Jet Propulsion Laboratory
California Institute of Technology

Atmospheric Correction with the Bayesian Empirical Line

David R. Thompson[1], Dar A. Roberts[2] , Bo Cai Gao[3], Robert O. Green[1], Liane Guild[4], Kendra Hayashi[5], Raphael Kudela[5], Sherry Palacios[4,6]

[1] Jet Propulsion Laboratory, California Institute of Technology
[2] University of California Santa Barbara
[3] Naval Research Laboratory
[4] NASA Ames Research Center
[5] University of California Santa Cruz
[6] Bay Area Environmental Research Institute (BAERI)

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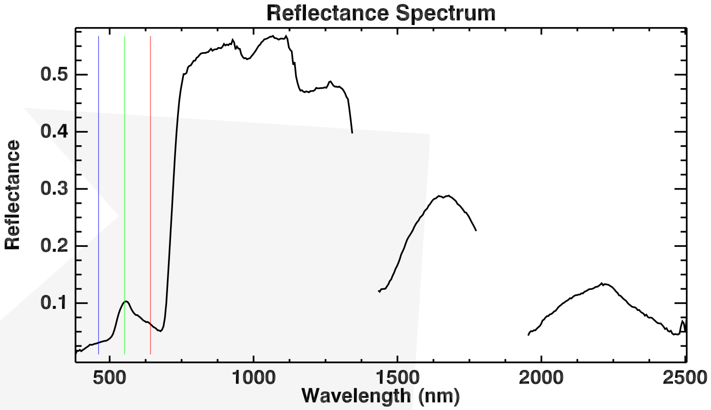
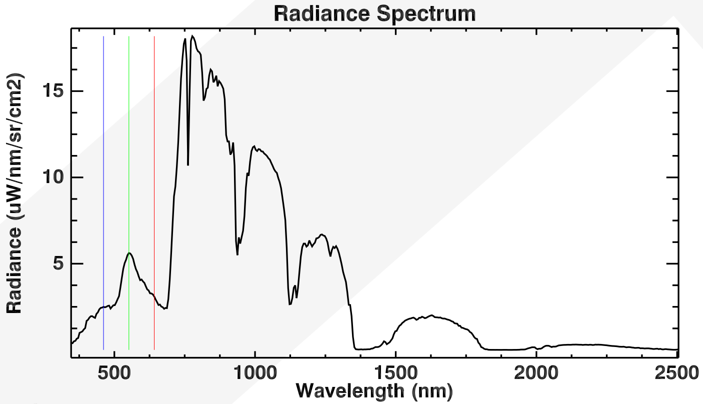
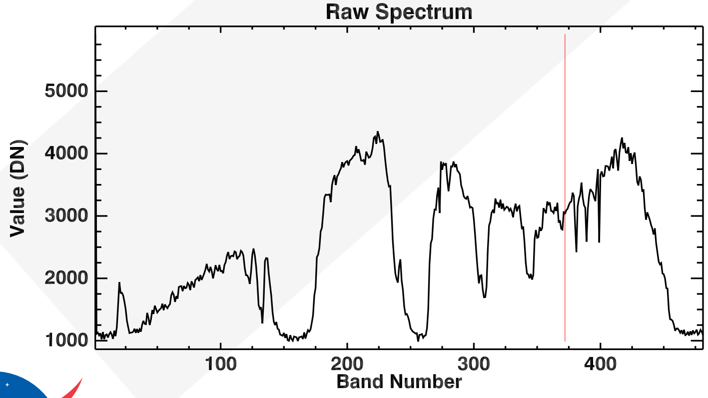
Atmospheric correction is fundamental



Lambertian Reflectance (HDRF)



Radiance at sensor $mW/nm/cm^2/sr$



Raw Digital Numbers

[Gao et al., 1993; Green et al., 1998, Thompson et al., 2015]

Traditionally bifurcated into RTM and empirical methods

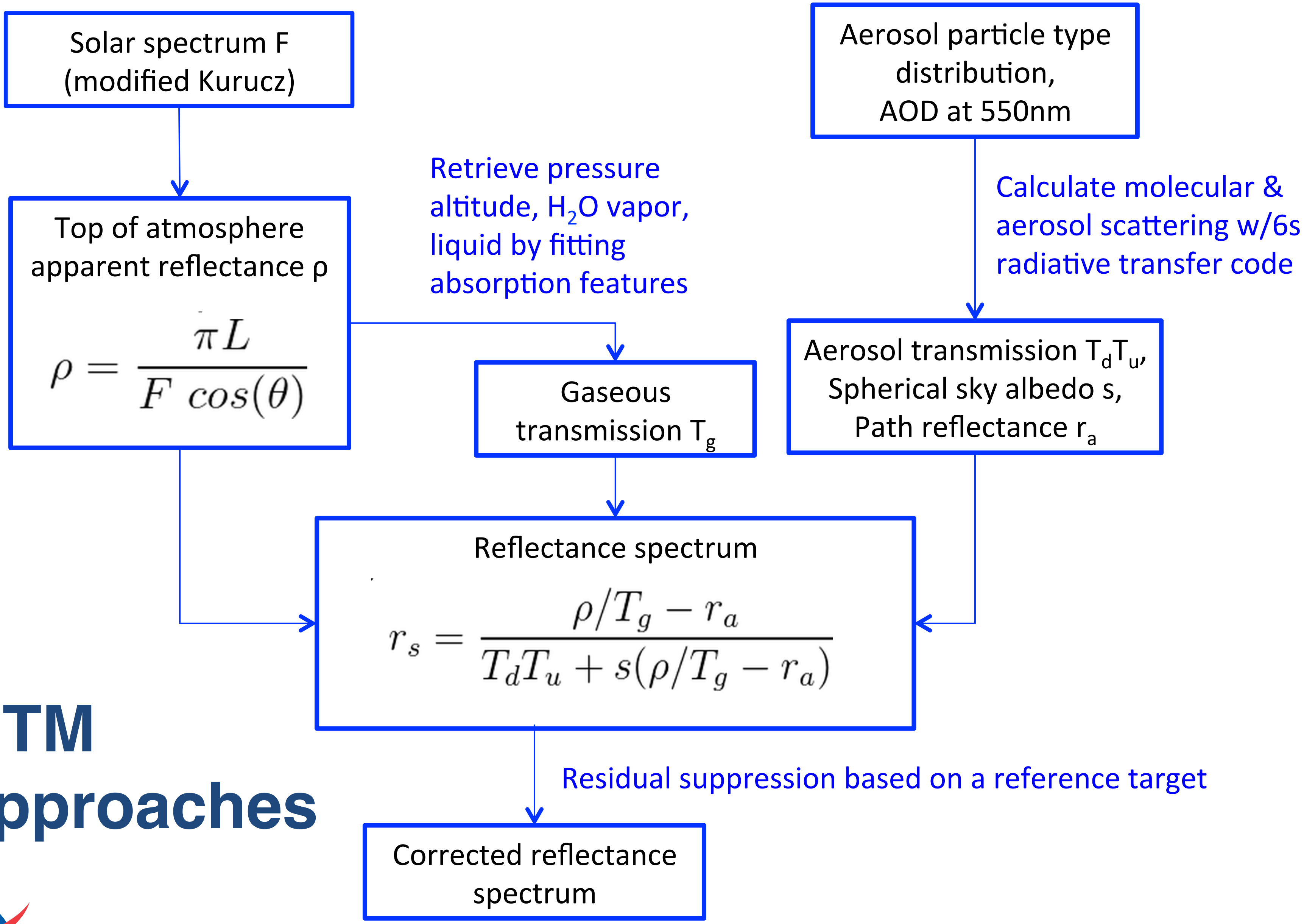
RTM (model-based)

- No in-situ measurements needed
- Stable and physically Interpretable
- Can be inaccurate if model assumptions are violated

Empirical

- Highly accurate when provided many in situ spectra
- Tedious field measurements
- Unstable with few spectra
- Heterogeneity assumption

RTM approaches



Solar spectrum F (modified Kurucz)

Top of atmosphere apparent reflectance ρ

$$\rho = \frac{\pi L}{F \; cos(\theta)}$$

Retrieve pressure altitude, H_2O vapor, liquid by fitting absorption features

Gaseous transmission T_g

Aerosol particle type distribution, AOD at 550nm

Calculate molecular & aerosol scattering w/6s radiative transfer code

Aerosol transmission $T_d T_u$, Spherical sky albedo s, Path reflectance r_a

Reflectance spectrum

$$r_s = \frac{\rho/T_g - r_a}{T_d T_u + s(\rho/T_g - r_a)}$$

Residual suppression based on a reference target

Corrected reflectance spectrum

The classical empirical line

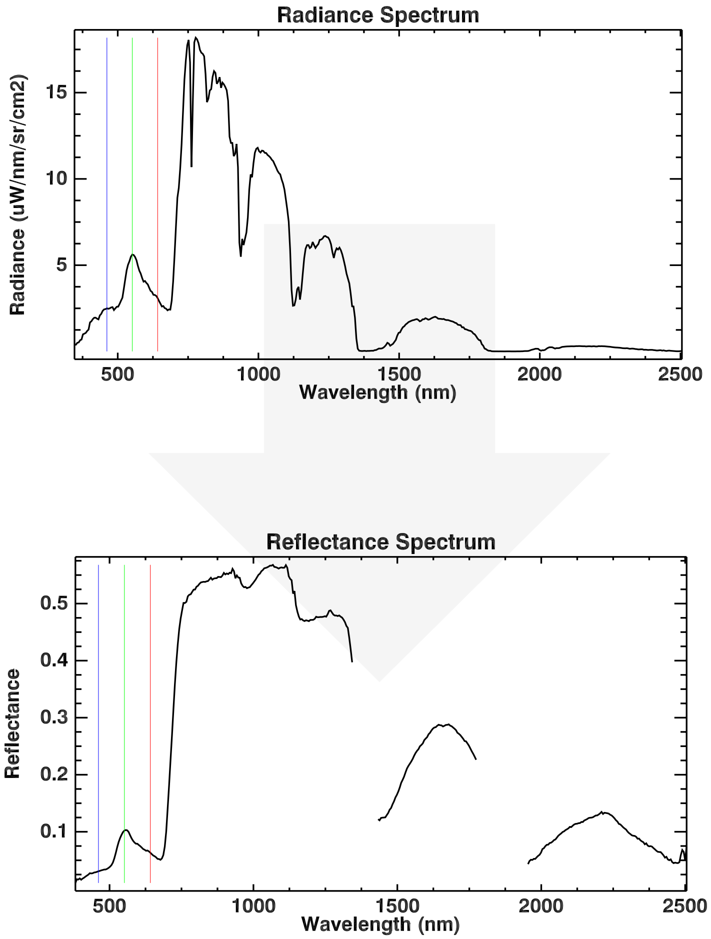
Uses in-situ measurements to fit a linear transformation

$$\mathbf{x}_{\mathrm{el}} = \mathrm{argmin}_{\mathbf{x}} \left(\|\mathbf{A}\mathbf{x} - \mathbf{t}\|^2 \right)$$

Data matrix with radiances

Linear correction

Reference spectra



Examples

RTMs

- ATREM
- ACORN
- MODTRAN-based methods
- HyspIRI Level 2 product
- Spectral polishing

Empirical

- Empirical line
- Modified empirical line [Moran et al., 2006]

Toward a unified approach

- Model-based methods can be sensitive to aerosol uncertainty and minor model approximations

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- But we often lack enough in-situ spectra for an empirical correction
  - Aquatic environments
  - Regional or global investigations

Toward a unified approach

- **Model-based methods can be sensitive to aerosol uncertainty and minor model approximations**
- **But we often lack enough in-situ spectra for an empirical correction**
  - **Aquatic environments**
  - **Regional or global investigations**
- **Can we unify model-based and empirical methods, achieving benefits of both?**

The idea: apply RTM, then perform empirical adjustment

Transforming to reflectance means empirical correction factors are predictable

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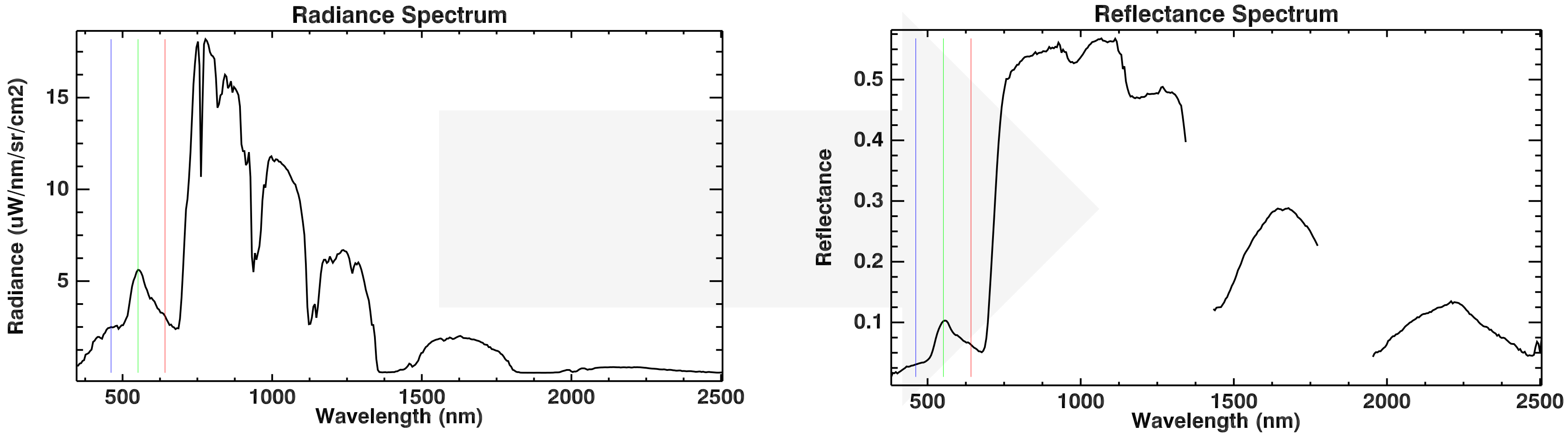
Transforming to reflectance means empirical correction factors are predictable

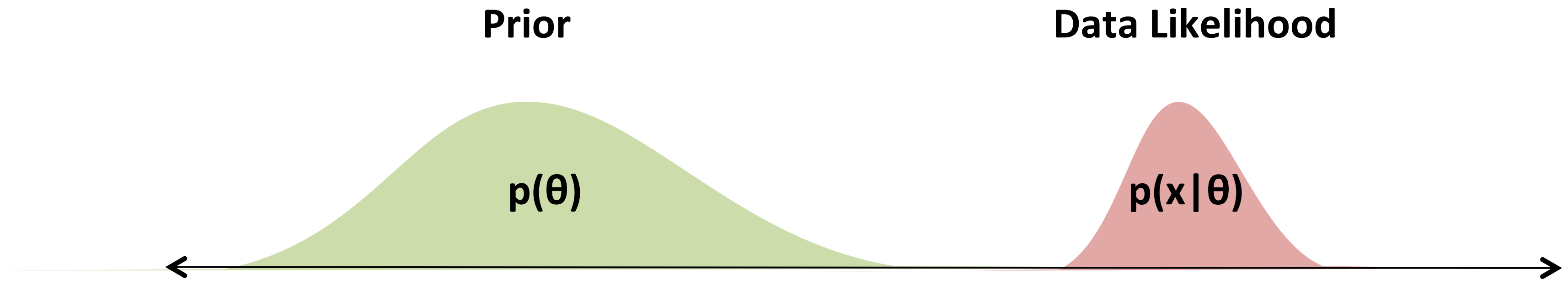


Empirically-derived correction factors are highly scene-dependent

Empirically-derived correction factors are *predictable* (centered on the identity)

The idea: apply RTM, then perform empirical adjustment

Specifically, use the model-based solution to define a Bayesian prior on correction coefficients



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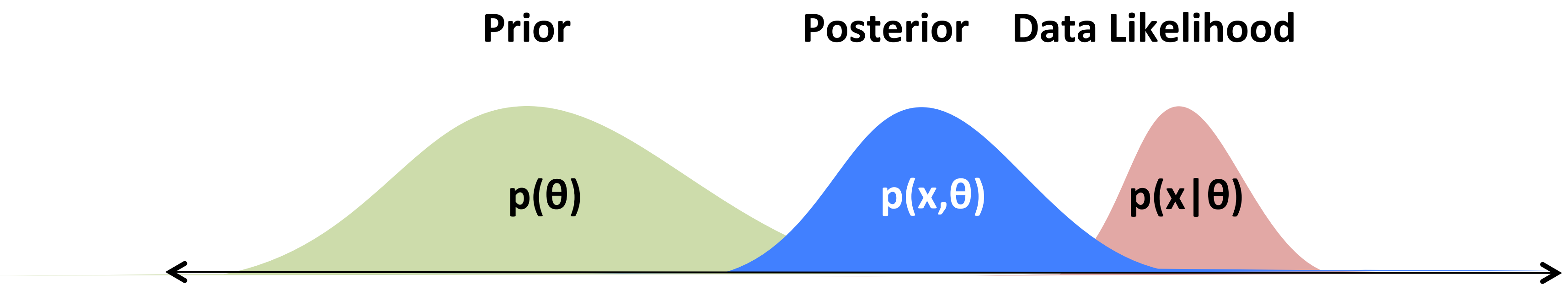


Classical empirical line

$$\mathbf{x}_{\mathrm{el}} = \mathrm{argmin}_{\mathbf{x}} \left(\|\mathbf{A}\mathbf{x} - \mathbf{t}\|^2 \right)$$

Data matrix
with radiances

Linear
correction

Reference
spectra

Bayesian empirical line

$$\mathbf{x}_{\mathrm{gtr}} = \mathrm{argmin}_{\mathbf{x}} \left(\|\mathbf{B}\mathbf{x} - \mathbf{t}\|^2_{\mathbf{P}} + \underbrace{\|(\mathbf{x} - \mu)\|}^2_{\mathbf{Q}} \right)$$

Data matrix with
reflectances

Linear
correction

Reference
spectra

Gaussian prior on
correction coefficients,
centered on identity

Classical empirical line: Ordinary linear least squares

$$\begin{aligned}\mathbf{x}_{\mathrm{el}} &= \operatorname{argmin}_{\mathbf{x}} \left(\|\mathbf{A}\mathbf{x} - \mathbf{t}\|^2 \right) \\ &= (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{t}\end{aligned}$$

Bayesian empirical line: Generalized Tikhonov Regression

$$\begin{aligned}\mathbf{x}_{\mathrm{gtr}} &= \operatorname{argmin}_{\mathbf{x}} \left(\|\mathbf{B}\mathbf{x} - \mathbf{t}\|^2_{\mathbf{P}} + \|(\mathbf{x} - \mu)\|^2_{\mathbf{Q}} \right) \\ &= \mu + (\mathbf{B}^T\mathbf{P}\mathbf{B} + \mathbf{Q})^{-1}\mathbf{B}^T\mathbf{P}(\mathbf{t} - \mathbf{B}\mu)\end{aligned}$$

See Mead, J. L. in Journal of Inverse and Ill-posed Problems, 16(2), 2008

DISORT simulation

- **Simulated atmospheric interference and correction using the standard relation:**

Transmission

$$\rho_0 = \frac{\pi L}{F cos(\psi)} = \rho_a + \frac{T\rho}{1 - \rho S}$$

Reflectance

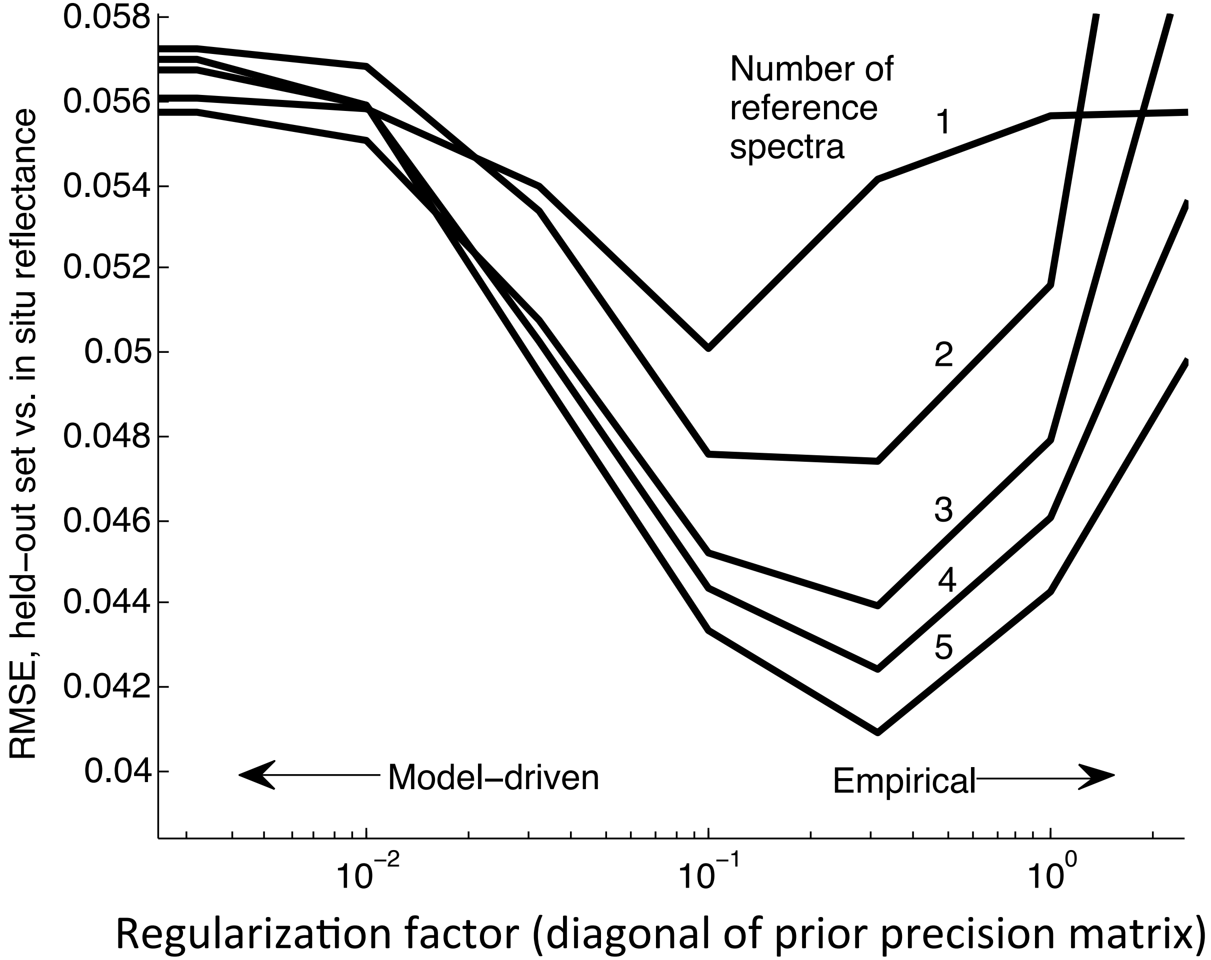
Spherical sky albedo

Top Of Atmosphere Reflectance

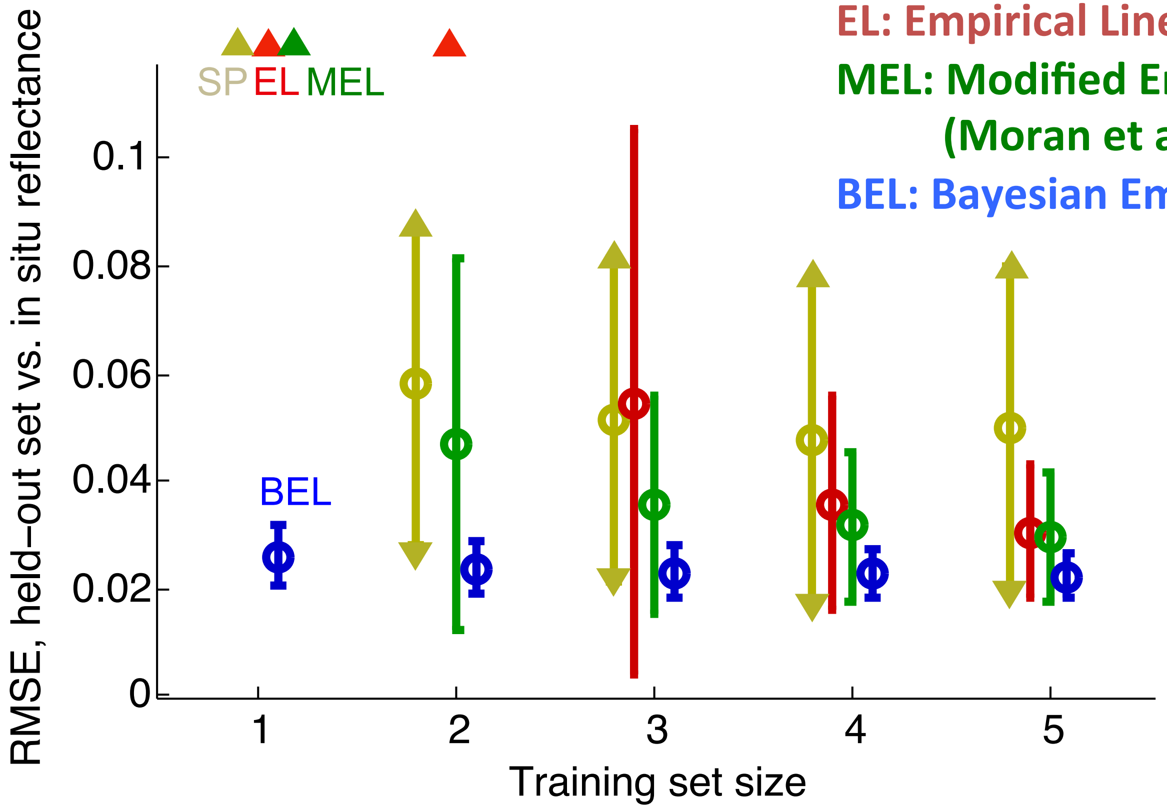
Path Reflectance

- **Introduced errors from two sources:**
  - **Perturbed TOA spectrum by a gain and offset, simulating errors in atmospheric model**
  - **Random white measurement noise**
- **Used 20 references of varying brightness from the USGS spectral library**

DISORT simulation results



DISORT simulation results: 20 reference targets



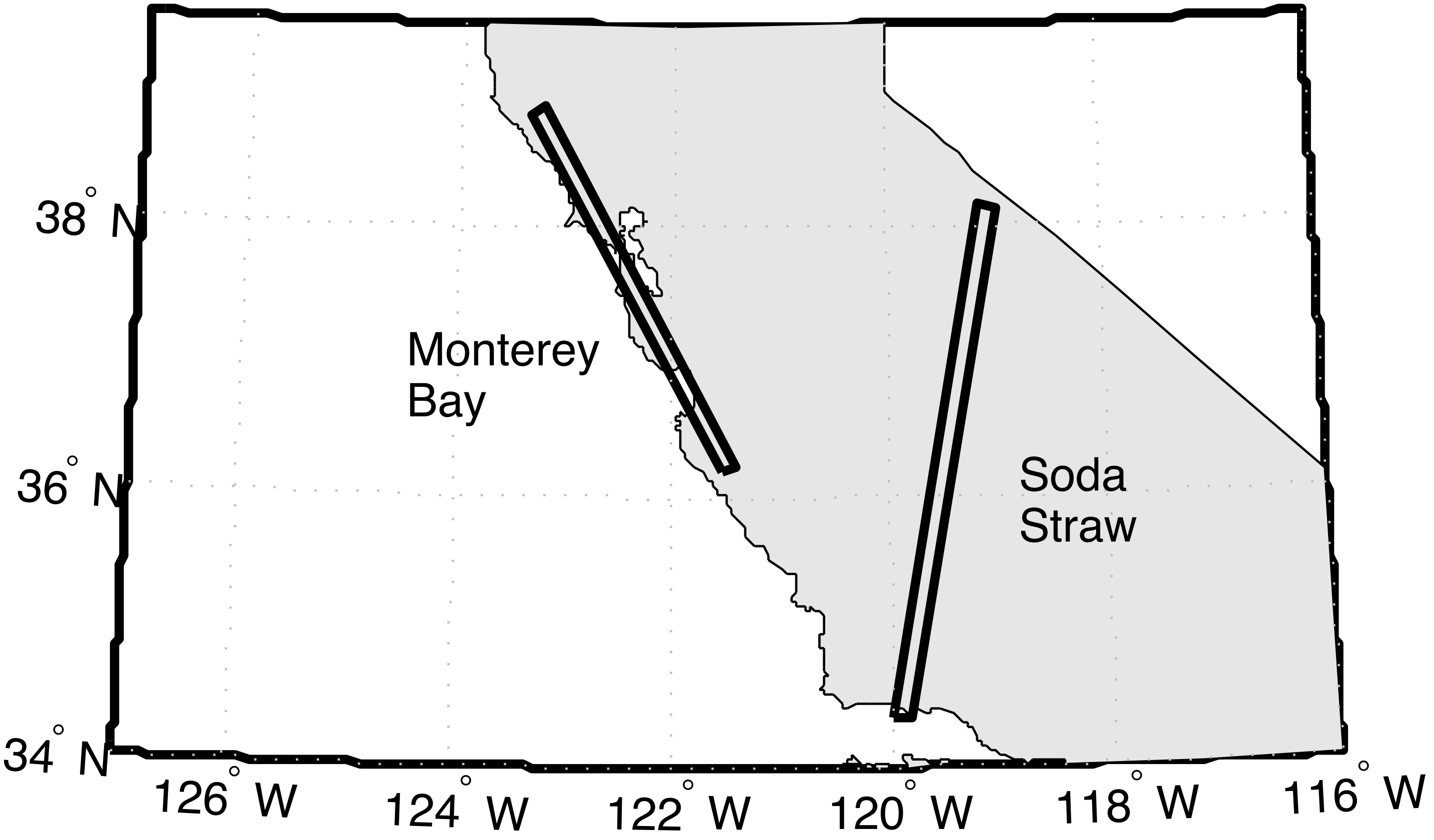
SP: Spectral Polishing

EL: Empirical Line

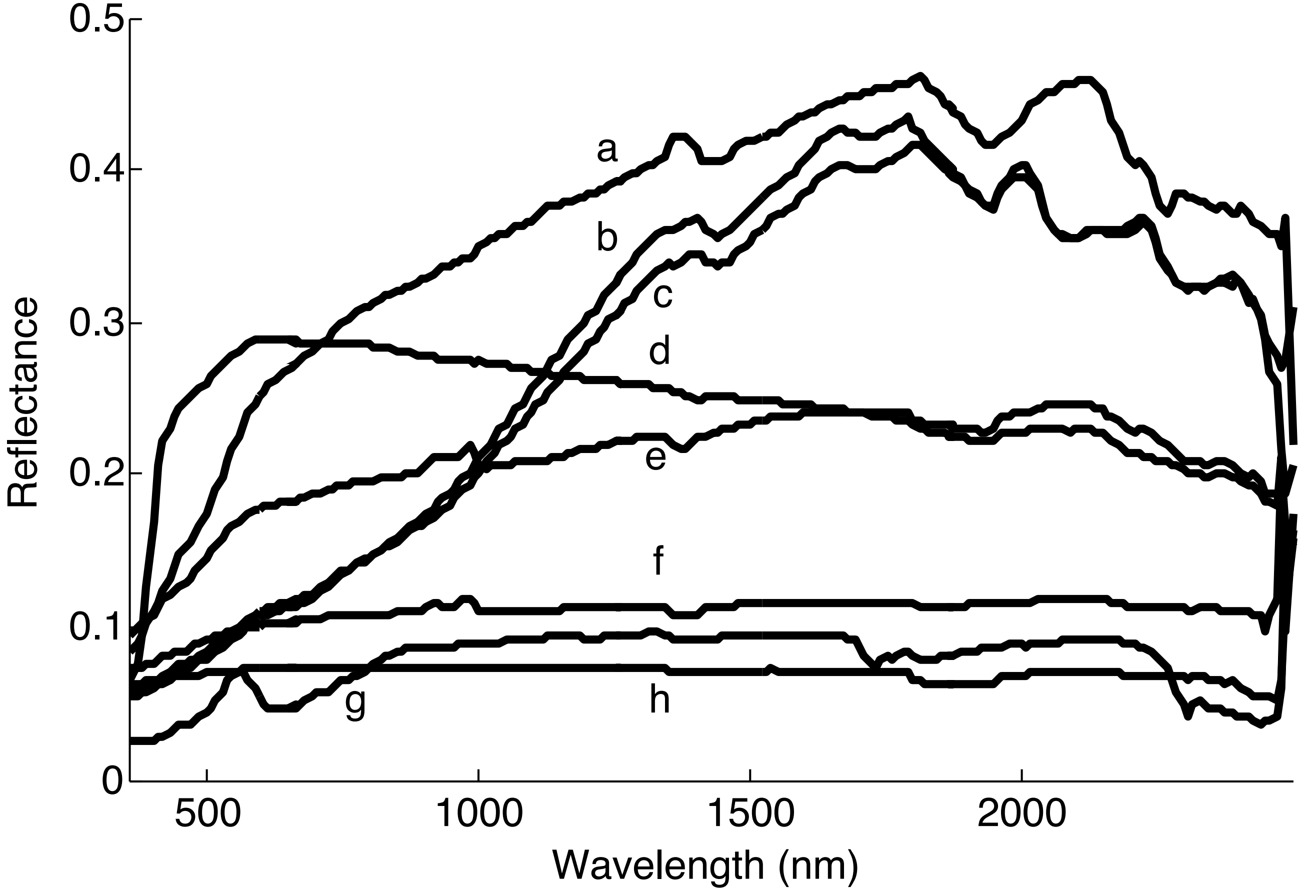
MEL: Modified Empirical Line (Moran et al., 2006)

BEL: Bayesian Empirical Line

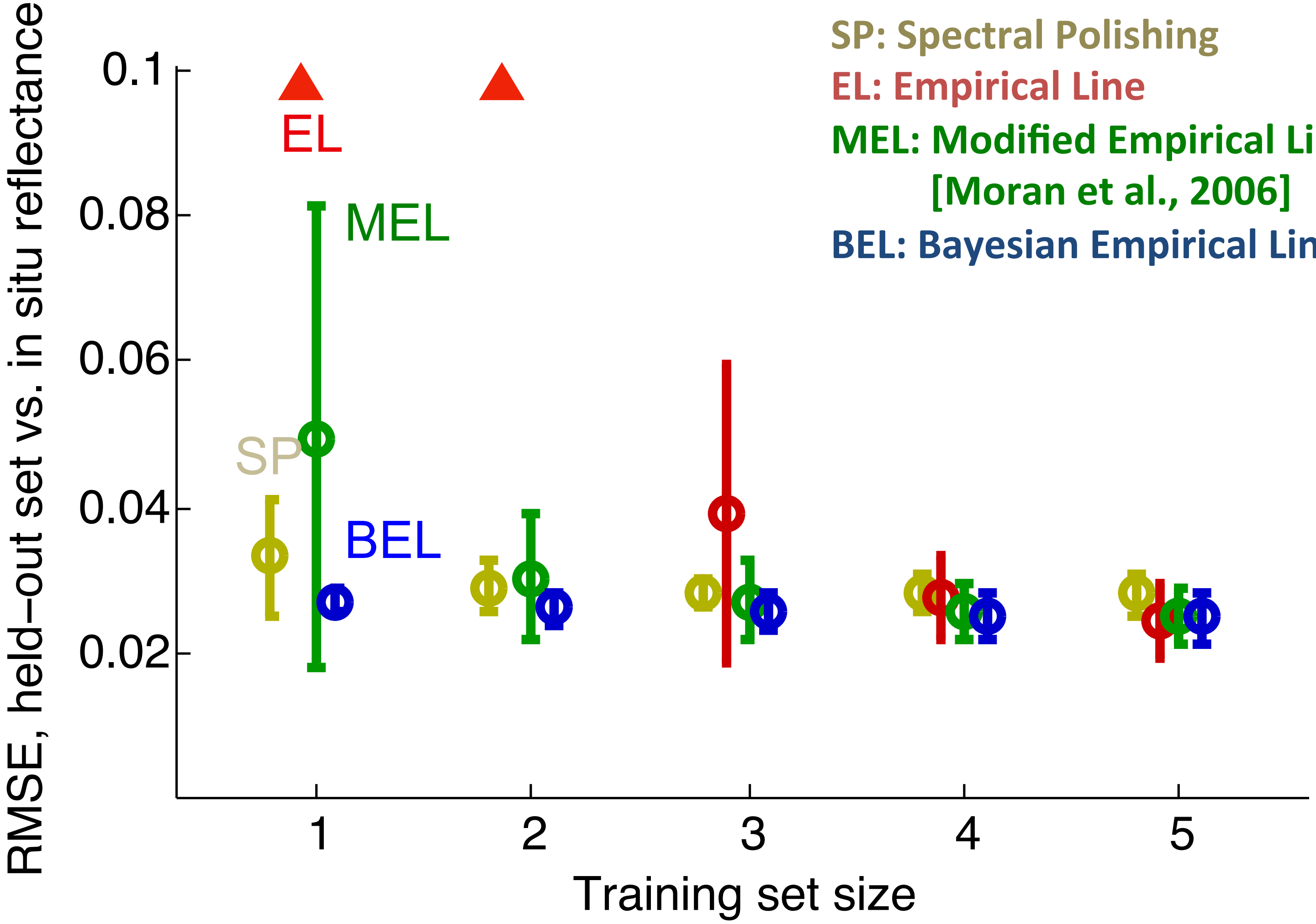
Two case studies with real data



Terrestrial example:
8 reference targets



Terrestrial example



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Conclusions

- Incorporating a Radiative Transfer Model significantly increases the stability of the empirical line
- In many cases it permits reliable corrections from a single in situ measurement.
- The statistical formalism generalizes model-based and empirical methods

For more information

David R. Thompson, Dar A. Roberts, Bo Cai Gao, Robert O. Green, Liane Guild, Kendra Hayashi, Raphael Kudela, and Sherry Palacios, "Atmospheric correction with the Bayesian empirical line," *Optics. Express* 24, 2134-2144 (2016)

Or shoot me an email,
David.r.thompson@jpl.nasa.gov

Atmospheric correction with the Bayesian empirical line

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[1] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA USA*
[2] *University of California Santa Barbara, CA USA*
[3] *US Naval Research Laboratory, Washington, DC USA*
[4] *NASA Ames Research Center, Moffett Field, CA USA*
[5] *University of California Santa Cruz, CA USA*
[6] *Bay Area Environmental Research Institute (BAERI), NASA Ames Research Center, Moffett Field, CA USA*
[*] *david.r.thompson@jpl.nasa.gov*

Abstract: Atmospheric correction of visible/infrared spectra traditionally involves either (1) physics-based methods using Radiative Transfer Models (RTMs), or (2) empirical methods using in situ measurements. Here a more general probabilistic formulation unifies the approaches and enables combined solutions. The technique is simple to implement and provides stable results from one or more reference spectra. This makes empirical corrections practical for large or remote environments where it is difficult to acquire coincident field data. First, we use a physics-based solution to define a prior distribution over reflectances and their correction coefficients. We then incorporate reference measurements via Bayesian inference, leading to a Maximum A Posteriori estimate which is generally more accurate than pure physics-based methods yet more stable than pure empirical methods. Gaussian assumptions enable a closed form solution based on Tikhonov regularization. We demonstrate performance in atmospheric simulations and historical data from the "Classic" Airborne Visible Infrared Imaging Spectrometer (AVIRIS-C) acquired during the HyspIRI mission preparatory campaign.

OCIS codes: (010.0280) Remote sensing and sensors; (010.1285) Atmospheric correction; (300.6340) Spectroscopy, infrared; (300.6550) Spectroscopy, visible.

References and links

1. G. Schaepman-Strub, M. E. Schaepman, T. H. Painter, S. Dangel, and J. V. Martonchik, "Reflectance quantities in optical remote sensingdefinitions and case studies, " Remote Sens. Environ. **103**(1), 27–42 (2006).
2. C. D. Mobley, "Estimation of the remote-sensing reflectance from above-surface measurements, " Appl. Opt. **38**(36),7442–7455 (1999).
3. D. R. Thompson, B. C. Gao, R. O. Green, D. A. Roberts, P. E. Dennison, and S. Lundeen, "Atmospheric correction for global mapping spectroscopy: ATREM advances for the HyspIRI preparatory campaign, " Remote Sens. Environ. **167**, 64–77 (2015).
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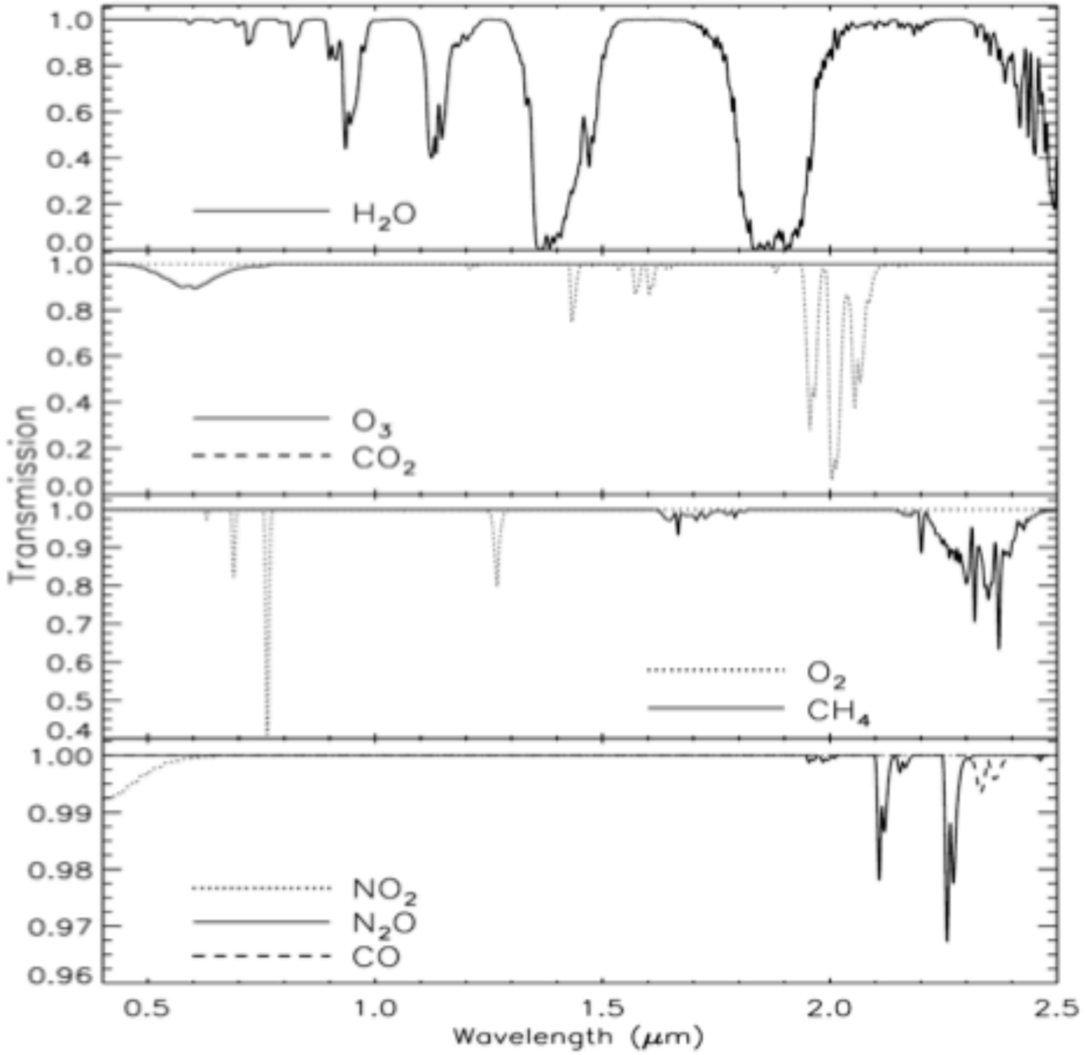
Backup slides

Typical transmittance



Absorption is modeled for 7 gases

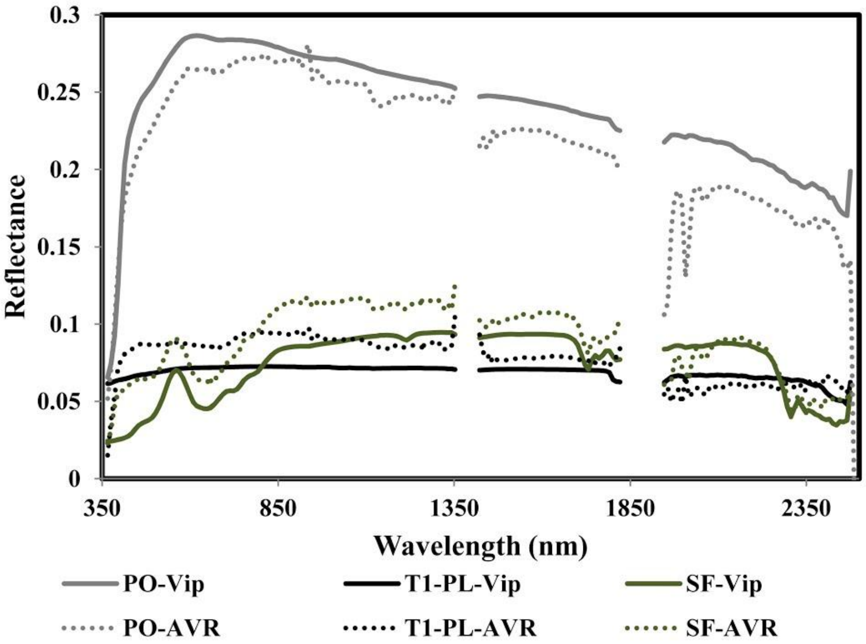
ATREM retrieves water vapor for each pixel using 0.94 and 1.14 μm H_2O band depths

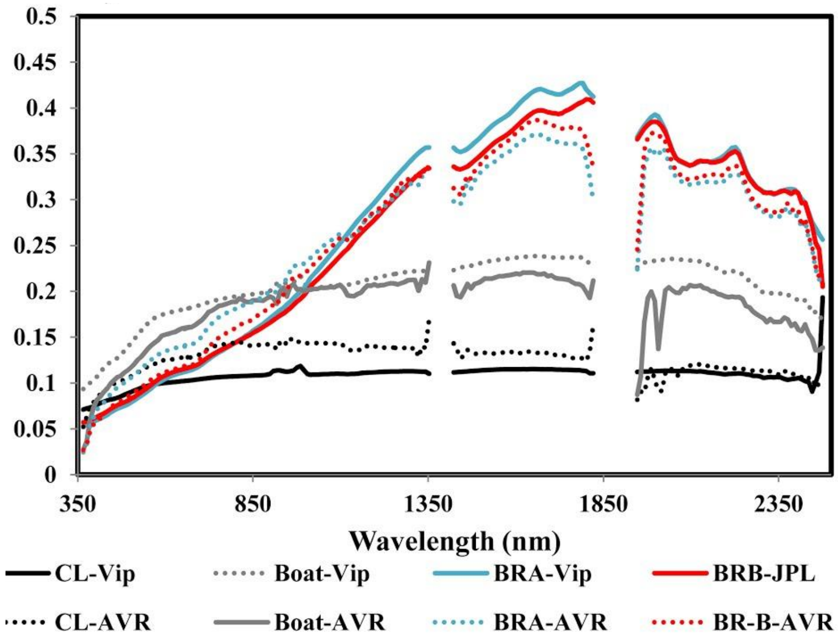
Vertical profiles use 20-layer atmospheres

[Gao and Green 2010]

Ground truth validation targets

- Dark targets too bright, bright targets too dark
- This suggests uncorrected scattering is a major offender
- Accuracy degrades somewhat at short wavelengths
- Water vapor maps (not shown) still show some “vegetation bias”





Courtesy Dar Roberts from Thompson et al., RSE 2015 (in press)

DISORT simulation

- **Simulated atmospheric interference and correction using the standard relation:**

$$\underbrace{\rho_0}_{\text{Top Of Atmosphere Reflectance}} = \frac{\pi \overset{\text{Radiance}}{L}}{\underbrace{F}_{\text{Solar flux,}}\, cos(\underbrace{\psi}_{\text{zenith}})} = \underbrace{\rho_a}_{\text{Path Reflectance}} + \frac{\overset{\text{Transmission}}{T}\,\overset{\text{Reflectance}}{\rho}}{1 - \rho \underbrace{S}_{\text{Spherical sky albedo}}}$$

- **Introduced errors from two sources:**
  - **Perturbed TOA spectrum by a gain and offset, simulating errors in atmospheric model**
  - **Random white measurement noise**
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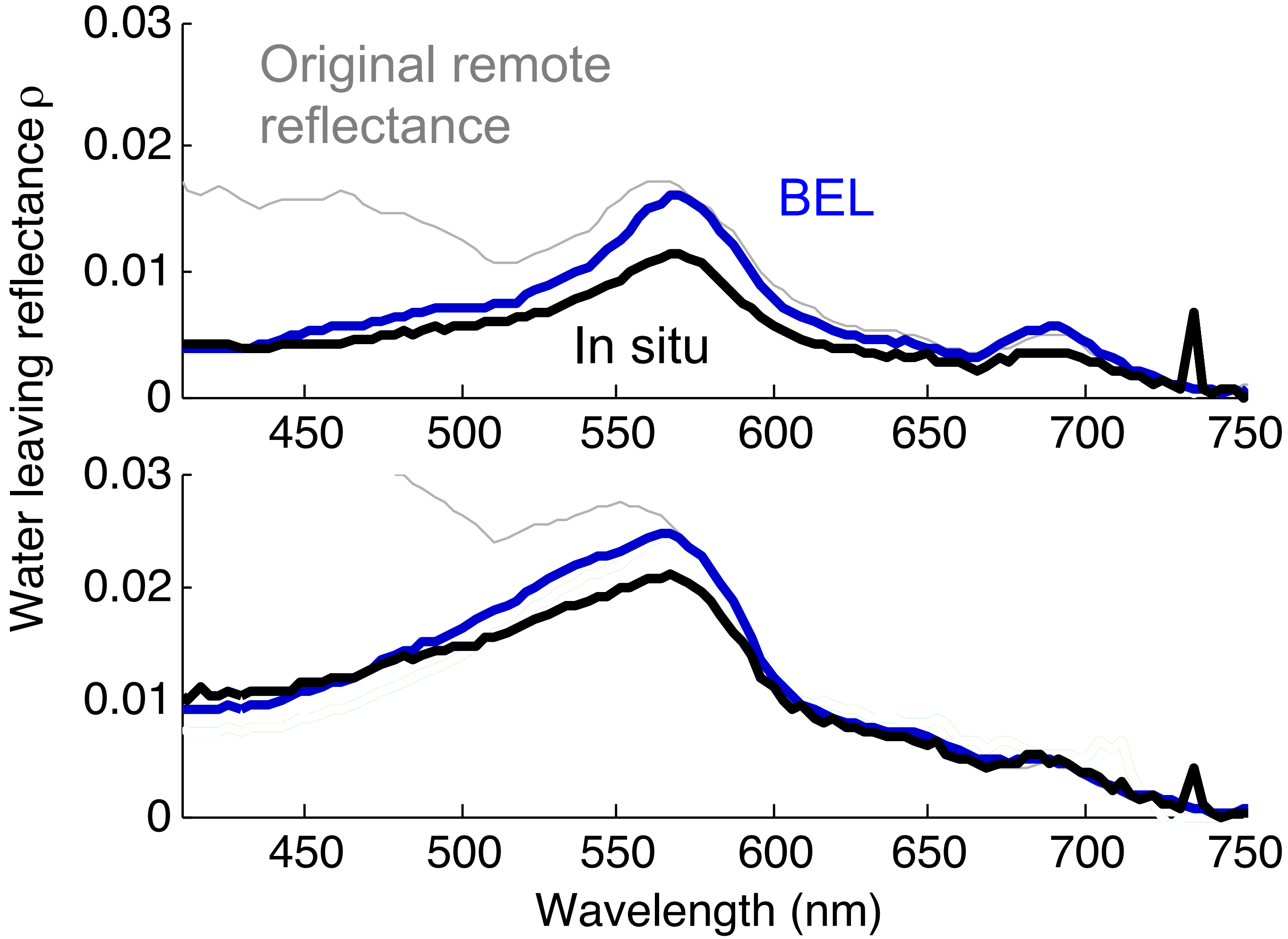
Aquatic example



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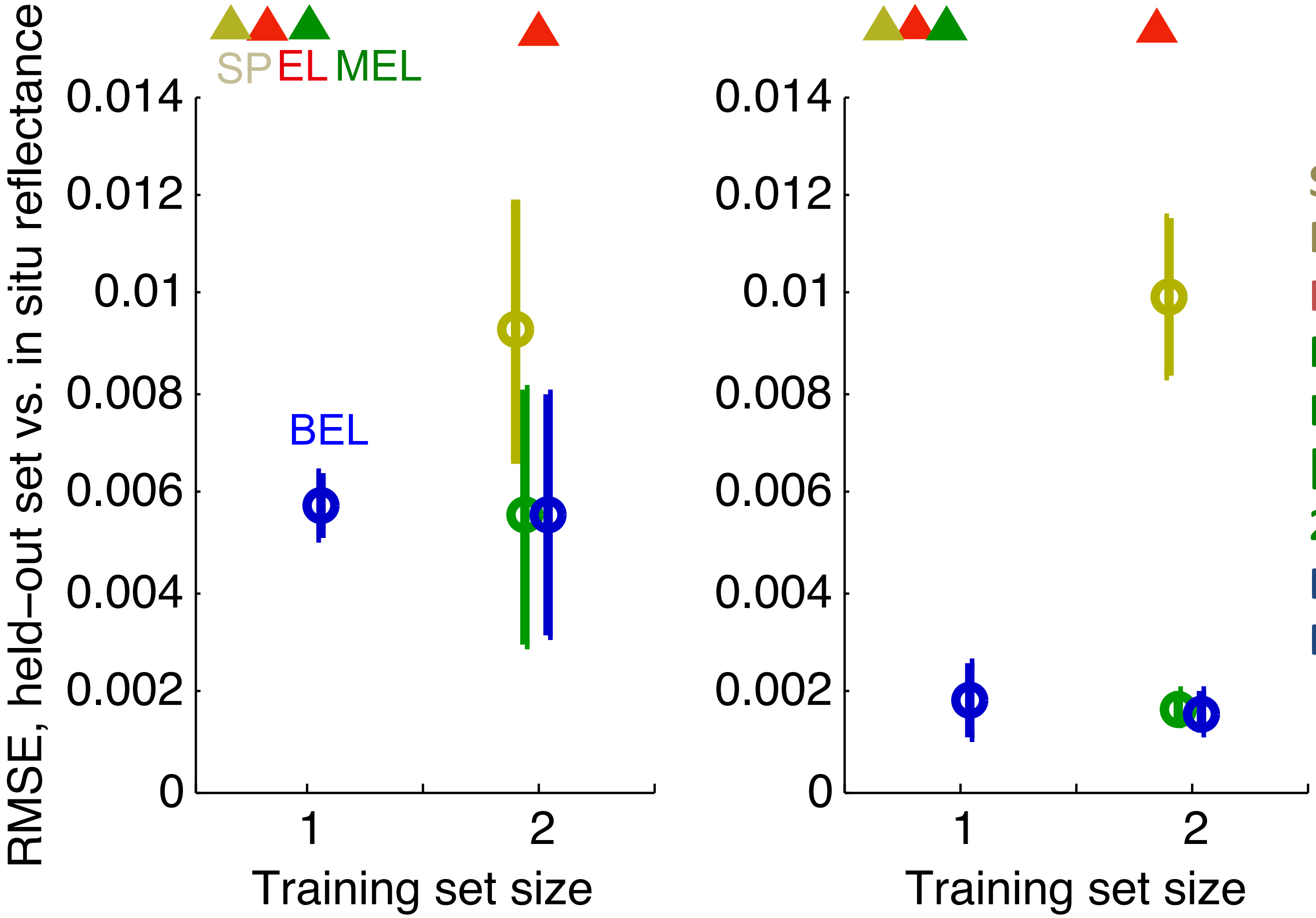

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