Advances in Pulsed Lidar Measurements of CO_2 Column Concentrations in Airborne Campaigns and for Space

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Presentation at IWGGMS-12

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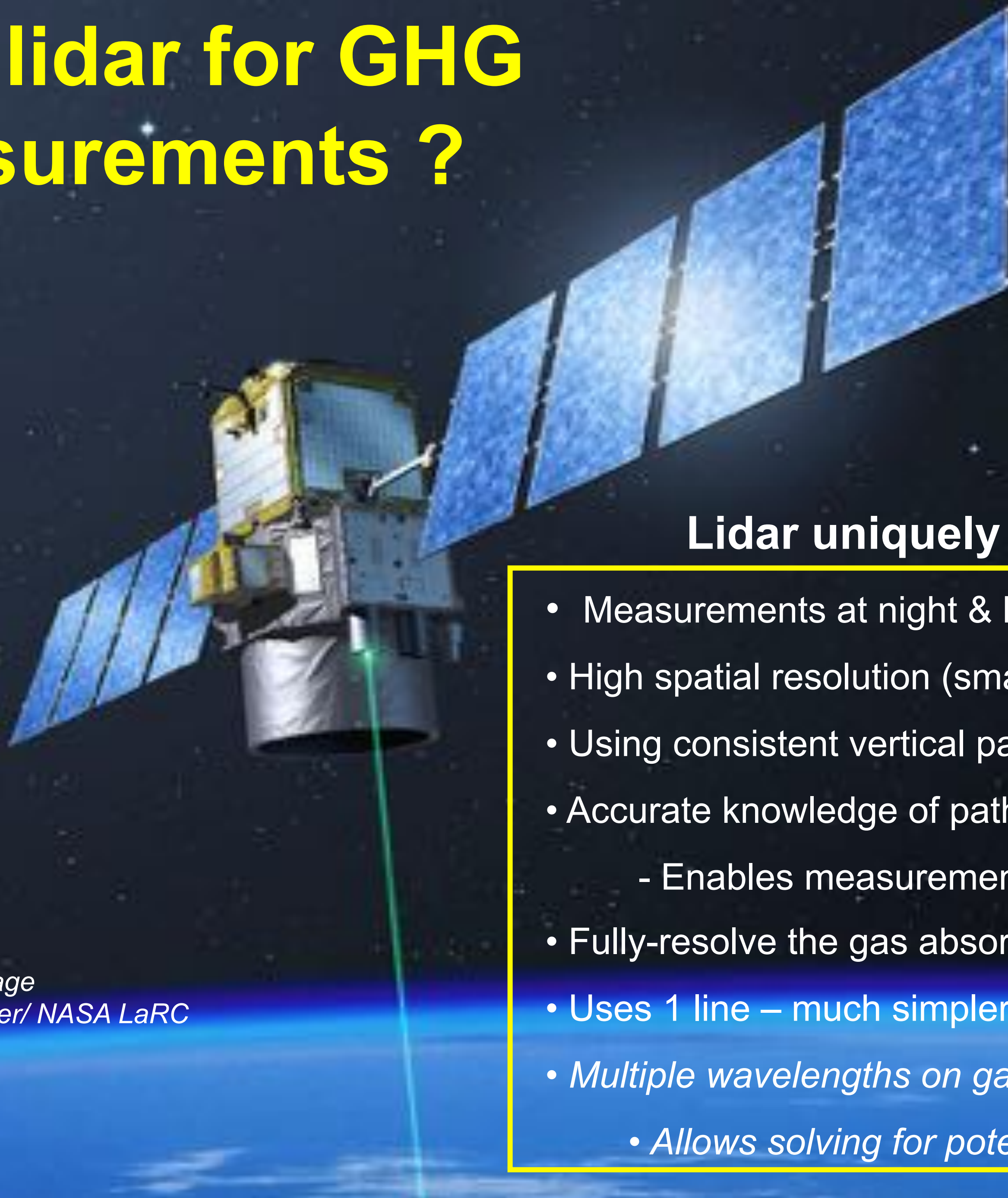
Outline:

- Why Lidar
- Airborne Lidar Demonstrator
- Airborne Measurement Highlights
- Path to Space
- Predicted Space Performance

Photo by Graham Allan

Acknowledgements:
ASCENDS Preformulation Activity, ESTO Office, Goddard IRAD program, ASCENDS Measurement Team

Why lidar for GHG measurements ?



Calipso Mission Image
courtesy of D. Winker/ NASA LaRC

Lidar uniquely provides:

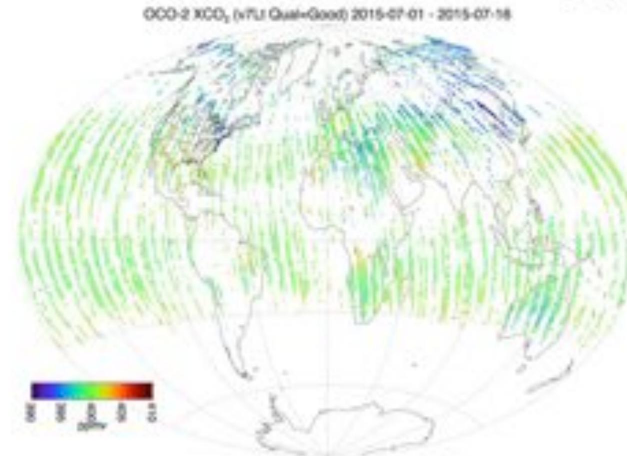
- Measurements at night & high latitudes
- High spatial resolution (small footprint)
- Using consistent vertical path
- Accurate knowledge of path length
  - Enables measurements to cloud tops
- Fully-resolve the gas absorption line(s)
- Uses 1 line – much simpler spectroscopy
- *Multiple wavelengths on gas line shape:*
  - *Allows solving for potential biases*

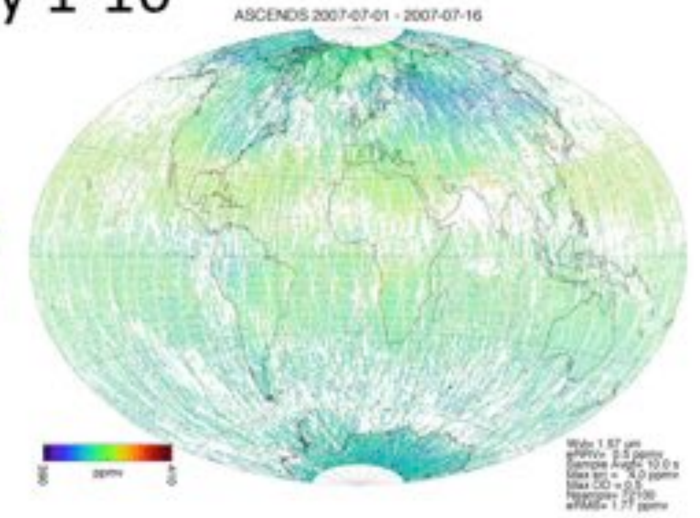
Comparison of Coverage from actual OCO-2 with ASCENDS simulator*

(* R. Kawa et al.)

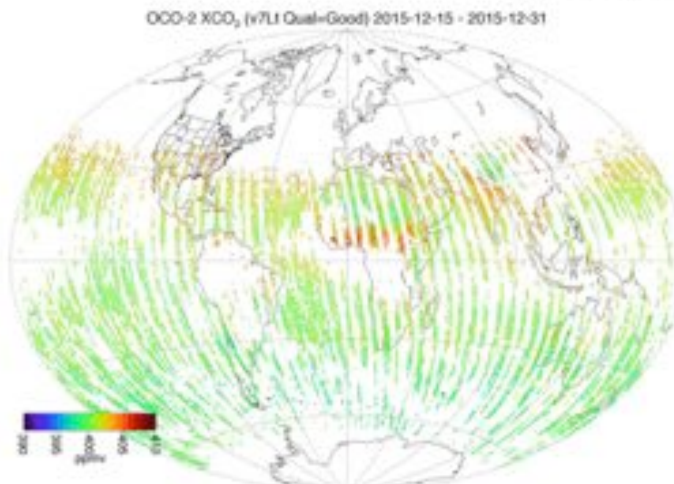
OCO-2 **ASCENDS**

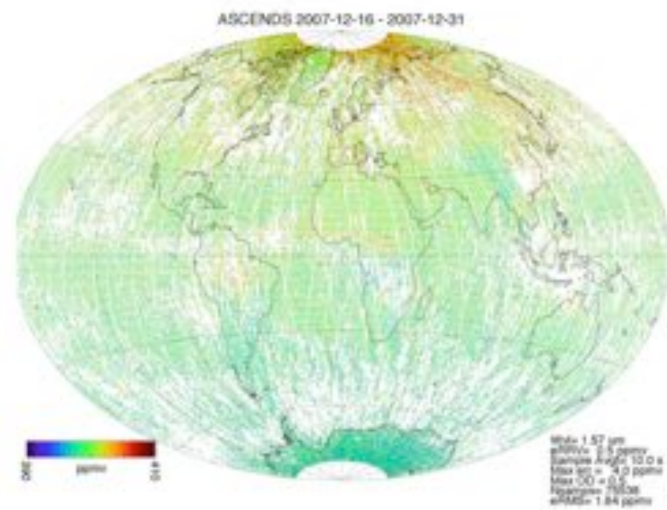
July 1-16





December 16-31





ASCENDS shows:

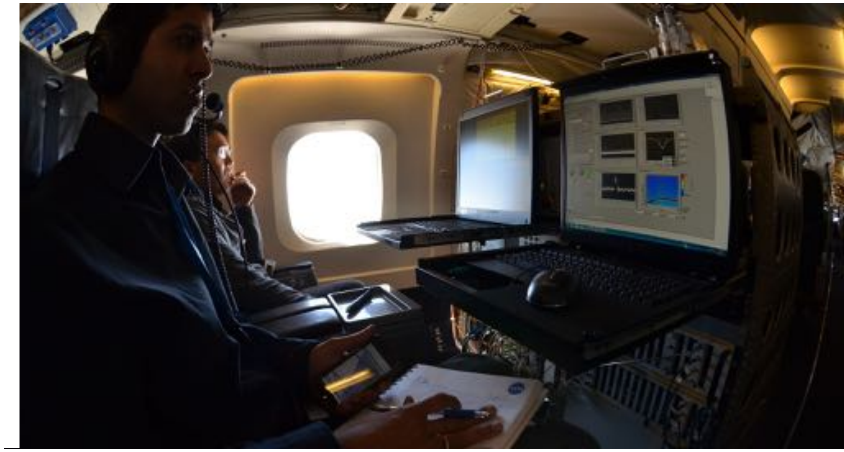
1. ***More spatially uniform coverage***
2. ***Coverage* is *uniform throughout year***
3. ***Much better sampling* in key areas:**
   - **Tropics**
   - **N. Hemisphere**
   - **Southern Ocean**

2014 & 2016 CO2 Sounder Airborne Lidar

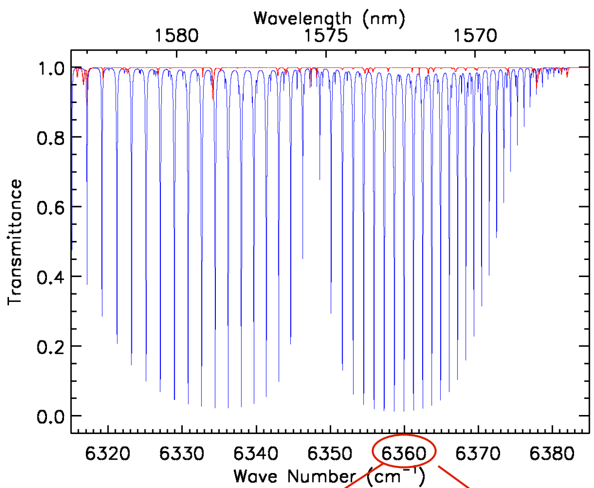
(with Graham Allan, Anand Ramanthan, Kenji Numata)

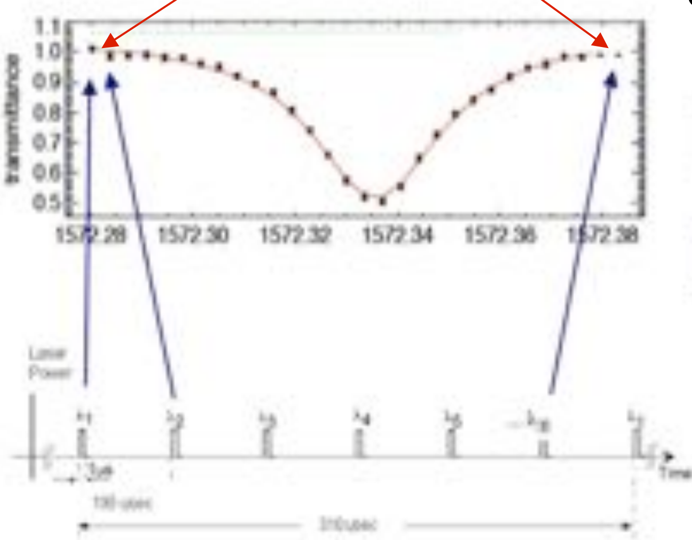
Improvements for 2014 & 2016 ASCENDS flights:

1. Step-locked laser seed source
2. Wider wavelength sampling across CO2 line
3. Optimized wavelength spacing
4. HgCdTe APD detector in receiver
5. Analog digitizer data recording
6. 10 Hz recording & retrieval resolution
7. Larger laser footprint (2016)
8. Allow 15 or 30 wavelength samples (2016)

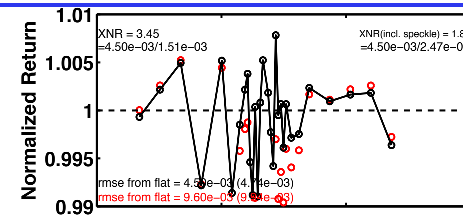


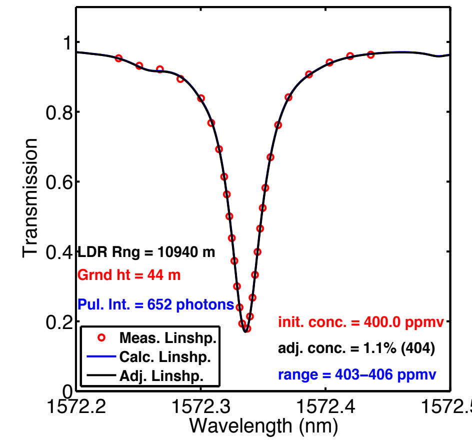
CO_2 Sounder Approach: Airborne CO_2 Line Sampling & Absorption line analysis

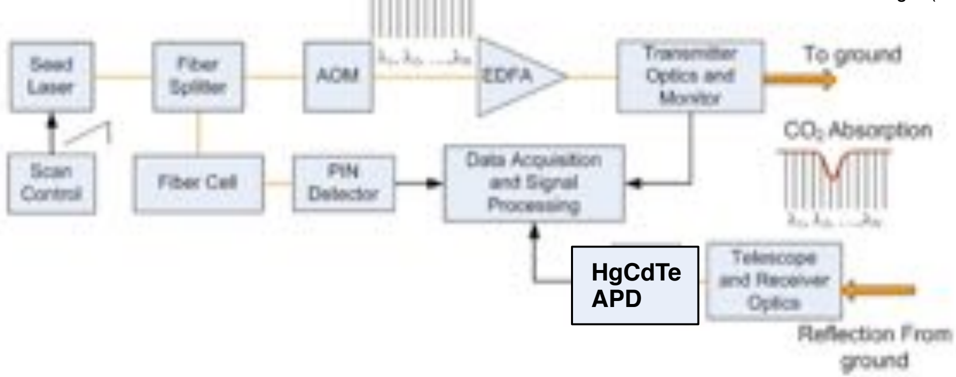




- *Presently measure line at 1572.33 nm*
- *Lidar* - measures "dots" (wavelength samples) to all scattering surfaces
- *Post flight – Retrievals** (based on model atmosphere): Calculates range, normalized line shapes & solves for best fit concentration



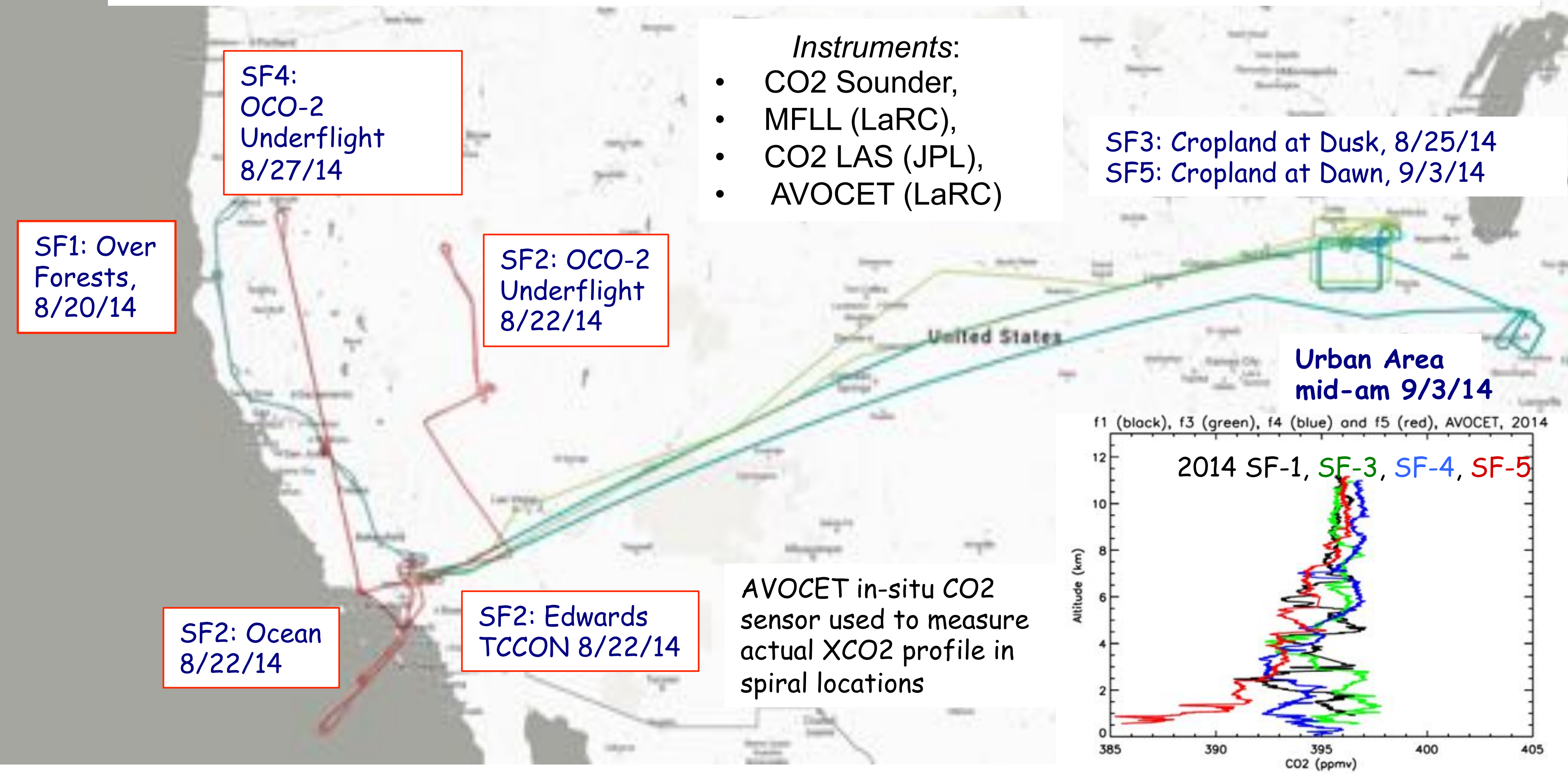




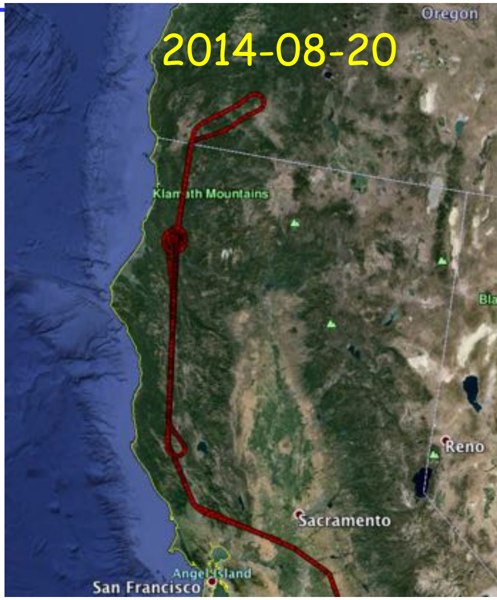
** more- see Poster 56, Ramanathan et al.*

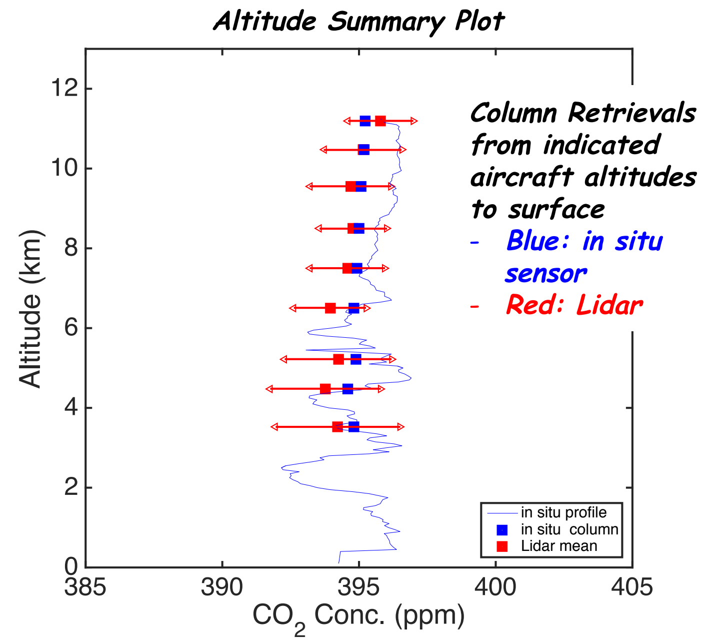
Example of ASCENDS Airborne Campaign (this one August 2014)

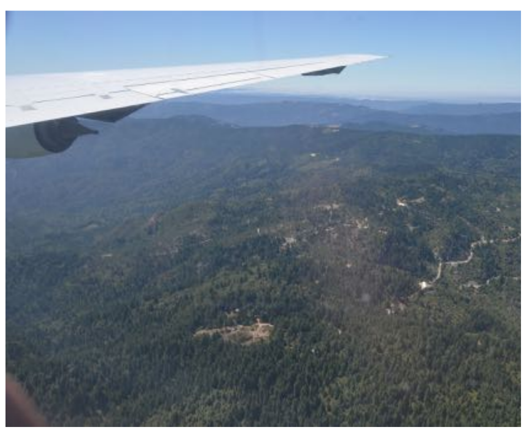
- Targets: forests in CA, growing agriculture at dusk and dawn over Iowa, & urban area
- IPDA lidar allows measurements under conditions that are difficult for passive sensors.
- Two flights under flew the OCO-2 satellite.



2014 SF-1 Tall forests in Coastal California
(Redwood forests on several km high mountains)

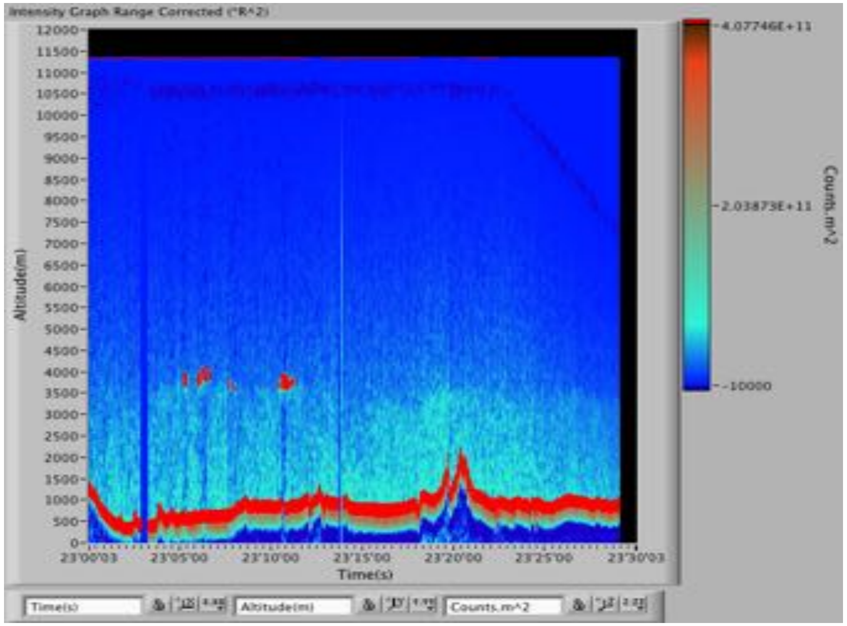




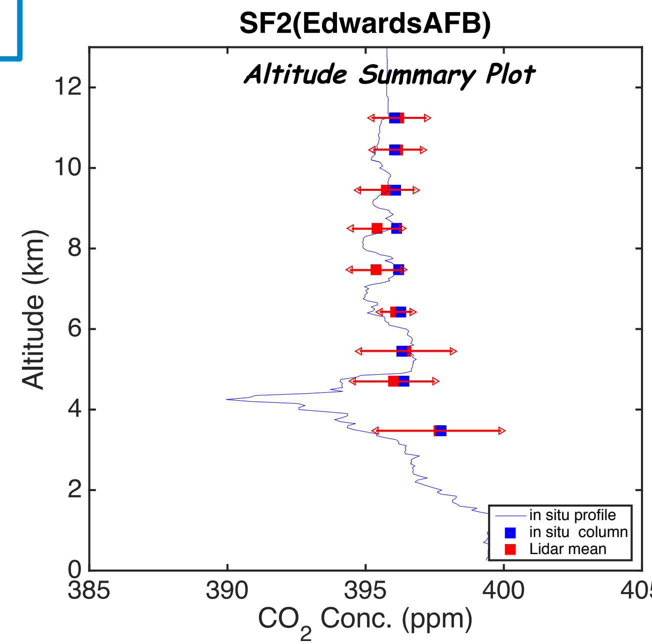


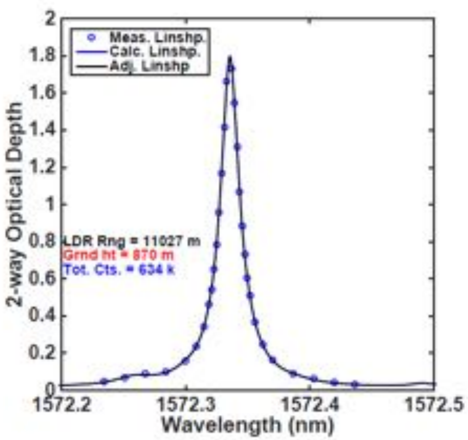
- **Why ?: Accurate CO_2 measurements over Amazon, Congo & Boreal forests are important for ASCENDS**
- **Varying tree canopy & terrain -> rapid change in column length**
- **Results show accurate (very low bias) measurements in challenging conditions**

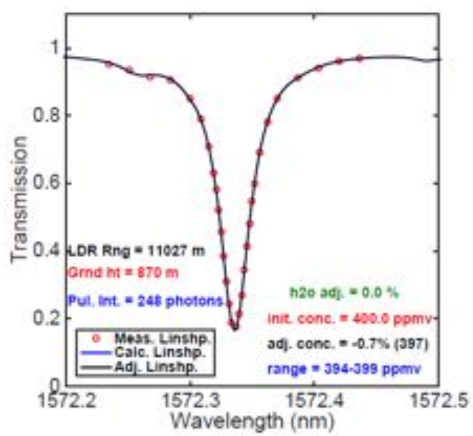
Accurate Column Retrievals over desert - through aerosol layers (2014 SF-2 over Edwards AFB)



8/22/2014



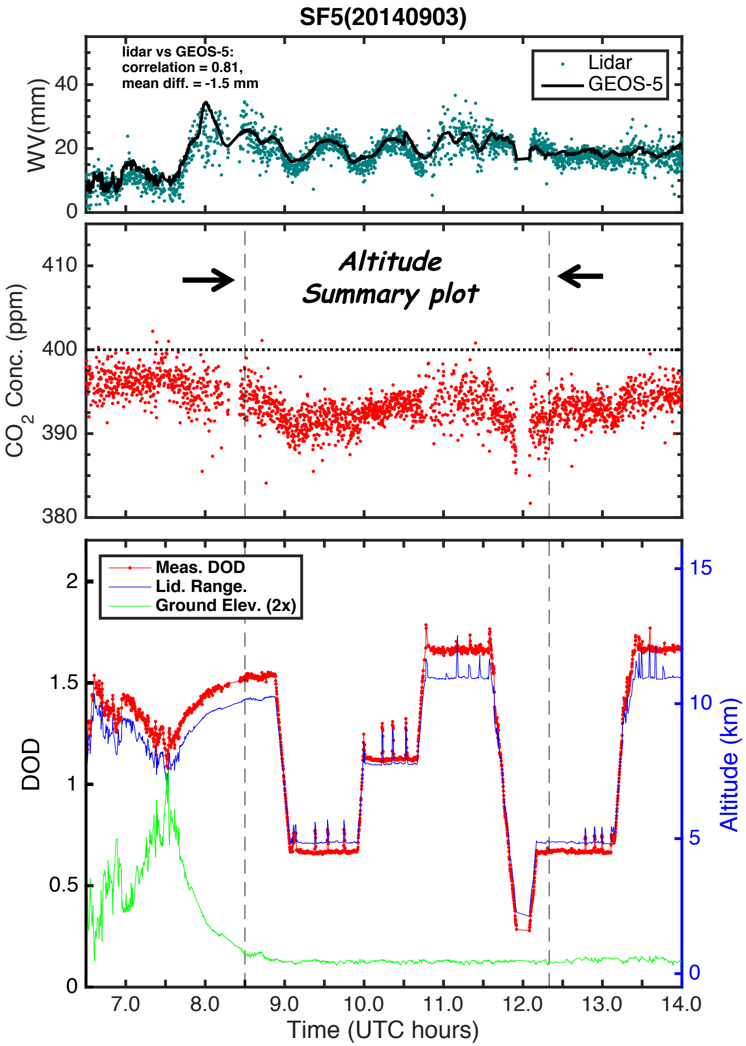




- Range-resolved measurements allow timing gating to minimize impact from atmospheric scattering
- Allow robust retrievals with low bias
- Minimizes retrieval errors over rough surfaces (terrain, and tree cover)

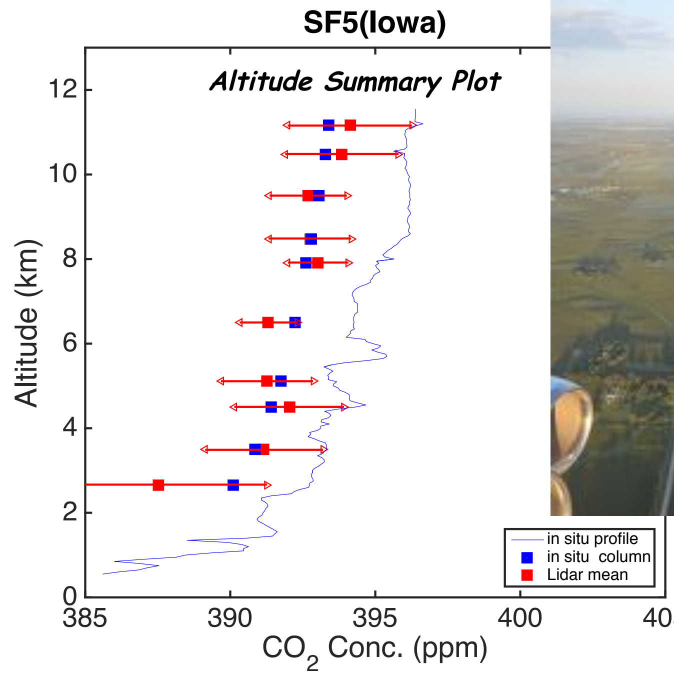
Observing CO_2 drawdown over Cropland

Measurements at Dawn over Iowa (2014 SF-5) 2014-9-03



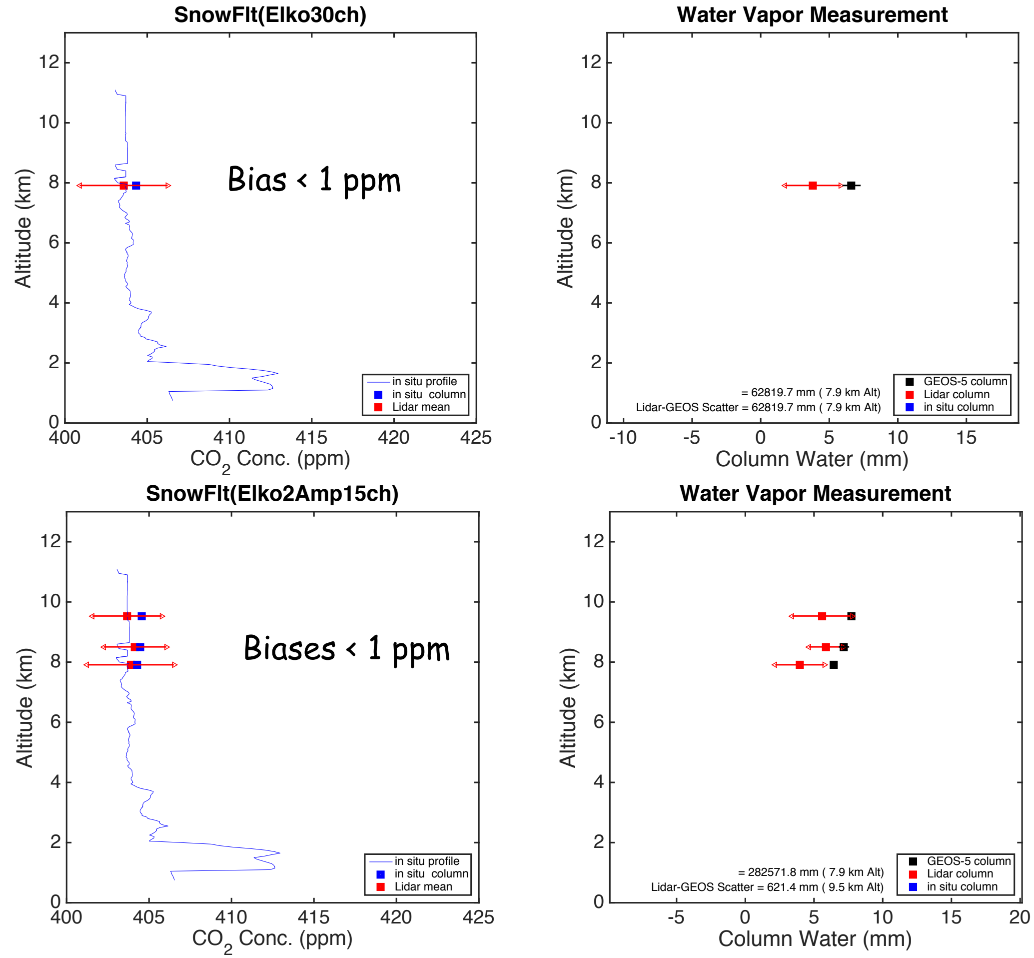
Flight Pattern:

- Square pattern over Iowa at 3 altitudes
- Spiral down over Iowa West Branch tower



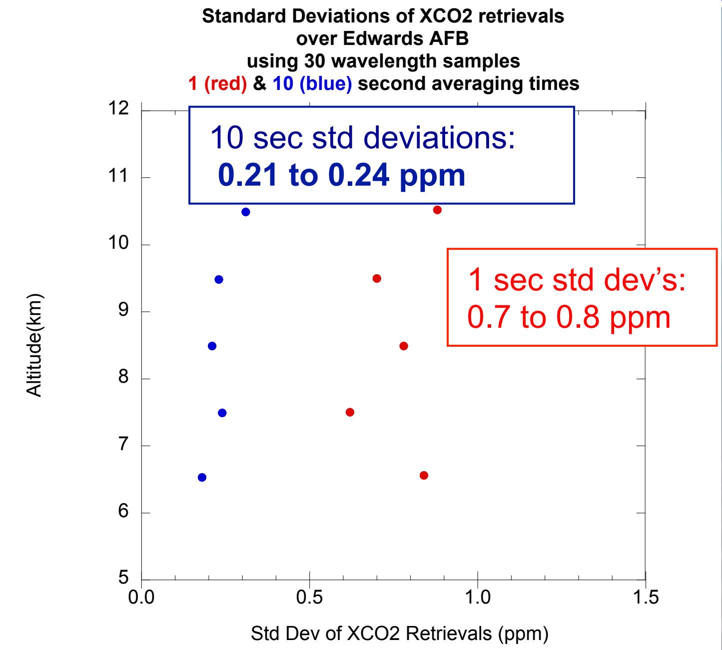
Lidar measurements show the CO2 drawdown (decrease with altitude) seen by AVOCET

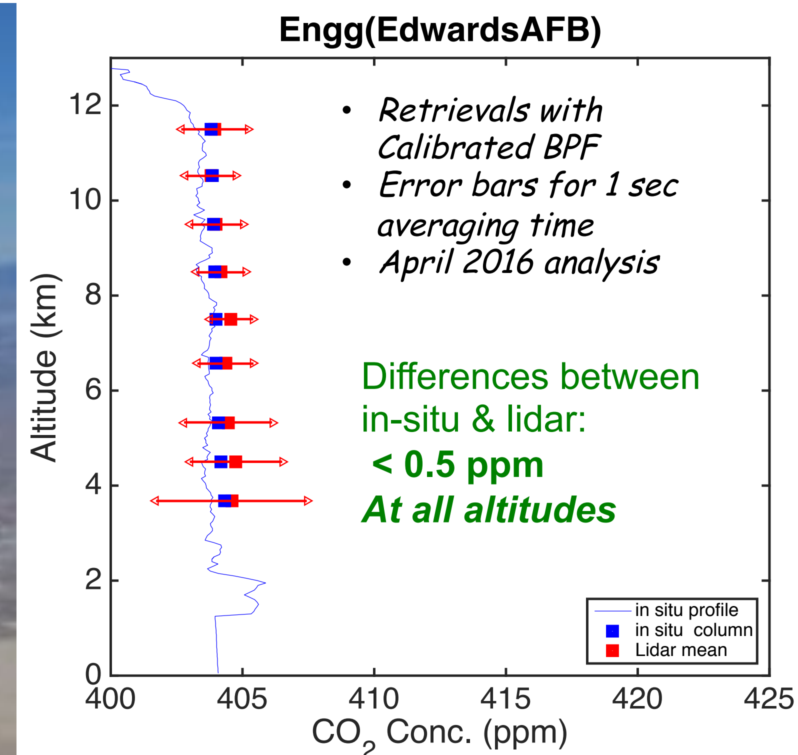
Flight over cold snow – Elko, NV & south at low sun angle: 2016-02-11

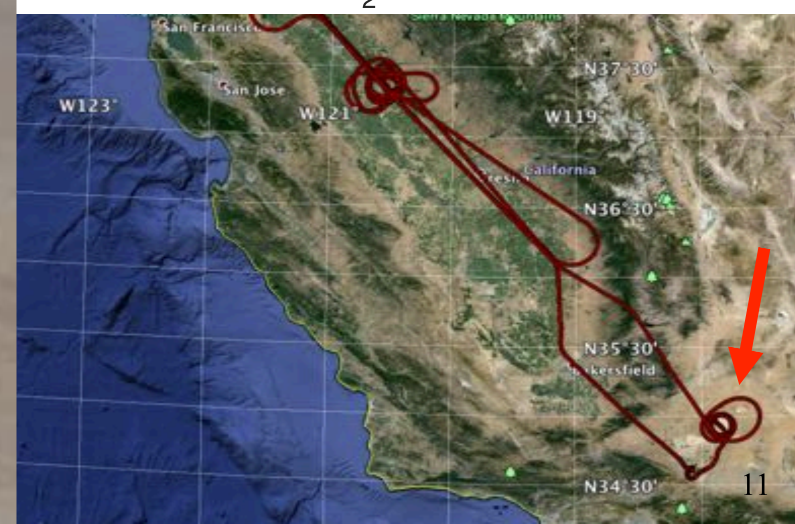


- Standard deviations: 3x larger than over Edwards AFB
  - Expected from ~8x lower reflectivity of snow.
  - Smaller s.d. with 2 laser amplifiers, as expected

Measurements over desert on February 10, 2016
Spiral over Edwards AFB CA

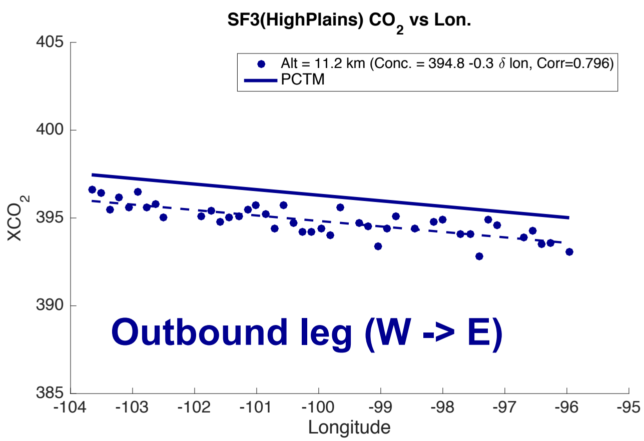


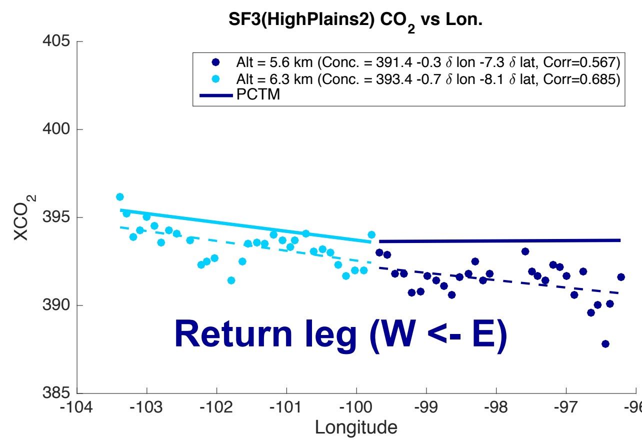




Lidar measurement of *Horizontal Gradient* in XCO_2 over Midwest (Colorado – Nebraska - Iowa on 2014 SF-3)

- Clear (-0.3 to -0.7 ppm/deg. Long.) E-W CO_2 gradient over Great Plains, US.
- Consistent across both legs & 2-altitudes and in good agreement with PCTM





Each point:
-50 sec ave
~12 km along track

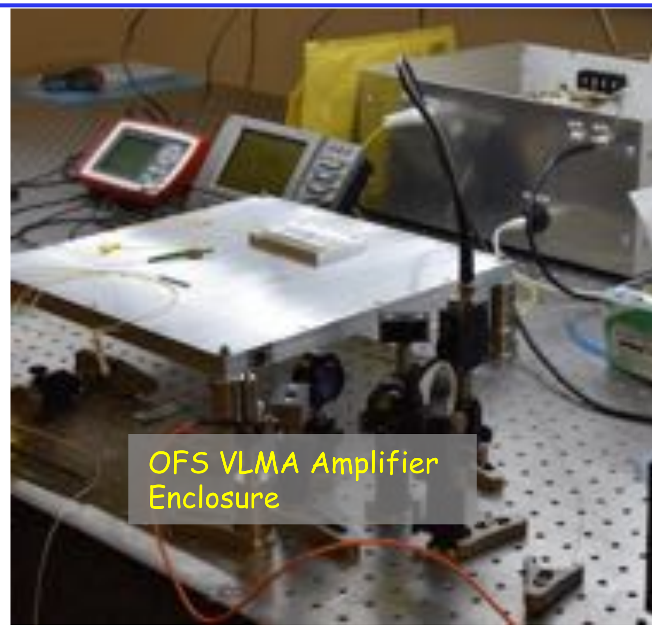
Similar result seen in NS track over NV in 2014

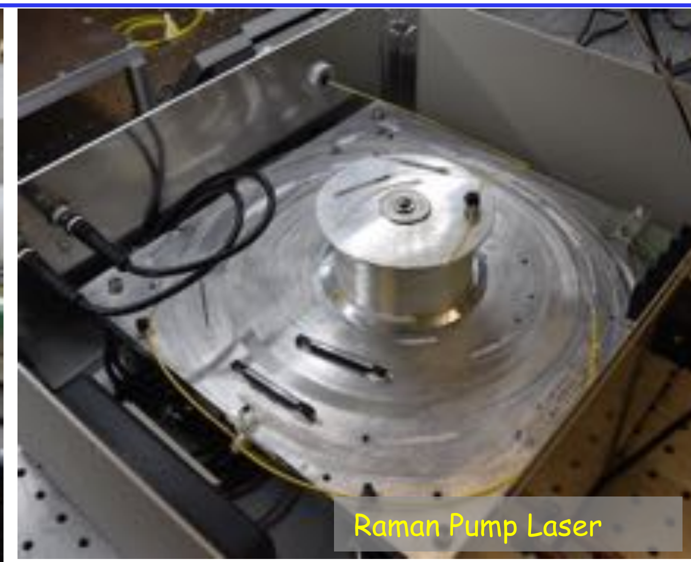
Space Scaling Approach

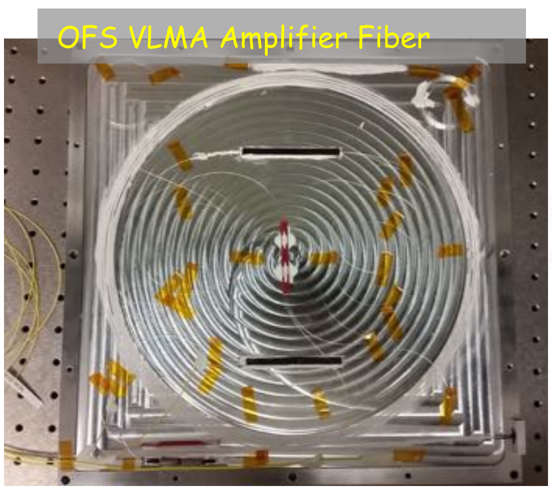
HgCdTe APD detector for CO2 Sounder (TRL 6 summer 2016)

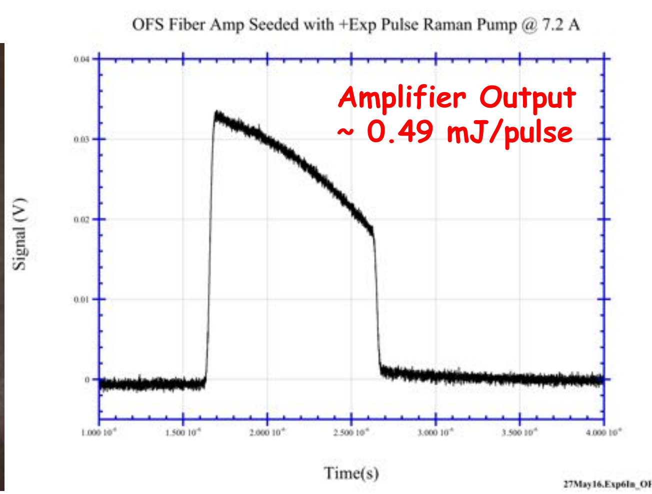
- **ESA's ADM Aeolus wind lidar: Mass: 470kg, *Power 830W***
- **ASCENDS (CO2 only) expected to be ~ same size, mass & but less (500-600W) power**
  - **CO2 Sounder approach baseline is to use same 1.5 diameter telescope**
  - **Detector near TRL 6 now (see above)**
  - **CO2 Sounder laser: much easier than ADM's UV laser (see next slide)**
- **ADM spacecraft power allows flying another laser, for simultaneous measurements of CH4, or O2**

Laser Power Amplifier breadboard
Recent GSFC test shows space-need power





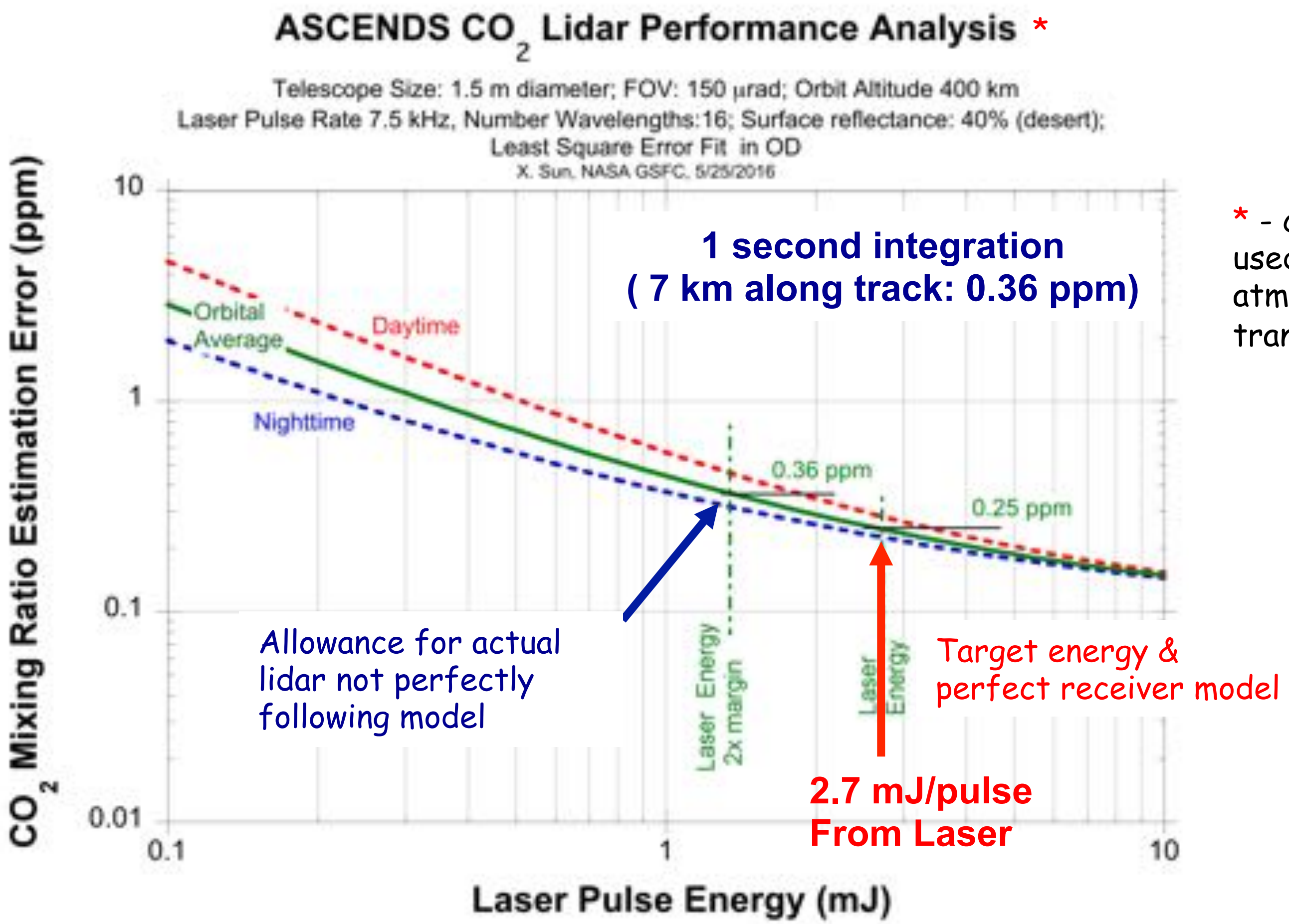




- Demonstration of one laser fiber output (OFS Laboratories)
- Measurements in May 2016
- **6 in parallel will emit > 2.7 mJ**
- More energy than is required for space
- Engineering model of full laser now under development
- Will be vibration & vacuum tested by September 2017

Performance Prediction for Space (Desert Surfaces)

GSFC



* - calculations used 70% offline atmospheric transmission

For desert model shows ≤ 0.36 ppm with 1 sec (7 km) averaging
Global average precision ~ 1ppm (1 sec)

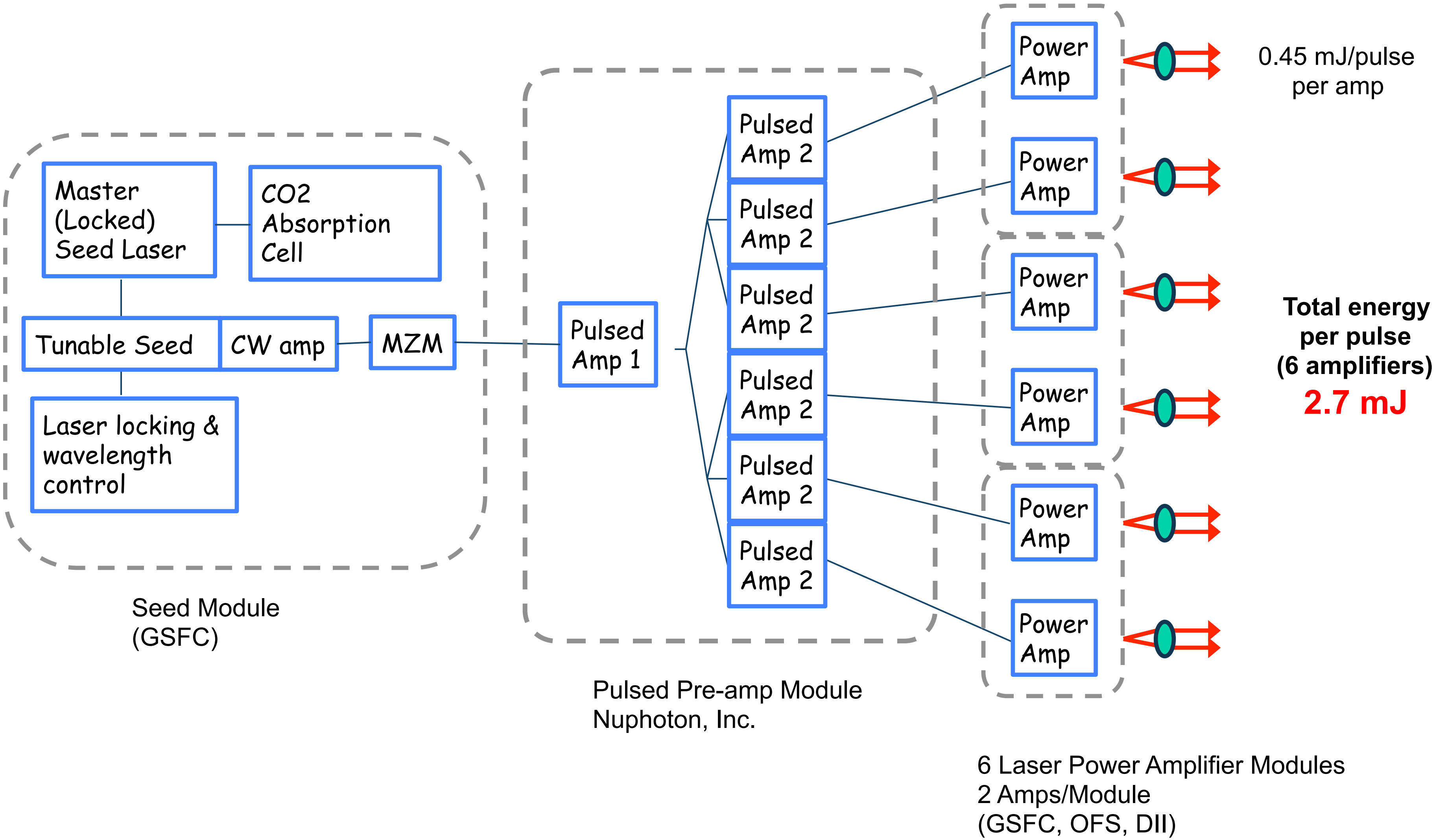
Summary*

- ASCENDS offers new, important capabilities:
  - Much *more uniform coverage*
  - *Measurements (year round) in the Arctic, tropics, S. Oceans*
- Made more improvements of CO2 Sounder Airborne simulator
- Campaigns show robust measurements of CO_2 & retrieved mixing ratio:
  - *For mountainous regions with tall trees*
  - *Through haze, cirrus clouds & broken cumulus clouds*
  - *Over vegetation with CO2 drawdown & over snow fields*
  - *Measured horizontal gradients in XCO2* that agree well with PCTM models
- Results:
  - Average retrieved XCO2 values agree from 0.5 to 1ppm with in-situ measurements
  - *Random errors ~ 0.7 ppm in 1 sec averaging time over desert*
- CO2 Sounder approach: a practical path for ASCENDS
  - Model shows ~1 ppm random errors globally (1 sec ave time)*
  - Laser: Breadboard shows space-needed power

***- Related presentations:* Kawa et al (O48), Ramanathan (P56), Mao (P57)**

Backup

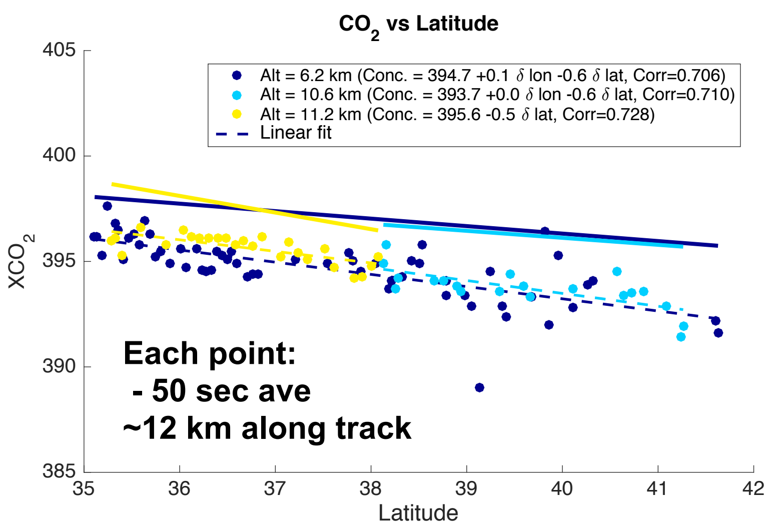
Pathway to Space – Laser
(Mark Stephen – NASA ESTO work ongoing)



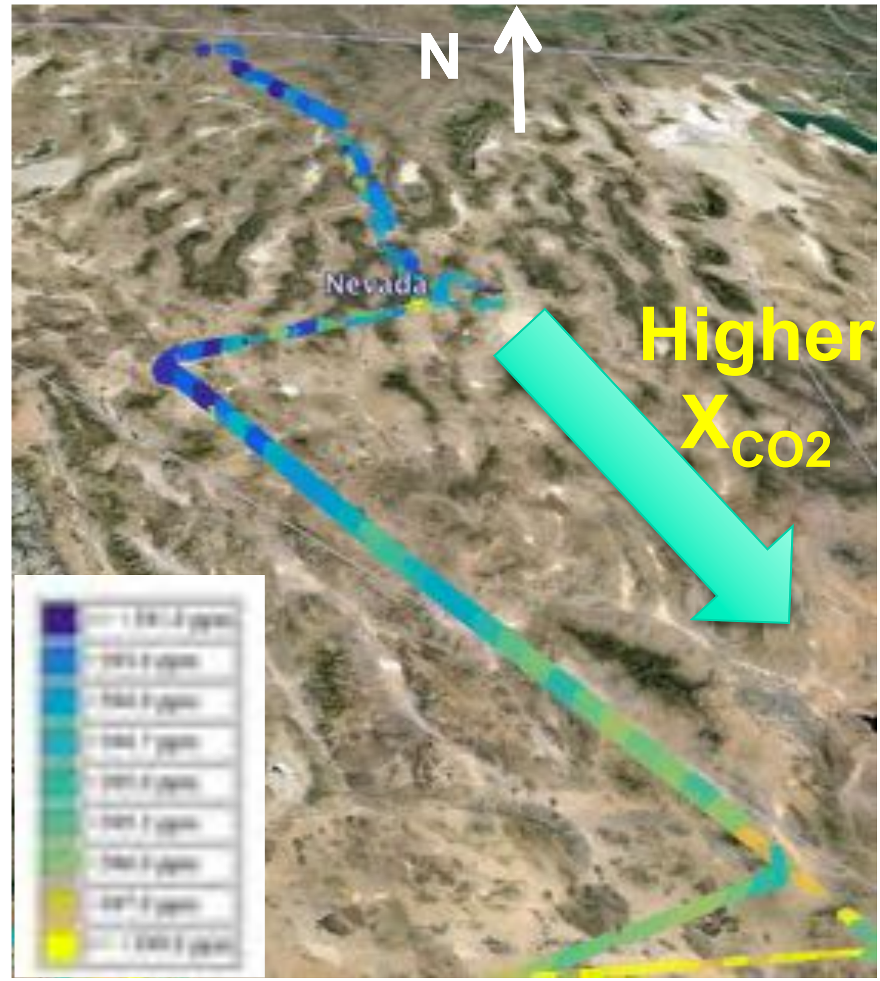
Lidar measurement of Horizontal Gradient in XCO_2 over Nevada (SF-2)

ASCENDS

- Lidar measurements show a N-S gradient over Nevada
- Seen at 3 independent flight altitudes
- Gradient is ~1 ppm/deg. lat. ($R^2 > 0.4$)
- Gradient matches that seen in NASA PCTM*
- (*-Parameterized Chemistry Transport Model)



S ~ 700 km N



Initial Examples of surface reflectivity histograms Edwards AFB, Castle (Central Valley), Snow