ADVANCED SOUNDING PROJECT, Summary
Summer 98

AIRS
+
Radiative Transfer
+
Groundwork for the Future Retrievals of CO_2, CO, CH_4, and Strospheric Water with the AIRS Instrument

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Contents

1 The Short-Shrift

Brief, simplistic, and informal are three good words to describe this little paper. There are references to (and inclusions of) better, more thorough information sources within the text, for the more serious. My goal was to sum up relevant knowledge, not impress. Speaking of not impressing you, the following glosses over some pretty difficult stuff and leaves out many a topic (such as clouds), but it's a pretty good start.

2 AIRS

The Atmopheric Infrared Sounder (AIRS) is a grating interferometer designed to provide fast, global coverage of the earth in the infrared region. With an expected launch date of Dec. 31, 2000 on the EOS PM-1 satellite, the AIRS instrument will provide spectral data for 2,373 unique frequencies (channels) in the IR band, sampling ninety 1.10 degree footprints per scan, 200,232 footprints per EOS orbit, 2,916,000 footprints per day, at a rate of 270 footprints in 8s (corresponding to 30 footprints of the AMSU, a microwave sounder also hosted on the EOS platform). A 1.1° FOV at the PM-1 altitude corresponds to a 13.5km(nadir-0° scan angle) to 41x22.4km(49°) spot size on the earth.

2.1 The AIRS Design

AIRS represents a major advance over previous sounders. The following was lifted from the AIRS website [http://www-airs.jpl.nasa.gov/].

> In the spectrometer, infrared energy from the surface and atmosphere enters the instrument via a telescope that directs the energy to eleven different spectrometer slits. Each slit is covered by an optical bandpass filter, providing the first stage of spectral separation. The energy from each slit is then dispersed across the focal plane.
>
> The focal plane consists of an array of HgCdTe detectors cooled to 60K (-213C) by a Stirling/pulse tube cryocooler. The IR spectrometer is also cooled to 150K (-123C) by a two stage radiative cooler (the large "scoop" on the side of the instrument). Cooling of the spectrometer and the detectors is necessary for the required instrument sensitivity determined by the required accuracy of the measurements.
>
> The VIS/NIR photometer uses optical filters to define four spectral bands in the 400 nm to 1000 nm region. It operates in ambient ranges of 293 to 300K (20C to 27C). Signals from both the spectrometer and the photometer pass through onboard signal and data processing electronics. Data from AIRS are finally transmitted to the spacecraft an average rate of 1.27 Mbps.
>
> Calibration of the instrument will be done in-flight during each scan period. The primary spectral calibration is based on the precise knowledge of the location of the spectral features in the upwelling radiance spectra. Additionally, AIRS uses four independent cold space views and on-board calibration sources.
>
> **Key AIRS Facts** · Prime Contractor: Lockheed Martin · Responsible Center: Jet Propulsion Laboratory, California Institute of Technology · High spectral resolution, multispectral infrared sounder · Operates with AMSU for all-weather capability · 1K temperature retrieval accuracy · 0.05 emissivity accuracy · Array grating spectrometer (3.74 to 15.4 um), with a spectral resolution of 1,200 (l/Dl) · Physical size: 116.5 x 80 x 95.3 cm (stowed); 116.5 x 158.7 x 95.3 cm (deployed)

3 The Data

3.1 Radiances

The AIRS instrument seperates the incoming light by wavelength via a grating, piping the result to a bank of presicely placed photodetectors. Each of the 2,373 channels measures the radiance (number of photons) for its frequency and when plotted, these give us a spectra like that shown in Figure 1. This spectra represents the molecular activiy in the atmosphere, i.e.. the absorption, emission, etc., of the active atmospheric constituents (e.g. water, ozone, carbon dioxide, ...). (See list of atmospheric constituents, Table 1)

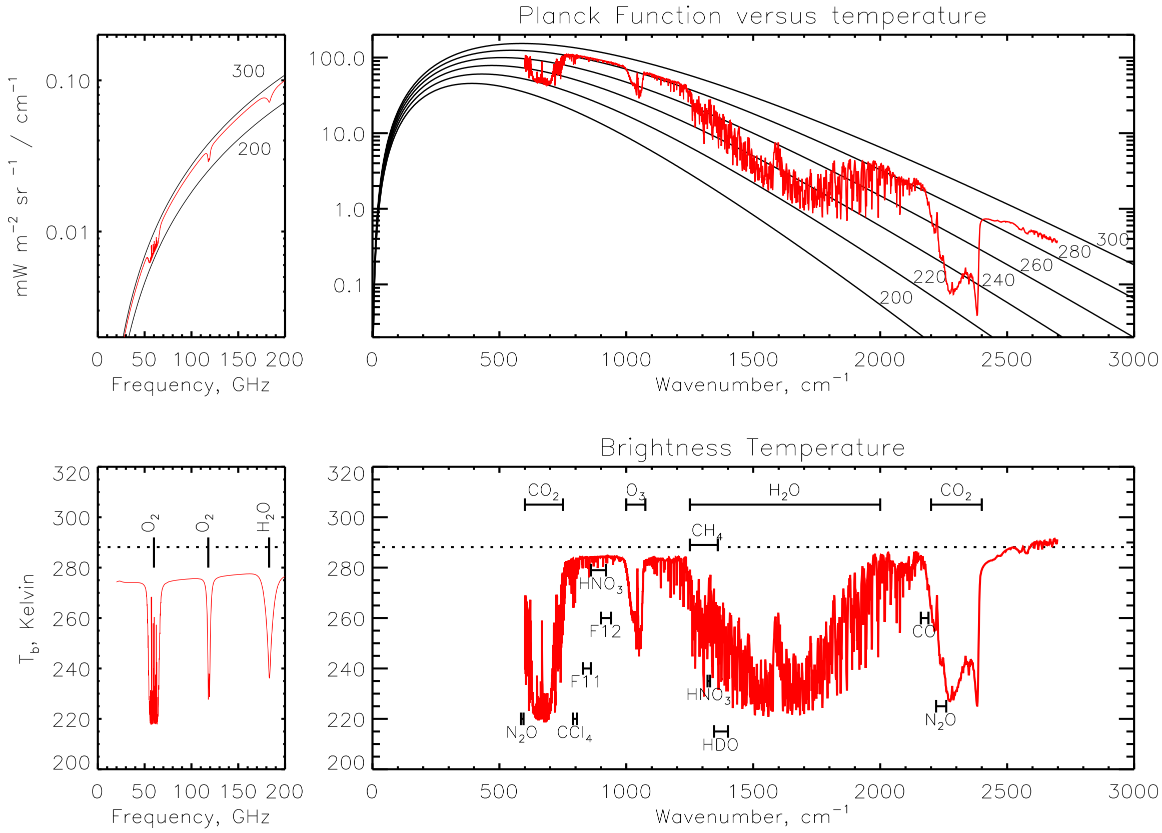

Figure 1a: bottom right, sample spectra in AIRS range.

Table 1: The Composition of the Atmosphere*

Permanent		Variable	
Constituent	% by volume	Constituent	% by volume
Nitrogen (N_2)	78.084	Water vapor (H_2O)	0-0.04
Oxygen (O_2)	20.948	Ozone (O_3)	0-12$\cdot10^{-4}$
Argon (AR)	0.934	Sulfur dioxide (SO_2)[b]	0.001$\cdot10^{-4}$
Carbon Dioxide (CO_2)	0.033	Nitrogen dioxide (NO_2)[b]	0.001$\cdot10^{-4}$
Neon (Ne)	18.18$\cdot10^{-4}$	Ammonia (NH_3)[b]	0.004$\cdot10^{-4}$
Helium (He)	5.24$\cdot10^{-4}$	Nitric oxide (NO)[b]	0.0005$\cdot10^{-4}$
Krypton (Kr)	1.14$\cdot10^{-4}$	Hydrogen sulfide (H_2S)[b]	0.00005$\cdot10^{-4}$
Xenon (Xe)	0.089$\cdot10^{-4}$	Nitric acid vapor (HNO_3)	Trace
Hydrogen (H_2)	0.5$\cdot10^{-4}$		
Methane (CH_4)	1.5$\cdot10^{-4}$		
Nitrous oxide (N_2O)[b]	0.27$\cdot10^{-4}$		
Carbon monoxide (CO)[b]	0.19$\cdot10^{-4}$		

* US Standard Atmosphere, 1976

[b] Concentration near the earth's surface

3.2 A Real Brief Atmospheric Spectroscopy Review

If you dare remember some quantum mechanics, you'll recall that atoms can absorb (except a photon and enter a higher energy state) or emit (release that photon lowering their energy state) and do so at different frequencies. The same is true for groups of atoms (molecules) in the atmosphere, although more complex. The electromagnetic radiation emitted by free atoms is concentrated at a number of discrete wavelengths [or lines, because of their appearance].[7] This information can be used to find quantities of a particular type of atmospheric component at different altitudes (called a profile). Complication occurs due to the diversity/quantity of molecules in the atmosphere emitting and absorbing; the spectra we see in the IR is the *combination* thereof. Factors such as rotation, collisions, pressure/temperature broadening and other quantum-level effects further muddy the result making the seperation of one particular molecule's line structure extremely difficult.

· Certain channels will "see" a specific atmospheric gas at some altitude in the atmosphere better than others (possible because of the high spectral resolution of AIRS and good channel selection), but the intensity will still be skewed by the effect of overlapping molecules absorbing/emitting in that same frequency.

· We must also recognize the effect of the atmosphere itself as photons emitted from below are absorbed and re-emitted as they travel to space.

· By the way, peaks in the spectra usually represent emission and "U"s usually represent absorption. So, for example, the structure between roughly 2300 and 2400 wavenumbers in Figure 1 represents a set of emission lines of carbon dioxide in that frequency range.

· The major constituents nitrogen and oxygen, because of their symmetry, possess no electric dipole transitions and hence no strong bands due to them occur in the infrared.[10]

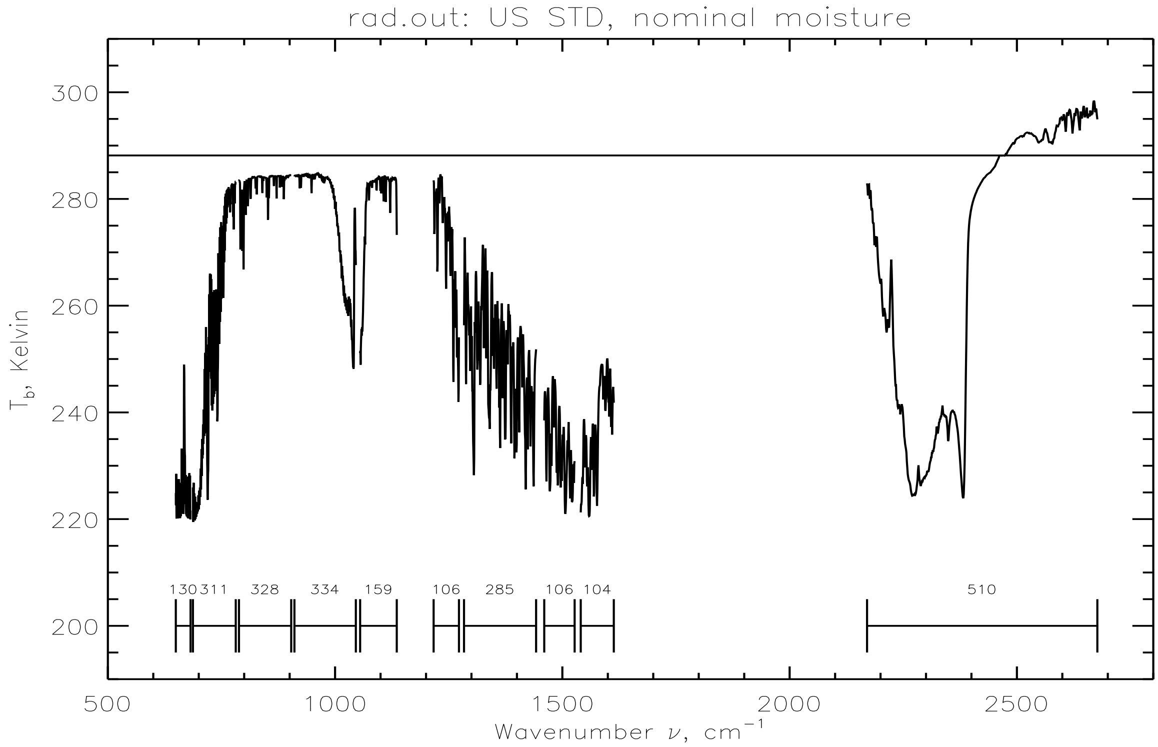

Figure 1b: Simulated radiances for AIRS channels. US standard atmophere, nadir scan angle, sun overhead.

4 The Products

4.1 What We've Got and What We Want

This is earth science, remember? Our goal is to provide useful data to all those scientists out there running their little 'tests' to save the world. AIRS gives us radiances (aka photon counts): useless, right? Enter physics. From those radiances, the geophysical state of the atmosphere can be deduced, e.g. the vertical temperature profile, $T(p)$, the moisture profile, $q(p)$, the vertical ozone profile, $O_3(p)$, the surface temperature, T_s, the spectral surface emissivity, ϵ_ν, and the surface reflectivity, ρ_ν. This difficult process constitutes a **retrieval**. (We're *retrieving* these products from the instrument radiances.)

Leaving this rather global topic for a later section, let's tackle a simpler problem first: namely going backwards, calculating the expected radiances at the satellite from profile data (the aptly named "forward" problem), which is needed in the retrievals.

5 Radiative Transfer

5.1 The "Forward" Problem, Total Monochromatic Radiances

As mentioned before, the "forward" problem refers to the process of calculating the radiances at the top of the atmosphere from the geophysical input data, $T(p)$, $q(p)$, $O_3(p)$, T_s, ϵ_ν, and ρ_ν. This total monochromatic radiance, $R(\nu,\theta)$, at frequency, ν (corresponding to one channel), and zenith angle, θ (local zenith to spacecraft), can be seperated into components from the surface, atmosphere, reflected downwelling, and reflected solar plus cosmic background radiation:[2]

$$R(\nu,\theta) = R_s(\nu,\theta) + R_a(\nu,\theta) + R_d(\nu,\theta) + R_s(\nu,\theta) \tag{1}$$

ν, wavenumber (cm^{-1} = $10^4/\lambda$, λ in μm or $\nu = f/30$, f in GHz)

θ, angle from the local zenith to the spacecraft

- The surface component, R_s:

$$R_s(\nu,\theta) = \epsilon_\nu \cdot B_\nu(T_s) \cdot \tau_\nu^{\uparrow}(P_s,\theta) \tag{2}$$

$\hookrightarrow$ ϵ_ν, spectral surface emissivity

$\hookrightarrow$ $B_\nu(T_s)$, planck function (blackbody spectrum):

$$B_\nu(T) = \frac{2hc^2 \cdot \ \nu^3}{exp(\frac{\frac{hc}{k}\cdot\nu}{T}) - 1}$$

T, temperature in degrees K
$2hc^2 = 1.191066 \cdot 10^{-5}$ for radiance in units of mW $\cdot$m^{-2} $\cdot$ steradian^{-1}/cm^{-1}
$hc/k = 1.438833$ K/cm^{-1}
c = speed of light = $2.99792458 \cdot 10^{10}$ cm/s
h = Planck's constant = $6.626075(40) \cdot 10^{-27}$ erg sec
k = Boltzmann's constant = $1.380658(12) \cdot 10^{-16}$ erg/K

[2]Note: All equations lifted from documentation by Chris Barnet unless wrong. In that case, he had nothing to do with it.

$\hookrightarrow$ $\tau_\nu^\uparrow(P_s,\theta)$, surface to space transmittance:

$$\tau_\nu^\uparrow(\nu,\theta) = e^{-\int\limits_z \sum\limits_i \kappa_\nu^i(T,p,a)dz/sec(\theta)} \tag{3}$$

"Transmittance is the fraction of light propagating through a medium. The values of transmittance range from zero (opaque) to one (completely transmissive). It represents a vertical integration of the absorption coefficients, κ^i, which are strongly dependant on the composition, a (the mixing ratio of the radiatively active species), temperature, and pressure along the path [from the surface to the instrument defined by the angle, θ]."[6] This equation is also known as Beer's Law.

In atmospheric science, the atmosphere is usually broken up into isobaric 'layers', counted from 0 to N_L from the *top* of the atmosphere (space). Each layer, L, is defined by pressure levels at the top, $p(L-1)$, and bottom, $p(L)$, giving the layer a thickness, $\Delta z(L)$. The bottom layer, or surface, defined at $P_s \equiv p(N_L)$, includes the effect of topography and local weather systems. Refer to the Appendix for a figure that might help you visualize.

The current implementation defines a hundred such layers (101 pressure levels).

- The atmospheric component, R_a:

$$R_a(\nu,\theta) = \int\limits_{p=P_s}^{0} B_\nu(T(p)) \cdot \frac{d\tau_\nu^\uparrow(p,\theta)}{dp} \cdot dp \tag{4}$$

p, the isobaric level

- The downwelling component, R_d:

$$R_d(\nu,\theta) = \tau_\nu^\uparrow(P_s,\theta) \int\limits_{p=0}^{P_s} B_\nu(T(p)) \frac{d\left[2\pi \int\limits_{\theta'=0}^{\pi/2} \sin(\theta')\cos(\theta')\rho_\nu(\theta,\theta') \cdot \tau_\nu^\downarrow(p,\theta') \cdot d\theta'\right]}{d\ln(p)} \cdot d\ln(p) \cdot d\nu \tag{5}$$

θ', angle from local zenith to an arbitrary location in the atmosphere

$\rho_\nu(\theta,\theta')$, the monochromatic reflectivity of the thermal downwelling radiance

$\tau_\nu^\downarrow(p,\theta')$, the monochromatic thermal downwelling transmittance, related to the upwelling transmittance: $\tau_\nu^\downarrow(p,\theta') = \frac{\tau_\nu(P_s,\theta')}{\tau_\nu(p,\theta')}$

- The reflected solar component, R_s:

$$R_s(\nu,\theta) = \Omega(t) \cdot cos(\theta_\odot) \cdot \rho_\nu(\theta,\theta_\odot) \cdot H_\nu \cdot \tau_\nu^\downarrow(P_s,\theta_\odot) \cdot \tau_\nu^\uparrow(P_s,\theta) \tag{6}$$

$\Omega(t)$, the solar solid angle as a function of season; $\bar{\Omega} = \pi \cdot 2.15976 \cdot 10^-5$

$\theta_\odot$, angle from local zenith to the sun

$\rho_\nu(\theta,\theta_\odot)$, the monochromatic solar reflectivity

H_ν, solar radiance

An Aside: Brightness Temperature

Since normal values of radiances can be spread over several orders of magnitude it is convenient, instead, to display multi-spectral radiance information in terms of brightness temperature, Θ_b. Defined as that temperature where the Planck function equals the radiance, R_ν, it can be thought of as the inverse of the Planck function.

$$R \equiv B_\nu(\Theta_b)$$

$$\Theta_b \equiv B_\nu^{-1}(R_\nu) = \frac{\frac{hc}{k} \cdot \nu^3}{log_e[1 + \frac{2hc^2 \cdot \nu^3}{R_\nu}]}$$

Now that we understand how to calculate the monochromatic radiances, let's look at what's really used.

5.2 Complicating Matters: The SRF, Speed, and Channel Averaging

AIRS is a real instrument with a finite spectral resolution, thus the theoretical radiances explained above that don't utilize the spectral or channel response function (SRF), $\phi_i(\nu - \nu_i)$, are inaccurate when used on AIRS data. "The radiance recorded by the observing instrument is the incident atmospheric monochromatic radiance convolved by the instrument's Spectral Response Function."[4] To compare forward computation results with radiances acquired by AIRS, the theoretical radiances would first have to be convolved with the AIRS SRF, a sensitivity weighting for each channel.

Calculating the monochromatic radiances and then convolving them with the SRF is much too slow to keep up with the data rate from AIRS (and remember, the forward problem is only one part of the retrieval process). To greatly speed things up, the convolved radiances can be calculated directly (since this is all we want anyway) from channel averaged values of τ_ν, τ_n, which have been weighted by the SRF and averaged per channel (this process will be further clarified in the next section). The resulting radiances differ from the convolved monochromatic radiances by $\leq$ 0.1 K which is generally less than the nominal 0.2 K RMS noise of AIRS.[3] Further, τ_n can be precomputed and fit to a rapid transfer algorithm (next section) decreasing a calculation time on the order of a day to seconds or less.

6 The Rapid Transmittance Algorithm

(a.k.a the FTC, FTM, RTM, or the FFM)

The RTA described here was developed by Strow *et al* of the University of Maryland Baltimore County Physics Department. Much of the following content is based on his documentation.

6.1 The Basic Idea

The following is another (simplified) form of the monochromatic radiative transfer equation without downwelling or reflected solar:

$$R = \epsilon_s \cdot B(T(s)) \cdot \tau_z(L) + \sum_{i=1}^{L} B(T(i))(\tau_{z(i-1)} - \tau_{z(i)}) \qquad (7)$$

ϵ_s, the surfuce emissivity
T, the temperature profile where $T(s)$ is the surface temperature and $T(i)$ is a layer temp.
τ_z, monochromatic layer-to-space transmittance

But this isn't what we need. We need radiances convolved with the AIRS SRF to compare with the actual AIRS data. Using a polychromatic approximation (the above equation where monochromatic values are replaced with their like channel averaged values) we can solve for the convolved radiances directly, saving us from calculating the monochromatic radiances first and then convolving them (much slower). The product of the RTA is a set of convolved, channel averaged transmittances used to compute the convolved radiances; it's heart is a set of coefficients and predictor definitions that together with inputted profile and physical data produce these τ_n. Here's a very brief outline (editted) of the process from documentation by Strow *et al* - see that and the next section for more detailed information.

1. Select a small set of atmospheric profiles that statistically spans the set of all possible observed atmospheric profiles. Currently, 36 profiles at 5 viewing angles are used for this spanning set. More profiles or angles can be added as desired.
2. Generate monochromatic layer-to-space transmittances for all layers for these 36 profiles. [This is done with the GENLN2 line by line algorithm with corrections based on more detailed lab spectroscopy in critical areas.]
3. Convolve the layer-to-space profiles with the AIRS SRF.
4. Ratio the convolved layer-to-space transmittances to form effective layer transmittances.
$$\tau_{eff}(L) = \frac{\tau_{z,L}}{\tau_{z,L-1}} \tag{8}$$
Note, $\tau_{z,L}$ is a convolved layer-to-space transmittance, and τ_{eff} is an effective (channel averaged) layer transmittance. [This ratio of the $\tau_{convolved}$'s avoids the breakdown of Beer's Law (causing large radiance errors) which occurs if polychromatic radiative transfer is performed using layer transmittances that have been directly convolved from the monochromatic layer transmittances.]
5. Take the natural log of these effective transmittances [to get optical depth].
$$k_{eff} = -ln(\tau_{eff}) \tag{9}$$
6. Fit the $36 * 5 k_{eff}$'s for each layer to an empirical function,
$$k_{eff} = \sum_{i=1}^{n} c_i Q_i \tag{10}$$
where Q_i is the i^{th} profile dependant predictor, n the number of predictors, and the c_i are the so called fast transmittance coefficients that are determined from a least-squares fit.

The predictors are simple functions of parameters such as layer temperature, absorber amount, and viewing angle. However, because of the loss of Beer's Law, some predictors involve profile parameters in layers above the layer of interest. Note, the regression is performed on $-ln(\tau)$, the optical depth, and not on τ itself. The generation of the monochromatic layer-to-space transmittances depends on accurate spectroscopy and a good line-by-line algorithm.

That's the basic gist of it. You can think of the RTA as a black box that cranks out radiances per channel with profile and physical data as inputs. For the interested, here's a summary of the implementation oriented, channel averaged radiative transfer equations for the new algorithm that require more than a simple interchange of τ_ν and τ_n.

· The channel averaged effective layer transmittance:

$$\tau_n = exp(-\kappa) \tag{11}$$

The RTA actually deals internally with the total layer optical depth, κ, (it's more accurate) rather than τ. κ is calculated from the coefficients, predictors, and profiles, and this simple relation is used at the end before output.

· The solar component:

$$R_s = H \cdot \Omega \cdot cos(\theta_\odot) \cdot \tau_n(P_s, \theta) \cdot \rho(\theta, \theta_\odot) \tag{12}$$

· To be continued...

6.2 The Old and the New - The Impetus of What I Did This Summer

Earlier this year, UMBC delivered a new rapid algorithm much more advanced (and complex) than the old. It's implementation and a brief analysis of its new abilities constituted most of the useful part of my summer.

The new algorithm has been improved over the old on nearly all levels. The lab spectroscopy is better, the physics is better (bugs have been fixed), reflected solar and downwelling have been added (not present in the previous RTA), all making the predicted radiances more accurate. In addition, the algorithm now uses the most up to date SRFs and measurements of the yet to be flown instrument's actual channel-centered frequencies. But what's even more interesting is that the new RTA 'breaks out' methane and carbon monoxide allowing the user to perturb these individually (along with CO_2) to see their relative effects on the the radiation budget. This makes it possible (given that their effects are visible) to 'retrieve' these gases just as is currently done for other retieval products such as air temperature and moisture. The new accuracy, especially dealing with water (OPTRAN), also allows close inspection of the effects of stratospheric water as well. (More on all this below.)

The transmittance through a layer is a function of the gaseous quantites within that layer (plus liquid water). These are made up of the normal atmospheric constituents, mostly nitrogen and O_2 (which are inactive), and active gases like ozone, methane, and CO_2. Changes in the amount of the active gases and water can have a great effect on the transmissivity. The RTA, to make calculations feasible and possible, groups most of the gasses into a 'fixed' category while the important quantities are "broken out" of this category and can be perturbed seperately. This is a very difficult thing to do because of the approximations made throughout the process and the fact that each broken out gas is not isolated from the others but rather dependant on them. This is impressive stuff.

This new UMBC RTA represents the state of the art. It's based on the best instrument data, the best lab spectroscopy, and the best physics with incredibly small noise. Now let's do something with it.

6.3 A Note About Implementation for GSFC

Nothing's ever perfect and neither was this. UMBC's implementation philosophy differred greatly from that needed in the GSFC retrieval code. For three plus weeks, my task was to 1) get the UMBC code into a form suitable for GSFC and 2) get it working. The biggest obstacle to overcome was that whereas GSFC requires a channel-by-channel ability to calculate τ and R, UMBC designed their code to calculate a whole spectra at a time. There were many, little (and big) changes to the UMBC code that aren't worth mentioning here. Just realize that by the time all was said and done, the code looked very different, did what we wanted, and worked. (And after Chris was done with it, it was totally unrecognizable, still did what we wanted, and worked better.)

7 The Magic That is a Retrieval

The goal of a retrieval is to find the geophysical state of the atmosphere from brightness temperatures, converted from radiances measured on the orbiting instrument (the reverse of the forward problem). There are two basic types of retrievals: statistical retrievals and physical retrievals.

- statistical retrievals:
  - based on regression
$$X^n = A \cdot \tilde{\Theta} \tag{13}$$
$$\begin{pmatrix} T_s \\ \epsilon(\nu_1) \\ \epsilon(\nu_2) \\ T(1) \\ \dots \\ T(L) \\ \\ q(1) \\ \dots \\ q(L) \end{pmatrix}_I = \begin{pmatrix} A_{11} & \dots & A_{1N} \\ A_{21} & \dots & A_{2N} \\ \dots & \dots & \dots \\ A_{I1} & \dots & A_{IN} \end{pmatrix} \cdot \begin{pmatrix} \tilde{\Theta}(1) \\ \tilde{\Theta}(2) \\ \dots \\ \tilde{\Theta}(N) \end{pmatrix} \tag{14}$$
The idea is to use A to calculate the profile quantities from the observed radiances where A is based on a statistically spanning set of known cases with noise built in. Regression is very fast and is based on statistical knowledge of the Earth's atmosphere. It linearizes a nonlinear problem however, and can be hard to trust.

- physical retrievals
  - begins with a first guess (from climatology, statistics, forecast, etc.)
  - The sensitivity of a channel is computed by taking derivitives with respect to the goephysical parameters to be solved for, X_j,
$$S_j \equiv \left.\frac{\partial \Theta_c}{\partial X_j}\right|_{X^n} \tag{15}$$
In the code, this is done by first perturbing X_j, rerunning the forward algorithm, then taking the difference between the result and the base radiance (this is called a difference Jacobian).
  - "The brightness temperature residuals are minimized by adjusting the geophysical state
$$\tilde{\Theta} - \Theta_c^n = \sum_j S_j \cdot \left(X_j^{n+1} - X_j^n\right) \tag{16}$$
We can weight this equation by the inverse of the noise co-variance matrix, $W = N_{ij}^{-1}$. The noise co-variance is derived from the instrumental noise, $\delta\Theta$, and computational noise. The minimum residual can be found via the least squares solution to Eqn. 16
$$X^{n+1} = X^n + \left[S^T W S\right]^{-1} S^T W \left(\tilde{\Theta} - \Theta_c^n\right) \tag{17}$$
The physical retrieval can solve non-linear equations; however, it is computationally burdensome due to the large number of forward computations."[6]

That's fancy talk. Essentially, we're trying to minimize the differences between the theoretical and acquired brightness temperatures so as to get more accurate products. This process takes into account the noise of the instrument and the noise caused by approximations throughout the code.

8 New Products?

8.1 Possible New Abilities

The combination of this powerful instrument, AIRS, and this new forward algorithm creates the possibility of new products in addition to those mentioned in section 4.1. As I mentioned before, the new RTA allows the perturbation of CO_2 as well as methane and carbon monoxide. Because of this, retrievals of these quantities may be possible if their effects can be detected. Although these gases make up a small portion of the atmosphere (very small where CH_4 and CO are concerned), they have a tremendous effect on the radiation budget. Therefore, a stable measurement, as is possible with AIRS, of any of these quantities, even if it was only an approximate value, would be very valuable. For example, increasing CO_2, the accused prime culprit of global warming, is currently only measured at sporadic places across the globe. AIRS would provide global coverage with incredible stability and precision from sample to sample (even if the actual measurement were off, the relative differences would be reliable).

8.2 Plausibility Investigations

So, what's the problem? The set of radiances from AIRS, if you'll remember, represents a combination of the spectral lines of all the active gases in the atmosphere. Seperating the subtle effects of CH_4, CO, stratospheric water, and CO_2 from the powerhouses water and ozone as well as temperature is the problem. The key is to find channels that are simulataneously responsive to one of the sought after quantities and are indifferent to T, H_2O, and O_3. This is extremely unlikely and so the new goal becomes finding a like channel that at least beats the noise of the instrument (giving us a fighting chance). We're looking for the sensitivity (signal over noise) of a certain channel to the sought after quantity.

To do this we remove the effects of ozone, water, and temperature:

For example, carbon dioxide signal to noise sensitivity, $CO_2 S/N$, per percent change,

$$CO_2 \frac{S}{N} = \frac{\frac{R(x+\delta CO_2)-R(x)}{pctperturb}}{\sqrt{(NE\Delta N)^2 + \sum_k (R(x+\delta x_L) - R(x))^2}} \tag{18}$$

$NE\Delta N$, the instrument noise

x_L, the profile quantity to weed out (here k=3, for ozone column density, temp., and water column density)

$R(x + \delta x_L)$, the perturbed radiance (the amount of perturbation is chosen to match noise)

$pctperturb$, the percent peturbation of the quantity designated for retrieval

8.3 Results

The incredible depth of my analysis:

· 1 profile (US standard atmosphere)

· at nadir with sun directly overhead (unless otherwise noted)

· clear computation (no clouds)

· 9 AIRS spots (1 AMSU region) - 0.2K RMS noise for AIRS

$NE\Delta N$ becomes $\frac{0.2}{sqrt(9)} \cdot B(\nu, 250K)$
The following were not calculated per percent perturbation but per total perturbation.

9 Conclusions

Carbon Dioxide, CO_2

The results were nominal but not nonexistant. It's very difficult to simultaneously retrieve temperature and carbon dioxide. In fact, known values of CO_2 are used to find $T(p)$ in the first place. That we got what we did is promising in and of itself. The results show that there are indeed several channels that are more responsive to CO_2 then to T, O_3, or q. Although CO_2 retrievals on a per scan basis would be useless, CO_2 as a research retrieval product might prove valuable. Regional or time-based averages could be performed, decreasing random noise error, thus improving sensitivity.

Carbon Monoxide, CO

McMillan *et al* claim, using standard signal processing techniques for noise reduction, the ability to retrieve total column density of CO from AIRS spectra to within 10%, but no profile information.[17] The simple data here support that assessment. With a ten percent perturbation of CO, a subset of channels (see figure) showed signal to noise values slightly greater than one making CO retrievals feasible and worthwhile. CO as a retrieval product is recommended.

Methane, CH_4

Methane shows much the same promise as CO.

Stratospheric Water

From simplistically perturbed stratospheric sensitivity runs, there do appear to be channels sensitive to this small region of moisture. The cabability of retrievals is promising and attractive enough to encourage future investigations.

The AIRS instrument and the new UMBC RTA seem very capable. The addition of CO_2, CO, CH_4, and stratospheric water to the current set of retrieval products is recommended. At a minimum, further investigation into AIRS sensitivity to these quasntities should be undertaken. Although these products may be worthless on a spot per spot basis, their value as research products, where extensive noise reduction techniques can be applied over large data sets, may be invaluable.

Real Conclusion

The world is a better place because of what I did.

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A Appendix Stuff

Definitions