Airborne Demonstration of 1.57-micron Laser Absorption Spectrometer for Atmospheric CO_2 Measurements

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Abstract

A unique, multi-frequency, single-beam, laser absorption spectrometer (LAS) that operates at 1.57 micron has been developed for a future space-based mission to determine the global distribution of sources and sinks of atmospheric carbon dioxide (CO_2). A prototype of the space-based LAS system was developed by ITT, and it has been successfully flight tested in five airborne campaigns conducted in different geographic regions over the last three years.

Flight tests were conducted over Oklahoma, Michigan, New Hampshire, and Virginia under a wide range of atmospheric conditions. Remote LAS measurements were compared to high-quality in situ measurements obtained from instrumentation on the same aircraft on spirals under the ground track of the LAS.

LAS flights were conducted over a wide range of land and water reflectances and in the presence of scattered clouds. An extensive data set of CO_2 measurements has been obtained for evaluating the LAS performance. LAS CO_2 measurements with a signal-to-noise in excess of >250 (<1.5 ppm CO_2) were obtained for averages of 1-s over land and 10-s over water. Absolute comparisons of CO_2 remote and in situ measurements showed agreement over a range of altitudes to better than 1.5 percent (~5 ppm CO_2).

ASCENDS Mission

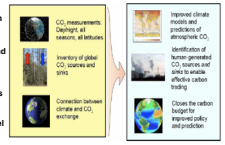
Mission Objectives

Goal: To significantly enhance the understanding of the role of CO_2 in the global carbon cycle and its impact on climate change by launching a "laser-based CO_2 mission" as "the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO)"

Objective 1. Quantify global spatial distribution of atmospheric CO_2 on scales of weather models

Objective 2. Quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1 degree grids at weekly resolution

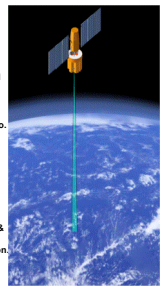
Objective 3. Provide a scientific basis for future projections of CO_2 sources and sinks through data-based process Earth System model enhancements



ASCENDS Measurements

CO_2 column mixing ratio (XCO_2) measurement with Laser Absorption Spectrometer (LAS) technique requires the simultaneous measurement of the CO_2 column number density (CND); the O_2 column number density for converting the CND to XCO_2; and the path length of the measurement. A temperature profile measurement is also required to constrain the XCO_2 measurement. A column CO measurement over the same XCO_2 path is also recommended for interpreting sources and sinks of CO_2.

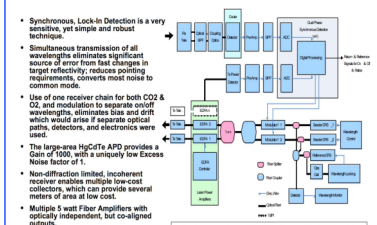
- CO_2 column measurement
  - CO_2 Laser Absorption Spectrometer to resolve (or weight) the CO_2 altitude distribution, particularly across the mid to lower troposphere.
  - 1.6-micron LAS only baseline or integrated 1.6-micron + 2.0-micron LAS option
- Surface pressure measurement
  - O_2 Laser Absorption Spectrometer to convert CO_2 number density to mixing ratio.
- Surface/cloud top altimeter
  - Laser altimeter to measure CO_2 column length.
- Temperature sounder
  - Six channel passive radiometer to provide temperature corrections.
- CO sensor
  - Gas Filter Correlation Radiometers (at 2.3 & 4.6 µm) to separate biogenetic fluxes from biomass burning and fossil fuel combustion.
- Imager
  - To provide cloud clearing for soundings.



1.57-micron Laser Absorption Spectrometer (LAS)

LAS Architecture

- Synchronous, Lock-In Detection is a very sensitive, yet simple and robust technique.
- Simultaneous transmission of all wavelengths eliminates significant source of error from fast changes in target reflectivity; reduces pointing requirements, converts most noise to common mode.
- Use of one receiver chain for both CO2 & O2, and modulation to separate on/off wavelengths, eliminates bias and drift which would arise if separate optical paths, detectors, and electronics were used.
- The large-area HgCdTe APD provides a Gain of 1000, with a uniquely low Excess Noise factor of 1.
- Non-diffraction limited, incoherent receiver enables multiple low-cost collectors, which can provide several meters of area at low cost.
- Multiple 5 watt Fiber Amplifiers with optically independent, but co-aligned outputs.
- Nominal data rate is 50Hz which corresponds to ~1 FOV from space.



We are in the process of integrating the O2 channel which adds a transmitter but shares the receiver.

ITT

Advanced CO_2 and Climate LAser International Mission (ACCLAIM)

ITT Engineering Development Unit used to validate end-end system performance model; technology readiness for ACCLAIM Mission; and capability for high precision CO_2 measurements.

ACCLAIM Flight Test Campaigns

May 21-25, 2005
Ponca City, Oklahoma (DOE ARM Site)
(5 Science Flights: Land, Day & Night,)

June 20-26, 2006
Alpena, Michigan
(6 Science Flights: Land & Water, Day & Night)

October 20-24, 2006
Portsmouth, New Hampshire
(4 Science Flights: Land (inc. mountains) & Water, Day & Night)

May 20-24, 2007
Newport News, Virginia
(8 Science Flights: Land & Water, Day & Night)

October 17-22, 2007
Newport News, Virginia
(9 Science Flights: Land & Water, Day & Night, Clear & Cloudy)

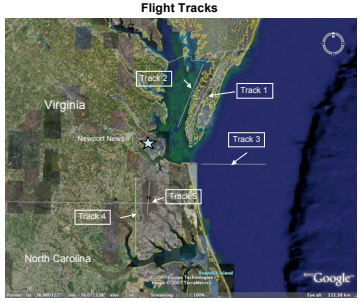
ACCLAIM & JPL LAS Flight Test Campaign, 17-23 October 2007

Aircraft at Newport News/ Williamsburg Airport

Requirements for Validation Experiments

- Complementary Measurements
  - –High-precision in situ CO_2 profiles under ACCLAIM.
  - –Nearby, contemporaneous radiosonde temperature, moisture, and pressure profiles.
  - –Simultaneous lidar altimeter measurements.
  - –Accurate gps unit with aircraft attitude information.
- Measurement Conditions
  - –Wide range of surface (land and water) types.
  - –Ability to operate from several aircraft altitudes.
  - –Flight plan to repeat flight legs to compare remote measurements with different settings.
  - –Operate under both day and night conditions.
  - –Evaluate measurements in presence of scattered clouds.
  - –Ability to do horizontal laser calibrations between flights.

Flight Tracks

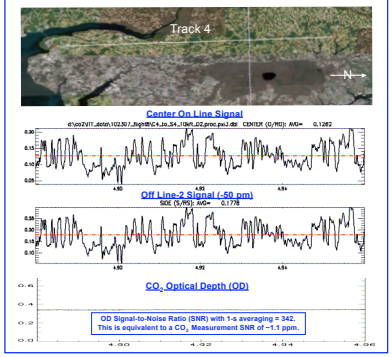


Test Flights (Land-Brown; Water-Blue)

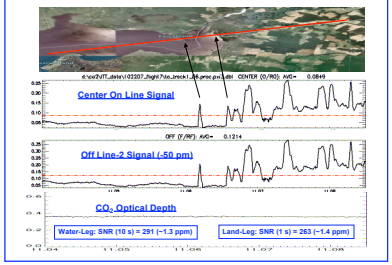
Flight #	Date (2007)	Objectives	Track	Aircraft	TO Time (EDT)	Landing (EDT)	Comments
1	10/17	Inland, Afternoon	4	Lear	1541	1659	Mostly Clear
2	10/18	Coast, Mid-Day	1	Lear Twin Otter	1021 1000	1242 1305	Low & Mid Scat. Clds
3	10/20	Inland, Mid-Day	4	Lear	1100	1320	Mid Clds on N Tk
4	10/20	Ocean, Afternoon	3	Lear	1550	~1800	Clear
5	10/21	Inland, Late-Morning	4	Lear	1008	1234	Clear
6	10/21	Inland, Night	4	Lear Twin Otter	1900 1825	2030 ~2100	Clear Below 20kft
7	10/22	Bay & Coast, Late-Morning	1 & 2	Lear Twin Otter	1005 1010	1208 ~1230	Mostly Clear
8	10/23	Inland, Pre-Dawn	4	Lear Twin Otter	431 441	645 706	Clear
9	10/23	Ocean, Late-Morning	3	Lear Twin Otter	949 1010	1217 ~1245	Many Clds

ACCLAIM Signals & CO_2 Measurements

Measurements Over Land on 23 Oct. 2007 (Flt. 8)



Water-Land Transition on 22 Oct. 2007 (Flt. 7)



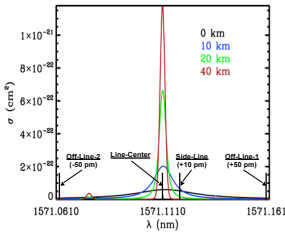
CO_2 Measurement SNR

DATE	FLIGHT	FILE	Start Hour	End Hour	Delta Time, sec	ALT	OD	OD	OD	ON/OFF Ratio	OD	ON/OFF Ratio
LAND							MEAN-1s¹	STDV-1s¹	SNR-1s¹	SNR-1s¹	SNR-10s¹	SNR-10s¹
101807	2	7	11.505	11.515	36	3306	0.3579	0.0043	332.96	630.83		
102107	5	6	11.560	11.672	403	3126	0.3574	0.0040	252.89	707.60	324.85	908.95
102107	6	5	20.200	20.354	554	3141	0.3567	0.0047	212.79	596.61	272.71	764.61
102207	7	3	11.145	11.200	198	3132	0.3536	0.0028	263.06	743.86	395.89	1119.47
102307	8	2	4.880	4.960	288	3153	0.3392	0.0030	336.11	990.93	563.39	1661.01
102307	8	3	5.070	5.170	360	3144	0.3363	0.0024	291.73	867.54	393.05	1168.85
									Ave SNR	264.92	759.56	389.98	1124.50
									CO2 (ppm)	1.43	0.50	0.97	0.34
WATER													
102207	7	5-W	10.940	11.020	288	3127	0.3567	0.0076	131.09	367.50	299.54	814.52
									CO2 (ppm)	2.90	1.03	1.31	0.47

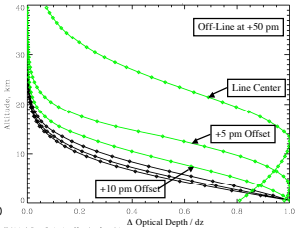
Off/off signal ratios show SNR = 5,000 for 10-s average with root-N dependence.

Laser Measurements Across CO_2 Absorption Line

CO_2 Absorption & Laser Wavelengths

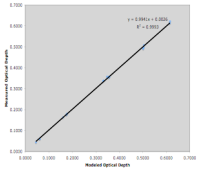


Normalized CO_2 Weighting Functions



ACCLAIM CO_2 Measurements

CO_2 OD Comparisons



- In situ profiles of CO_2 on each flight were used to determine in situ OD and comparisons with measured CO_2 OD showed high correlation under wide range of surface and background conditions.

CO_2 OD and Mixing Ratio Comparisons

FLIGHT	FILE	Start Hour	End Hour	Altitude	CO2 Optical Depths (OD) & Mixing Ratios (MR)					
					OD MEASURED (M)	MR MEASURED (M)	OD MODELED (A)	MR MODELED (A)	OD DIFF (%)	MR DIFF (ppm)
1	2	16.213	16.325	4701	0.4955	378.6	0.5005	382.5	-1.01	-3.8
	3	16.383	16.445	4702	0.4934	376.7	0.5008	382.5	-1.49	-5.6
	4	16.585	16.634	4700	0.4909	374.8	0.5010	382.5	-2.00	-7.6
2	3	10.795	10.886	4725	0.5081	385.8	0.5045	382.3	0.70	2.7
	4	10.95	10.97	4715	0.4986	378.8	0.5032	382.3	-0.91	-3.5
	7	11.505	11.515	3306	0.3579	394.2	0.3474	382.4	3.05	11.6
	9	11.988	12.024	1720	0.1813	390.2	0.1778	382.4	1.98	7.5
5*	5	11.31	11.44	5382	0.6127	383.8	0.6142	384.7	-0.25	-0.9
	6	11.56	11.672	3126	0.3574	388.1	0.3560	386.6	0.39	1.5
	7	11.82	12	1526	0.1758	395.7	0.1737	391.2	1.19	4.5
	8	12.07	12.092	1524	0.1771	394.6	0.1755	391.2	0.96	3.4
6*	4	19.9	20	5398	0.6221	389.1	0.6154	385.0	1.07	4.1
	5	20.2	20.354	3141	0.3567	385.6	0.3579	386.9	-0.35	-1.3
7*	S-W	10.94	11.02	3127	0.3567	385.3	0.3554	383.9	0.37	1.4
	7-L	11.145	11.2	3132	0.3536	383.4	0.3541	383.9	-0.14	-0.5
8	2	4.88	4.96	3153	0.3392	391.6	0.3328	384.0	1.92	7.3
	3	5.07	5.17	3144	0.3363	390.2	0.3310	384.0	1.58	6.0
	4	5.28	5.44	1543	0.1631	393.4	0.1599	385.3	2.03	7.7
	5	5.52	5.67	599	0.0606	384.3	0.0608	386.0	-0.48	-1.8
	6	5.73	5.95	597	0.0605	386.2	0.0605	386.0	-0.01	0.0
	7	6.055	6.15	447	0.0444	379.9	0.0451	386.0	-1.62	-6.1
								Average	384.84	0.33	1.25
								Std Dev	2.62	1.35	5.13

* Operational mode change, in-flight calibration on Flt 7, Leg 8, and altitudes limited to <5500 m.

Results from ACCLAIM Flight Tests

- Obtained EXTENSIVE data set for ACCLAIM instrument performance evaluation and CO_2 column measurement accuracy and precision.
- Flight tests conducted over wide range of surface reflectances, including measurements in presence of scattered clouds, and determined their effective backscatter reflectance at 1.57 micron.
- Obtained high signal-to-noise (SNR >250 or <1.5 ppm CO_2 uncertainty) for CO_2 column measurements with 1-s averaging times over land and 10-s averaging over water.
- Absolute comparisons show ACCLAIM CO_2 optical depths were within ~1.5% (~5 ppm) of the modeled optical depths calculated from in situ CO_2 profiles - cases with larger differences thought to be associated with large boundary layer CO_2 variability.
- October flight tests were coordinated with JPL 2-micron heterodyne laser system on Twin Otter aircraft - results to follow.
- Follow-on series of proposed joint flights in summer/fall of 2008 will build on this initial set of successful results.

Acknowledgements: This study was funded by NASA's Earth Science Division, NASA Langley Research Center, ITT Corporation, and the University of New Hampshire.