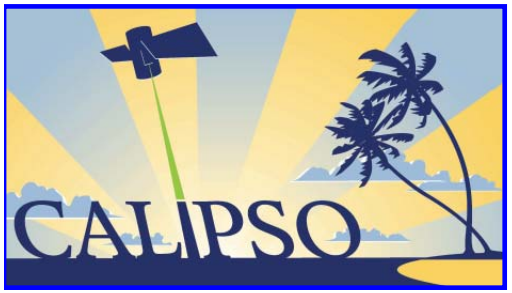

Aerosol properties from combined oxygen A band radiances and lidar

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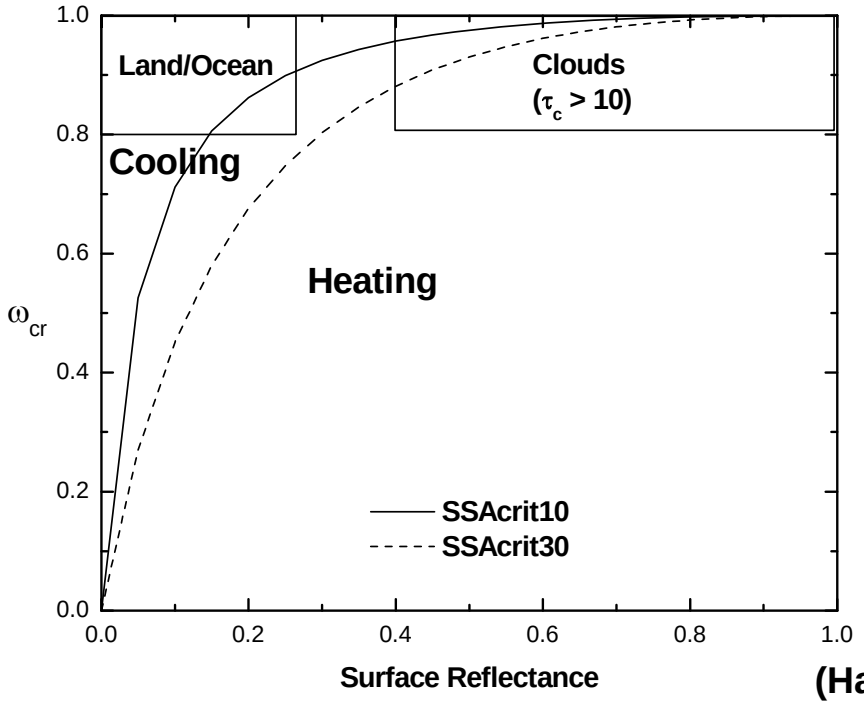
MOTIVATION

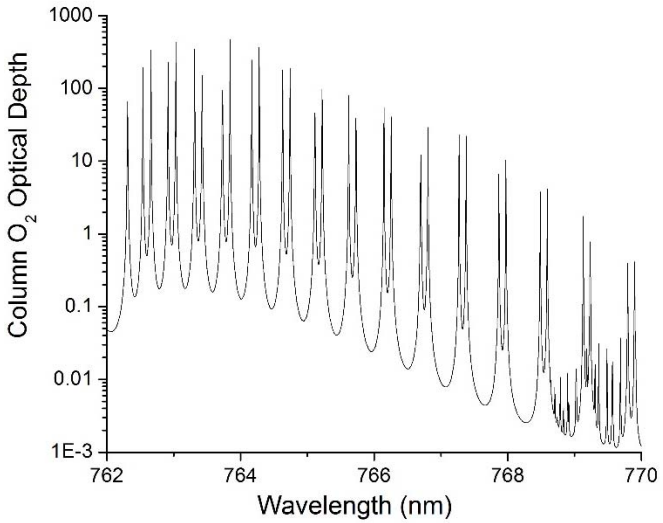
- **Much of the uncertainty in estimating global direct aerosol radiative forcing comes from uncertainties in aerosol absorption**
- **Current satellite retrieval capabilities are very limited**
  - Multi-angle polarimetric methods have received a lot of attention
  - High spectral resolution O_2 A-band spectra offer another possibility



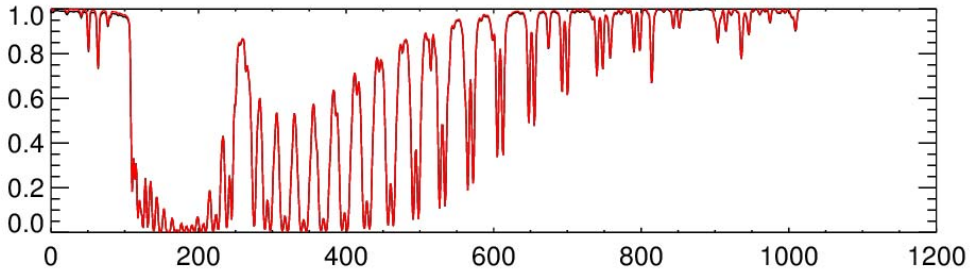
(Haywood and Shine, 1995)

High spectral resolution required

Column O_2 OD from line-by-line calculations

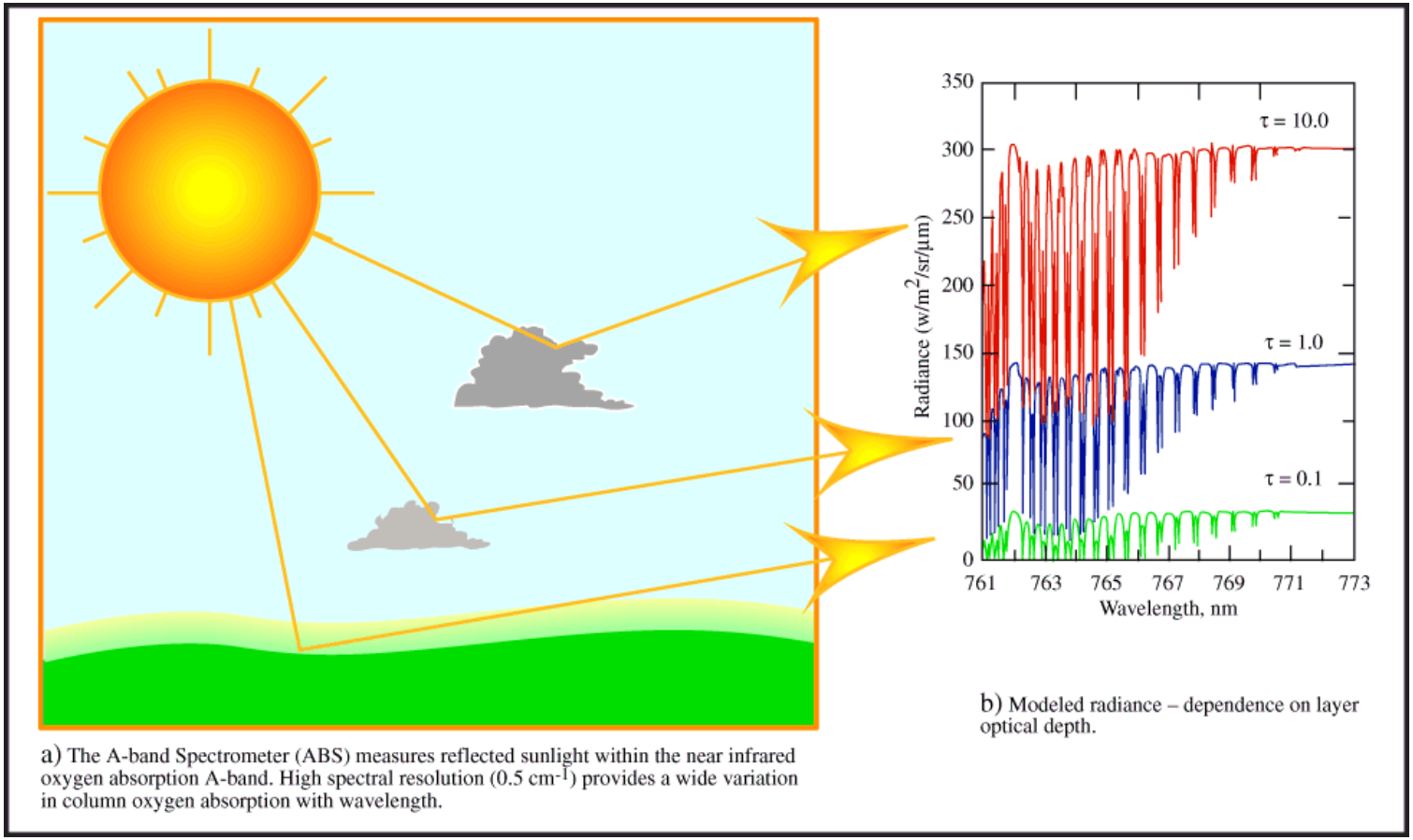


Atmospheric transmission at the resolution of OCO-2 spectrometer



When the maximum column oxygen optical depth reaches ~5, transmission to the surface is very low and A-band measurements can be used to separate surface and atmospheric scattering.

Both CALIPSO and CloudSat originally included A-band spectrometers for cloud and aerosol retrievals

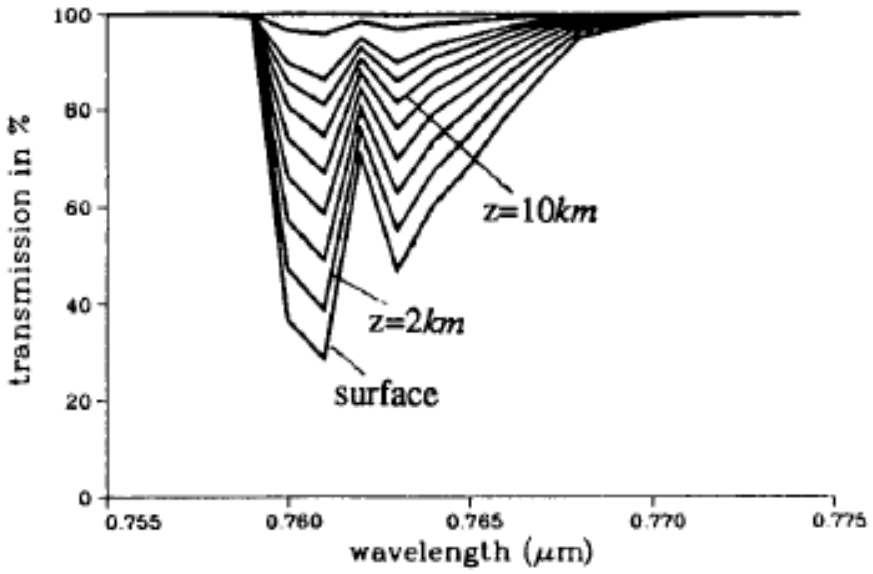


a) The A-band Spectrometer (ABS) measures reflected sunlight within the near infrared oxygen absorption A-band. High spectral resolution (0.5 cm^{-1}) provides a wide variation in column oxygen absorption with wavelength.

b) Modeled radiance – dependence on layer optical depth.

A short history of A-band

- **Unique potential of reflected O_2 A-band radiances (for cloud height retrievals) was recognized in the early 1960's**
- **First satellite measurements: 1965, Gemini V**
- **Many instruments with A-band channels have flown since, but mostly with low spectral resolution**

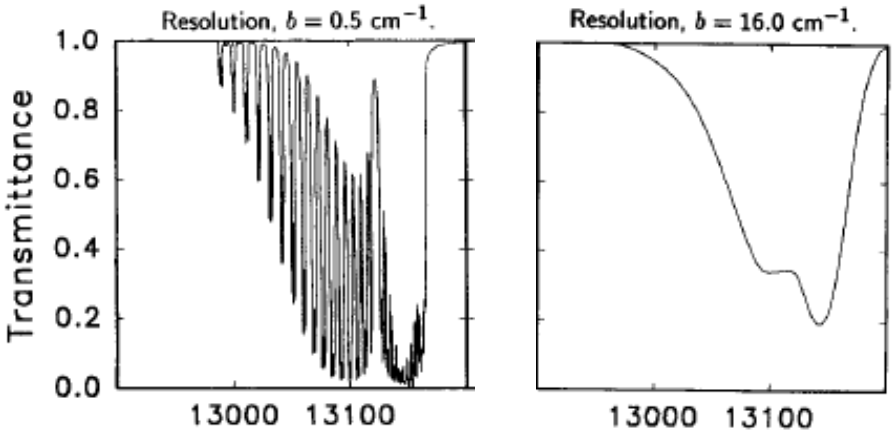


A-band spectrum at 1-nm resolution

(J. Fischer and H. Grassl, 1991)

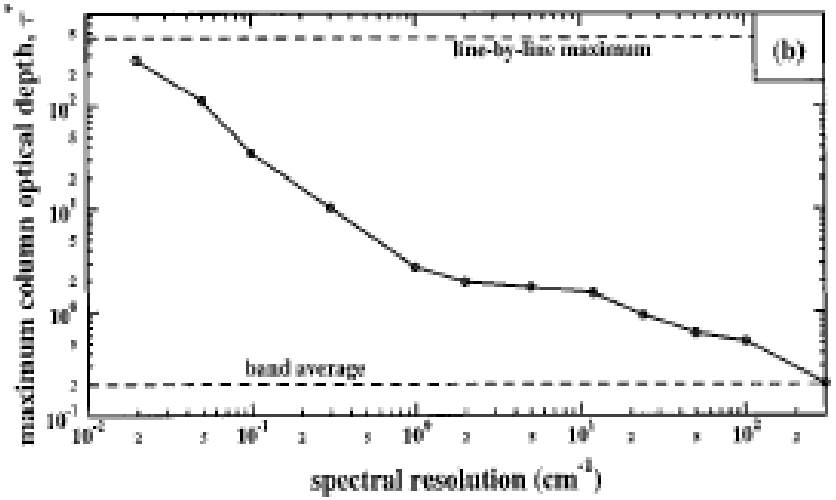
High resolution A-band spectra

- **O'Brien and Mitchell (1992) were the first to realize the advantages of high spectral resolution A-band measurements**



- **With resolution < 0.5 cm^{-1}, maximum O_2 optical depth exceeds 5**

- **Combining weak and strong channels allows separating surface and atmospheric scattering.**

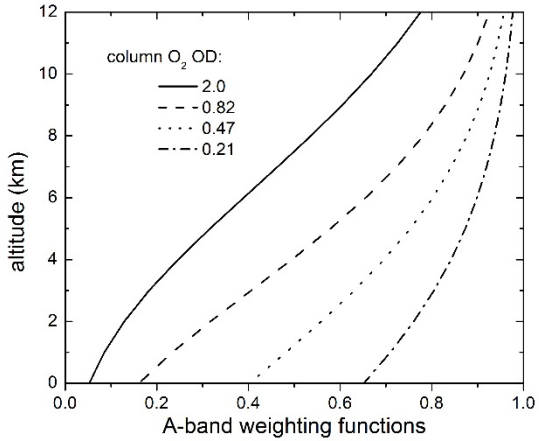


(Stephens and Heidinger, JAS, 2000)

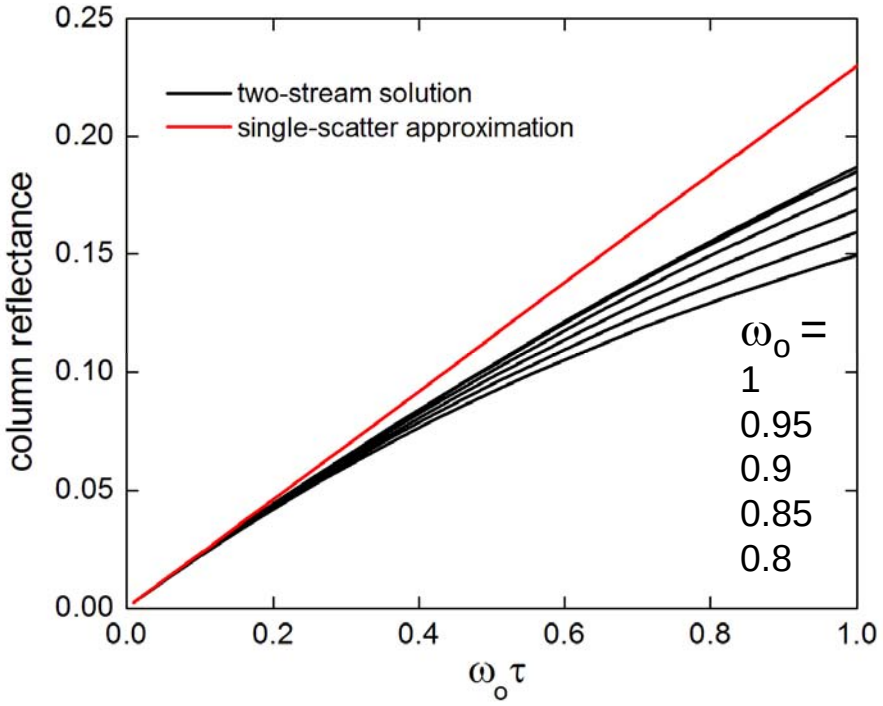
Retrieval Sensitivities

The A band offers 2 critical advantages:

A-band weighting functions

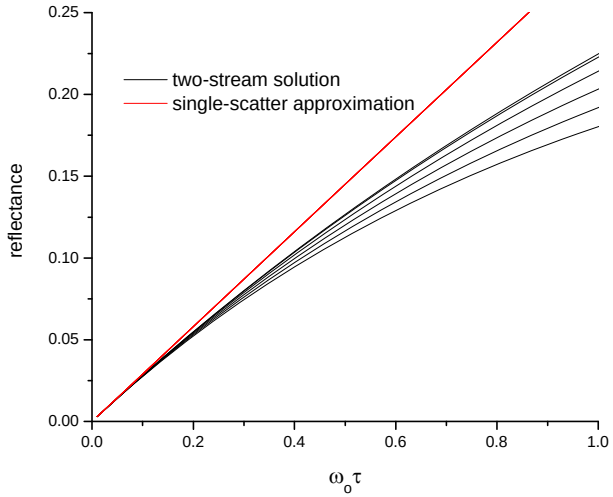


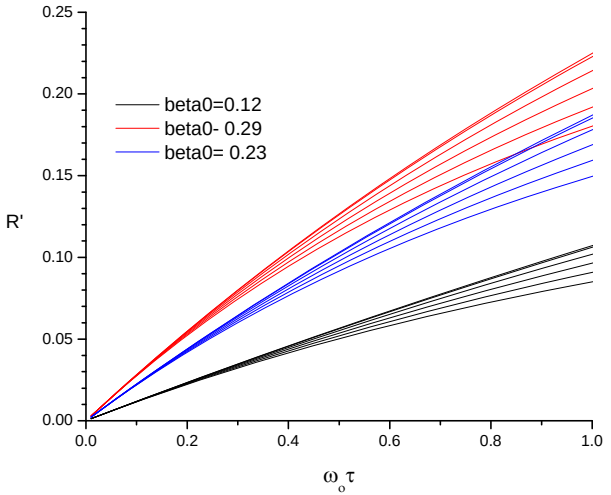
Sensitivity to surface and aerosol scattering



As OD increases, multiple scattering breaks the degeneracy between ω_o and τ

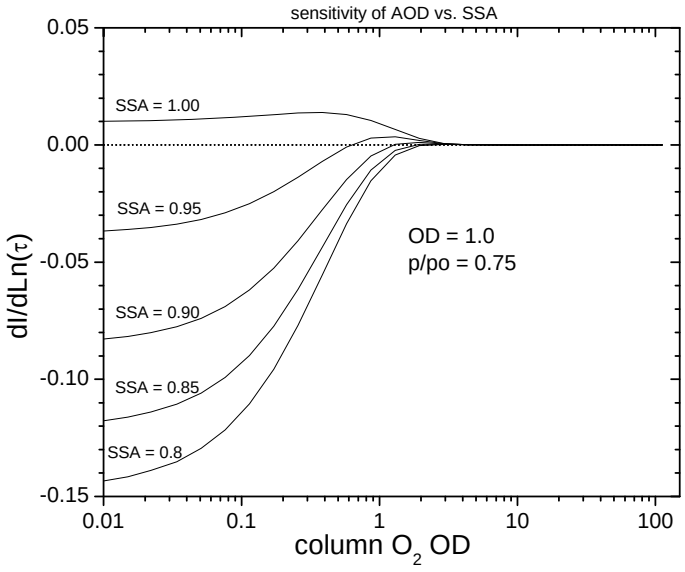
Impacts of differences in aerosol scattering are small relative to impacts from aerosol absorption



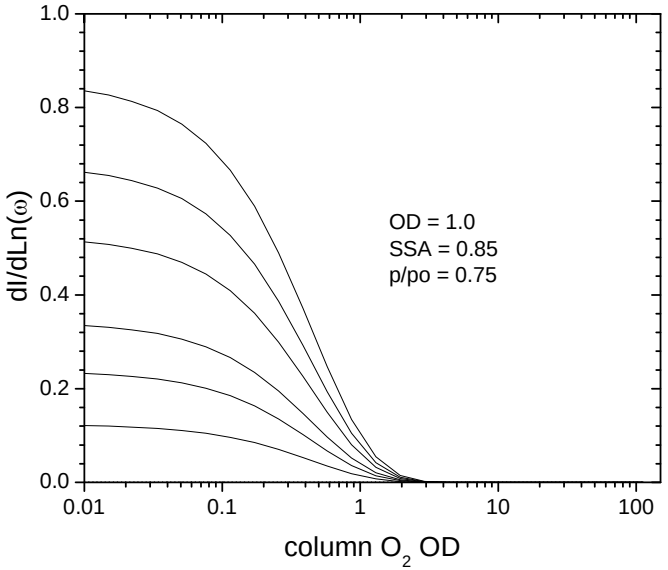


Dependence of TOA radiances on:

aerosol optical depth



aerosol SSA



Optimal Estimation Retrieval

Initial retrieval state vector:

$$\mathbf{x_o} = (\tau_a, \omega_o, \alpha_{sfc})$$

Forward model:

$$\mathbf{y} = \mathrm{F}(\mathbf{x},\mathbf{b}) + \varepsilon$$

Atmospheric description, including lidar constraints

Iterative retrieval based on cost function:

$$\chi^2 = (\mathbf{F}(\mathbf{x},\mathbf{b}) - \mathbf{y})^T \mathbf{S}_\epsilon^{-1} (\mathbf{F}(\mathbf{x},\mathbf{b}) - \mathbf{y}) + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

Forward model uses a vector radiative transfer model based on the successive order of scatter method (Zhai et al., JQSRT, 2010)

In practice:

Model for instrument SNR:

$$N(I) = I_{\max} \cdot \sqrt{\frac{I}{I_{\max}} \cdot C_{\text{photon}}^2 + C_{\text{background}}^2}$$

$$\Phi = \sqrt{\sum_i \left(\frac{\left(I_I^l(i) - I_I^m(i) \right)^2}{C_I^m} \right) + \sum_j \left(\frac{x_j - x_{j,a}}{S_{j,a}} \right)^2}$$

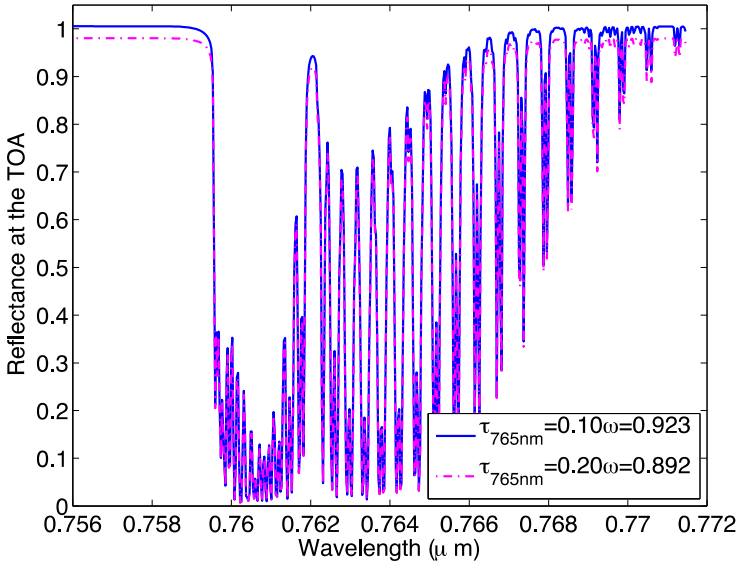
Forward Model and Retrieval Algorithm

CALIPSO Aerosol Profile

Molecular Number Concentration Profile

OCO ABSCO Line Absorption Cross Sections

Vector Radiative Transfer Model (Successive Order of Scattering Method, Zhai et al. 2010)



Levenberg-Marquardt Algorithm is used to minimize differences between measurements and forward model simulations. The state parameters are:

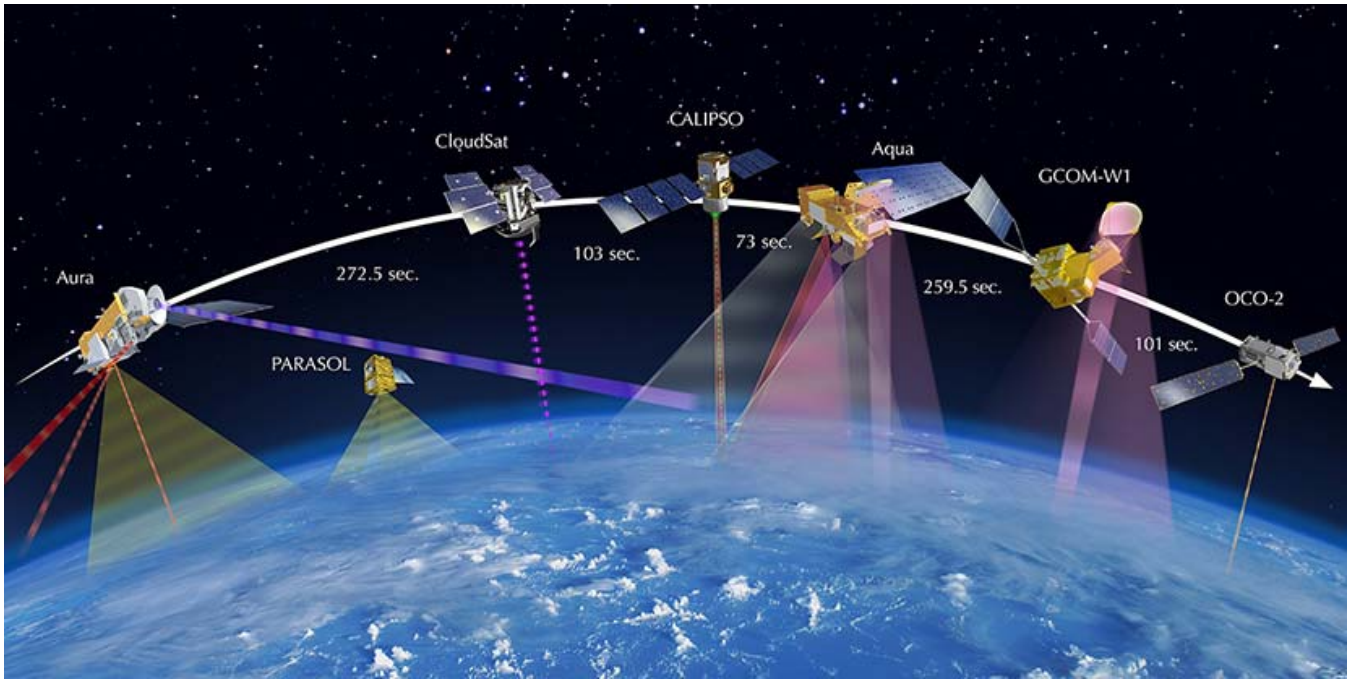
Aerosol Optical Depth

Aerosol Single Scattering Albedo

Ground reflection Albedo

- **But: even high-resolution A-band spectra have limited information content**
- **For an aerosol layer over a non-black surface, radiances depend on: τ, g, ω_o, α_{sfc}, and aerosol vertical distribution**
- **Information content analysis shows 4-5 parameters at best can be derived from an OCO-like spectrometer (Heidinger and Stephens, 2000)**
- **Lidar provides constraints allowing improved retrievals of aerosol properties**
    - Scene ID (identification of layering, cloud masking)
    - Aerosol vertical distribution

OCO-2 now in the A-Train: new possibilities



OCO-2 carries 3 spectrometers

- **2.1 um (strong CO_2)**
- **1.6 um (weak CO_2)**
- **0.76 um (oxygen A-band)**

A-band spectrometer performance similar to that planned for CALIPSO:

- **$\Delta\lambda$ = 0.044 nm**
- **SNR > 200**
- **1-km IFOV**

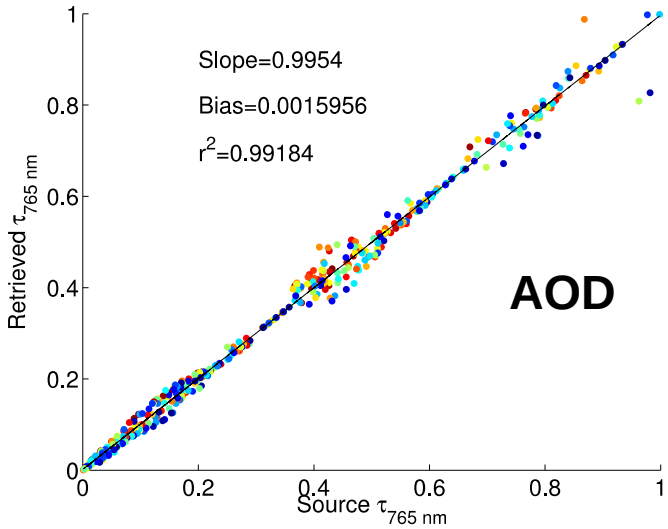
We have incorporated recent developments from the OCO-2 team:

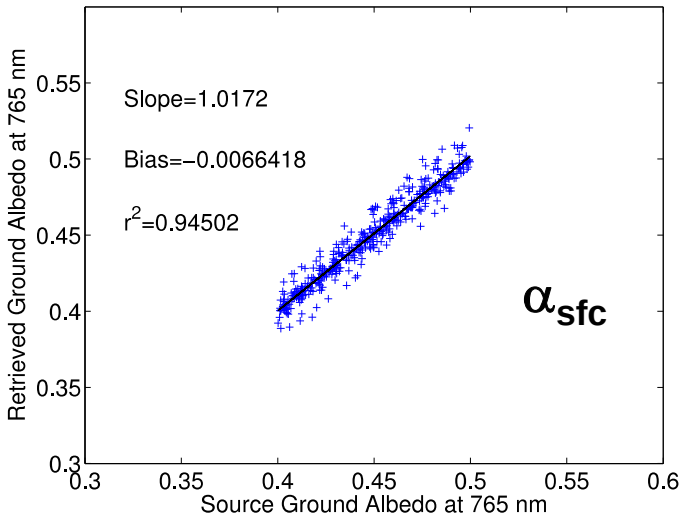
- **Development of improved oxygen absorption line coefficients (ABSCO look-up table)**
  - OCO-2 requires modeling spectra to < 1% accuracy
  - Better accounting for line mixing, collision-induced absorption, O_2-H_2O broadening, non-Voigt lineshapes

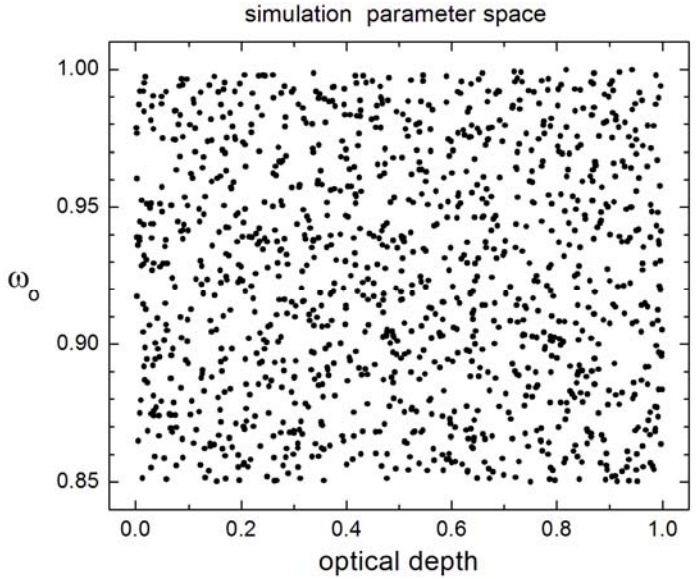
- **Improved high spectral resolution solar spectrum**

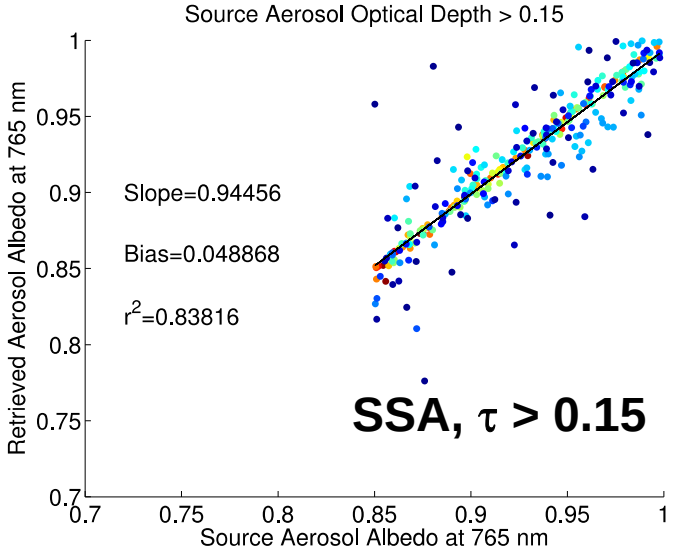
Retrieval from OCO-2 A-band spectra (synthetic data) assuming aerosol model is known

(using lidar to constrain aerosol model)

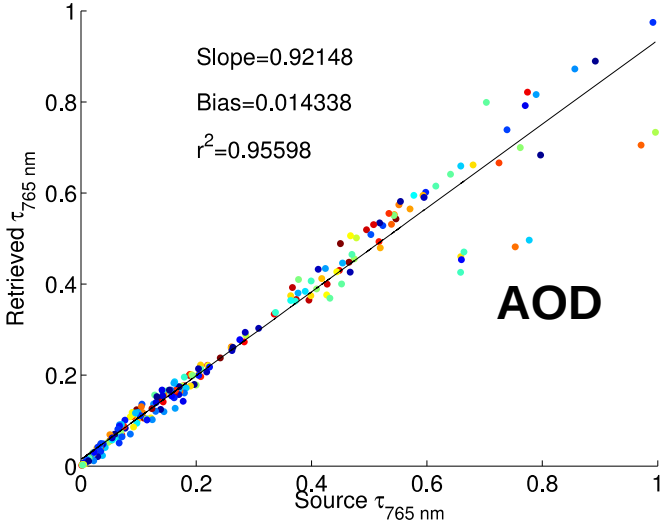


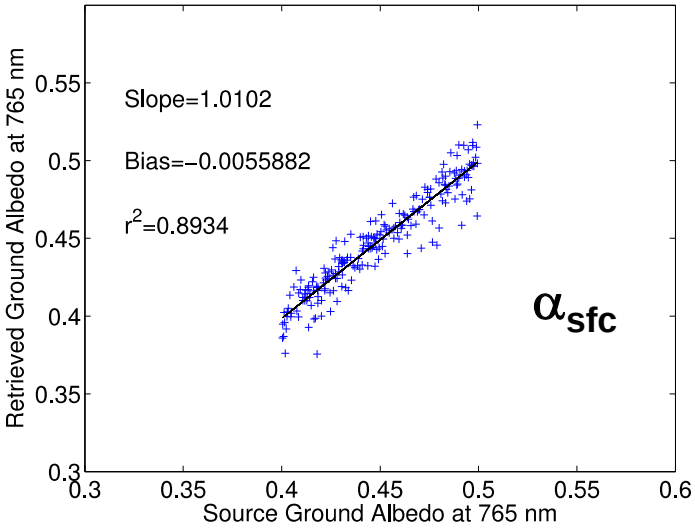


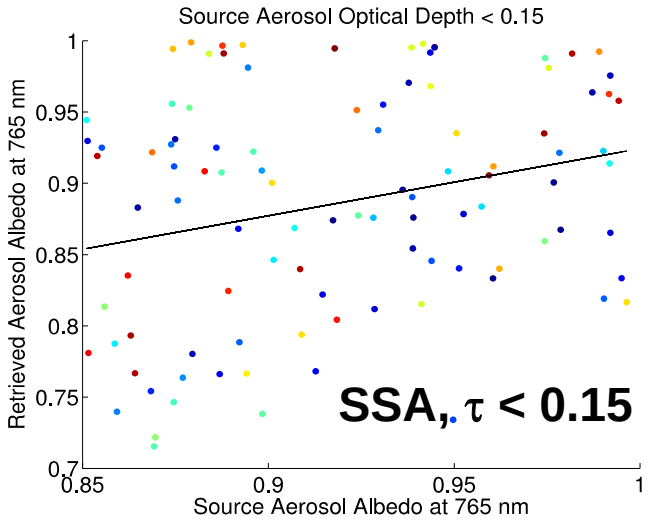


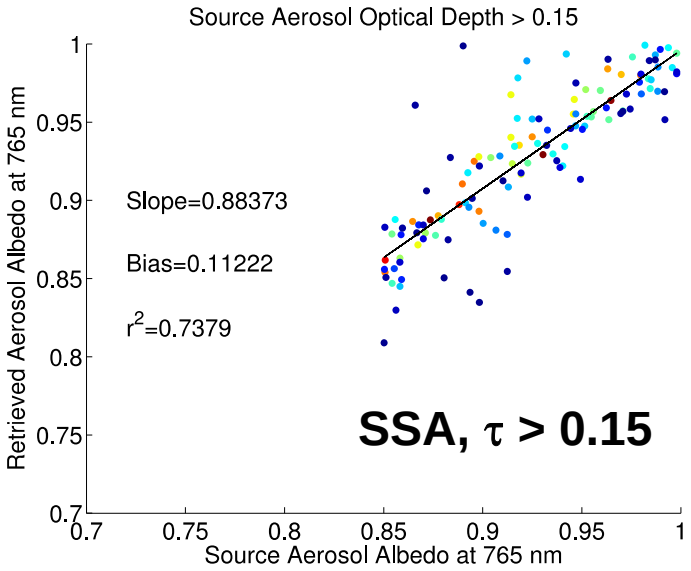


Retrieval from OCO-2 A-band spectra (synthetic data) assuming aerosol model is unknown

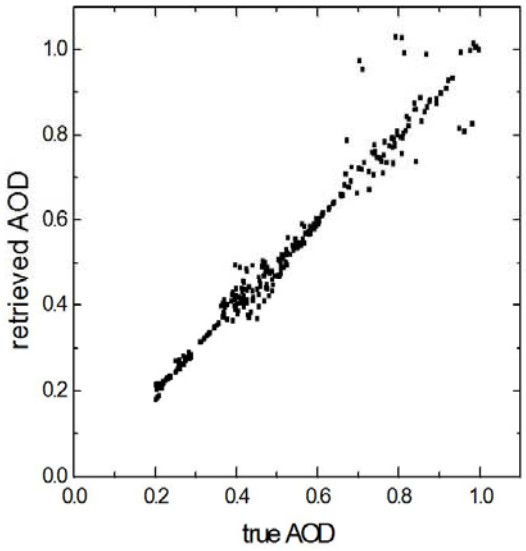


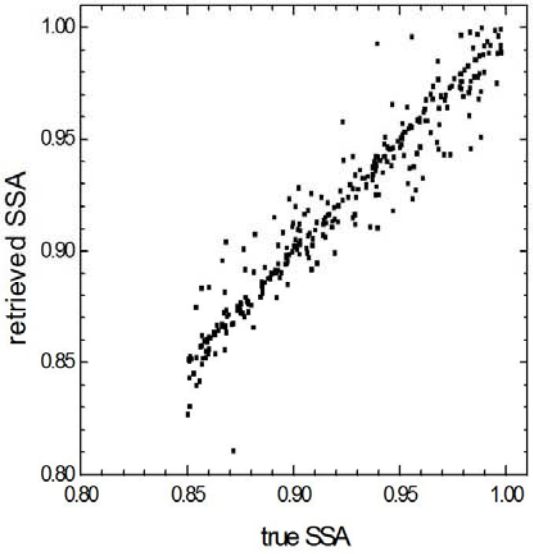


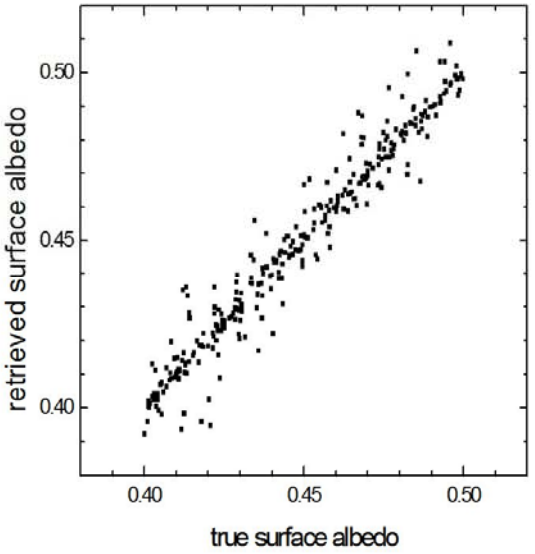


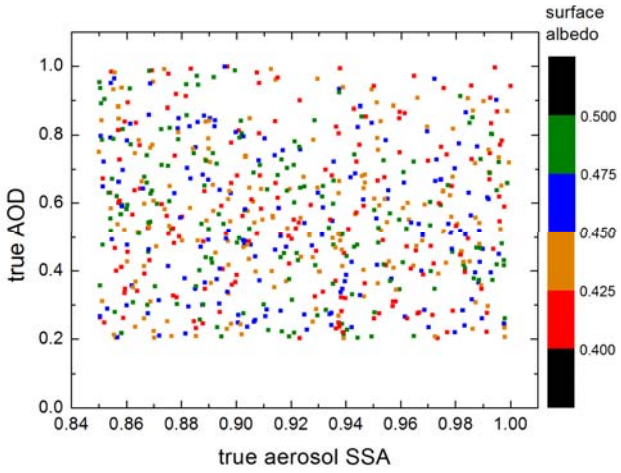


Filtered simulation results









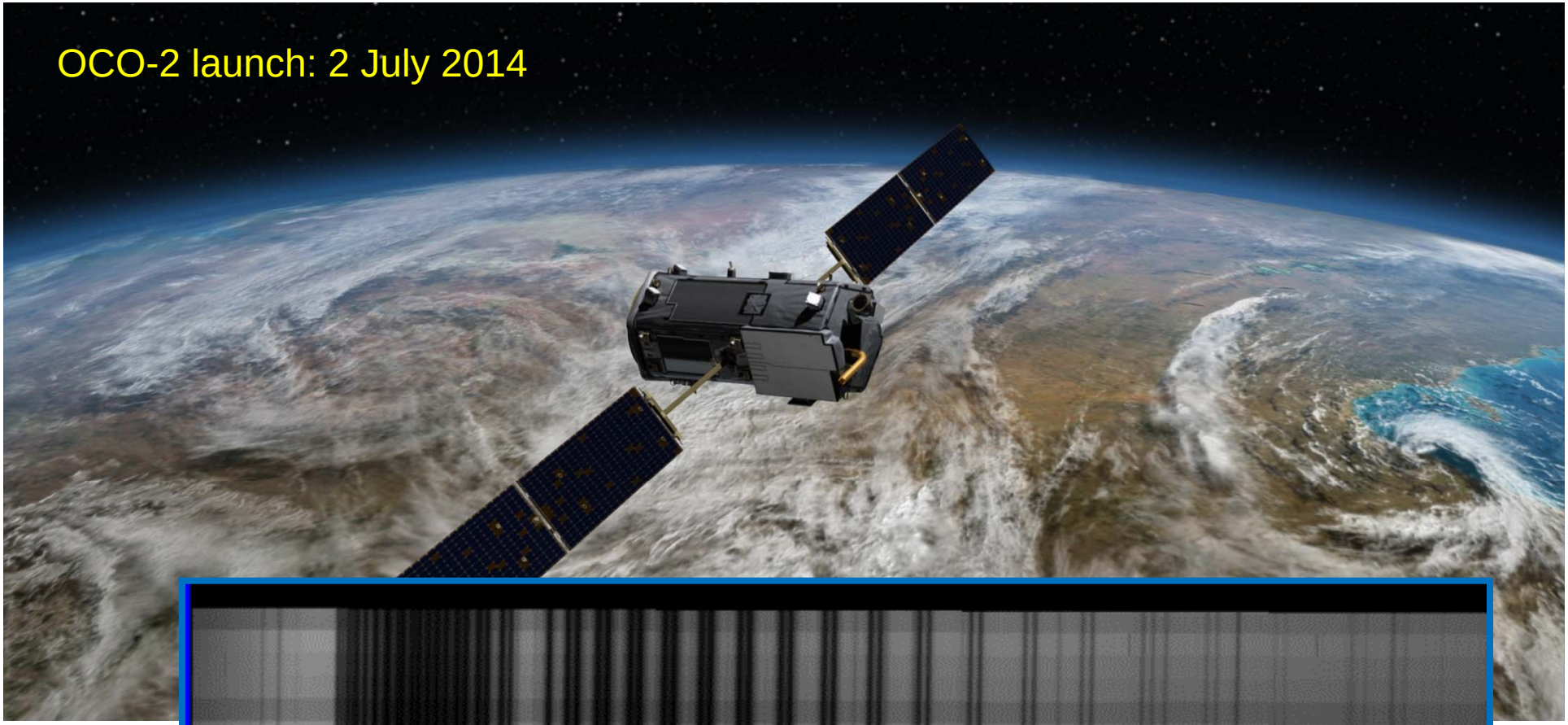
Summary

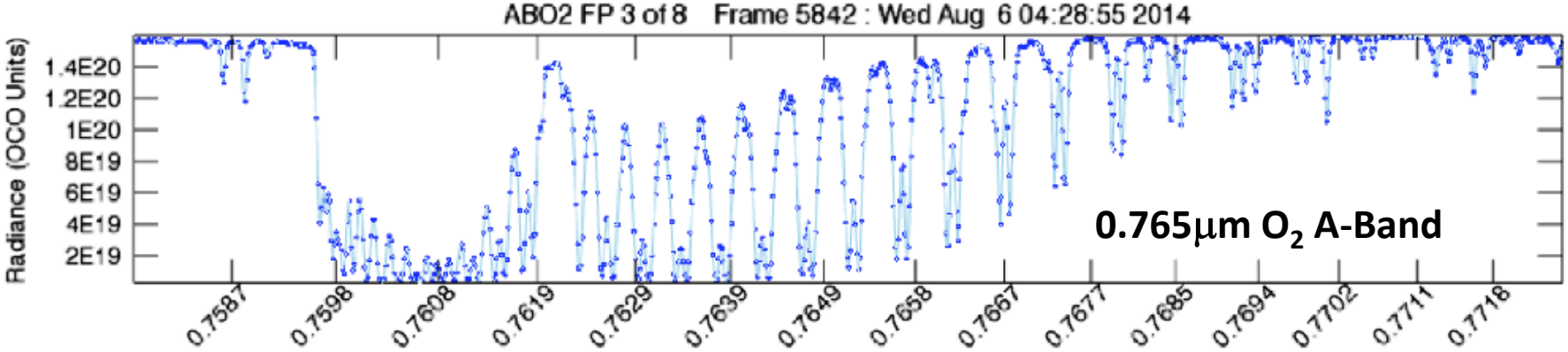
Results from 964 retrieval simulations with AOD > 0.2,
as a function of the degree of filtering applied.

N is the number of samples which pass the filter criteria.

Flag Value	AOD (%)		SSA		Surface albedo		N
	Bias	Std Dev	Bias	Std Dev	Bias	Std Dev	
1	0.093	6.6	-0.0016	0.012	-0.00086	0.0069	300
2	- 2.2	16.0	-0.00013	0.019	0.0021	0.014	477
4	- 1.1	21.2	-0.00046	0.027	0.0014	0.015	671

OCO-2 launch: 2 July 2014





Practical Considerations

- **Current status of Level 1b product indicates data quality will be sufficient**
  - Spectral calibration (Doppler shifts, dispersion) well in hand
  - SNR currently about 400:1
  - Radiometric calibration exceeds what we require
- **OCO-2 team still working some details**
  - Bringing solar model into agreement with OCO-2 high spectral resolution observations
  - Work is continuing to reduce residuals in observed high-resolution O_2 spectrum

(Preliminary) Conclusions

- Have tried to incorporate realistic instrument characteristics into retrieval simulations
- AOD retrieval performance appears to be good, even at very low OD
- The ground albedo retrieval is also very good
- Aerosol single scattering albedo retrieval performance is promising, for AOD > 0.2
- OCO-2 satellite has just moved into formation with CALIOP
  - Co-located data now available

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Many thanks to Dave Crisp, Dave Pollack and the OCO/OCO-2 team