Jet Propulsion Laboratory
California Institute of Technology

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

David R. Thompson, Vijay Natraj, Brian D. Bue, Robert O. Green

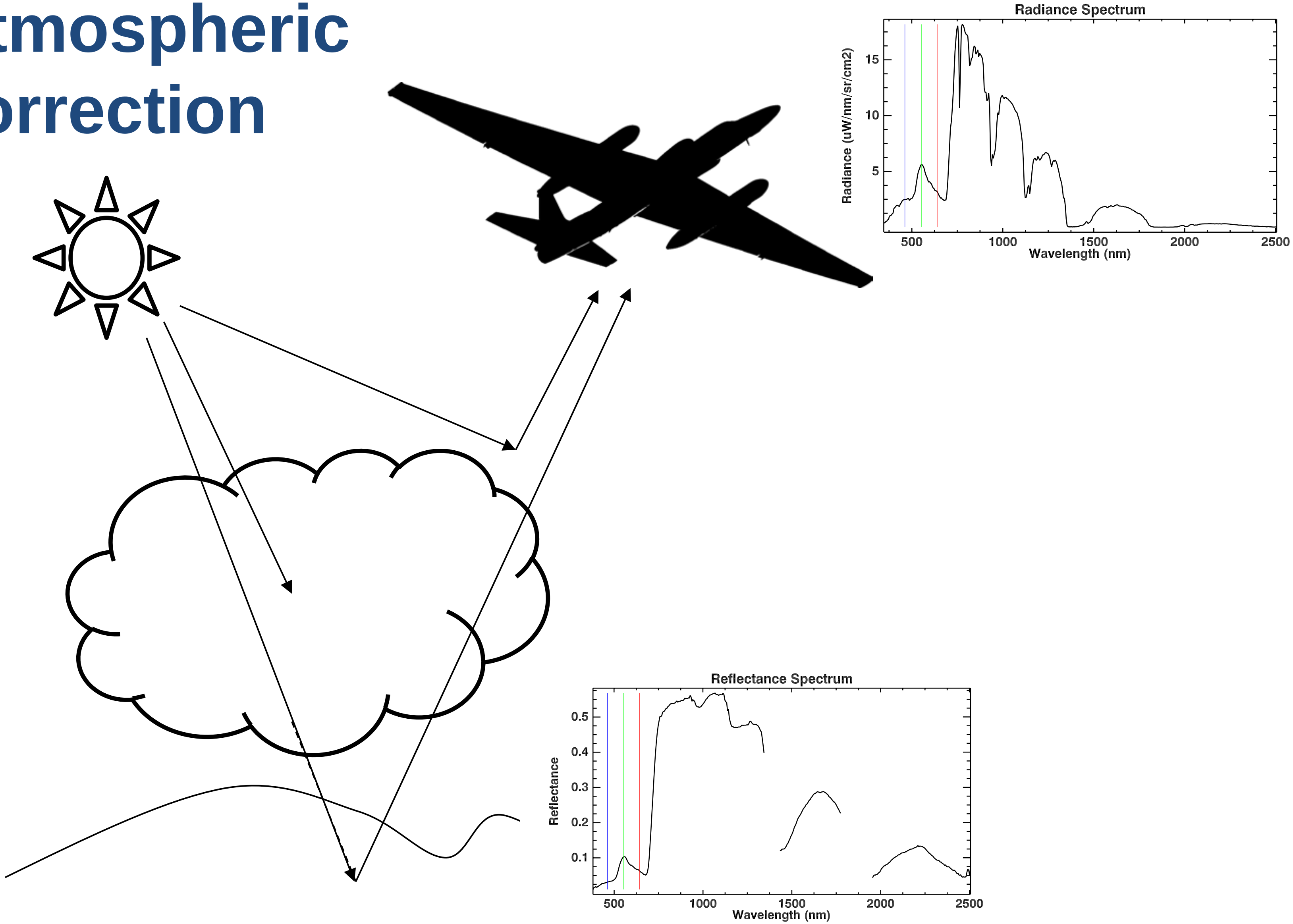
Jet Propulsion Laboratory, California Institute of Technology

This research has been performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. NASA programmatic support through ESTO and Terrestrial Ecology programs is gratefully acknowledged.

Agenda

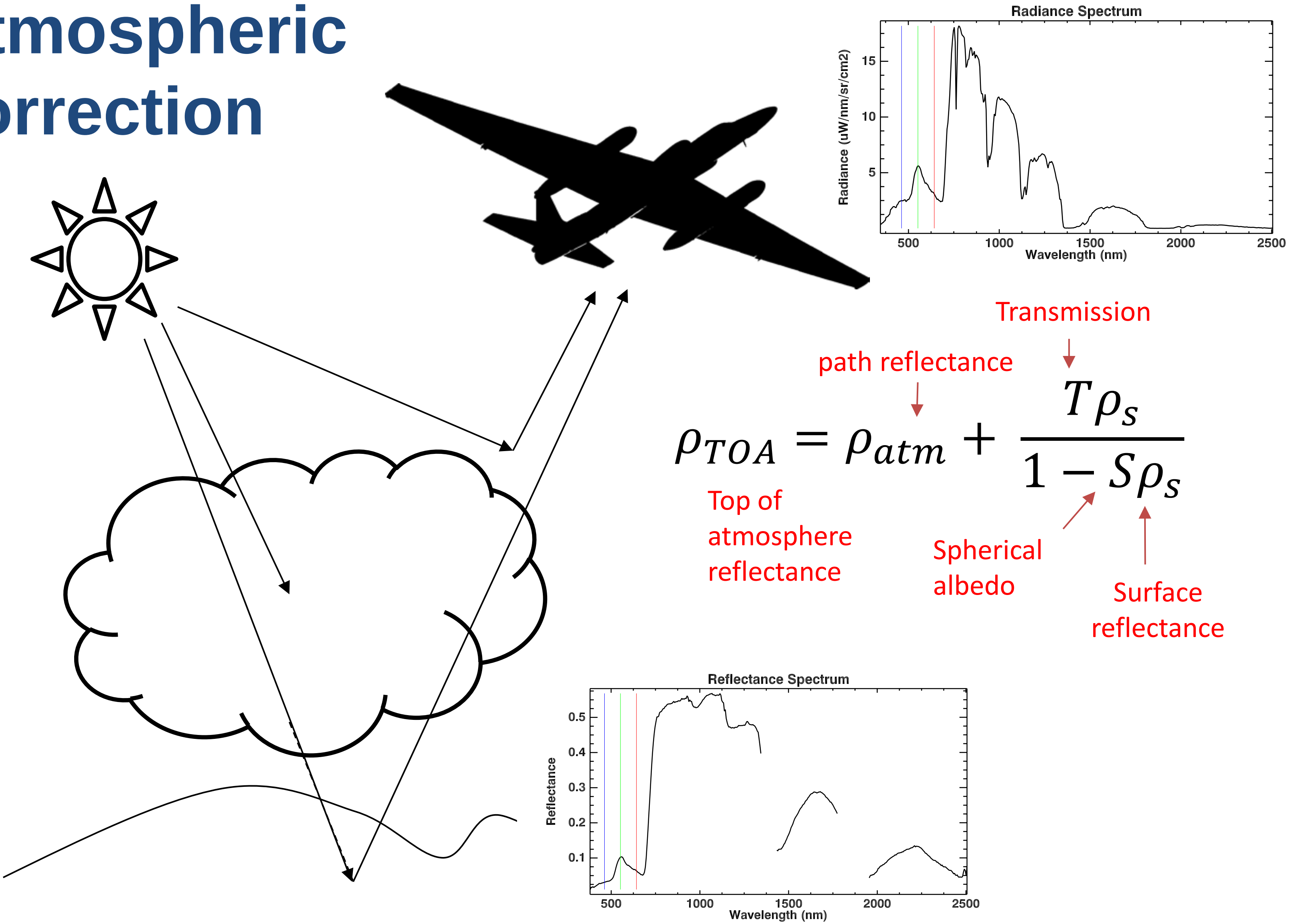
1. Status quo atmospheric correction methods and gaps
2. Optimal Estimation and its advantages
3. Implementation possibilities

Atmospheric correction



davidraythompson@gmail.com

Atmospheric correction



Transmission

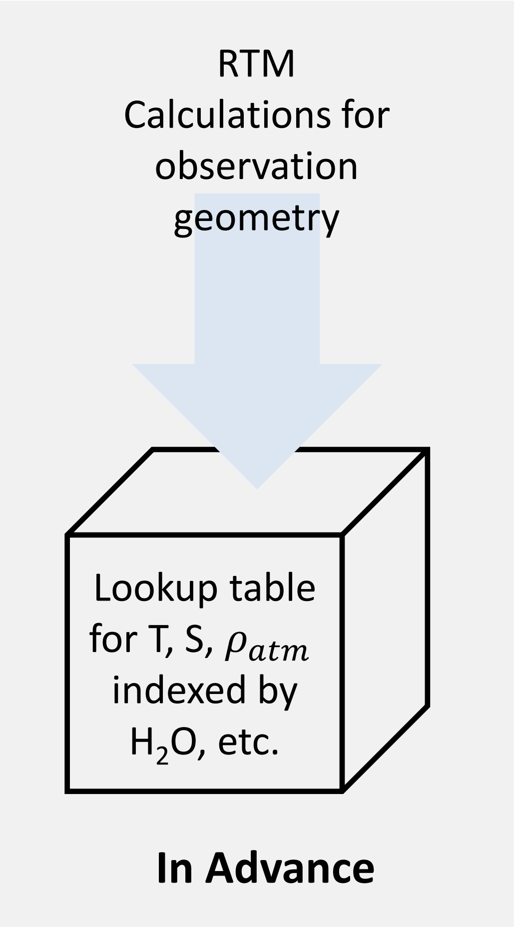
path reflectance

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

Top of atmosphere reflectance

Spherical albedo

Surface reflectance



RTM Calculations for observation geometry

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

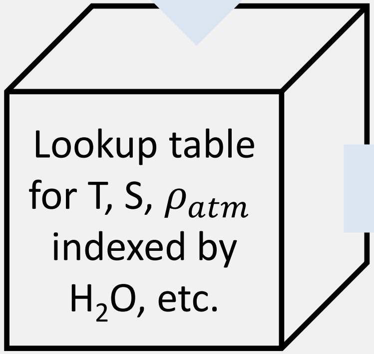
In Advance

Typical approach

davidraythompson@gmail.com

Typical approach

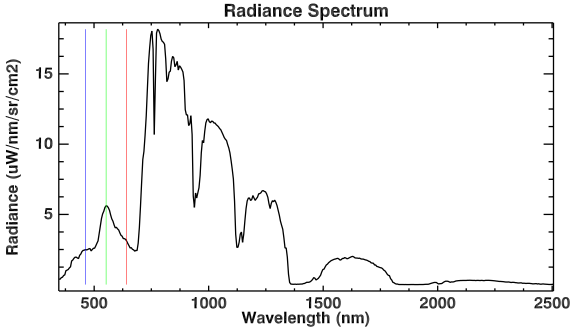
RTM
Calculations for
observation
geometry



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

In Advance

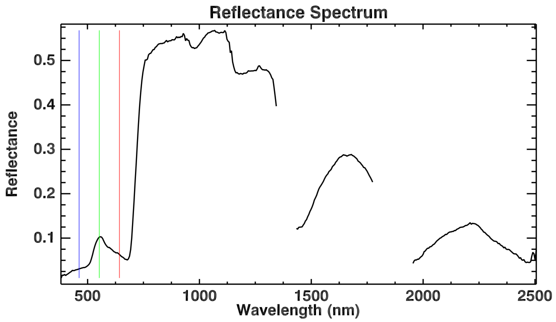
Look up
atmospheric
state



Estimate
atmospheric state

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

Algebraic inversion
for reflectance

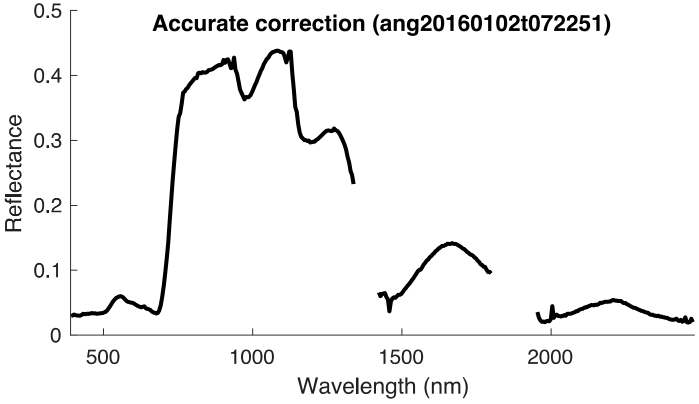


davidraythompson@gmail.com

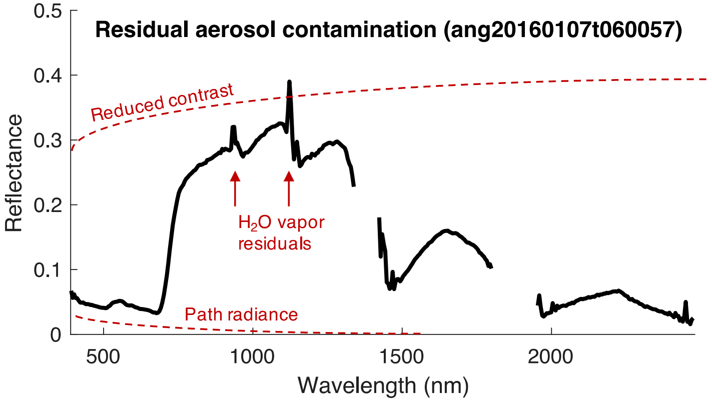
Key attributes of status quo methods

- **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



Accurate correction (ang20160102t072251)



Residual aerosol contamination (ang20160107t060057)

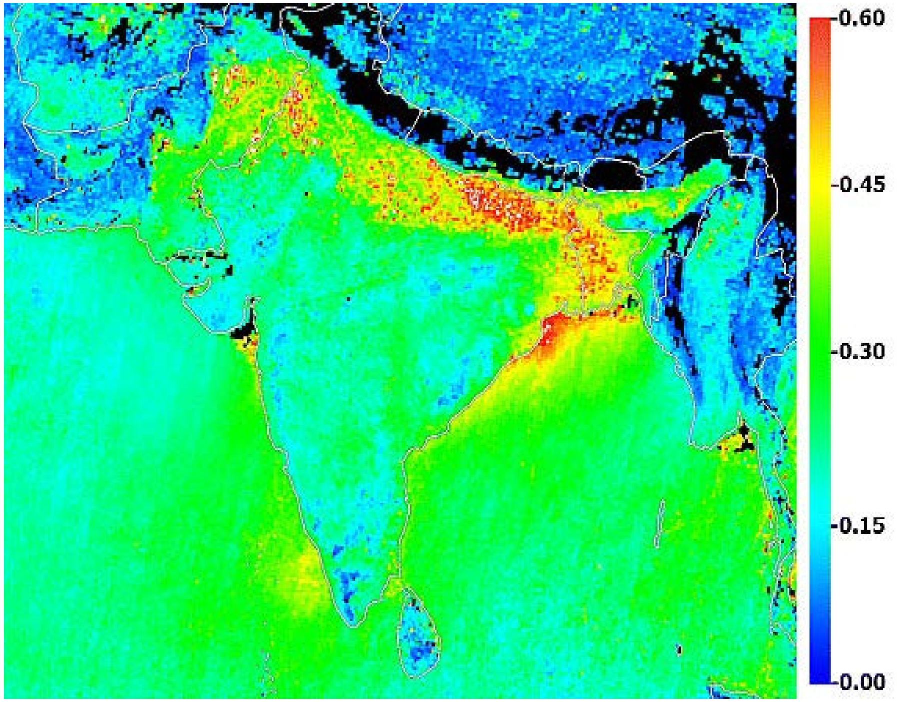
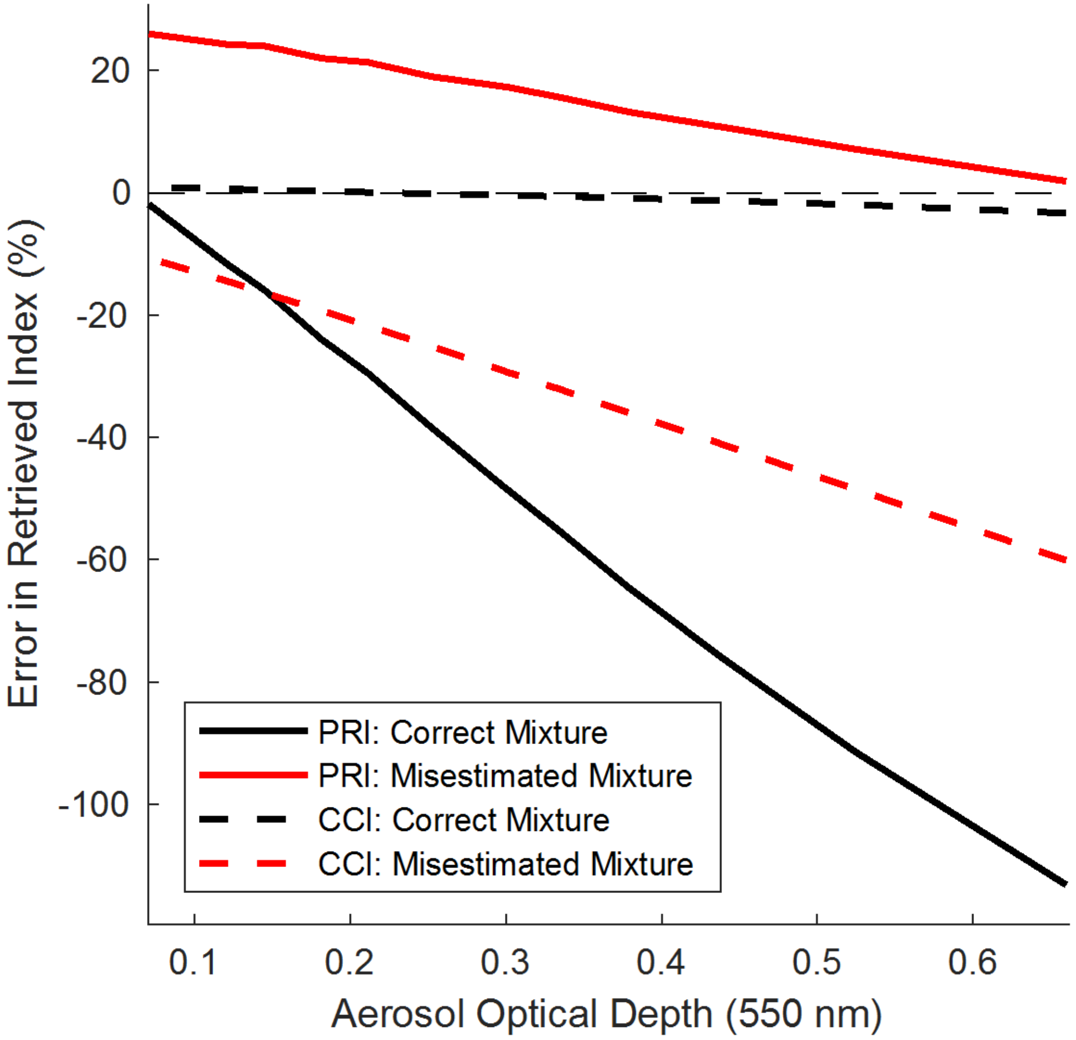


Figure 1: Aerosol Optical Depth (AOD) for the Indian Subcontinent, averaged over winter months of 2001-2004. Here the MISR instrument reveals spatial variability with AOD values of 0.3 or greater for many of the areas overflown during the AVIRIS-NG India campaign (Di Girolamo et al., 2004). Aerosol loadings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

Small inaccuracies can matter



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:

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

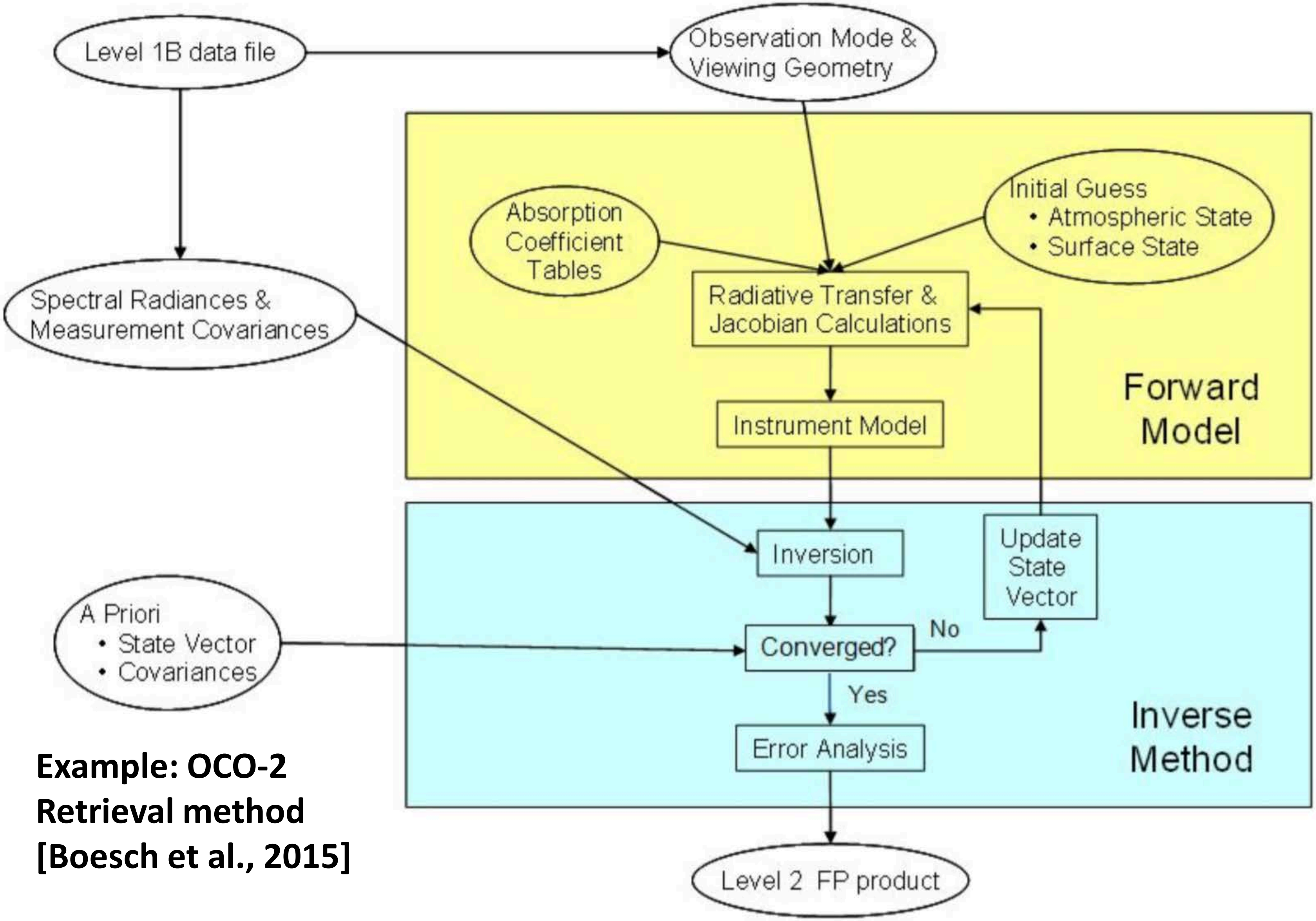
Radiance measurement

RTM prediction

random error

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

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



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

davidraythompson@gmail.com

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.

Agenda

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

Option 1: Fast RTMs

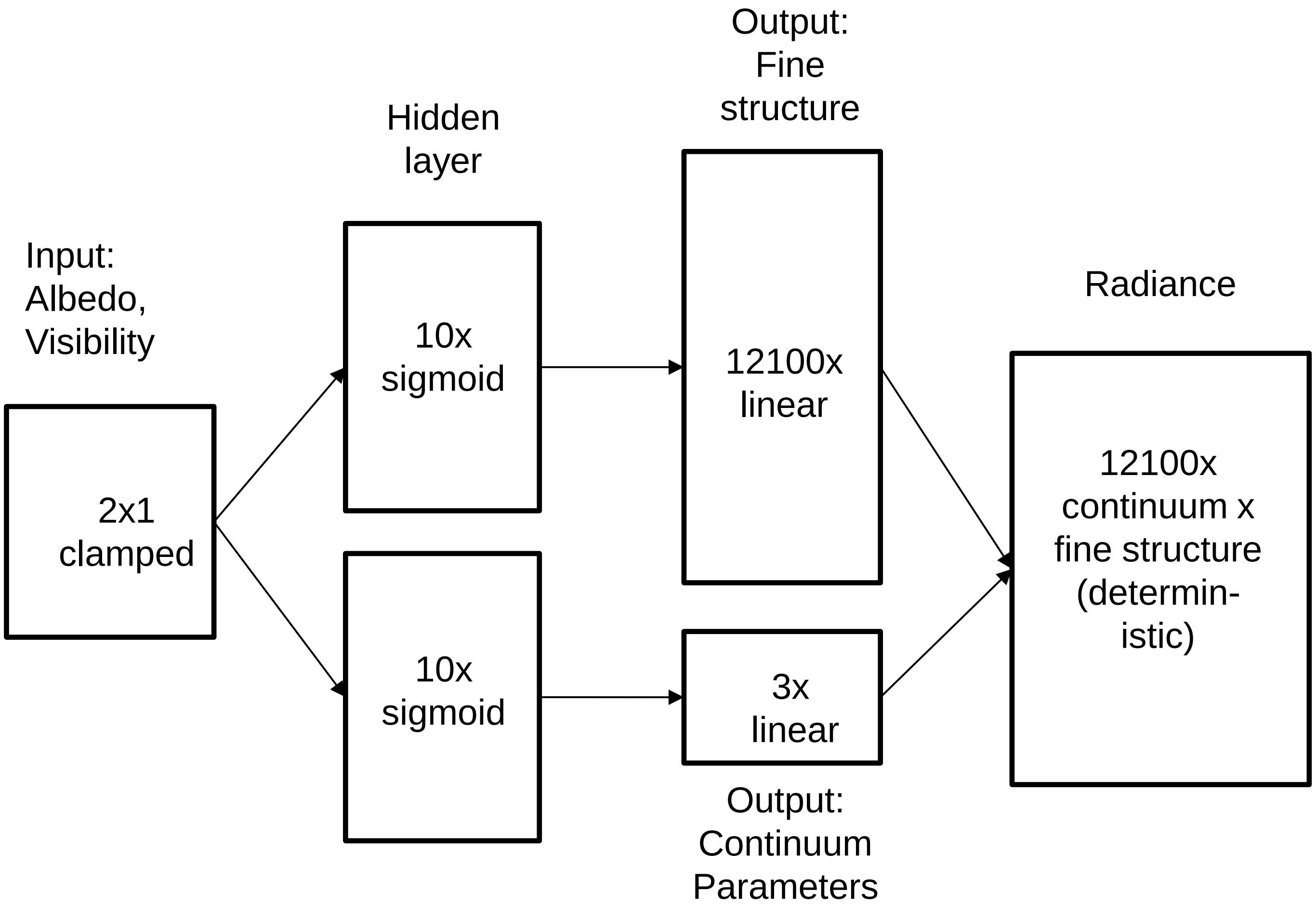
- Two-stream exact-single-scattering (2S-ESS) model (Spurr and Natraj, 2011)
    1. 2S computes the approximate multiple scattering field
    2. ESS calculates the single-scatter field.
- Incorporates state of art representations
    - Nakajima-Tanaka (N-T) correction
    - Delta-M scaling
- For calculations 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.**

david.r.thompson@jpl.nasa.gov - ICRS

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



Input:
Albedo,
Visibility

2x1
clamped

Hidden
layer

10x
sigmoid

10x
sigmoid

Output:
Fine
structure

12100x
linear

3x
linear

Output:
Continuum
Parameters

Radiance

12100x
continuum x
fine structure
(determin-
istic)

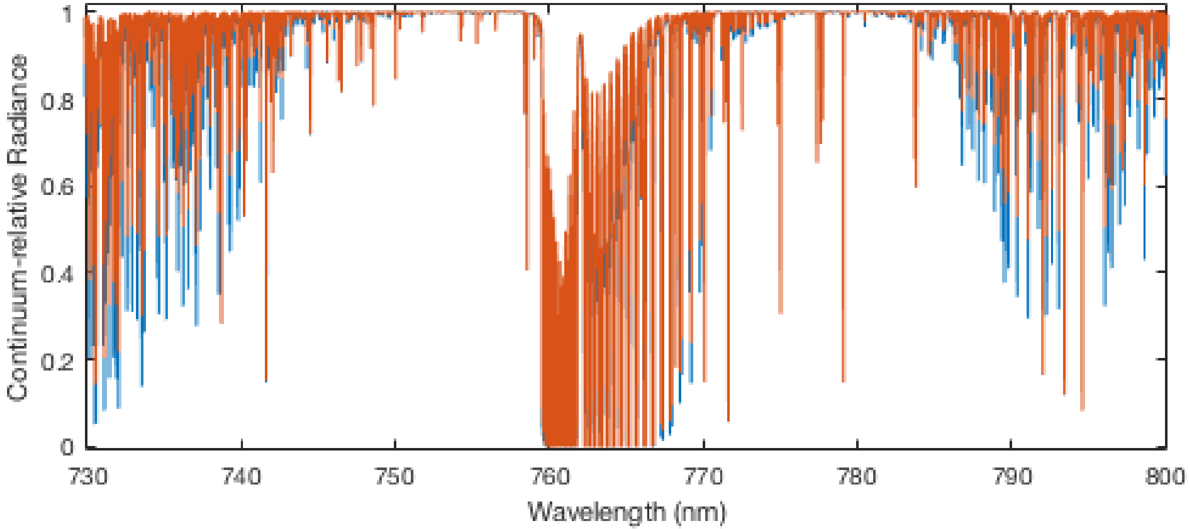
david.r.thompson@jpl.nasa.gov - ICRS

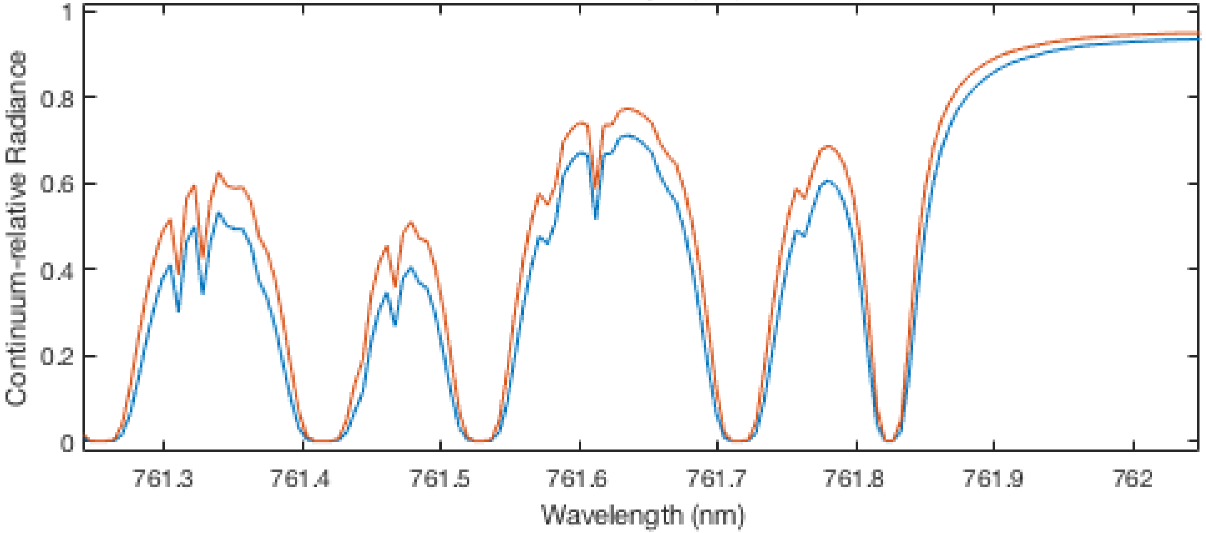
Oxygen A band at two AODs

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.





david.r.thompson@jpl.nasa.gov - ICRS

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!

NASA Earth Science Division (AVIRIS-NG India Science Analysis Grant)

National Science Foundation National Robotics Initiative

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