TECHNOLOGY ADVANCEMENTS FOR ACTIVE REMOTE SENSING OF CARBON DIOXIDE FROM SPACE USING THE ACTIVE SENSING OF CO_2 EMISSIONS OVER NIGHTS, DAYS, AND SEASONS (ASCENDS) CARBONHAWK EXPERIMENT SIMULATOR

Michael D. Obland[1]*, Joel Campbell[1], Susan Kooi[2], Tai-Fang Fan[2], William Carrion[2], Jonathan Hicks[2], Bing Lin[1], Amin R. Nehrir[1], Edward V. Browell[3], Byron Meadows[1], Kenneth J. Davis[4]

*[1]NASA Langley Research Center, Hampton, Virginia, USA, *michael.d.obland@nasa.gov*
[2]Science Systems and Applications, Inc., Hampton, Virginia, USA
[3]STARSS-III Affiliate, NASA Langley Research Center, Hampton, Virginia, USA
[4]Pennsylvania State University, University Park, Pennsylvania, USA

ABSTRACT

This work describes advances in critical lidar technologies and techniques developed as part of the NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons CarbonHawk Experiment Simulator system for measuring atmospheric column carbon dioxide (CO_2) mixing ratios. This work provides an overview of these technologies and results from recent test flights during the NASA Atmospheric Carbon and Transport – America (ACT-America) Earth Venture Suborbital summer 2016 flight campaign.

1 INTRODUCTION

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. ACES seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios in support of the NASA ASCENDS mission, which was identified in the U.S. National Research Council's report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, as a midterm space mission necessary to better understand global sources and sinks of CO_2 [1]. 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-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 leverages the measurement techniques and instrument architecture of the Harris, Corp. Multifunctional Fiber Laser Lidar (MFLL) instrument that has flown on multiple measurement campaigns [2]. ACES has 6 times more transmit power, 14 times more power-aperture product, and increased detector subsystem bandwidth compared with the MFLL instrument.

ACES was given the opportunity to fly on the NASA C-130 aircraft as a piggy-back instrument during the summer 2016 Atmospheric Carbon and Transport – America (ACT-America) campaign. 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 will enable and demonstrate 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) [3, 4] 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 that will be combined with data from existing measurement networks and integrated 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). A total of five campaigns, each six weeks in length, are being performed across the eastern half of the United States. The 2016 summer measurement campaign comprised 24 research flights and over 151 hours of science data. Aircraft flight tracks for this campaign are shown in Figure 1.

The ACT-America 2016 summer campaign was the first opportunity for significant flight time for the ACES instrument during a science-focused airborne campaign. During this campaign, ACES collected data over a wide variety of surface reflectivities, terrain, and atmospheric conditions. Simultaneous data collected by in situ instrumentation on the aircraft were used to evaluate the ACES measurements of column-integrated CO_2 mixing ratios.

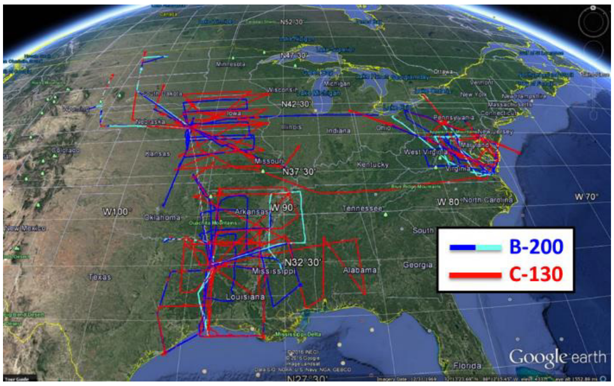

Figure 1 C-130 and B-200 flight tracks during the 2016 ACT-America Summer measurement campaign, which took place July 18 through August 29, 2016.

2 INSTRUMENT

ACES employs 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 [5]. This approach is analogous to mature frequency-modulated continuous wave radar and GPS measurement techniques.

The transmitter, receiver, and detector subsystems are housed in an environmental enclosure originally built for the Global Hawk aircraft. The enclosure is shown in Figure 2 during early testing on the NASA HU-25 aircraft. Data acquisition and control hardware is located in electronic racks that are separate from the instrument enclosure.

Figure 2 The ACES instrument box installed on the NASA HU-25 aircraft for early development tests. The instrument box is present in the foreground. Racks for data acquisition and control systems are located immediately behind the instrument box.

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 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 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.

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 $fW/Hz^{1/2}$ with an excess noise factor of about 1.1. While this detector is still in development, a commercially available detector with higher noise and lower responsivity is being used for the ACT-America research flights.

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 RESULTS AND FUTURE PLANS

Some preliminary results show encouraging comparisons with atmospheric model CO_2 optical depth values derived from in situ measurements collected on board the C-130 on spirals under the remote ACES measurements. For example, see Figure 3, where the optical depth differences were found to be less than 2%. Other results show significant deviations from model CO_2 optical depth values due to hardware instabilities. These instabilities are likely due to the use of a commercial off-the-shelf detector in place of the higher quality DRS detector, which is being built and is expected to significantly improve measurement quality. Gain instabilities in the commercial detector likely led to biases in measurements during portions of the flights.

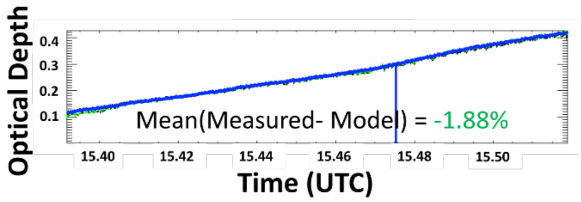

Figure 3 Example measurement data from ACES compared with results from an atmospheric model based on in situ CO_2 and meteorological measurements made on spirals under the ACES measurements.

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. Advanced correlation techniques have used ACES data to resolve cloud and forest features [6, 7].

Current plans for ACES during the upcoming ACT-America flights are to improve the measurements via improving detector gain stability and data acquisition hardware, and to improve calibration of the instrument through comparisons with other ACT-America measurements of CO_2 column density.

4 CONCLUSIONS

The ACES project is advancing key technologies in support of the NASA ASCENDS satellite mission. 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 ACES instrument was flown extensively during ACT-America flights on the NASA C-130 aircraft in July and August 2016, and demonstrated encouraging comparisons with in situ measurements. Hardware improvements will continue to increase the quality of measurements in future campaigns, including flights with the next ACT-America campaign in winter, 2017, with the eventual goal of flights on board a high-altitude airborne platform.

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