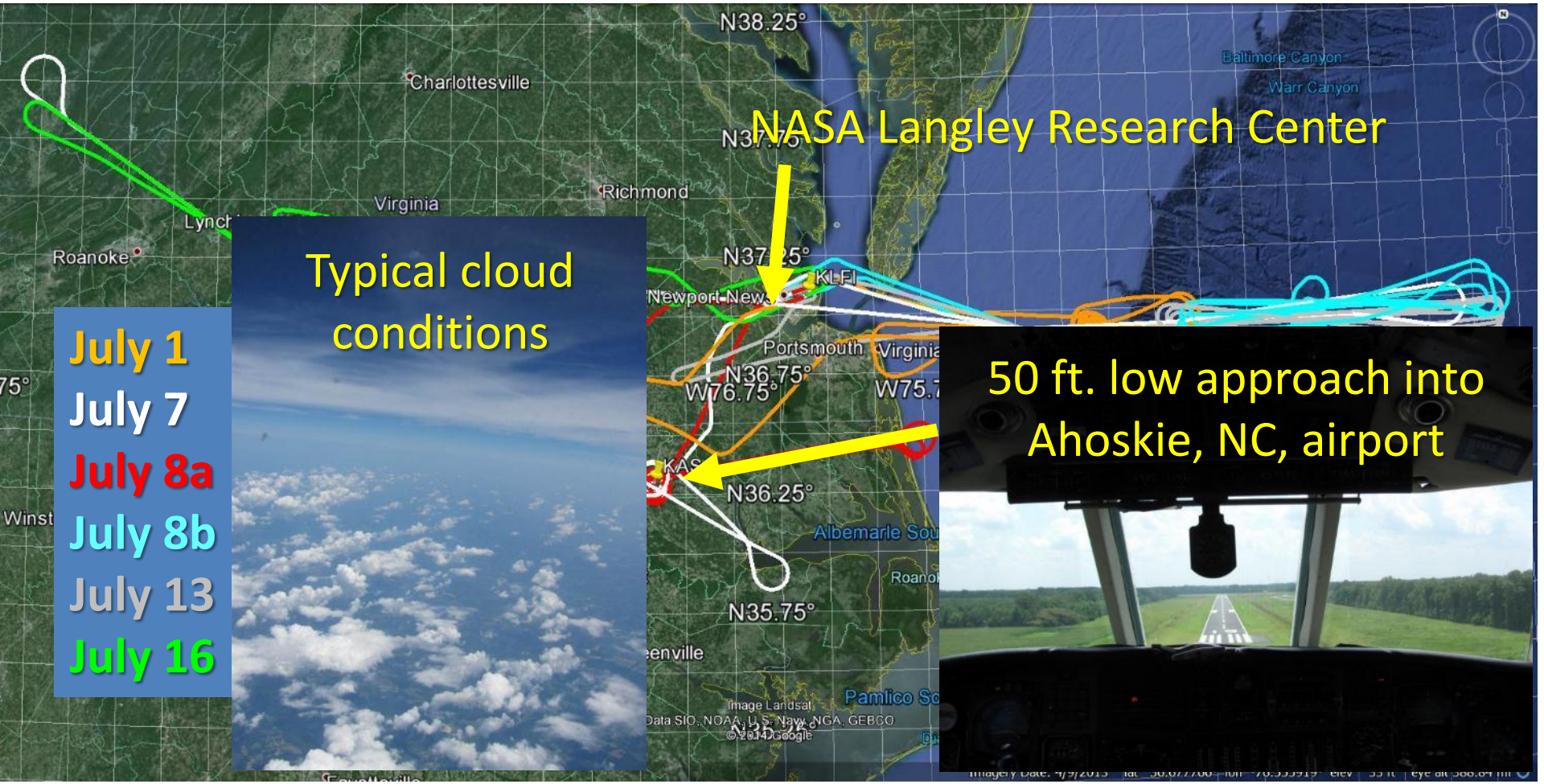


Transmitters:

- Three Erbium-Doped Fiber Amplifiers (each 10 W average, 20 W peak) locked to CO_2 absorption line (1.57 microns)
- Wavelength tunable within +/- 50 pm (6 GHz) from line center

Combination of low-noise detector, higher power transmitters, and larger collection apertures improves signal-to-noise ratio; increased bandwidth allows for use of more advanced modulation waveforms.

Flight Summary: 17.4 flight hours



Data recorded at multiple altitudes over land and ocean surfaces with and without intervening clouds.