USING PSEUDO-MONOCHROMATIC RADIANCE FOR THE RETRIEVAL OF ATMOSPHERIC TEMPERATURE AND MOISTURE PROFILES

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1. ABSTRACT

This study provides a new approach for processing hyper-spectral radiance data. It uses a transformation matrix to convert an instrument radiance spectrum into a pseudo-monochromatic radiance spectrum. One common approximation in the atmospheric profile remote sensing field is to approximate instrument channel radiances through spectral convolution of the monochromatic radiative transfer equation (RTE). When determining the atmospheric parameters from the observed radiance spectrum, a retrieval algorithm is used. The retrieval algorithm is based on the inversion of the RTE. A fast forward radiative transfer model (RTM) is generally used to calculate instrument channel radiance when applying a retrieval algorithm for determining atmospheric profiles. One of the difficulties involved in developing a fast RTM for instrument channel radiance is that Beer's law is not valid for instrument channel radiance, only for monochromatic radiation. The new approach described in this paper uses a monochromatic radiance spectrum for retrieval so that Beer's law can be employed. The pseudo-monochromatic radiance spectrum is produced by an empirical transform of the instrument channel spectrum to a monochromatic equivalent spectrum (i.e., a pseudo-monochromatic spectrum). Eigenvector regression is used to produce the empirical transformation. Although the transformation does not produce the monochromatic radiance spectrum without error, it is shown that this transformation error in the radiance spectrum is generally well below nominal instrumental noise levels for most spectral channels. The reduction in instrument noise results from the noise filtering effect of the eigenvector transformation. Another major advantage of this approach is that it eliminates the need to build different fast radiative transfer models for different observing instruments, since the retrieval of geophysical parameters is based on the inversion of the monochromatic radiative transfer model. Although a different transformation matrix is required for different instrument spectral channel characteristics, the production of this transformation matrix is straightforward and much simpler than the production of an accurate channel radiance fast forward model. Simulation studies show that the accuracies of the atmospheric temperature and moisture profiles retrieved from monochromatic radiance spectra are better than the accuracy of profiles retrieved from typical hyper-spectral instrument channel radiance spectra.

2. INTRODUCTION

For improving the accuracy of a numerical weather prediction, accurate global observations of atmospheric temperature and moisture profiles are needed. Satellite and airborne hyper-spectral infrared sounders, with spectral resolving power greater than 1200, provide the capability needed to achieve this goal. At least two factors are required for obtaining accurate atmospheric temperature and moisture profiles from hyper-spectral observations. One is the accuracy and precision of the sounding spectrometer instrument. Another is the accuracy of the retrieval algorithm and the numerical approach used to process the data. Many studies have shown that reducing the instrument noise and increasing the spectral resolution will increase the quality of the retrieved atmospheric profiles. A new generation of infrared sounders provides much higher spectral resolution with relatively low noise levels as a result of new technology development. However, the remote sounding spectrometer will always have a finite spectral resolution and measurement noise. A compensatory way to filter instrument noise and approximate 'infinite' spectral resolution is to perform an empirical transformation of the observed spectrum to a monochromatic radiance spectrum (i.e., a pseudo-monochromatic measurement spectrum). This empirical transformation will enable the rapid extraction of atmospheric profile information using a monochromatic forward radiative transfer model. Retrieval and/or radiance assimilation algorithms must be fast enough to meet operational time constraints, particularly the cut-off times for the ingestion of the radiance information into Numerical Weather Prediction (NWP) models.

Retrieval of atmospheric parameters, like temperature and water vapor profiles, from an infrared sounder data is based on the atmospheric radiative transfer equation (RTE).

$$R_\upsilon(\eta) = \varepsilon(\eta)\, B_\upsilon(T_s)\, \tau_\upsilon(\eta,0,p_s) - \int_0^{p_s} B_\upsilon(T(p))\, (\partial\tau_\upsilon(\eta,0,p)/\partial p)\, dp + (1-\varepsilon_\upsilon(\eta))\tau_\upsilon(\eta,0,p_s) \int_{p_s}^{0} B_\upsilon(T(p))\, (\partial\tau_\upsilon(\eta,p_s,p)/\partial p)\, dp + \rho_\upsilon(\eta,\theta)\, \tau_\upsilon(\eta,0,p_s)\, \tau_\upsilon(\theta,p_s,0)\, F_\upsilon \cos\theta . \quad (1)$$

In the above RTE, R_υ is radiance observed from the satellite or airborne instrument at wavenumber υ (cm^{-1}). ε_υ represents the earth surface emissivity at $\tilde{\upsilon}$. $B_\upsilon(T)$ is the Planck function at absolute temperature T (in Kelvins). T_s is earth surface skin temperature. $\tau_\upsilon(\eta,p',p)$ describes transmittance along the observation view angle (η), of the atmosphere between the pressure level p' and the pressure level p, and p_s indicates earth surface pressure. F_υ is the solar irradiance. $\rho_\upsilon(\eta,\theta)$ and $\tau_\upsilon(\theta, p_s,0)$ are the solar bi-directional surface reflectance and the transmittance of the atmosphere respectively, along the solar zenith angle θ. The atmospheric monochromatic transmittance $\tau_\upsilon(\eta,p',p)$ is defined as

$$\tau_\upsilon(\eta,p',p) = \exp(-1/g \int_{p'}^{p} (\sum_i k_i(p,T)\, q_i(p))\, \sec(\eta)\, dp), \quad (2)$$

where $k_i(p,T)$ is the absorption coefficient for absorber type i with absorber mixing ratio q_i. g is gravitational acceleration, and k_i varies with temperature and pressure. The atmospheric absorber, i, can be water vapor, ozone, carbon dioxide, etc. A relationship between radiance observed and the corresponding earth atmospheric temperature and any absorber profile can be established from equations (1) and (2). Given the atmospheric temperature and absorber mixing ratio at every pressure level p, with the surface temperature and emissivity/reflectivity properties, the monochromatic radiance can be calculated based on equations (1) and (2). Spectral convolution of the monochromatic radiance spectrum using the instrument spectral response function produces an estimate of the observed radiance spectrum. This is called the forward problem, and it is well defined. Retrieval of atmospheric parameters from the observed radiance spectrum is called the inverse problem. The inverse problem is ill-conditioned in the sense that many solutions can be obtained from one set of radiance observations containing a relatively small noise level. Statistical relationships between the atmospheric parameters and the spectral radiance measurements are commonly produced through radiative transfer simulation to provide a statistical constraint for obtaining an acceptable solution.

3. MONOCHROMATIC RADIANCE VS. CHANNEL RADIANCE

Equations (1) and (2) are strictly valid for monochromatic radiance for which Beer's law holds. However, equation (1) is commonly used to interpret radiance observations by defining a spectral channel atmospheric transmittance function, which provides close agreement between the calculation and observation. Monochromatic radiance cannot be directly observed with a practical instrument, which has a finite spectral resolution, even though the atmospheric species emit (or absorb) radiance monochromatically. Most absorption lines in the infrared region are from molecule vibration energy level transitions. These monochromatic lines have been broadened in the atmosphere by molecular collisions, the number of which depends on atmospheric temperature and pressure. Monochromatic radiative transfer models use analytical formulae to simulate absorption line shape variation with temperature and pressure. More than 35 species with over 1,700,000 spectral lines have been measured for applications to the earth's atmosphere. Simulation of all monochromatic lines is very time consuming, especially since one must account for all the different absorption lines that can affect any given frequency as a result of pressure broadening.

The monochromatic RTE is a very accurate model. However, any instrument observed radiance has a finite spectral resolution such that the observed radiance is channel radiance rather than a monochromatic radiance. Channel radiance is a spectral convolution of the atmospheric monochromatic radiance with an instrument line shape (ILS), or spectral response function, φ. Thus,

$$R_c(\nu') = \frac{\int_{\Delta\nu} \varphi(\nu) R^{mono}(\nu) d\nu}{\int_{\Delta\nu} \varphi(\nu) d\nu} \qquad (3)$$

where ν' is the central wavenumber of the channel radiance. For small Δν

$$\tau_c(\nu') \sim \frac{\int_{\Delta\nu} \varphi(\nu) \tau^{mono}(\nu) d\nu}{\int_{\Delta\nu} \varphi(\nu) d\nu} \qquad 4)$$

Many different channel radiance RTMs have been developed based on the monochromatic RTM. A recent detailed summary of channel RTMs has been provided by Xu Liu (2006). All channel RTMs employ some mathematical technique to speed up the radiance calculation to satisfy operational application time constraints.

4. MONOCHROMATIC RETRIEVAL APPROACH

This paper provides a new approach to the retrieval of atmospheric temperature and moisture profiles from satellite and/or airborne hyper-spectral infrared sounder observations. Observed spectra of channel radiance are based on the known instrument ILS characteristics. The transformation function is derived from simulated monochromatic radiance and corresponding instrument channel radiance simulated from a large global sample of atmospheric profiles for representative surface and cloud conditions. The data base used here to demonstrate the methodology is for cloud-free atmospheric conditions and consists of more than 2000 radiosonde measurements. Line by line (LBL) monochromatic radiance is calculated by LBLRTM. Channel radiances are simulated using these monochromatic radiances with an appropriate ILS function. The following steps apply to the transformation matrix determination.

a) Calculate noise-free monochromatic radiance spectra.

b) Use a particular instrument ILS function to convolve LBL radiance into channel radiance, without instrument noise.

c) Reduce the number of monochromatic frequencies by selecting representative monochromatic radiances.

d) Perform eigenvector analysis of the error free monochromatic radiance to extract the independent pieces of information (i.e., the eigenvector amplitudes) contained in monochromatic radiance spectra.

e) Perform eigenvector analysis of the error free instrument channel radiance in order to extract most significant independent pieces of information (i.e., the eigenvector amplitudes) contained in channel radiance spectra.

f) Determine the minimum number of eigenvectors required to fit the channel radiance spectra to within the instrumental noise level.

g) Use multiple-linear regression algorithm to compute a regression matrix, which can be used to predict the monochromatic radiance eigenvector amplitudes from the instrument channel radiance eigenvector amplitudes. The regression coefficient matrix is used to transform instrument channel radiance measurement spectra into pseudo-monochromatic radiance spectra for the profile retrieval or radiance assimilation process.

Once the regression transformation matrix is determined, one can apply it to any observed channel radiance spectra to obtain pseudo-monochromatic radiance spectra for the instrument considered. The transformation matrix and associated eigenvector representation serve two purposes; (1) to convert channel radiance into pseudo-monochromatic radiance, and (2) to filter instrument noise. Therefore, using theoretical simulations of monochromatic and instrument channel radiances to generate the transformation matrix, measurement spectral resolution can be enhanced and instrument random noise can be reduced. One major advantage of this approach is that a common monochromatic RTM can be used for different instruments since the observed radiance spectrum can be transformed to monochromatic radiance on a common spectral scale.

Channel Radiance Approach: Fig.(1) gives one of the current approaches for the retrieval of atmospheric profiles. Offline work focuses on building a fast radiative transfer model for the computation of channel radiance for a particular instrument. The fast RTM is used in a retrieval algorithm to evaluate the difference between observed channel radiance and that simulated from a guess profile. The left side of this diagram is offline work. The instrument channel radiance RTM is based on regression training with atmospheric parameters, the results used to in either a large Table for each atmospheric species or forward model parameter files containing regression coefficients. These lookup tables or forward model parameter files are the core part of a fast RTM used in retrieval algorithms.

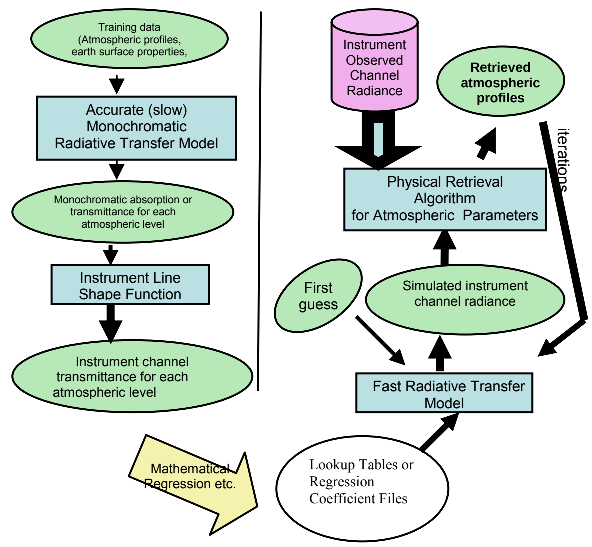

Fig.(1) One popular concept for developing an instrument channel RTM used in atmospheric profile retrieval.

Monochromatic Radiance Approach: Figures (2) and (3) display the flow charts for the monochromatic approach for the retrieval of atmospheric profiles from observed radiance spectra. Fig.(2) is the diagram for derivation of transformation matrix between channel radiance and monochromatic radiance. This is offline work, which only needs to be performed once for a given instrument ILS. Fig.(3) presents the monochromatic approach for the retrieval of atmospheric profiles.

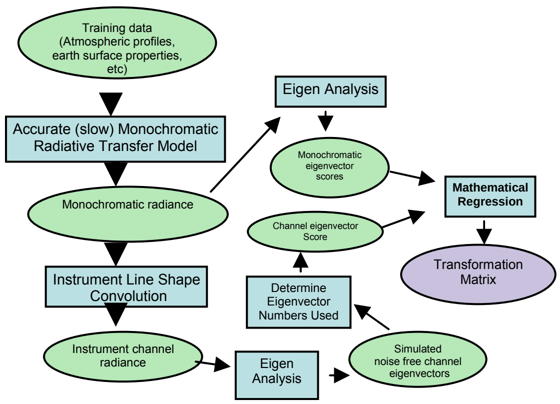

Fig.(2) Derivation of the monochromatic transformation matrix from accurately simulated radiance data.

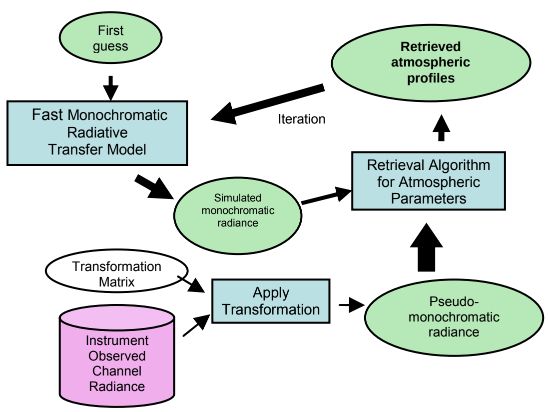

Fig.(3) Application of transformation matrix and fast monochromatic RTM in retrieval algorithm.

5. PRELIMINARY RESULTS

The regression retrieval algorithm is used for initial testing of this new approach. Here we present the accuracies of the atmospheric temperature and moisture profiles retrieved from channel radiances for different instrument spectral resolutions including using the pseudo-monochromatic radiance derived from the instrument channel radiances. Also, shown is the comparison between the pseudo-monochromatic radiance and the true monochromatic radiance. The pseudo-monochromatic radiance is derived using the regression transformation matrix and the true monochromatic radiance is provided by LBLRTM.

5.1 Influence of Spectral Resolution

The radiance along an absorption line of any species has a magnitude dependent upon the spectral position relative to line center, the line strength and the pressure and temperature of the molecule. Radiances from strong absorption line centers arise from the upper atmosphere whereas radiances from the far wing of an absorption line, or near the center of weak absorption lines, arise from the lower atmosphere. The line structure of the radiance, and consequently the vertical resolution of the measurement, will be smeared as a result of low instrument spectral resolution. Fig.(4) and Fig.(5) exhibit the RMS errors of temperature and moisture profiles for different instrument spectral resolutions. A typical spectral resolution and coverage are assumed to be the nominal instrument measurement condition. The noise is the same for all cases with 0.2K NEDT at 250K across whole spectral region from 650-2550 cm^{-1}. As can be seen, the error in the retrieval becomes smaller when observing at a higher spectral resolution, despite the fact that most new infrared sounders already employ a spectral resolution able to resolve the spacing in-between individual absorption lines. The RMS error of the lowest layer temperature retrieval is reduced from 1.13K for the nominal instrumental observing condition to 1.01K, for the monochromatic measurement condition. This is an improvement of about 10%. The error of moisture profile is given in percentage of relative humidity. The RMS error has been improved from 10.0 to 8.7 going from a typical instrument spectral resolution to the monochromatic radiance resolution near the earth's surface. Minimizing the smearing of spectral structure optimizes the atmospheric vertical resolution, thereby yielding more accurate profile results.

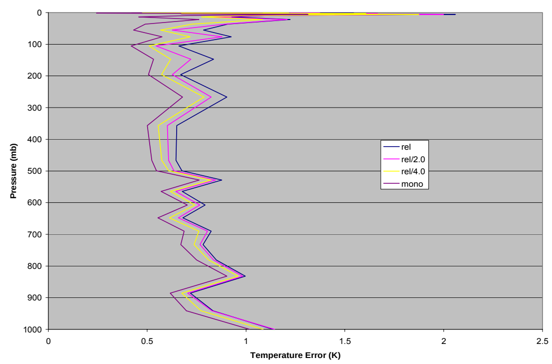

Fig. (4) Retrieval temperature RMS errors from radiance simulated at different spectral resolutions. The curve labeled Rel corresponds to a nominal instrument spectral resolution, whereas rel/2 and rel/4 refer to results obtained for two times and four times higher than nominal spectral resolution. Mono indicates the result from simulated monochromatic radiance at the central channel wavenumber.

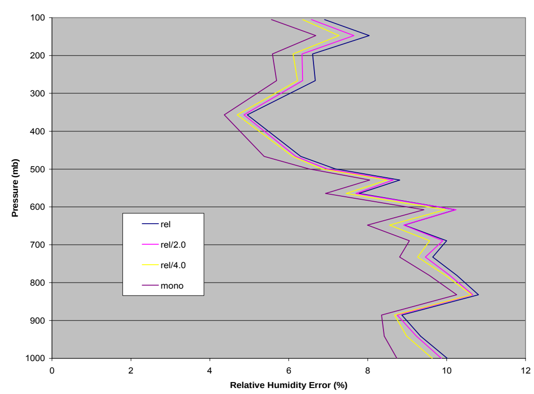

Fig. (5) Retrieval moisture RMS errors from different spectral resolutions. Labels have same meaning as Fig. (4).

5.2 Pseudo-Monochromatic Radiance

Pseudo-monochromatic radiance can be derived from instrument channel radiance using an empirically determined transformation matrix. The transformation matrix is derived from simulated channel radiance and monochromatic radiance at central channel wavenumber from LBLRTM for over 2000 atmospheric profiles. Eigenvector analysis is performed on channel radiance R_c and monochromatic radiance R_υ so that

$$R_c = E_c C_c \quad (5)$$

$$R_\upsilon = E_\upsilon C_\upsilon \quad (6)$$

Here E_c and E_υ are eigenvectors for channel and monochromatic radiance, respectively. C_c is a matrix of eigenvector amplitudes for channel radiance and C_υ is a matrix of eigenvector amplitudes for monochromatic radiances. In general, eigenvectors capture the spectral variation of radiances. The spectral structures are dependent on the number of eigenvectors resolved above the instrument noise level. Once the eigenvectors have been calculated, they remain fixed for a given instrument. Generally, it only takes one to two hundred eigenvectors, determined from a global sample of atmospheric conditions, to re-construct any particular measured radiance spectrum with very good accuracy. The eigenvector amplitudes account for the dependence of the measured radiance spectrum on the particular atmospheric and surface properties being observed. In equations (5) and (6) above, R_c and R_υ are simulated from the same atmospheric profiles. Thus, the same atmospheric and surface state information are contained in C_c and C_υ. C_υ can be specified from C_c using a transformation matrix;

$$C_\upsilon = B\, C_c \quad (7)$$

The transformation matrix B can be generated using multiple-linear regression; that is

$$B = C_\upsilon C_c^T (C_c C_c^T)^{-1} \quad (8)$$

Once B is generated, any monochromatic radiance spectrum can be derived using equations (7) and (6). Since the monochromatic radiance is not directly observed, there is an error associated with its estimation. However, this error of estimation is believed to be smaller than the errors associated with fast forward models, such that this procedure greatly simplifies the procedure for the retrieval of atmospheric profiles from instrument channel radiance spectra. There is no longer a need to develop a fast forward model for different sounding spectrometer instruments since the same monochromatic radiative transfer model can be used for all instruments. A different transformation matrix must be estimated for each instrument, but this is a far simpler determination process than that required for accurate fast forward model development.

The transformation matrix will contain the statistical characteristics of the training data set. Consequently, the more representative the training samples, the more accurate the estimation process will be for a given number of eigenvectors. For the application to be shown here, diverse global samples of clear sky atmospheric and surface conditions are assumed. It is recognized that in any practical application the statistical training data set must include a wide range of realistic cloud conditions as well. Cloudy cases will be included in the future applications of the pseudo-monochromatic radiance profile retrieval technique provided here.

Fig.(6) is the RMS error of pseudo-monochromatic radiance, produced from a typical hyper-spectral instrument channel radiance spectra, using the regression transformation determination method discussed above. The error is shown in terms of brightness temperature (BT) error. The instrument noise level is 0.2K. The error is smaller than this instrument noise for 90% of the spectral channels with the largest errors occurring near the center of 4.3 μm, 15 μm of CO_2 bands and 9.6 μm O_3 band.

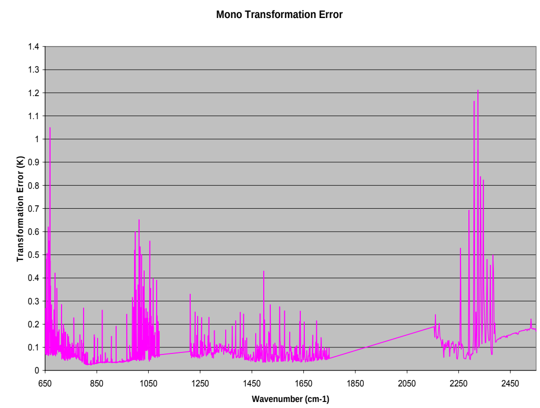

Fig. (6) RMS error of pseudo-monochromatic radiance transformation in BT units. An error of 0.2K denotes an error equal to the instrument noise.

5.3 Retrieval from pseudo-monochromatic radiance

The errors of the retrieved atmospheric temperature and moisture profiles from pseudo-monochromatic radiance are displayed in Fig.(7) and Fig.(8). The errors are significantly smaller than that associated with the original retrieval results obtained from instrument channel radiance, but worse than the results provided by pure theoretical monochromatic radiance spectra because of the transformation error shown above (i.e., Fig.(6)). For temperature, the lowest atmospheric retrieval errors associated with the pseudo-monochromatic are very similar to those obtained from pure simulated monochromatic radiance spectra. Even in the upper atmosphere, temperature profile errors from pseudo-monochromatic radiance are at least 10% better than those achieved using instrument channel radiance spectra. Moisture retrieval errors associated with pseudo-monochromatic radiance spectra are similar to those associated with simulated pure monochromatic radiance spectra, particularly for the lower atmosphere, because of very small transformation errors throughout most of the water vapor band.

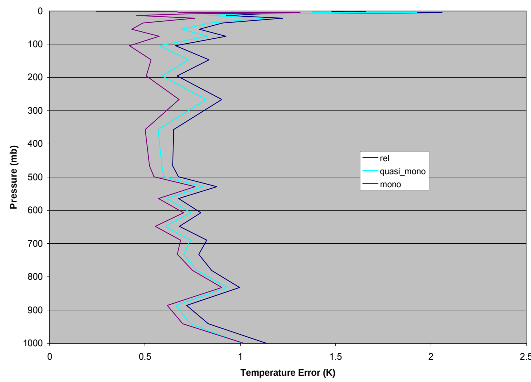

Fig. (7) Temperature errors for retrievals using pseudo-monochromatic radiance spectra.

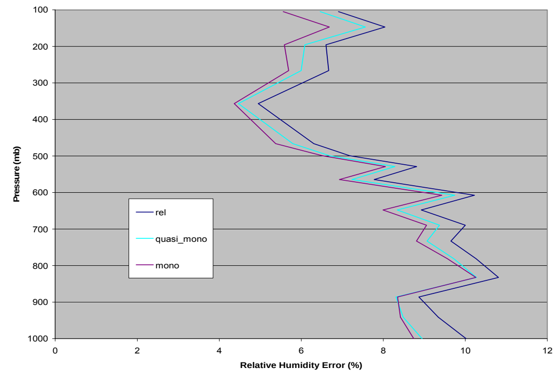

Fig. (8) Moisture errors for retrievals using pseudo-monochromatic radiance spectra.

6. SUMMARY

This paper illustrates a new approach to the retrieval of atmospheric temperature and moisture profiles from any hyper-spectral radiance spectra. The technique involves using a pseudo-monochromatic radiance spectrum, as the profile predictor. The pseudo-monochromatic radiance spectra are produced by a transformation from channel radiance spectra by performing an empirical radiance spectrum de-convolution. A least square regression between eigenvector amplitudes of channel radiance and monochromatic radiance is used to provide the desired transformation. Noise in observed channel radiance spectra are filtered through the eigenvector transformation approach. Although there is an error of estimation in radiance transformation, the error is believed to be smaller than that associated with fast forward model representations of channel radiance spectra. The major advantage of the pseudo-monochromatic radiance approach is that an instrument independent monochromatic radiative transfer model can be used for profile retrieval and/or the radiance data assimilation process. This greatly simplifies the application of observed hyper-spectral sounding radiance spectra for the weather analysis/prediction operation.

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