Airborne Laser Remote Measurements of Atmospheric Carbon Dioxide

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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 six airborne campaigns conducted in different geographic regions over the last four 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 at the center of 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 from an altitude of 3.3 km and an optical depth of 0.36 for 1-s averages over land and 10-s over water. The SNR increases at higher optical depths, and it exceeds 800 (<0.5 ppm CO_2) at optical depths greater than 1.0. This capability was confirmed in SNR studies using two unabsorbed laser wavelengths.

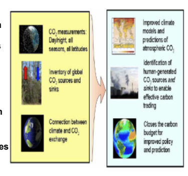
In the latest flight experiments conducted in September-October 2008, the absolute accuracy of the CO_2 remote measurements were shown to agree with the in situ measurements to better than 0.75 percent (<3 ppm CO_2). The results presented here are the first high-quality, quantitative measurements of CO_2 made with an airborne laser remote sensing system. This airborne LAS could make significant contributions to large-scale studies of CO_2 over North America.

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)"

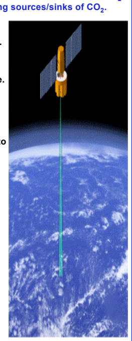
- **Objective 1.** Quantify global spatial distribution of atmospheric CO_2 on scales of weather models
- **Objective 2.** Quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1 degree grids at weekly resolution
- **Objective 3.** Provide a scientific basis for future projections of CO_2 sources and sinks through data-based process Earth System models


CO2 measurements: Daylnight, all seasons, all latitudes
Inventory of global CO2 sources and sinks
Connection between climate and CO2 exchange
Improved climate models and predictions of atmospheric CO2
Identification of human-generated CO2 sources and sinks to enable effective carbon trading
Closes the carbon budget for improved policy and prediction

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/sinks of CO_2.

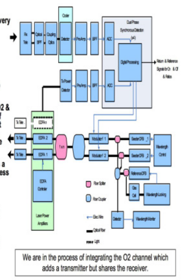
- CO_2 column measurement
  - CO_2 Laser Absorption Spectrometer to resolve (or weight) the CO_2 altitude distribution, particularly across the mid to lower troposphere.
  - 1.6-micron LAS only baseline or integrated 1.6-micron + 2.0-micron LAS option
- Surface pressure measurement
  - O_2 Laser Absorption 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.



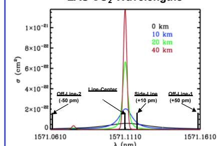
1.57-micron Laser Absorption Spectrometer (LAS)

LAS Architecture

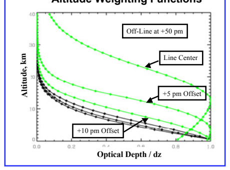
- Synchronous, Lock-In Detection is a very sensitive, yet simple and robust technique.
- Simultaneous transmission of all wavelengths eliminates significant source of error from fast changes in target reflectivity; reduces pointing requirements, converts most noise to common mode.
- Use of one receiver 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.


Cooler
Rx Tele
Optical BPF
Coupling Optics
Detector
PreAmp
BPF
ADC
Dual Phase Synchronous Detection
Digital Processing
Tx Power Detector
EDFA 2
EDFA 1
EDFA Controller
Laser Power Amplifiers
Modulator 1
Modulator 2
Wavelength Control
Wavelength Locking
Wavelength Monitor
Gas Cell
We are in the process of integrating the O2 channel which adds a transmitter but shares the receiver.
ITT

LAS CO_2 Wavelengths



Altitude Weighting Functions



ACCLAIM LAS Flight Test Campaigns

Advanced CO_2 and Climate LAser International Mission (ACCLAIM)

(Active CO_2 Instrument for ASCENDS Mission)

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 Lear Flights: Land, Day & Night)

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

October 20-24, 2006
Portsmouth, New Hampshire
(4 Lear Flights: Land & Water, Day & Night)

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

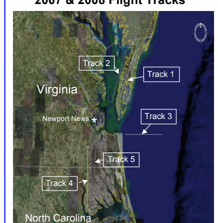
October 17-22, 2007
Newport News, Virginia
(9 Lear Flights: Land & Water, Day & Night, Clear & Cloudy)

September 22-October 30, 2008
Newport News, Virginia
(10 UC-12 Flights: Land & Water, Day & Night, Rural & Urban)

ACCLAIM on Lear-25

ACCLAIM on UC-12

2007 & 2008 Flight Tracks



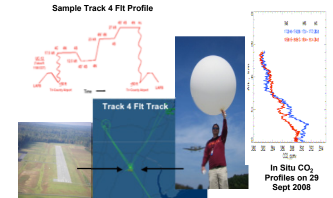
October 2007 Flights (Land-Brown; Water-Blue)

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	1021	1242	Low & Mid Scat. Clds
				Twin Otter	1000	1305	
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	1900	2030	Clear Below 20kft
				Twin Otter	1825	~2100	
7	10/22	Bay & Coast, Late-Morning	1 & 2	Lear	1005	1208	Mostly Clear
			2	Twin Otter	1010	~1230	
8	10/23	Inland, Pre-Dawn	4	Lear	431	645	Clear
				Twin Otter	441	706	
9	10/23	Ocean, Late-Morning	3	Lear	949	1217	Many Clds
				Twin Otter	1010	~1245	

Enhanced In Situ Sampling Approach

- High precision (<0.05 ppm) in situ CO_2 measurements made on UC-12 on spirals done at center of legs at start and finish of each flight
- Spirals done over low-use airport so sampling could be done to surface on touch-and-go at airport (see example of in situ CO_2 profiles)
- Radiosondes launched before and after each flight at airport for T, P, & RH profiles to constrain CO_2 retrievals
- Flight legs flown at various altitudes (see sample flight profile)

Sample Track 4 Flt Profile



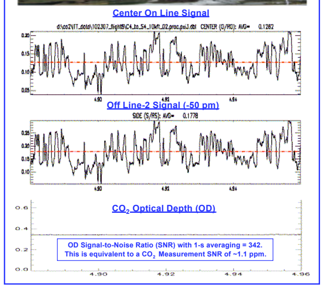
Tri-County Airport North Carolina

Sondes & Touch and Go

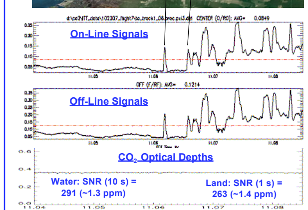
In Situ CO_2 Profiles on 29 Sept 2008

ACCLAIM Signals & CO_2 Measurements

Measurements Over Land on 23 Oct. 2007



Water-Land Transition on 22 Oct. 2007



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-1s*	STDV-1s*	SNR-1s*	SNR-1s*	SNR-10s*	SNR-10s*
101807	2	7	11.505	11.515	36	3306	0.3579	0.0043	232.96	650.83		
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	7-L	11.145	11.200	198	3132	0.3536	0.0038	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	0.0034	291.73	867.54	393.05	1168.85
								Ave [SNR]	264.92	759.56	389.98	1124.58
								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	290.54	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.

CO_2 Optical Depth & Mixing Ratio Comparisons

CO_2 Comparisons, October 2007 Campaign

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	10.806	4725	0.5081	385.0	0.5045	382.3	0.70	2.7
	4	10.95	10.97	4715	0.4986	379.8	0.5032	382.3	-0.91	-3.5
	7	11.505	11.515	3306	0.3579	394.3	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	0.90	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*	5-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	-6.2
							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.

- 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 Comparisons, September-October 2008

Center Line (CL)/Primary Offline (PO)

IDENT	FLIGHT	FILE	Start Hour	End Hour	Delta Time, sec	CH2, CH3, CH4	ALT	CL/PO			
								MEASURED* (M)	MODEL-1 (A)	DIFF (M-A)	(DIFF/A)* 100
092908_flight2	2	0	17.79	17.83	144.0	CL, SO, PO	5553	0.598776	0.600648	-0.001871	-0.31
092908_flight2		1	17.95	18.06	396.0	CL, SO, PO	5549	0.597535	0.599859	-0.002324	-0.39
092908_flight2		2	18.255	18.338	298.8	CL, SO, PO	5546	0.600098	0.599939	0.000159	0.03
092908_flight2		2	18.342	18.442	360.0	CL, SO, PO	5549	0.600321	0.599748	0.000573	0.10
092908_flight2		3	18.543	18.561	64.8	CL, SO, PO	4600	0.494888	0.491909	0.002979	0.61
092908_flight2		4	18.572	18.648	273.6	CL, SO, PO	4593	0.493848	0.491944	0.001904	0.39
092908_flight2		4	18.652	18.731	284.4	CL, SO, PO	4598	0.496579	0.493105	0.003473	0.70

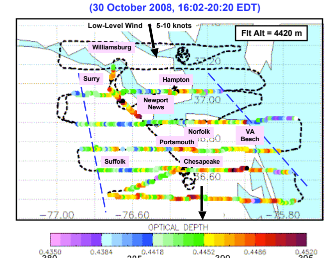
IDENT	FLIGHT	FILE	Start Hour	End Hour	Delta Time, sec	CH2, CH3, CH4	ALT	CL/PO			
								MEASURED* (M)	MODEL-1 (A)	DIFF (M-A)	(DIFF/A)* 100
100208_flight3	3	2	12.05	12.17	432.0	CL, SO, PO	5460	0.590927	0.592422	-0.001495	-0.25
100208_flight3		3	12.225	12.305	288.0	CL, SO, PO	5456	0.590424	0.592030	-0.001605	-0.27
100208_flight3		3	12.36	12.47	396.0	CL, SO, PO	5467	0.593952	0.595124	-0.001171	-0.20
100208_flight3		4	12.55	12.775	810.0	CL, SO, PO	3884	0.419915	0.416640	0.003274	0.79

Side Line (SL)/Primary Offline (PO)

IDENT	FLIGHT	FILE	Start Hour	End Hour	Delta Time, sec	CH2, CH3, CH4	ALT	SL/PO (*0.5-W Power)			
								MEASURED (M)	MODEL-1 (A)	DIFF (M-A)	(DIFF/A)* 100
100808_flight7	7	7*	13.216	13.294	280.4	CL, SL, PO	3906	0.279730	0.279843	-0.000113	-0.04
100808_flight7		8*	13.367	13.525	568.4	CL, SL, PO	3903	0.276990	0.279437	-0.002447	-0.88
100808_flight7		9*	13.648	13.664	57.6	CL, SL, PO	3905	0.278852	0.279500	-0.000648	-0.23
100808_flight7		9*	13.687	13.707	72.0	CL, SL, PO	3905	0.278759	0.279457	-0.000698	-0.25

Urban Plume Observations

(30 October 2008, 16:02-20:20 EDT)



Equivalent CO_2 Column Average, ppm

Results from Flight Tests and Future Applications

- First high-precision, high-accuracy, remote measurements of CO_2 were demonstrated from an airborne platform.
- High-precision CO_2 column measurements were made with a Signal-to-Noise Ratio (SNR) of >250 (<1.5 ppm CO_2 uncertainty) for 1-s averaging times (~150 m) over land and 10-s (~1.5 km) averaging over water, and the SNR increased to >390 (<1 ppm CO_2) with 10-s averaging over land.
- Absolute accuracy of the remote CO_2 optical depth measurements were shown to be within ~1.5% (~5 ppm) of the modeled optical depths calculated from in situ CO_2 profiles in the 2007 campaign, and using the enhanced in situ sampling approach, they were within <0.75% (~3 ppm) in the 2008 campaign.
- Extensive data sets were collected for ACCLAIM instrument performance evaluation over a wide range of surfaces and in presence of scattered clouds.
- First airborne remote observations of enhanced CO_2 in urban plumes were obtained during the October 2008 campaign where the column CO_2 were seen to increase from background CO_2 levels in the mid-380 ppm to well over 395 ppm in many down-wind locations.
- This airborne remote CO_2 measurement capability can be used in regional to continental-scale studies of CO_2 over North America to investigate CO_2 sources and sinks and to evaluate and improve carbon budget models.

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