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High Spectral Resolution Infrared Radiance Modeling Using Optimal Spectral Sampling (OSS) Method

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Background

- Optimal Spectral Sampling (OSS) method is a fast and accurate monochromatic RT modeling technique applicable to a wide range of remote-sensing platforms
- Originally developed to support instrument/sounding algorithm trades, validation studies
  - Same method is applicable across the spectrum (from microwave to UV)
  - Monochromatic radiative transfer makes it directly applicable to multiple scattering, non-positive ILS (interferometers)
  - Physically based approach makes the method robust and ultimately alleviates need for extensive fast model validation
  - Trade-off between accuracy and speed depends on specifics of problem at hand
- Computationally efficient calculation of radiances and Jacobians makes OSS attractive for operational environment
- Initial research-grade version of OSS model:
  - NPOESS CrIS, CMIS, ATMS EDR algorithms
  - AMSU/MHS processing at AER
  - NAST-I (W. Smith)
- Parallel R&D effort (under Navy SBIR) led to improved training and new faster and more accurate RT model
- Used for AIRS instrument

ESFT and *k*-distribution methods

Correlated-*k* assumption breaks down for single absorber in the presence of lines of different strengths or non-regularly spaced lines

No satisfactory treatment of gas mixture when relative abundance of individual species changes with altitude

- The exponential sum fitting (ESFT) and *k*-distribution methods approximate band transmittances in homogenous atmospheres as,

$$\bar{\tau}(u) = \sum_{i=1}^{N} w_i e^{-k_i u}$$

- Weights w_i can be interpreted in terms of the probability distribution of the absorption coefficient over the spectral interval

$$w_i = \Delta g_i = \int_{k'_{i-1}}^{k'_i} p(k)\,dk \qquad (k'_{i-1} < k'_i)$$

and k_i is a representative *k*-value for the interval $[k'_{i-1}, k'_i]$

- Problems with extending ESFT or *k*-distribution concept to inhomogeneous atmospheres lies in difficulty of ensuring physical consistency between the *k*-values in each layers
  - Extension of the *k*-distribution method to non-homogeneous atmospheres is based on observation that minima and maxima of absorption in different layers coincide spectrally
  - Correlated-*k* method vertically integrates RT equation in *g*-space
  - Equivalent to assuming a correspondence between *k*'s of same ranking in different layers

OSS solution for inhomogeneous atmospheres

- **Proper treatment of overlapping absorbers requires accurate characterization of the multivariate probability distribution of absorption coefficients for all layers and molecules**

- **High dimensionality of the problem makes it impractical to attempt to solve directly for the *k* 's without use of appropriate constraints**

- **OSS solution:**
  - **Reduce the problem to a one-dimensional frequency search**
  - **Impose the constraint that the *k* 's correspond to actual values of absorption coefficient for all molecules and layers at the selected frequencies**

OSS parameters generation

- **Parameter generation starts from a set of *M* uniformly spaced monochromatic transmittances (or radiances)**
  - **Compute with a line-by-line model (currently LBLRTM)**
  - **Use a globally representative ensemble (*S*) of atmospheres**

- **Search for the smallest subset of frequencies (nodes) and associated weights**

$$\left\{ \left(\nu_i, w_i \right) \quad i = 1,.., N \right\}$$

for which the *rms* error computed over the ensemble *S*

$$\varepsilon_N \left(p_l \right) = \left[\sum_s \left(\overline{\tau}^s \left(p_l \right) - \sum_{i=1}^{N} w_i \tau_{\nu_i}^s \left(p_l \right) \right)^2 \right]^{\frac{1}{2}}$$

is less than a prescribed tolerance for all levels

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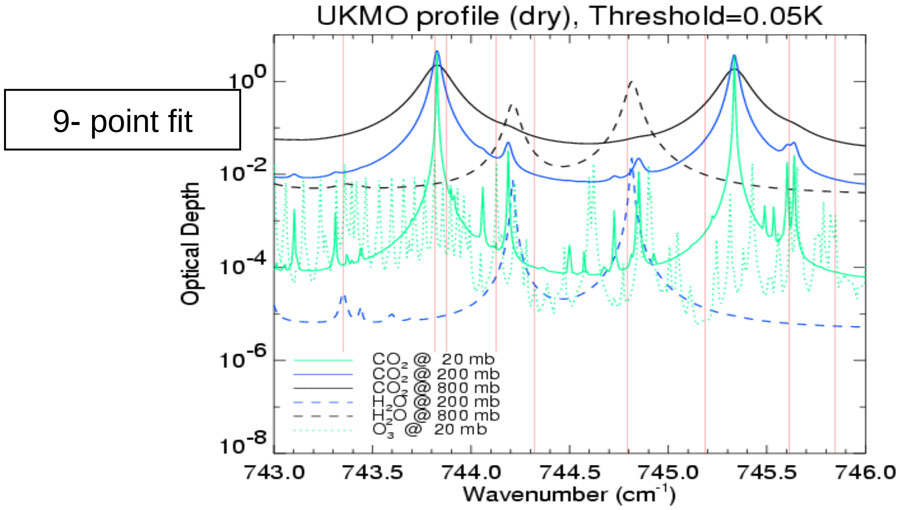
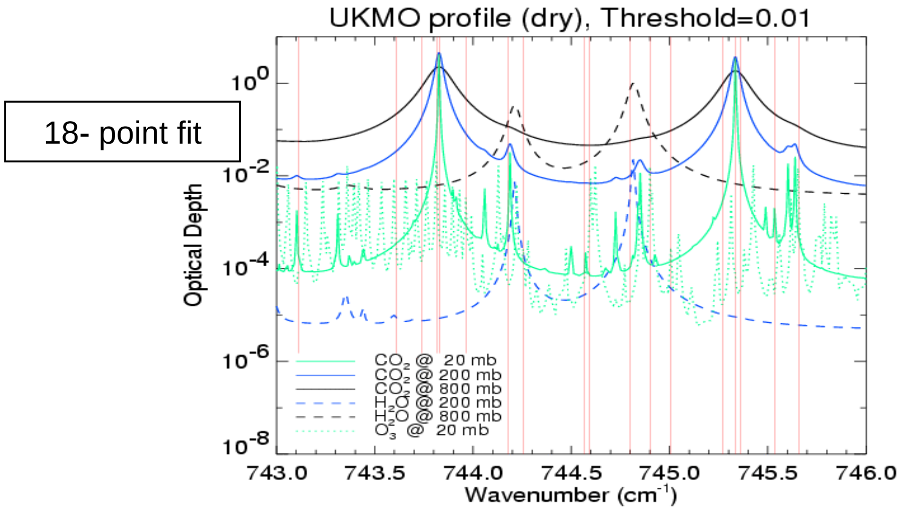
OSS Search Procedure

- Procedure consists of starting with number of nodes *N*=1 and searching for the spectral location ν_1 that produces the smallest error among the *M* possible locations
- *N* is then incremented by one and search for ν_N proceed in the same fashion
- Procedure stop when prescribed error tolerance for training set is reached
- For each trial combination, weights are obtained by linear regression
- Details of search method are provided in companion poster





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Radiance training

- For infrared remote sensing, fit is done in radiances (or brightness temperatures), which naturally emphasizes levels near the peak of channel weighting function

$$\varepsilon_N = \left[\sum_s \left(r^s - \sum_{i=1}^{N} w_i r_{\nu_i}^s \right)^2 \right]^{\frac{1}{2}}$$

- Radiance training takes into account functions that vary slowly across channel passband (Planck function, surface emissivity/reflectivity,…etc)

- Set of training scenes includes appropriate variability
  - Viewing angle
  - Surface emissivity and reflectivity
  - Observer altitude
  - Solar angles

- Stratification (in viewing angle, surface emissivity,…etc) may be used to ensure uniform level of accuracy (threshold *rms*) across the range of conditions

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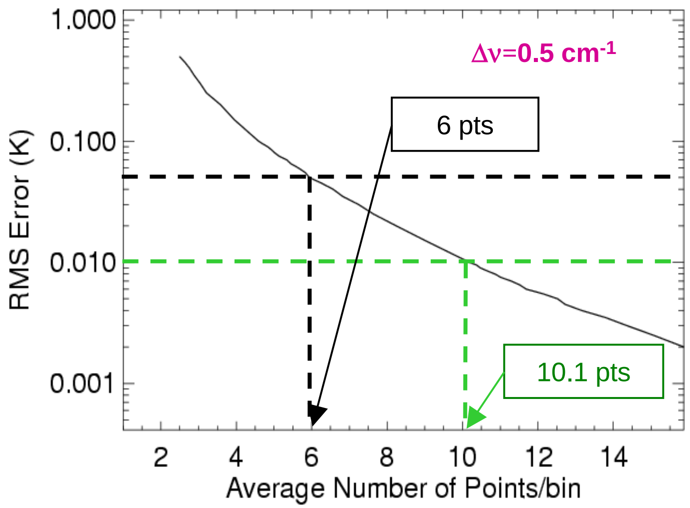
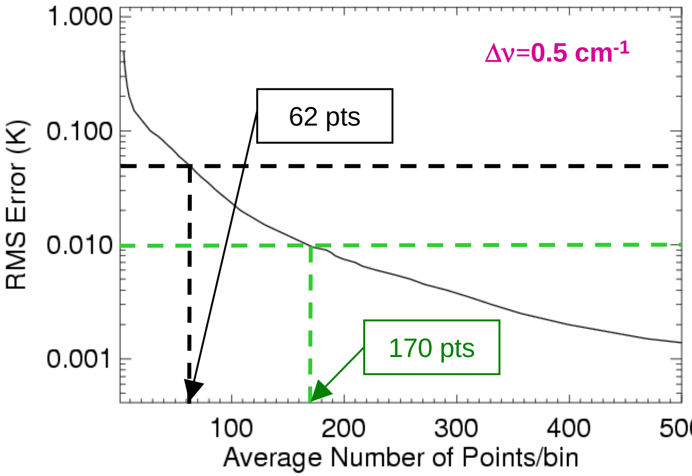
OSS vs. Frequency (or Radiance) Sampling Method

- **Comparison of number of points used by OSS and RSM provide some quantitative assessment of ability of OSS approach to exploit spectral redundancies**
- **RSM treats radiance as random variable and relies on fact that estimates of mean improves as number of samples increases (no weighting)**
- **For a same level of accuracy, reduction in number of samples with OSS, in 700-750 cm^{-1} region, is greater than 90% (in this example line-by-line calculations are sampled on 10^{-4} cm^{-1} grid, i.e. 5000 pts per bin)**





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OSS Radiative Transfer Model (1)

- Radiative transfer is performed monochromatically (one node at a time) from pre-computed absorption coefficients for the fixed and variables constituents

$$R \cong \sum_{l=1}^{N} \left(\mathrm{T}_{l-1}^{\uparrow} - \mathrm{T}_{l}^{\uparrow} \right) B(\Theta_l) + \varepsilon_s \mathrm{T}_N B_s + (1-\varepsilon_s)\mathrm{T}_N \sum_{l=1}^{N} \left(\mathrm{T}_{l}^{\downarrow} - \mathrm{T}_{l-1}^{\downarrow} \right) B(\Theta_l)$$

- Planck function and surface emissivity are evaluated at the precise “node” spectral location (as opposed to using effective values for the channel)
- Several channels may share the same node: computed radiance is added (after appropriate weighting is applied) to partial results for the channels that use that node

- Number of variable molecules varies from node to node
- Molecules currently included are: H_2O, CO_2,O_3, N_2O, CO, CH_4
- Grouping between fixed and variable gases is decided at run time

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OSS Radiative Transfer Model (2)

- **Total monochromatic optical depth for a layer**

$$\tau = \tau_{fix} + \tau_w + \sum_{m=2}^{N\text{var}} \tau_m$$

- **Fixed gases optical depth**

$$\tau_{fix} = k_{fix} u_{dry} = k_{fix}\left(\frac{\Delta P}{g} - u_w\right)$$

where k_{fix} is the effective absorption coefficient for the fixed gases mixture

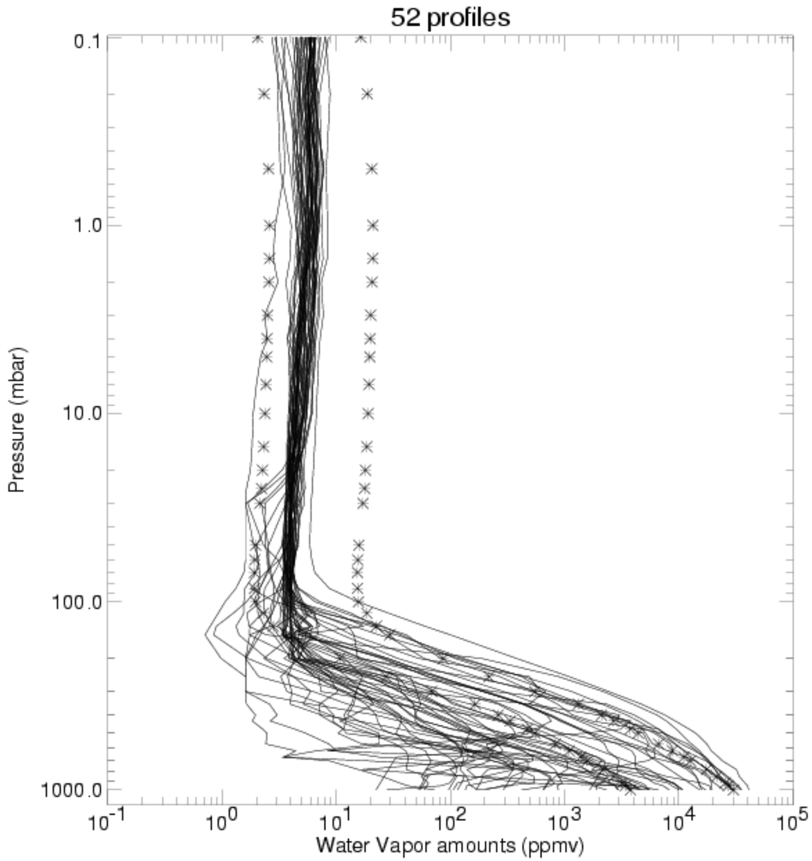
- **Dry variable gases**

$$\tau_m = k_m u_m$$

- **Water vapor self-broadening effect handled by assuming that absorption coefficient depends linearly on specific humidity**

$$\tau_w = \left[k'_w + \bar{q} \times \frac{\partial k_w}{\partial \bar{q}}\right] u_w$$

- **Approximation does not hold in the near wing (non-linear dependence of absorption of line half-width)**

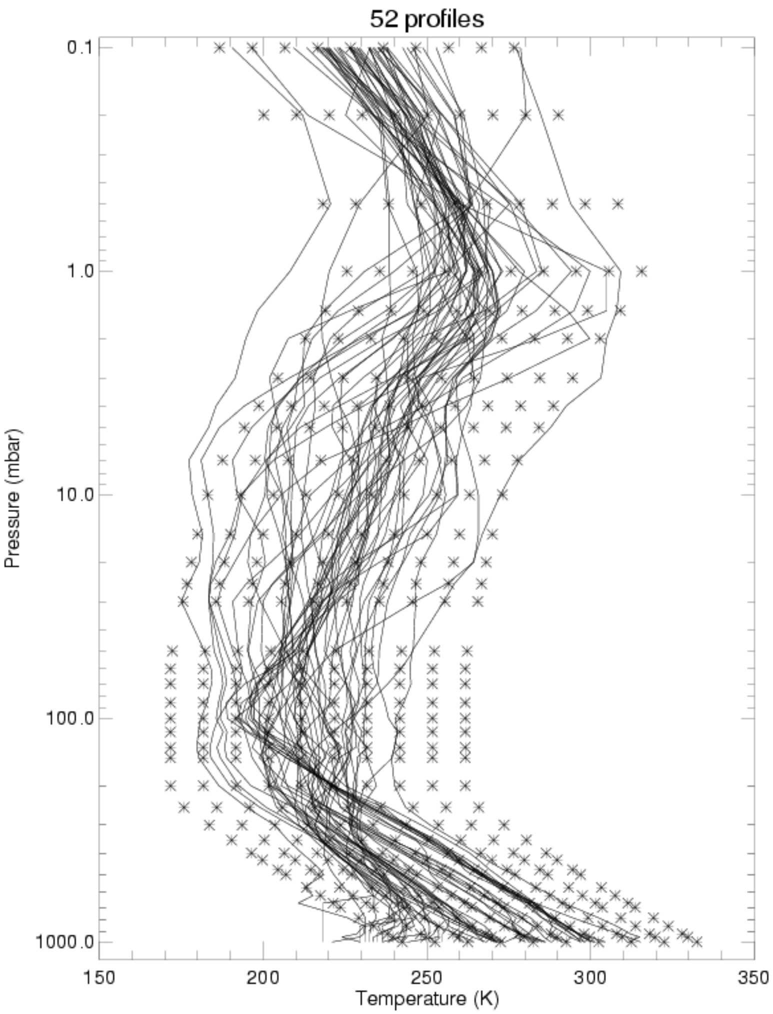


OSS Radiative Transfer Model (3)

- **Absorption coefficients are stored in each layer as a function of temperature**
- **Use quadratic interpolation in temperature**
- **3-points Lagrange interpolation provides continuous 1st derivatives**

$$k(\theta) = \frac{(\theta-\theta_i)(\theta-\theta_{i+1})}{(\theta_{i-1}-\theta_i)(\theta_{i-1}-\theta_{i+1})}\left(k_{i-1}-k_{i+1}\right) + \frac{(\theta-\theta_{i-1})(\theta-\theta_{i+1})}{(\theta_i-\theta_{i-1})(\theta_i-\theta_{i+1})}\left(k_i-k_{i+1}\right)+k_{i+1}$$

Depend only on layer temperature; computed only once prior to performing the RT calculations



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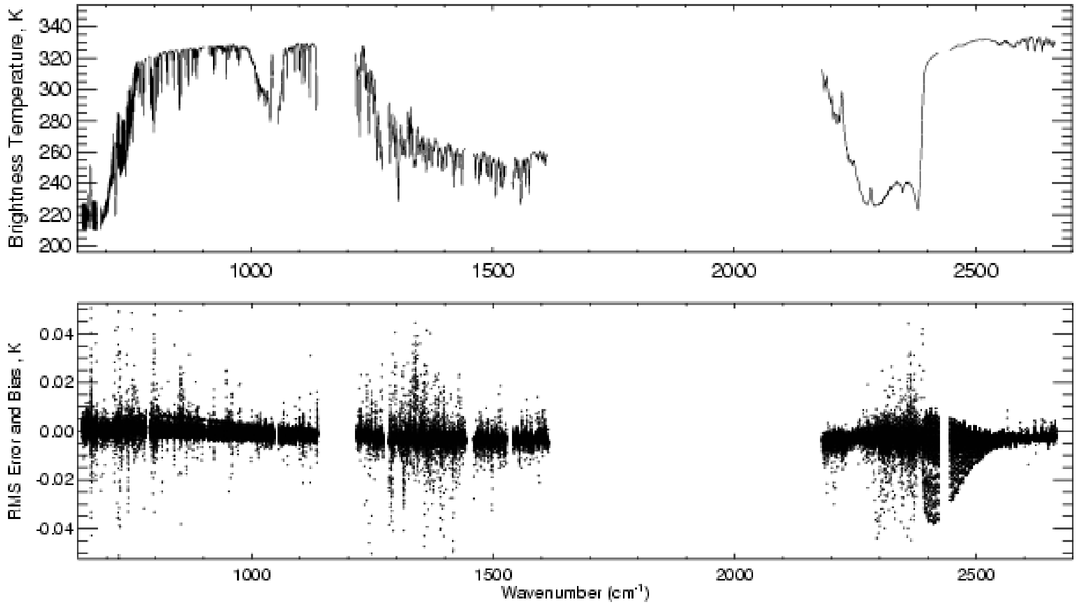
Impact of absorption coefficient errors

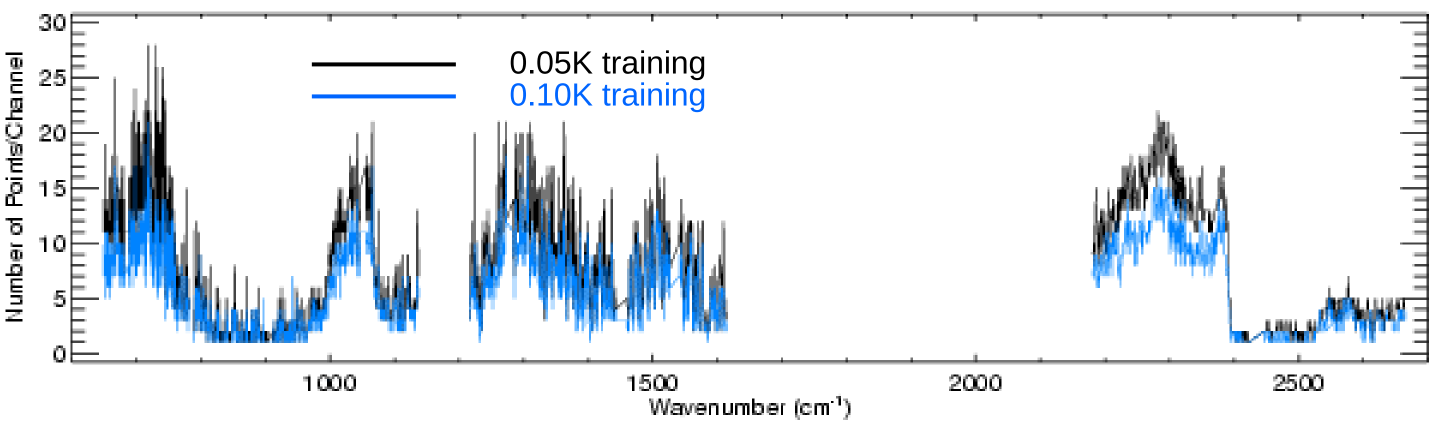
- Impact of errors in treatment of absorption coefficients on computed brightness temperatures is small
- Maximum errors for AIRS reach 0.05 K (*rms* error < ~0.02K)
- Could be reduced further in CO_2 bands and 2400-2500 cm^{-1} region (N_2 continuum) by extending temperature range of the tables (and by reducing temperature step size - no impact on computational efficiency)
- Not a high priority

Example:
AIRS instrument - nadir viewing



AIRS OSS model

- Selection accuracy of 0.05K and 0.1 K in brightness temperature
- EIA: 0 to 60 º
- Random surface emissivity in range 0.9-1.
- Variable H_2O and O_3



- 73-74% of nodes are common to at least two channels
- Average number of points per channel is 2.1 and 1.36 for 0.05K and 0.1K training, respectively

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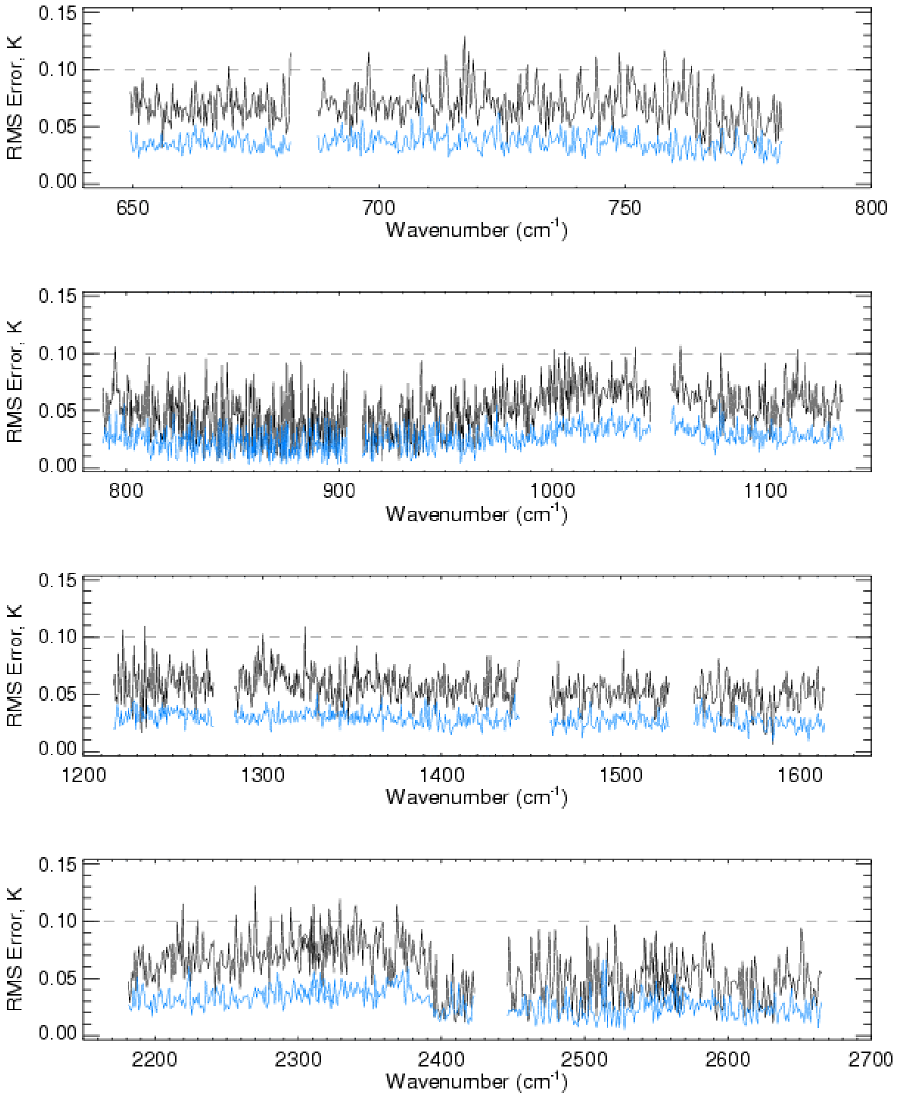
AIRS model accuracy

Validate: 52 diverse ECMWF profile

Errors are due to OSS sampling and optical depth interpolation (no radiative transfer errors)

- Independent set: 52 ECMWF profiles (see Saunders, 2003)
- Nadir viewing angle
- Surface emissivity =0.99
- Same 101-level RT scheme used for both LBLRTM and fast OSS model



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Analytical Jacobians (1)

- With monochromatic RT, analytical Jacobian computation is trivial
- For example, in the case of a non reflective surface computation of Jacobians wrt molecular amounts reduces to

$$\partial R / \partial u_{ml} = D_l \, \partial \tau_l / \partial u_{ml}$$

where

$$D_l = \overline{B}_l \mathrm{T}_l - \Sigma_{l+1}$$

Contribution to TOA radiances of upwelling radiation incident at bottom of layer *l*

is independent of *X* and is derived in the process of merging layers successively (from bottom up) for radiance computation

- Temperature Jacobians:

$$\partial R / \partial \Theta_l = \frac{\partial B_l}{\partial \Theta_l} \left(\mathrm{T}_{l-1} - \mathrm{T}_l \right) + D_l \, \partial \tau_l / \partial \Theta_l$$

Analytical Jacobians (2)

- **Derivative wrt amount for variable molecules**
  - Dry variable gases

$$\frac{\partial \tau_l}{\partial u_{ml}} = k_{ml}(\theta_l)$$

  - Water vapor

$$\frac{\partial \tau\left(\bar{\theta}_l, \bar{q}_l\right)}{\partial u_w} = \frac{\partial \tau_w\left(\bar{\theta}_l, \bar{q}_l\right)}{\partial u_w} + \bar{k}_{fix} \frac{\partial u_{fix}}{\partial u_w} + \sum_{m \in dry} k_m \frac{\partial u_m}{\partial u_w}$$

$$\frac{\partial \tau_w\left(\bar{\theta}_l, \bar{q}_l\right)}{\partial u_w} = k_w\left(\bar{\theta}_l, \bar{q}_l\right) + \frac{\partial k_w}{\partial \bar{q}_l}\left(\bar{\theta}_l\right)\bar{q}_l$$

Dry gas amounts derived from relative concentration with respect to moist air (not mixing ratios)

- **Derivatives of optical depth wrt to temperature**

$$\frac{\partial \tau\left(\bar{\theta}_l, \bar{q}_l\right)}{\partial \bar{\theta}} = \frac{\partial k_w\left(\bar{\theta}_l, \bar{q}_l\right)}{\partial \bar{\theta}} u_w + \frac{\partial k_{fix}\left(\bar{\theta}_l\right)}{\partial \bar{\theta}} u_{fix} + \sum_{m \in dry} \frac{\partial k_m\left(\bar{\theta}_l\right)}{\partial \bar{\theta}} u_m$$

$$\frac{\partial k(\theta)}{\partial \theta} = \frac{(2\theta - \theta_i - \theta_{i+1})}{(\theta_{i-1} - \theta_i)(\theta_{i-1} - \theta_{i+1})}\left(k_{i-1} - k_{i+1}\right) + \frac{(2\theta - \theta_{i-1} - \theta_{i+1})}{(\theta_i - \theta_{i-1})(\theta_i - \theta_{i+1})}\left(k_i - k_{i+1}\right)$$

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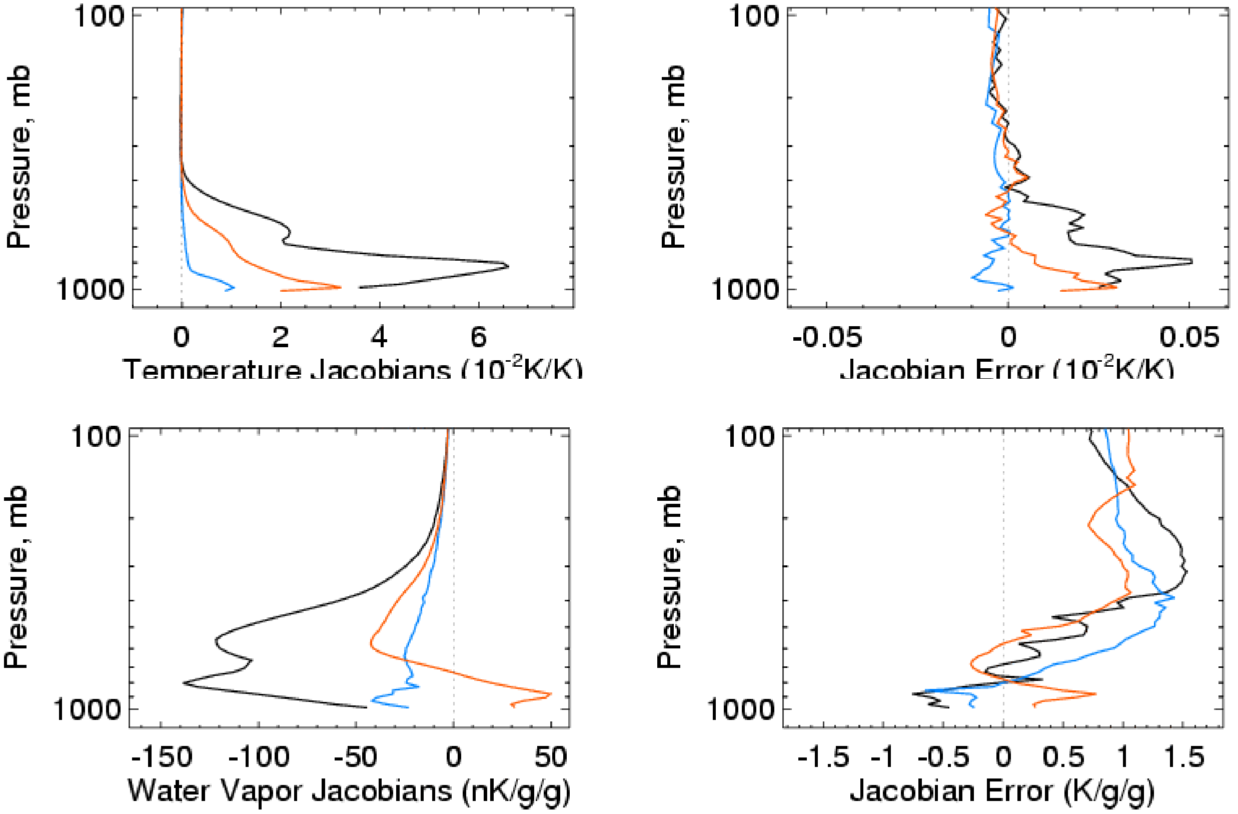
AIRS Jacobians accuracy

- **OSS Jacobians for temperature and water vapor compared to LBLRTM finite difference results**
- **Differences generally within 5 % (profile average) with 0.05 K model, reaching 8% (water vapor and ozone) for a few profiles**



Channel # 453 (793.1 cm^{-1})

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Computational Efficiency

- Number of operation/layer for clear sky transmittance calculations at a single node:
  - 3 multiplications per constituent (6 for water vapor) (see Slide 10 and 11)
  - 1 exponential
- OSS and existing transmittance parameterizations (e.g. OPTRAN, RTTOV or SARTA) should become similar in terms of number of operations when number of nodes approaches ~2.5
- Average number of points per channel for AIRS model is 2.1 and 1.36 with 0.05K and 0.1K threshold
- Adding Jacobians wrt all state vector elements (atmosphere and surface) to radiance computation only doubles execution time (in clear sky)

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Future work

- Tune training for "non-localized" ILS (e.g. weakly apodized interferometer functions or narrowband imagers) for handling spectral variation of emissivity within band pass
- Tune training for clouds (with and w/o scattering in daytime and nighttime)
- Improve handling of variable viewing angles
- Trade improved schemes for treatment of layer emission (e.g. linear-in-tau) against number of levels