Optimal Spectral Sampling (OSS) Method: Current Research and New Prospects

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Overview of the OSS approach

- OSS method (Moncet et al. 2003, 2001) models the channel radiance as

\[
\bar{R} = \int_{\Delta \nu} \phi(\nu) R(\nu) d\nu \approx \sum_{i=1}^{N} w_i R(\nu_i) ; \quad \nu_i \in \Delta \nu
\]

- Wavenumber \( \nu_i \) (nodes) and weights \( w_i \) are determined by fitting “exact” calculations (from line-by-line model) for globally representative set of atmospheres (training set)

- Monochromatic RT (using look-up tables of absorption coefficients for relevant species stored at the selected nodes)
  - Maximum brightness temperature error with current LUT < 0.05K in infrared and <~0.01K in microwave

OSS vs. LBLRTM - AIRS clear-sky, ARM TWP site (08/12/08)
OSS attributes

- Fast/accurate
  - Possibility of trade of between speed/accuracy and tailoring for specific applications
  - Possibility of fitting multiple channels/instruments (generalized training)
    - Speed only driven by total spectral coverage (not number of instruments)
- Flexible handling of variable molecular species
  - Easy selection of variable absorbers at runtime
  - Low memory/computational cost of adding minor absorbers
- Unsupervised training
  - No empirical adjustment: minimizes validation effort!
- Applicable to both high-resolution and wide band (models slow spectral functions within band) sensors
- Applicable to scattering atmospheres
Ongoing OSS efforts

**JCSDA/CRTM:**
- Joint NOAA/AER OPTRAN-OSS intercomparison in clear and cloudy atmospheres (SSMIS, AMSU, GOES sounder/imager, HIRS and AIRS)
  - Accuracy and timing
- OSS currently being implemented in CRTM
  - Beta version of CRTM with OSS engine delivered

**MODTRAN (under DoD funding):**
- Look at best approach for interfacing OSS with MODTRAN for _generic_ high/low resolution radiative transfer modeling
- Wide array of users and applications
  - Same method should cover it all
Current priorities

- Cloudy sky training and validation (thermal and solar)
- Molecular optical depth database compression
  - Exploring new approaches for speeding up (and reducing memory requirements) the method in clear and cloudy skies
    - Goal: relax memory requirements and further increase model speed
    - “Local” compression (scale of the order of 100 cm\(^{-1}\)):
      - Multiple channel generalized training/clustering techniques
    - Large scale compression (MODTRAN application)
- Treatment of “slowly” varying functions (Planck, surface, clouds/aerosols)
  - Must consider both high-spectral resolution over wide spectral bands and single broadband channels
OSS cloudy validation

- Two aspects are being considered and tested separately:
  - Treatment of clouds on a narrow spectral intervals (cloud properties do not change across interval)
    - Can be done over wide range of conditions using line-by-line models over restricted spectral domains
  - Handling of spectral variations in cloud optical properties across broad intervals (single broadband “channel” or multiple high spectral resolution channels – see “generalized training”)
    - Use purely absorptive clouds first
    - With scattering: use high spectral resolution/high accuracy OSS model as reference
OSS cloudy validation (narrow spectral interval)

- Scatterers effect is to increase photon path lengths in the layers within and below the clouds (reflective surface)
- For narrow channels (*no spectral variation in cloud optical properties across channel*) clear sky (transmittance?) RT using representative distribution of path lengths may be used
- Present results were obtained without any modification to the present clear-sky training (i.e. clouds not accounted for in generating model parameters)
  - In thermal IR (and microwave) current clear-sky radiance training appears so far to work well
Example of OSS cloudy validation (no scattering)

- Instrument: AIRS
- Mean UMBC profile
- 2 cloud layers:
  - liquid (P=670 mb)
  - spherical ice (P=220 mb)

Performance quite insensitive to dependence on scan angle and cloud absorption
OSS/CHARTS Comparison

- CHARTS (Moncet and Clough, 1997):
  - Fast adding-doubling scheme for use with LBLRTM
    - Uses tables of layer reflection/transmittance as a function of total absorption computed at run time
  - Plans for routine analysis of Rotating Shadowband Spectroradiometer (RSS) spectra at the AMR/SGP site
OSS/CHARTS Comparison (2)

- **OSSSCAT:**
  - Single wavelength version of CHARTS (no tables)

- **Cloudy validation:**
  - Molecular absorption from 740-900 cm\(^{-1}\) domain
  - Full range of extinction optical depth, asymmetry and single scatter albedo explored
  - No spectral variation of scatterer’s optical properties
  - Thermal and solar regimes considered

- 1 cm\(^{-1}\) boxcars, *thermal only* (high cloud: 300-200 mb)
Approaching the current CHARTS LUT accuracy for large OD’s when SSA ~1

(low cloud: 925-825 mb)
OSS/CHARTS Comparison (4)

(high cloud: 300-200 mb)
Generalized training

- OSS selection simultaneously operates on $N$ channels, instead of one channel at a time
- Two selection methods considered:
  - **Method A**: Extension of current method to multiple channels, i.e. nodes are successively added until $rms$ difference between exact and approximate calculation for all channels in domain considered falls below prescribed threshold (reference)
  - **Method B**: Clustering: start from set of pre-selected nodes encompassing domain of interest and coalesce pairs of nodes with similar information content
  - Clustering (not optimized yet) is fast and applies to broad spectral domains (large number of channels) - Method A is limited to a few hundred cm$^{-1}$
Generalized training

- Large computational gains in clear sky (i.e. when cloud-clearing is used)
  - Gain is mainly the result of the fact that eliminated nodes are reconstructed as linear combinations of the retained nodes
  - Gain increases as size of spectral domain increases or spectral resolution increases

- In these examples, gain can be further increased by ~30-40%
Cloudy RT considerations

- **Channel based RT**
  - Required number of nodes for any given channel actually increases compared to single channel training (i.e. current approach is optimal)
  - In this example (gain ~ 15 in clear-sky), scattering calculations actually is ~3-4 times more time consuming than with current single channel approach
Generalized cloudy training

- Must include slowly varying cloud/aerosol optical properties in training
  - Over wide bands: training can be done by using a database of cloud/aerosol optical properties
  - More general training obtained by breaking spectrum in intervals of the order of 10 cm\(^{-1}\) in width (impact of variations in cloud/aerosol properties on radiances is quasi-linear) and by performing independent training for each interval (lower computational gain but increased robustness)

- Direct cloudy radiance training not recommended!
  - Clouds tend to mask molecular structure which makes training easier
  - If “recipe” for mixture of clear and cloudy atmospheres in direct training not right: clear-sky performance degrades
Generalized cloudy training

- Alternate two-step training preserves clear-sky solution
  - First step: normal clear-sky (transmittance/radiance) training to model molecular absorption
  - Second step: duplicate/spectrally redistribute nodes and recompute weights to incorporate slowly varying functions in the model

$$R^\text{cld}_i(v_k) = a_{ik} R^\text{cld}_i(v_1) + (1 - a_{ik}) R^\text{cld}_i(v_2)$$

$$\bar{R} = \sum_i w_i \sum_k (a_{ik} R_i(v_1) + (1 - a_{ik}) R_i(v_2)) \frac{\Delta v_{ik}}{\Delta v_i} = \sum_i w_i' R_i(v_1) + (w_i - w_i') R_i(v_2)$$

\(i=\text{molecular database index}\)
Training method performance comparison (AIRS Channel 1-1262)

<table>
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<tr>
<th>Channel number</th>
<th>Wavenumber range (cm⁻¹)</th>
<th>Number of selected nodes</th>
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<td>1</td>
<td>649-669</td>
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<tr>
<td>2</td>
<td>669-889</td>
<td>239</td>
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<td>3</td>
<td>689-709</td>
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<td>4</td>
<td>709-729</td>
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<td>5</td>
<td>729-749</td>
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<td>6</td>
<td>749-769</td>
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<td>Total number of nodes</td>
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<tr>
<td>Avg. number of nodes/channel</td>
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<td>1.98</td>
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- **Training conditions:**
  - ECMWF set
  - 7 angles (minimize \( \text{rms} \) for each angle)
  - Accuracy threshold = 0.05K
  - Domain size (Method A) = \(~20 \text{ cm}^{-1}\)
  - Random cloud spectra with smoothness constraint (1st and second spectral derivatives) derived from realistic optical properties

- **AIRS results (Method A)**
  - Clear-sky gain: \(~3.4\)
  - Cloudy gain: \(~2.4\)
Generalized training validation
(no scattering)

- 48 UMBC profiles
- 3 cloud layers: 300 mb, 500 mb, 700 mb
- Independent set of random cloud spectra

<table>
<thead>
<tr>
<th>Cloud code</th>
<th>Optical depth range</th>
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<td>0</td>
<td>=0</td>
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<tr>
<td>1</td>
<td>&gt;0 and &lt; 0.5</td>
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<tr>
<td>2</td>
<td>&gt;0.5 and &lt; 1</td>
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<tr>
<td>3</td>
<td>&gt;1 and &lt; 2</td>
</tr>
<tr>
<td>4</td>
<td>&gt;2</td>
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</table>

Clear-sky solution left intact

Model accuracy tends to improve as cloud optical depth increases (which is a good sign!)
Summary

- **OSS cloudy validation**
  - Clear-sky transmittance training seem to be adequate for scattering atmospheres (thermal sources only)
  - Validation in solar regime just started - may need to use wider range of layer optical paths

- **“Generalized training” offers potential for large memory/time savings over single channel approach in the modeling of clear (or cloud-cleared) radiances**
  - Variations in cloud/aerosol optical properties limits gain achievable with multi-channel training
    - Estimated worst case for AIRS: gain 2-3
    - Higher gain when model is trained for limited number of particle types
  - Same training algorithm can handle multi-channel and single channel training
Summary (2)

- Robust approach for handling of slowly varying functions in the training
  - New approach for dealing with slow spectral functions (Planck, cloud/aerosols) preserves clear-sky solution and handles seamlessly clear/cloudy transition (optically thin limit)
  - Applies to surface emissivity/reflectivity as well
  - Deals with any spectral function – optimizes solution according to characteristics of input data
  - Can the method be generalized to handle band-to-band correlation?