

Intensity-Modulated Continuous-Wave Laser Absorption Spectrometer at 1.57 μm
for Atmospheric CO₂ Measurements

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July 23, 2014

The 1st International Workshop on
Space-based Lidar Remote Sensing Techniques and Emerging Technologies
08 - 12 September 2014, Paris, France

1. Overview of Intensity Modulated Continuous Wave Measurement Approach

The NASA Langley Research Center (LaRC) and ITT Exelis, Inc. (Exelis) have been jointly developing and testing advanced lidar technologies for the Active Sensing of CO₂ Emissions over Nights, Days and Seasons (ASCENDS) space mission. A critical aspect of these activities is the development of a prototype Intensity-Modulated Continuous-Wave (IM-CW) Laser Absorption Spectrometer (LAS) for high-precision, column CO₂ mixing ratio (XCO₂) measurements using the Integrated Path Differential Absorption (IPDA) approach. Airborne flight campaigns have demonstrated that the CO₂ measurements of current IM-CW LAS system meet the accuracy and precision requirements of the ASCENDS mission. Furthermore, analyses of space CO₂ measurements show that this IM-CW LAS technology and approach will enable the ASCENDS mission to achieve its science goals.

The first IM-CW LAS system, called the Multifunctional Fiber Laser Lidar (MFL) developed by Exelis (Dobbs et al. 2008; Dobler et al. 2013), was used to demonstrate the capability of CO₂ column measurements from several aircraft under a variety of atmospheric and surface conditions (Browell et al., 2008, 2009, 2010, 2012; Dobler et al., 2013). Extensive demonstrations have been conducted in laboratory and horizontal ground test-range environments and in flight campaigns. The MFL CO₂ column measurements over desert and vegetated surfaces have been found to agree with those calculated from in-situ measurements of atmospheric meteorological and CO₂ profiles to within an average of 0.17% or ~0.65 ppmv. A measurement precision of 0.08% or ~0.3 ppmv for a 10-s average over these surfaces has also been achieved (Browell et al., 2009; Dobler et al., 2013).

2. Basic characteristics of IM-CW LAS system

The lidar discussed here is based on the airborne prototype LAS system, MFL (Dobbs et al., 2007, 2008; Dobler et al., 2013; Lin et al., 2013). Figure 1 shows the concept of the LAS lidar design (right) and the MFL lidar onboard the NASA DC-8 aircraft (left). The main parameters of the instrument are listed in Table 1.

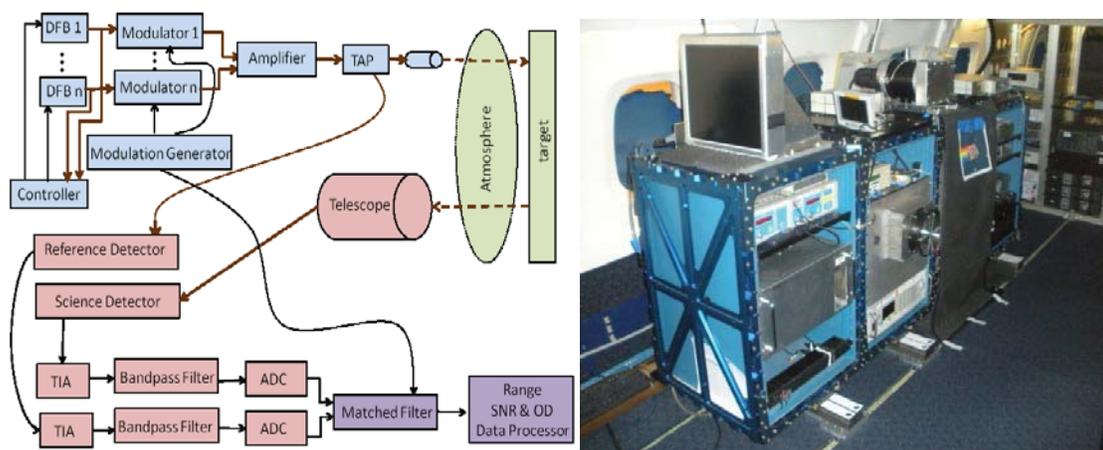


Figure 1 (right) Architecture of the airborne prototype lidar; (left) The MFL lidar mounted inside the NASA DC-8 aircraft. The onboard data processing and onboard display unit, detection system, and CO₂ transmitter subsystems are seen from front to back. The telescope and transmit optics are housed under the black laser curtain.

The LAS system has one laser wavelength positioned at the center of the CO₂ absorption line at 1571.112 nm (called the “online”) and two other laser wavelengths in the distant wings of the absorption line at offsets of ± 50 pm (called the “offlines”) for the CO₂ IPDA measurements. The wavelengths were selected to minimize water vapor and other trace gas interferences on the IPDA measurements and to simultaneously maximize the signal-to-noise ratio (SNR) of the differential absorption optical depth (DAOD) measurements (Ismail et al., 1989; Remsberg and Gordley, 1978). The altitude-dependent gas absorption weighting function; the DAOD sensitivity to knowledge of the laser wavelength and line-width; and the wavelength stability of the laser spectra are other major considerations in the laser line selections (Menzies and Tratt 2003; Ehret et al., 2008; Kameyama et al., 2010; Lin et al., 2013). For range determination, a range-encoded IM technique, swept frequency, has been applied to the lidar system. This results in the advanced range measurement and cloud/aerosol discrimination, which is an essential capability to achieve precise CO₂ measurements. After recording lidar return signals by the receiver and data acquisition subsystems, the key element for post processing of the recorded data is a matched filter that correlates the transmitted IM waveforms with

Table 1 Airborne MFL Lidar Parameters

Seed laser type:	DFB diode laser
Line width	< 6 MHz each wavelength
Side mode suppression	Ratio > 45 dB
CO ₂ lines: (vacuum)	1.571112 μm (On), 1.571061 μm (Off 1), 1.571161 μm (Off 2)
Modulator:	Semiconductor Optical Amplifier
Modulation type:	Intensity-modulated continuous-wave (IM-CW)
Optical amplifier:	CO ₂ : EDFA
Output power:	5 Watts for CO ₂
Optical bandpass filter:	2.4 nm
Telescope	Cassegrain, 8 in. diameter.
Optical throughput	8.5%
Detector	DRS; HgCdTe APD gain: ~940; Excess noise factor ~1.3, 77 K as operated
Transimpedance amplifier	Gain: 10 ⁶
Sample rate	2 MHz
Swept-frequency:	~350 ± 250 KHz;
Unambiguous range:	15-km; 30-km (after 2012)
Laser divergence angle:	190 urad (half angle)
Receiver FOV:	240 urad (half angle)
Receiver duty cycle:	100%
Reporting interval:	0.1 sec (10 Hz)

of 13 flight campaigns with various aircraft such as NASA UC-12 and DC-8 since May 2005 to evaluate the capability in making remote CO₂ and XCO₂ column measurements for the ASCENDS mission (Dobler et al., 2013). Accurate CO₂ column measurements have been demonstrated by these comprehensive aircraft flight tests. For example, 1-second averaged CO₂ column measurements over desert regions resulted in high precision measurements with SNR of DAOD (SNR_{DAOD}) higher than 600 (Browell et al., 2012; Dobler et al., 2013). Figure 2 shows two comparison examples of 1-s MFL CO₂ DAOD measurements and in-situ-derived (modeled) values in drastically different geographic regions.

The top panel of Figure 2 shows the CO₂ measurements on a constant altitude flight leg over the Central Valley, CA in comparison to modeled DAOD values derived from in-situ CO₂ data of a DC-8 spiral at the center of the leg and radiosonde data obtained within about 1 hour of the over-flight. The small variations in the in-situ-derived (i.e., modeled) DAOD across the flight leg were due to small changes in the range from the aircraft to the surface. The resulting difference of 1-s averages between the measured and modeled DAOD values on the Central Valley flight leg was found to be -0.28% or the equivalent of ~1.1 ppmv. The bottom panel shows the DAOD comparison while

the received IM waveforms reflected from the surface as well as clouds. From matched filter outputs, the location and magnitude of correlation peak powers are obtained and used to estimate the range and DAOD, respectively. The accuracy of range estimates was found to be better than 3 m from ground-range and flight campaigns (Dobler et al., 2013; Lin et al., 2013). Details on the instrument and data processing can be found in Dobler et al. (2013) and Lin et al. (2013).

3. Airborne CO₂ column measurements

To evaluate the accuracy and precision of the MFL remotely-sensed CO₂ column measurements, actual CO₂ DAOD values are needed. These DAOD values were derived based on the knowledge of the in-situ observed vertical profiles of XCO₂ and meteorological conditions; the altitude- and meteorologically-dependent spectroscopy of CO₂ and any interfering gas, such as water vapor; the path length from the aircraft to the surface; and the off-nadir pointing of the laser beam (Browell et al., 2008, 2009, 2010, 2012; Dobler et al., 2013; Lin et al., 2013). High-quality in-situ measurements of XCO₂ (Choi et al., 2008; Vay et al., 2003), temperature (T), pressure (P), and relative humidity (q) profiles and other meteorological conditions were obtained from onboard instruments during aircraft spirals and collocated with contemporaneous radiosonde launches. A laser altimeter was also included to make an independent measurement of the range to the surface or cloud tops. A GPS and the aircraft navigation system provided the additional aircraft location including altitude and attitude information. Comparisons of MFL remotely sensed and in-situ-derived DAOD values were typically limited to a horizontal distance of less than 10 km of the aircraft spiral and radiosonde comparison locations. When multiple in-situ spirals were conducted during a flight, the spiral data corresponding to the closest MFL overpass time was used.

The LaRC ASCENDS team has conducted a total

transiting across the Rocky Mountains. The in-situ data (spiral and radiosonde) came from Railroad Valley, NV, and the variation in DAOD values across the mountains was almost entirely due to surface elevation changes as the aircraft was at a constant altitude. The comparison of 1-s measured and modeled DAOD values demonstrated a high level of agreement ($\Delta\text{DAOD} = -0.44\%$ or ~ 1.7 ppmv) even when one expects some change in CO_2 across the mountains that could not be captured in the modeled DAOD due to the lack of in-situ data. Flight tests of the current LAS instrument have demonstrated very high-precision CO_2 DAOD measurements ($\text{SNR}_{\text{DAOD}} > 1300$) with a 10-s averaging interval (Browell et al., 2012; Dobler et al., 2013).

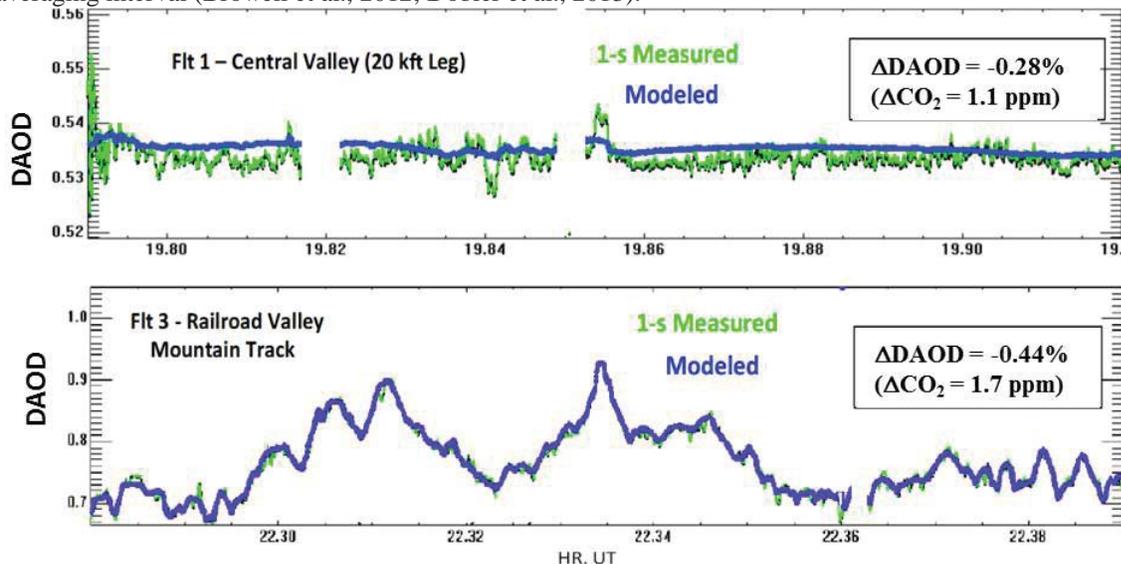


Figure 2 Comparison of airborne measured and modeled CO_2 DAODs for flights over California’s Central Valley (top) and the Rocky Mountains (bottom) in route to Railroad Valley, NV.

Since variations in surface types and reflectance can significantly affect lidar return powers and CO_2 column retrievals, different surface conditions were analyzed from MFLN flight data. For farm fields and deserts, moderate to high reflectance values were observed, and strong signals for CO_2 column retrievals were received. For some surfaces especially snow, ice, and rough water surfaces, very low reflectance was expected and observed. From MFLN data, the measured surface reflectance of snow and ice was as low as about 0.02/sr. Fresh snow (less than 1-2 days old) was found to have even significantly lower reflectance (about ~ 0.01 /sr). Even in these low reflectance cases, enough backscattered signal was obtained for CO_2 column retrievals from high altitude flight legs (Nehrir et al. 2013). The variability in the surface reflectance for complete snow covered terrain was found to be relatively homogeneous, however the magnitude of the surface reflectivity for both snow covered mountainous and farmland terrain was observed to vary by more than an order of magnitude over distances of less than 10-20 meters from the nominal snow and ice surface reflectance values (Nehrir et al. 2013).

In addition to surface types, the presence of thin clouds and aerosol layers are an important factor that can affect the accuracy of CO_2 column measurements. The capability for discrimination of cloud returns from ground returns is achieved using the swept frequency IM-CW approach as shown in Figure 3. The data were obtained from the DC-8 flight on 4 August 2011 over Railroad Valley, NV (Harrison et al. 2013). Distinct altitudes and reflections of the surface and clouds were clearly observed from the swept-frequency measurements. The presence of intermediate thin clouds can decrease lidar return signals and reduce the precision of CO_2 column estimates, but the CO_2 measurements still satisfy mission requirements when cloud attenuation scaling is considered (Lin et al. 2013). Ranging precisions of ~ 3 m for these surfaces and clouds have also been achieved (Dobler et al. 2013; Harrison et al. 2013).

4. Near-future development and advancing airborne IM-CW instruments to space

The key areas for LaRC near-term measurement development and demonstration include maturing low-mass high-power lasers, low noise detector subsystems, and real-time data processing electronics required for the ASCENDS space mission (Obland et al. 2012, 2013; Beyon et al. 2013) via the next generation airborne LAS system. LaRC team conducted ground tests at LaRC lidar test range in April 2014 and flight tests in July 2014 for this LAS system. Initial ground and flight data analysis indicates that the instrument has performed as expected and precise

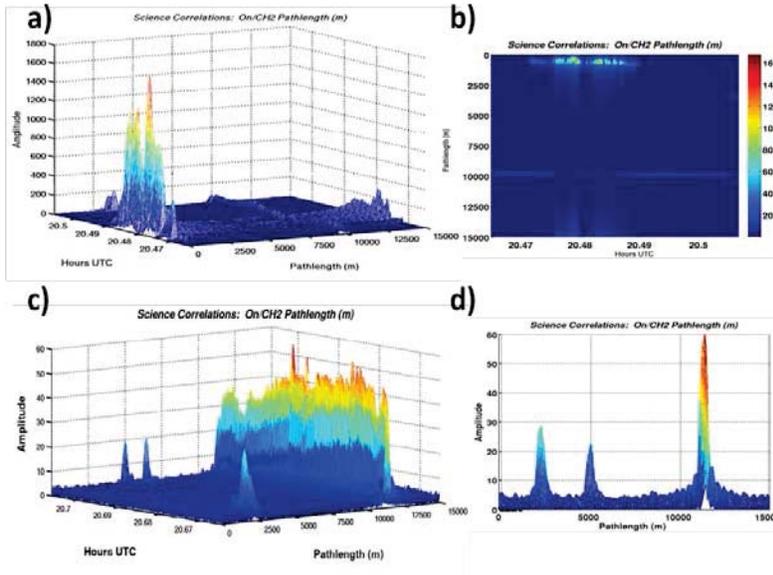


Figure 3 Range discrimination of cloud returns from ground returns using the swept frequency IM-CW approach. Panels a) and b) show 3-D and 2-D, respectively, representation of a large cloud return above a small ground return; panel c) shows the distribution of signals from weak clouds and strong ground return signals, and panel d) is a superposition of data from c) on a signal vs. path length.

model for the lidar and its measurement environment is important to guide improvement of LAS systems and allows predictions of CO₂ measurements for future space missions. The model accounts for fundamental physics and characteristics of the instruments and their related measurement environments. The model results are presented statistically from simulation ensembles that include noise sources and uncertainties related to the LAS instruments and the CO₂ measurement environments. The characteristics of simulated LAS system are based on existing technologies and their implementation in existing systems. Validations of the model show excellent agreement of simulated results with measurements.

For the ASCENDS space mission, the LaRC team has formulated a conceptual design of the space lidar based on current technologies. The architecture of this space lidar is similar to the prototype airborne lidar (c.f. Figure 1). Compared to the airborne lidar, the main changes for the space LAS sensor are using two sideline wavelengths with one at +3 pm (called Side-1) and the other at +10 pm (called Side-2) offset from the CO₂ absorption line center; increasing the transmitted laser output power to 42 W and the telescope diameter to 1.5 m; and reducing the optical bandpass filter bandwidth to 0.5 nm FWHM and laser half-angle divergence to 50 μrad (Lin et al., 2013). The receiver's FOV is set to be 33% larger than that of laser divergence, and the optical throughput is 0.65. The sideline wavelengths are selected to avoid excessive absorption of the entire atmospheric CO₂ column at the line center and to have more weighting of the measurement across the mid to lower troposphere, where most of the CO₂ flux exchanges with ecosystems and advection within the atmosphere take place.

To understand the IM-CW LAS performance for space applications, model simulations are conducted for a sun-synchronous, dawn/dusk orbit (Ehret et al., 2008) with an altitude of 390 km which is consistent with the mission design. Under clear conditions, simulation shows that the precision of the DAOD measurements for surfaces similar to the playa of Railroad Valley, NV (reflectance 0.176 sr⁻¹) will be better than 0.07% for 10-s averages. Clear-sky bias errors are found to be very small and below 0.04 % from the simulations. Including thin clouds with optical depths up to 1, the CO₂ SNR_{DAOD} measurements with 0.1-s integration period for surfaces similar to that of Railroad Valley, NV will be greater than 94 and 65 for Side-1 and Side-2, respectively (Fig. 4a). The CO₂ column bias errors introduced by the thin clouds are ≤0.1% for cloud optical depth ≤0.4, but they could reach ~0.5% for more optically thick clouds with cloud optical depths up to 1 (Fig. 4b).

atmospheric CO₂ measurements have been obtained. The systematic errors in the retrievals of CO₂ column amounts from thin clouds will be further assessed using previous and future flight campaign data sets.

The cloud slicing technique, which is enabled by the ranging-encoded lidar approach, will be investigated from various airborne data sets. This should provide the capability to determine CO₂ columns across both the free troposphere and the planetary boundary layer. Furthermore, advanced lidar intensity modulation algorithms that eliminate cloud impacts on lidar surface returns when clouds are very close to the surface are developed (Campbell et al., 2013) and will be tested. Along with these efforts, modeling of LAS atmospheric CO₂ column measurements is also a key part of the measurement development and demonstration. The LaRC ASCENDS team has developed a model for LAS system and CO₂ measurement simulations (Lin et al., 2013). This

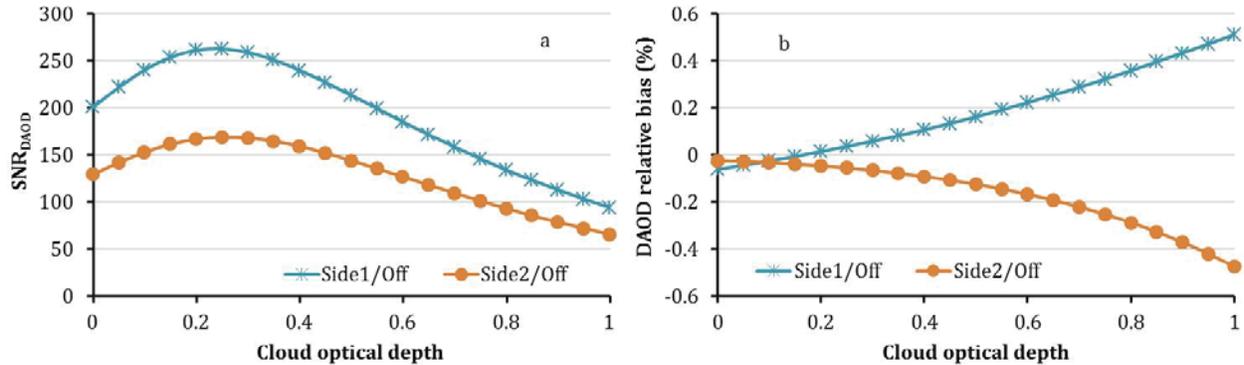


Figure 4 Simulated 0.1-s results for a spaceborne lidar under thin cirrus cloud conditions. The CO₂ SNR_{DAOB} (a) and relative bias error (b) values are calculated for the surface assuming the reflectance of Railroad Valley, NV.

When the cloud and surface ranges and scattering amplitudes are obtained from the analysis of matched filter outputs, the cloud bias errors can be further reduced as seen from the compensating feature of the bias errors between the retrievals of the two sidelines (Fig. 4b). Other simulation studies indicate that the present IM-CW LAS concept for space can provide ASCENDS required CO₂ measurements from not only the dawn/dusk orbit but also other Low Earth Orbits (LEOs) such as sun-synchronous, day/night orbits, maximizing the flexibility of the space instrumentation to various CO₂ measurement needs.

5. Summary

The approach of an Intensity-Modulated Continuous-Wave 1.57 μm Laser Absorption Spectrometer for atmospheric CO₂ measurements that NASA Langley Research Center and ITT Exelis, Inc. have been assessing has a great potential for applications to the ASCENDS space mission using the Integrated Path Differential Absorption technique. This approach takes the advantage of telecommunication technologies and can achieve required transmitted power and other key specifications of space instrumentation. Airborne flight campaigns of the current prototype IM-CW LAS systems have demonstrated high accuracy and precision CO₂ measurements in various atmospheric and surface conditions. Model simulations of atmospheric CO₂ measurements using this kind of LAS instruments under relevant space, atmospheric and surface environmental conditions have shown that this IM-CW LAS technology and approach will enable the ASCENDS space mission to meet its science goals.

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