A Multifunctional Fiber Laser Lidar for Measuring Atmospheric CO_2 and O_2

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Photo of the instrument as flown on the DC-8 in July and August 2011

Introduction

ITT Geospatial Systems has been developing a multi-functional fiber laser lidar (MFLL) for altimetry and high precision laser absorption spectroscopy (LAS) of atmospheric CO2 since 2004. The instrument utilizes a unique intensity modulated (IM) continuous wave (CW) measurement technique, allowing simultaneous transmission and collection of multiple wavelengths which are separated through an all digital lock-in approach. The CO2 and altimeter components of the MFLL prototype have been extensively evaluated through 12 different flight campaigns using 3 different aircraft which include more than 70 individual flights conducted over an extensive range of atmospheric and surface conditions. These evaluations have been conducted in collaboration with our partners at NASA Langley Research Center and Atmospheric and Environmental Research, Inc. Airborne data acquired by MFLL show an absolute agreement of <0.9 ± 3.2 ppmv in comparison to simultaneous in-situ CO2 measurements referenced to the WMO primary CO2 scale. To the best of our knowledge, this represents the only airborne remote CO2 measurement technique that has demonstrated this precision and accuracy to date.

Many recent upgrades to the airborne instrument have been made including:
1) Increased system bandwidth
2) Hybrid modulation techniques for discriminating against thin cloud interference
3) Addition of a 1262.5 nm transmitter for measurements of atmospheric O2

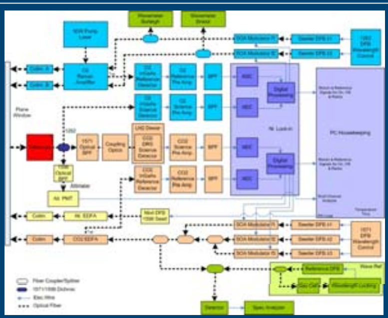
Historical Perspective

The LAS instrument was developed by ITT Space Systems in 2004 and has been extensively tested, matured, and thoroughly evaluated after more than 1000 hours of ground testing and 12 flight campaigns consisting of more than 70 Aircraft sorties.

The collection flexibility of the system is evident through the flight testing conducted over a variety of meteorological conditions, various land types, water, and during both days and nights. The instrument has been validated in conjunction with our partners at NASA Langley Air Research Center (LaRC), and Atmospheric and Environmental Research, Inc.

The current aircraft rack was designed to be compatible with the UC-12, P3 and DC-8 aircraft. The LAS instrument is currently TRL-7 for aircraft use due to its extensive use in relevant environments and application to full scale problems.

Measurement Method



Instrument Schematic as flown on the DC-8 in July and August 2011

The LAS instrument transmitter consists of;
1) A reference laser locked to a gas cell used to continuously monitor the wavelengths of the outgoing lasers through a heterodyne process
2) Three Distributed Feedback (DFB) lasers controlled to +/- 0.2pm and which are the signal lasers for CO_2. Two DFB's provide the signal for the O_2 channel.
3) A Semiconductor Optical Amplifier (SOA) or Electro-Optical Modulator (EOM) for each of the signal lasers used to impart a unique analog modulation to each of the transmitted wavelengths
4) An Erbium Doped Fiber Amplifier (EDFA) which amplifies the combined signal laser waveform to an average power of 5 W with a reference tap to monitor the outgoing power, and a fiber Raman amplifier for amplification of the O_2 signal lasers to 1.5 W average power.
5) A high quality fiber collimator.

All of the wavelengths are transmitted simultaneously out of the fiber collimator and thus have 100% spatial and temporal overlap. This eliminates sensitivity to highly varying surface reflectance as well as minimizing effects of atmospheric turbulence by making it common mode.

The transmitter is all fiber-based and has no free space optics; this results in a rugged design that does not have many of the alignment issues of more complicated transmitter system.

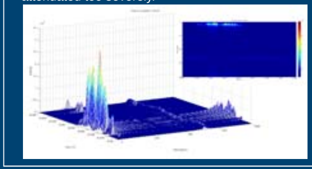
The reflected light from the target is collected by a single telescope and sent to a low excess noise 8X8 HgCdTe Avalanche Photodiode (APD) array and a Transimpedance Amplifier (TIA) to convert the optical signal to an analog voltage signal. A high resolution (24 bit) analog-to-digital converter is used to sample the analog waveform into the computer for processing.

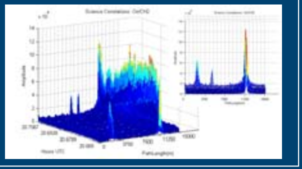
The fact that the optical and electrical path is common mode for all of the signal wavelengths results in a significant reduction in sensitivity to instrument drift; reducing noise from the atmosphere, target and sensor into a common mode term which is removed when the signals are ratioed. The signal is then processed through a custom all software-based lock-in amplifier described in the next panel.

The altimeter has its own transmitter, but shares the telescope with the LAS system. The return altimeter signal is separated from the LAS signal dichroically, and sent to the altimeter detector and associated electronics.

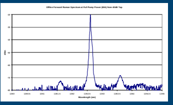
Thin Cloud Rejection

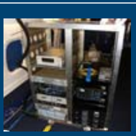
- Thin clouds pose an operational error source due to early short path reflections for a standard sinusoidal lockin approach. By adding more complex modulations, range discrimination to ignore early returns vs. the desired ground returns is performed.
- These techniques require higher bandwidth than used previously, on both transmitter and receiver paths. For this first demonstration of these range discrimination techniques we increased the receiver bandwidth to 2 MHz, with the transmitter frequencies spanning 100 – 600 kHz.
- This summer's flights offered a wide range of cloud conditions for evaluating the range discriminating techniques. Using a 3D rendering with 2D insets, the examples below show a case where the ground return and cloud returns are distinguishable until the cloud return dominates and the ground signal is attenuated too severely.



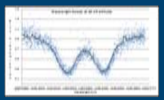


1262 nm O_2 Amplifier





Oxygen Lidar at 1260 nm Development
- O_2 Raman amplifier has been developed under a NASA ESTO Advanced Component Technology Grant, which produces 1.5 W combined on and off line average power (3 W peak).
- Linewidths of <3 MHz and 45 dB side mode suppression have been demonstrated at this power level.
- First flight testing of the O_2 amplifier was conducted on the DC-8 in July and August 2011.

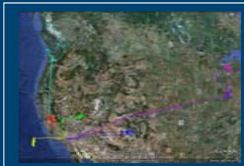


Other Key Technology Development - Lightweight Mirror
- First parabolic mirror blank has been molded using the corrugated mirror process and is under test.
- To date ITT has been able to polish a plano 0.6-m blank, built using the corrugated mirror technology without a center-hole to ~25 nm-rms
- ITT has currently brought its corrugated borosilicate mirror technology to TRL 5 for planos and to TRL ~4 for f/1.6 parabolas.

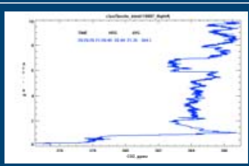
Current and Future Efforts

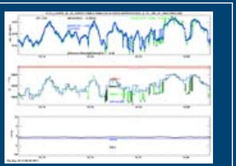
- Converting the present LN2 cooled Dewar to active cooling. This work is being supported by ITT as part of a NASA LaRC, ESTO IIP grant.
- ITT Geospatial Systems, along with TIPD LLC, is currently pursuing the development of specialty fibers to allow scaling of the O2 amplifier to >5W and > 10% WPE through a 2011 ACT.
- ITT is working with Atmospheric and Environmental Research Inc. to advance the algorithms for using coincident CO2 and O2 measurements to retrieve XCO2 through a 2011 ACT.
- Multiple transmitter demonstration of XCO_2 measurement expected in CY2012 under the ACES IIP.
- Multi-aperture telescope demonstration planned for CY2013 under the ACES IIP.

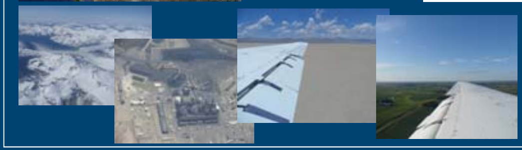
Validation



July and August 2011 DC-8 Flights
- Completed 7 science flights and one engineering check flight
- Total of 43 hours of flight data
- Flight 0 Castle AFB (eng chk flt)
- Flight 1 Castle AFB (clear conditions)
- Flight 2 Open Ocean (over thick stratus deck)
- Flight 3 Rail Road Valley Nevada (some low level and high cirrus clouds)
- Flight 4 British Columbia (Snow and Ice)
- Flight 5 Four Corners (power plant plumes)
- Flight 6 WBTT (Iowa tall tower site)
- Flight 7 WLEF (Wisconsin tall tower site)







Remote data is compared to high accuracy in-situ data traceable to the WMO standard, spirals are made as close as possible to the center of the track and the in-situ data is used to estimate the integrated column optical depth. The modeled optical depth is then compared to the retrieved remote lidar data. An example of data taken over the rocky mountains is shown above on the right. This data set was more complex and extensive than any previous campaign and data processing is ongoing.

Acknowledgements

We would like to acknowledge the significant support of ITT Geospatial Systems (formerly ITT Space Systems) for internal investment enabling the development of the EDU. NASA LaRC, and NASA HQ for supporting flight cal/val demonstrations of the EDU. NASA ESTO for their previous support developing the PN altimeter under the IIP program and their support for both the Raman amplifier development for O_2, and the corrugated mirror development under the NASA ACT program.