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
Atmospheric correction

\[
\rho_{TOA} = \rho_{atm} + \frac{T \rho_S}{1 - S \rho_S}
\]

Top of atmosphere reflectance

Path reflectance

Transmission

Spherical albedo

Surface reflectance
RTM
Calculations for observation geometry

Lookup table for $T$, $S$, $\rho_{atm}$ indexed by $H_2O$, etc.

In Advance

Typical approach
RTM Calculations for observation geometry

Lookup table for $T$, $S$, $\rho_{atm}$ indexed by H$_2$O, etc.

In Advance

Typical approach

Estimate atmospheric state

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

Look up atmospheric state

Algebraic inversion for reflectance
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.
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:

\[ y = F(x) + \epsilon \]

- Radiance measurement
- RTM prediction
- Random error

• For covariances \( S \), minimize the error function:

\[ \chi^2(x) = (F(x) - y)^T S_{\epsilon}^{-1} (F(x) - y) + (x - x_a)^T S_{a}^{-1} (x - x_a) \]

- Model match to measurement
- Bayesian prior
Example: OCO-2
Retrieval method
[Boesch et al., 2015]
Potential benefits

• **RTM solution for each spectrum**, models exact absorption-in-scattering for accurate correction of H₂O 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.

- 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

Hidden layer:
- 2x1 clamped
- 10x sigmoid

Output:
- Fine structure
- Continuum Parameters

Radiance:
- 12100x
- continua x fine structure (deterministic)

10x sigmoid

12100x linear

3x linear
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.
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

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**State vector**
- H$_2$O
- Elevation
- Aerosol
- AOD