Jet Propulsion Laboratory
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On Optimal Estimation Theory for Atmospheric Correction of Visible Shortwave Infrared (VSWIR) Imaging Spectroscopy

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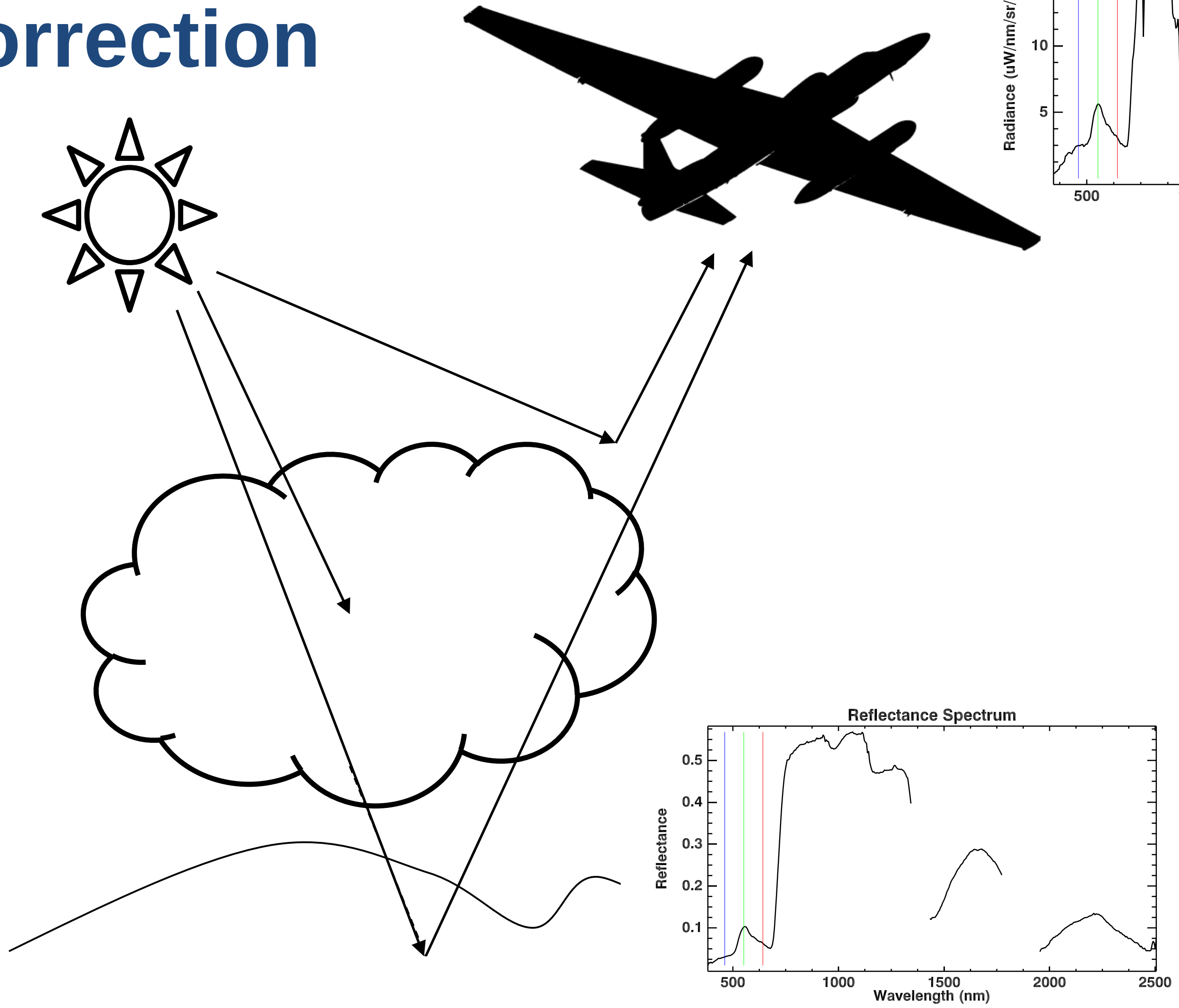
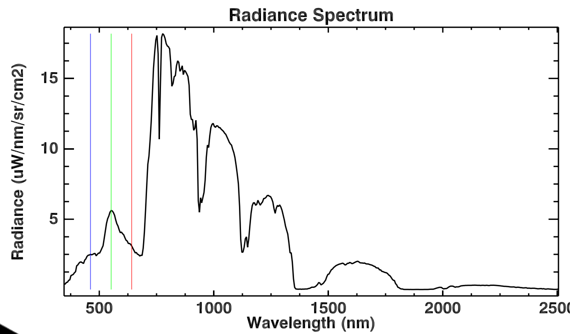
Agenda

1. Status quo atmospheric correction methods and gaps
2. Optimal Estimation and its advantages
3. Implementation possibilities

Atmospheric correction





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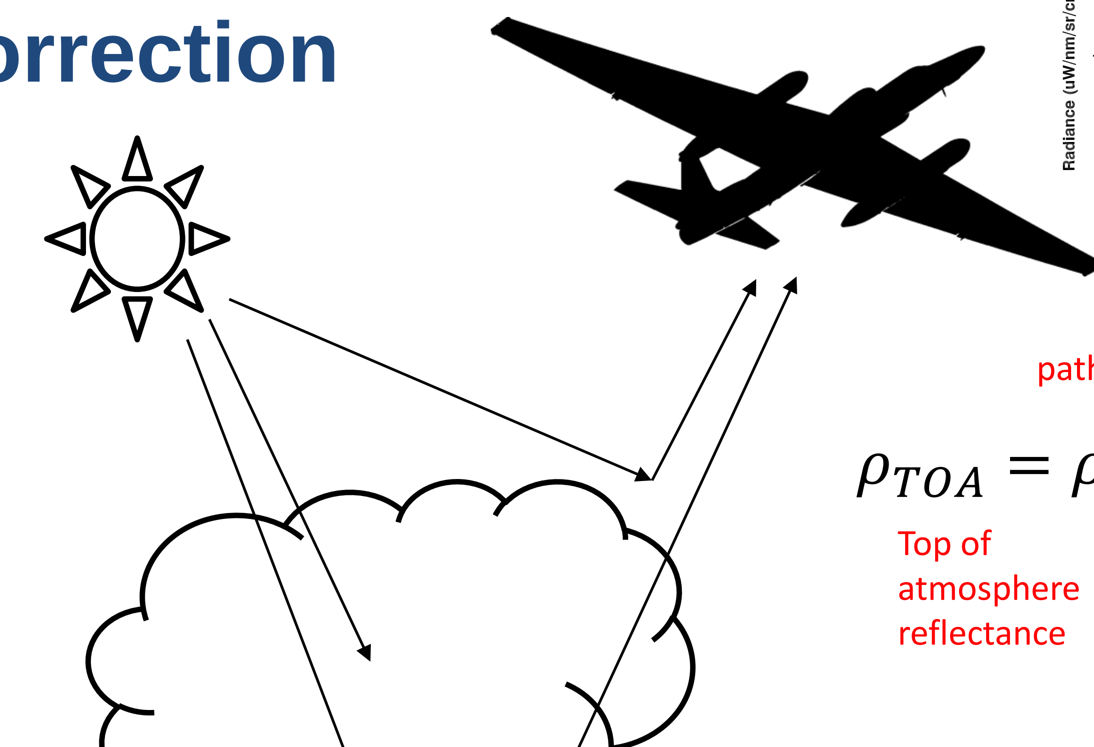
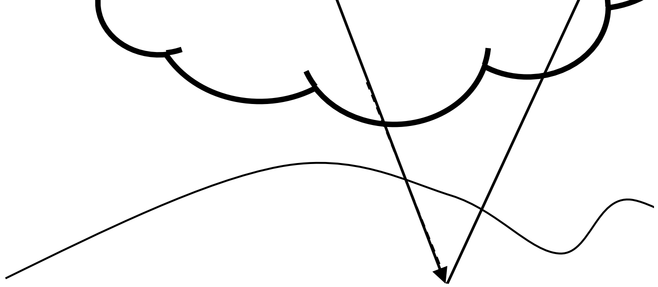
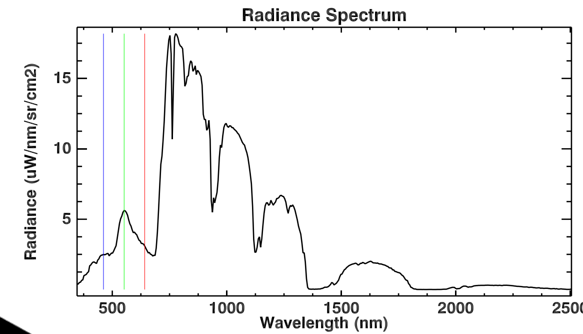
Atmospheric correction







Transmission

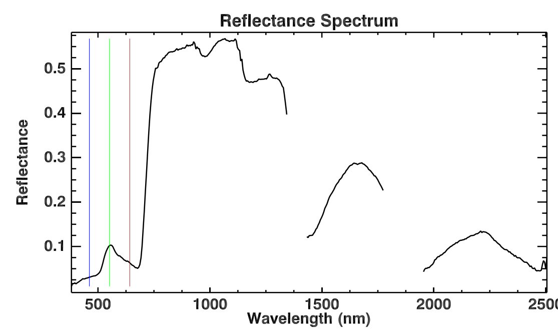
path reflectance

$$\rho_{TOA} = \rho_{atm} + \frac{T\rho_s}{1 - S\rho_s}$$

Top of atmosphere reflectance

Spherical albedo

Surface reflectance



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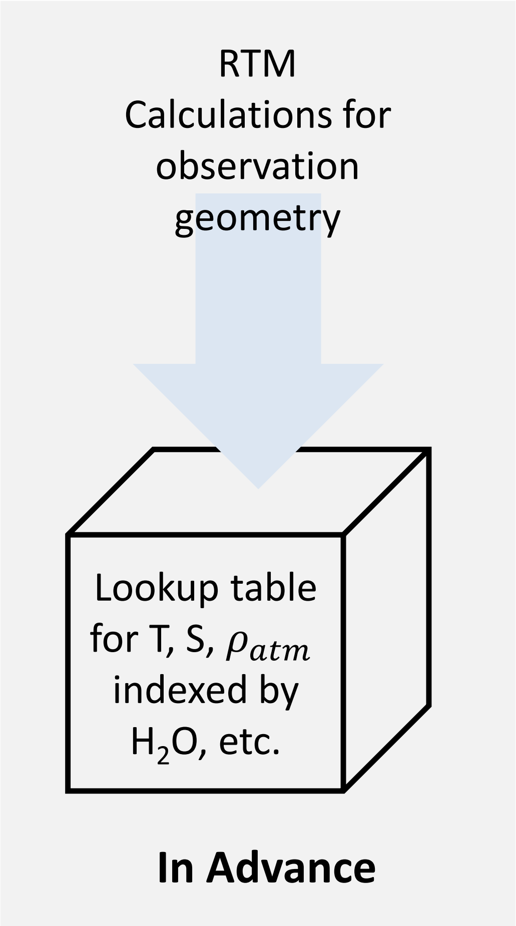


Typical approach

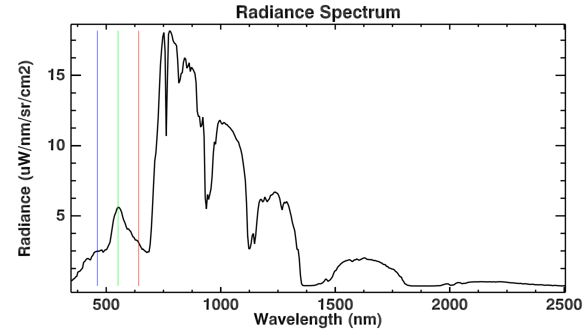
Typical approach

RTM Calculations for observation geometry

Lookup table for T, S, ρ_{atm} indexed by H_2O, etc.

In Advance

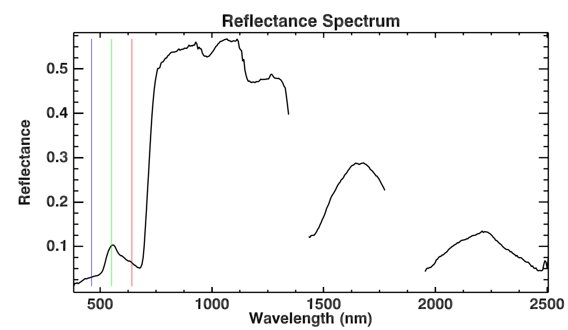
Look up atmospheric state



Estimate atmospheric state

$$\rho_{TOA} = \rho_{atm} + \frac{T\rho_s}{1 - S\rho_s}$$

Algebraic inversion for reflectance



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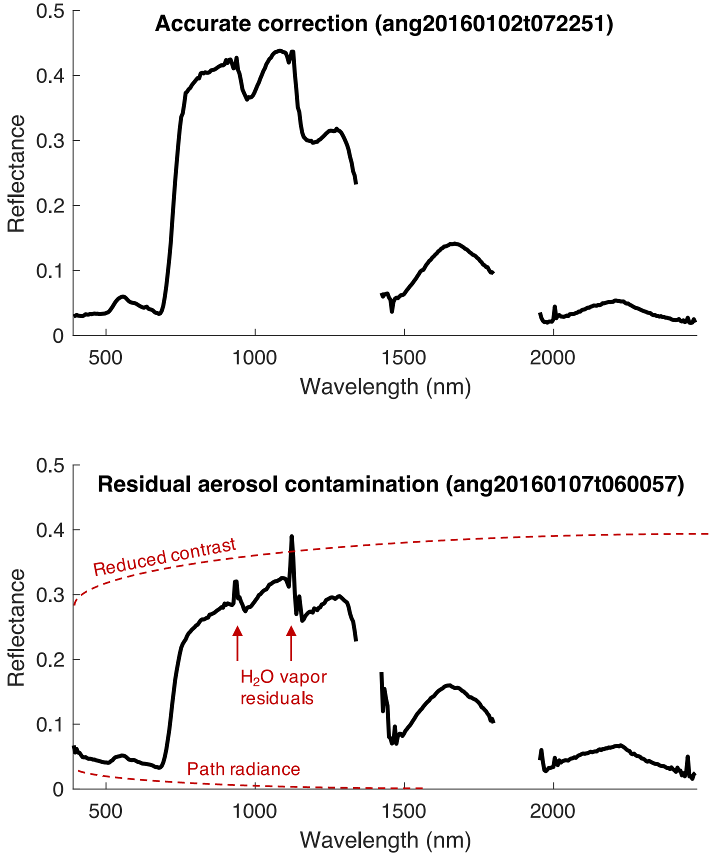
Key attributes of status quo methods

- **Surface and atmosphere retrieved separately.** Cannot always estimate smooth atmospheric perturbations.
- **Number of retrieved atmospheric parameters must be small.** The state vector size is limited by LUT dimension.

Big deal for tropical atmospheres



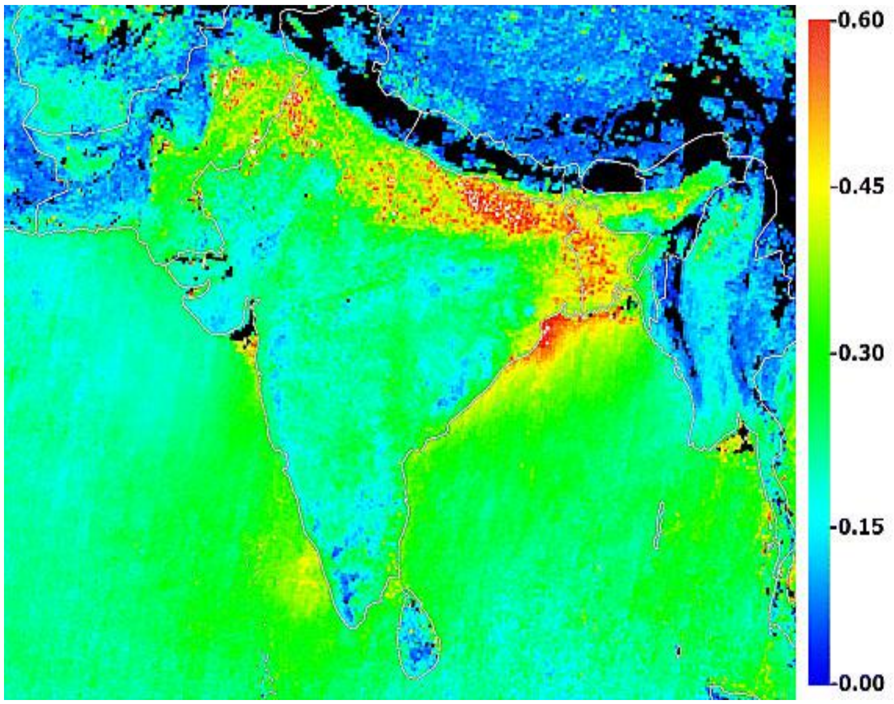


Figure 1: Aerosol Optical Depth (AOD) for the Indian Subcontinent, averaged over winter months of 2001-2004. Here the MISR instrument reveals spatial variability with AOD values of 0.3 or greater for many of the areas overflown during the AVIRIS-NG India campaign (Di Girolamo et al., 2004). Aerosol loadings over urban areas are typically higher.

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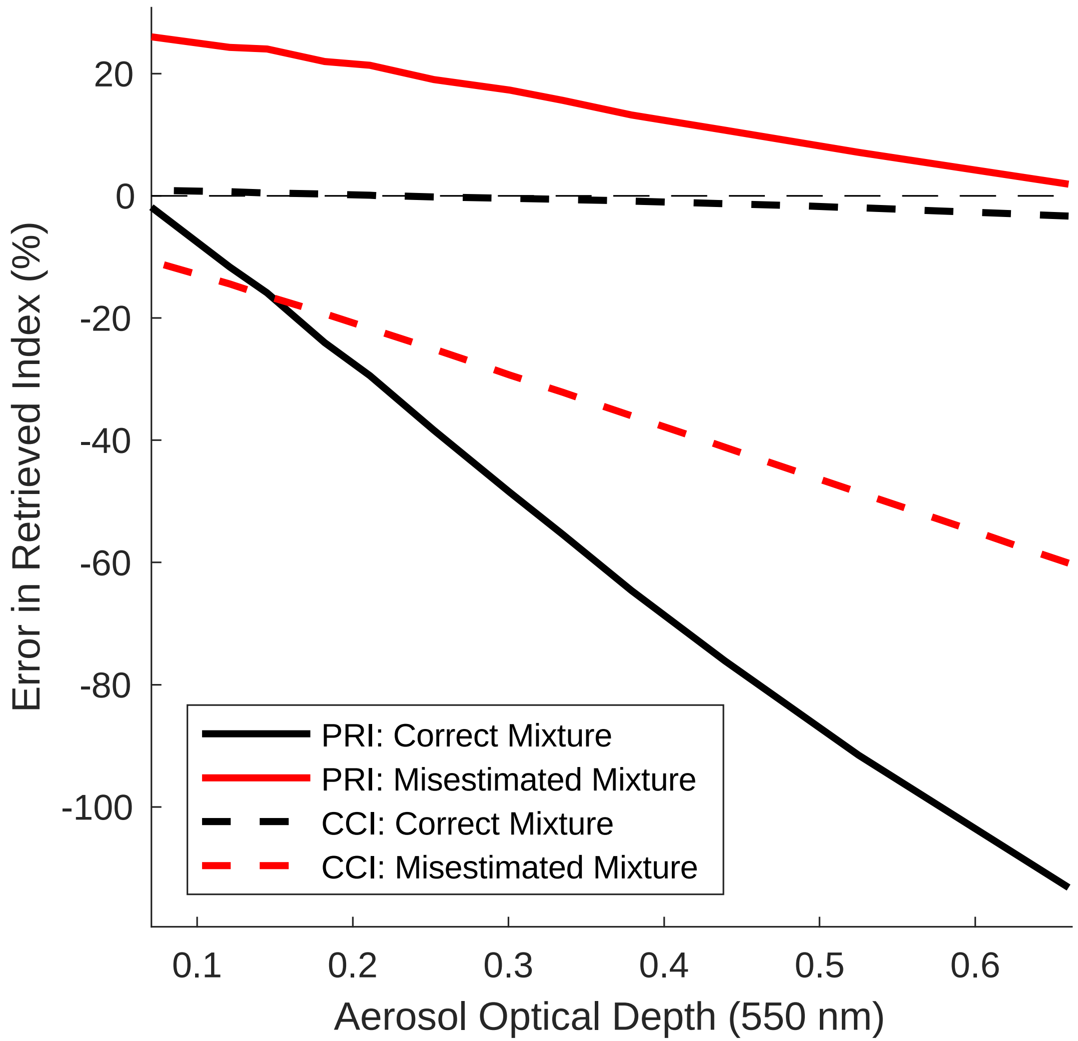
Small inaccuracies can matter



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Alternative: Optimal Estimation

[Rodgers et al., 2000]

- **Estimate atmosphere and surface together**
- **Free parameters are a state vector of arbitrary size**
- **Probabilistic, permits uncertainty analysis and Bayesian priors**

Alternative: Optimal Estimation

[Rodgers et al., 2000]

- Measurement model:

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \epsilon$$

Radiance measurement

RTM prediction

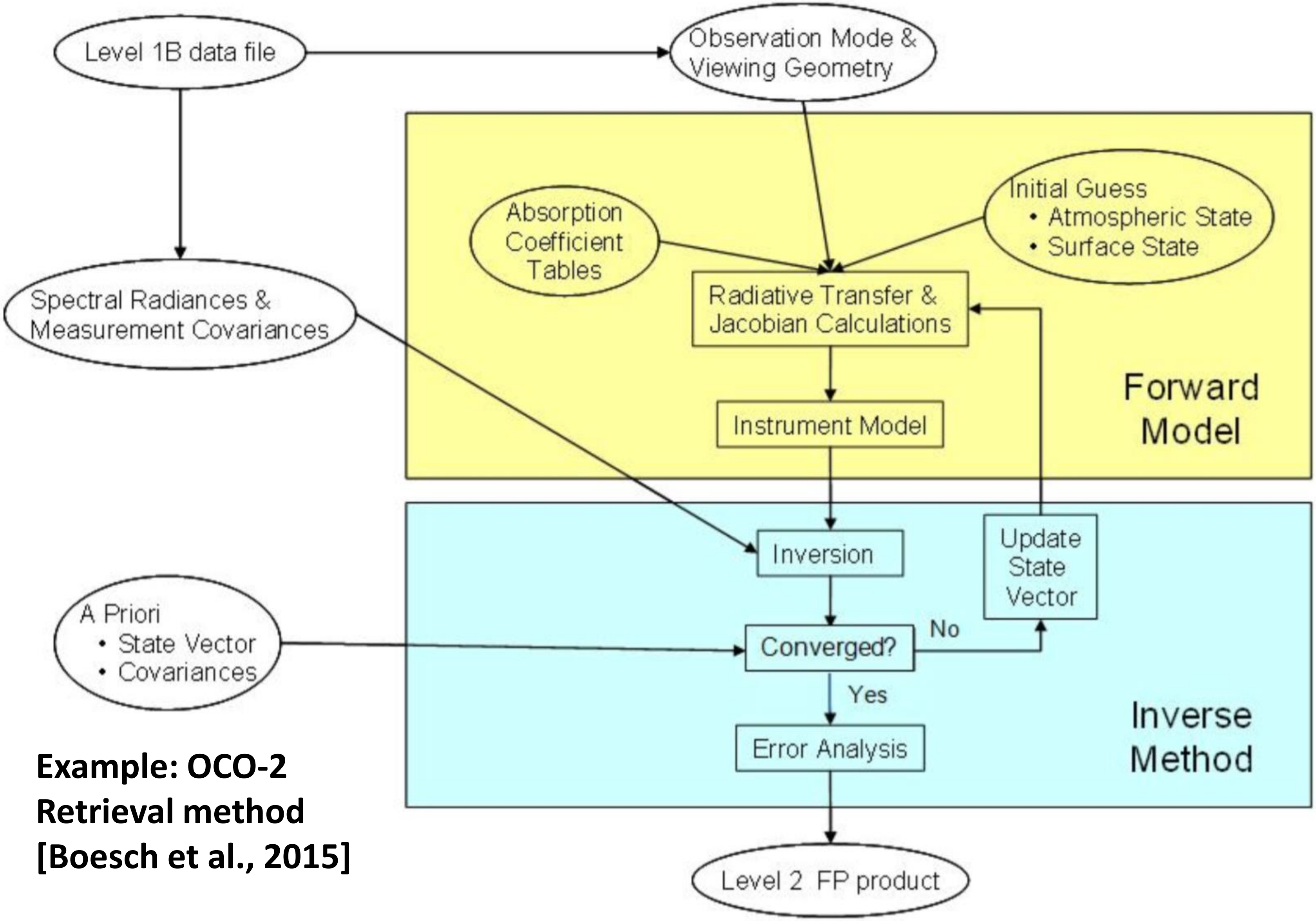
random error

- For covariances **S,** minimize the error function :

$$\chi^2(\mathbf{x}) = \underbrace{(\mathbf{F}(\mathbf{x}) - \mathbf{y})^{\mathbf{T}}\, \mathbf{S}_{\epsilon}^{-1}\, (\mathbf{F}(\mathbf{x}) - \mathbf{y})}_{\text{Model match to measurement}} + \underbrace{(\mathbf{x} - \mathbf{x_a})^{\mathbf{T}}\, \mathbf{S_a}^{-1}\, (\mathbf{x} - \mathbf{x_a})}_{\text{Bayesian prior}}$$

Model match to measurement

Bayesian prior



Example: OCO-2 Retrieval method [Boesch et al., 2015]

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Potential benefits

- **RTM solution for each spectrum,** models exact absorption-in-scattering for accurate correction of H_2O vapor absorption – get past interpolation inaccuracy of LUT and limited number of state variables
- **Relaxes Lambertian assumption**
- **Retrieve aerosol parameters** using information across the VSWIR range, improving accuracy of aerosol correction.
- **Incorporates ancillary measurements** in a principled way via the prior distribution
- **Degree of Freedom (DOF) analysis** permits a rigorous analysis of VSWIR atmospheric information content
- **Posterior uncertainty estimates** for use in downstream analyses.

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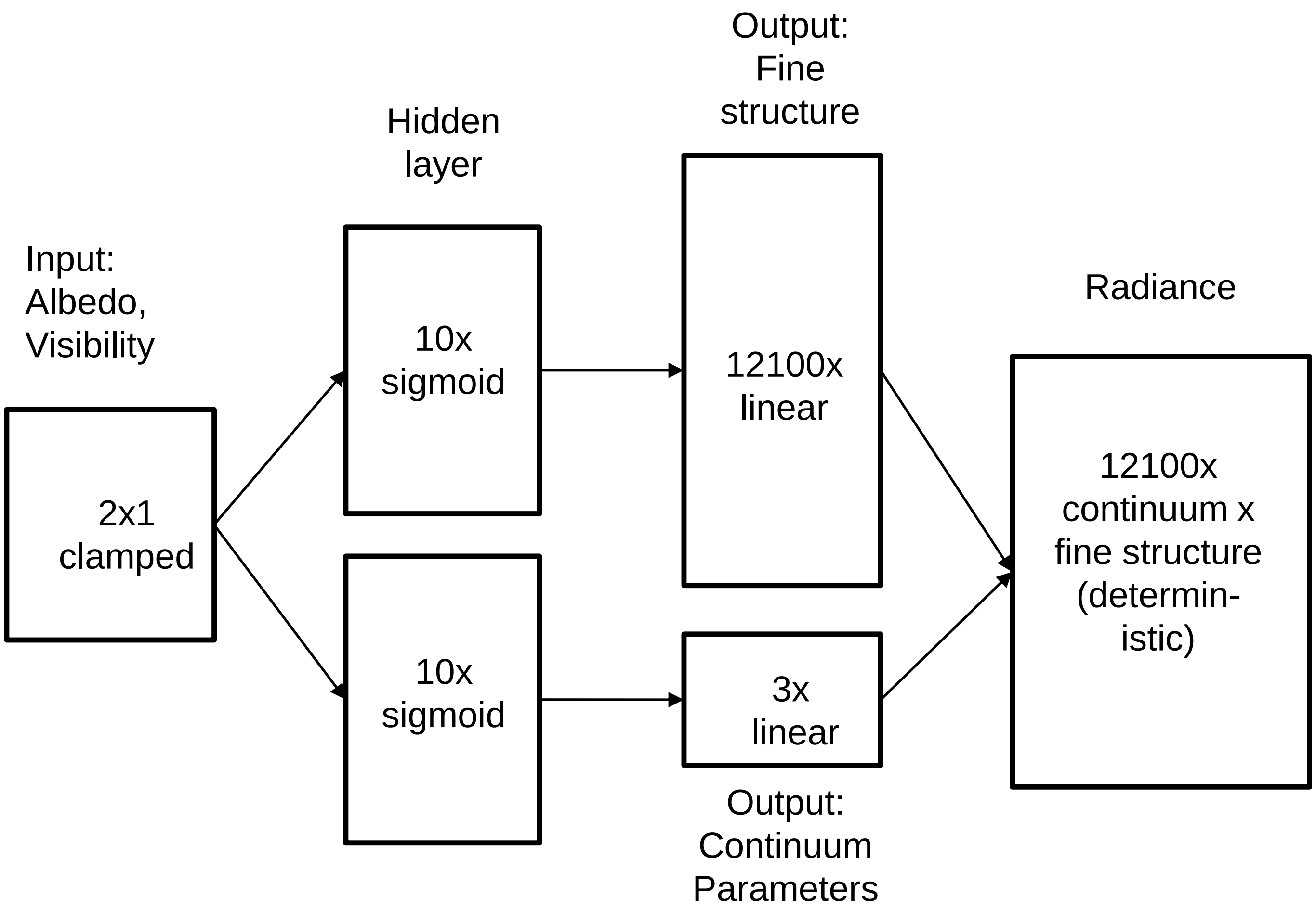
Option 1: Fast RTMs

- Two-stream exact-single-scattering (2S-ESS) model (Spurr and Natraj, 2011)
    1. 2S computes the approximate multiple scattering field
    2. ESS calculates the single-scatter field.
- Incorporates state of art representations
    - Nakajima-Tanaka (N-T) correction
    - Delta-M scaling
- For calculations in a 20-layer atmosphere with 100 spectral points, 2S is ~800 times faster compared to DISORT with eight discrete ordinates in the half-space.
- **Accurate to within 0.1% of an "exact" RT model, but with computational speed comparable to two-stream models.**

Option 2: Neural Network Emulation [Rivera, Verrelst, et al., *Remote Sensing* 2015].

- A powerful, flexible regression model
- Major advances 2012-present
- Learns the RTM response function based on training data
- Runs in *milliseconds* on commodity hardware
- Can achieve accurate emulation within numerical precision

Example: modeling the MODTRAN A band, line by line

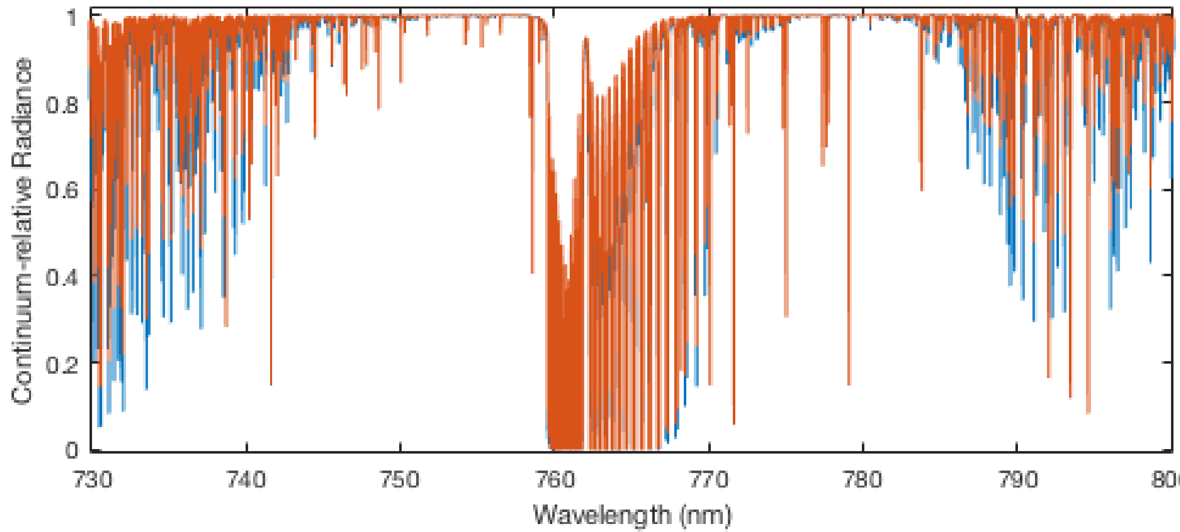


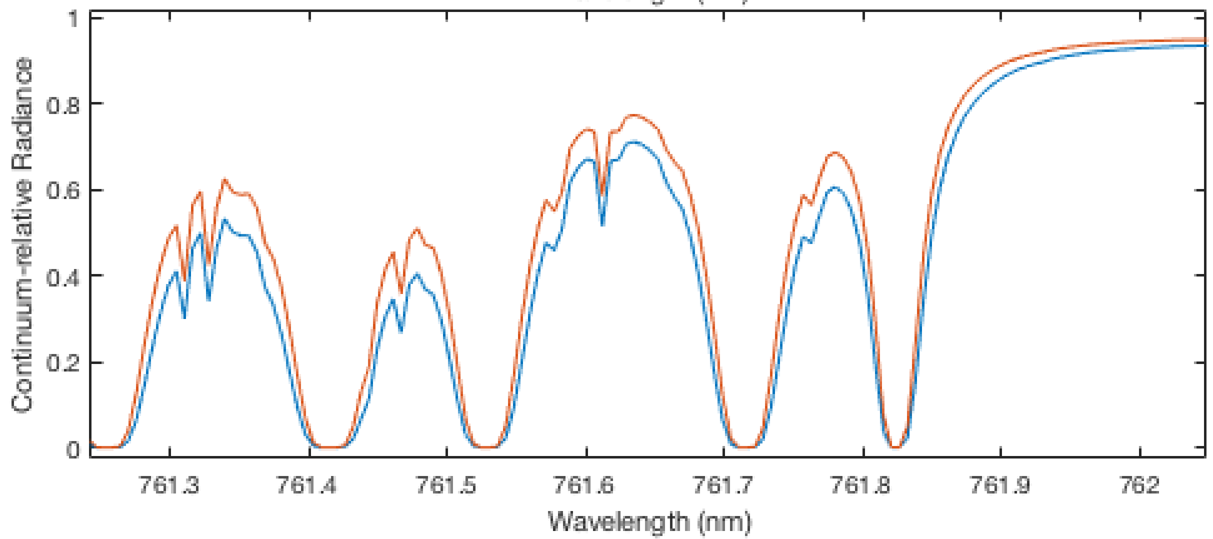
Oxygen A band at two AODs

The fine structure calculation is trained easily on a modern laptop CPU in just a few minutes

Achieves arbitrary accuracy (<0.0005 transmittance units).

The forward model runs in three milliseconds.





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Conclusions

- Optimal Estimation: A principled probabilistic approach to advance atmospheric correction with combined estimation of surface and atmosphere
- Now tractable thanks to mature technologies from other fields
- Watch this space for more…

Thanks!

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RTMs compared

Codebase	Radiative Transfer	Method	State vector				Exact scattering	Coupled Surface
			H_2O	Elevation	Aerosol	AOD		
ATREM	6S	LUT	S					
HyspIRI	6S	LUT	S	S	C	C		
FLAASH	DISORT	LUT	S					
ACORN	DISORT	LUT	S					
ATCOR	DISORT	LUT	S		C	C		
OE	2S-ESS	OE	S	S	S	S	S	S