Atmospheric and Environmental Research

Evaluation of OSS Node-Based Assimilation: Initial Assessment

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Overview of problem

- Hyperspectral sounders typically have thousands of channels
- The number of channels is much higher than the number of independent elements of information regarding profiles of temperature, water vapor, and trace gases
- The redundancy is useful for reducing the effective noise of the channel set as a whole, and variational data assimilation methods are capable of extracting the information while exploiting the noise reduction
- It is impractical, however, to assimilate the full channel sets due to the high computational costs of the variational solution and of the radiative transfer calculations
- Observations are generally reduced to ~300 – 400 channels by channel selection before assimilation
- Channel selection causes minor loss of profile information and major loss of channel redundancy for noise suppression
- Principal component (PC) approaches to channel set compression have been proposed, but have drawbacks:
  - PC transformation relies on covariance and eigenvectors of radiance database, and PCs blend the spectral correlations from radiative transfer physics with climatological correlations of vertical profile shapes and inter-constituent correlations
  - The blending of vertical profile signals inhibits using dynamic selection to retain only the information relative to the clear atmosphere above cloud top or to screen out the signal from the land surface

Assimilation with OSS

- OSS reduces the number of radiative transfer calculations as much as channel selection and PC approaches, but:
  - no loss of information or noise reduction
  - retains the ability to dynamically screen for cloud or surface effects
  - is much less reliant on profile database statistics than PC method (more robust)
- OSS forward model is very fast at monochromatic radiative transfer calculations, including Jacobians used in assimilation
- Mapping monochromatic Jacobians $\tilde{\mathbf{K}}$ from nodes to channels ($\mathbf{K} = \mathbf{W}\tilde{\mathbf{K}}$) is slow when the number of channels is large
  - the mapping is larger for the Jacobian matrix than for the radiance by a factor of the additional dimension (the number of retrieved profile and surface parameters)
- The mapping burden can be vastly reduced by **performing the assimilation directly on monochromatic nodes instead of channels**

Optimal Spectral Sampling (OSS) fast forward model

OSS approximates a set of channel radiances (vector $\mathbf{y}$) as a linear combination ($\mathbf{W}$) of monochromatic radiances at selected spectral points (vector $\tilde{\mathbf{y}}$).
We call theses spectral points "nodes".

$$\mathbf{y} = \mathbf{W}\tilde{\mathbf{y}}$$

Nodes and weights are optimally selected to fit calculations from a reference line-by-line model for a highly diverse set of training profiles
With the **global training method** (Moncet et al., 2015) the optimization is simultaneous over all spectral channels
Exploits across-spectrum correlations in the *radiative physical* properties to minimize the total number of nodes used to represent a set of channels
The number of nodes required depends on:
- the number of variable gases modeled
- the required accuracy of the fit of the OSS approximation to the reference LBL model
  - selectable in OSS training

The entire IASI 8461 set of channels can be modeled with computations at about 300 monochromatic nodes
6 variable gases
fits reference model within 20% of NEDN (rms) in every IASI channel
OSS implementation as an option in CRTM is being merged in the current master CRTM

Formulation of node-based assimilation

Consider variational analysis framework that minimizes a cost function J:

$$J = \left\{\mathbf{x}^T\mathbf{B}^{-1}\mathbf{x} + \left[\mathbf{y} - \mathbf{y}^{\text{obs}}\right]^T\mathbf{R}^{-1}\left[\mathbf{y} - \mathbf{y}^{\text{obs}}\right]\right\}$$

$\mathbf{x}$ = atmospheric state vector
$\mathbf{y}^{\text{obs}}$ = vector of radiance observations
$\mathbf{B}$ = background error covariance
$\mathbf{R}$ = observation error covariance
$\mathbf{y}$ = vector of radiances generated by a forward model operating on $\mathbf{x}$

The observations are linearly related to the node radiances as:

$$\mathbf{y}^{\text{obs}} = \mathbf{W}\tilde{\mathbf{y}}^{\text{obs}} + \varepsilon_{\text{OSS}} + \varepsilon_{\text{LBL}} + \varepsilon_{\text{instrument}}$$

For node-based assimilation, we can invert this relationship so that node radiances can be estimated from the observed channel radiances using least-squares:

$$\hat{\tilde{\mathbf{y}}}^{\text{obs}} = \mathbf{A}\mathbf{y}^{\text{obs}}$$

$$\mathbf{A} = \left(\mathbf{W}^T\mathbf{R}^{-1}\mathbf{W}\right)^{-1}\mathbf{W}^T\mathbf{R}^{-1}$$

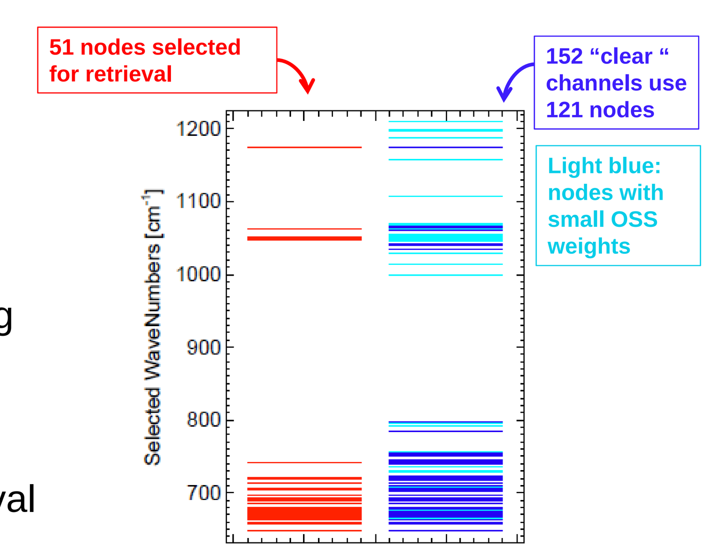
The term $\tilde{\mathbf{R}} = \left(\mathbf{W}^T\mathbf{R}^{-1}\mathbf{W}\right)^{-1}$ = error covariance for the estimated node radiances
The cost function becomes:

$$J = \left\{\mathbf{x}^T\mathbf{B}^{-1}\mathbf{x} + \left[\tilde{\mathbf{y}} - \hat{\tilde{\mathbf{y}}}^{\text{obs}}\right]^T\tilde{\mathbf{R}}^{-1}\left[\tilde{\mathbf{y}} - \hat{\tilde{\mathbf{y}}}^{\text{obs}}\right]\right\}$$

This operates directly on node radiances
The result in node space is identical to the result in channel space, within numerical error

Application to assimilation with measurements above cloud top

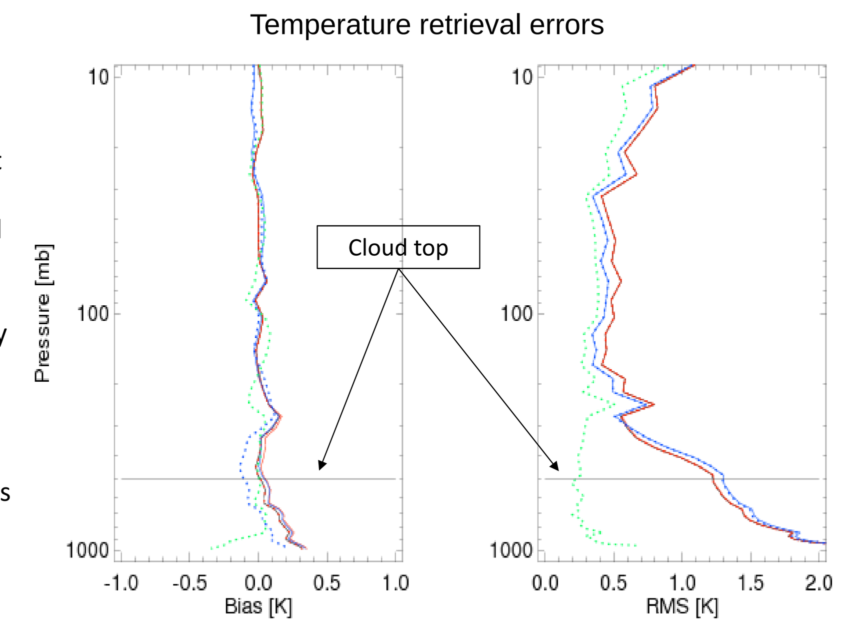
Approach:
- Project full cloudy radiance spectrum onto nodes
- Perform dynamic node selection
  - Using Jacobians and 1Dvar cloud top retrieval or other technique
  - Nodes have sharper weighting functions than channels
  - 51 clear nodes selected
- Trim obs error covariance matrix (node space) and perform retrieval with reduced set of nodes
- Compare with dynamic channel selection
  - 152 channels selected use 121 OSS nodes



Demonstration with IASI Band 1 and opaque cloud at 500 mb

Demonstration with 1Dvar retrievals
Climatology background
Dashed = radiances simulated without cloud
Solid = radiances simulated with cloud
Overlapping dashed and solid curves indicate the selection of nodes or channels above cloud worked properly

Red: Node space
with selection of above-cloud nodes
Blue: Channel space
with selection of above-cloud channels
Green: Channel space
Full Band 1 channel set clear-sky retrieval (for reference only)

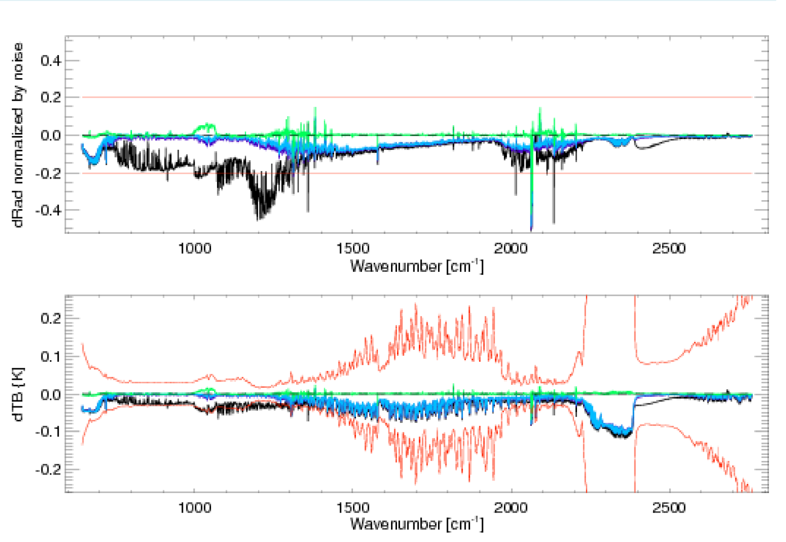


Reduction to 51 clear nodes gives almost the same retrieval errors as with 152 channels that depend on 121 nodes
Retrieval errors would be identical in node space and channel space if all 121 nodes were used

OSS model validation

- Validate that the OSS forward model has high fidelity with the current version of the line-by-line model used as a reference for fast model training: LBLRTM (v. 12.6)
- OSS accuracy depends on:
  - OSS approximation to the spectral integral over the instrument ILS
  - the monochromatic radiative transfer model, including computation of absorber amounts and absorption coefficient LUT interpolation
- New features:
  - option to use same altitude calculation (CMPALT) as LBLRTM (compressible)
  - altitude-based computation of absorber amounts between levels (LZSUM)
  - separate and more accurate treatment of water vapor self-broadened continuum in LUT

Differences from LBLRTM for IASI:
black = old OSS
dark blue = OSS with new LUT
light blue = OSS with new LUT and CMPALT and LZSUM
green = OSS with new LUT and CMPALT and LZSUM and LBLRTM linear-in-τ layer temperature
red = noise

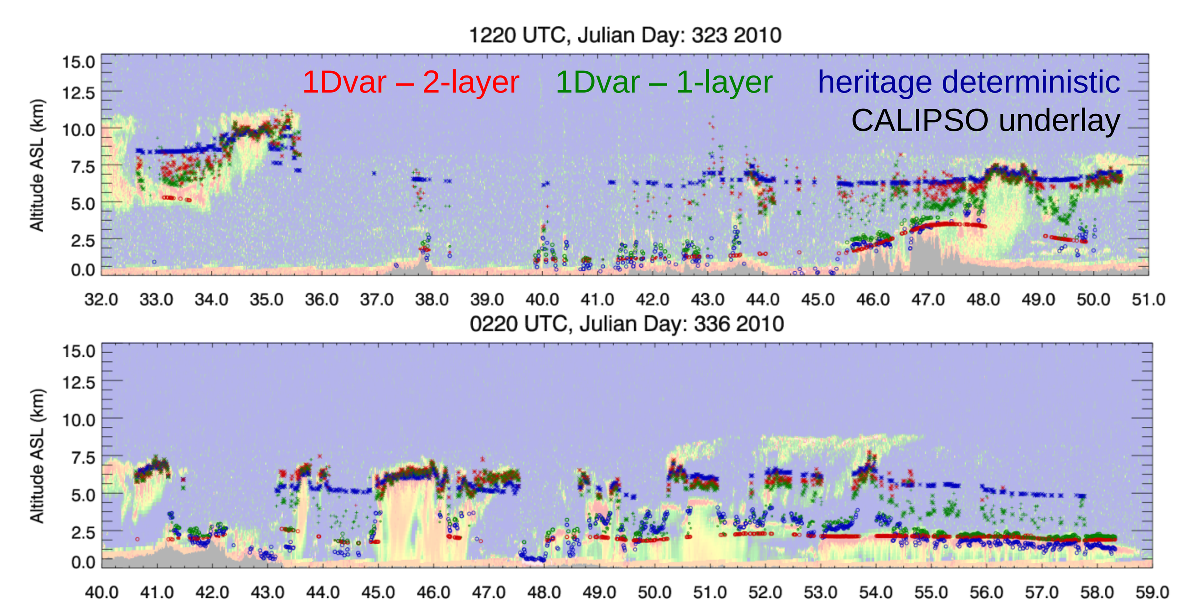


Cloud screening with 1Dvar

- 1Dvar can be used as assimilation pre-processor to identify clouds and determine cloud top
- Accurate cloud top depends on appropriate treatment of radiative transfer in semi-transparent clouds

MODIS demonstration validated with CALIPSO and CloudSat data

- MODIS has high spatial resolution, low spectral resolution
- 8 IR channels used
- Retrieve skin temperature and up to 6 cloud variables: 3 each for for ice and liquid: top pressure, water path, effective radius
- Temperature and water vapor from NWP



Evaluation approach being implemented

- Compare assimilation approaches on JCSDA experimental assimilation environment with data from AIRS, IASI, CrIS:
  - channel-based current CRTM with channel selection (current operational baseline)
  - channel-based current CRTM full channel set (impact of additional information and noise suppression)
  - channel-based CRTM-OSS full channel set (computation time and accuracy)
  - node-based full channel set (computation time savings)
- Compare capabilities for avoiding cloud contamination with minimal loss of clear-sky signal in assimilation:
  - channel selection
  - node selection