Retrieval Algorithm for Column CO_2 Mixing Ratio Measurements from a Multi-wavelength IPDA Lidar

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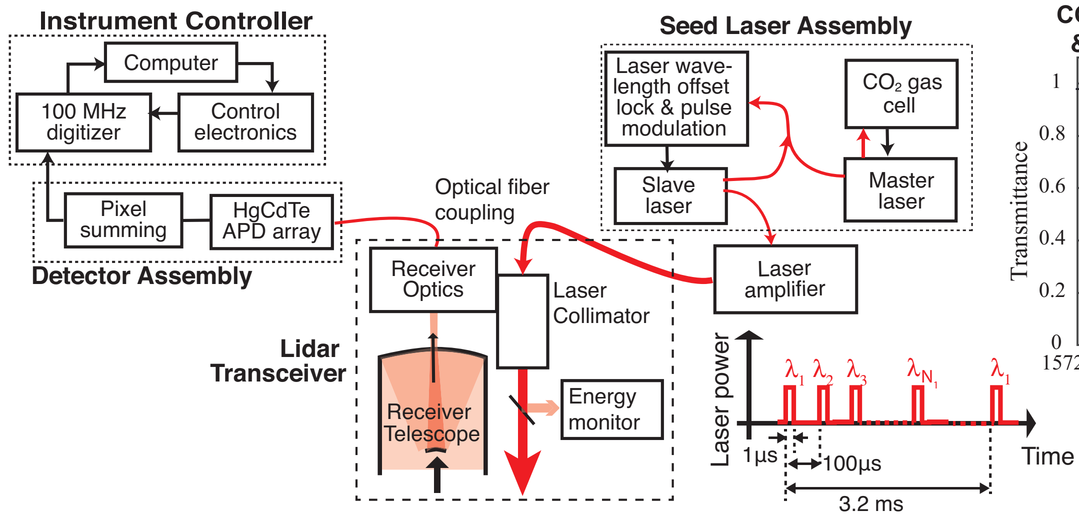
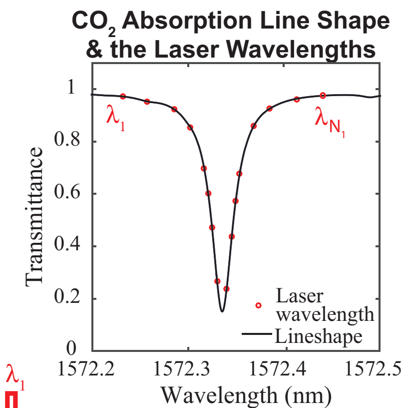
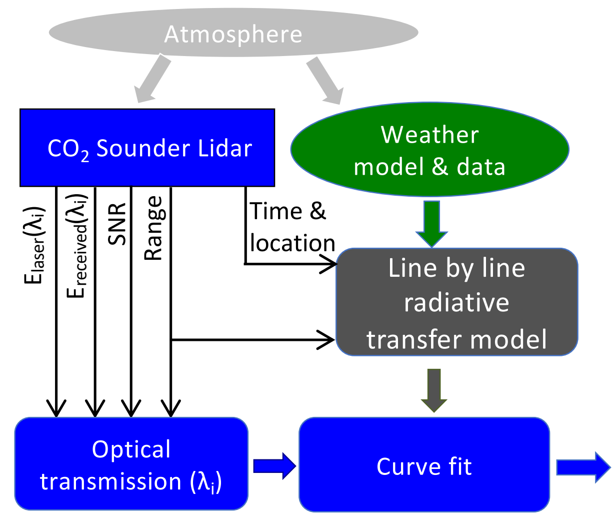
- **A multi-wavelength CO_2 Sounder lidar was developed at NASA Goddard Space Flight Center**
- **A new retrieval algorithm for the CO_2 Sounder lidar has been developed to simultaneously solves for XCO2 , surface reflectance, water vapor, Doppler shift, & non uniformity in receiver spectral response**
- **The technique provides a robust and low bias measurement of the column CO_2 mixing ratio, as demonstrated by a series of airborne CO_2 mixing ratio measurement since 2014.**
- **More details: Sun *et al*., *Atmos. Meas. Tech*, Vol. 14, 2021** https://doi.org/10.5194/amt-14-3909-2021







Retrieval Algorithm – Flow Chart

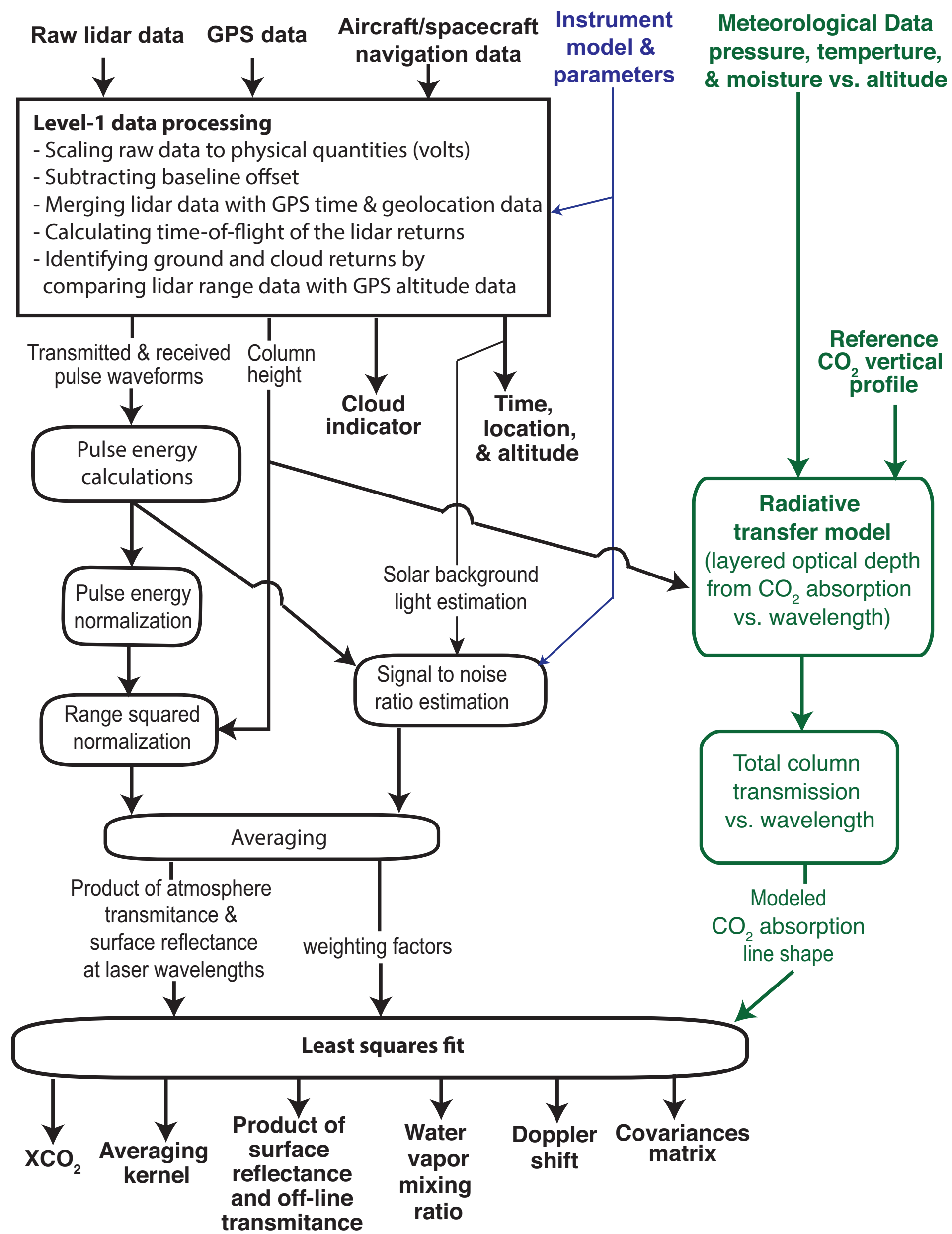
Level-0: raw radiance data

- 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_2 mixing ratio and a few other parameters from the multi-wavelength lidar measurements using a linear lease squares method



Lidar Signal and Atmosphere Modeling and Linear Least Squares Fit

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Lidar Signals

$$y(\lambda) = r_s T_A^2(\lambda) = \left(\frac{\pi}{A_r \eta_r}\right)\left[\frac{E_r(\lambda)}{E_t(\lambda)} \cdot \frac{1}{R^2}\right].$$

Modelled CO_2 Absorption Line Shape using a line-by-line radiative transfer model

$$T_A^2(\lambda) = T_{CO2}^2(\lambda) \cdot T_w^2(\lambda) \cdot T_o^2.$$

$$T_{CO2}^2(\lambda_i) = exp[-2OD_{CO2}(\lambda_i)]$$

$$OD_{CO2}(\lambda_i) = \sum_{j=1}^{N_2} \rho_{CO2}(H_j)\sigma_{CO2}(H_j,\lambda_i)\,\Delta H_j$$

$$\approx \alpha_{CO2} \sum_{j=1}^{N_2} xco2_a(H_j)\,\rho_{air}(H_j)\,\sigma_{CO2}(H_j,\lambda_i)\,\Delta H_j$$

$$= \alpha_{CO2} OD_{CO2a}(\lambda_i)$$

$$T_{CO2}^2(\lambda_i) \approx exp\{-2\,\alpha_{CO2} OD_{CO2a}(\lambda_i)\}.$$

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 $\boldsymbol{S}$ the parameters to be solved

Linearization: $\mathbf{F}(\mathbf{S}) \approx \mathbf{F0} + \frac{\partial \mathbf{F}(\mathbf{S})}{\partial \mathbf{S}}\big|_{\mathbf{S}=\mathbf{S0}}(\mathbf{S}-\mathbf{S0})$

Normalization: $\Delta y1(\lambda_{i1}) = \frac{\Delta y(\lambda_i)}{f0(\lambda_i)}$, $f1_i(\mathbf{S})$=$f_i(\mathbf{S})/f0(\lambda_i)$

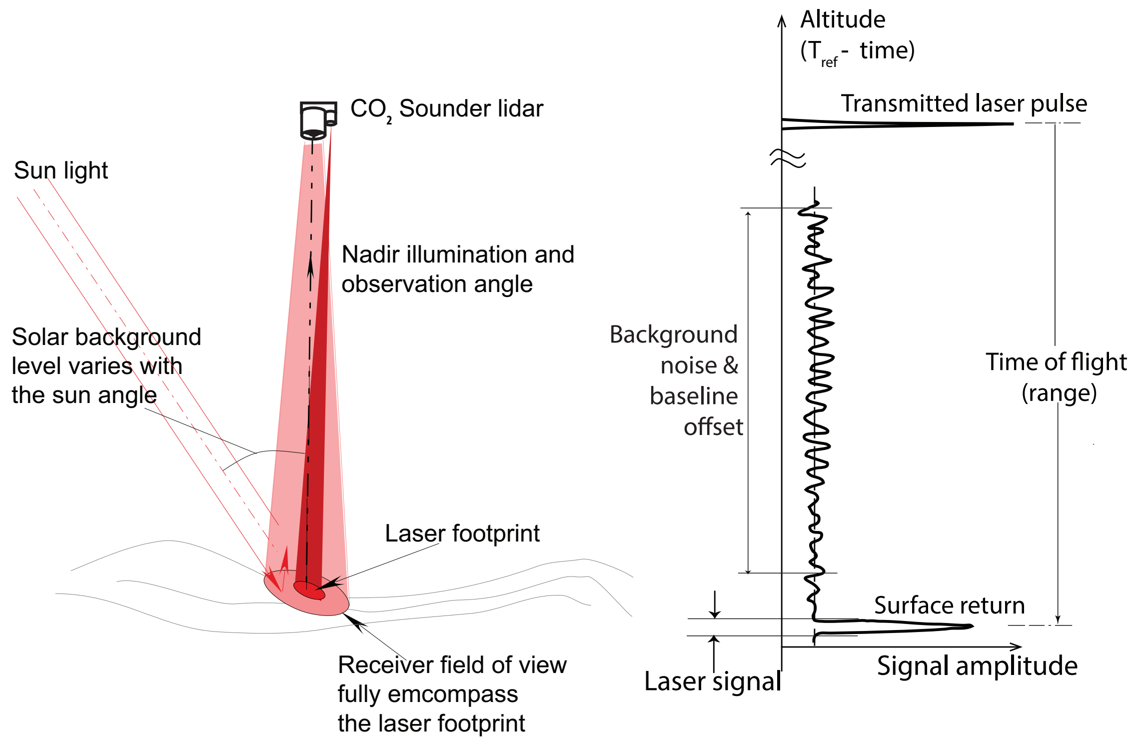
Solution (using the pseudo-inverse function): $\boldsymbol{\Delta\hat{S}} = \mathbf{G}\ \boldsymbol{\Delta}\mathbf{Y1}$

Covariance Matrix: $\boldsymbol{cov}(\boldsymbol{\Delta\hat{S}}) = \mathbf{G}^{\mathrm{T}}\ \boldsymbol{var}(\boldsymbol{\Delta}\mathbf{Y1})\ \mathbf{G}$

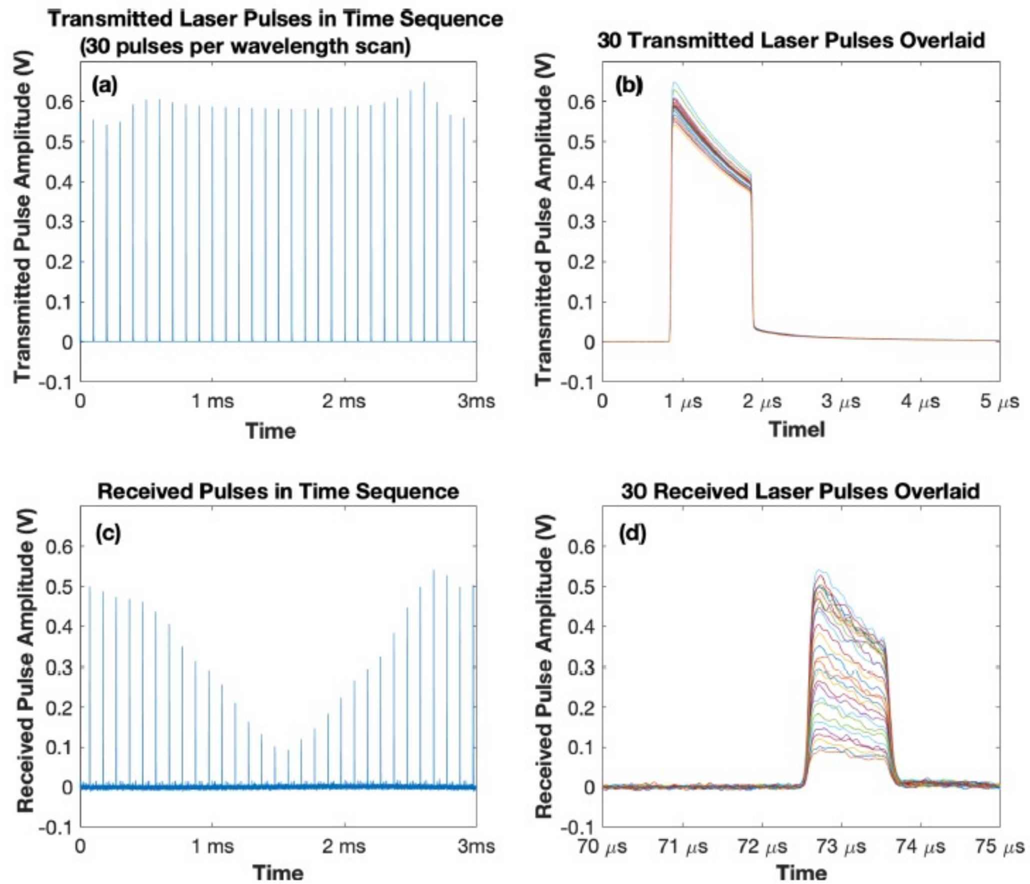
Averaging Kernel: $\mathbf{A} = \frac{\partial \widehat{XCO2}}{\partial \boldsymbol{xco_2}} = \mathbf{G}_{\boldsymbol{XCO2}}\mathbf{K_x}$, $\mathbf{K_x} = \frac{\partial \mathrm{F1}(XCO2_{ref})}{\partial \mathbf{xco2}}$

$$K_x(i,j) = \rho_{air}(H_j)\,\sigma_{CO2}(H_j,\lambda_i)\,\Delta H_j.$$

Use of the Retrieval Algorithm with Airborne Measurement Data

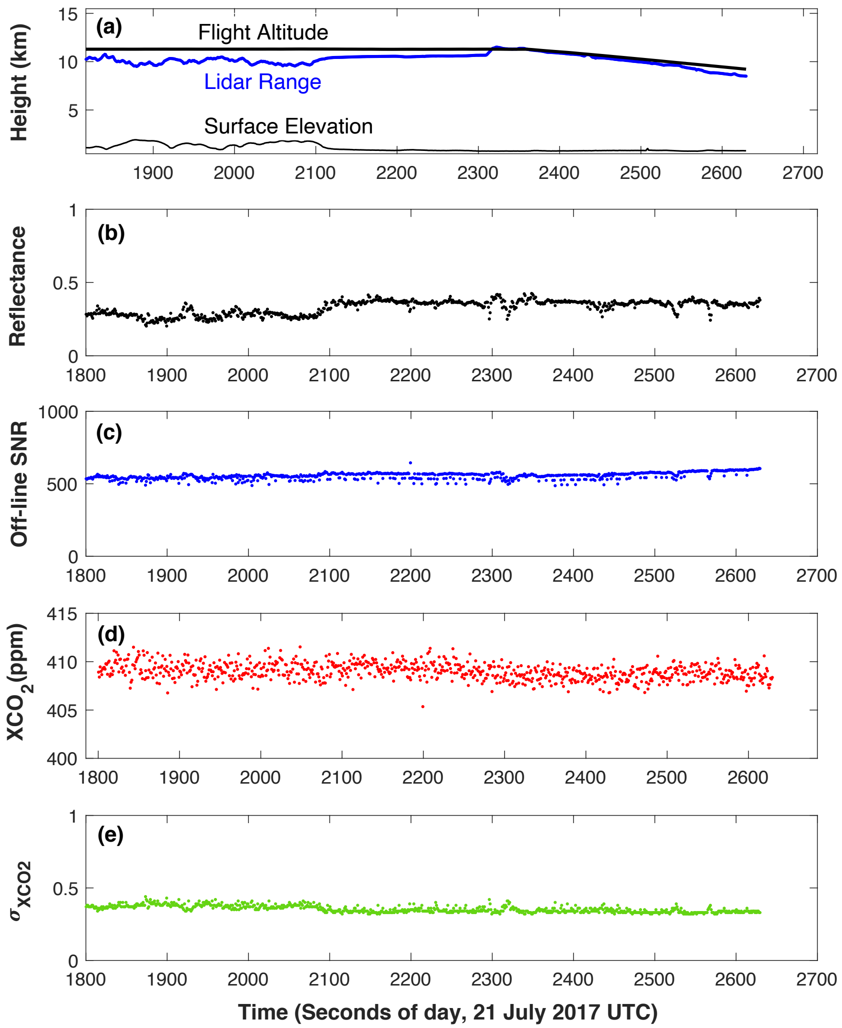


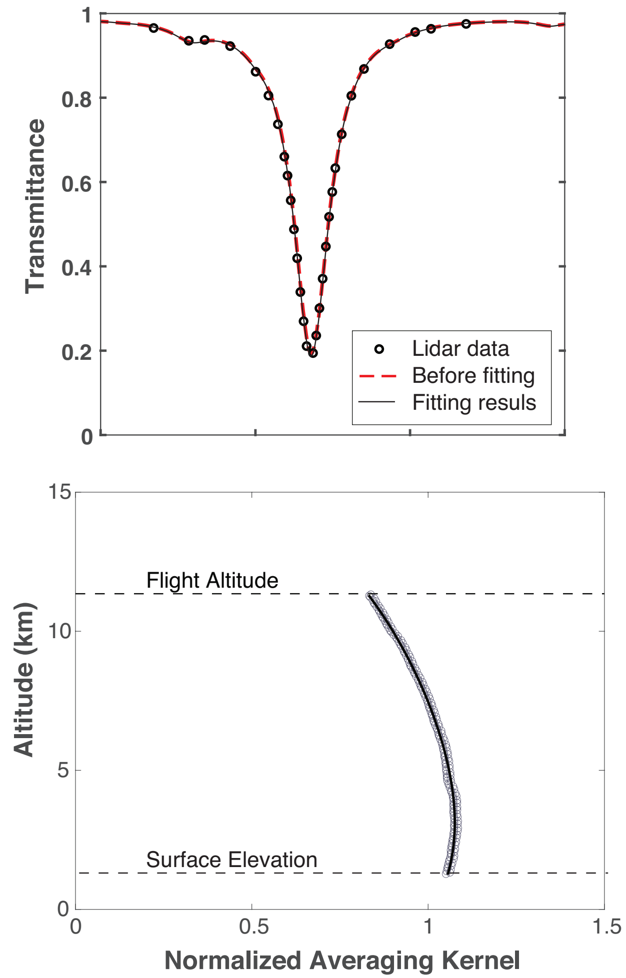
Sample data from the 2017 engineering flight over Edwards Air Force Base, 7/20/2017 17:30 local time

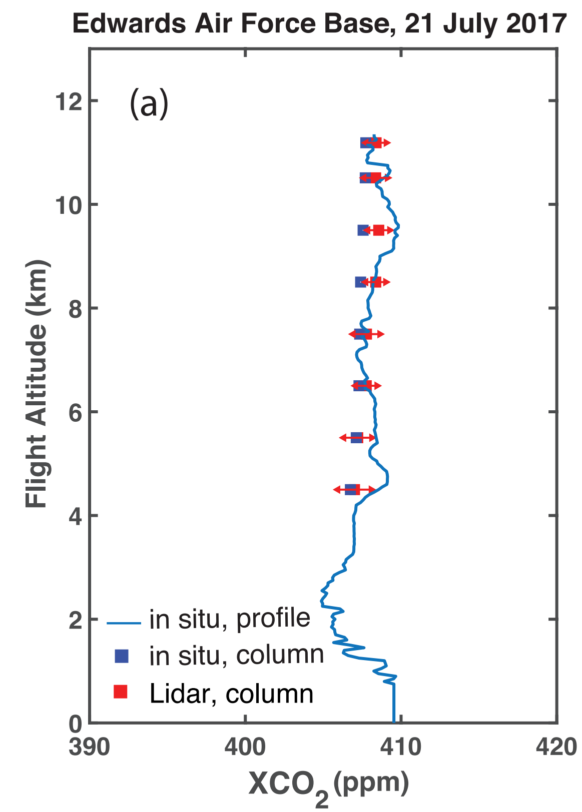


Sample Results of the Column CO_2 Mixing Ratio Retrieval

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







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_2 error and the measurements for the 2016 airborne measurements over Edwards Air Force Base with 1-sec averaging