Technology Advancement for Active Remote Sensing of Carbon Dioxide from Space using the ASCENDS CarbonHawk Experiment Simulator (ACES)

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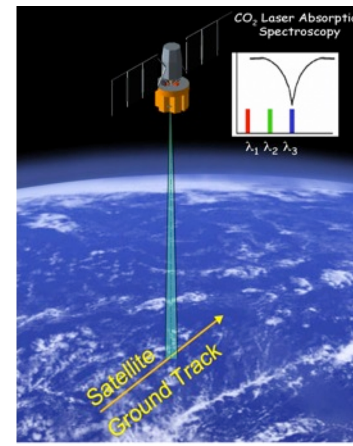

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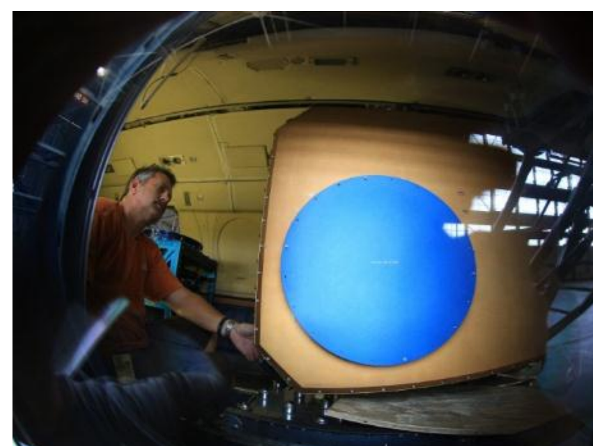
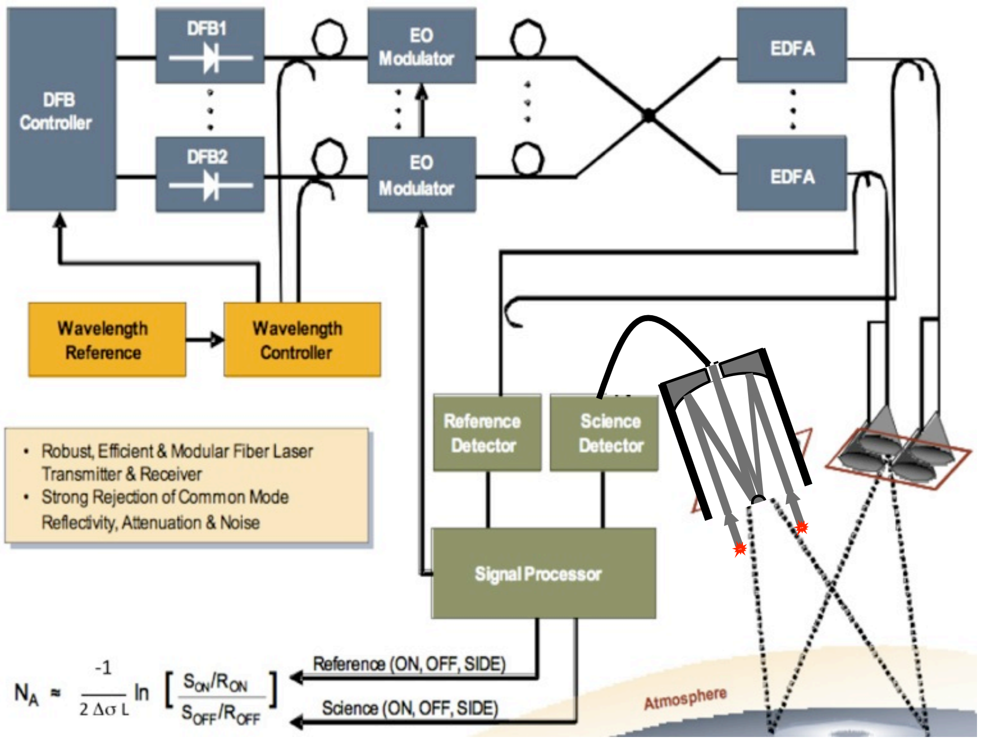


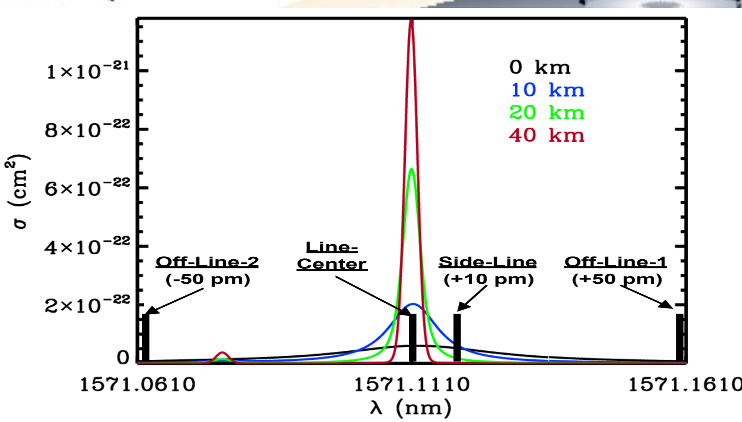
ACES Scientific Motivation

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 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.

Multifunctional Fiber Laser Lidar (MFLL) 1.57-μm CO_2 Measurement Architecture

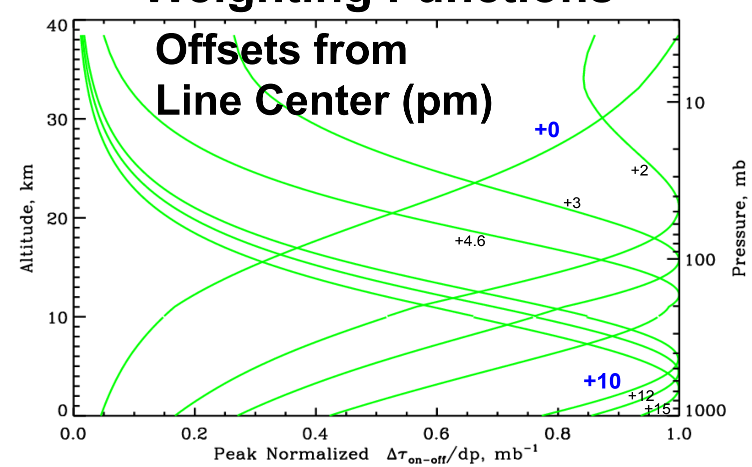




– Simultaneously transmits two wavelengths (l_{on} / l_{off}) reducing atmospheric noise & eliminating surface reflectance variations.

– Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 mm) measurements for deriving mixing ratio (XCO_2).

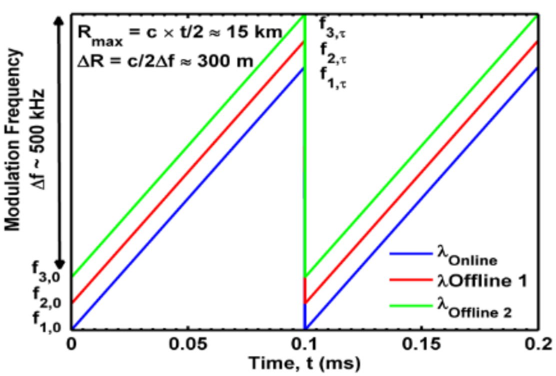
Weighting Functions

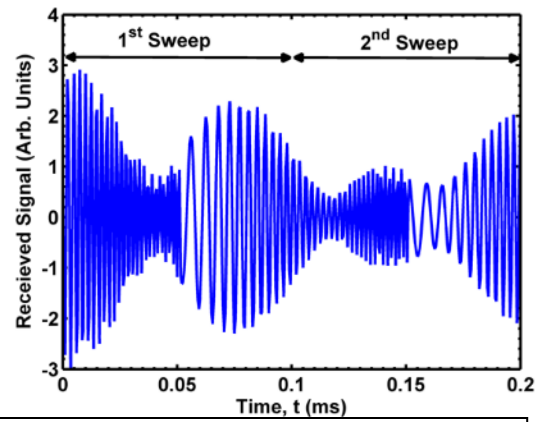


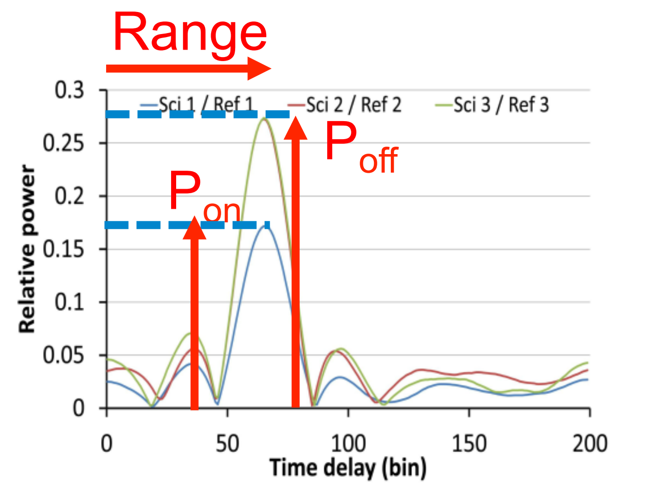
Multifunctional Fiber Laser Lidar (MFLL) Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

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





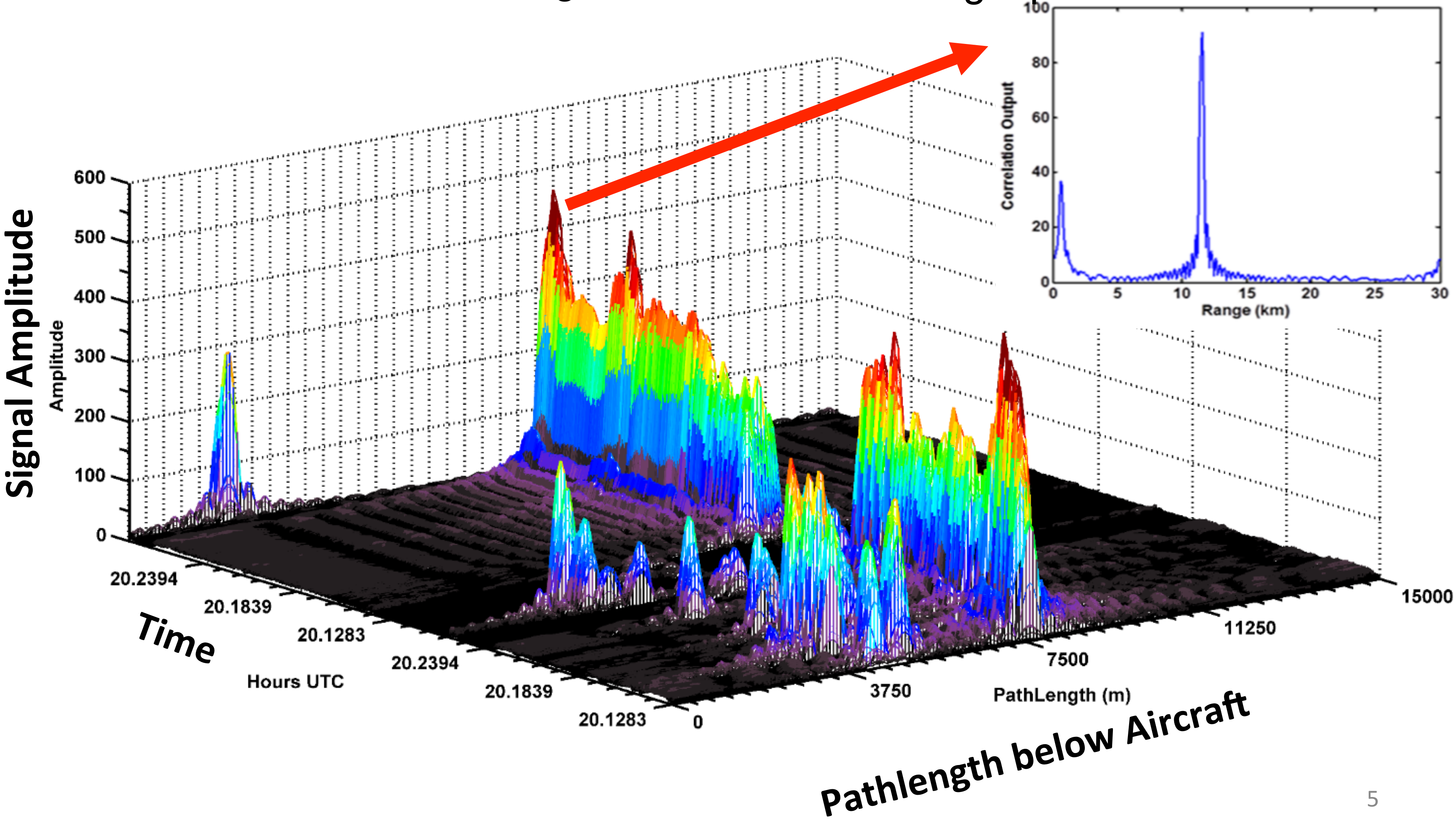


Range-encoded approach for detection and ranging is analogous to mature Frequency-Modulated Continuous Wave (FM-CW) Radar and GPS measurement techniques

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

Multifunctional Fiber Laser Lidar (MFLL) Intensity-Modulated Continuous-Wave (IM-CW) Measurement Technique

Offline backscattered return signal time-series: Single profile from time-series



Technology Challenges

ACES is advancing 4 key technology areas:

(1) Advancement of detector and trans-impedance amplifiers (TIAs)

- Increase detector/TIA electronic bandwidth to enable development of more advanced modulation waveforms
- Package for unattended, high-altitude operations

(2) Development of advanced 1.57 (CO_2) and 1.26 micron (O_2) fiber laser transmitters

- Increase transmit power and efficiency at 1.57 microns
- Develop new, high efficiency fiber laser amplifier at 1.26 microns

(3) Simultaneous operation of multiple transmitter and multiple telescope-apertures

- Demonstrate column CO_2 retrievals with alignment of multiple laser beams transmitting simultaneously in the far-field
- Evaluate performance of three compact apertures vs. single larger aperture

(4) Development of advanced cloud/aerosol discrimination algorithms

- Advance algorithms to mitigate effects of low optical depth clouds and distributed scattering layers (i.e. aerosol layers) on the CO_2 column retrievals

Project Overview

ACES concept demonstration strategy:

- Detector/TIA advancement completed in January, 2013
  - Detector subsystem completed first test flights on the DC-8 with the MFLL instrument in February/March, 2013

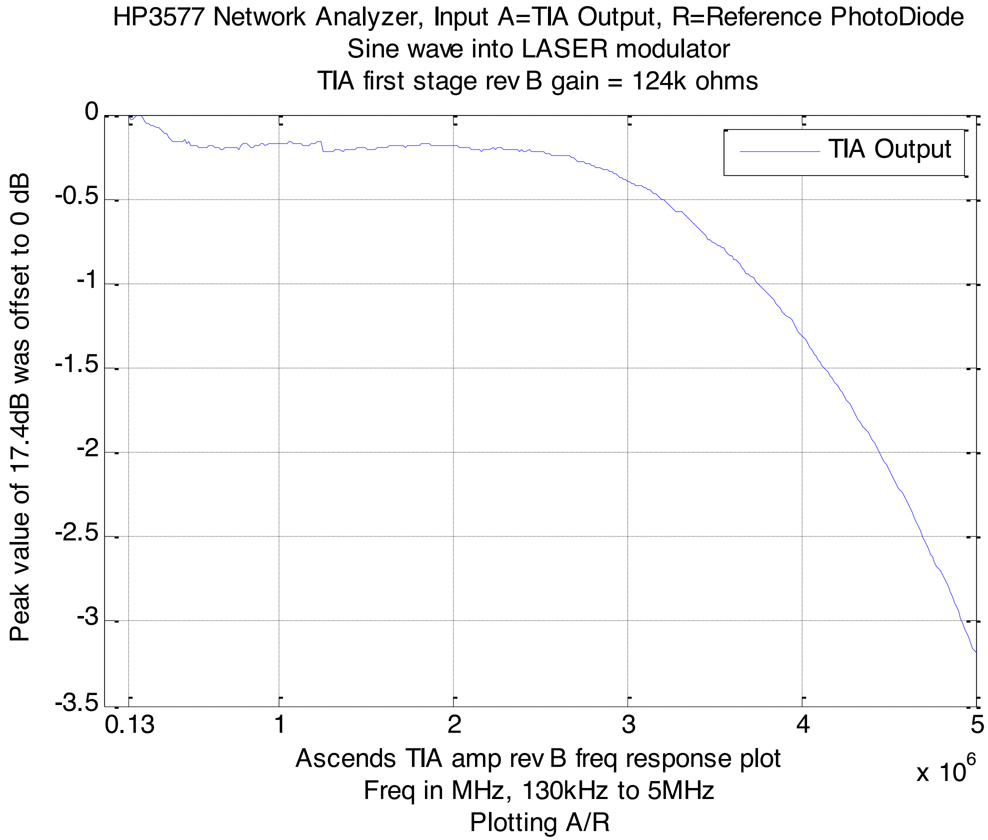
- Laser transmitter advancement and all other subsystems completed by February, 2014
  - Ground tests of fully integrated system completed at NASA Langley laser range facility March-May, 2014

- Flight tests of fully integrated system completed on the HU-25 in July, 2014

Detector Subsystem

- Exelis/LaRC fully characterized and integrated super pixel detector (8x8 array) from DRS Technologies into tactical dewar and developed custom TIA
- Criteria for I_{dark} < 40 pA @ -12V (internal avalanche photodiode (APD) gain of 1080) yields map with 59 good diodes – diodes stitched together to form single mega pixel

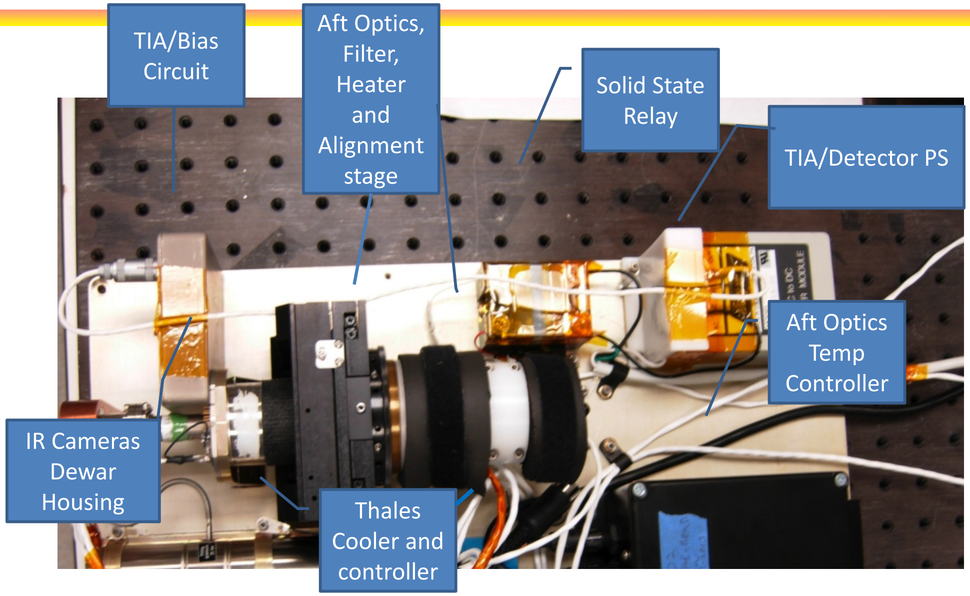
- Detector subsystem performance near original goal of 5 MHz: 3 dB point measured bandwidth is ~4.9 MHz @ gain of 10^6
- NEP: 2.4 $fW/Hz^{1/2}$
- Excess Noise Factor: ~1.1

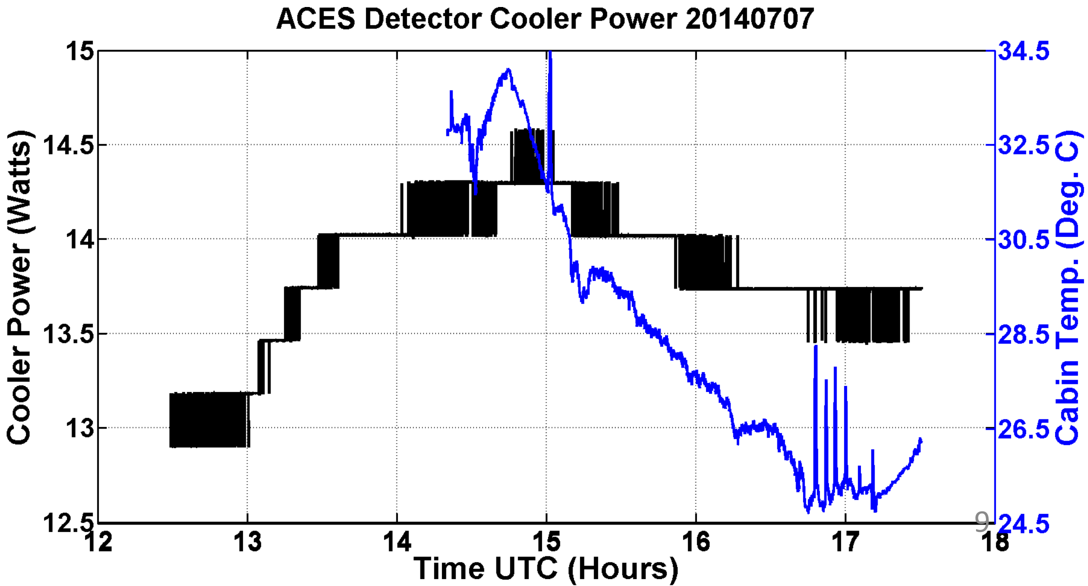


Detector Subsystem

Detector installed in tactical dewar to allow for unattended operations

- Continuously cooled at 77 K (selectable 60 K to 100 K)
- Complete detector subsystem is shown, including detector, dewar, cooler, optical interface, bandpass filter, TIA, thermal control, and power supplies.





Transmitters

CO_2 (1.57 microns):

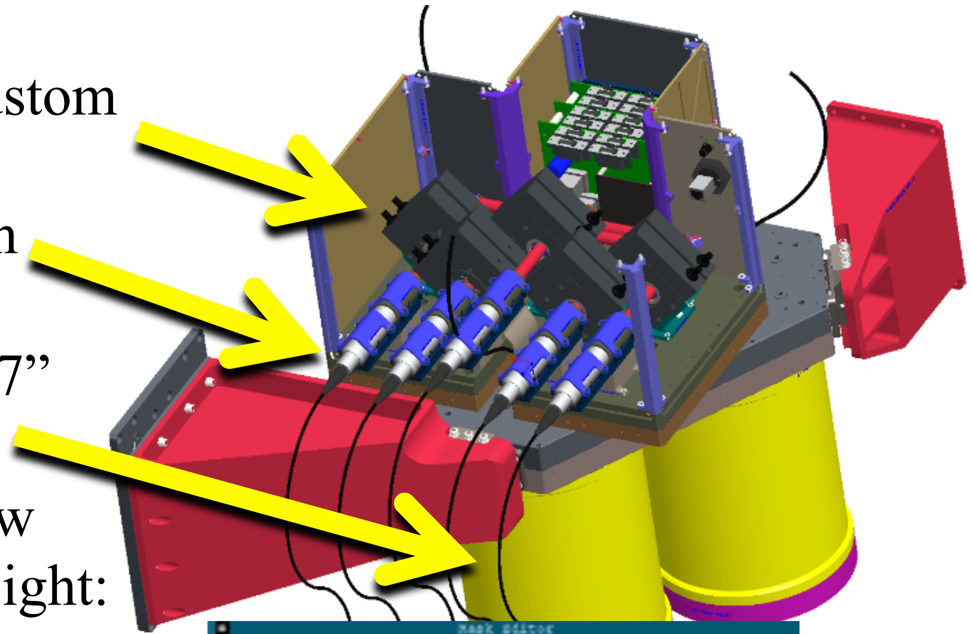
- Three fiber-coupled distributed feedback (DFB) seed lasers
- CO_2 absorption cell and Pound-Drever-Hall (PDH) technique for locking
- Three Erbium-Doped Fiber Amplifiers (each 10 W average, 20 W peak) – 3 transmitted beams
- Wavelength tunable within +/- 50 pm (6 GHz) from line center
- Wavelength stability: locked within <0.1 pm (<12 MHz); tests limited by wavemeter resolution

O_2 (1.26 microns):

- Two seed DFB lasers
- One amplifier – Exelis Advanced Component Technologies (ACT) project (~3 W average, 6 W peak) – 2 transmitted beams

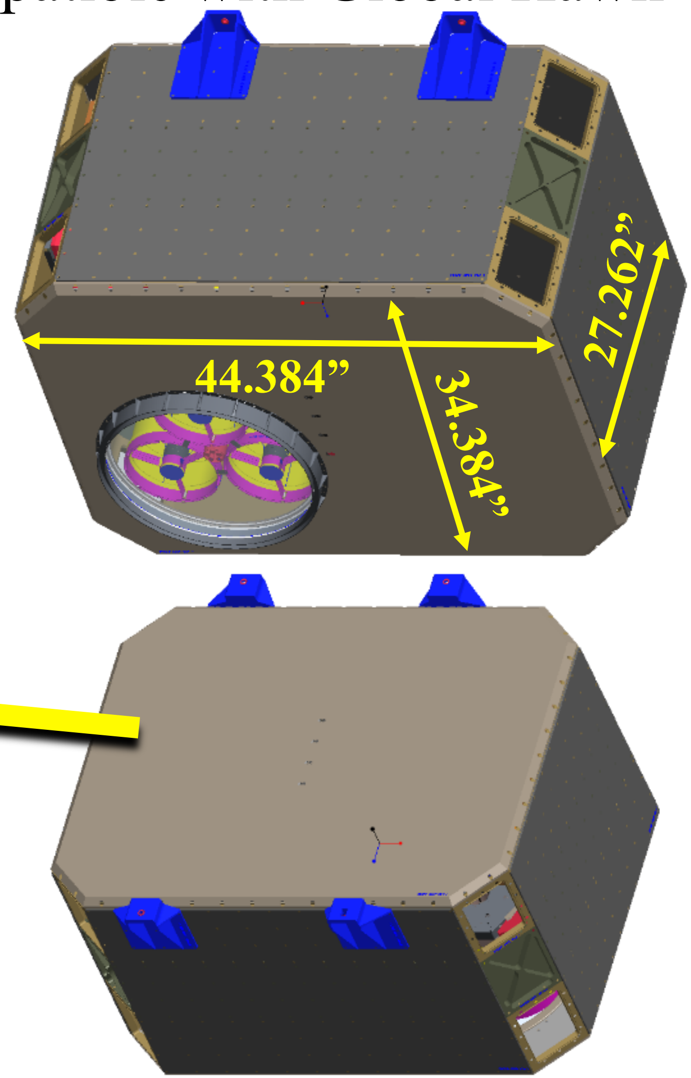
Telescopes and Beam Steering

- Risley prism beam steering using custom beam steering boards and software
- Custom collimator mounts and beam expanders
- F4.54 Ritchey-Chrétien telescopes (7” diameters)
- Test data and lab measurements show specifications met for focus & boresight:
  - Boresight spec: aligned to within 25 microradians
  - Boresight measured: aligned to < 2.5 microradians
- Beam Divergence: ~350 microradians
- Telescope FOV: 496 microradians



Environmental Enclosure Box

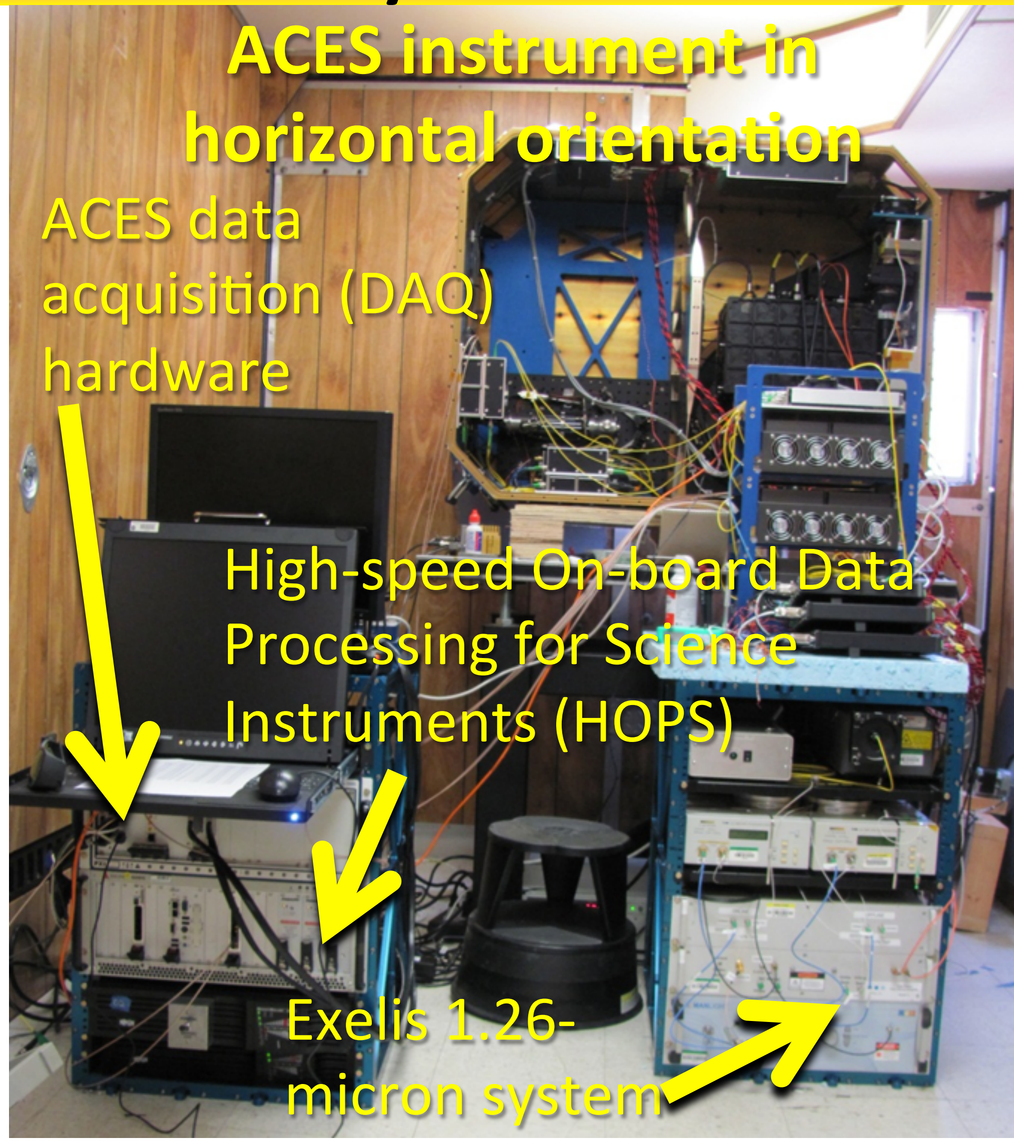
- Environmental enclosure is compatible with Global Hawk UAV



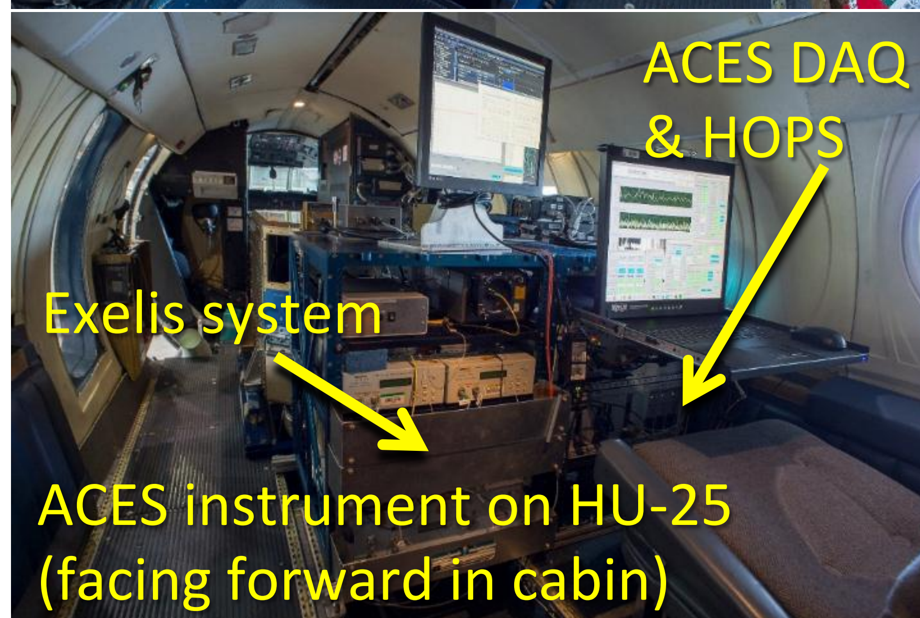
Testing at Langley Ground Range Facility

Fully integrated instrument tested at ground range facility:

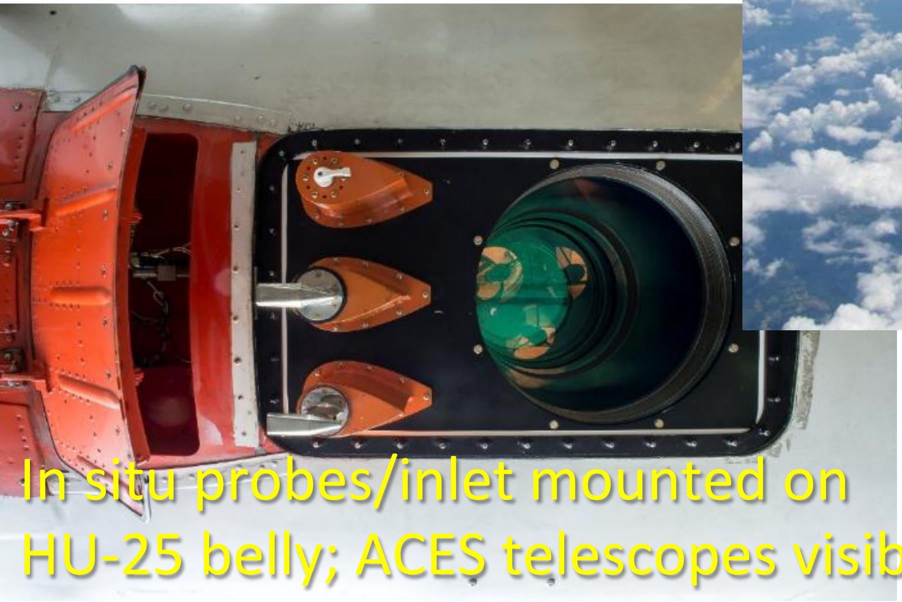
- Various targets with known reflectances & ranges used to calibrate ACES signals and simulate intervening thin clouds along 860 meter range
- Tests used to optimize and understand performance of multiple transmitters, multiple telescopes, and data acquisition hardware and software
- Test results indicated ACES ready for flight tests



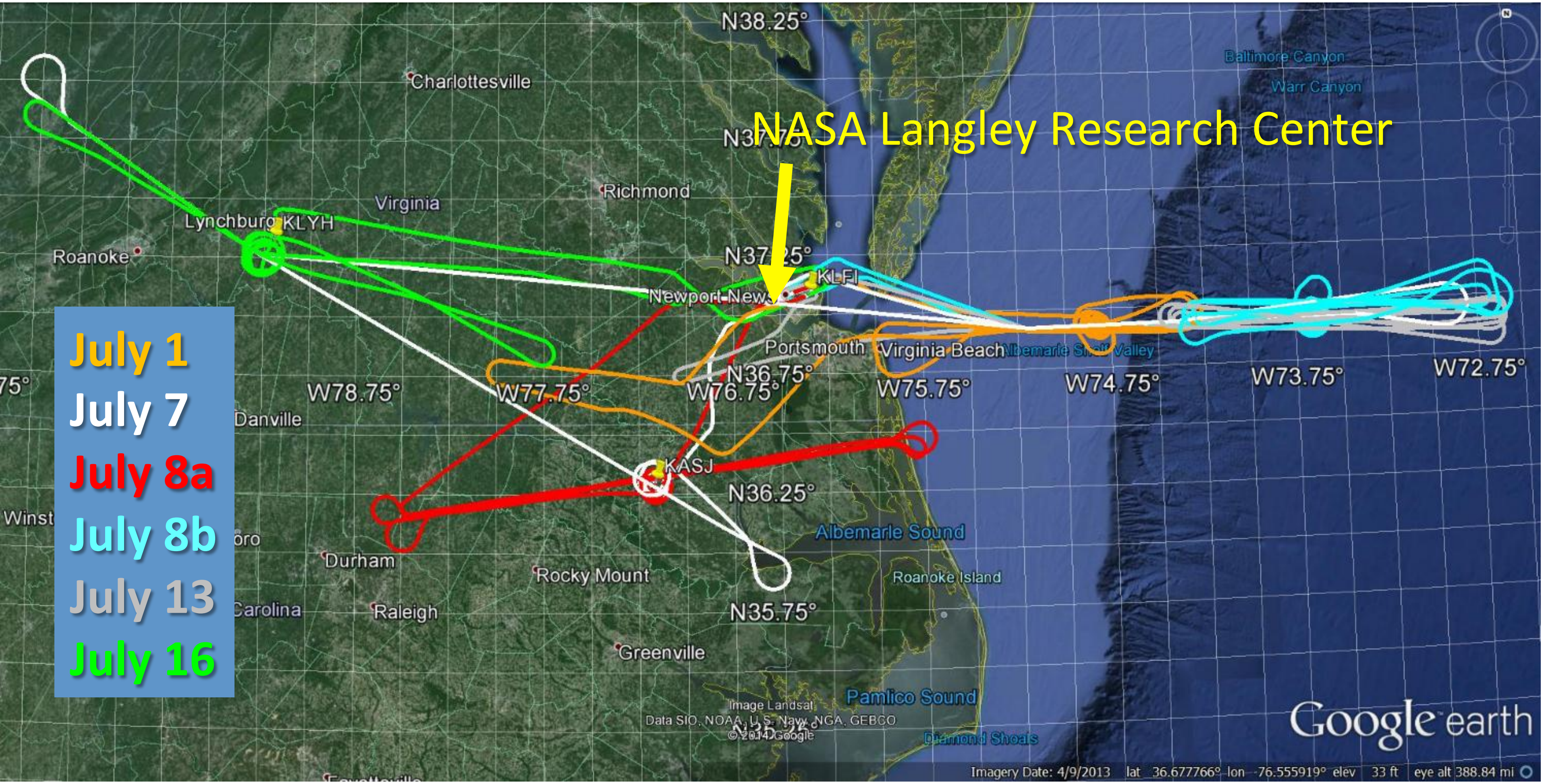
Integration on NASA HU-25



In situ instruments and sampling approach



Flight Summary: 17.4 flight hours



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

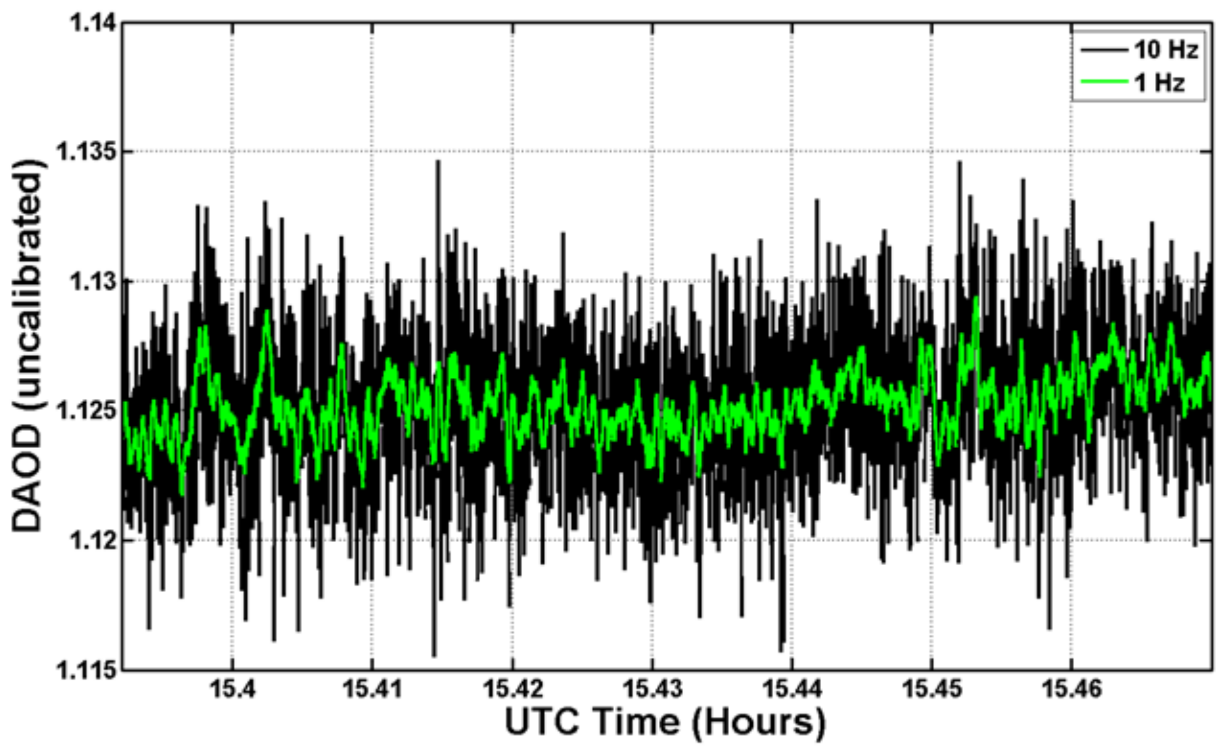
Flight Summary: 17.4 flight hours

Flight	Objectives	Land	Ocean	Spiral	Altitude (ft)
7/1	System checkout (aircraft heating issues)	Y – used for prelim. alignment; mostly cloudy	Y	Y - ocean	29K
7/7	System checkout (aircraft heating issues fixed)	Y – scattered small cumulus clouds	Y	Y – Ahoskie, NC	30K
7/8	Altitude dependence of signals	Y	N	Y – Ahoskie, NC	20K, 25K, 28K
7/8	Multiple transmitters, multiple modulations, SNR	N	Y	Y – ocean	35K, 30K
7/13	Multiple transmitters, sideline wavelengths	Y	Y	Y – ocean	30K, 25K
7/16	Cloud discrimination	Y – multiple cloud layers	N	Y – Lynchburg, VA	35K

Preliminary Results: Signal-to-Noise Ratios

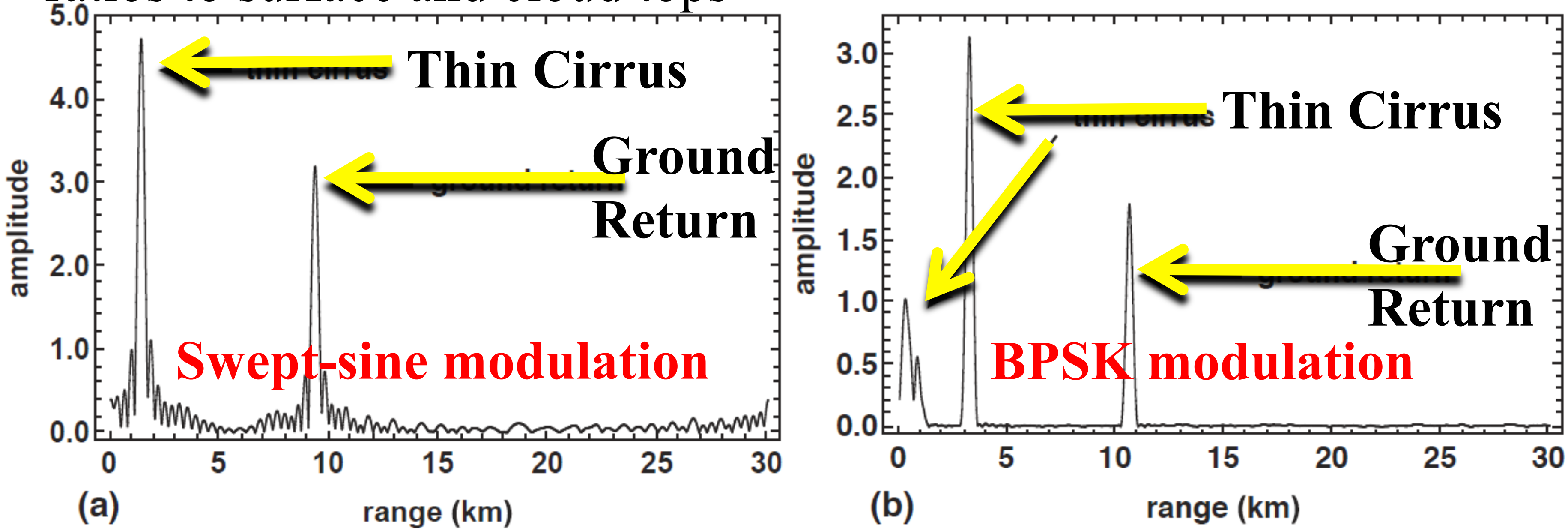
- 14x increase in power aperture product over MFLL is observed and consistent with simulated returns over ocean and vegetated surfaces

07 Jul 2014 ACES flight over Chesapeake Bay: 10 Hz SNR = 403 (~0.9 ppmv)



Preliminary Results: Ranging

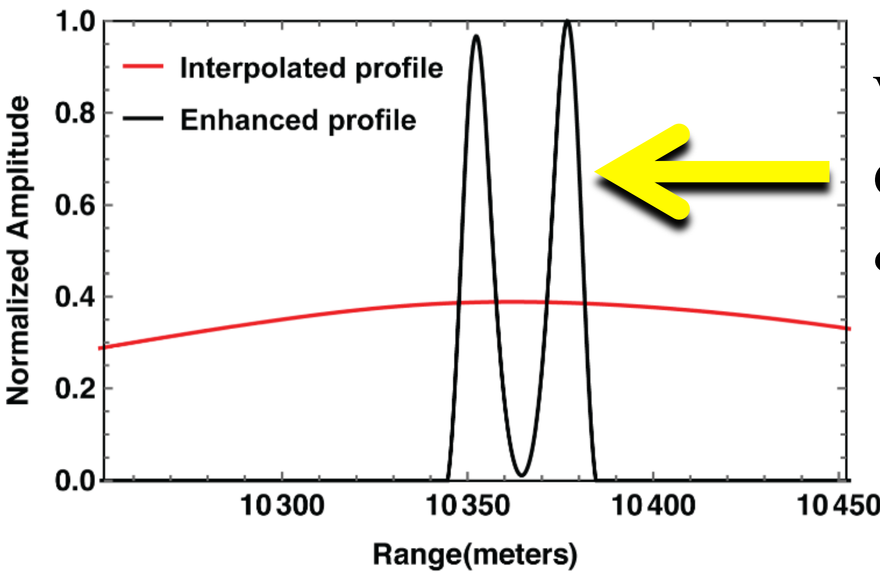
- IM-CW technique can measure backscattered returns through optically thin clouds, allowing for retrievals of column CO_2 mixing ratios to surface and cloud tops



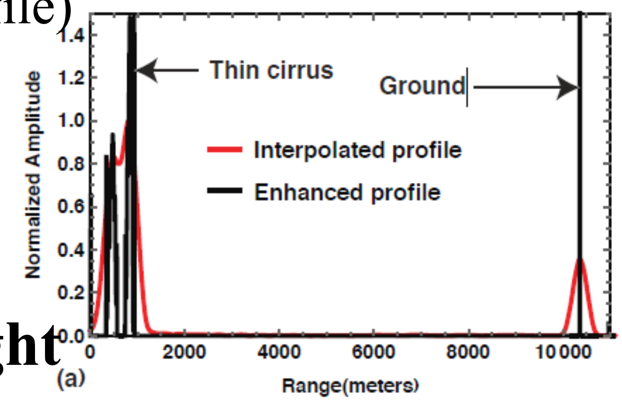
- ACES team studied hardware and mathematical trades of different modulation techniques
- Different modulations tested on different HU-25 flight legs for comparison
- Binary Phase-Shift Keying (BPSK) modulations eliminate sidelobes and increase measurement accuracies

Preliminary Results: Ranging

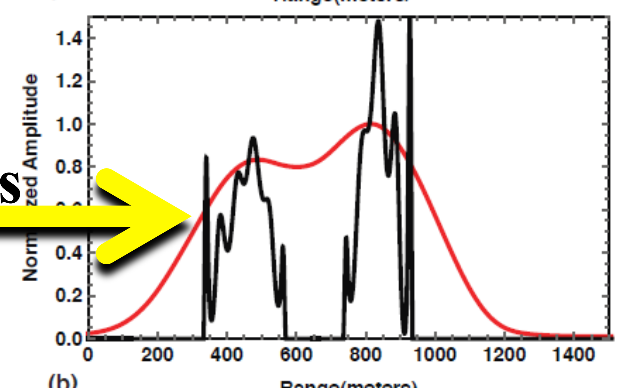
- Advanced deconvolution techniques resolve cloud and forest features:
  - Fourier transform reordering (**Interpolated** profile)
  - Richardson-Lucy deconvolution (**Enhanced** profile)



Vegetation canopy height & thickness



Thin Cirrus Structure



Campbell, J. F., et al., "Binary Phase Shift Keying on Orthogonal Carriers for Multi-Channel CO2 Absorption Measurements in the Presence of Thin Clouds", Optics Express, 22, DOI:10.1364/OE.22.0A1634, A1634 – A1640, 2014.

Campbell, J. F., et al., "Super-resolution technique for CW lidar using Fourier transform reordering and Richardson-Lucy deconvolution," submitted to Optics Letters, 2014.

Future Directions

- Continue data analysis to fully quantify instrument performance
- Continue flight testing of new modulation algorithms, measurement techniques, 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
  - Example: Small Business Innovation Research project with Fibertek for laser amplifier advancement

Summary

- The ACES team is advancing technologies critical to making CO_2 column mixing ratio measurements from space.
- ACES recorded meaningful data at multiple altitudes over land and ocean surfaces, with and without intervening clouds during its first test flights.
- Preliminary data show that the system performed reliably across all flight situations, consistent with performance simulations.
- Data analysis and technology advancement efforts are continuing.

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- The authors wish to thank the many contributions to this work from the rest of the ACES team at Exelis (Douglas McGregor, Nathan Blume, Michael Braun, Mark Shure, Mark Neal, Joe Bender, Steve Horney), Welch Mechanical Designs (Wayne Welch), Oklahoma University (Berrien Moore, Sean Crowell), the University of Melbourne (Peter Rayner), NP Photonics (Arturo Chavez-Pirson), NASA Langley (Chuck Antill, Michael Kissam, Melissa Yang, Jim Plant, Yonghoon Choi, Narasimha Prasad, Keith Murray, Tony Notari, Craig Cleckner, John Barrick, Ali Aknan, Janet Dail, Carl Mills, Chris Herdey, Rebecca Stavely, Nick Vitullo, Marie Avery), and the aircraft support teams at Langley Research Center and Armstrong Flight Research Center.

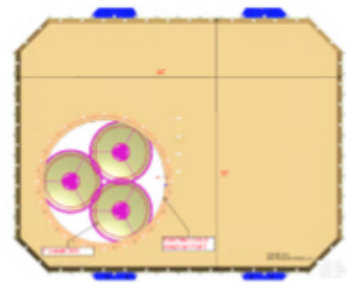
Backup Slides

ASCENDS CarbonHawk Experiment Simulator (ACES)

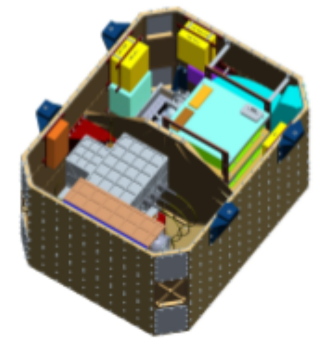
PI: Michael Obland, NASA LaRC

Objective

- Demonstrate measurements of column CO_2 mixing ratios with a high-altitude airborne instrument architecture scalable to the ASCENDS mission requirements
  - Technologies include a high bandwidth detector, a multi-aperture telescope, advanced algorithms for cloud/aerosol discrimination, and high efficiency CO_2 and O_2 transmitters .
- Deploy instruments on the DC-8 and Hu-25 aircraft to demonstrate discrimination of surface returns from clouds and aerosols, derivation of ranging information from the continuous wave laser system, and measurements of column CO_2 mixing ratios



Multiple telescope design addresses technical performance and affordability



Compact transmitter and detector subsystems housed in a Global Hawk-compatible enclosure

Approach

- Improve existing CO_2 measurement capability by:
  - Advancing detector, receiver, and transmitter components for higher signal to noise performance for higher altitude operation
  - Improving spectroscopic models to support wavelength optimization
  - Advancing techniques and algorithms to allow for cloud/aerosol discrimination and ranging
- Conduct ground and flight tests of the instrument components and subsystems to quantify instrument performance

Co-Is/Partners: Ed Browell, SSAI; Jeremy Dobler, ITT Exelis; Berrien Moore, Univ. of Oklahoma; Scott Zaccheo, AER

Key Milestones

• Complete requirements, architecture, design	11/11
• Complete detector integration	07/12
• Complete detector subsystem	12/12
• Validate and test detector on DC-8	03/13
• Deliver telescope subsystem	09/13
• Complete CO_2 transmitter subsystem	08/13
• Complete O_2 transmitter subsystem	08/13
• Validate and test on Hu-25	07/14

TRL_{in} = 3 $TRL_{current}$ = 5

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