Fast Model for the Atmospheric Infrared Sounder (AIRS)

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Abstract

Rough draft

This paper provides an overview of the construction of the the AIRS fast model (AIRS-RTA), with a focus on the basic modelling techniques and approxiations.

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1 Introduction

The Atmospheric Infra-Red Sounder (AIRS) is the primary instrument on the Aqua polar orbiting satellite which is due for launch in March 2002. Together with the Advanced Microwave Sounding Unit (AMSU-A) and Humidity Sounder of Brazil (HSB), AIRS will be used to gather atmospheric profile soundings covering nearly the entire Earth every day. With 2378 spectral IR channels and 90 new observations every 2.67 seconds, the resulting high data rate demands that the operational data processing system be very fast so as to keep up with the observations. For the physical retrieval method employed by the AIRS+AMSU+HSB processing, this requires a means of very quickly computing a simulated AIRS radiance for any plausible atmospheric profile. For this purpose we have developed a fast model for AIRS transmittances and radiances, the development and design of which is discussed in this paper.

2 Overview of the fast model technique

AIRS is a grating spectrometer with 2378 separate channels in the infra-red between 650 cm^{-1} (15 μm) and 2700 cm^{-1} (3.7 μm). The resolution (full width at half maximum) is approximately $\nu/1200$ and the spectral response function (SRF) for each

channel can be approximated as a gaussian centroid with lorentzian wings. A simlated AIRS radiance can be computed using some existing monochromatic radiance code (such as GENLN2, LBLRTM, KCARTA) and convolving the radiance with the AIRS SRFs, but such an approproach is orders of magnitude too slow for use in operational AIRS data processing. We therefore have developed a "fast model" which generates simulated AIRS radiances directly.

Our AIRS fast model, the AIRS-RTA (AIRS Radiative Transfer Algorithm), makes use of a polychromatic approximation whereby convolved monochromatic radiances are replaced by radiances generated from convolved transmittances. This is a technique that has previously been used for fast models of a number of other instruments (refs). A brief summary of the technique follows.

For the case of clear air and no reflections, the upwelling monochromatic radiance as seen by AIRS can be calculated as

$$R_{mono} = e_s\, B(T_s)\, \tau_{\blacktriangle s} + \sum_{L=1}^{N} B(T_L)\, (\tau_{\blacktriangle L-1} - \tau_{\blacktriangle L}) \tag{1}$$

where the radiative transfer equation has been converted from an integral into a discrete layered atmosphere of N layers. In this equation e_s is the surface emissivity, B the Planck function, T the temperature, and $\tau_{\blacktriangle L}$ is the transmittance for layer L. The upward pointing triangle subscript on the transmittance terms donotes the transmittance is between the specified layer and the top of the atmosphere.

The monochromatic radiance can then be converted into an AIRS radiance by convolving R_{mono} with the AIRS SRFs.

$$R_{AIRS} = R_{mono} * SRF \tag{2}$$

For a high resolution instrument, the Planck function does not change greatly over the spectral interval defined by the width of the channel, and thus the Planck term is nearly a constant of the convolution integral. To a good approximation, one can replace convolved monochromatic radiances with radiances calculated using convolved transmittances along with the Planck function evaluated at some single effective channel frequency.

The convolved transmittances can be modelled using a regression based approach. The first step is to generate a training set of convolved transmittances for some corresonding set of training profiles. The transmittances can be calculated with some monochromatic code and then convolved with the instrument SRFs. The regression then involves solving for the coefficients that relate some set of profile based predictor variables to the convolved transmittances. For each component gas and layer, this requires solving the an equation of the form

$$AX = B \tag{3}$$

where A is a (m x n) matrix of predictors, X is a (n x 1) vector of coefficients, and B is a (m x 1) vector of transmittances, for the case of m profiles and n predictors. This equation can then be used to predict the convolved transmittance for any other profile by multiplying the coefficients by the predictors for the desired profile.

3 Convolved Transmittance

The discrete form of the radiative transfer equation makes use of transmittances spanning the distance between the observing instrument and the bottom of each layer. For a satellite instrument such as AIRS, this is sometimes called the "layer-to-space" transmittance. For our fast model we are dealing with convolved layer-to-space transmittances rather than monochromatic transmittances, and this introduces some complications.

Monochromatic atmospheric transmittances can be expressed as a simple product of the individual component gas transmittances, but in general this is not true of convolved transmittances. That is, the convolution of a product of terms is not the same as the product of each term convolved individually. We would like to allow for variations in a number of absorbing gases in our AIRS fast model, but we can not simply model each gas individually. Instead we chose to model ratios of convolved transmittance such that the product of the separate component terms gave the correct total transmittance. For the simple case of three sets of absorbing gases A, B, and C, we define two effective transmittances

$$\tau_{Be} = \frac{\tau_{AB}}{\tau_A} \tag{4}$$

$$\tau_{Ce} = \frac{\tau_{ABC}}{\tau_{AB}} \tag{5}$$

so that

$$\tau_{ABC} = \tau_A \, \tau_{Be} \, \tau_{Ce} \tag{6}$$

Each of the transmittances τ_A, τ_{AB}, and τ_{ABC} is a convolved layer-to-space transmittance containing the indicated sets of component gases, while the effective transmittances τ_{Be} and τ_{Ce} come from ratios of convolved transmittances. This method can be entended as needed to allow for more separate component transmittances, but each gases that is broken out adds to the complexity, size, and run time of the final fast model.

For the AIRS fast model, we allow 5 gases to vary; these are H2O, O3, CO, CH4, and CO2. All other atmospheric gases are kept constant so that their transmittance is a function of temperature only. CO and CH4 only have a significant impact on AIRS radiances in localized spectral regions, so these gases were only broken out in those small regions. H2O and O3 were broken out nearly everywhere.

Different sets of convolved transmittances were used for different regions depending upon which gases are present and which ones we wish to break out as separate components. We used the following sets of transmittances:

fixed, ozone, water
fixed, methane, water
fixed, carbon monoxide, ozone, water

with the component gases listed in order of breakout. For example, in most regions we used the first set which consists of three layer-to- space convolved transmittances:

fixed
fixed + ozone
fixed + ozone + water.

3.1 Variable CO2

CO2 is a major atmospheric absorber, but its concentration is believed to only vary by a few percent across the globe. This is quite unlike H2O, the other major IR aborber, which varies by a few orders of magnitude. For a small perturbation in CO2, the change in the atmospheric optical depth (the log of the transmittance) varies almost linearly with the size of the perturbation. To simplify the AIRS fast model, we decided to treat CO2 as one of the "fixed" (ie constant) gases and model the few percent variability in CO2 as a separate perturbation term.

We model the variable CO2 perturbation term by doing a regression for the change in optical depth for one particular offset in CO2 concentration, and then scaling this delta in optical depth for the desired perturbation. The scaled delta optical optical depth for the CO2 perturbation is then add to the total (non-perturbed) optical depth and the sum is converted to a transmittance.

The training transmittances for the CO2 regression consist of two parts: one for "all gases" transmittances using the reference CO2 amount, and the other the same except the CO2 amount has been offset. We chose to use a +5 % offset for the training data, as this would allow modelling CO2 variations of up to +- 10 % with very good accuracy. The regression training data is the difference in optical depth between these two sets, ΔK_{offset}.

For our AIRS fast model, the change in total optical depth for some small perturbation in CO2 is calculated as

$$\Delta K_{scaled} = \Delta K_{offset} \frac{p}{o} \tag{7}$$

where p is the perturbation and o is the offset, both in percent.

3.2 Effective Layer Optical Depth

The AIRS fast model is based upon a fit of effective layer optical depths rather than layer-to-space transmittances. This imposes a time penalty since these optical depths must be converted to transmittances for the radiative transfer, but they are much easier to fit to the required degree of accuracy.

The effective layer transmitance for each layer is computed by dividing the effective layer-to-space effective transmittance for this layer by the value in the layer directly above. The optical depth is simply the natural log of this transmittance. Due to the repeated ratioing of convolved transmittances to derive the effective layer transmittance, it is sometimes possible to obtain values that are slightly less than zero or slightly greater than one. Simply put, the math does not guarantee effective transmittances with values between zero and one. Fortunately this tends to occur only when the layer effective transmittance is negligible, and thus we may truncate the values to the usual zero to one range without significantly impacting the accuracy of the fast model.

A similar problem can arise due to the limited precision of 4-byte real numbers. To prevent numerical difficulties, we used 8-byte reals for the convolved transmittances.

3.3 Pressure Layers and Amount Layers

The AIRS fast model uses two different layering methods to model the optical depths. The first method is the most intuitive, with the atmosphere sliced in vertical slabs defined by some particular pressure level grid. In this case, each layer is the slab defined by the two bounding grid pressure levels (so N layers require a N+1 level grid). We chose to use the same pressure grid for all component gases as well as for the final radiative transfer. If different pressure layers had been used for some of the components, then it would have been necessary to interpolate them to a common grid for use in the radiative transfer calculations.

The constant pressure level grid method has been used for the AIRS fast model for all component gases, with the exception of water vapor in a subset of channels. The training set of convolved layer-to-space transmittances were calculated on this grid. The AIRS grid has 100 layers and spans the range 1100 to 0.005 mb. The grid

Table 1: The AIRS pressure level grid (in millibars)

0.0050	0.0161	0.0384	0.0769	0.1370
0.2244	0.3454	0.5064	0.7140	0.9753
1.2972	1.6872	2.1526	2.7009	3.3398
4.0770	4.9204	5.8776	6.9567	8.1655
9.5119	11.0038	12.6492	14.4559	16.4318
18.5847	20.9224	23.4526	26.1829	29.1210
32.2744	35.6505	39.2566	43.1001	47.1882
51.5278	56.1260	60.9895	66.1253	71.5398
77.2396	83.2310	89.5204	96.1138	103.0172
110.2366	117.7775	125.6456	133.8462	142.3848
151.2664	160.4959	170.0784	180.0183	190.3203
200.9887	212.0277	223.4415	235.2338	247.4085
259.9691	272.9191	286.2617	300.0000	314.1369
328.6753	343.6176	358.9665	374.7241	390.8926
407.4738	424.4698	441.8819	459.7118	477.9607
496.6298	515.7200	535.2322	555.1669	575.5248
596.3062	617.5112	639.1398	661.1920	683.6673
706.5654	729.8857	753.6275	777.7897	802.3714
827.3713	852.7880	878.6201	904.8659	931.5236
958.5911	986.0666	1013.9476	1042.2319	1070.9170
1100.0000				

was designed to provide the vertical spacial resolution desired by the the AIRS team, and also meets the needs for accurate calculation of AIRS simulated radiances.

The AIRS pressure level values come from the equation:

$$P_{lev}(i) = (ai^2 + bi + c)^{7/2} \tag{8}$$

where i is level number, and a, b, and c are constants determined by solving the equation for some set of P_{lev} points. The AIRS grid is based upon a solution of the above equation for $P_{lev}(1) = 1100$, $P_{lev}(38) = 300$, and $P_{lev}(101) = 0.005$, with constants of (approximate) values of $a = -1.55x10^{-4}$, $b = -5.59x10^{-2}$, $c = 7.45$.

A second method of layering the atmosphere was used for water vapor in a subset of the channels. Water vapor amount can vary by 3 orders of magnitude in the lower troposphere from profile to profile, with a resultant strong variation in the transmittances in the those AIRS channels where water is a major absorber. For these channels we used an alternate layering technique to model the water optical depth that is better suited to handling these large variations. In this case, we sliced

the atmosphere using a grid of constant layer-to-space absorber amount. Since water amount varies with profile, the corresponding air pressure for every point on the amount grid usually varies with every profile. However, since optical depth is more strongly dependent upon absorber amount than air pressure, the variation in the regression data is significantly reduced and easier to fit than if we used a constant pressure grid. This is the layering scheme used by the OPTRAN model (refs).

4 Regression data set

The regression training data set consists of 48 profiles, each calculated at 6 viewing angles between 0 and 60 degrees (measured from the vertical, ie nadir = 0 degrees). The 48 profiles were selected to span the expected range of profile variability. Data for an additional 6 angles extending out to 83 degrees was created for the shortwave channels for use in creating a model of reflected solar radiance. We used different sets of break-out gases in different spectral regions. For most channels the break-outs were "fixed", water, and ozone, plus offset CO2. Methane was broken out in the 1300 cm^{-1} region, and Carbon Monoxide was broken out in the 2200 cm^{-1} region. The "fixed" gases consist of all gases not broken out as separate components.

The monochromatic transmittances for each profile were calculated using the KCARTA (refs) code, and included all gases contained in the 1998 HITRAN (refs) database. The far wing continuum component of the water vapor spectra was not included in the transmittances, and instead it was broken out by itself. The water continuum is nearly a constant over the width of an AIRS channel, and thus it can be separated from the non-continuum portion of the transmittance and moved outside the convolution integral. The water continuum is easily fit with a simple model, and by pulling it out as a separate component we simplify the problem of modelling the non-continuum water optical depth.

To simplify the fast model, the "fixed" gases amounts were kept identical in all profiles, with only the layer temperature allowed to vary. There is ordinarily a small variation in gas amount due to the combined effects of water displacement, air density, and gravity. This variation is typically less than a couple percent, and this is small enough to allow it to be adequately modelled as a separate term which multiplies the nominal fixed gases optical depth.

In addition to the transmittances, we also calculated a pair of radiances with and without the reflected downwelling thermal radiance term. This data is for use in creating a model of the downwelling term.

5 Predictors

The layer effective optical depths are modelled as simple functions of various profile dependent predictors. Typically these predictors are terms related to the layer temperature, absorber amount, and viewing angle. For OPTRAN layers, pressure would be used as a predictor instead of absorber amount. We chose the predictors for the AIRS fast model using a trial-and-error approach to determine the optimal set. The AIRS fast model uses seven main sets of predictors for the optical depths, with three supplemental sets for the water continuum, offset CO2, and water using the OPTRAN method.

Each predictor must be unique; no predictor can be a simple linear combination of other predictors. Otherwise nearly anything goes. Most of the predictors are terms involving layer values, but some predictors involve sums of terms in the layers above the current layer. Unlike monochromatic layer transmittances, the layer effective optical depths often depend upon the layers above as well as the current layer. While this might seem to be "unphysical" behavior, it is a natural consequence of deriving the layer effective optical depths from ratios of layer-to-space transmittances, and it is necessary to model this behavior to obtain accurate transmittances for the fast model.

The predictors used by our fast model are based upon simple functions involving the basic atmospheric state variables for the given profile. These are:

$P(i)$: mean air pressure in layer i
$T(i)$: mean air temperature in layer i
$W(i)$: Water amount in layer i
$O(i)$: Ozone amount in layer i
$M(i)$: Methane amount in layer i
$C(i)$: CO amount in layer i

The gas amounts used here refer to the amount of the absorber contained within the layer along a nadir path. This is sometimes called a column amount or an integrated cross-sectional density, and typically has units of molecules per square centimenter.

To prevent unforeseen numeric complications, it is a good idea to avoid using predictors of greatly different magnitudes. To help center our fast model predictor values around unity, most of the AIRS predictors have been ratioed or differenced with a layer temperature or amount from a "reference" profile. The choice of reference profile is somewhat arbitrary, for example it might be the mean of your regression profile set, or it might be some "typical" profile. For the AIRS fast model, we chose to use the US Standard Model profile.

Table 2: Fixed gases predictors

index	set 1,2,3	set 4	set 5	set 6,7
1	a	a	a	a
2	a^2	a^2	a^2	a^2
3	aT_r	aT_r	aT_r	aT_r
4	aT_r^2	aT_r^2	aT_r^2	aT_r^2
5	T_r	T_r	T_r	T_r
6	T_r^2	T_r^2	T_r^2	T_r^2
7	aT_z	aT_z	aT_z	aT_z
8	aT_z/T_r	a^2T_z	aT_z/T_r	$\sqrt{a}$
9	-	a^2T_r	a^2T_r	-
10	-	a^3	$\sqrt{a}$	-
11	-	$\sqrt{a}$	T_z	-

Table 3: Water line predictors for sets 1 to 3

index	set 1	set 2	set 3
1	aW	aW	aW
2	$\sqrt{aW}$	$\sqrt{aW}$	$\sqrt{aW}$
3	aWW/W_z	$aW\Delta T$	aWW/W_z
4	$aW\Delta T$	$aW(aO_x)$	$aW\Delta T$
5	$(aW)^2$	$(aW)^2$	$(aW)^2$
6	$\sqrt{aW}\Delta T$	$\sqrt[4]{aW}$	$\sqrt{aW}\Delta T$
7	$\sqrt[4]{aW}$	$\sqrt{aW}\Delta T$	$\sqrt[4]{aW}$
8	$\sqrt{aW}W/W_z$	aWW/W_z	$(aW)^3$
9	$(aW)^3$	$(aW)^3$	W
10	W	$aW(aO_x)^2$	$\sqrt{aW}W/W_z$
11	$aW\Delta T\lvert\Delta T\rvert$	$\sqrt{aW}W/W_z$	$aW(aM_z)$

Table 4: Water line predictors for sets 4 to 7

index	set 4	set 5	set 6	set 7
1	aW	aW	aW	aW
2	W	$(aW)^{3/2}$	$(aW)^{3/2}$	$(aW)^{3/2}$
3	$\sqrt{aW}$	$aW\Delta T$	$aW\Delta T$	$aW\Delta T$
4	$aW\Delta T$	-	$(aW)^2$	$(aW)^2$
5	$(aW)^2$	-	$(aW)^{3/2}\Delta T$	$(aW)^{3/2}\Delta T$
6	$\sqrt{aW}\Delta T$	-	$(aW)^3$	$(aW)^3$
7	$\sqrt[4]{aW}$	-	aWa	aWa
8	aWW/W_z	-	-	aWW/W_z
9	aWa	-	-	$(aW)^{3/2}W/W_z$
10	$(aW)^3$	-	-	$(aW)^{5/4}$
11	$aW(aC_z)$	-	-	$(aW)^2W/W_z$
12	$\sqrt{aW}W/W_z$	-	-	aWW
13	$aWa\Delta T$	-	-	$(aW)^{7/4}$

Table 5: Ozone predictors

index	set 1	set 2	set 4	set 5,6,7
1	aO	aO	aO	aO
2	$\sqrt{aO}$	$\sqrt{aO}$	$\sqrt{aO}$	-
3	$aO\Delta T$	$aO\Delta T$	$aO\Delta T$	-
4	$(aO)^2$	$(aO)^2$	-	-
5	$\sqrt{aO}\Delta T$	$\sqrt{aO}\Delta T$	-	-
6	-	aOO/O_x	-	-
7	-	$\sqrt{aO}O/O_x$	-	-
8	-	aOO_z/O_x	-	-
9	-	$aO\sqrt{aO_x}$	-	-
10	-	$aOaT_O$	-	-

Table 6: Methane and Carbon Monoxide predictors

index	CH4 set 3	CO set 4
1	aM	aC
2	$\sqrt{aM}$	$\sqrt{aC}$
3	$aM\Delta T$	$aC\Delta T$
4	$(aM)^2$	$(aC)^2$
5	aMa	aCC/C_z
6	aM_z	$\sqrt{aC}\Delta T$
7	$M\Delta T$	$\sqrt[4]{aC}$
8	aT_M	$\sqrt{aC}C/C_z$
9	$\sqrt{aM_z}$	C
10	-	aCa
11	-	$\sqrt{aC}a$

Table 7: Water continuum and offset Carbon Dioxide predictors, all sets

index	H2O con	offset CO2
1	aW/T_r^2	a
2	aW^2/T_r^4	T_r
3	aW/T_r	aT_r
4	aW^2/T_r	aT_r^2
5	aW^2/T_r^2	-

5.1 Predictor notation

The predictor tables use the following notation:

a : secant of the path zenith angle
T_r : Temperature ratio T_{prof}/T_{ref}
ΔT : Temperature difference $T_{prof} - T_{ref}$
W : Water amount ratio W_{prof}/W_{ref}
O : Ozone amount ratio O_{prof}/O_{ref}
M : Methane amount ratio M_{prof}/M_{ref}
C : CO amount ratio C_{prof}/C_{ref}
P : layer mean pressure, with special case $P(0) = 2P(1) - P(2)$
T_z : pressure weighted temperature ratio above

$$T_z = \sum_{i=2}^{L} P(i)\,(P(i) - P(i-1))\,T_r(i-1) \tag{9}$$

W_z : pressure weighted water ratio above

$$W_z = \frac{\sum_{i=1}^{L} P(i)\,((P(i) - P(i-1))\,W_{prof}(i)}{\sum_{i=1}^{L} P(i)\,((P(i) - P(i-1))\,W_{ref}(i)} \tag{10}$$

O_z : pressure weighted ozone ratio above (similar to W_z)
O_x : ozone ratio above

$$O_x = \frac{\sum_{i=1}^{L} O_{prof}(i)}{\sum_{i=1}^{L} O_{ref}(i)} \tag{11}$$

T_O : pressure and ozone weighted temperature difference above

$$T_O = \sum_{i=2}^{L} P(i)\,(P(i) - P(i-1))\Delta T(i-1)\,O(i-1) \tag{12}$$

C_z : pressure weighted CO ratio above (similar to W_z)
M_z : pressure weighted methane ratio above (similar to W_z)
T_M : pressure and methane weighted temperature ratio above

$$T_M = \sum_{i=2}^{L} P(i)\,(P(i) - P(i-1))\,T_r(i-1)\,M(i-1) \tag{13}$$

Table 8: Water lines OPTRAN predictors

index	H2O OPTRAN
1	1
2	P_{op}
3	T_{op}
4	$\sqrt{P_{op}}$
5	T_{op}^2
6	$P_{op}T_{op}$
7	a_{op}
8	P_{zop}
9	T_{zop}

5.2 OPTRAN water lines

The OPTRAN method was used to model the water optical depth in some longwave channels. For these channels the OPTRAN model is used instead of the nominal pressure layer model for water. In use, the OPTRAN determined optical depths are interpolated onto the pressure layer grid so that they may be added to the optical depths for the other gases.

The table of OPTRAN predictors uses the following notation:
a_{op} : secant of the path zenith angle
P_{op} : pressure
T_{op} : temperature
P_{zop} : water amount weighted pressure above
T_{zop} : water amount weighted temperature above

Since the OPTRAN layering scheme uses a layer-to-space water amount grid while the main portion of our AIRS fast model uses a constant pressure grid, we calculate the above OPTRAN predictors at the AIRS pressure layers and then linearly interpolate them to the OPTRAN grid. At layer L on the constant pressure grid, the meaning of the OPTRAN predictors becomes:

$$a_{op} = a(L) \tag{14}$$

$$P_{op} = P(L) \tag{15}$$

$$T_{op} = T_{prof}(L) \tag{16}$$

$$P_{zop} = \frac{\sum_{i=1}^{L} P(i)\, a(i)\, W_{prof}(i)}{\sum_{i=1}^{L} a(i)\, W_{prof}(i)} \tag{17}$$

$$T_{zop} = \frac{\sum_{i=1}^{L} T_{prof}(i)\, a(i)\, W_{prof}(i)}{\sum_{i=1}^{L} a(i)\, W_{prof}(i)} \tag{18}$$

To help avoid potential numeric problems, once the four main OPTRAN predictors P_{op}, T_{op}, P_{zop}, and T_{zop} are interpolated from the constant pressure grid onto the water amount OPTRAN grid, they are scaled so as to normalize them close to unity. This is accomplished by dividing them by what is essentially a separate OPTRAN reference profile value. The OPTRAN reference value for each of the four main predictors is the mean value of that predictor over the regression profile set.

6 Weighting the data

The main purpose of the AIRS fast model is to compute simulated AIRS radiances. The accuracy of the simulated radiances will depend upon the quality of the modelling of the convolved transmittances, but the radiance calculation is more sensitive to some ranges of transmittance values than others. Returning to the discrete form of the radiative transfer equation, we can re-write the radiance contribution of each atmospheric layer as

$$B(T_L)\,(\tau_{\blacktriangle L-1} - \tau_{\blacktriangle L}) = B(T_L)\,(1 - \tau_L)\,\tau_{\blacktriangle L-1} \tag{19}$$

where τ_L is the effective layer transmittance of layer L, with $\tau_{\blacktriangle L} = \tau_L\,\tau_{\blacktriangle L-1}$.

With the equation re-written in this form, it is easier to see that the radiance contribution of each layer depends upon both the layer transmittance as well as the layer-to-space transmittance of the layer above. This transmittance product is often refered to as the "weighting function" since it acts as a weight on the layer Planck term and thus the radiance contribution.

Since the regression fits optical depths rather than transmittances, we must also consider how an error in optical depth will translate into an error in transmittance. We can write the transmittance error in terms of the optical depth K as

$$exp(\,-K(1+\epsilon)\,) - exp(-K) \tag{20}$$

Table 9: Optical depth weight table

original	weighted
0.0553	1
0.190	3
0.385	5
0.540	6
1.00	7
1.65	6
2.90	3
3.49	2
4.41	1

where ϵ is some small magnitude fractional error in K. This equation has a maximum at $K = 1$, indicating the transmittance is most sensitive to the optical depth when the value is close to unity.

We made note of these dependencies when weighting the regression data. For the AIRS fast model regression, the weight applied to the training data was a product of weights determined separately for the layer optical depth and the layer-to-space optical depth. The weights were determined by interpolating a simple lookup table of optical depths versus weighted values. The table was developed from a trial and error approach.

[The actual weight computation is more complicated than explained here, but this is the gist of it]

The weighted value from the table is the new value for the optical depth, not the weight itself. The weight is obtained by dividing the original optical depth by the weighted value. To balance the equations, the same weight applied to the optical depth must also be applied to the predictors. In the notation used previously, this is equavalent to

$$WAX = WB = A_w X = B_w \tag{21}$$

where
W is the (m x m) diagonal matrix of weights,
$A_w = WA$ is the weighted (m x n) matrix of predictors, and
$B_w = WB$ is the weighted (m x 1) vector of optical depths.

The regression then solves for X, the vector of coefficents for the predictors. Note that the weight is only used to help optimize the error characteristics of the

regression; otherwise it has no effect on the values of coefficents.

7 Radiative transfer

The simple radiative transfer equation introduced earlier ignores the issue of radiances reflected from the surface. The two main sources of reflected radiance in the IR are solar radiance and downwelling thermal radiance emitted by the atmosphere.

7.1 Reflected Solar Radiance

The solar radiance term comes from sunshine that passes down through the atmosphere, strikes the surface, and is reflected back upward through the atmosphere to the observing instrument. The reflected solar radiance that reaches the observing instrument is

$$R_{solar} = R_{in}\,\tau_{\blacktriangle s}(\theta_{sun})\,\cos(\theta_{sun})\,\rho\,\tau_{\blacktriangle s}(\theta_{sat}) \tag{22}$$

where R_{in} is the incoming solar radiance at the top of the atmosphere, θ_{sun} and θ_{sat} are the solar and satellite zenith angles, and ρ is the reflectivity. $\tau_{\blacktriangle s}(\theta_{sun})$ is the surface-to-space transmittance along the downward path though the atmosphere, and $\tau_{\blacktriangle s}(\theta_{sat})$ is the transmittance on the upward path. The cosine term accounts for the dependence of the projected solar beam area on the zenith angle.

If the atmosphere is the same along both paths through the atmosphere, then the product of the two monochromatic transmittances can be expressed as

$$\tau_{\blacktriangle s}(\theta_{sun})\,\tau_{\blacktriangle s}(\theta_{sat}) = \tau_{\blacktriangle s}(\theta_{eff}) \tag{23}$$

where θ_{eff} is the effective total angle through the atmosphere, and is given by

$$\theta_{eff} = \sec^{-1}(\,\sec(\theta_{sun}) + \sec(\theta_{sat})\,) \tag{24}$$

Thus the reflected solar radiance depends on a single transmittances whos secant is equal to the sum of the secants of the solar and satellite zenith angles. If both R_{in} and ρ vary slowly compared to the instrument SRF, then we can again use the trick of approximating a convolved monochromatic radiances with a radiance computed using a convolved transmittance. Although there is some fine structure in the solar spectra, it is relatively unimportant for AIRS and this technique works well.

While this model is fairly simple, note that it does require a separate transmittance calculation at the total secant angle. In addition, the fast model must be

capable of calculating transmittances at large secants. Due to the spectral characteristics of the incoming solar radiance, the reflected solar contribution is only significant in the AIRS shortwave channels (514 channels between 4.8 and 3.7 μ m). For these channels the transmittance model was extended out to secant=9, which allows for modelling of the solar term out to $\theta_{sun} = 80°$. The large range of secants increases the difficulty of fitting the optical depths, and this partially explains our use of a large number of predictors for some of the shortwave channels.

7.2 Reflected Downwelling Thermal Radiance

The reflected downwelling radiance term comes from the thermal emission of the atmosphere, and includes radiance contributions from all directions. If we assume azmuthal symmetry, the monochromatic reflected downwelling can be expressed as

$$R_{down} = \tau_{\blacktriangle s}(\theta_{sat}) \sum_{L=1}^{N} \int_0^{\pi/2} B(T_L)\,(1 - \tau_L(\theta))\,\tau_{\blacktriangledown L+1}(\theta)\,\cos(\theta)\,\rho\,2\pi\,\sin(\theta)\,d\theta \quad (25)$$

Here we have explicitly denoted the dependency of the transmittances on the path zenith angles as this is the variable we must integrate over. The downward pointing triangle in $\tau_{\blacktriangledown L+1}$ is used to denote this is the transmittance is between layer $L + 1$ and the surface.

An approximation can be made to replace the integral over all possible downward angles with a single angle θ_d that best represents the integral. If the reflectivity is the same at all angles (ie Lambertian), then the best angle is typically close to 53°. This is called the diffusivity approximation, and the equation becomes

$$R_{down} = \pi\,\rho\,\tau_{\blacktriangle s}(\theta_{sat}) \sum_{L=1}^{N} B(T_L)\,(1 - \tau_L(\theta_d))\,\tau_{\blacktriangledown L+1}(\theta_d) \quad (26)$$

Even in this simplified form, the equation still presents no simple solution for use with a fast model. Note that the transmittances in the sum are between the layer and the surface, not the layer and the top of the atmosphere. It might be possible to do another regression to calculate convolved transmittances along the total path (layer to surface to space), but that is obviously not a simple or quick solution.

For a typical surface reflectivity of just a few percent, the reflected thermal term typically only adds a few tenths of a Kelvin to the observed brightness temperatures. In such cases a crude approximation might be adequate if the errors in the reflected thermal term are generally below the noise level of the instrument. The AIRS fast model makes use of an approximation suggested by Susskind and Barnet

Table 10: "F" predictors

index	predictor
1	1
2	$1/a$
3	$B(T_t)$
4	$B(T_t)/a$
5	$B(T_s)/B(T_t)$

(refs):

$$R_{down} = \pi \rho \tau_{\blacktriangle s}(\theta_{sat}) (1 - \tau_{\blacktriangle s}(\theta_{sat})) B(T_t) F \quad (27)$$

where T_t is the temperature of some particular layer t, and F is a fudge factor to be determined by regression.

Note that this approximation uses only a single layer-to-space transmittance, and this particular transmittance is one of those already calculated for the upward atmospheric thermal emission. For the AIRS fast model, the F term is a simple function of view angle and Planck emissions for layer t and the surface, with the coefficients of these predictors determined by regression. The simplicity of the R_{down} approximation allows the AIRS fast model to calculate the term very quickly, but the crudeness of the approximation limits its accuracy; the RMS errors are estimated to be 15 to 20 %.

8 Results

We used the kCARTA line-by-line code to calulate simulated monochromatic radiances for an independent set of 212 TIGR profiles each at 5 angles spanning 0 to 48 degrees. These radiances were then convolved with the AIRS SRFs, and the convolved radiances were then compared with radiances calculated using the AIRS-RTA. The difference between the kCARTA and AIRS-RTA radiances thus provides an estimate of the accuracy of the parameterizations and approximations used by the AIRS-RTA. See the three plots of the mean brightness temperature and RMS errors for the AIRS-RTA.

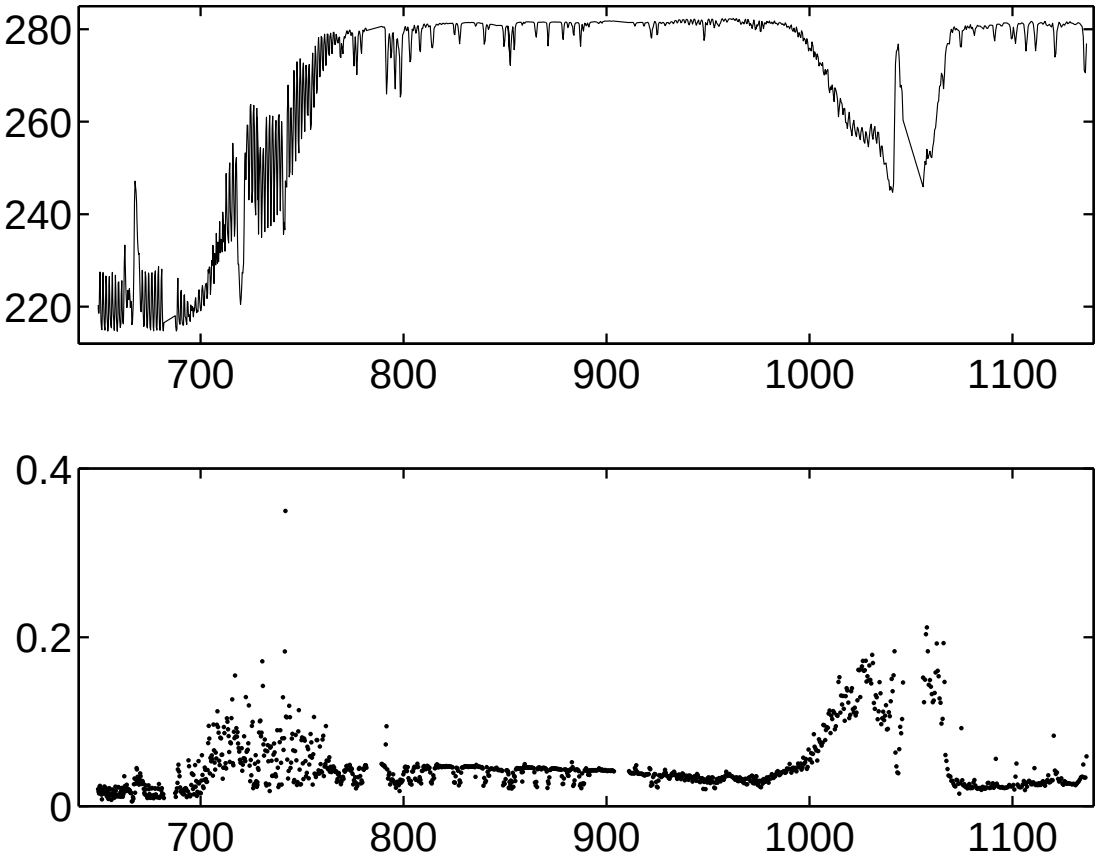

Figure 1: The top plot shows the mean brightness temperature for the independent set of TIGR profiles for AIRS channels in the 640 - 1140 cm^{-1} region. The bottom plot shows the RMS difference of AIRS-RTA calculations compared to kCARTA calculations.

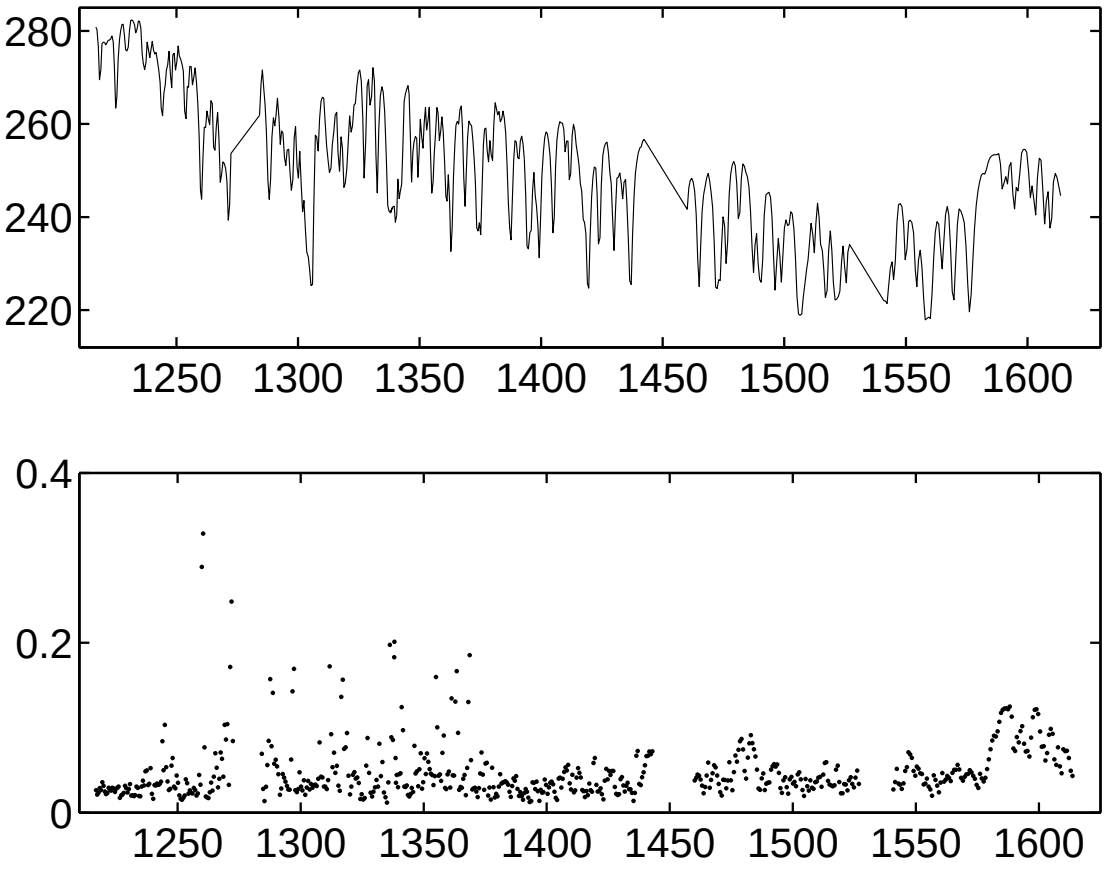

Figure 2: The top plot shows the mean brightness temperature for the independent set of TIGR profiles for AIRS channels in the 1210 - 1620 cm^{-1} region. The bottom plot shows the RMS difference of AIRS-RTA calculations compared to kCARTA calculations.

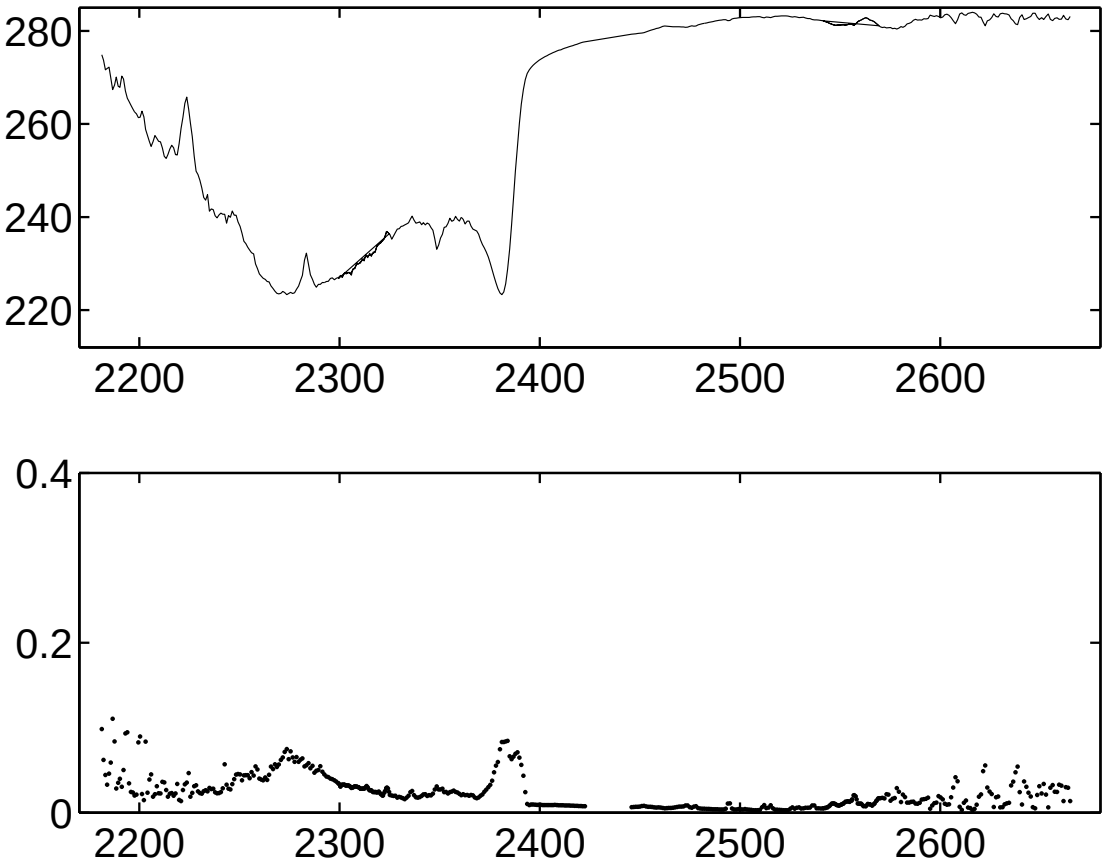

Figure 3: The top plot shows the mean brightness temperature for the independent set of TIGR profiles for AIRS channels in the 2180 - 2670 cm^{-1} region. The bottom plot shows the RMS difference of AIRS-RTA calculations compared to kCARTA calculations.