ATMOSPHERIC RADIANCE MODELING USING THE
OPTIMAL SPECTRAL SAMPLING (OSS) METHOD

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1. INTRODUCTION

Radiative transfer models are an integral part of the extraction of data from remote sensing instrumentation. To extend beyond ongoing research efforts and be effective in the operational environment a radiative transfer model must have sufficient radiometric accuracy for the problem at hand while also possessing a high degree of computational efficiency. However, computational speed often comes at the expense of overall radiometric accuracy or limitations in the ability to adapt the model to changes in sensor or mission parameters. A further limitation of models designed for operational use is that they tend to be based on the parameterization of atmospheric optical depth. In this case the radiative transfer no longer obeys Beer's law and is not amenable to multiple scattering atmospheres. Also, for many types of parameterization it is inefficient to calculate the radiance Jacobians (the change in radiance with respect to a geophysical quantity) necessary for retrieval calculations, and the overall accuracy depends strongly on the choice of predictors.

In order to address these concerns we have set some criteria that must be met for the development of a robust, computationally efficient model for generic remote sensing applications. Most importantly, the model must be applicable to a wide range of remote sensing problems, with only minor configuration changes: down-looking (satellite sensors), up-looking (ground-based sensors), aircraft or balloon (variable viewing and altitude ranges), limb or line-of-sight measurements, and the inverse adjoint for radiance assimilation algorithms. In order to make the process of multi-sensor data fusion all the more tractable, the ideal model must have consistent physics throughout all spectral ranges, from the microwave through the ultraviolet, and be applicable to both narrow-band and wide-band applications. It will also work equally well in

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scattering and non-scattering atmospheres and be easy to couple with multiple-scattering and/or atmospheric polarization models. Both accuracy and execution speed are important parameters and the ideal model would allow a trade-off depending on the specifics of the problem. Such a trade-off should allow for both highly accurate calculations of total radiance as well as high accuracy for each of the individual layers in the calculation. (Thus the model would be suitable for both "atmospheric correction" and radiance inversion problems). Finally, the algorithm should be capable of calculating the radiance Jacobians (derivative of radiance with respect to geophysical parameters) necessary to perform the radiance inversion, and to consider any number of gases as having fixed or variable (retrievable) amounts. The Optimal Spectral Sampling (OSS) approach meets these criteria and directly addresses the need for highly accurate real-time monochromatic radiative transfer calculations (including the Jacobians) for any class of multispectral, hyperspectral, or ultraspectral sensor (AER, 2001, 2002, 2004; Moncet et al., 2003).

2. DISCUSSION

The exponential sum fitting of transmittances (ESFT) and k-distribution methods of radiative transfer approximate transmittance as a function of layer transmission ($\tau(u)$, where u is the layer absorber amount) over a band as

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

The weights (w) associated with these techniques can be interpreted in terms of the probability distribution of the absorption coefficient (k) over the spectral interval:

$$w_i = \Delta g_i = \int_{k_{i-1}}^{k_i} p(k)dk \tag{2}$$

An extension of this k-distribution method to non-homogeneous atmospheres is based on the observation that minima and maxima of absorption

in different layers are spectrally coincident. The correlated-k method vertically integrates the radiative transfer equation by assuming a correspondence between k's in "g-space" for different layers. This assumption of homogeneity breaks down for a single absorber in the presence of lines of different strengths or non-regularly spaced lines. None of the published methods provide a satisfactory treatment of overlapping absorbers when the relative abundance of individual species changes with altitude.

Proper treatment of overlapping absorbers requires accurate characterization of the multivariate probability distribution of absorption coefficients for all layers and molecules. The high dimensionality of this problem makes it impractical to attempt to solve directly for the k's without appropriate constraints. The solution used by OSS is to reduce the problem to a one-dimensional frequency search and require that the k's correspond to actual values of the absorption coefficient for all molecules and layers at the selected frequencies. Thus with the OSS method, specific frequencies are selected which are directly relevant to the calculation of radiance (U.S. Patent #6,584,405). Further, the use of specific monochromatic spectral elements retains the ability to perform multiple scattering calculations or provide an easy mechanism for parallel processing of the calculation (because the algorithm still obeys Beer's law).

To this end the OSS technology automatically determines the optimal set of wavelengths ("nodes") and weights to completely characterize the radiance reaching a sensor for a specified spectral interval, sensor resolution, and desired radiometric accuracy. The parameter generation starts from a set of uniformly spaced monochromatic transmittances (or radiances) that are computed with a line-by-line (monochromatic) radiative transfer model (such as FASCODE, LBLRTM, or GENLN) using a globally representative ensemble of atmospheres (pressure, temperature and relevant molecular, cloud and aerosol properties), surface conditions and viewing geometries. For example a typical mid-infrared calculation to simulate a cross-track scanning, satellite sounder might use of the order of 50 atmospheric profiles of temperature, water vapor, CO_2, O_3, and CH_4 along with variability in other parameters influencing the radiance, for a total of about 200-250 training scenes. An automated search is made for the smallest subset of nodes and weights for which the error is less

than a prescribed tolerance where the weights are computed by linear regression for each trial combination of frequencies. The error (ε) is defined over the full range of training scenes (s) by the difference between a full monochromatic calculation integrated over the spectral bandpass (R_s) and that of the sum of monochromatic radiances (r_v) at the selected number of nodes (N) with the appropriate weights (w_i):

$$\varepsilon_N = \sum_s \left[R_s - \sum_{i=1}^{N} w_i r_{s,v} \right]^2 . \qquad (3)$$

For the mid-infrared scenario described above, a typical threshold would be 0.05K. This is sufficiently less than the radiometric noise of the sensor, to ensure that algorithm accuracy is not a significant source of error for the radiance inversion, yet large enough to reduce computation time over that of a more accurate calculation.

Radiative transfer accuracy and computation time requirements for the final fast forward model must be considered when selecting the error threshold because the number of selected nodes increases with increasing spectral complexity (i.e. the degree to which spectrally-dependent features from different gases, aerosols, etc., overlap and exhibit rapid change within a given spectral interval) and/or reduced error threshold. The choice of training scenes is an important consideration for spectral variability. Scene stratification ensures model accuracy is maintained for a larger set of conditions while minimizing the total number of selected nodes: a "global" ensemble includes all viewing angles, a wide range of atmospheric profiles, and the full range of surface emissivity values, while stratified selection for a subset of conditions (such as one viewing angle, a small range of solar zenith angles, or a certain type of surface) can be done to minimize errors and the number of nodes. Different scene stratifications will have different weights and (for most cases) a different node selection.

As an example of this fitting, consider the spectrum measured by a nadir-viewing spacecraft sensor (shown in Figure 1). The left panels of the figure show the spectrum as a function of total optical depth (top line) and decomposed by different molecular species at different levels of the atmosphere. The vertical lines give an example of the node locations selected by OSS for a channel encompassing this spectral range. The top panel is for a radiometric brightness temperature threshold of 0.05K, while the bottom

panel is for 0.01K. The right panels show the overall top-of-atmosphere brightness temperature for a calculation in this spectral region. The upper panels are for a lower radiometric threshold and thus require fewer points to minimize the error with the monochromatic calculation.

Tightening the threshold clearly requires additional nodes to be added to account for minor spectral features. Examination of the selected nodes shows that the selection process exploits the information content of the spectrum, selecting only those points that contribute to the total radiance without redundant information. Even when increasing the error threshold from 0.05K to 0.01K the additional selected node points represent additional spectral information, not redundant spectral information. Further, given that a monochromatic calculation in this spectral region represents about 30,000 points, it is clear that the number of selected nodes represents a considerable computational savings over the monochromatic spectral integration.
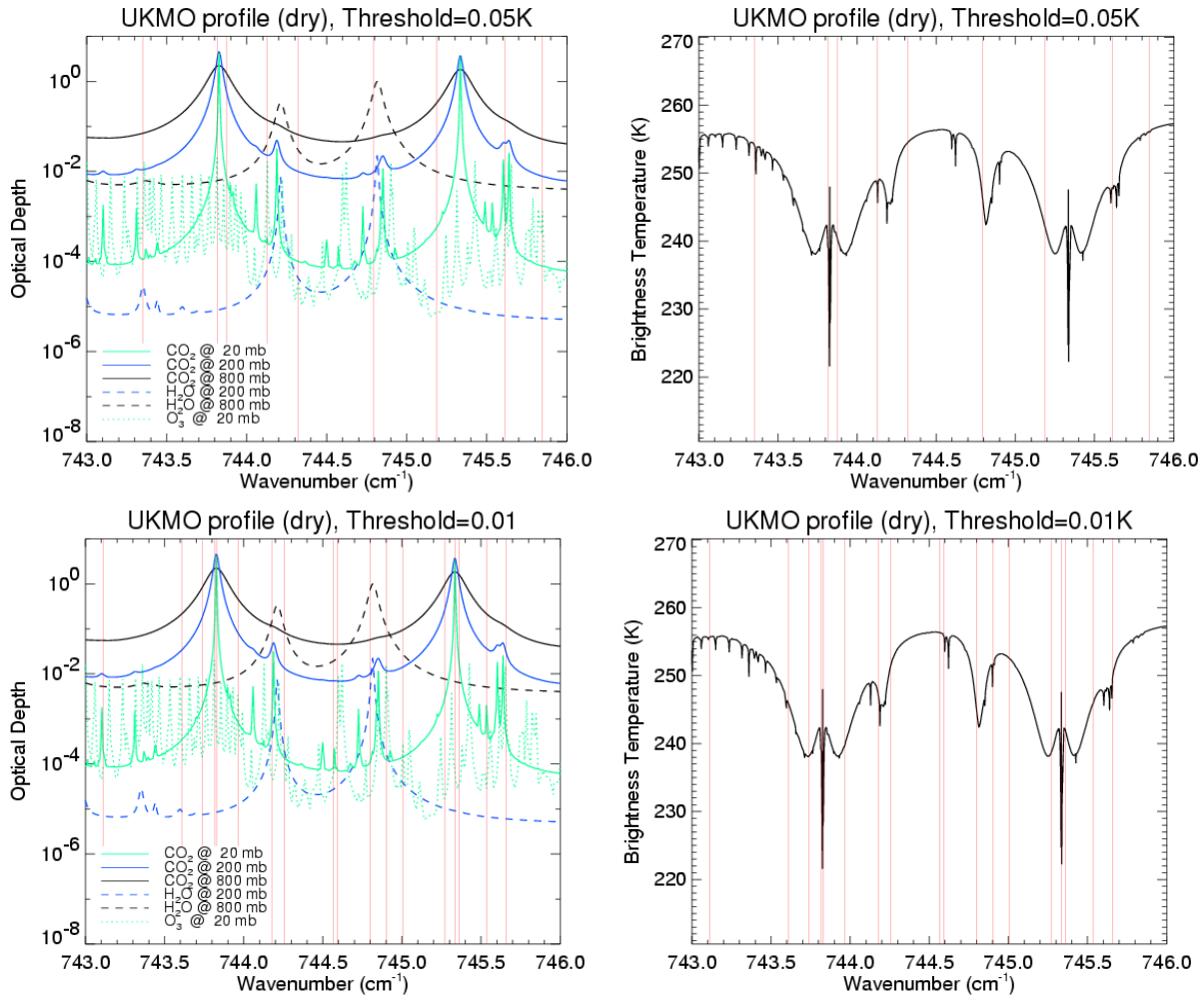

Figure 1: Example of OSS node selection for a region of the mid-infrared spectrum. The left panels indicate the selected nodes relative to the optical depth spectrum, while the panels on the right give selected nodes as a function of total (top-of-atmosphere) brightness temperature. The thin vertical lines represent the locations of selected nodes.

The number of selected nodes depends dynamically on the number of atmospheric constituents, the extent to which their spectral features overlap, and the required training accuracy threshold. These relationships are illustrated in Figure 2. Two key features are evident: (1) where there are overlapping gases, or where a single gas contributes at a wide range of altitudes, more nodes must be selected to achieve the desired accuracy and (2) as the desired threshold decreases, the number of selected nodes will increase, except for regions with minimal spectral complexity. The first aspect is illustrated by comparing the region of CO_2 absorption around 650 cm^{-1} with the CO_2, H_2O, O_3 overlap around 700-750 cm^{-1} and the window region beyond 800 cm^{-1}. The second point is illustrated in Figure 3, which shows a comparison of the number of nodes selected for different spectral regions.
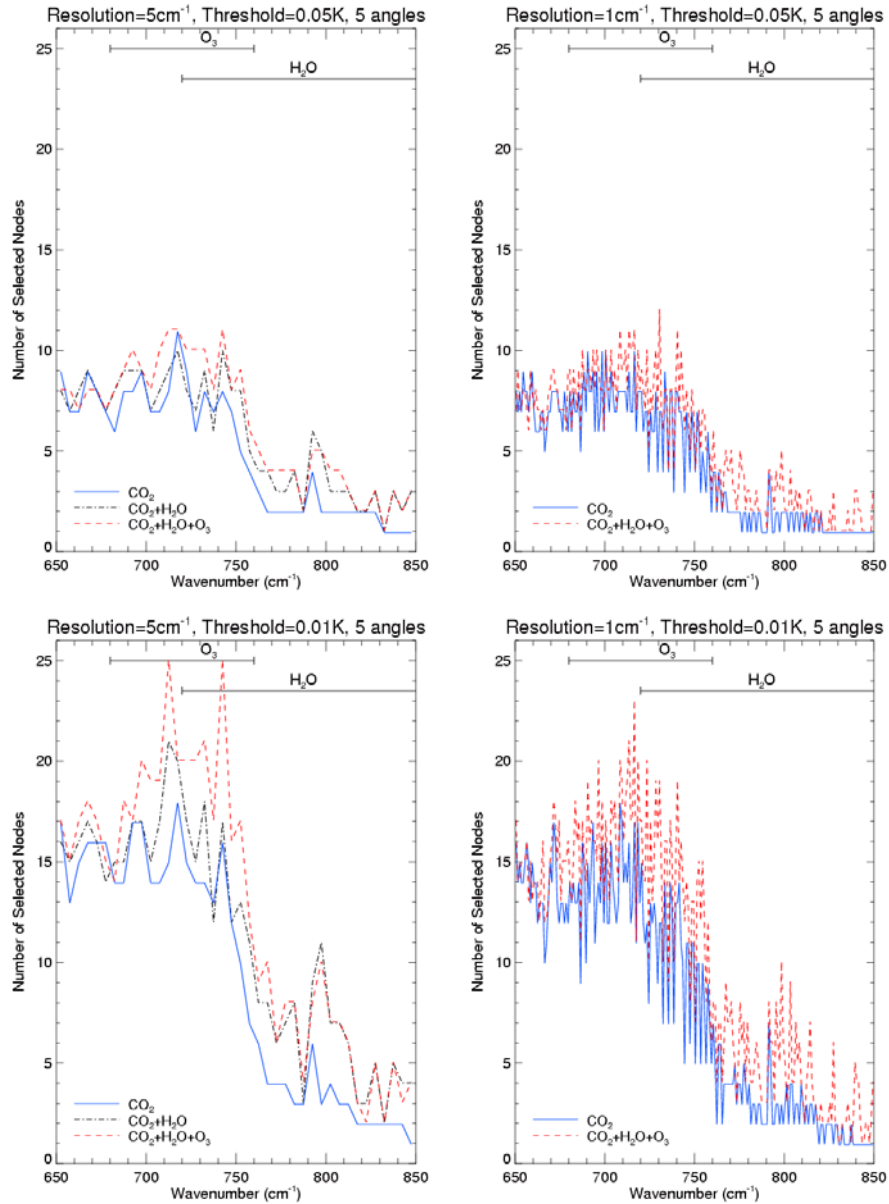

Figure 2: Number of selected nodes as a function of wavenumber for changes in channel resolution (left panels versus right panels) and desired radiometric accuracy (top panels versus bottom panels).
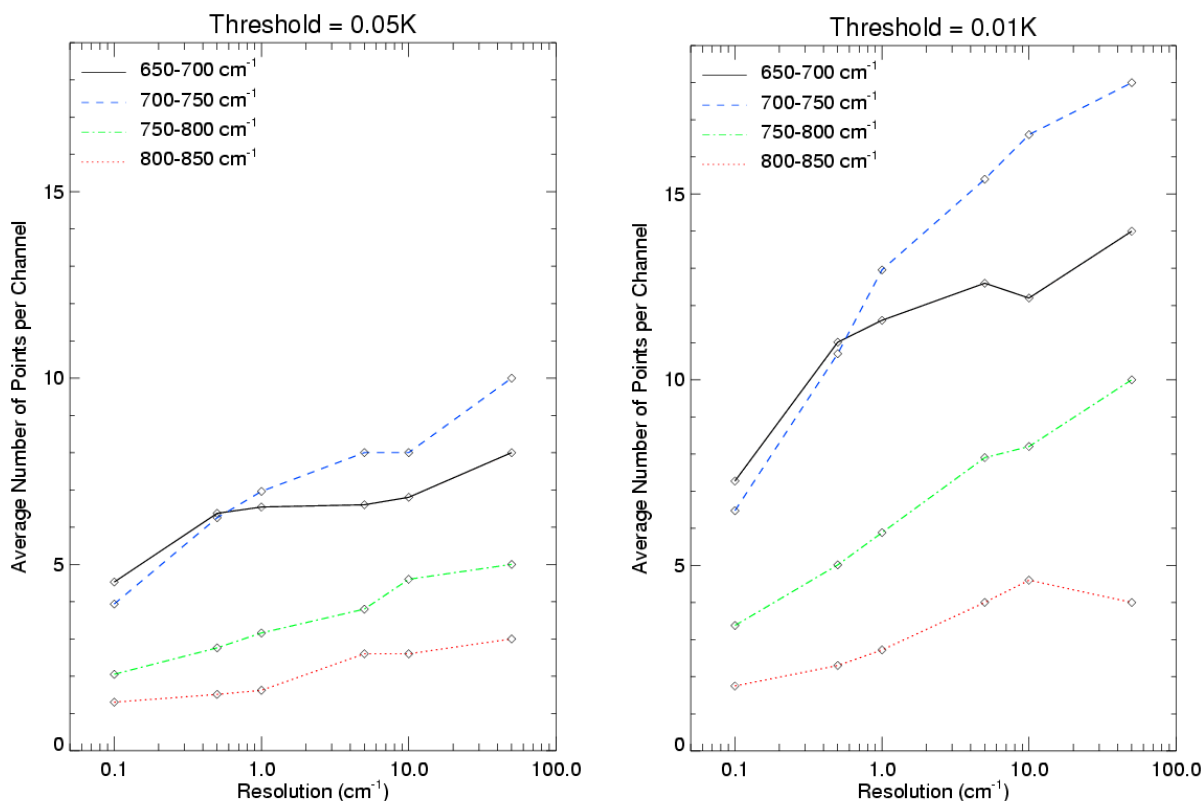
Figure 3: Comparison of the number of points per channel as a function of channel spectral resolution for different spectral ranges. The left panel represents a training threshold of 0.05K while the right panel is for 0.01K.

3. APPLICATION

An OSS-based radiative transfer model has been developed specifically for sensor simulation studies, retrieval algorithm development and the assessment of operational capabilities. This model is the basis for the operational retrieval algorithms selected for the NPOESS CrIMSS and CMIS sensors (AER, 2001, 2002, 2004), and has been applied to a number of other current and future sensors (e.g., AIRS, AMSU, NAST-I, GOES-HES).

For these models the radiative transfer is performed monochromatically from pre-computed absorption coefficients at each selected node. The molecular absorption coefficients are stored for each vertical layer as a function of temperature. For a given profile the tabulated absorption properties are scaled by the actual amount in the layer and linearly interpolated between temperature entries in order to preserve the computational efficiency. Note that water vapor requires special treatment to account for self-broadening effects. Thus the water vapor absorption coefficients must be stored as a function of both temperature and water vapor.

An example of the OSS node selection is given in Figure 4 for the Atmospheric Infrared Sounder (AIRS) flying as part of the EOS-Aqua spacecraft (Aumann et al., 2000; Pagano et al., 2002). The number of points per channel decreases as the training threshold increases. Nonetheless, the actual number of monochromatic calculations required is substantially less than the total number of selected nodes per channel because about 73% of the nodes are common to two or more channels. The average number of unique points per channel is 2.1 for the 0.05K training threshold, and 1.36 for the 0.1K training threshold. Figure 5 shows the resulting errors for the OSS calculation compared to the monochromatic calculation. These errors were computed using a set of 52 profiles that are independent from the profile set used for the node selection.
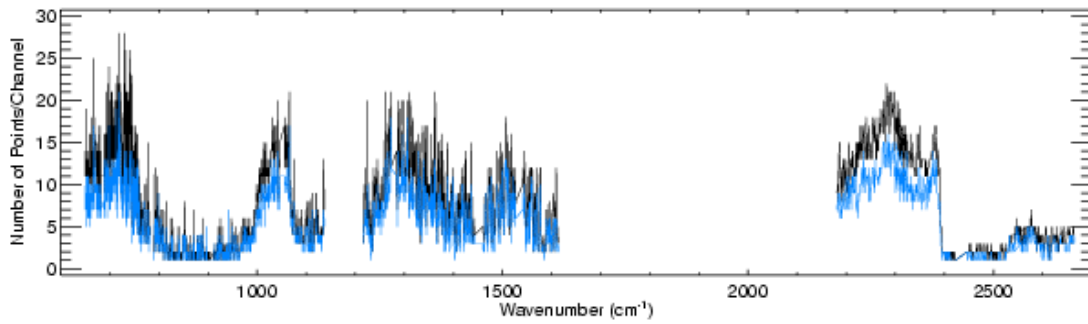
Figure 4: Example of the number of points per channel as a function of wavenumber. The upper (darker) curve corresponds to a 0.05K training threshold while the lower (lighter) curve is for a 0.1K training threshold.
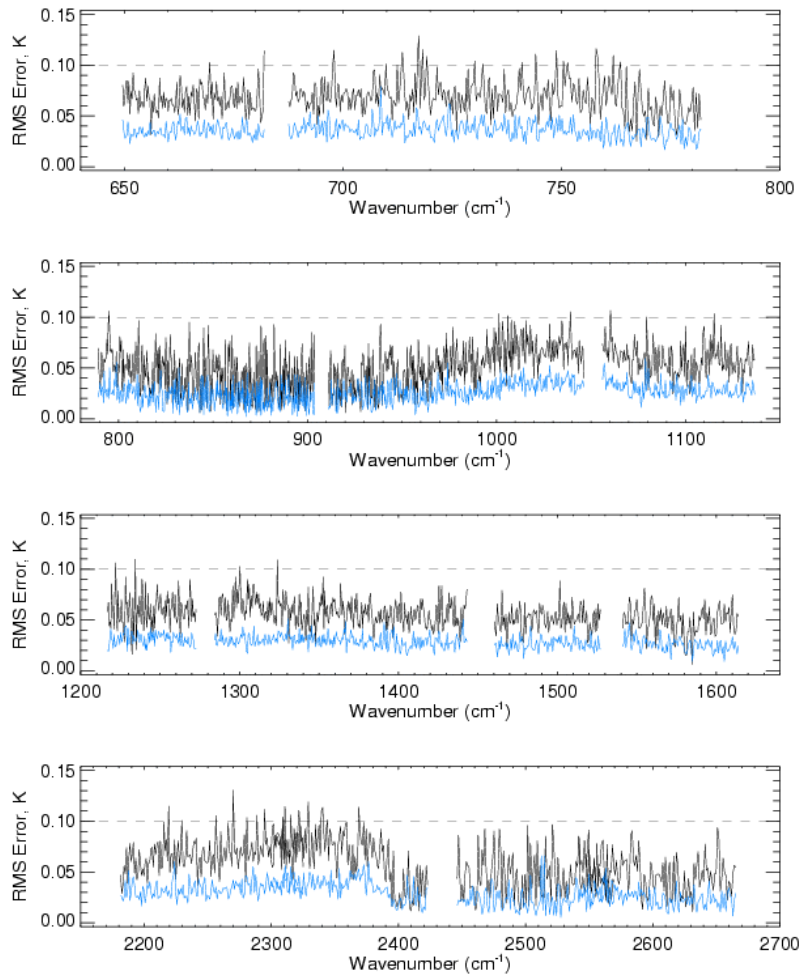

Figure 5: RMS error of the OSS channel radiances compared to those computed monochromatically. The upper curve in each plot corresponds to the training threshold of 0.1K while the lower curve corresponds to a training threshold of 0.05K.

4. CONCLUSION

The OSS technique represents an automated, unsupervised node and weight generation process that can be used to develop a fast radiative transfer model with reasonable constraints on computational speed, accuracy and flexibility. The OSS technique is designed such that no tuning is needed and it is easily adaptable to changes in sensor parameters, mission objectives, variable observer levels or viewing geometry, or to simply update the spectroscopy. Application of OSS-derived nodes and weights allows for monochromatic radiative transfer calculations and accurate treatment of surface reflection. Because the radiative transfer is performed monochromatically it is amenable to thermal and solar multiple scattering applications. The overall radiometric accuracy can be traded for computational speed depending on factors such as the signal-to-noise level of the measurement and the computational requirements of the problem. An OSS-based radiative transfer model has been applied to a number of remote sensing problems and is the basis for the operational geophysical parameter retrieval algorithms used by the NPOESS CrIMSS and CMIS sensors.

5. ACKNOWLEDGEMENTS

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