

# Retrieval Algorithm for Column CO<sub>2</sub> Mixing Ratio Measurements from a Multi-wavelength IPDA Lidar

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- A multi-wavelength CO<sub>2</sub> Sounder lidar was developed at NASA Goddard Space Flight Center
- A new retrieval algorithm for the CO<sub>2</sub> Sounder lidar has been developed to simultaneously solves for XCO2, surface reflectance, water vapor, Doppler shift, & non uniformity in receiver spectral response
- The technique provides a robust and low bias measurement of the column CO<sub>2</sub> mixing ratio, as demonstrated by a series of airborne CO<sub>2</sub> mixing ratio measurement since 2014.
- More details: Sun et al., Atmos. Meas. Tech, Vol. 14, 2021 <u>https://doi.org/10.5194/amt-14-3909-2021</u>



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### Level-0: raw radiance data

- Removing instrument artifacts
- Scaling raw waveform data to optical power
- Calculating time of flight (column height)
- Merging waveform data with airplane or spacecraft housekeeping data
- Identifying cloud returns

### Level-1: calibrated radiance data

- Calculating laser pulse energies from waveforms
- Calculating the atmospheric transmission as a function of laser wavelengths
- Estimating SNR to use as the weighting factors for the fit

### Solving column CO<sub>2</sub> mixing ratio and a few other parameters from the multi-wavelength lidar measurements using a linear lease squares method



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# Lidar Signal and Atmosphere Modeling and Linear Least Squares Fit

**Lidar Signals**  $y(\lambda) = r_s T_A^2(\lambda) = \left(\frac{\pi}{A_r n_r}\right) \left[\frac{E_r(\lambda)}{E_t(\lambda)} \cdot \frac{1}{R^2}\right].$ Modelled CO<sub>2</sub> Absorption Line Shape using a line-by-line radiative transfer model  $T_A^2(\lambda) = T_{CO2}^2(\lambda) \cdot T_w^2(\lambda) \cdot T_o^2.$  $T_{CO2}^2(\lambda_i) = exp[-20D_{CO2}(\lambda_i)]$  $OD_{CO2}(\lambda_i) = \sum_{i=1}^{N_2} \rho_{CO2}(H_i) \sigma_{CO2}(H_i, \lambda_i) \Delta H_i$  $\approx \alpha_{CO2} \sum_{i=1}^{N_2} x co2_a(H_i) \rho_{air}(H_i) \sigma_{CO2}(H_i, \lambda_i) \Delta H_i$  $= \alpha_{CO2}OD_{CO2a}(\lambda_i)$  $T_{co2}^2(\lambda_i) \approx exp\{-2 \alpha_{co2}OD_{co2a}(\lambda_i)\}$ 

**The Least-Squares Fit** Loss function:  $J(\mathbf{Y}, \mathbf{S}) = [\mathbf{Y} - \mathbf{F}(\mathbf{S})]^{\mathrm{T}} \mathbf{W} [\mathbf{Y} - \mathbf{F}(\mathbf{S})] = \sum_{i=1}^{N_{1}} w_{i,i} [y(\lambda_{i}) - f_{i}(\mathbf{S})]^{2}$ with  $f_i(\mathbf{S}) = r_s T_A^2(\lambda_i, \mathbf{S})$  and **S** the parameters to be solved Linearization:  $F(S) \approx F0 + \frac{\partial F(S)}{\partial s}|_{s=s0}(S-S0)$ Normalization:  $\Delta y 1(\lambda_{i1}) = \frac{\Delta y(\lambda_i)}{f_0(\lambda_i)}, f 1_i(\mathbf{S}) = f_i(\mathbf{S}) / f 0(\lambda_i)$ Solution (using the pseudo-inverse function):  $\Delta \hat{S} = G \Delta Y 1$ Covariance Matrix:  $cov(\Delta \hat{S}) = G^T var(\Delta Y1) G$ Averaging Kernel: A =  $\frac{\partial \bar{XCO2}}{\partial rco2}$  = G<sub>XCO2</sub>K<sub>x</sub>, K<sub>x</sub> =  $\frac{\partial F1(XCO2_{ref})}{\partial rco2}$  $K_{x}(i,j) = \rho_{air}(H_{i}) \sigma_{CO2}(H_{i},\lambda_{i}) \Delta H_{i}.$ 

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## Use of the Retrieval Algorithm with Airborne Measurement Data



Sample data from the 2017 engineering flight over

### Edwards Air Force Base, 7/20/2017 17:30 local time Altitude **Transmitted Laser Pulses in Time Sequence** (T<sub>ref</sub>- time) **30 Transmitted Laser Pulses Overlaid** (30 pulses per wavelength scan) (**A**) **Amplitude** (**V**) 0.6 0.4 Amplitude (V) (a) (b) Transmitted laser pulse CO, Sounder lidar 0.6 0.5 Sun light 0.4 **Transmitted Pulse A** 0.2 0.1 0.1 0.1 Mannana **Transmitted Pulse** 0.3 Nadir illumination and 0.2 observation angle 0.1 Background Solar background C Time of flight level varies with noise & (range) baseline -0. the sun angle 3ms 0 $2 \mu s$ 2 ms 0 $1 \mu s$ 1 ms 3 µs 4 us $5 \mu s$ offset Timel Time **Received Pulses in Time Sequence 30 Received Laser Pulses Overlaid** Laser footprint Received Pulse Amplitude (V) Amplitude (V) (c) (d) 0.6 0.6 0.5 0.5 Surface return 0.4 0.4 Signal amplitude Receiver field of view Pulse 0.3 Laser signal 0.3 fully emcompass 0.2 0.2 the laser footprint Received 0.1 0.1 -0.1 -0. 71 μs 72 µs 0 2 ms 3ms 70 µs 73 μs 74 μs 75 μs 1 ms

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Time

4

Time



## Sample Results of the Column CO<sub>2</sub> Mixing Ratio Retrieval



Data from the 2017 engineering flight over Edwards Air Force Base, 7/20/2017 17:30 local time



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# Predicted vs. Actual Airborne Lidar Performance



- The retrieval can be carried out equivalently by fitting the logarithm of the lidar signal do the modelled OD under high SNR.
- An analytical solution to the fit can be derived when solving only the CO2 mixing ratio and surface reflectance.
- The predicted and the actual airborne measurement performance agreed well
- The model can be used for the dual wavelength IPDA lidar by reducing the number of laser wavelengths to two.

Comparison of the predicted XCO<sub>2</sub> error and the measurements for the 2016 airborne measurements over Edwards Air Force Base with 1-sec averaging



Standard Deviation of XCO2 (ppm)

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