Jet Propulsion Laboratory
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Atmospheric Correction with the Bayesian Empirical Line

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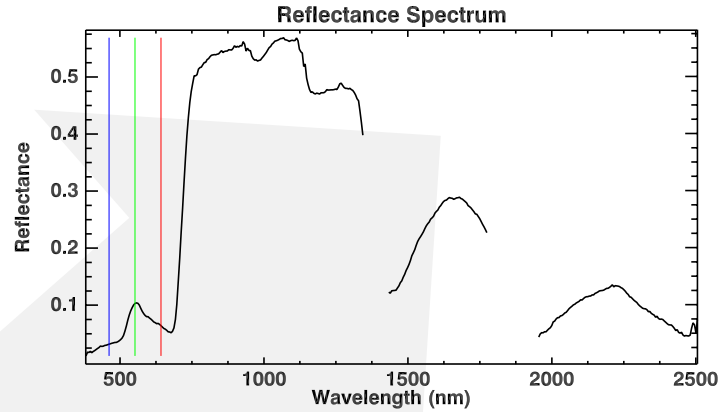
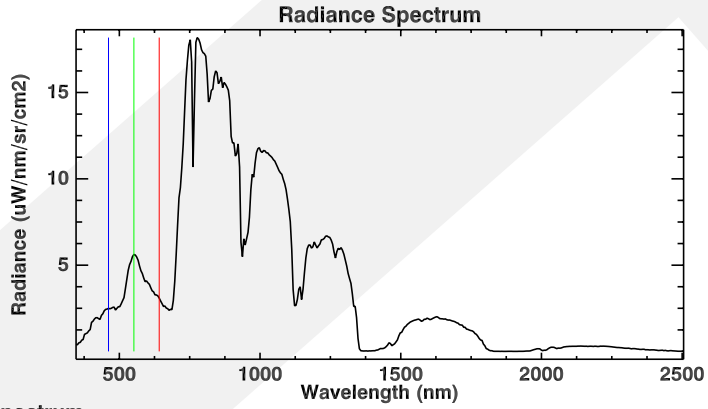
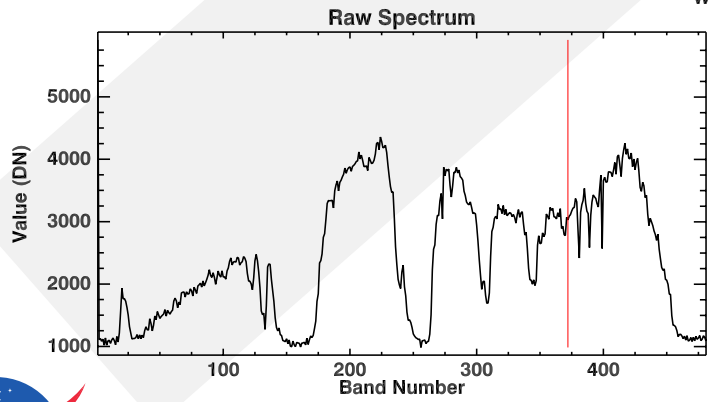
Atmospheric correction is fundamental



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

Examples

RTMS

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

Empirical

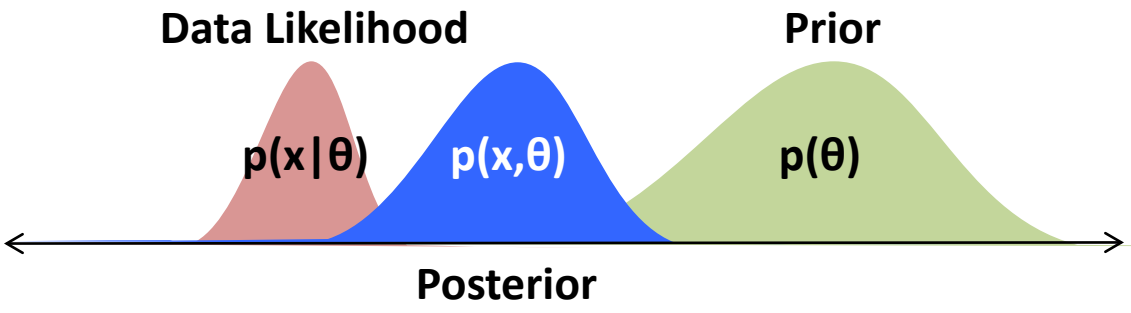
- Empirical line
- Modified empirical line [Moran et al., 2006]

Toward a unified approach

- **Model-based methods can be vulnerable to aerosol uncertainty**
- **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

- **When working in reflectance, the correction factors have predictable distributions**
- **Use the model-based solution to define a Bayesian prior on correction coefficients**



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

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

Data matrix with **reflectances**

Linear correction

Reference spectra

Gaussian prior on correction coefficients, **centered on identity**

Classical empirical line: Ordinary linear least squares

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

Bayesian empirical line: Generalized Tikhonov Regression

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

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

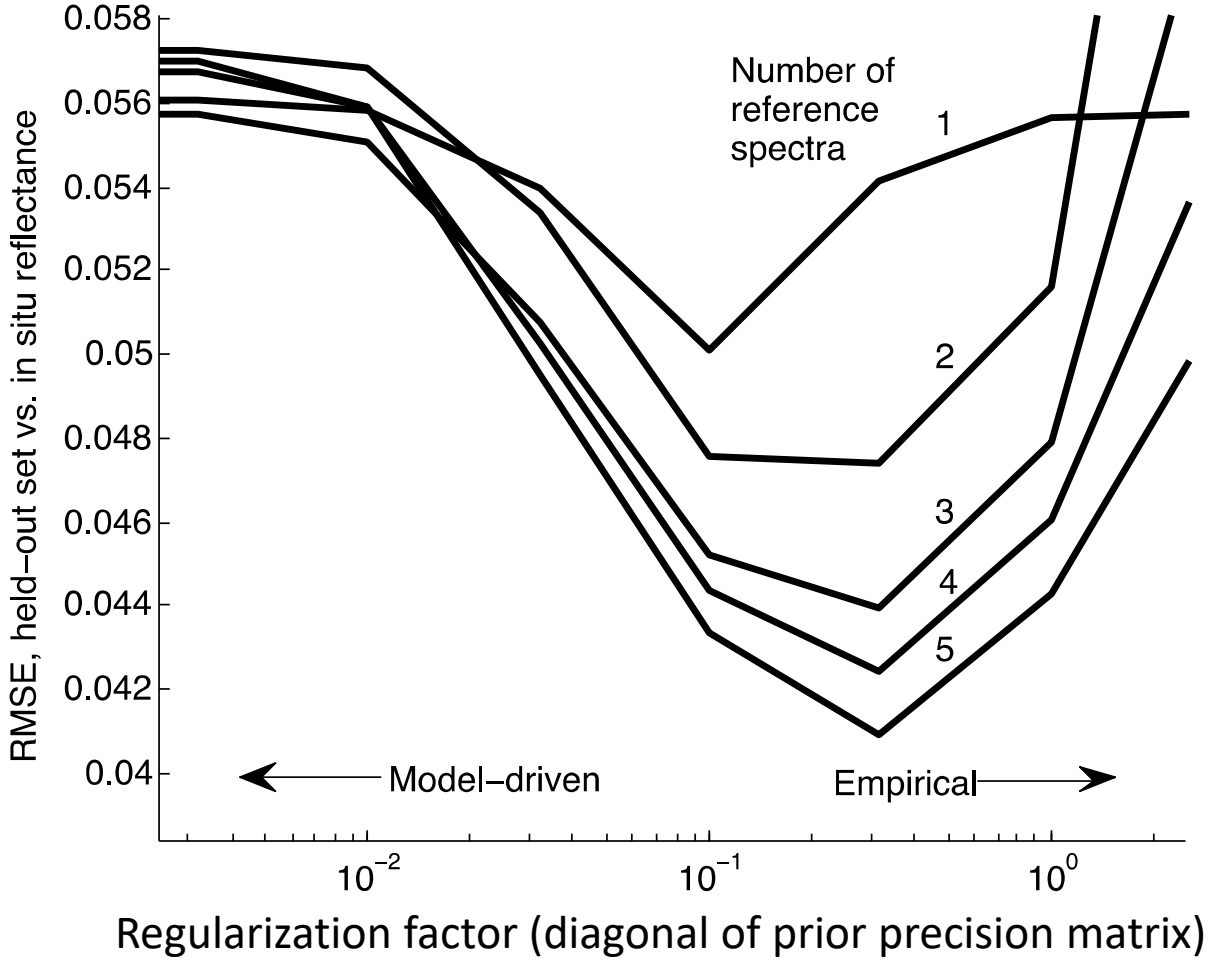
Spherical sky albedo

Top Of Atmosphere Reflectance

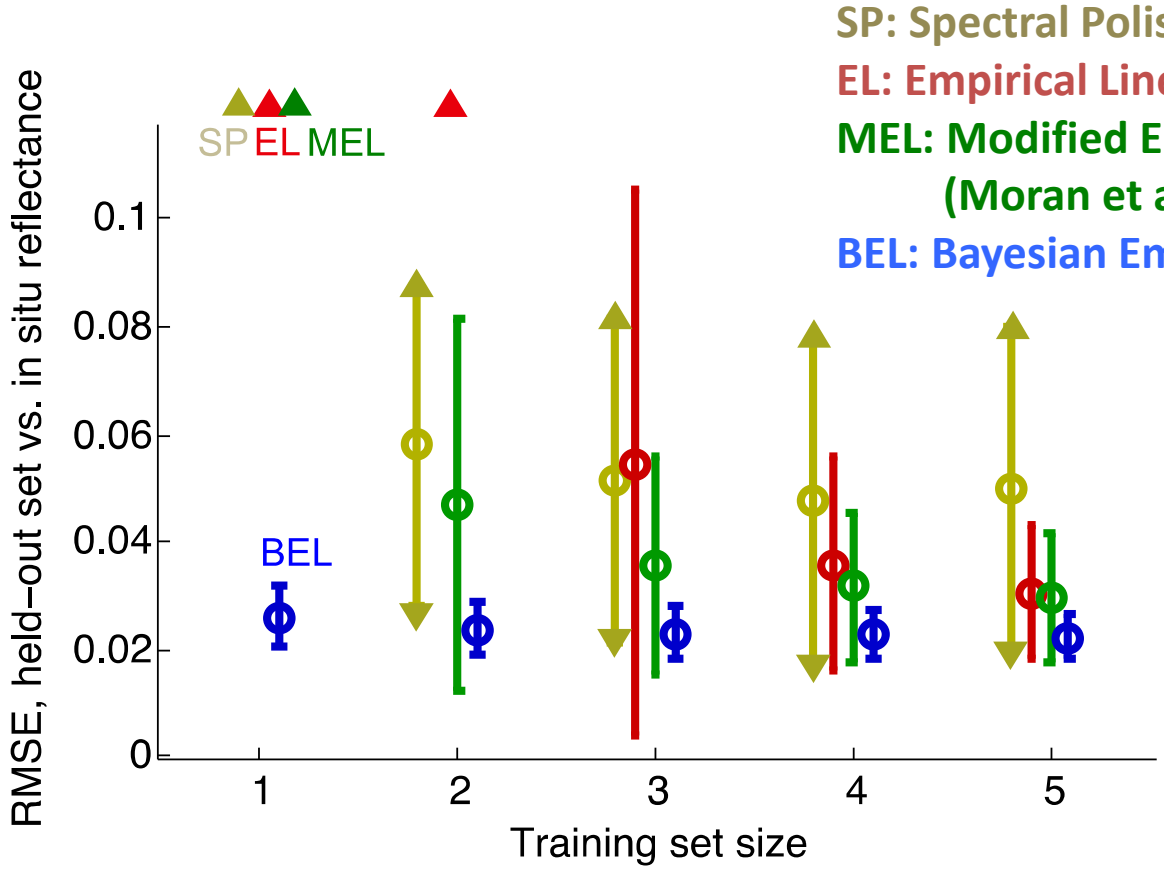
Path Reflectance

- **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

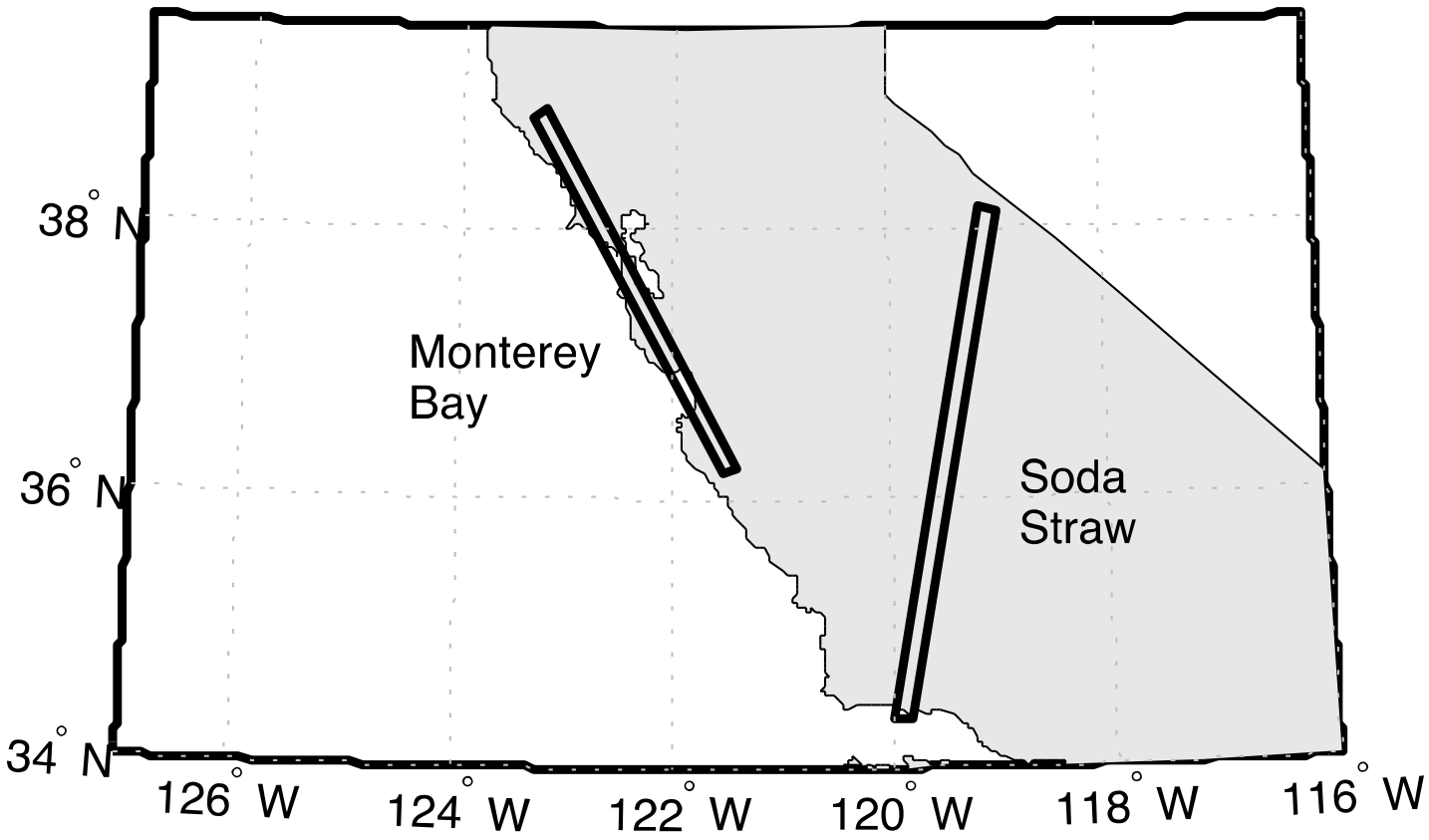


DISORT simulation results: 20 reference targets

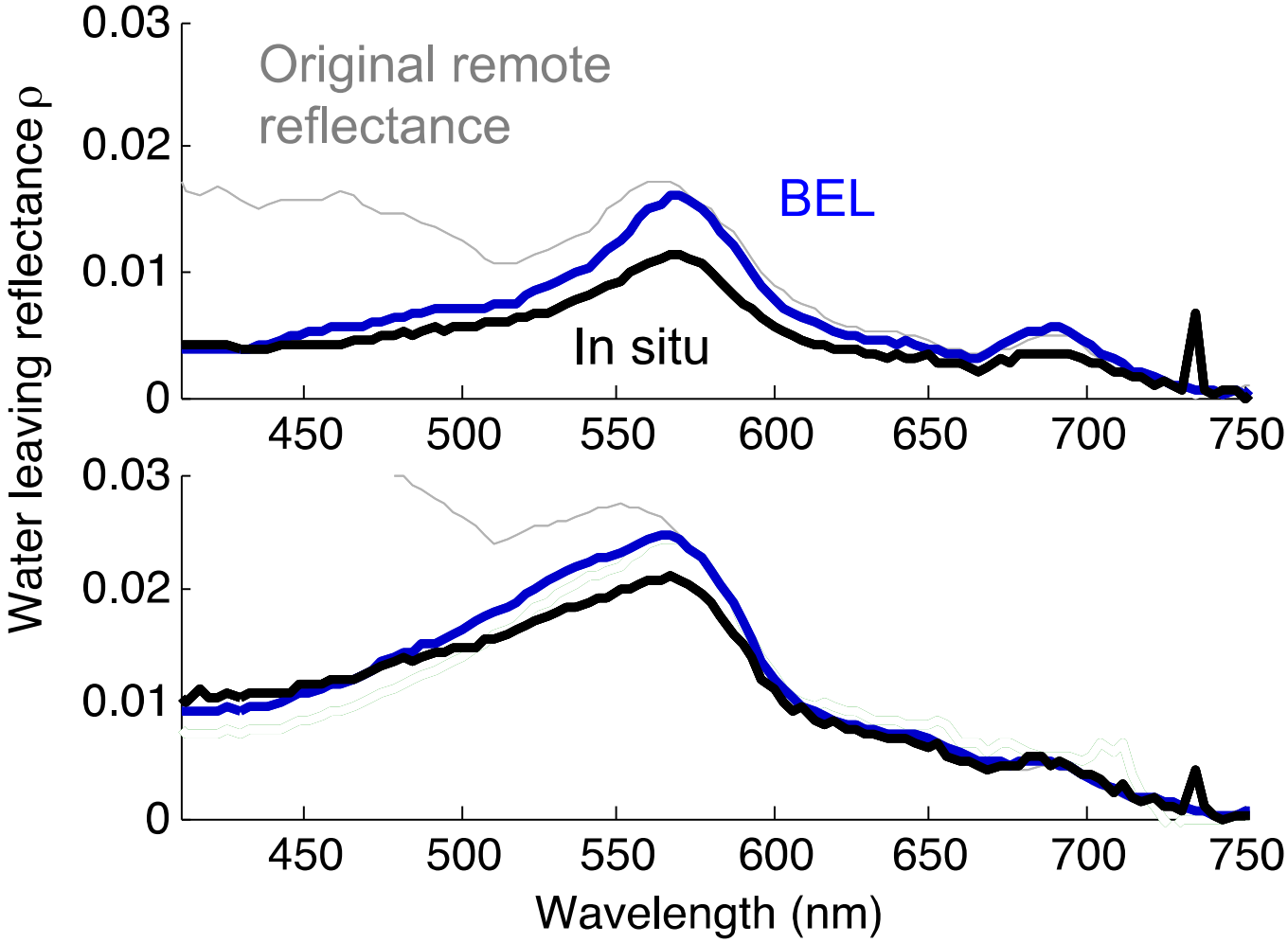


SP: Spectral Polishing
EL: Empirical Line
MEL: Modified Empirical Line (Moran et al., 2006)
BEL: Bayesian Empirical Line

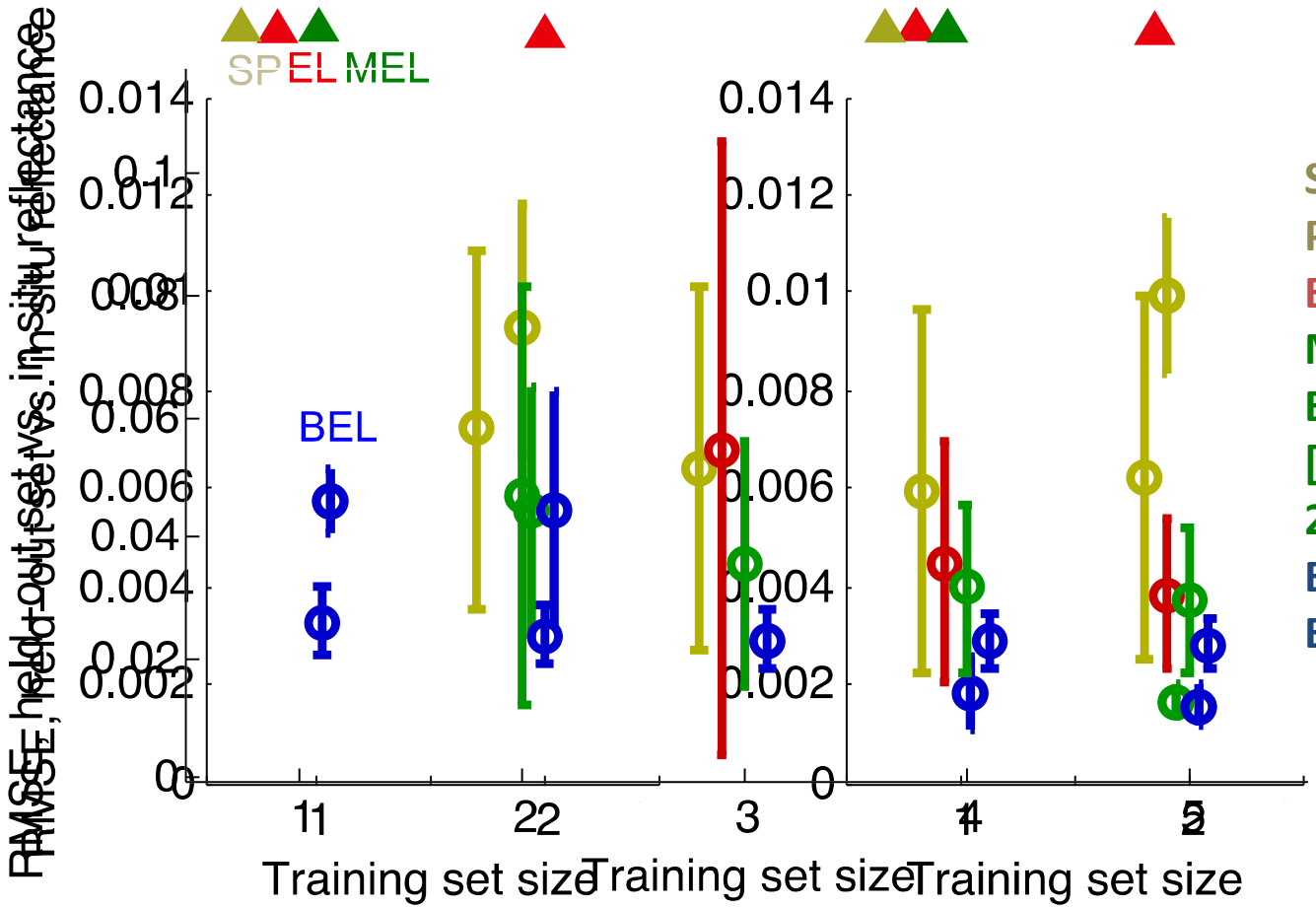
Two case studies with real data



Aquatic example



Aquatic example



SP: Spectral Polishing

EL: Empirical Line

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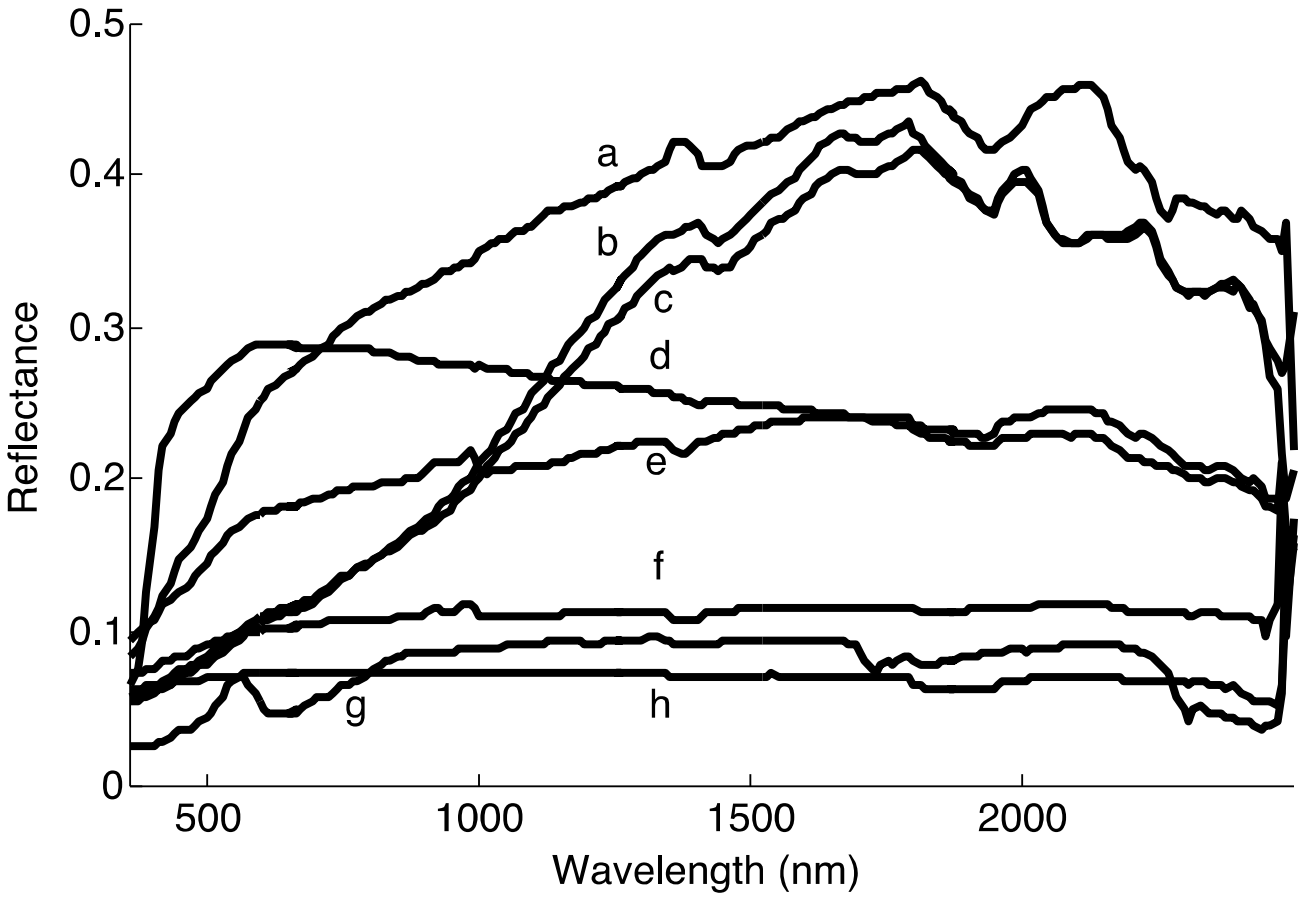
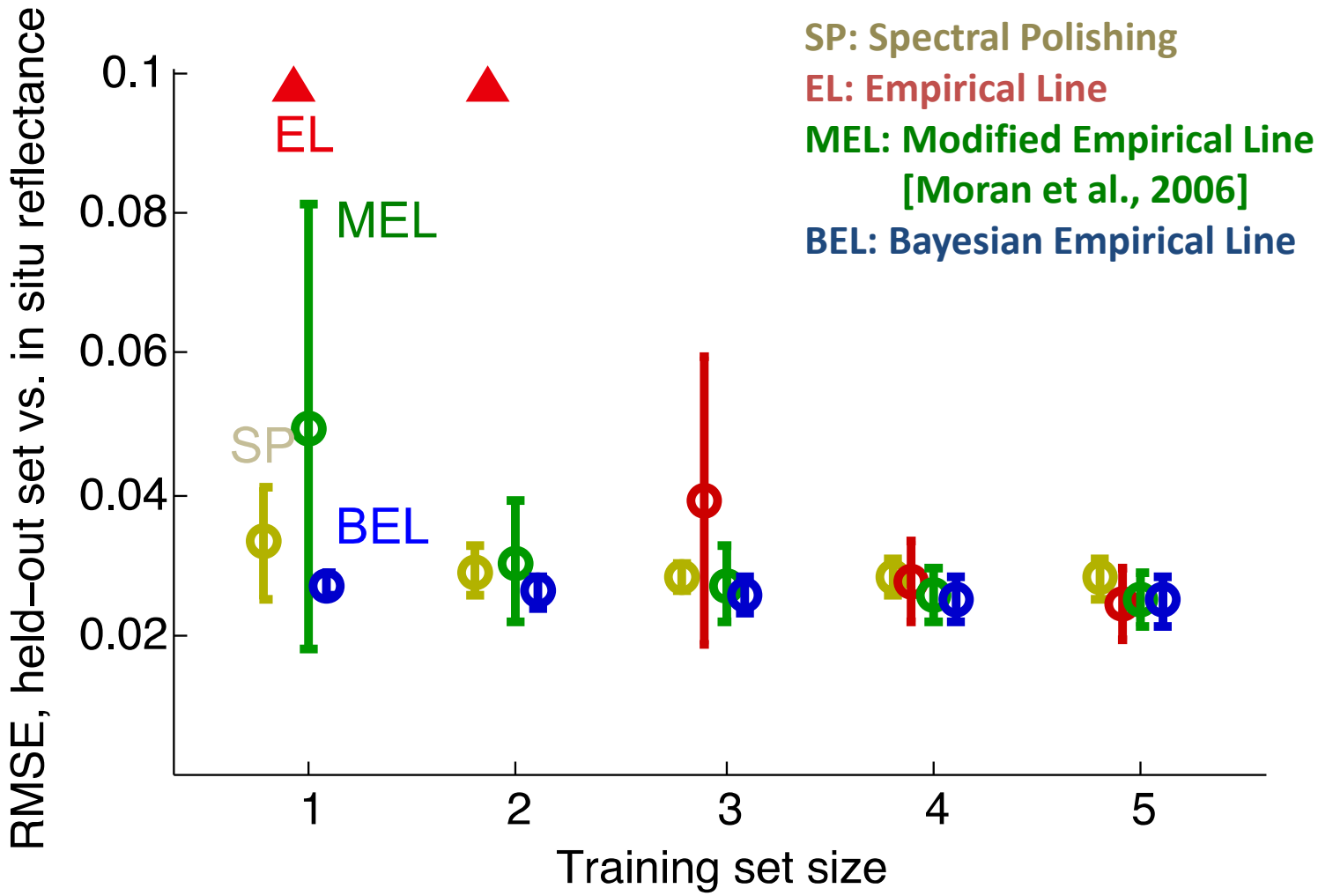
Terrestrial example: 8 reference targets



Terrestrial example



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**

Backup slides

L2 Surface reflectance

Solar spectrum F (modified Kurucz)

Aerosol particle type distribution, AOD at 550nm

Top of atmosphere apparent reflectance ρ

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

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

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

Gaseous transmission T_g

Aerosol transmission T_dT_u, Spherical sky albedo s, Path reflectance r_a

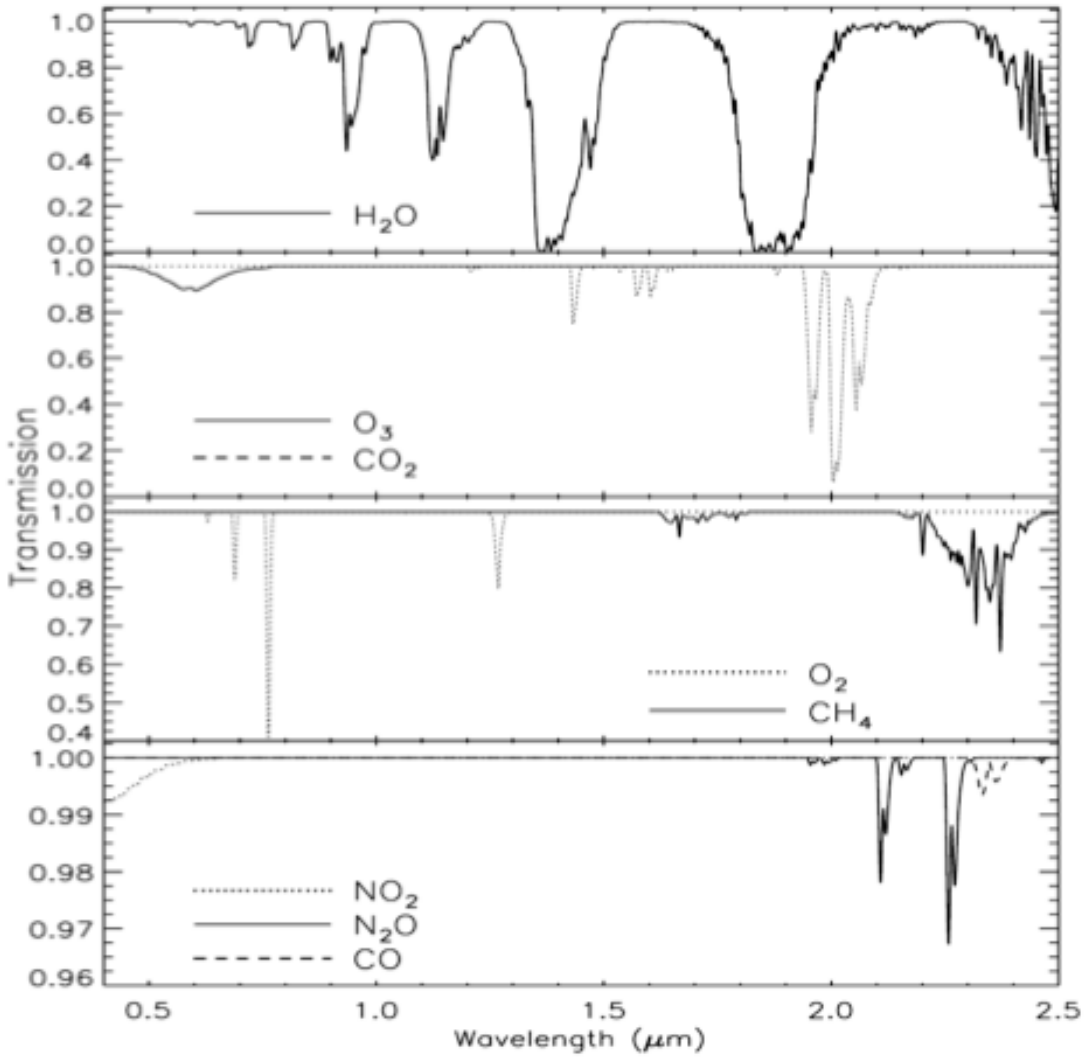
Reflectance spectrum

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

Residual suppression based on a reference target

Corrected reflectance spectrum

Typical transmittance



Absorption is modeled for 7 gases

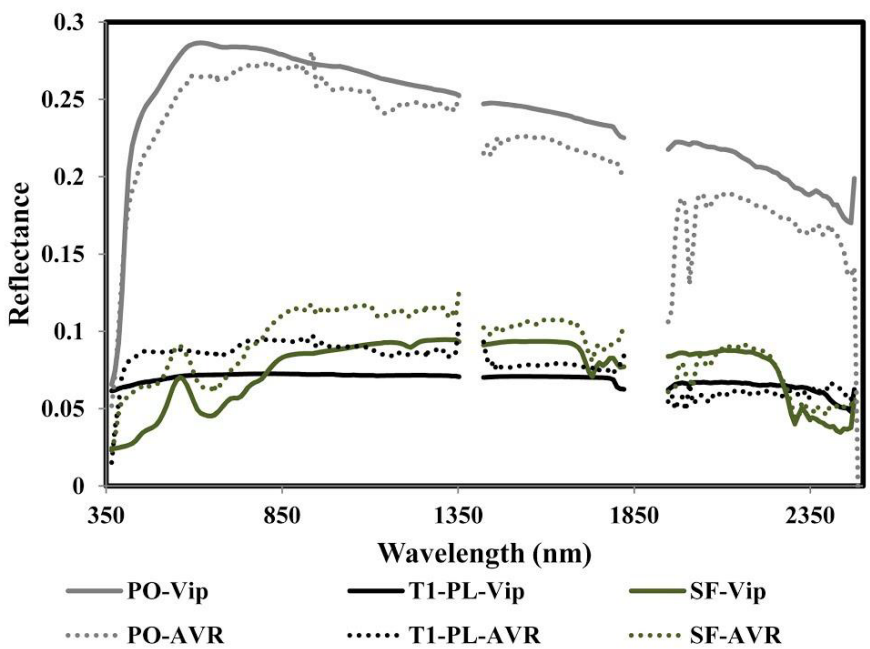
ATREM retrieves water vapor for each pixel using 0.94 and 1.14 µm H_2O band depths

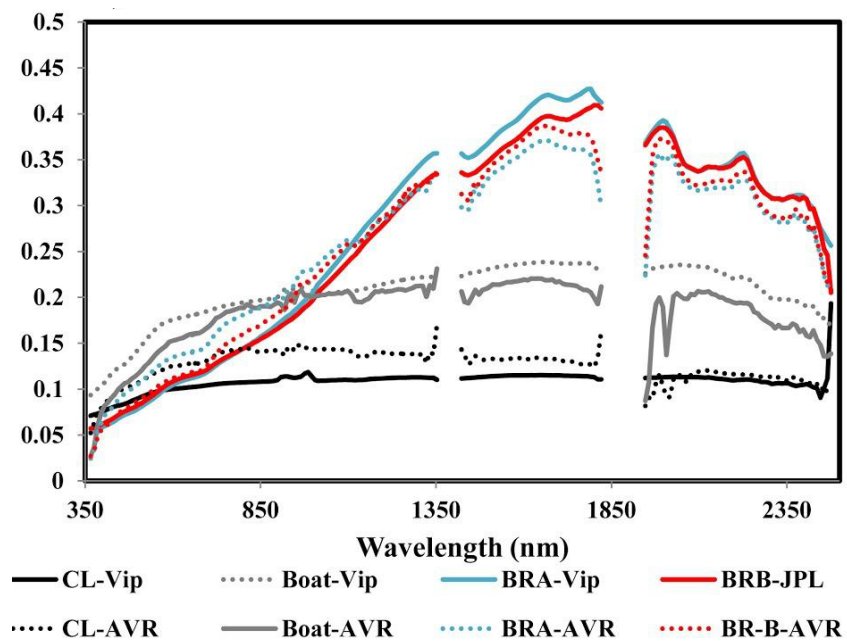
Vertical profiles use 20-layer atmospheres

[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)

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Reflectance

Spherical sky albedo

Top Of Atmosphere Reflectance

Solar flux, zenith

Path Reflectance

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