Multi-wavelength lidar : Airborne results with high accuracy CO_2 measurements, CO_2 gradients & Water Vapor

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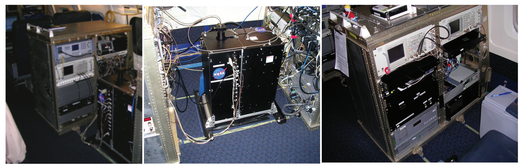
Introduction : Wavelength channel selection for lidar CO_2 mission

- How many channels for a satellite instrument?
  - Sun + passive sensor: broad spectrum source, any number (OCO-2 & GOSAT: >1000 channels),
  - Laser + detector : single wavelength, more wavelengths=more $$
- CO_2 Sounder employs a **step-locked laser technology:**
  - **One laser -> many wavelengths,** at no additional $$
  - Additional channels reduce biases
  - Also enables CO_2 vertical gradient, water vapor content

The CO_2 Sounder Instrument

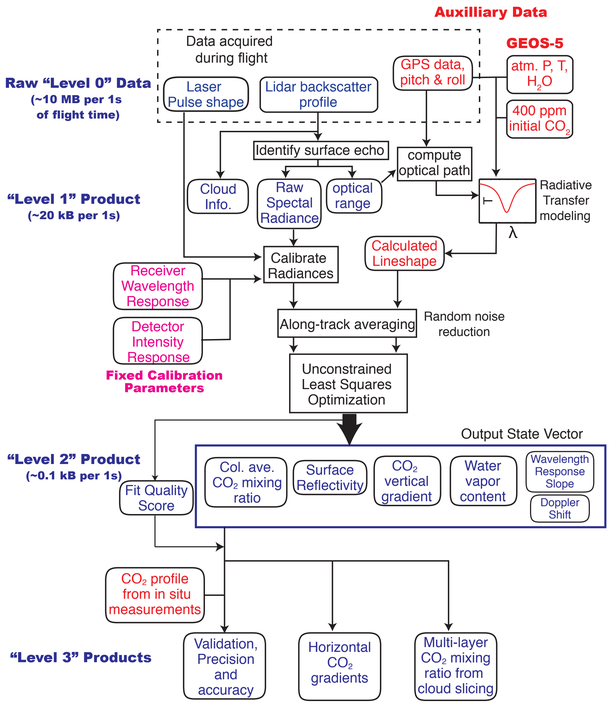
- Prototype of the space-borne concept
- Mostly commercial off-the shelf components
- Extensive airborne testing of concept.



CO_2 Sounder Full Retrieval Algorithm

Simple algorithm, applicable to space instrument too

No a priori CO2 information required or used



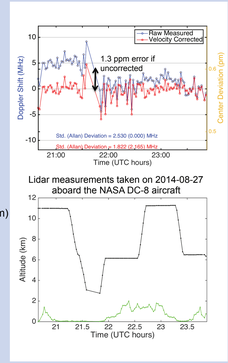
Bias control

Bias from uncorrected Doppler Shift in airborne measurements

Aircraft/spacecraft motion -> Doppler shift of CO_2 absorption -> bias if uncorrected

Aircraft speed = 250 m/s, Shift= 5 MHz (0.05 pm), potential bias in XCO2= 1.3 ppm

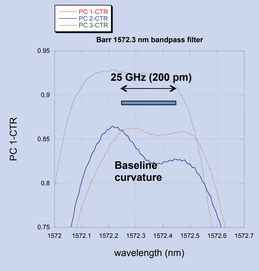
Satellite speed ~ 7 km, Shift=150 MHz (1.5 pm)



Even an uncorrected tilt of 0.1 deg from satellite will cause a 7 MHz Doppler shift and 2 ppm bias.

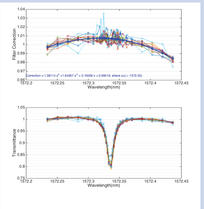
Need to correct for baseline curvature from Optical Bandpass Filter

- A band-pass filter essential for a direct detection lidar receiver.
- However its peak transmission is not flat at 0.1% level (1/10th of a tick mark)
- And the transmission curve shifts with temperature & can age (in vacuum) with time



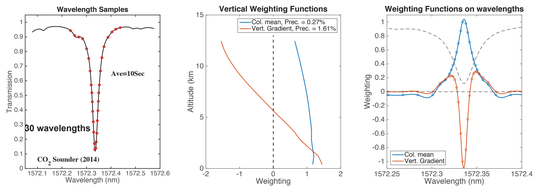
Potentially 2 ppm bias if linear baseline is uncorrected for
Nonlinear baseline correction is necessary for good linefits and data quality

Optical Band Pass Filter calibration for CO2 Sounder from airborne data



Principal Component Analysis for CO_2 Sounder

Analysis is based on the Rodgers framework (Rodgers, 2000). Present signal to noise ratio gives ~2.5 degrees of freedom for CO_2 profile. Lowest two principal components are column mean and vertical gradient



- Doppler Shift and instrument baseline measured
- Two CO_2 degrees of freedom retrievable with reasonable precision
  - Column mean
  - Vertical Gradient

What info. do more wavelengths enable?

Each wavelength is an additional degree of freedom

Present airborne configuration

Planned space configurations

No. of Wavelengths	1	2	3	4	6	8	10+	30
Reflectivity	✓	✓	✓	✓	✓	✓	✓	✓
CO_2 column mean	✗	✓	✓	✓	✓	✓	✓	✓
Linear baseline	✗	✗	✓	✓	✓	✓	✓	✓
Doppler shift	✗	✗	✗	✓	✓	✓	✓	✓
CO_2 vertical gradient	✗	✗	✗	✗	✓	✓	✓	✓
Nonlinear baseline	✗	✗	✗	✗	✗	✓	✓	✓
Water vapor content	✗	✗	✗	✗	✗	✗	✓	✓
CO_2 mid-troposphere	✗	✗	✗	✗	✗	✗	✗	✓
Fit quality	✗	✗	✗	✗	✓	✓✓	✓✓✓	✓✓✓✓✓✓✓✓

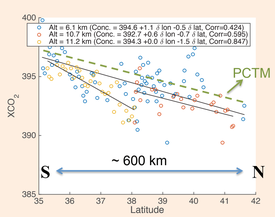
Key

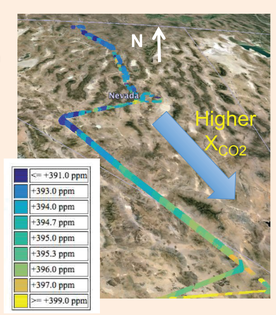
- ✗ not possible
- ✓ possible, but bias prone
- ✓ possible

CO_2 Gradients - Horizontal & Vertical

CO_2 Horizontal Gradients (~12 km ground track avg.)

- We see a N-S gradient over Nevada from 3 independent flight altitudes
- Gradient is ~1 ppm/deg. lat. ($R^2 > 0.4$)
- Gradient matches that seen in NASA PCTM

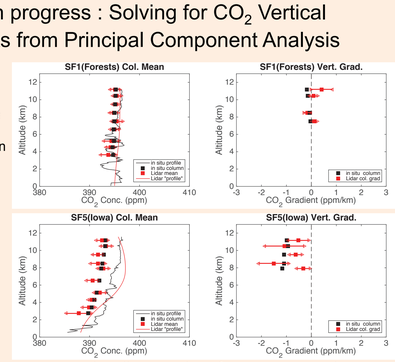




Work in progress : Solving for CO_2 Vertical Gradients from Principal Component Analysis

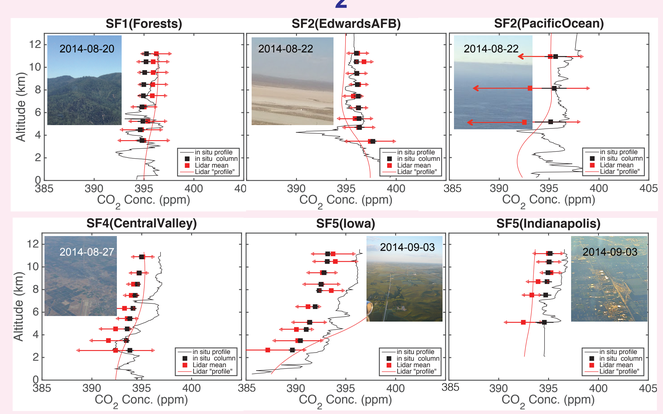
N. California forests (2014-08-20) No CO_2 gradient seen

Iowa cornfields (2014-09-03) CO_2 drawdown seen close to ground



Measurement needs to be improved with better calibration of receiver wavelength response

Total column CO_2 measurements



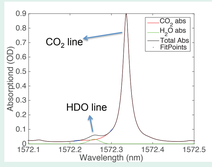
~2.5 km ground track (10 s averaging)

- Precision over desert is 1.0 ppm. Close to the photon shot noise limit
- For 7 (out of 9) flight segments of the ASCENDS 2014 campaign for which in situ data was available, the bias (at altitudes > 7.5 km) was less than 1.2 ppm.

Flight	Surface	Shot Noise limit	Measured precision	Bias	Comments
2011 Railroad Valley	Desert	1.5 ppm	2.7 ppm	0.4 ppm	
2013 Central Valley	Desert/ vegetation	0.7 ppm	1.5 ppm	0.1 ppm	Best with PMT. Limited by detector dynamic range.
2014 Central Valley	Desert/ vegetation	0.45 ppm	0.9 ppm	0.3 ppm	Limited by optical losses, electronic & speckle noise
2014 N. California	Forest	0.5 ppm	1.3 ppm	0.7 ppm	Limited by optical losses, electronic & speckle noise

Water Vapor measurement using HDO absorption line

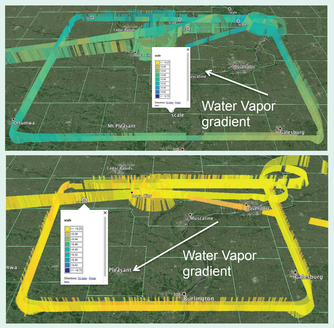
- HDO constitutes ~300 ppm water vapor (on Earth)
- HDO line lies adjacent to the 1572.335 CO_2 line
- Adjusting the HDO abundance improves CO_2 line fitting and is incorporated in CO_2 retrievals



Water vapor for two different flights

Flight over Iowa (2014-08-25) : Afternoon flight – high water vapor

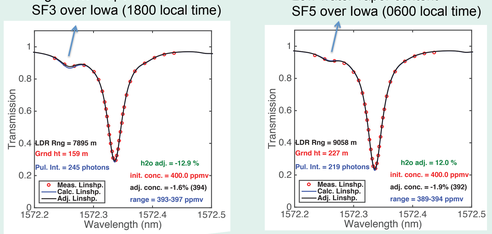
Flight over Iowa (2014-09-03) : Morning flight – low water vapor



Sample HDO line fitting

High water vapor content SF3 over Iowa (1800 local time)

Low water vapor content SF5 over Iowa (0600 local time)



Conclusions

- A multi-wavelength approach has several benefits
- Using a step-locked laser and 30 wavelengths, the CO2 Sounder instrument has demonstrated:
  - a. Low bias (<1.2 ppm) total column XCO2
  - b. CO_2 horizontal gradients
  - c. Water vapor measurements via HDO
- Multi wavelength approach shows promise for CO_2 vertical gradient measurements. Higher order terms need very precise calibrations