Advancements towards active remote sensing of CO_2 from space using Intensity-Modulated, Continuous-Wave (IM-CW) lidar

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ABSTRACT

The Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) CarbonHawk Experiment Simulator (ACES) is a NASA Langley Research Center instrument funded by NASA's Science Mission Directorate that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios in support of the NASA ASCENDS mission. The ACES instrument, an Intensity-Modulated Continuous-Wave (IM-CW) lidar, was designed for high-altitude aircraft operations and can be directly applied to space instrumentation to meet the ASCENDS mission requirements. The ACES design demonstrates advanced technologies critical for developing an airborne simulator and spaceborne instrument with lower platform consumption of size, mass, and power, and with improved performance.

ACES recently flew on the NASA DC-8 aircraft during the 2017 NASA ASCENDS/Arctic-Boreal Vulnerability Experiment (ABoVE) airborne measurement campaign to test ASCENDS-related technologies in the challenging Arctic environment. Data were collected over a wide variety of surface reflectivities, terrain, and atmospheric conditions during the campaign's 8 research flights. ACES also flew during the 2017 and 2018 Atmospheric Carbon and Transport – America (ACT-America) Earth Venture Suborbital -2 (EVS-2) campaigns along with the primary ACT-America CO_2 lidar, Harris Corporation's Multi-Frequency Fiber Laser Lidar (MFLL). Regional CO_2 distributions of the lower atmosphere were observed from the C-130 aircraft during the ACT-America campaigns in support of ACT-America's science objectives. The airborne lidars provide unique data that complement the more traditional in situ sensors. This presentation shows the applications of CO_2 lidars in meeting these science needs from airborne platforms and an eventual spacecraft.

Keywords: Carbon dioxide, remote sensing, intensity-modulated continuous-wave lidar, ABoVE, ACT-America

1. INTRODUCTION

The ability to measure column-averaged carbon dioxide (CO_2) mixing ratios in regions that are currently difficult or impossible for space-based passive instruments (e.g. OCO-2, GOSAT), such as in high latitudes, in the presence of clouds, and at night, is critical for improving our understanding of global sources and sinks of CO_2. To address this critical need, the U.S. National Research Council's report "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" identified the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) as a space mission necessary to reduce current gaps in our understanding of the global carbon cycle[1]. Several instrument candidates have been built and tested (see, for example, Dobler, et al., 2013[2], Abshire, et al., 2018[3] and Menzies, et al., 2014[4]). The ASCENDS CarbonHawk Experiment Simulator (ACES) is a NASA Langley Research Center instrument funded by NASA's Science Mission Directorate that leverages the measurement techniques and instrument architecture of the Harris Corporation's Multifunctional Fiber Laser Lidar (MFLL) instrument[2] that has flown on multiple measurement campaigns. ACES seeks to advance technologies critical to measuring atmospheric column CO_2 mixing ratios in support of the NASA ASCENDS mission. The ACES design demonstrates advances in: (1) multiple high-efficiency, high-power Erbium-Doped Fiber Amplifiers (EDFAs); (2) enhanced power-aperture product through the use and operation of multiple co-aligned laser transmitters and a multi-aperture telescope design; (3) high-

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bandwidth, low-noise HgCdTe detector and transimpedence amplifier (TIA) subsystem capable of long-duration operation, and (4) advanced algorithms for cloud and aerosol discrimination. The ACES instrument, an Intensity-Modulated Continuous-Wave (IM-CW) lidar, was designed for high-altitude aircraft operations and can be directly applied to space instrumentation to meet the ASCENDS mission requirements. These advanced technologies are critical for developing an airborne simulator and spaceborne instrument with lower platform consumption of size, mass, and power, and with improved performance.

ACES flew on the NASA DC-8 aircraft during the 2017 NASA ASCENDS/Arctic-Boreal Vulnerability Experiment (ABoVE) airborne measurement campaign to test ASCENDS-related technologies in the challenging Arctic environment[5]. Data were collected over a wide variety of surface reflectivities, terrain, and atmospheric conditions during the campaign's 8 research flights, with flight tracks shown in Figure 1. Flights were based out of Palmdale, California, USA, and Fairbanks, Alaska, USA.

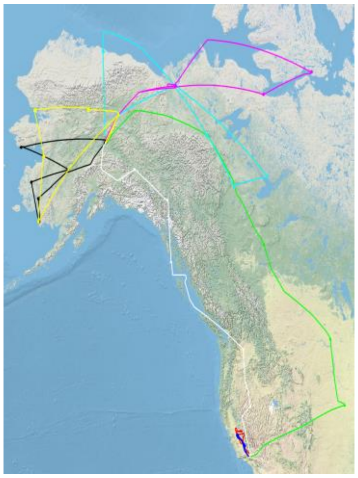

Figure 1. Ground tracks for the 8 research flights of the 2018 ASCENDS/ABoVE flight campaign over Alaska and the Canadian arctic. Flights were based out of Palmdale, California, USA, and Fairbanks, Alaska, USA. Graphic courtesy of Jim Abshire, NASA Goddard Space Flight Center.

Both the MFLL and ACES lidars flew on the NASA C-130 aircraft during recent campaigns for the Atmospheric Carbon and Transport – America (ACT-America) mission[6], with the MFLL as the primary ACT-America CO_2–measurement lidar and ACES as a piggy-back technology demonstration instrument. ACT-America is part of NASA's Earth Venture Suborbital-2 program and is designed to advance society's ability to predict and manage future climate change by enabling policy-relevant quantification of the carbon cycle. ACT-America is enabling and demonstrating a new generation of atmospheric inversion systems for quantifying CO_2 and CH_4 variations via three mission goals: 1) reducing atmospheric transport uncertainties; 2) improving regional-scale estimates of CO_2 and CH_4 fluxes; and 3) evaluating the sensitivity of Orbiting Carbon Observatory-2 (OCO-2)[7, 8] column CO_2 measurements to regional variability in tropospheric CO_2. ACT-America is achieving these goals by deploying airborne and ground-based platforms to obtain data, combining these data sets with data from existing measurement networks, and integrating these data sets with an ensemble of atmospheric inversion systems. Two NASA aircraft are used for this experiment: the C-130 (outfitted with both remote and in situ sensors), and the B-200 (outfitted with a complementary suite of in situ sensors). Simultaneous data collected by in situ instrumentation on the aircraft were used to evaluate the ACES and MFLL measurements of column-integrated CO_2 mixing ratios. Five campaigns, each six weeks in length, are being performed across the eastern half of the United States. Both MFLL and ACES participated in the fourth campaign covering the North America spring season, which finished in May 2018. The 2018 spring measurement campaign comprised 26 research flights and over 100 hours of science data. Aircraft flight tracks for this campaign are shown in Figure 2.

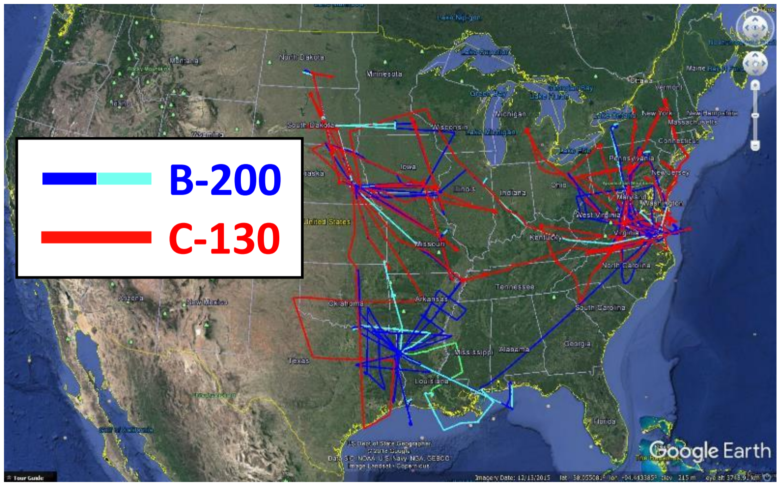

Figure 2. Ground tracks for the 26 research flights of the 2018 ACT-America spring flight campaign over the eastern United States. Flights were based out of Wallops Flight Facility and Langley Research Center in Virginia, Lincoln, Nebraska, and Shreveport, Louisiana. Graphic courtesy of Sandip Pal, Texas Tech University (formerly Pennsylvania State University).

2. INSTRUMENT DESCRIPTIONS

Both MFLL and ACES employ the IM-CW measurement technique, in which unique intensity-modulated, range-encoded waveforms are applied to lasers with wavelengths located on and off of a CO_2 absorption line. These lasers are simultaneously transmitted into the atmosphere, and the online and offline signals are then simultaneously received. A measurement of the correlation between the transmitted and received waveforms provides accurate measurements of range to the scattering surface and an integrated optical depth due to absorption by CO_2 within the measurement column. The scattering surface can be ground terrain, water, or clouds[9]. This approach is analogous to mature frequency-modulated continuous wave radar and GPS measurement techniques.

The transmitter, receiver, and detector subsystems are housed in racks for the MFLL (Figure 3A), and in an environmental enclosure originally built for the Global Hawk aircraft for ACES (Figure 3B). Data acquisition and control hardware is located in electronic racks for both instruments. Basic architecture of the two instruments is similar, with some of the differences described in the sections below.

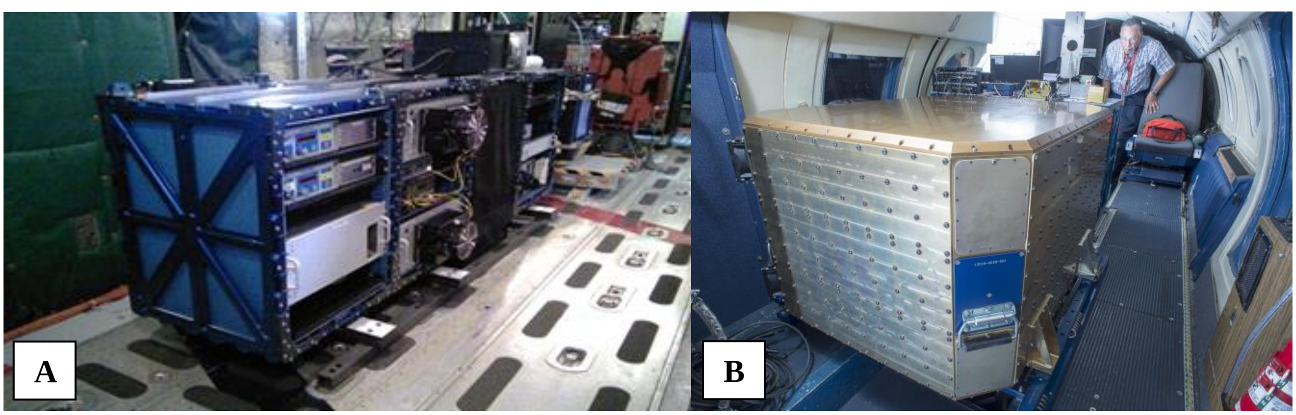

Figure 3. A) The MFLL instrument installed on the NASA C-130 aircraft. B) The ACES instrument installed on the NASA HU-25 aircraft.

2.1 Laser Transmitter

The ACES laser transmitter includes fabrication of high-efficiency fiber seed laser electronics, modulators, and amplifiers for sensing of CO_2 at 1.57 micron. The transmitter utilizes Master Oscillator Power Amplifier (MOPA) technology meant to resonantly probe the atmosphere using an Integrated-Path Differential Absorption Lidar (IPDA) approach.

ACES simultaneously transmits three beams from commercial Erbium-Doped Fiber Amplifiers (EDFAs) operating near 1.57 micron. Each EDFA has a transmit power of 10 W, for a total transmit power of 30 W. The MFLL uses a single 5-W similar EDFA. The EDFAs are seeded by temperature-stabilized seed lasers locked to a CO_2 absorption line. Fine steering and alignment of the transmitted beams is performed by Risley prisms that are housed on an optical bench fed by fiber-coupled collimators from each EDFA. The three laser beams are combined in the far-field and a three-telescope receiver is used to collect return signals from all three beam simultaneously. These signals are then combined on a single detector.

2.2 Detector

The baseline ACES detector is an HgCdTe array with 64 diodes wire-bonded together to form a single pixel. The array is designed for integration into a tactical Dewar with an operational temperature range of 60 to 100 K to optimize detector performance. Temperature stability of the detector and Dewar has been shown to be stable to +/- 0.25 K over 1 hr and +/- 1.0 K over 24 hr. The detector NEP is 2.4 fW/Hz1/2 with an excess noise factor of about 1.1. The ACES detector is improved from previous detector subsystems by increasing the bandwidth to 4.9 MHz (at a gain of 10^6), reducing overall mass from 18 lb to less than 10 lb, and extending the duration of autonomous, service-free operation from 4 hr to greater than 24 hr. These technology advancements permit higher laser modulation rates, allowing greater flexibility for implementing advanced retrieval algorithms as well as improving range resolution and error reduction. While this detector was unavailable for the recent ASCENDS/ABoVE and ACT-America research flights, a commercially available detector with higher noise and lower responsivity was used.

2.3 Receiver

The ACES receiver system consists of a three-telescope design originally built for the constraints of the Global Hawk aircraft. The outgoing laser beams are aligned to the field of view of three fiber-coupled 17.8-cm diameter telescopes. The backscattered light is then collected by the same three telescopes, which are fiber-coupled to the aft optics and a single-detector/TIA subsystem. The receiver design tests the ability of multiple smaller telescopes to provide equal or greater collection efficiency compared with a single larger telescope with a reduced impact on launch mass and cost.

3. PRELIMINARY RESULTS AND DISCUSSION

Preliminary results show encouraging comparisons with atmospheric model CO_2 optical depth (OD) values derived from in situ measurements collected on board the DC-8 on spirals under the remote ACES measurements during the ASCENDS/ABoVE experiment. For example, Figure 4 shows optical depth data from a southbound leg 7.4 km above ground level just prior to an aircraft spiral maneuver during a flight over California's Central Valley on July 21, 2017. Optical depth differences between ACES' measurements and a model of CO_2 OD co-located with the lidar differ by about 0.34% or <1.4 ppm CO_2.

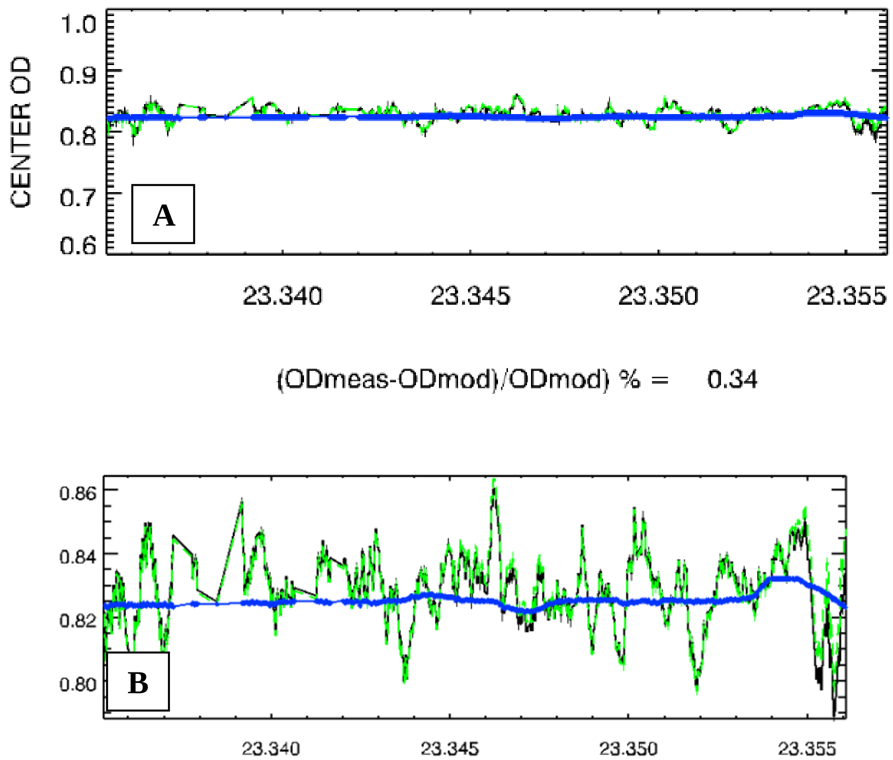

Figure 4. A) ACES CO_2 optical depth measurements collected on July 21, 2017, during the ASCENDS/ABoVE airborne campaign are compared with an in-situ derived model of CO_2 optical depth. In situ sensors were co-located with the lidar. B) The same as Figure 4A with an expanded y-axis.

Similarly, column-averaged CO2 measurements from the MFLL instrument were compared with in situ-derived measurements during the first ACT-America campaign covering summer, 2016. Figure 5 shows calibrated optical depth comparisons for portions of 10 science flights during this campaign. The percent difference between the lidar and in situ derived measurements is 1.49 ppmv, with a mean bias of 0.10 ppmv. As future data data revisions are released with improved calibrations, these differences may decrease.

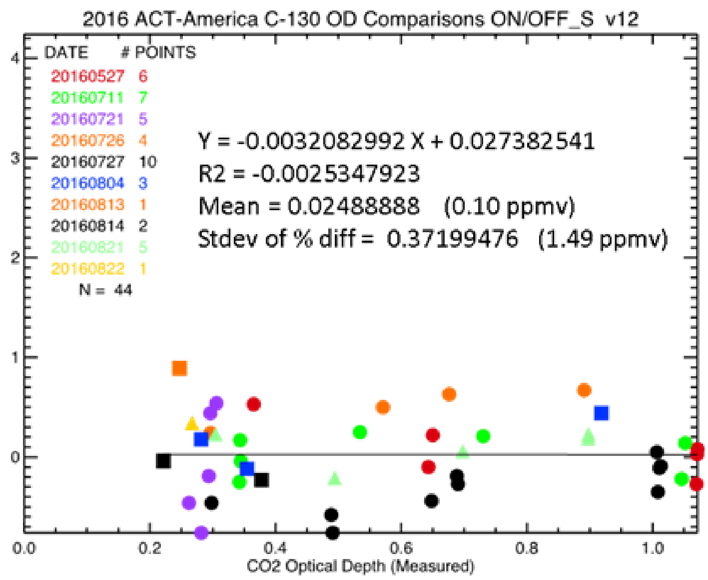

Figure 5. MFLL calibrated optical depth comparisons for portions of 10 science flights during the ACT-America 2016 summer campaign.

4. SUMMARY

The ACES project is advancing key technologies in support of spaceborne measurements of column-averaged carbon dioxide mixing ratios. These technologies are viewed as critical towards developing an airborne simulator and eventual spaceborne instrument with lower size, mass, and power consumption, and improved performance. The IM-CW technique continues to accurately measure range over a variety of surfaces and in the presence of optically thin clouds allowing for retrievals of column CO_2 mixing rations to surface and cloud tops. The ACES instrument, and the MFLL instrument that ACES is based on, were flown extensively during the ACT-America campaigns on the NASA C-130 aircraft, and ACES was flown on the NASA DC-8 during the 2017 ASCENDS/ABoVE measurement campaign. Both lidars are demonstrating encouraging comparisons with in situ measurements. Hardware improvements will continue to increase the quality of measurements in future campaigns, with the eventual goal of flights on board a high-altitude airborne platform. Current plans for ACES are to improve the measurements via improving the instrument calibration through comparisons with measurements of CO_2 column density from other co-located in situ instruments.

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