CO_2 Sounder lidar : Retrieval Algorithm and Analysis Approach for airborne instrument and application to space instrument

Anand Ramanathan*‡, Jianping Mao*, James B. Abshire, Xiaoli Sun

‡ - anand.ramanathan@nasa.gov

NASA Goddard Space Flight Center, Greenbelt, MD - 20771;

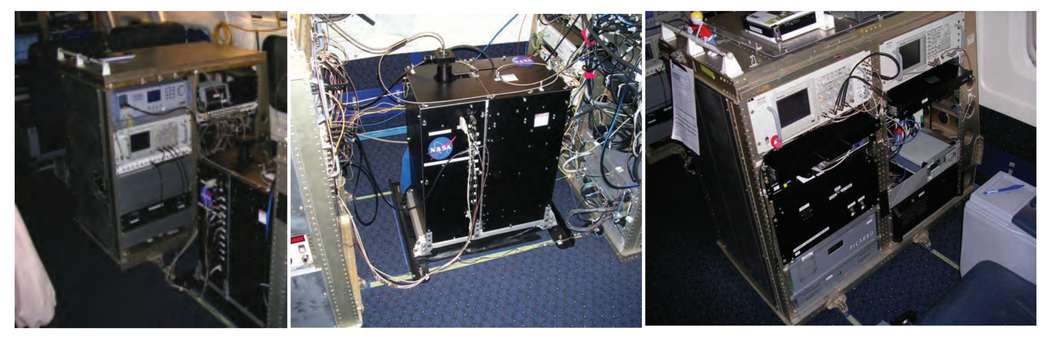
* - Earth Systems Science Interdisciplinary Center, University of Maryland, College Park, MD - 20740;

Abstract

The CO_2 Sounder lidar multi-wavelength measurement needs a complex retrieval algorithm to best use all the information present in the lineshape. In this poster, we describe:
(1) Retrieval algorithm of the CO2 Sounder measurements and airborne instrument calibration
(2) Analysis of the retrieval approach and the implications on space scaling
(3) Lidar column water vapor measurements using a HDO absorption line that occurs next to the CO2 absorption line.

The CO_2 Sounder Instrument

- Built by NASA Goddard. Prototype of the space-borne concept
- Flown as part of the ASCENDS field campaigns of 2009-2014.
- Uses a pulsed, multi-wavelength Integrated Path Diff. Abs. approach.

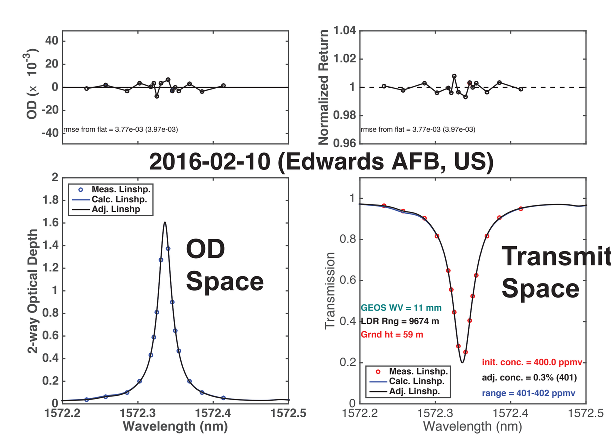


The Multi-wavelength approach

CO_2 Sounder samples the absorption line at many wavelengths

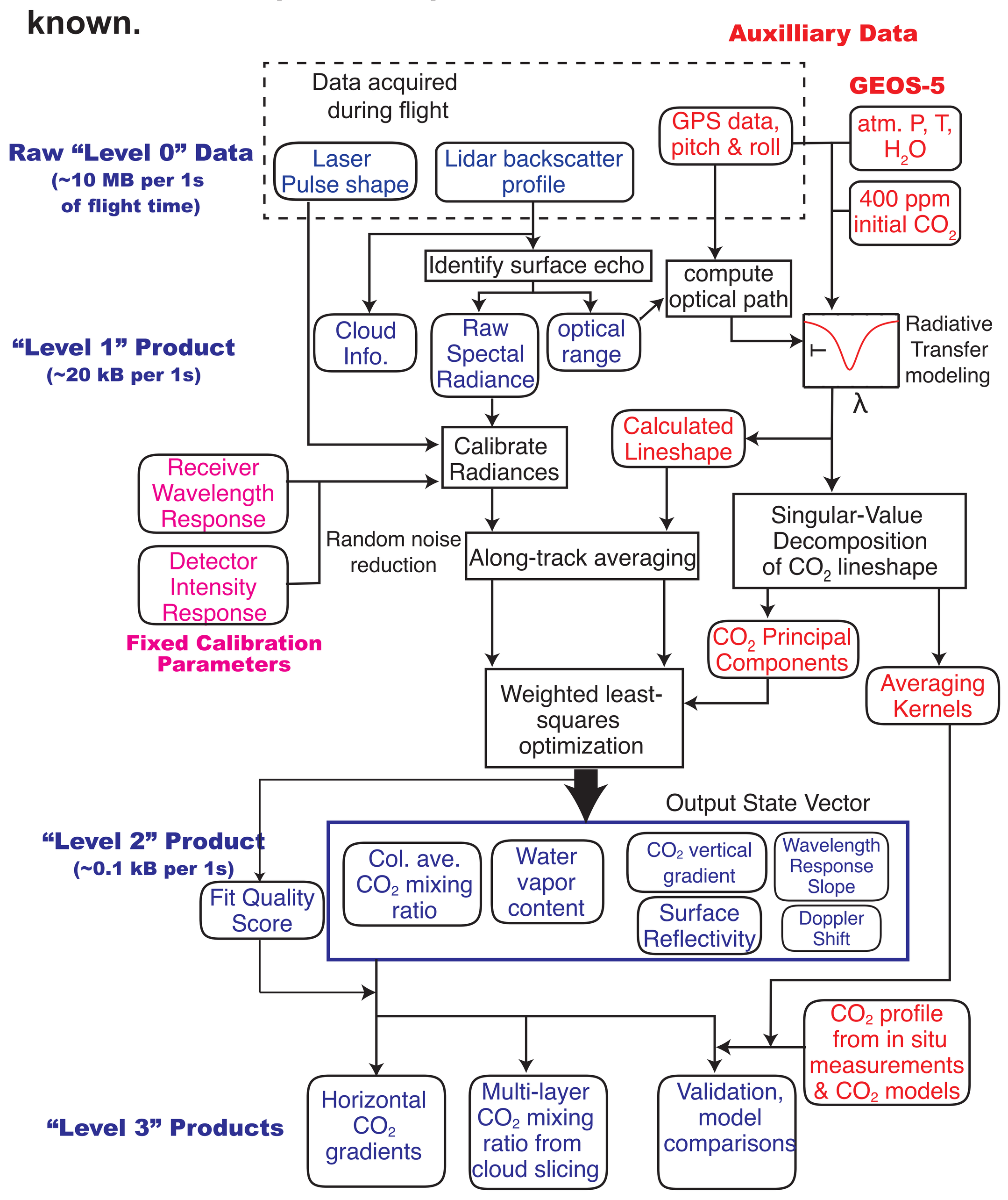
- Additional channels reduce biases
- Also enables CO_2 vertical gradient, water vapor content

Sample line-fit (1s average)



CO_2 Sounder Full Retrieval Algorithm

- Simple algorithm, applicable to space instrument too
- No a priori CO2 information required, which is suited to cases where prior and prior covariance are not well known.

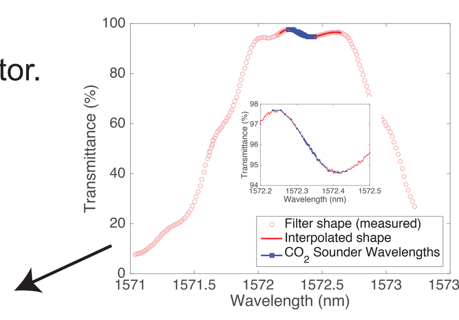


Receiver Wavelength Response Calibration

Lidar instruments require an optical bandpass filter to prevent sunlight from flooding the detector.

Such filters have a non-uniform wavelength response, which needs precise calibration.

Laboratory calibration of filter used on the CO2 Sounder for the 2016 ASCENDS campaign.



Detector (non-linear) Intensity Response Calibration

The received lidar signal undergoes several stages of amplification. These stages of amplification can result in deviation from linearity, especially if one of the stages approaches saturation.This deviation needs to be properly calibrated so as to not cause a bias in the XCO2 measurement.

Calibration/Validation during airbone campaigns

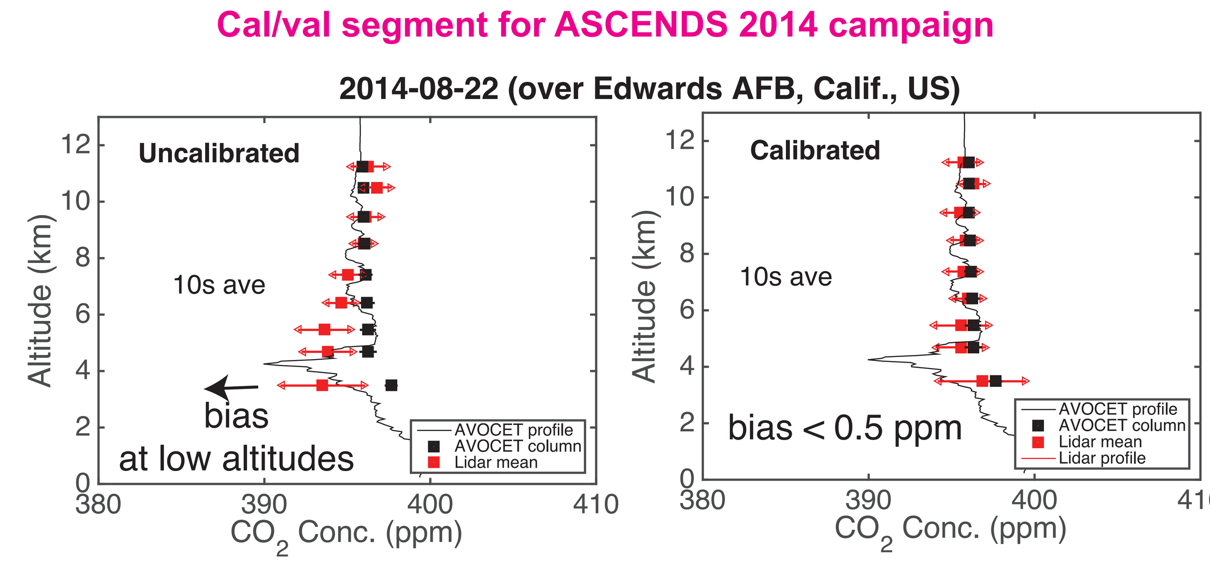
- Installation of the instrument on the aircraft (or launch of an instrument to space) can cause changes in the instrument calibration, which need to be monitored.

- For airborne campaigns, we choose a flight segment with the following properties:
  1. In situ CO2 validation data from ground to highest flown altitudes
  2. Radiosonde data for precise atmospheric P, T, X_{H2O} information
  2. Few CO2 sources and sinks
  3. Repeated tracks over the same area at varying altitude
  4. Higher reflectivity to probe detector response at high lidar return signals

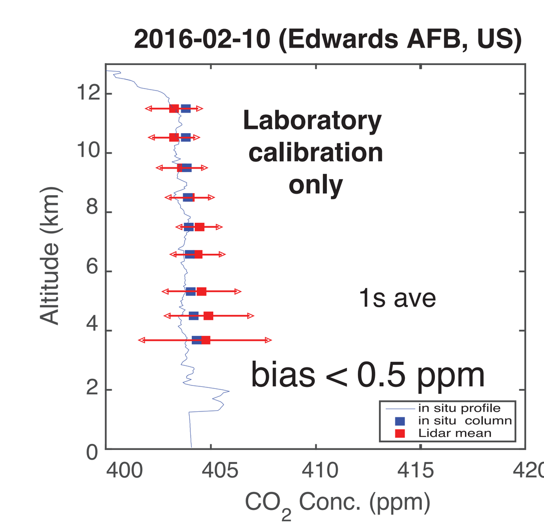
- We check calibration as well as the precision and accuracy of the spectroscopic model used. Once a calibration has been established, it is kept fixed for the rest of the campaign

- **We do not use any bias correction**

Cal/val segment for ASCENDS 2014 campaign



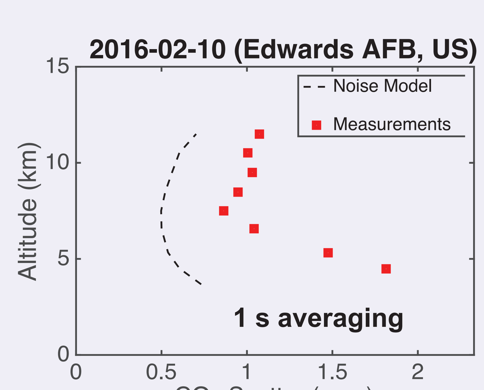
Cal/Val segment for ASCENDS 2016



laboratory calibration worked well for 2016 campaign.

Analysis of the Retrieval Approach and Space Scaling

Performance of CO2 Sounder instrument compared to analysis model for Feb 2016 ASCENDS airborne campaign



Present version of analysis produces XCO2 scatter only 1.5x higher than model

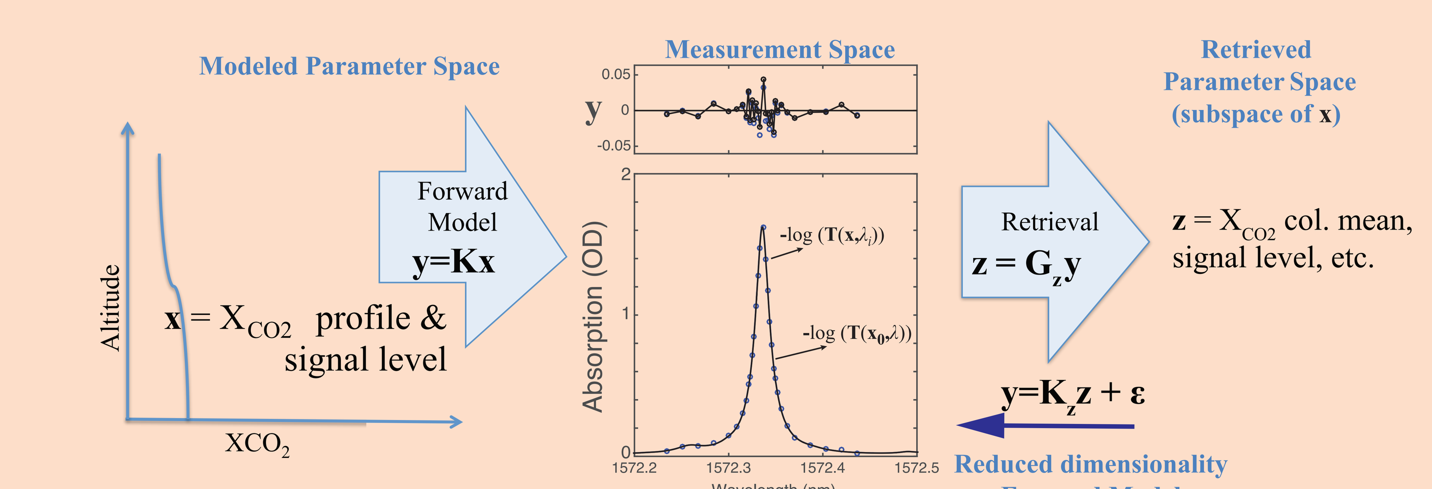
- We have developed an instrument model to characterize the random noise in the measurement and how it affects XCO2 .

- **Noise Sources for CO2 Sounder instrument**
  1. **Detector and electronic noise**
  2. **Solar background**
  3. **Photon shot noise**
  4. **Laser speckle noise**

- The noise model is fed into our retrieval model to obtain the retrieval uncertainty and the averaging kernel.

- Given the multi-wavelength line fitting approach, we have several ways of choosing the retrieval basis and its vertical sensitivity. We focus on two particular choices:

1. **Single principal component column mean optimized for uniform vertical sensitivity**
2. **Minimum variance solution with multiple principal components**



Retrieval $G_z=(K_z^T S_\varepsilon^{-\gamma} K_z)^{-1} K_z S_\varepsilon^{-\gamma}$

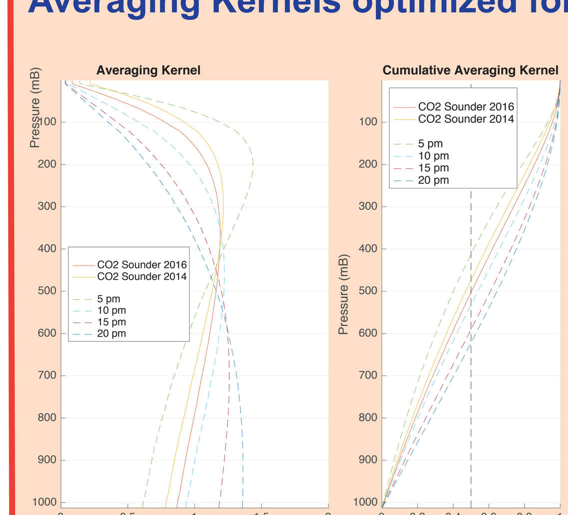
Column Averaging Kernel $A=G_z K$

Retrieval Uncertainty $S_x=G_z S_\varepsilon G_z^T$

γ = 1 corresponds to the minimum variance solution.
S_ε is calculated from the **noise model**

Note
- Forward model is linear in the OD space
- Notation derived from Rodgers (2000) and Eskes and Boersma ACP (2003)

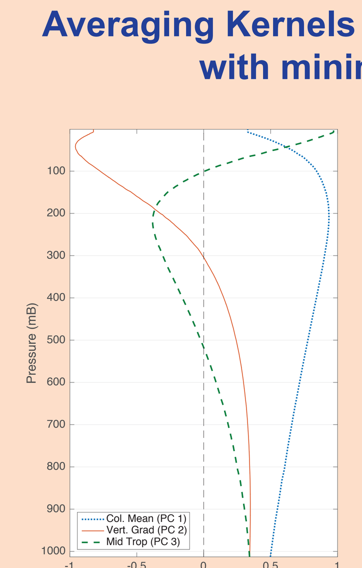
Averaging Kernels optimized for uniform vertical sensitivity



Advantages:

1. **Vertical sensitivity can be tuned so as to aid flux modeling.**
2. **Column mean with uniform vertical sensitivity captures changes in CO2 regardless of the extent of vertical mixing (e.g. night time PBL height can be hard to determine).**

Averaging Kernels for principal components with minimum variance fit



Advantages:

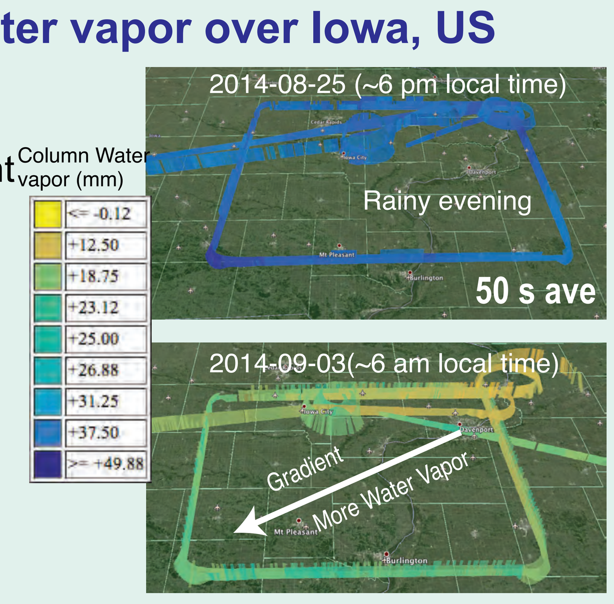
1. **Principal Components (PCs) capture maximally useful information from the retrieval. 1st PC is a column mean.**
2. **Higher order PCs provide information about the vertical distribution of CO2**
3. **By using a Singular Value Decomposition to get the PCs, retrieval errors between PCs are uncorrelated.**

Lidar Water Vapor measurement using adjacent isotope line

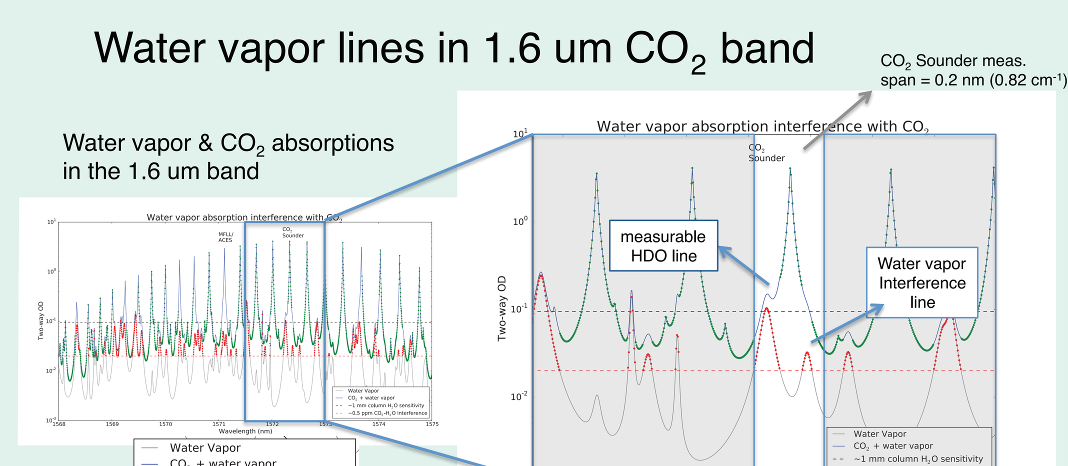
- **Water vapor affects the dry air fraction, which is used to calculate XCO_2**
- **Water vapor lines also interfere with the majority of CO_2 lines in both the 1.6 um and 2.0 um bands. This can cause line-fitting errors and bias.**
- **Weather models have much larger spatial resolution than lidar footprint**
- **Lidar measurement of water vapor is important, especially in the absence of an O_2 channel**

Retrieved Water vapor over Iowa, US

- Lidar provides clear measurement of water vapor
- Lidar can also senses horizontal water vapor gradients.



Water vapor lines in 1.6 um CO_2 band



Conclusions

1. We have established a retrieval algorithm and calibration/validation approach for the CO2 Sounder instrument, that is also directly applicable to the space version

2. We have demonstrated water vapor measurements and identified spatial water vapor gradients in the 2014 ASCENDS airborne campaign.

3. We have analyzed the retrieval approach to calculate the averaging kernel and the retrieval uncertainty. When applied to the airborne instrument, the retrieval uncertainty compares well against measurements indicating that we have a good understanding of our instrument.