Atmospheric Infrared Fast Transmittance Models: A Comparison of Two Approaches

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ABSTRACT

The next generation of atmospheric temperature and humidity sounders will have thousands of radiometrically accurate spectral channels throughout the infrared. The retrieval of atmospheric parameters from these radiances will stress both the accuracy and efficiency of forward model radiative transfer algorithms.

We are developing a forward model for the Atmospheric Infrared Sounder (AIRS) which will fly on the EOS PM platform. The work presented here is based on algorithms developed over a number of years by McMillin, Fleming, and others for low resolution infrared sounders (HIRS) and microwave sounders. We have developed two "high-resolution" AIRS forward model algorithms for water vapor, one based on atmospheric layers with fixed pressures and variable water amounts, and another based on layers of fixed absorber amount but with variable pressures. These algorithms are compared for speed, accuracy, ease of development, and other factors that must be considered in developing a complex operational retrieval system.

Keywords: atmospheric transmittance, atmospheric radiance, radiative transfer, forward model

1. INTRODUCTION

Remote sensing of atmospheric temperature and humidity from satellites is critically dependent on our ability to calculate observed radiances as a function of the atmospheric state. This so–called “forward problem” is at the heart of the physically–based retrieval algorithms that will be used to retrieve global atmospheric temperatures and humidity with the next generation of satellite sounders. The high rate of satellite observations requires a forward model fast enough to keep pace with the observations. While various line-by-line models exist to accurately compute atmospheric transmittance, they are far too slow to be practical. Thus, fast atmospheric transmittance models are required for operational atmospheric soundings.

We present here the preliminary development of a fast forward model for the Atmospheric Infrared Sounder[1] (AIRS), which is scheduled to fly on the Earth Observing System (EOS) PM platform. AIRS will measure radiances in almost 2400 spectral channels between $3.7\mu m$ and $15\mu m$ with a spectral resolution 1-2 orders of magnitude better than existing nadir temperature sounders. The large number of channels, high spectral resolution, low noise, and relatively high data rate of AIRS combine to put great demands on the AIRS fast forward algorithm. Over the years, a number of fast transmittance models have been developed for various satellite instruments.[2–8] In this paper we discuss two such approaches for the AIRS fast forward model. We concentrate totally on the accuracy of the *fast* forward model compared to line-by-line computations of atmospheric radiances, and do not address spectroscopic errors in these models.

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2. BASIC METHOD OF FAST TRANSMITTANCE MODELS

The goal of the fast model is to enable the rapid calculation of simulated radiances to compare to actual radiances recorded by an observing instrument. The radiance recorded by the observing instrument is the incident atmospheric monochromatic radiance convolved by the instrument's Spectral Response Function (SRF). Computing simulated radiances by calculating the monochromatic radiance and then convolving it with the instrument's SRF takes much too long to be practical. Instead, a polychromatic approximation for the transmittance is made whereby one directly computes the approximate convolved radiance.

The monochromatic radiance leaving the top of the atmosphere, excluding any scattering and reflection, is given by

$$R = \epsilon_s B\Big(T(s)\Big)\,\tau_z(L) + \sum_{i=1}^{L} B\Big(T(i)\Big)\Big(\tau_z(i-1) - \tau_z(i)\Big) \tag{1}$$

where the atmospheric layers are numbered from space to the surface, 1 to L, respectively. $B(T(i))$ is the Planck function emission for layer i at temperature $T(i)$, and $\tau_z(i)$ is the layer-to-space transmittance from layer i to space, inclusive. $T(s)$ and ϵ_s refers to the Earth's surface temperature and emissivity, respectively.

Applying the polychromatic approximation, we convolve the layer-to-space transmittances and compute the radiances using Eq. 1 instead of computing and convolving the monochromatic radiances. Now τ_z represents convolved layer-to-space transmittances. For AIRS, simulations show this is a good approximation with typical errors ≤ 0.1 K. This error is generally less than the nominal 0.2 K RMS noise of AIRS, and thus does not introduce any serious inaccuracies.

The polychromatic approximation using convolved layer-to-space transmittances forms the common basis for the two techniques we have studied, Pressure Layer Optical Depth (PLOD) and Optical Path TRANsmittance (OPTRAN). The primary difference in the two techniques lies in how they slice the atmosphere into layers: PLOD uses layers of constant pressure, while OPTRAN uses layers of constant optical path (path integrated absorber amount). The OPTRAN algorithm has received renewed interest recently[5,6] for modelling microwave transmittances. The work presented here is a somewhat more difficult test of OPTRAN since the AIRS infrared resolution is significantly lower than the atmospheric emission linewidths.

Both techniques involve relating the convolved layer-to-space transmittances to a simple function involving various profile dependent predictors. These predictors are simple functions of parameters such as layer pressure, temperature, absorber amount, and viewing angle. The equation relating the convolved transmittances to the predictors is of the form

$$-\ln(\tau_{\text{eff}}) = \sum_{i=1}^{N} c_i\, Q_i \tag{2}$$

where τ_{eff} is the effective layer transmittance

$$\tau_{\text{eff}}(l) = \frac{\tau_z(l)}{\tau_z(l-1)} \tag{3}$$

and τ_z is the convolved layer-to-space transmittance, Q_i is the i^{th} profile dependent predictor, N is the number of predictors, and the c_i are the so called fast transmittance coefficients determined by a linear regression of the above equation for a set of representative atmospheric profiles. Note, as is the case in many other models, both the PLOD and OPTRAN techniques involve a regression on $-\ln(\tau)$, the optical depth, and not τ itself.

3. PRESSURE LAYER OPTICAL DEPTH (PLOD) MODEL

The PLOD model is a modification of the approach long used in many fast transmittance models.[2,3,7,8] In this technique, the atmosphere is sliced into layers using a fixed atmospheric pressure layer grid. Typically, the layer boundaries cover smaller pressure ranges, and larger altitude ranges, as the altitude increases.

3.1. Layering grid

The atmospheric pressure layer grid was selected to keep radiative transfer errors well below the instrument noise. Grid characteristics are a factor of the spectral region(s) of observation, the instrument resolution, and instrument noise. The speed of the final fast transmittance model will depend on the number of layers, so excessive layering should be avoided.

For AIRS, which covers most of the 650–1610 cm^{-1} (15.5–6.2 μm) and 2170–2675 cm^{-1} (4.6–3.74 μm) regions with a nominal resolving power of 1200, simulations using line-by-line codes indicate that some channels need a top layer with pressures as small as 0.01 mbar, an altitude of approximately $\sim$ 80 km. The region of primary importance to AIRS is the troposphere and lower stratosphere, where layers on the order of 1/3 of the nominal 1 km vertical resolution of AIRS are desired. Smoothly varying layers facilitate interpolation and avoid large changes in layer effective transmittances. After some experimentation, the following definition for the AIRS pressure layer grid was chosen:

$$P(i) = \left(a\, i^2 + b\, i + c\right)^{7/2} \tag{4}$$

where P is the pressure in mb; i is the layer boundary index and ranges from 1 to 101; and the parameters a, b, and c were determined by solving the equation for $P(1) = 1100$ mb, $P(38) = 300$ mb, and $P(101) = 5 \times 10^{-3}$ mb. The 101 pressure layer grid points in turn define the 100 AIRS layers, the slabs between each pair of adjacent grid points. These layers vary smoothly in thickness from several tenths of a kilometer near the surface to several kilometers at the highest altitudes.

3.2. Regression profiles

One other necessary pre-processing step is to select a set of profiles for calculation of the layer-to-space transmittances. The transmittances for these profiles become the regression data for the fast transmittance coefficients. These profiles should span the range of atmospheric variation, but on the whole, should be weighted towards the more typical cases. The range of variation provides the regression with data points covering the range of behaviors, while the weighting of the mix of profiles towards more typical cases produces a transmittance model that works best on more statistically common profiles.

The process of calculating and convolving monochromatic layer-to-space transmittances is generally computationally intensive, thus imposing a practical limit on the number of profiles one can calculate for use in the regression. For our AIRS fast transmittance model, we found 36 regression profiles (at 5 viewing angles each) was sufficient to cover most of the profile behavior. This number compromised the available time and computing resources and the estimated needs for spanning the range of profile behavior in the regression. Choosing too few profiles leads to accuracy problems for profiles outside the range of behaviors considered. Choosing more profiles than necessary does not hurt the fast model, but does consume extra time and computer resources in the creation of the model.

Each profile should cover the necessary pressure (altitude) range with data for temperature as well as absorber amount for each of the gases allowed to vary. Typically, only a few absorbing gases are allowed to vary in mixing ratio, with the others held constant or "fixed". The fixed gases include all those whose spatial and temporal concentration variations have a negligible impact on the observed radiances. For AIRS, the variable gases include H_2O, O_3, CO, CH_4, and N_2O. In this paper we will only present the transmittance models for fixed gases, H_2O, and O_3. In the future we will also let CO_2 vary. At present CO_2 dominates the fixed gas absorption.

3.3. Breakout of gases

With the layering grid and regression profiles selected, the monochromatic layer-to-space transmittance may be calculated. The gases are distributed into sub-groups as follows:

$$\begin{aligned} & F \\ & F \;+\; V_1 \\ & F \;+\; V_1 \;+\; V_2 \\ & \quad \cdots \\ & F \;+\; V_1 \;+\; V_2 \;+ \ldots +\; V_n \end{aligned} \tag{5}$$

where F refers to to the fixed gases, and V_j to the j^{th} variable gas. Such a grouping reduces the errors inherent in separating the gas transmittances after the convolution with the instrument spectral response function. The convolution of a sum of terms is in general not the same as the sum of the terms convolved individually. However, if we make use of the above form, the effective layer-to-space transmittance of the j^{th} variable gas by itself is

$$\tau_{z\,\mathrm{eff}}(V_j) = \frac{\tau_z(F + V_1 + V_2 + \cdots + V_{j-1} + V_j)}{\tau_z(F + V_1 + V_2 + \cdots + V_{j-1})} \tag{6}$$

and the total transmittance of all the individual gases together is

$$\tau_{z\,\mathrm{total}} = \tau_{z\,\mathrm{eff}}(F) \times \prod_{j=1}^{n} \tau_{z\,\mathrm{eff}}(V_j) \tag{7}$$

Thus, all the terms except $\tau_z(F + V_1 + V_2 + \cdots V_n)$ cancel, leaving only the correct, convolved sum. Generally, the order in which the variable gases are added after the fixed gases should be in order of increasing importance to the total transmittance. This depends upon the spectral region and particulars of the instrument, as well as the range of variation of gas amounts.

In the case of AIRS, the variable gases were water and ozone (and in a few particular spectral regions CO, CH_4, and N_2O); all other gases were treated as fixed. The monochromatic layer-to-space transmittances were calculated and grouped into three sets

$$\begin{aligned} F &= \tau_z(\text{fixed}) \\ FW &= \tau_z(\text{fixed} + \text{water}) \\ FWO &= \tau_z(\text{fixed} + \text{water} + \text{ozone}) \end{aligned} \tag{8}$$

and then convolved with the AIRS spectral response function. Water continuum absorption is excluded above since it varies so slowly with wavenumber and does not need to be convolved with the AIRS instrument function. We later add the water continuum to the total transmittance as a separate term.

For each layer l, the convolved layer-to-space transmittances are ratioed with transmittances in the layer above, $l-1$, to form effective layer transmittances for fixed (F), water (W), and ozone (O)

$$\begin{aligned} F_{\mathrm{eff}}(l) &= \frac{F(l)}{F(l-1)} \\ W_{\mathrm{eff}}(l) &= \frac{FW(l)}{F(l)}\,\frac{F(l-1)}{FW(l-1)} \\ O_{\mathrm{eff}}(l) &= \frac{FWO(l)}{FW(l)}\,\frac{FW(l-1)}{FWO(l-1)} \end{aligned} \tag{9}$$

The zeroth layer transmittance (*i.e.* when $l-1=0$) is taken to be exactly 1.0. We take the negative logarithm of these layer effective transmittances to get effective layer optical depths

$$\begin{aligned} k_{\mathrm{fixed}} &= -\ln(F_{\mathrm{eff}}) \\ k_{\mathrm{water}} &= -\ln(W_{\mathrm{eff}}) \\ k_{\mathrm{ozone}} &= -\ln(O_{\mathrm{eff}}) \end{aligned} \tag{10}$$

3.4. Predictors

These effective layer optical depths become the data points in a regression to calculate the fast transmittance coefficients that relate a set of profile dependent predictors to the layer effective optical depth. It is important that some care be used to restrict the regression to k values that are significant for radiative transfer.

The optimal set of predictors used to parameterize the effective layer optical depth depends upon the gas, the order in which they are separated out, the instrument's spectral response function, the range of viewing angle, the spectral region, and even the layer thicknesses. In short, no one set of predictors is likely to work

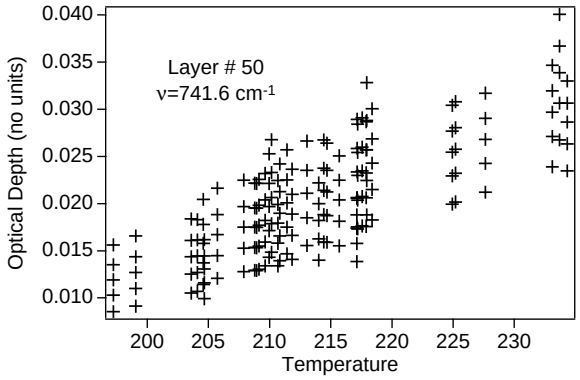

Figure 1. Example of how the PLOD k_{fixed} varies with layer temperature. The vertical stacks of points are variations in the AIRS viewing angle.

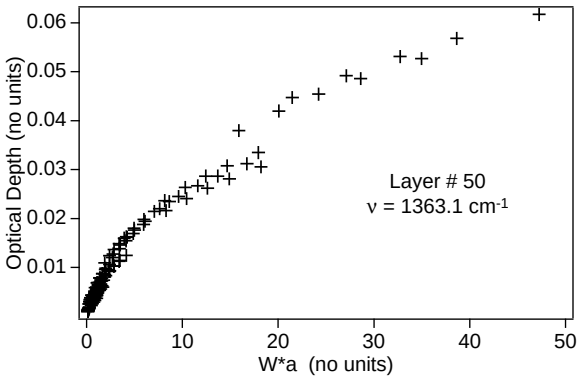

Figure 2. Example of how the PLOD k_{water} varies with $W * a$ (see text for definitions).

well in every case. Finding the set of predictors which gives the best results is in large part a matter of trial and error. However, there are some general trends. For example, Fig. 1 illustrates a representative variation of optical depth with temperature. The variable viewing angle primarily imparts an offset as well as a small change in slope to the curve. Fig. 2 shows a fairly well behaved variation of optical depth with water amount, while Fig. 3 shows a behavior that is more difficult to model. Note that Figs. 2 and 3 are for the *same* channel, but different layers!

For an instrument such as AIRS with thousands of channels, it is difficult to develop individual optimal predictors for each channel. At this point we have developed one set of predictors that works sufficiently well for all channels. This set of predictors was determined by extensive trial and error testing of a few representative channels estimated to span the range of behaviors present in the entire channel set. Once a first attempt at the fast model is complete, it can be tested over the complete channel set, and the channels with the maximum error isolated for use in testing an improved set of predictors. The most difficult channels to model appear to be ones with low altitude water lines and those covering the strong ozone band.

The regression is prone to numerical instabilities if the values of the predictors vary too greatly. Consequently, we follow the usual practice of defining the predictors with respect to the values of a reference profile, either by taking a ratio or an offset. There is also a danger of numerical instability in the results of the regression due to the interaction of some of the predictors. Sensitivity of the output to small perturbations in the predictors is avoided by systematic testing. There are practical difficulties in detecting small problems since we are performing on the order of 1 million regressions. We hope to regularize these regressions in the future in a way that allows us to automatically trim unnecessary predictors.

3.4.1. $\mathbf{k}_{\text{fixed}}$

For AIRS, we found that the following terms were the best predictors for the fixed gases:

$$\begin{array}{lll} 1)\ a & 2)\ a^2 & 3)\ a\,T_r \\ 4)\ a\,T_r^2 & 5)\ T_r & 6)\ T_r^2 \\ 7)\ a\,T_z & 8)\ a\,T_z/T_r & \end{array} \tag{11}$$

where a is the secant of the local path angle, T_r is the temperature ratio $T_{\text{profile}}/T_{\text{reference}}$, and T_z is the pressure weighted temperature ratio above the layer

$$T_z(l) = \sum_{i=2}^{l} P(i)\left(P(i) - P(i-1)\right) T_r(i-1) \tag{12}$$

where $P(i)$ is the average layer pressure for layer i.

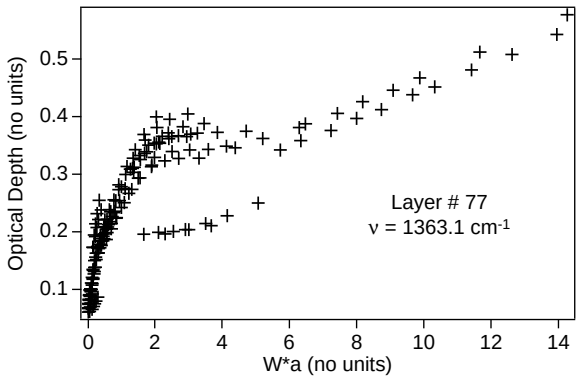

Figure 3. Example of how the variation of PLOD k_{water} with $W * a$ can change abruptly.

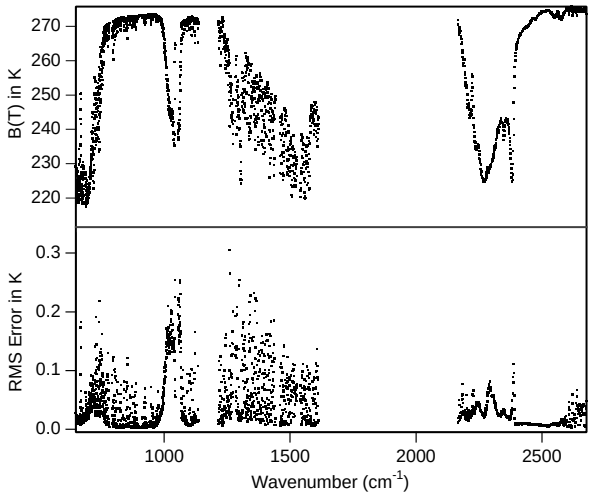

Figure 4. RMS fitting errors of the PLOD model for AIRS.

3.4.2. $\mathbf{k}_{water}$

The water algorithm is broken into two parts; one where the total water optical depth above the current layer is less than 5, denoted as profiles with $kz_{\text{water}} \leq 5$, and another for regions with profiles where $kz_{\text{water}} > 5$. For $kz_{\text{water}} \leq 5$ the best predictors for k_{water} were determined to be:

$$\begin{array}{rrr} 1)\, W\,a & 2)\, \sqrt{W\,a} & 3)\, W\,a\,dT \\ 4)\, (W\,a)^2 & 5)\, W\,a\,dT\ |\,dT\,| & 6)\, (W\,a)^3 \\ 7)\, W_z\,a & 8)\, \sqrt{W\,a}\,dT & 9)\, \sqrt[4]{W\,a} \\ 10)\, (W_z\,a)^2 & 11)\, \sqrt{W_z\,a} & \end{array} \tag{13}$$

and for $kz_{\text{water}} > 5$ we use

$$12)\, W\,a \quad 13)\, W\,a/(W_z\,a)^2 \tag{14}$$

where W is the water amount ratio $W_{\text{profile}}/W_{\text{reference}}$, dT is the temperature offset $T_{\text{profile}} - T_{\text{reference}}$, and W_z is the pressure weighted water amount above ratio

$$W_z(l) = \frac{\sum_{i=1}^{l} P(i)(P(i) - P(i-1))W_{\text{profile}}(i)}{\sum_{i=1}^{l} P(i)(P(i) - P(i-1))W_{\text{reference}}(i)} \tag{15}$$

where $P(i)$ is the layer pressure for layer i and $P(0) = 2\,P(1) - P(2)$.

Unfortunately, this results in the need to maintain a running sum of the water optical depth as one loops down over the layers in order to use the appropriate terms. The root of this problem is the occurrence in many strong water channels of an abrupt change in the functional dependence of the water predictors at total optical depths of 3–5. An example of this can be seen in Fig. 3, where there is a drastic change in the behavior of the optical depths for $W * a$ in the range of 2–5. We were spared similar problems with fixed gases because the only absorber amount variation comes from a variation in the secant of the local path angle.

Since the water continuum is not included above, the effective layer optical depth for water only includes the near wing portion of the water line absorption; the far wing portion is added in separately.

3.4.3. $\mathbf{k}_{\text{ozone}}$

For AIRS, the best predictors for ozone were determined to be:

$$\begin{array}{rrr} 1)\, O\,a & 2)\, \sqrt{O\,a} & 3)\, O\,a\,dT \\ 4)\, (O\,a)^2 & 5)\, \sqrt{O\,a}\,dT & 6)\, O_z\,a \\ 7)\, O\,a\sqrt{O_z\,a} & 8)\, O\,a\,W\,a & 9)\, TO_z\,O\,a \end{array} \tag{16}$$

where W is the water amount ratio $W_{\text{profile}}/W_{\text{reference}}$, O is the ozone amount ratio $O_{\text{profile}}/O_{\text{reference}}$, O_z is the pressure weighted ozone amount ratio above

$$O_z(l) = \sum_{i=2}^{l} P(i)\Big(P(i) - P(i-1)\Big)\, O(i-1) \tag{17}$$

and TO_z is the pressure and ozone weighted temperature ratio above

$$TO_z(l) = \sum_{i=2}^{l} P(i)\,\Big(P(i) - P(i-1)\Big)\, T_r(i-1)O(i-1) \tag{18}$$

3.5. Regression

The accuracy of radiative transfer calculations made with the PLOD fast transmittances improve significantly if the data is weighted prior to performing the regression. Radiative transfer is insensitive to layers for which the change in layer-to-space transmittance across the layer is ~ zero. This occurs when either the layer effective transmittance is ~ unity, or when the layer-to-space transmittance above the layer is ~ zero. Therefore, the data going into the regression is not all of equal importance to the final accuracy of radiative transfer calculations made with the model. We found it useful to weight the data in terms of both its effective layer optical depth as well as the total optical depth of all the layers above the layer under consideration. Usually, the best results are obtained when we weight the data with a look-up table similar to Table 1. Intermediate points are obtained by

k	weight
0.007	2.0
0.05	3.0
0.3	5.0
1.0	7.0
3.0	4.0
5.0	1.0

Table 1. Weights for k in the forward model regressions.

linear interpolation of the above data point pairs. Values of k outside the listed weight range are assigned the value of the appropriate extreme. The data is weighted once for its layer optical depth and then again for its layers-above optical depth with the final weighted values ranging between 1 and 49. The final weighted value replaces the original layer optical depth in the regression. To maintain balance on both sides of the equation, all the predictors must be multiplied by a scaling factor equal to the new weighted value divided by the original layer optical depth. This weighting is done individually for each of the gases.

The results of the PLOD model fit for AIRS is shown in Fig. 4. The errors are calculated with respect to the regression profile set, comparing the input data with the PLOD model calculated values. Errors calculated for a large independent profile set were very similar. In general the RMS errors are at or below the estimated signal noise and spectroscopic errors. As previously mentioned, the largest errors are generally associated with either low altitude water or are inside the strong ozone band near 1100 cm^{-1}.

4. THE OPTICAL PATH TRANSMITTANCE (OPTRAN) METHOD

The OPTRAN model is a recent development of an approach originally suggested in Ref. 4. In the newest OPTRAN model[5,6] the atmosphere is sliced into layers according to layer-to-space optical path (absorber amount) rather than atmospheric pressure. As such, the layer optical paths are always constant across a layer and pressure becomes a predictor. However, unlike PLOD, not all profiles will span all the layers. In general a profile will span only a top subset of the layers. For this approach, the local path secant is factored into the optical path values, and path angle is not generally used as a predictor. To a rough approximation, the optical depth varies linearly with optical path. Thus, for any given OPTRAN layer all the optical depths only vary over approximately one order of magnitude.

Other than the layering technique, the OPTRAN method is similar to the PLOD model. The first step is to select a group of regression profiles. This should be done following guidelines similar to those suggested with PLOD but with one important difference: one of the profiles must be a maximum absorber amount profile which no other profile can ever exceed. This results from defining the layering grid from a set range of variation of optical path. No transmittances can later be calculated for optical paths outside that range. Because path angle is factored into the optical path values, the maximum optical path corresponds to the maximum amount profile at nadir multiplied by the secant of the maximum path angle.

Once the maximum profile for each gas is selected, its layering grid may be calculated. Each gas has its own layering grid. We used the layering grid suggested in Ref. 6 to slice the atmosphere as follows,

$$\frac{e^{200a}-1}{e^{a}-1} = \frac{A_{200}}{A_1} \tag{19}$$

where A_{200} is the maximum optical path, A_1 is the optical path of the first level, and a is some positive constant determined by solving the above equation. The top most level A_0 is always defined as zero. This results in a layering grid of 201 levels defining 200 layer slabs whose thickness gets progressively greater as one goes down through the atmosphere. The value of A_1 should be chosen to place it high enough in the atmosphere such that the optical depths for values less than A_1 have a dependence upon predictors like that at A_1, or otherwise these optical depths are negligible and therefore not necessary to accurately model. The use of 200 layers in the above expression is somewhat arbitrary, and is a rough estimate of what was thought necessary to provide enough layers to allow OPTRAN to function accurately. The limiting factor is the minimal number of layers needed to accurately model the transmittance of the profile which spans the fewest number of layers. This corresponds to the profile with the least absorber amount viewed at nadir.

For ease of computation, the layer-to-space transmittances for the regression profiles may be calculated on a pressure level grid, and then later interpolated onto the optical path layering grid. Assuming the pressure layer grid is fine enough, this only requires a simple linear interpolation in layer-to-space optical path of the layer-to-space optical depths and the predictors.

As previously mentioned, in general a profile will not span all the OPTRAN layers. Only the most extreme profiles at maximum viewing angle will reach into all the layers. To provide sufficient data points to allow accurate modeling of the optical depth in the last few layers, Ref. 6 recommends doing one additional viewing angle whose secant is 10–15% greater than that of the maximum instrument viewing angle, so as to push more of the profiles into the bottom-most layers. This will result in the maximum profile (and perhaps some of the others) exceeding the maximum limits of the layering grid at this angle, but that data should be ignored.

The selection of the predictors for modeling the effective layer optical depths follows a similar trial and error procedure as for PLOD. For OPTRAN, the main predictors for all gases are generally a constant, pressure, and temperature. Figs. 5 and 6 show representative variations of OPTRAN optical depths with pressure for fixed gases and water.

Thus far, we have only developed OPTRAN for AIRS for two regions: the 15μm CO_2 region and the 8μm water region, and only for fixed gases and water. There was insufficient ozone absorption in either region to determine a good set of predictors for it. Our version of OPTRAN is slightly different than that in Ref. 6 in that the formulation is simpler and we use some different, but related, predictors. Our predictors are first

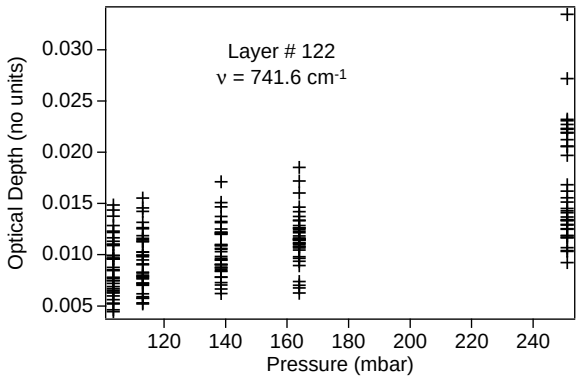

Figure 5. Example of how the OPTRAN k_{fixed} varies with pressure. The 5 groupings of points correspond to the 5 viewing angles used for each profile in the regression.

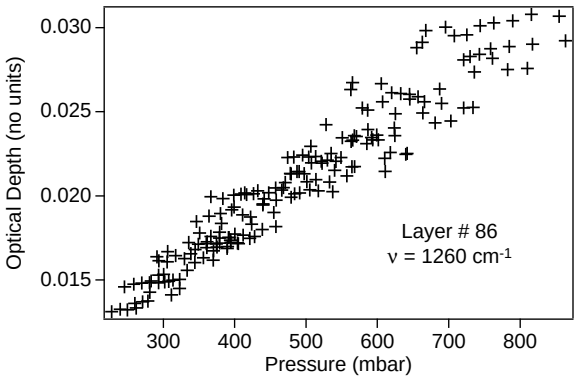

Figure 6. Example of how the OPTRAN k_{water} varies with pressure.

calculated on the pressure levels used for the layer-to-space convolved transmittances. Then they are linearly interpolated in layer-to-space optical path onto the OPTRAN layers. The predictors for each gas are:

$$\begin{array}{lll} 1)\ 1.0 & 2)\ P & 3)\ T \\ 4)\ \sqrt{P} & 5)\ P_z & 6)\ T_z \\ & 7)\ P\,a & \end{array} \tag{20}$$

where P is the pressure, T is the temperature, a is the local path angle secant,

$$P_z(l) = \frac{\sum_{i=1}^{l} A(i)\, a(i)\, P(i)}{\sum_{i=1}^{l} A_{ref}(i)\, P(i)} \tag{21}$$

and

$$T_z(l) = \frac{\sum_{i=1}^{l} A(i)\, a(i)\, T(i)}{\sum_{i=1}^{l} A_{ref}(i)\, T_{ref}(i)} \tag{22}$$

where $A(i)$ is the gas absorber amount in the i^{th} layer for nadir, and A_{ref} is the same but for the reference profile. One advantage of OPTRAN is the same predictors work well for both fixed gases and water. If ozone needs the same set of predictors our version of OPTRAN will require a total of 7 x 3 = 21 coefficients per OPTRAN water layer. This is slightly fewer than the 30 coefficients used per PLOD pressure layer. Given that both algorithms are still in development this difference in the number of coefficients is inconsequential.

When using the OPTRAN fast transmittance model, each gas has its own set of OPTRAN layers. However, for radiative transfer, one generally desires the total optical depth through a given slab in the atmosphere. Thus, after OPTRAN computes optical depths for each gas it must be interpolated onto a common pressure layer grid. Typically, the OPTRAN model is used as follows:

1. An input profile is supplied on a set of pressure layers with data for gas absorber amounts and temperature. The viewing angle should also be supplied if its effects are not already factored into the absorber amounts.
2. The predictors are determined on the pressure level grid.
3. The predictors for each gas are linearly interpolated in layer-to-space optical path onto that gas's OPTRAN layers. In general the maximum layer-to-space optical path in the input profile will not exactly correspond to one of the OPTRAN layer values. Thus, the interpolated values must be extended to the next closest larger OPTRAN layer to completely bracket the range covered by the input profile.

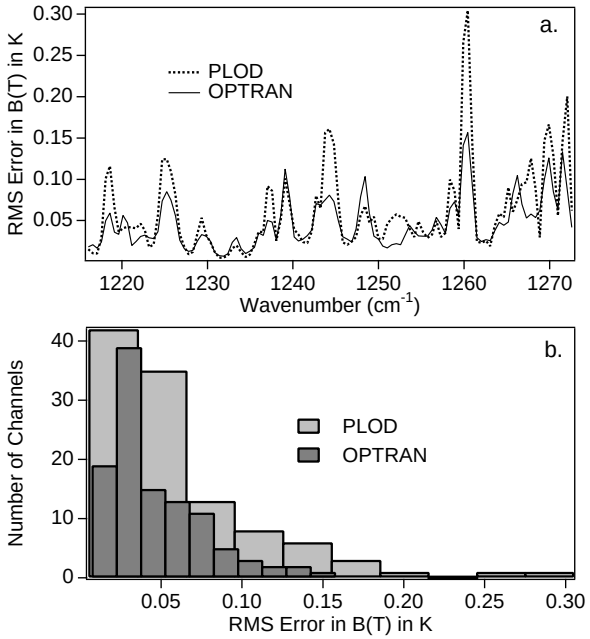

Figure 7. (a.) RMS fitting errors of PLOD and OPTRAN in the 1250 cm^{-1} spectral region. Customized OPTRAN layers were developed for this spectral region. (b.) Histogram of OPTRAN fitting errors in (a.)

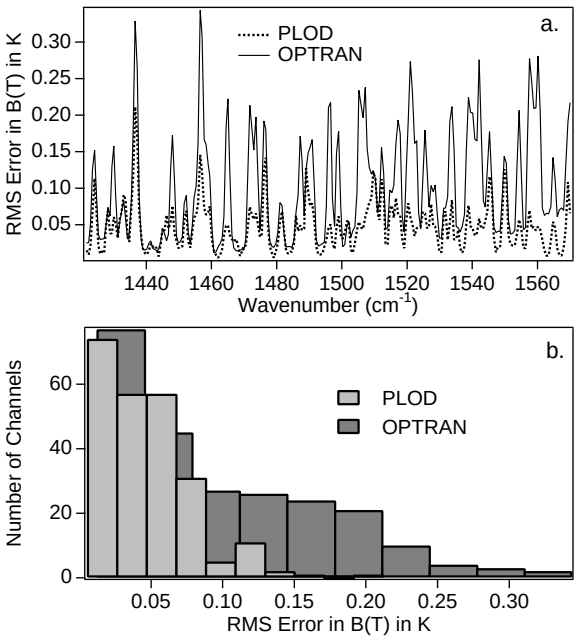

Figure 8. (a.) RMS fitting errors of PLOD and OPTRAN in the 1500 cm^{-1} spectral region. OPTRAN layers from the 1250 cm^{-1} spectral region were used in this regression. (b.) Histogram of OPTRAN fitting errors in (a.)

4. The optical depth for each gas in the profile is computed from the top layer down to the last necessary layer. We also keep a running sum of these optical depths because it is more convenient to interpolate back onto pressure layers using the layer-to-space optical depths.

5. The layer-to-space optical depth for each gas is linearly interpolated in layer-to-space optical path onto a common set of pressure layers. The gases are then summed for each layer to give the total layer-to-space optical depth. If the pressure layers are not the same as used to describe the input profile, the layer temperature will also need to be interpolated onto to these pressure layers.

The OPTRAN layer optical depths generally vary only over a range of perhaps one order of magnitude for any one layer, and thus are all very roughly of the same importance to radiative transfer. This greatly reduces the need to weight the data prior to the regression and is one of the best characteristics of the OPTRAN model. Otherwise the regression is carried out in an identical manner as for the PLOD model.

Fast forward model errors for both OPTRAN and PLOD are shown in Figs. 7 and 8. AIRS has a spectral resolution of approximately 1 cm^{-1} in these spectral regions, which are dominated by water. The 1250 cm^{-1} region was examined because most of the PLOD model's largest errors are located there. Generally, OPTRAN was as good or better than PLOD throughout this region. However, when OPTRAN was tested in the 1500 cm^{-1} region the results were, in general, quite inferior to PLOD. At 1500 cm^{-1} the radiances are occurring at higher altitudes than at 1250 cm^{-1}. The poorer performance of OPTRAN at 1500 cm^{-1} is probably due to an inappropriate OPTRAN layering grid; we used the same OPTRAN layers in this spectral region as we used in the 1250 cm^{-1} region. This grid, which had been developed for the 1250 cm^{-1} region, does not have enough layers at high altitudes to accurately handle the 1500 cm^{-1} radiances. This highlights one undesirable characteristic of OPTRAN. Either a very dense grid is needed for water, or different layer grid structures must be developed for different spectral regions.

The histograms of the RMS errors in Figs. 7b and 8b show that both models produce errors below the AIRS noise level for almost all profiles. The largest errors are generally on top of spectral lines, which are usually less optimal locations for sounding than channels that lie in line wings. Both algorithms are viable alternatives for the AIRS forward model. Practical considerations unrelated to the fundamental aspects of these algorithms may determine which is eventually chosen for AIRS.

5. COMPARISONS AND CONCLUSIONS

Both the PLOD and OPTRAN models are capable of accurate modeling of atmospheric transmittances for a variety of instruments. The work presented here has shown the utility of both models for the next generation of high resolution infrared sounders. Each model has its own set of advantages and disadvantages. The OPTRAN model is somewhat easier to construct and less time needs to be spent searching for the optimal set of predictors for each gas. In addition the data does not need to be weighted prior to regression. The regression itself is less prone to numerical problems due to the smaller range of variation of the optical depths and predictors. One of the more undesirable aspects of OPTRAN is the difficulty in determining the optimal layering for each of the gases. This is fairly easy in the case of just a few channels. However, if there are many channels covering a wide range of behaviors, tedious and time consuming testing may be required to ensure adequate layering for all channels.

The accuracy of the two models is in large part a matter of the number and appropriateness of the predictors and layers used. In general, the PLOD model requires more predictors but fewer layers to achieve a similar degree of accuracy as OPTRAN. Although neither algorithm can model all the behavior seen in the optical depths, OPTRAN is probably ultimately capable of a greater degree of accuracy. The range of variation in the PLOD optical depths and predictors makes it more difficult to fit. The ultimate speed of the two models is also largely dependent upon the number of layers and, to a lesser degree, the number of predictors. The number of layers required to process a profile with OPTRAN is profile dependent, and thus so is the speed. The linear interpolations needed for OPTRAN can be done quickly if many channels use the same layering grid, but it is still a significant factor in ultimate run time. In our tests of PLOD and OPTRAN for AIRS, the PLOD model was more than twice as fast as OPTRAN. However, this should be considered a very preliminary number.

The PLOD model is easier to use. The use of the same fixed pressure layers is convenient for use with radiative transfer, as well as computing analytic Jacobians ($\partial R/\partial T$ or $\partial R/\partial(\text{water})$). In contrast, the OPTRAN model requires separate interpolations of each of the gases onto its own layering grid, and then, after computation, back onto a common pressure layering grid. Computing analytic Jacobians with OPTRAN may be problematic. We have successfully generated analytic Jacobians with PLOD and found them to agree quite well with finite difference Jacobians.

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