A review of 10 years of CO2LAS flights

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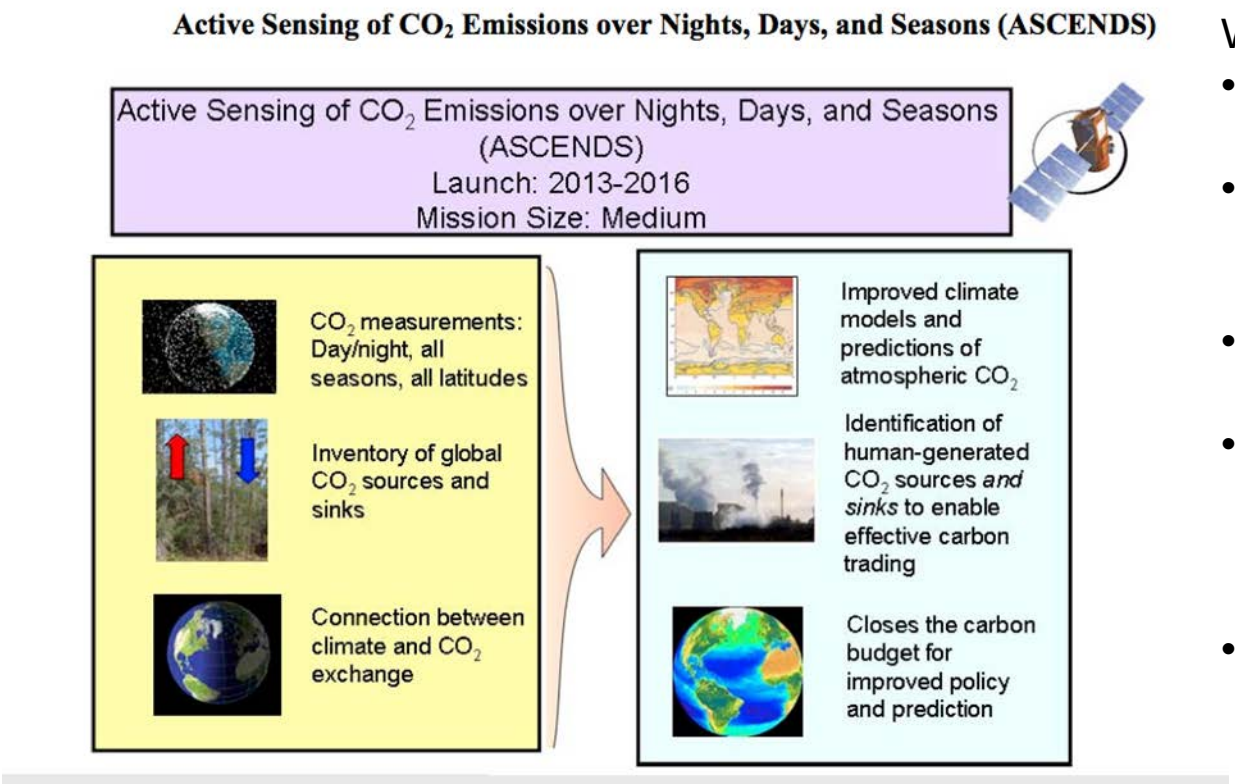
Outline

- Context: ASCENDS Mission Concept – Modeling and Measurements

- CO2LAS instrument concept
- The CO2LAS instrument
- Changes since initial construction
- Data processing overview
- Lab testing
- Installation on Twin Otter and early results
- Installation on NASA DC-8 and ASCENDS Campaigns
- Future Plans

NASA ASCENDS Mission

From the NASA 2007 Earth Science Decadal Survey:



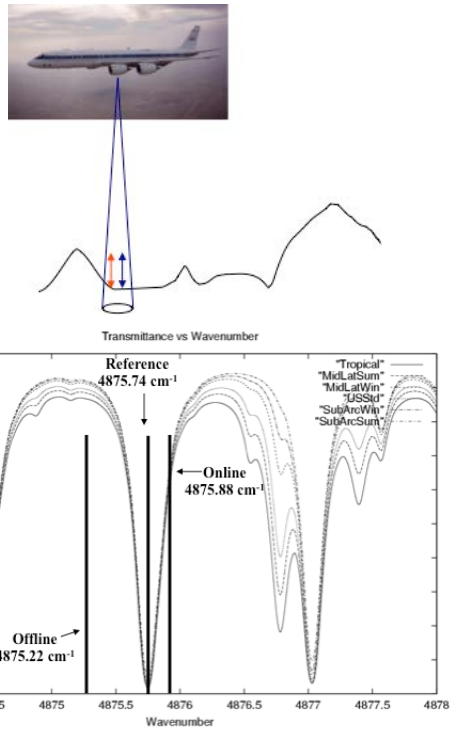
Why lasers ?

- Measures night & all times of day;
- Constant nadir/zenith path, mitigates scattering effects;
- Measurements at high latitudes, all seasons;
- Small measurement footprint (better coverage through broken clouds,
- Reduced bias issues

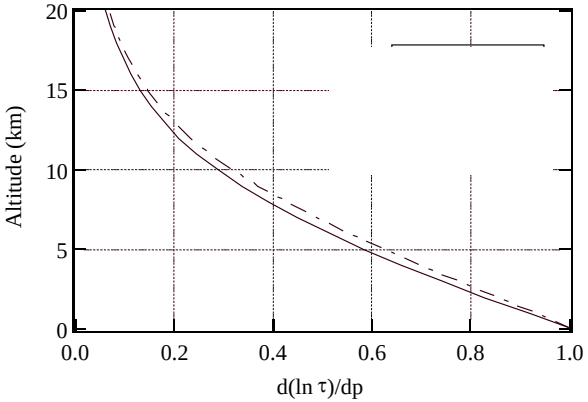
Use IPDA (Integrated Path Differential Absorption) method to measure weighted column abundance of CO_2 - rely on lidar reflectance from the Earth surface

CO2LAS Instrument Concept

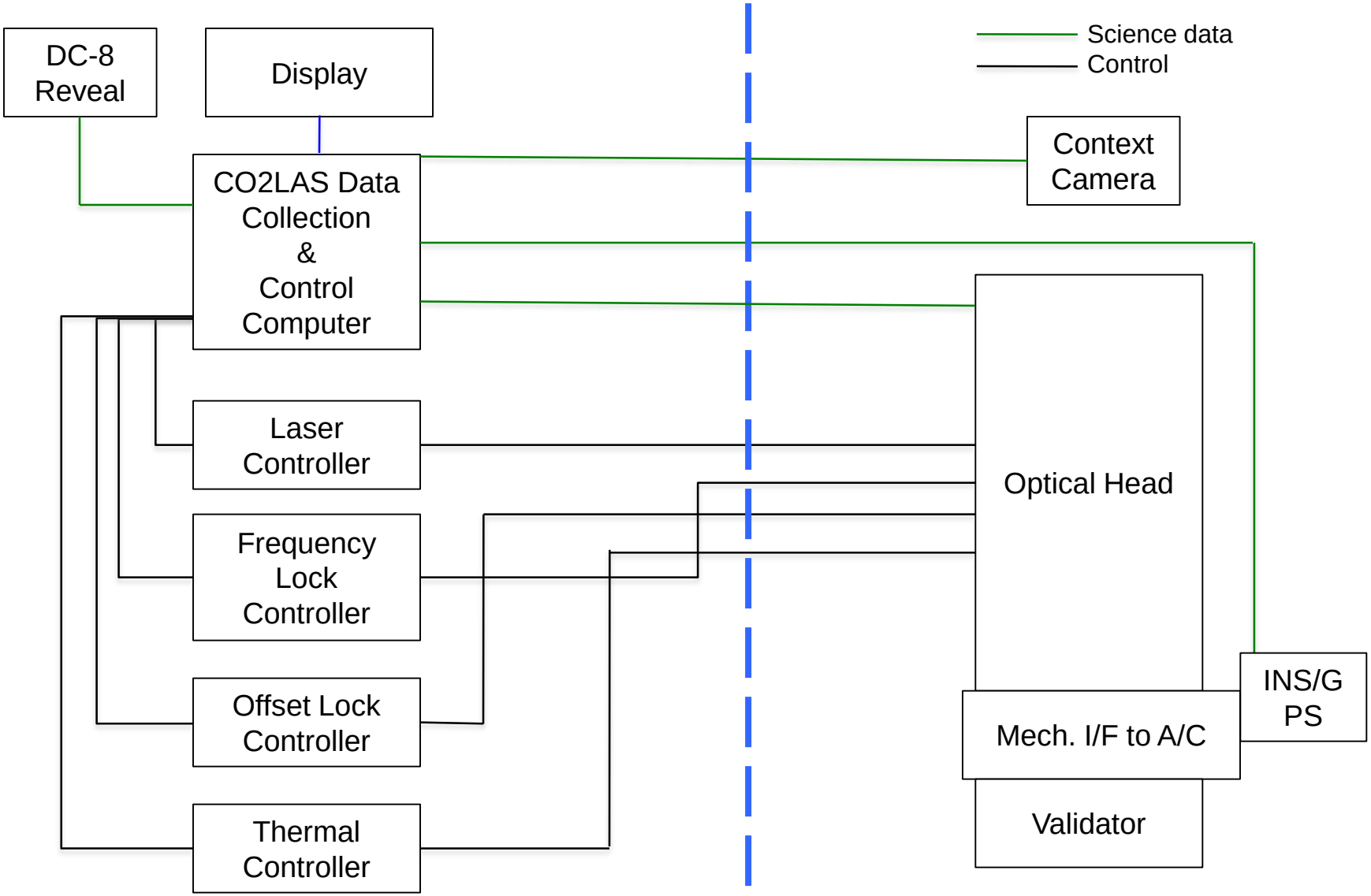
- Transmit and receive with near nadir-pointing of on- and off-line wavelength channels
  - Ground surface backscatter (land and sea) provides return signal
  - Measure integrated path differential absorption (IPDA)
  - Works in the dark, immune to solar contamination
- Heterodyne detection at 2-μm wavelength
  - high sensitivity reduces mass/power/size of system required
  - detected signal spectrum provides ancillary information (spectral purity, stability, cloud data)
- Use models and/or additional sensor data (T, P, RH, GPS, altimetry, line parameters) and forward model to retrieve weighted CO_2 column mixing ratio.
- Measurement preferentially weights PBL where CO_2 sink and source structures are most measurable against background
- Key is data processing and analysis to control for other error terms eg 10m range error ~ 1ppm
- Applicable to other trace gas species by changing laser wavelength



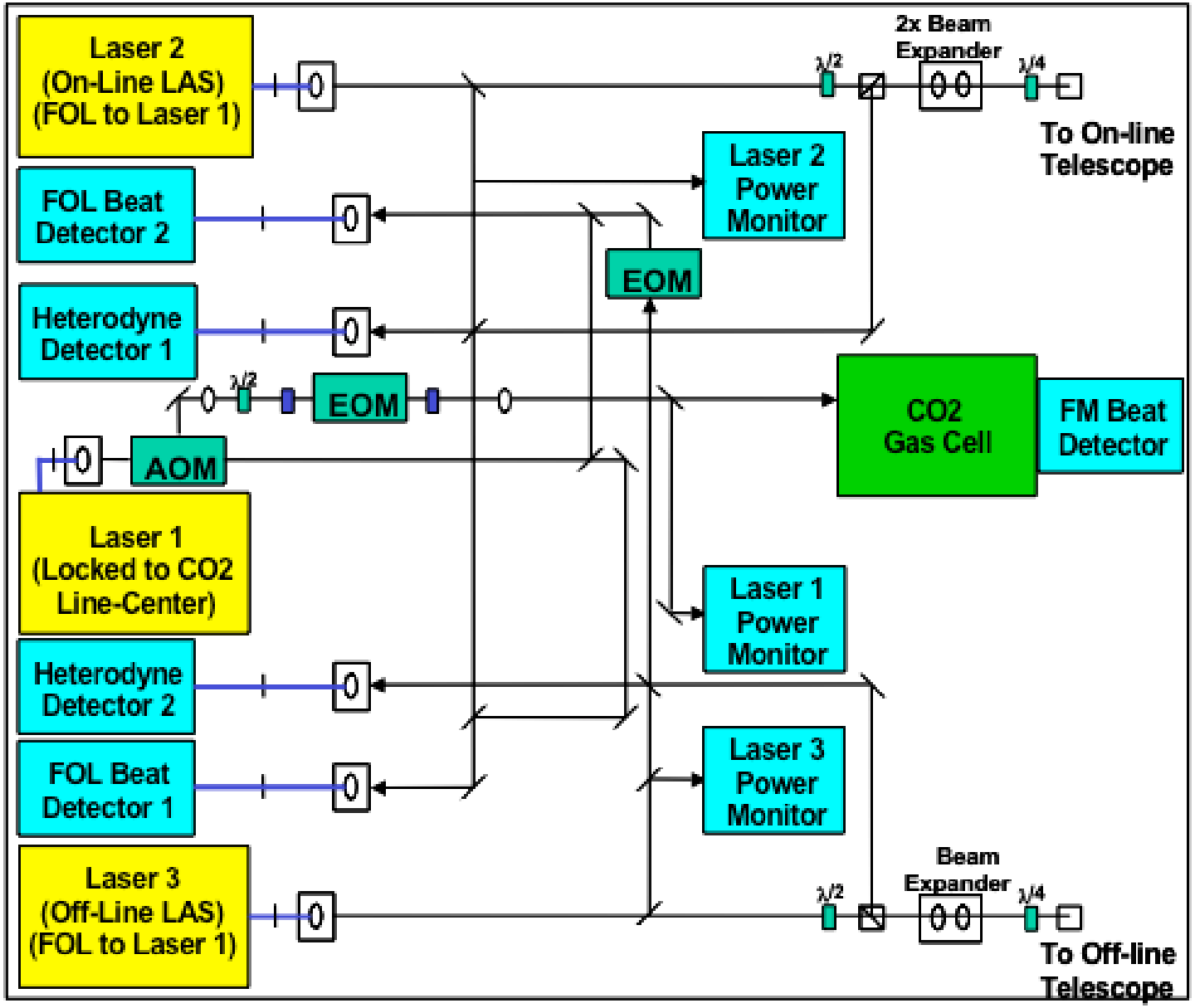
Weighting Functions at 2.0μm



System Block diagram



Functional Configuration of the CO2LAS Optical Head



CO2LAS Instrument

Parameter	Value
CO_2 Line Center	4875.747 cm^{-1}
Offline Laser	4875.225 cm^{-1}
Online Laser	4875.882 cm^{-1}
Transmitted Laser Power	<100 mW
Transmit/Receive Aperture	10 cm diameter
Receiver FOV	60 mrad
Photomixer type	InGaAs
Receiver heterodyne frequency window	10-25 MHz
Signal Digitization	14 bit/ 60 MHz ea. channel

- Single frequency, single mode, Th, Ho:YLF Lasers
  < 200kHz linewidth (<0.2 pm)
- Reference locked to CO2 cell
  better than $1:10^7$ or 0.2 pm

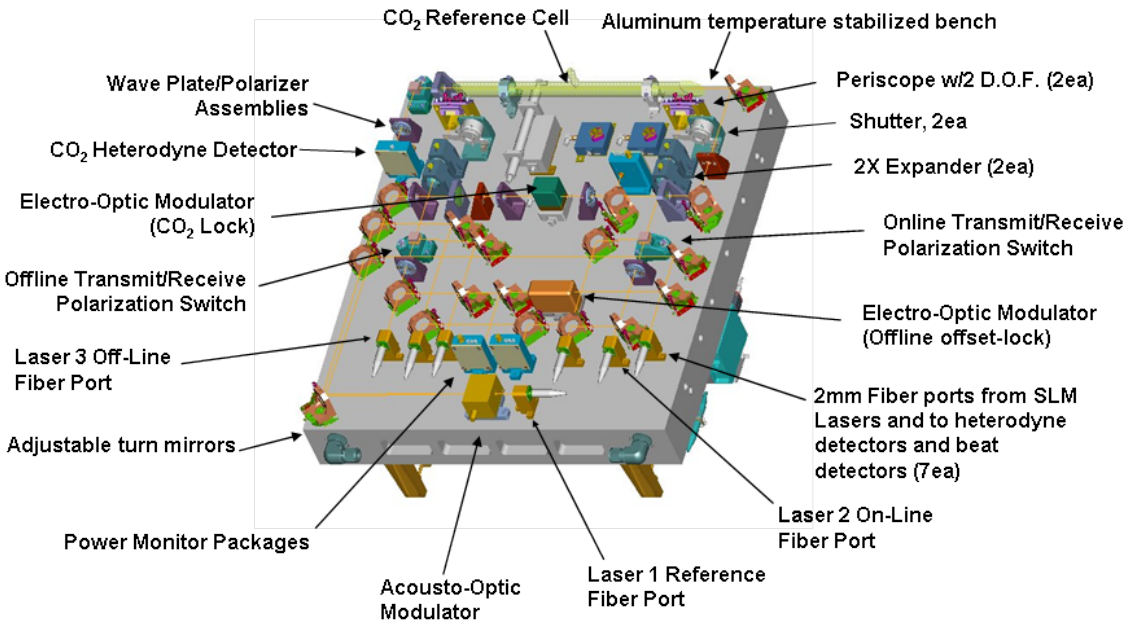
Offline and Online lasers offset locked to reference laser

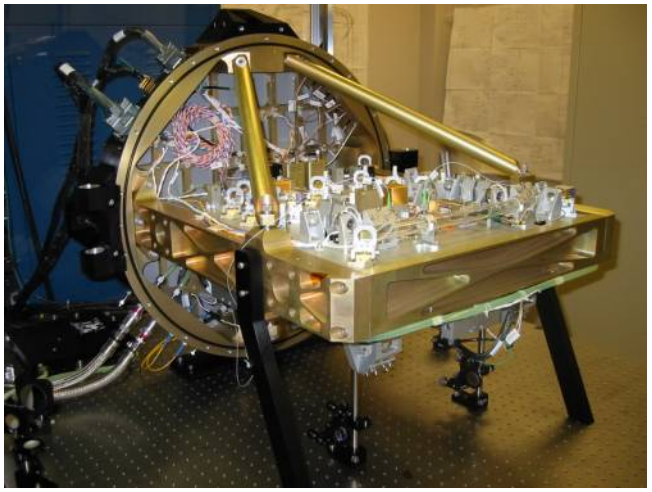
Instrument thermal control maintains < 1 deg temperature variation over all hold thermal conditions (-30 C to +40 C)

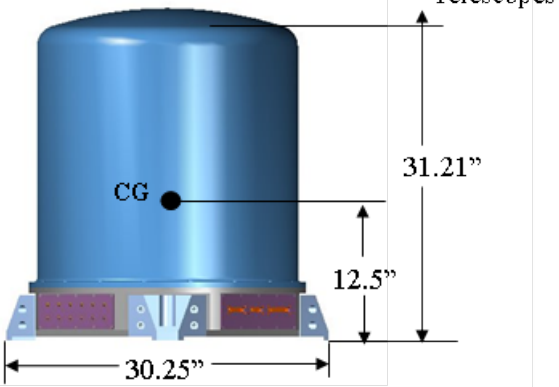
Ancillary Data Collected:

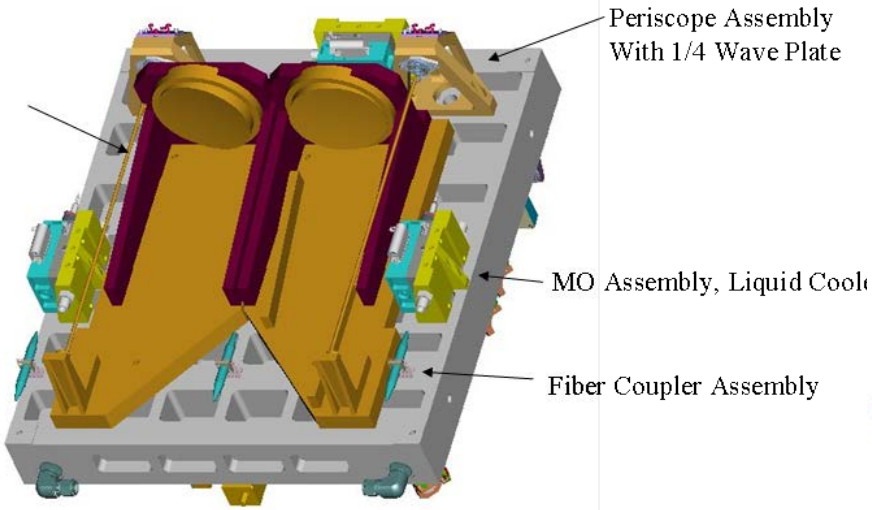
- Dedicated INS/GPS on aircraft mounting frame
- Nadir viewing context camera
- Pressure, temperature (multiple) and humidity in instrument
- A/C pressure, temperature

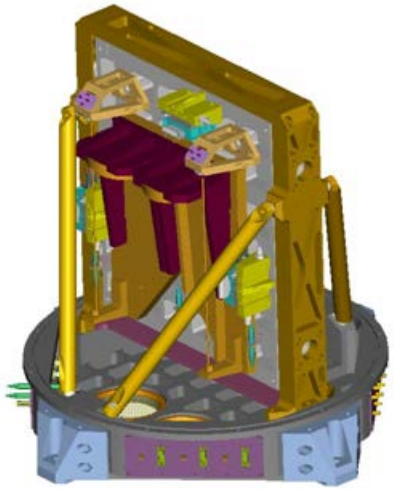
Optical Head Layout





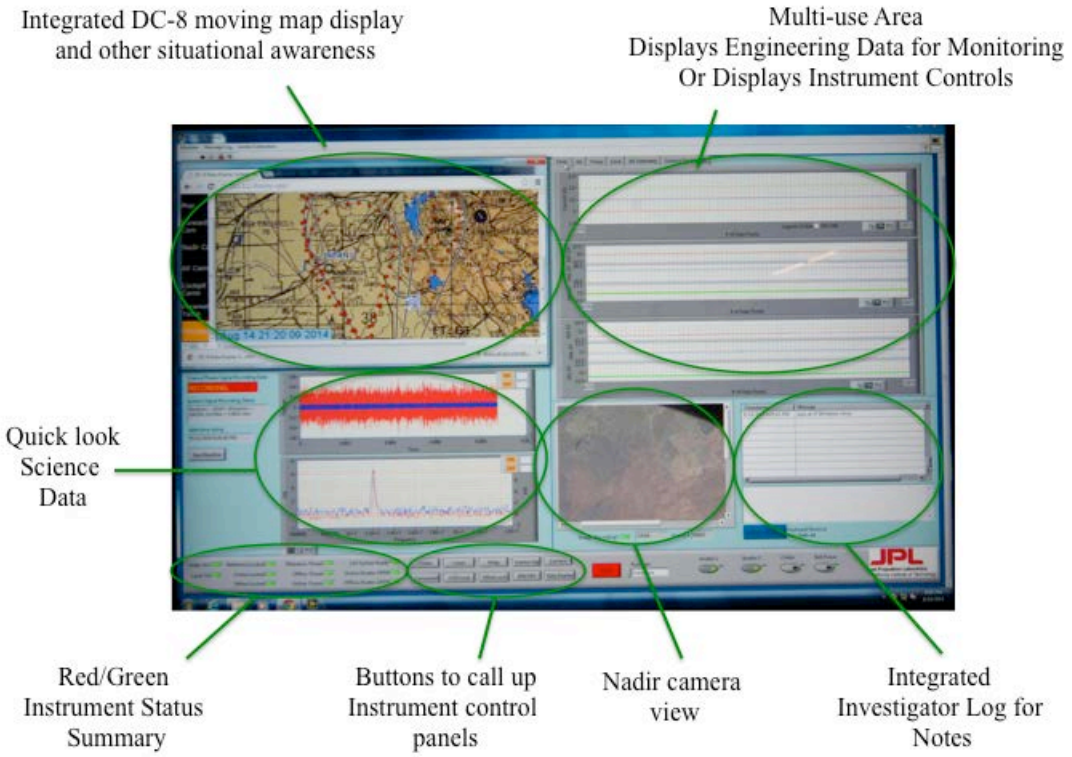


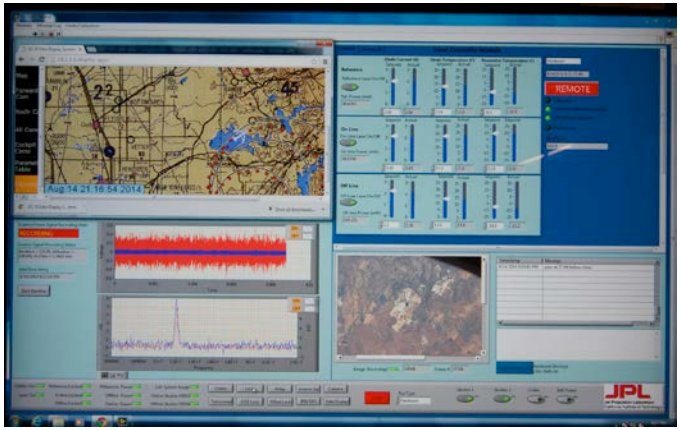




Upgrades

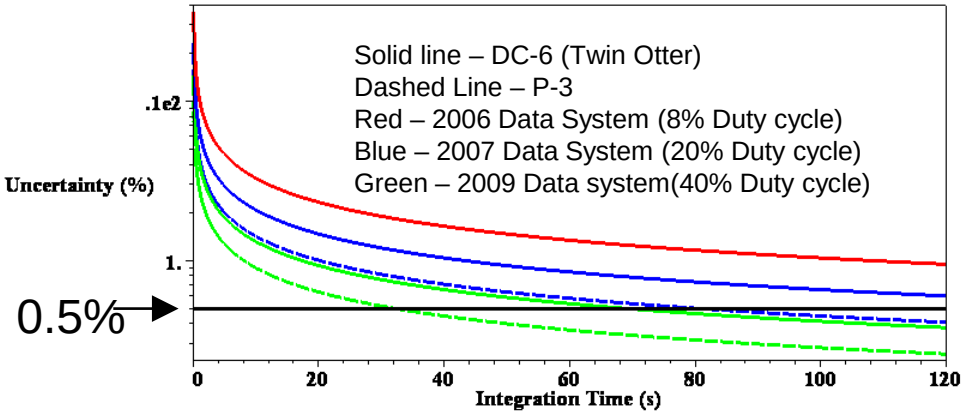
2012/13 Renovated offset frequency lock
2012/13 Refurbished online and offline lasers
2013/14 Upgraded thermal control system
2014 Command and data handling system upgraded
Replaced 3 computers with 1 allowing 100% data duty cycle
1 TB/hour data collection w. 12TB onboard storage
2015/16 1W amplifier added to online channel





Speckle Averaging & Data Duty Cycle

- **Heterodyne Detection requires averaging the return signal to reduce speckle fluctuations.**
- **It depends on the platform velocity as well as the data collection system duty cycle (in brackets).**
- **Current aircraft is DC-6. DC-8 was original design choice.**



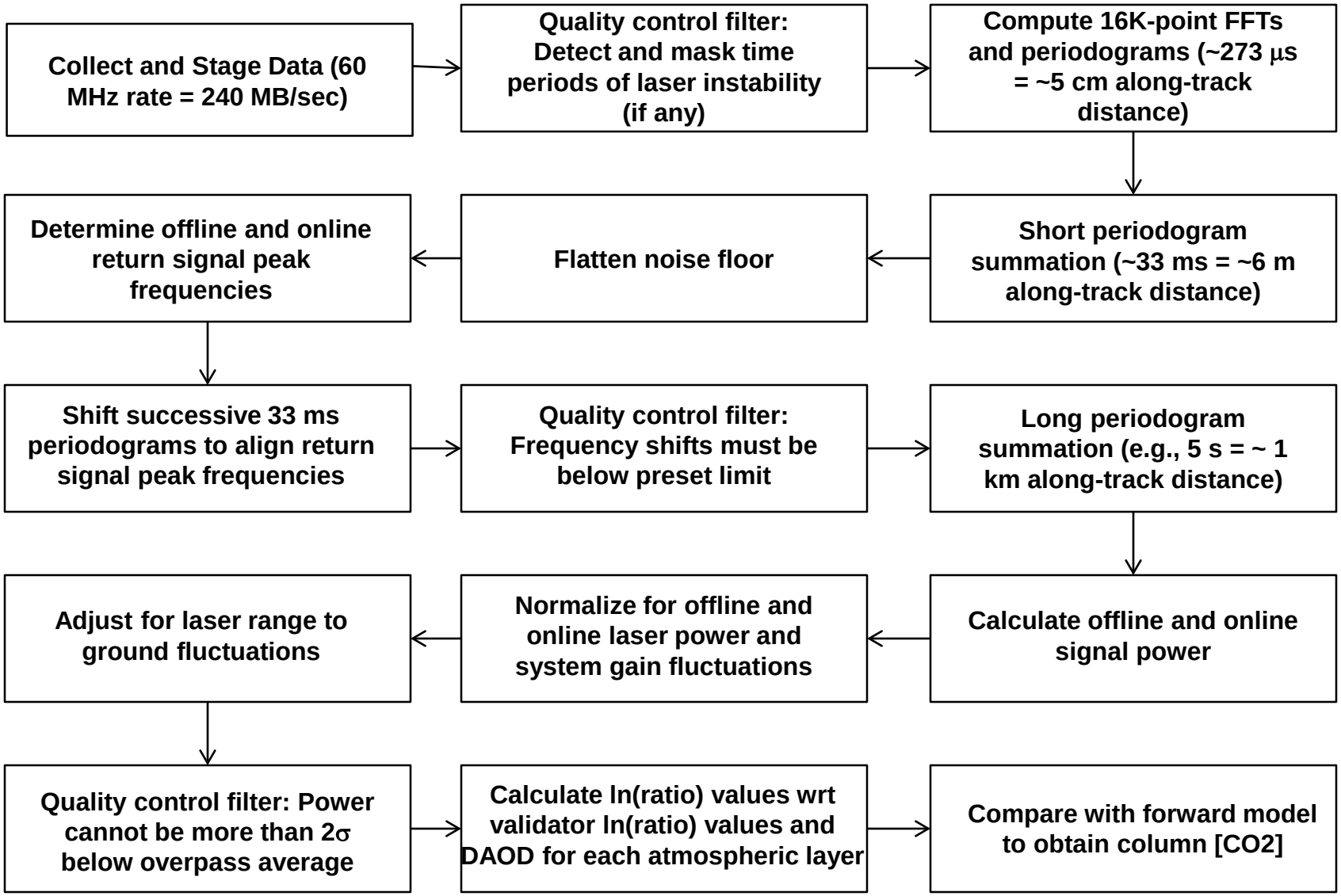
Accumulation time for 2 % precision

Data System	DC-6 70 m/s	P-3 150 m/s	DC-8 250 m/s
2006 (8%)	27 s	13 s	7 s
2007 (20%)	11 s	5 s	3 s
2008/9 (40%)	6 s	2.5 s	1.5 s
2014 (100%)	2.4 s	1 s	0.6 s

Accumulation time for 0.5 % precision

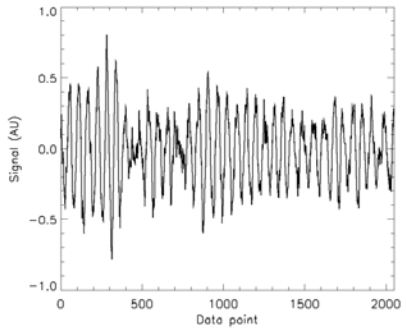
Data System	DC-6 70 m/s	P-3 150 m/s	DC-8 250 m/s
2006 (8%)	429 s	200 s	120 s
2007 (20%)	172 s	80 s	48 s
2008/9 (40%)	86 s	40 s	24 s
2014 (100%)	34 s	16 s	9.6 s

Data Processing Flow

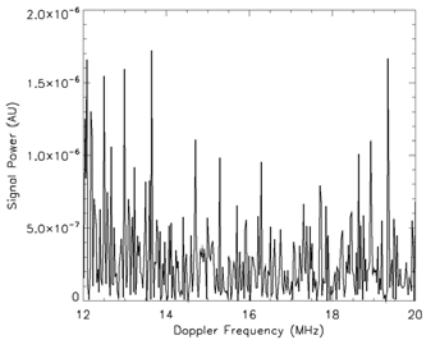


Example Short Period Signal Accumulation

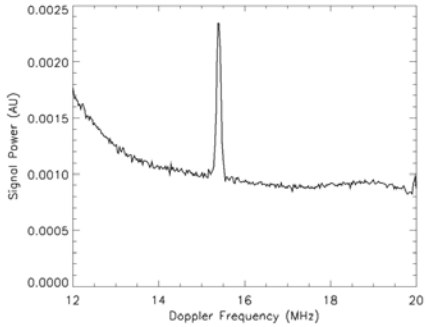
- Heterodyne Intermediate Frequency signals appear in 10-20 MHz window – based on ac ground speed and off-nadir point-ahead angle;
- Digitization rate: 60 MHz; (1) FFT operation (each successive 16K FFT: 273 μs time slice); (2) periodogram formation; (3) periodogram summing
- Data collection volume is ~1 TB/hour (for 2014 revision of the LAS data collection system)



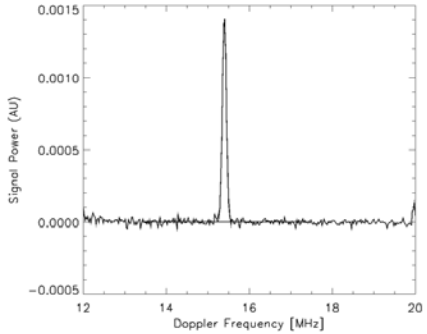
Step (1) Single Channel Raw Data, 2048 pts (0.04 ms)



Step (2) A single periodogram of data – signal buried in noise



Step (3) Sum of periodograms (160 ms)



Step (5) Subtract noise floor leaving signal peak (160 ms)

Initial Laboratory Testing

Laboratory testing has been conducted to evaluate noise performance of the instrument and to evaluate the precision of the instrument in a semi-controlled environment.

Beams from the LAS were directed down the laboratory to a belt sander 17 m from the instrument.

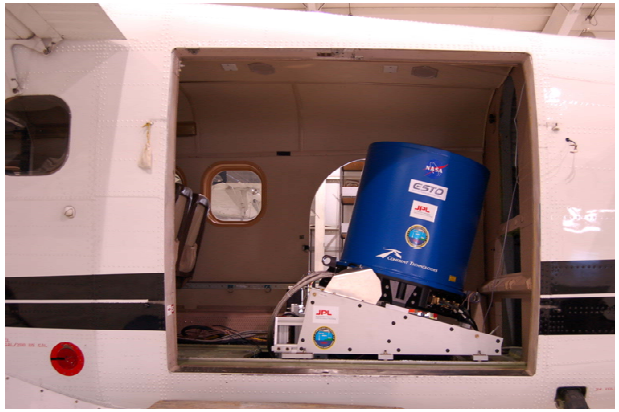
A gas cell of length 87.5 cm was placed in the beam path 7m in front of the belt sander.

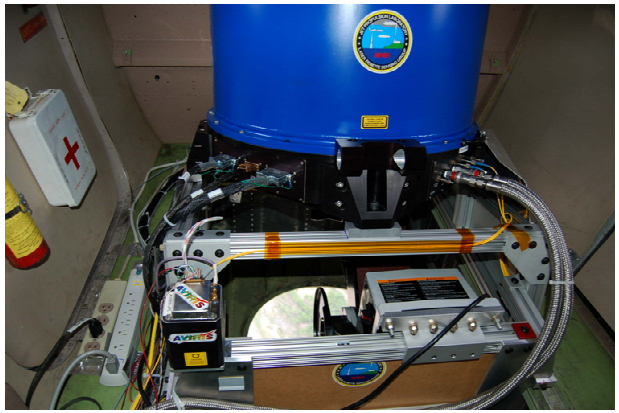
Measurements were collected both with and without CO2 in the gas cell.

Lab tests indicate differential transmittance measurements agree with theoretical prediction to ~1%

	Channel 1 (Offline)	Channel 2 (Online)
Dark noise	6.6E11	1.14E11
Shot noise	2.1E13	5.3E12
Mean value, no gas in cell	2.19 +/- 0.06 E14	7.50 +/- 0.21 E13
Mean value, gas in cell	1.86 +/- 0.04 E14	4.11 +/- 0.12 E13
I1/I2 no gas in cell	2.92	
I1/I2 gas in cell	4.53	

Accommodation on Twin Otter





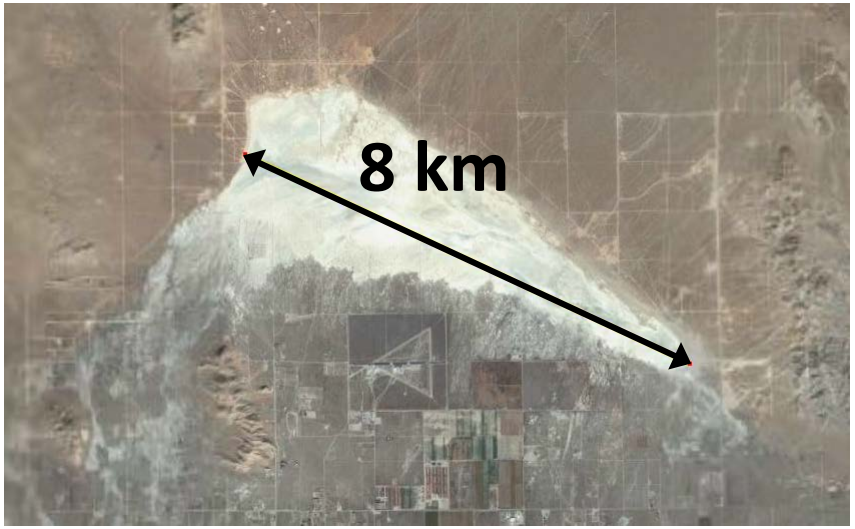
Twin Otter Flights:

• 2006 California: checkout flights conducted over Mojave desert and Pacific Ocean

•2007 Virginia: joint flights with LaRC/ITT

•2009 California: El Mirage, April, 2009.

•2009 Oklahoma: 4 flights near the ARM SGP site, July/August, 2009 – First ASCENDS campaign flights, joint with LaRC/ITT and GSFC airborne instruments all on separate aircraft.

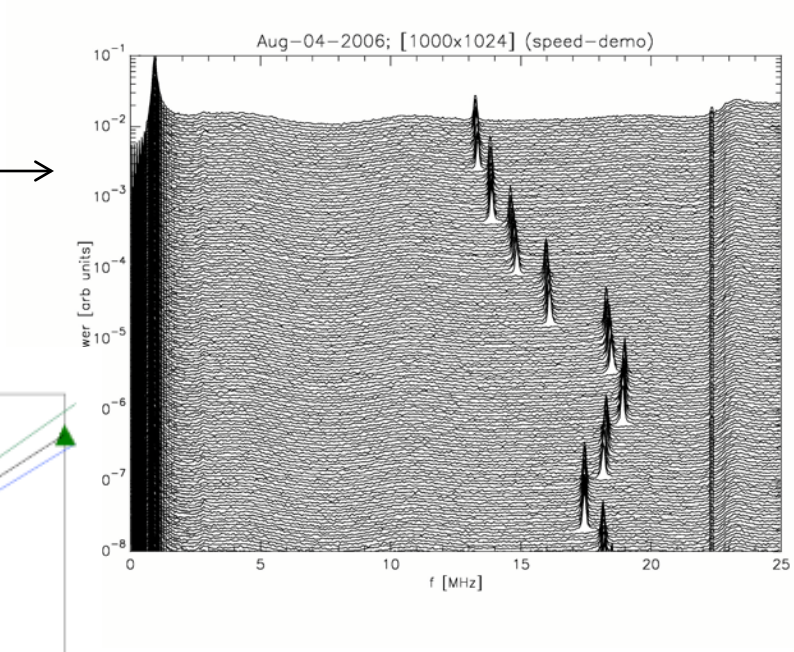


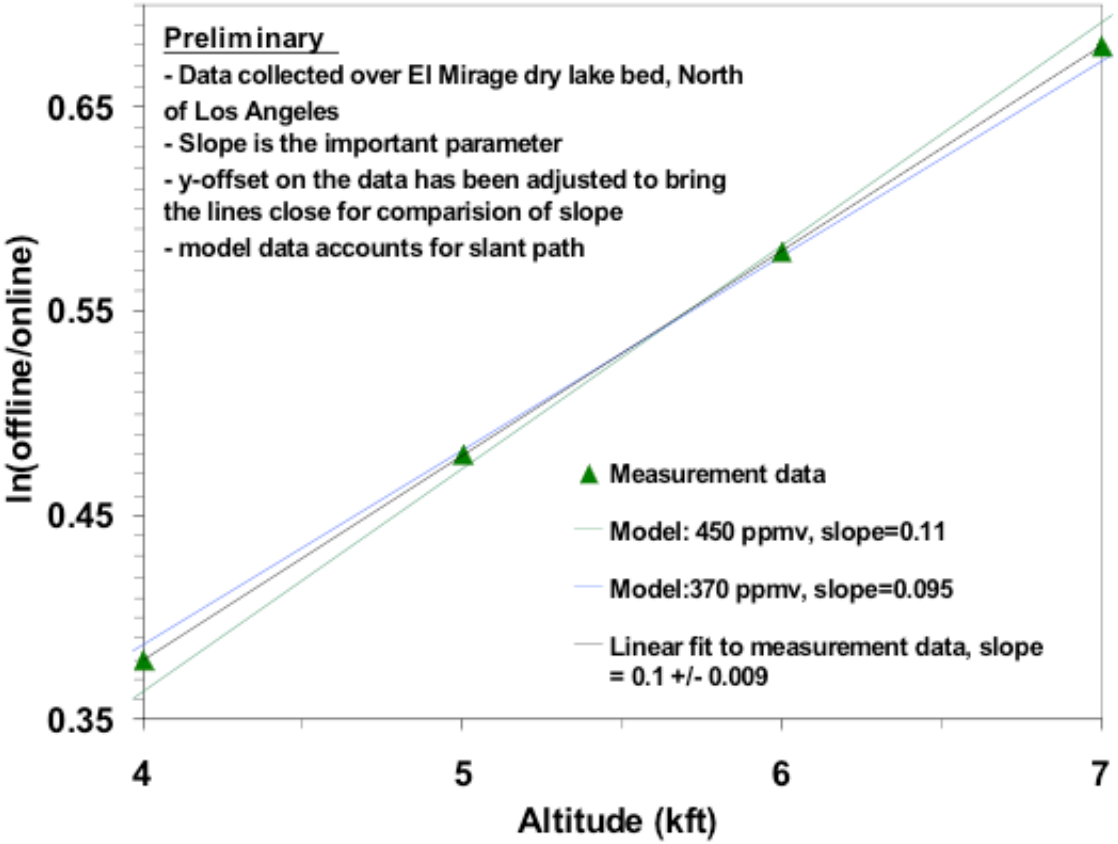
El Mirage Dry Lake Bed

34º 38’ 40” N, 117 35’ 51” W, 2800’ asl

First Aircraft Data (2006/2007)

First data demonstrated Doppler tracking of ground speed





Simple attempt at CO2 retrieval

Accommodation on NASA DC-8

CO2LAS DC-8 Flights:

- 2010 California central valley, desert, RRV cal site, Pacific Ocean
- 2011 California, British Columbia, RRV Pacific Ocean, Four Corners NM, Iowa, WLEF
- 2013 California, Coastal Redwoods, Snow (Rocky Mountains and Mid-West)
- 2014

Control Electronics in DC-8 cabin
Optical head remotely located in rear cargo hold
Despite large temperature variation and gradients the instrument operates correctly – the thermal and vibration isolation system works as designed to insulate the optical bench from the local environment.

DC-8 Accommodation

In-situ Picarro

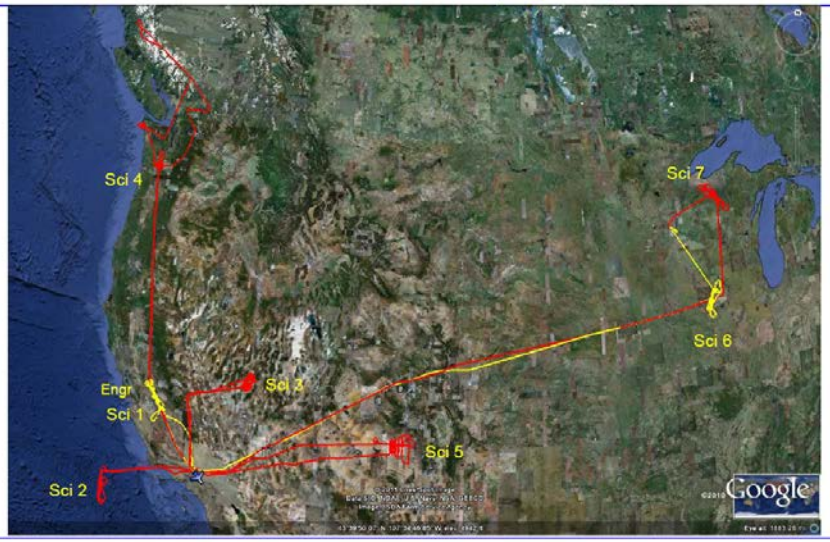
In-situ Avocet

DC-8 Summer 2011 Flight Campaign

- Provide opportunities to detect surface sources, source plumes, and sinks from 5-10 km aircraft altitudes:
  - Power plant plumes
  - CO2 drawdown due to mid-day photosynthetic activity

- Test capabilities to retrieve CO2 column mixing ratio in challenging environments:
  - Cloudy atmospheres: scattered clouds, broken cloud cover, solid cloud cover (e.g. stratocumulus over Pacific Ocean);
  - Terrain variability
    - Variable surface types with highly variable backscatter
    - Topography (e.g., mountains)

- Obtain backscatter data from snow and ice in natural environment at 1.57 μm and 2.05 μm
- 7 flights in total

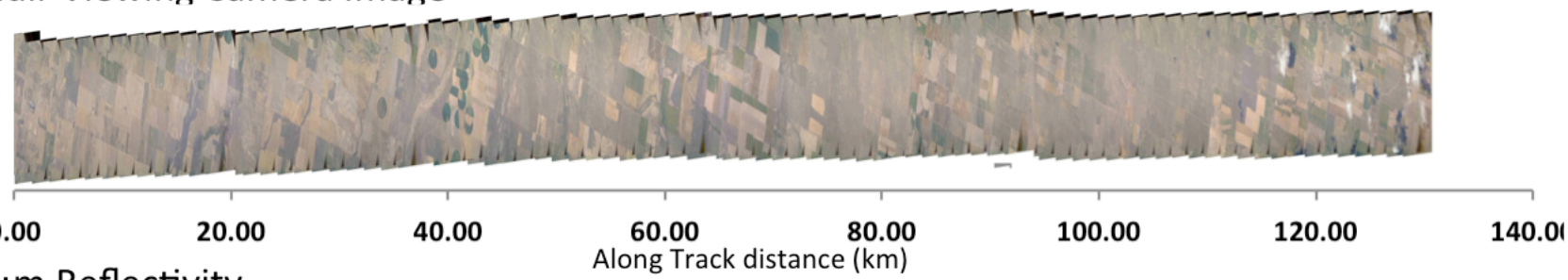


Observation of CO2 Drawdown over Eastern Colorado Plains

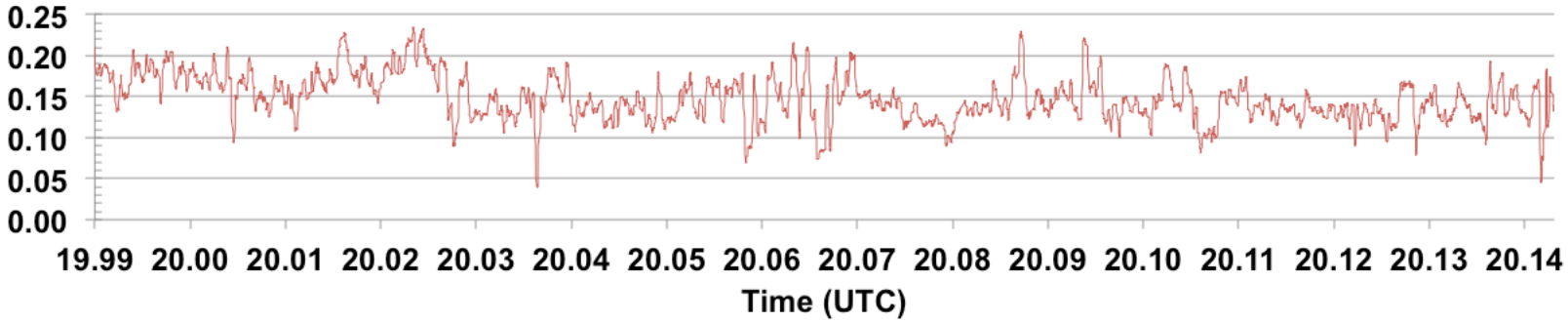
- Objective of 10 August Science Flight over Colorado, Nebraska, Iowa during mid-day:
  - the opportunity to detect/measure CO2 drawdown near the surface due to photosynthetic activity in vegetated areas;
  - Transit from Denver area eastward to Iowa at constant altitude; stable a/c attitude, gradual ground elevation change during transit
  - On-board *in situ* (Picarro) sensor data during spiral over western Iowa agricultural area showed ~ 15 ppm reduction in boundary layer;
- Cloudiness over Nebraska and Iowa: difficult to observe evidence of drawdown during transit at 20 kft;
- Concentrated on eastern Colorado when flying over terrain type transition from arid to vegetated
- Visible and IR reflectance data indicate reflectance variability depending on surface material

Observation of CO2 Drawdown over Eastern Colorado Plains

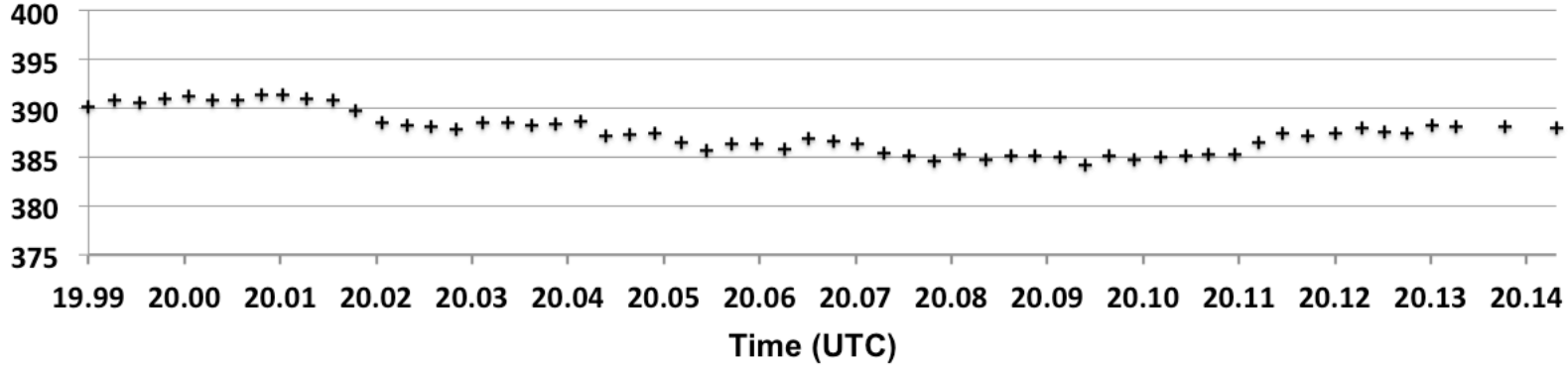
Nadir Viewing Camera Image



2 μm Reflectivity

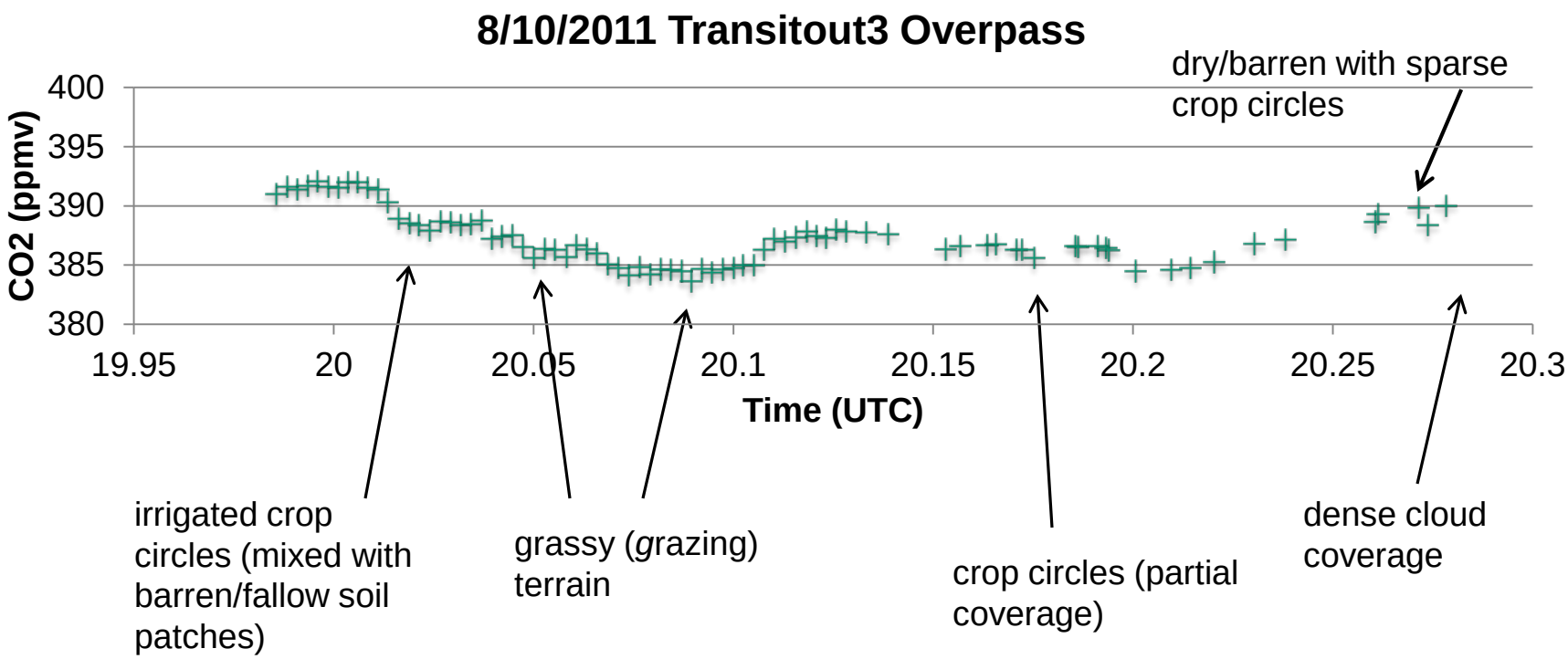


Retrieved CO_2 (ppm), overpass average is 388 ppm



Transit to U.S. Midwest: 20 kft flt. altitude
Evidence of Mid-day CO2 Drawdown

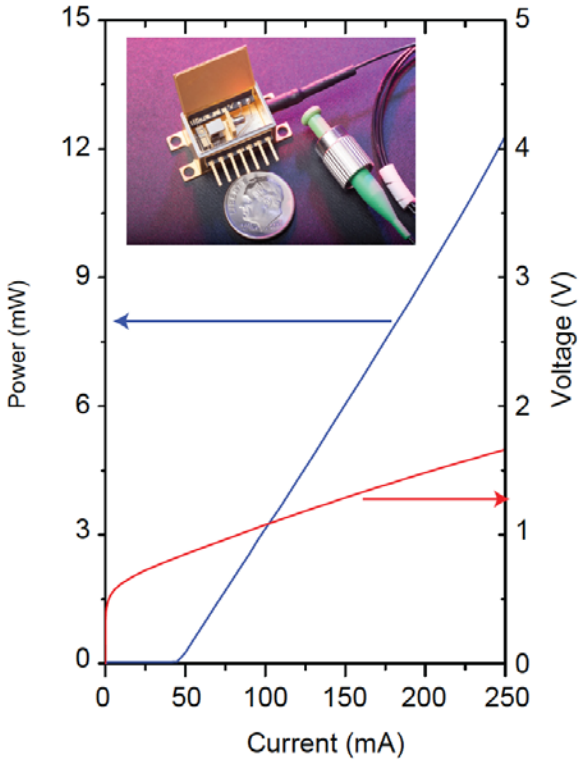
(data gaps due to increasing cloud cover beginning ~ 20.13 UTC)

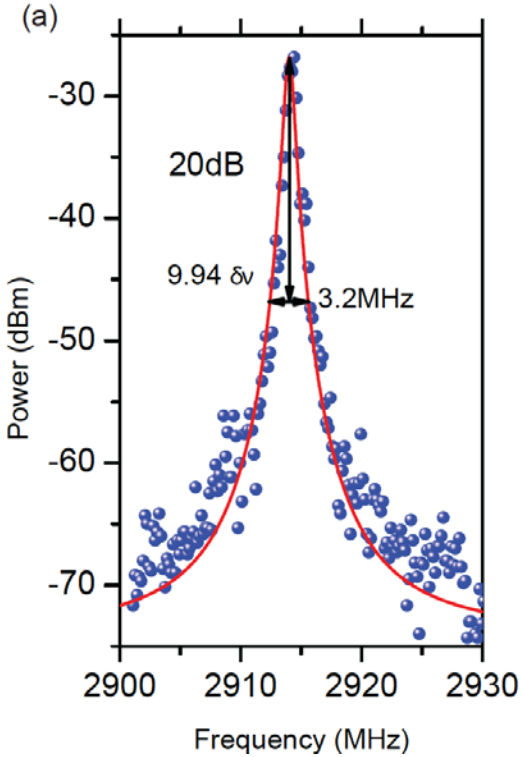


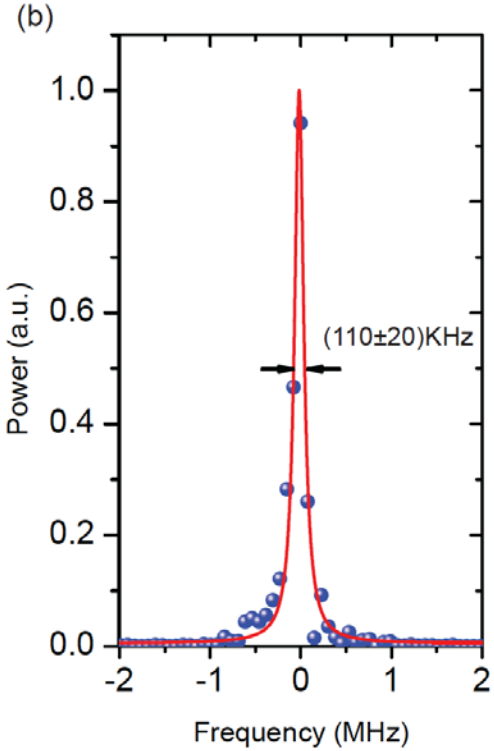
Total Distance: 260 km

Plans

- Next ASCENDS Field Campaign Summer 2017
- Upgrade offset lock electronics
- Fiber amplifier for offline channel
- Development of 2μm DFB laser for coupling to amplifier– see talk by Mahmood Bagheri, Wednesday morning

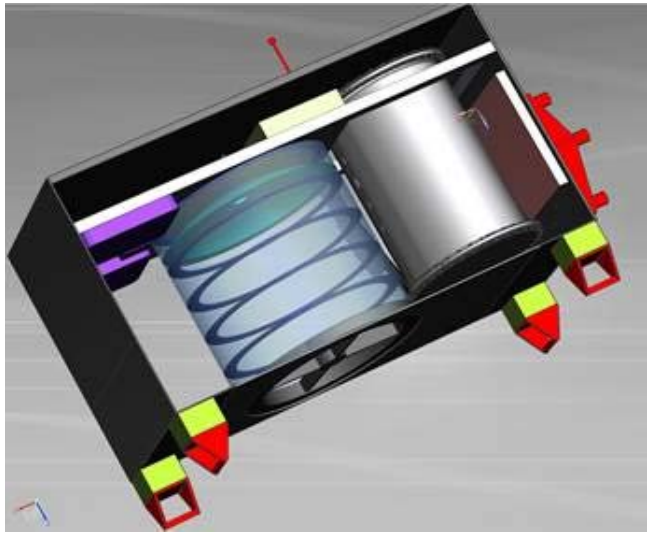






Scaling to Space

We can scale from the existing aircraft instrument to determine the instrument parameters needed to provide similar results over short ground track lengths.

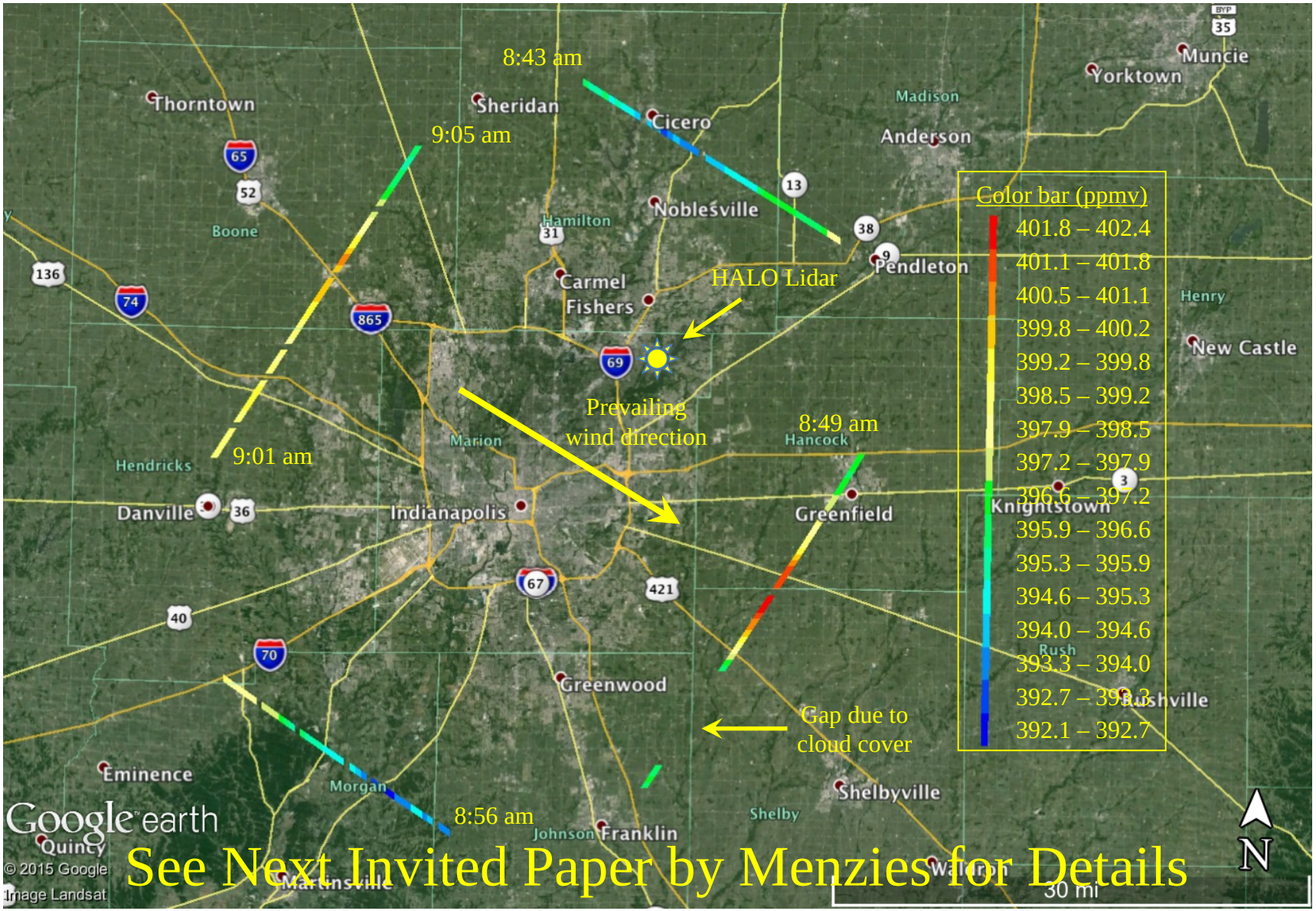


Assuming a space instrument with the same sensitivity using a 0.75 m telescope we would have to scale laser power as follows:

Ground track Length (km)	Aircraft	25	50	100
Integration Time (s)	20	3.3	6.5	13
Aperture (m)	0.1	0.75	0.75	0.75
Online Laser Power (W)	0.08	19.8	14	9.9

The offline laser power required is ¼ of the online laser power.

Current Data Processing Capability
9/3/2014 Indianapolis Box CO_2 Retrieval and Flux Calculation



See Next Invited Paper by Menzies for Details