Lecture 3B

The Community Radiative Transfer Model (CRTM)

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Satellite Data Assimilation Principle

$$J = \frac{1}{2}\left(\mathbf{x} - \mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x} - \mathbf{x}^b\right) + \frac{1}{2}\left[\mathbf{I}(\mathbf{x}) - \mathbf{I}^o\right]^T (\mathbf{E} + \mathbf{F})^{-1}\left[\mathbf{I}(\mathbf{x}) - \mathbf{I}^o\right]$$

where

x is a state vector including all possible atmospheric and surface parameters.

I is the radiance vector

B is the error covariance matrix of background

E is the observation error covariance matrix

F is the radiative transfer model error matrix

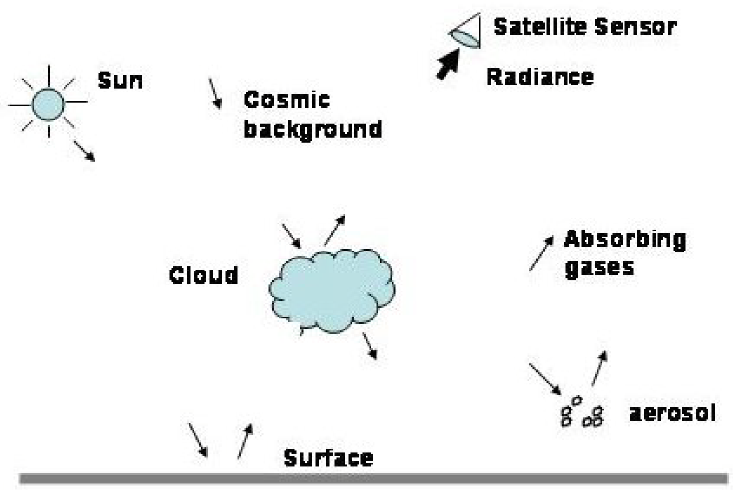
- Forward models and its Jacobians
- Error covariance matrices
  - Background
  - Forward model
  - Observations
- Bias corrections
  - Background
  - Forward model
  - Observations

Requirements on Radiative Transfer Models for Data Assimilation

- Fast and accurate in forward, tangent linear/adjoint models
  - All weather conditions
  - Surface and atmospheric spectroscopy
- Flexible interface with different NWP models
  - Global forecast system, GFS, NOGAPS, etc.
  - Regional forecast model: e.g. WRF
- Expansion for broader applications
  - satellite calibration/validation and climate reanalysis
  - Solar insolation (direct/diffuse) for renewable energy

What CRTM Does?

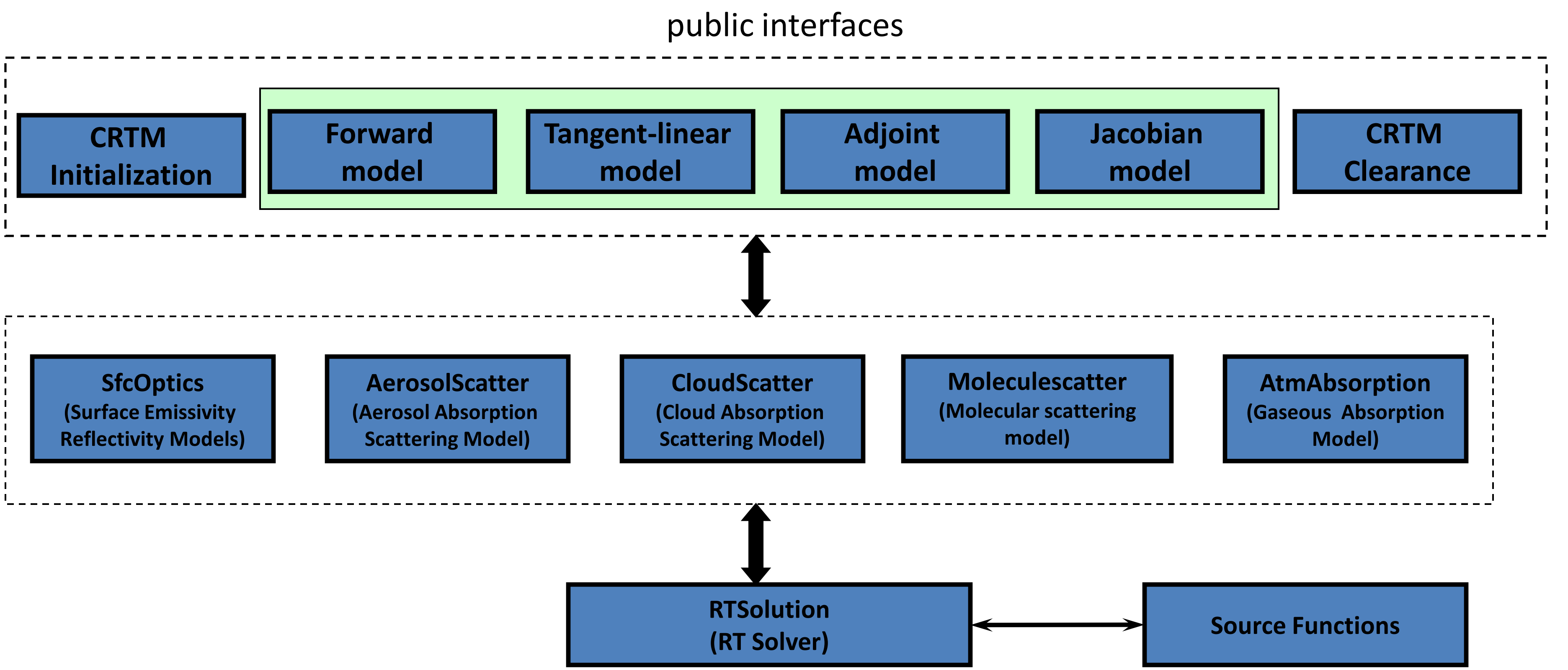
- Perform fast and accurate satellite radiance simulations (Forward model)
- Compute radiance sensitivities and derivatives (Tangent-linear, Adjoint and Jacobian models)
- Support IR, MW, Visible and UV sensors
- Work under all atmospheric and surface conditions



CRTM supports more than 100 Sensors

- **GOES-R ABI**
- **NPP/JPSS CrIS/ATMS/VIIRS**
- **Metop A and B IASI/HIRS/AVHRR/AMSU/MHS**
- **TIROS-N to NOAA-19 AVHRR**
- **TIROS-N to NOAA-19 HIRS**
- **GOES-8 to 15 Imager**
- **GOES-8 to 15 sounder IR and VIS**
- **Terra/Aqua MODIS**
- **MSG SEVIRI**
- **Aqua AIRS, AMSR-E, AMSU-A,HSB**
- **NOAA-15 to 19 AMSU-A**
- **NOAA-15 to 17 AMSU-B**
- **NOAA-18/19 MHS**
- **TIROS-N to NOAA-14 MSU**
- **DMSP F8, F10, F11, and 13 to15 SSM/I**
- **DMSP F13,15 SSM/T1**
- **DMSP F14,15 SSM/T2**
- **DMSP F16-20 SSMIS**
- **Coriolis Windsat**
- **TiROS-NOAA-14 SSU**
- **FY-3 A and B IRAS, MERSI, MWTS,MWHS,MWRI**
- **COMS MI**
- **GPM GMI**
- **TRMM TMI**
- **MT MADRAS/SAPHIR**

CRTM Major Modules



- Input profiles: pressure, temperature, water vapor and ozone profiles at user defined layers, and optionally, water content and mean particle size profiles with up to 6 cloud types; 8 types of aerosols.
- Surface emissivity: computed internally or supplied by user.
- Frequency coverage: MW, IR, and Visible/UV.

K-Matrix Model

Forward model: $R = F(x)$

Tangent-linear (TL) model: $R_{TL} = \mathbf{H}\, x_{TL}$

The matrix $\mathbf{H}$ contains the Jacobian element, $\dfrac{\partial R_i}{\partial x_j}$

Adjoint (AD) model: $x_{AD} = \mathbf{H}^T R_{AD}$

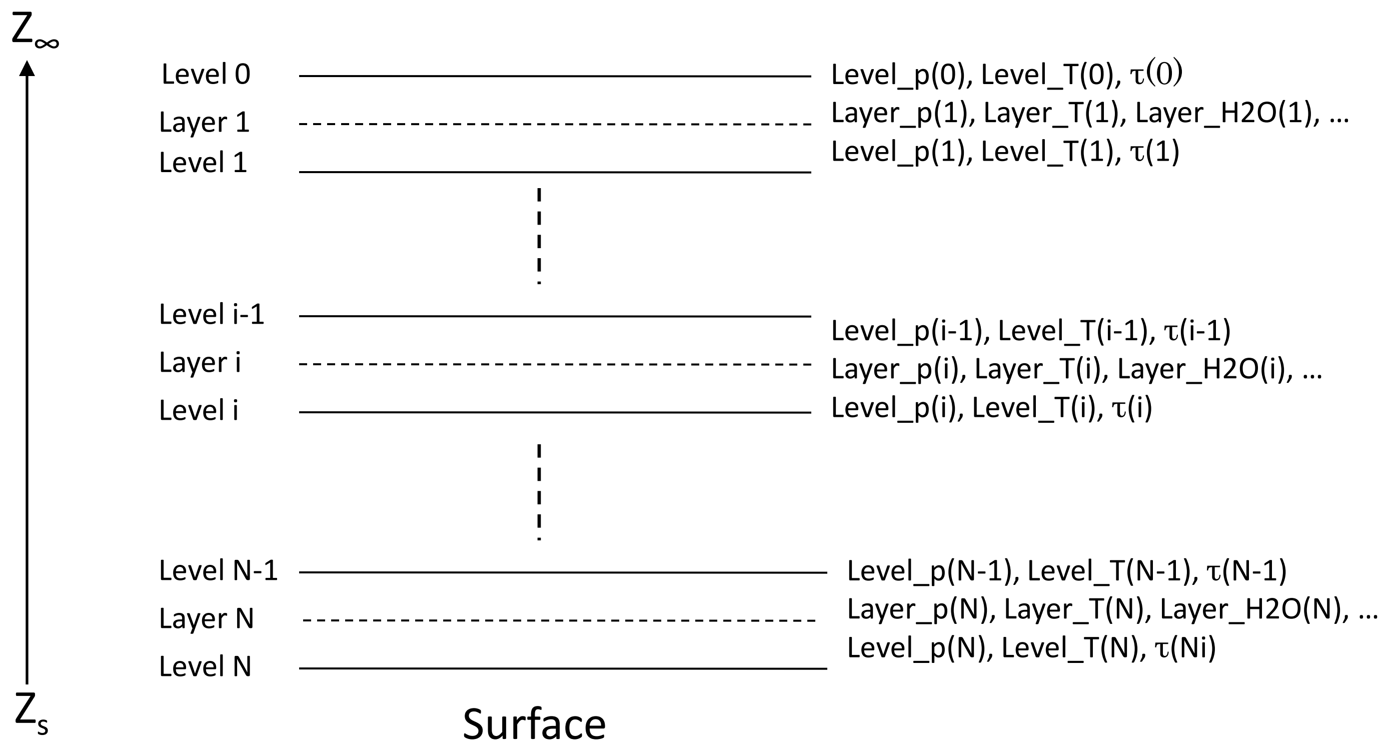
K-matrix (K) model: $x_K = [h_1 R_{K,1}, h_2 R_{K,2}, \ldots, h_m R_{K,m}]$

$$h_i = [\frac{\partial R_i}{\partial x_1}, \frac{\partial R_i}{\partial x_2}, \ldots, \frac{\partial R_i}{\partial x_n}]^T$$

Perturbation method:

$$\frac{\delta R}{\delta x} = \frac{F(x + \delta x/2) - F(x - \delta x/2)}{\delta x}.$$

Atmosphere Profile Layering Scheme



Example: AIRS science team level pressure definition (101 levels):

$$P_{lev}(i) = (Ai^2 + Bi + C)^{7/2}$$

$$P_{lev}(1) = 0.005 \qquad P_{lev}(38) = 300.0 \qquad P_{lev}(101) = 1100.0$$

A=-1.55 × 10^{-4}, B=-1.55 × 10^{-4}, and C=7.45

Layer pressure definition:

$$P_{layer}(1:N) = (P_{lev}(2:N) - P_{lev}(1:N-1)) / \log(P_{lev}(2:N) / P_{lev}(1:N-1))$$

General Radiative Transfer Equation for clear sky

$$R_\nu = \varepsilon_\nu B_s[\nu, T(z_s)]\tau(\nu, z_s) + (1-\varepsilon_\nu)\tau(\nu, z_s)\int_1^{\tau(\nu, z_s)} B[\nu, T(z)]d\tau(\nu, z)$$

$$+\int_{\tau(\nu, z_s)}^1 B[\nu, T(z)]d\tau(\nu, z) + r\mu_0 F_* \tau(\nu, z_s, \mu_0)\tau(\nu, z_s, \mu)/\pi$$

If surface emissivity $\varepsilon_\nu = 1$

$$R_\nu = B_s[\nu, T(z_s)]\tau(\nu, z_s) + \int_{\tau(\nu, z_s)}^1 B[\nu, T(z)]d\tau(\nu, z)$$

Channel radiance received by the satellite sensor

$$R = \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)]\tau(\nu, z_s) d\nu + \int_{\Delta\nu} \phi(\nu) \int_{\tau(\nu, z_s)}^1 B[\nu, T(z)] d\tau(\nu, z) d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu}$$

Line-by-Line Radiance

The radiance received by the satellite sensor is computed by convolving the monochromatic radiances with the instrument SRF:

$$R = \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] \tau(\nu, z_s) d\nu + \int_{\Delta\nu} \phi(\nu) \int_{\tau(\nu, z_s)}^{1} B[\nu, T(z)] d\tau(\nu, z) d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu}$$

After discretion at z direction

$$R \approx \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] \tau(\nu, z_s) d\nu + \sum_{i=1}^{N} \int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} (\tau(\nu, z_{i-1}) - \tau(\nu, z_i)) d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu},$$

Rearrange

$$R = \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu} \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] \tau(\nu, z_s) d\nu}{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] d\nu}$$

$$+ \sum_{i=1}^{N} \frac{\int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu} \left(\frac{\int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} \tau(\nu, z_{i-1}) d\nu}{\int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} d\nu} - \frac{\int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} \tau(\nu, z_i) d\nu}{\int_{\Delta\nu} \phi(\nu) \overline{B[\nu, T_i]} d\nu} \right)$$

$$\approx \frac{\int_{\Delta\nu} \phi(\nu) B_s[\nu, T(z_s)] d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu} \tau_s + \sum_{i=1}^{N} \frac{\int_{\Delta\nu} \phi(\nu) B[\nu, \overline{T_i}] d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu} (\tau_{i-1} - \tau_i)$$

Fast Model Approximations

Approximation 1 (Ordinary Transmittance), the variation of the Planck radiances within the channel spectra is not considered when calculating channel transmittance:

$$\tau_i^{ORD} = \frac{\int \phi(\nu)\tau_i(\nu)d\nu}{\int \phi(\nu)d\nu}$$

Approximation 2 (PW1), the layer temperature is used to calculate the Planck-weighted channel transmittance

$$\tau_i^{PW1} = \frac{\int \phi(\nu)B[\nu,\overline{T_i}]\tau_i(\nu)d\nu}{\int \phi(\nu)B[\nu,\overline{T_i}]d\nu}$$

Approximation 3 (PW2), the level temperature is used to calculate the Planck-weighted channel transmittance

$$\tau_i^{PW2} = \frac{\int \phi(\nu)B[\nu,T_i]\tau_i(\nu)d\nu}{\int \phi(\nu)B[\nu,T_i]d\nu}$$

Sensor Channel Band Correction

Convert the channel radiance to channel Brightness Temperature (BT)

Channel central wavenumber ν_i

$$\nu_i = \frac{\int_{\Delta\nu} \phi(\nu)\nu d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu}$$

For each channel, the channel effective brightness temperature T_e at the center wavenumber ν_i is calculated for the blackbody temperature *T* over SRF

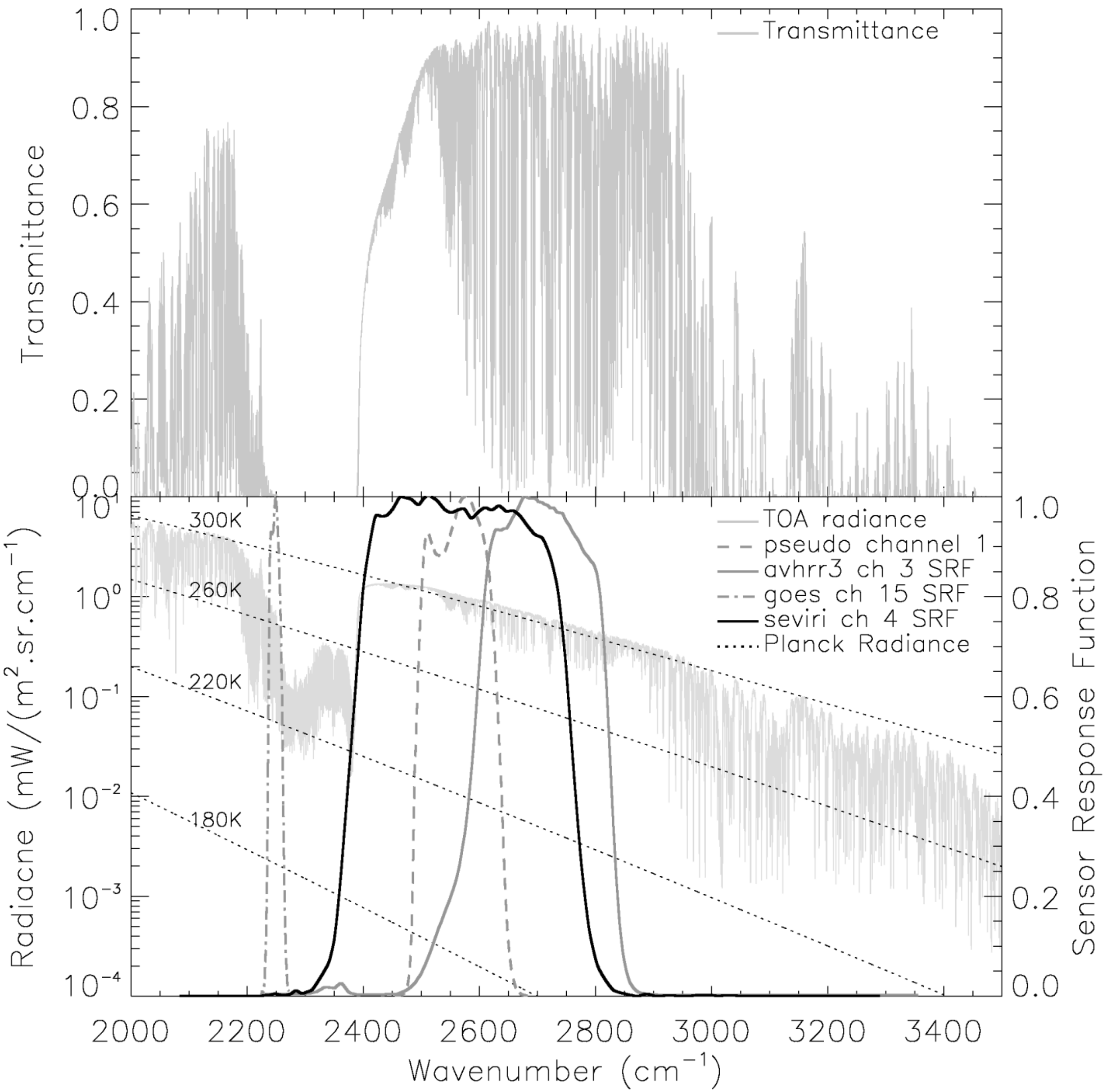
$$R = \frac{c_1 \nu_i^3}{e^{c_2 \nu_i / T_e} - 1} = \frac{\int_{\Delta\nu} \phi(\nu) B[\nu, T] d\nu}{\int_{\Delta\nu} \phi(\nu) d\nu}$$

A linear relationship between *T* and T_e is established by ranging *T* from 150 to 340 K

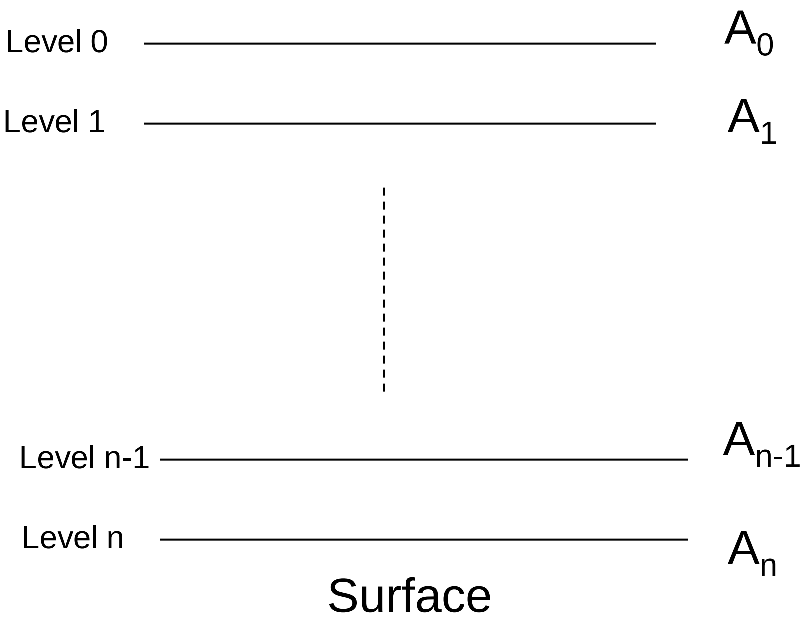
$$T_e = b + b_1 T$$

The band correction coefficient *b* is a very good indicator for Planck radiance variation across the channel SRF.

Atmosphere Radiance and Transmittance



Gaseous Transmittance Model 1 (AtmAbsorption) Compact OPTRAN (ODAS)



$$A_i = \int_0^p \frac{r_i}{g\cos(\theta)} dp'$$

$$\ln(k_{ch}(A)) = c_0(A) + \sum_{j=1}^{6} c_j(A) P_j(A)$$

$$c_j(A) = \sum_{m=0}^{n} a_{j,m} \ln(A)^m, \; j = 0,6, \; n < 10$$

$$\tau_{ch} = \exp(-k_{ch}\delta A)$$ estimate layer transmittance

$$\tau_{ch} := \int \tau_\nu \phi_\nu d\nu$$ Channel transmittance definition

ϕ_ν – spectral response function

K – absorption coefficient of an absorber

A – integrated absorber amount

P_j – predictors

a_j – constants obtained from regression

- Currently H_2O and O_3 are the only variable trace gases and other trace gases are "fixed".
- The model provides good Jacobians and is very efficient in using computer memory

Gaseous Transmittance Model 2 (AtmAbsorption) ODPS (Optical Depth in Pressure Space)

Regression formulation:

$$d_i - d_{i-1} = \sum_{j=1}^{N_p} c_{i,j} X_{i,j},$$

$(d_i - d_{i-1})$ – the layer optical depth

d_i – the level to space optical depth from level *i*

N_p – the number of predictors at layer *i*

$c_{i,j}$ – the regression coefficients

$X_{i,j}$ – the predictors

The regression is actually performed in terms of its departure from a reference profile for all variable gases.

- Variable gases H_2O, CO_2, O_3, and can add absorbers N_2O, CO, and CH_4 for hyper-spectral IR sensors: IASI, AIRS, and CrIS.
- Other features:

(1) Water vapor line computed using ODAS (optional)

(2) Water vapor continua transmittance is treated separately from the water vapor line absorption.

(3) Have reference profile, and each absorber has associated min and max values.

Water Line Predictors in Different Transmittance Models

ODPS | Optran | ODAS

Models	Method A[b]	Method B	Method C
Predictors	$\sec(\theta)W_r$, $\sec(\theta)W_r\delta T$, $(\sec(\theta)W_r)^2$, $\sec(\theta)W_r\delta T\lvert\delta T\rvert$, $\sqrt[4]{\sec(\theta)W_r}$, $(\sec(\theta)W_r)^3$, $\sqrt{\sec(\theta)W_r}$, $\sqrt{\sec(\theta)W_r\delta T}$, $(\sec(\theta)W_r)^4$, W_r/W_{tw}, $\sec(\theta)W_r^2/W_{tw}$, $(\sec(\theta)W_w)^2$, $\sec(\theta)W_w$, $\sec(\theta)$, $\sec(\theta)C_r$	T_x, P_x, T_x^2, P_x^2, T_xP_x, $T_x^2P_x$, $T_xP_x^2$, $T_x^2P_x^2$, P_x^4, $T_x^2P_x^4$, W, W/T_x^2, $T{*}_x$, $P{*}_x$, $T{**}_x$, $P{**}_x$, $T{***}_x$, $P{***}_x$	T, P, T^2, P^2, TP, T^2P, TP^2, T^2P^2, $\sqrt[4]{P}$, W, W/T^2, $T*$, $P*$, $T**$, $P**$, $T***$, $P***$

[a]Where $T_x = T/100(K)$, $P_x = \sqrt[4]{P}$(hPa), W is water vapor mixing ratio (g/kg), T is temperature (K), and P is pressure (hPa).
$T{*}_x(l) = \sum_{i=1}^{l}[(T_x(i) + T_x(i-1))(A(i) - A(i-1))]/(2A(l))$,
$T{**}_x(l) = \sum_{i=1}^{l}[(T_x(i)A(i) + T_x(i-1)(A(i-1)(A(i) - A(i-1))]/(2A^2(l))$,
$T{***}_x(l) = \sum_{i=1}^{l}[(T_x(i)A^2(i) + T_x(i-1)A^2(i-1))(A(i) - A(i-1))]/(2A^3(l))$,
where $A(i)$ is the ith level integrated absorber amount for water vapor. The same equations applied to $P{*}_x$, $P{**}_x$, $P{***}_x$, $T*$, $T**$, $T***$, $P*$, $P**$, and $P***$ for methods B and C.

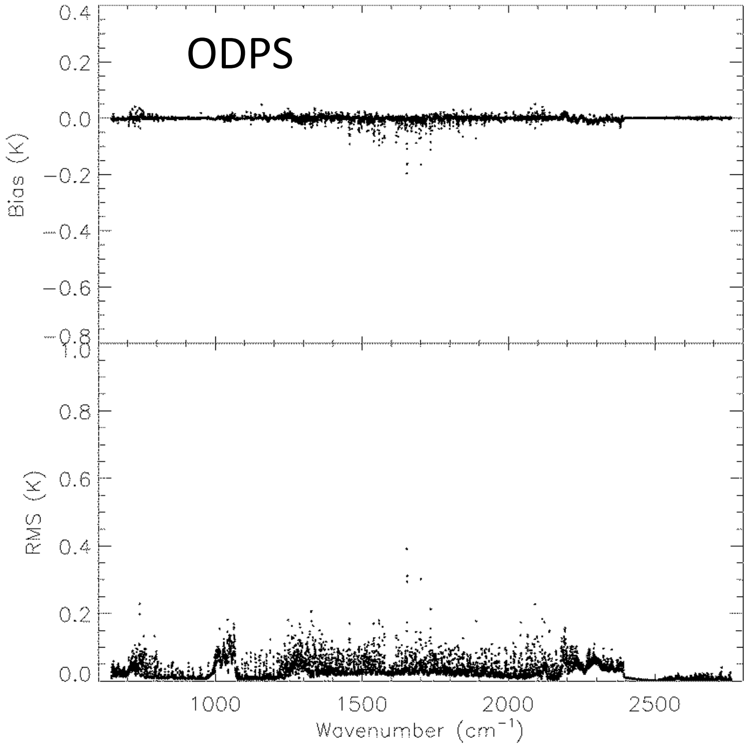
$$W_r(l) = W(l)/W^*(l),$$
$$C_r(l) = CO_2(l)/CO_2^*(l),$$
$$\delta T(l) = T(l) - T^*(l),$$
$$W_w(l) = \{\textstyle\sum_{i=1}^{l} P(i)[P(i) - P(i-1)]W(i)\}/\{\sum_{i=1}^{l} P(i)[P(i) - P(i-1)]W^*(i)\},$$
$$W_{tw}(l) = \{\textstyle\sum_{i=1}^{l} P(i)[P(i) - P(i-1)]W(i)T(i)\}/\{\sum_{i=1}^{l} P(i)[P(i) - P(i-1)]W^*(i)T^*(i)\}.$$

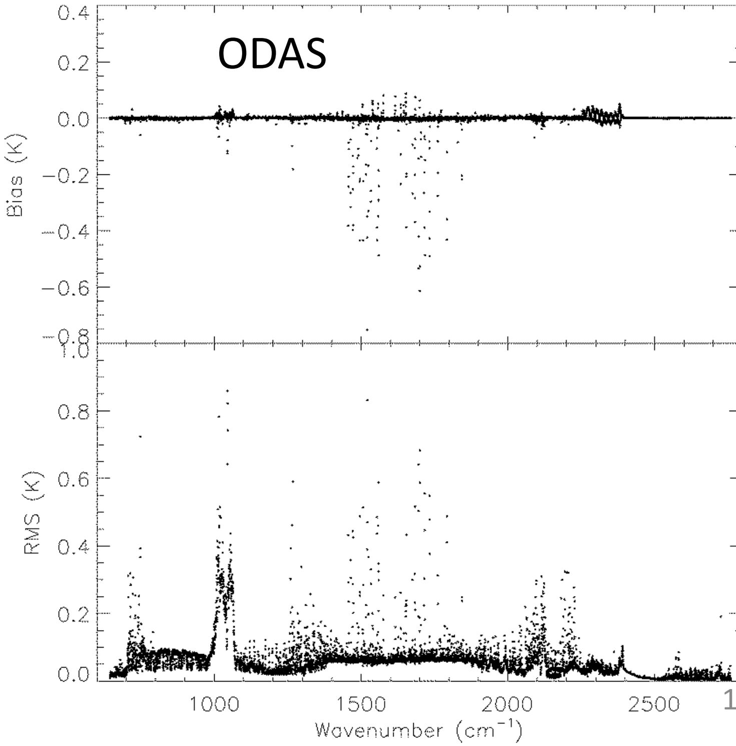
The asterisk refers to the value from reference profile for method A, and $\sec(\theta)$ is the secant of zenith angle.
[b]Data are from *Matricardi et al.* [2004].

ODPS vs ODAS

	ODPS (Optical Depth in Pressure Space)	ODAS (Optical Depth in Absorber Space) – CompactOPTRAN
Variable gases	H_2O, CO_2, O_3, and can add absorbers N_2O, CO, and CH_4 for hyper-spectral IR sensors: IASI, AIRS, and CrIS.	Only H_2O, and O_3
Other features	(1) Water vapor line computed using ODAS (optional) (2) Water vapor continua transmittance is treated separately from the water vapor line absorption. (3) Have reference profile, and each absorber has associated min and max values.	

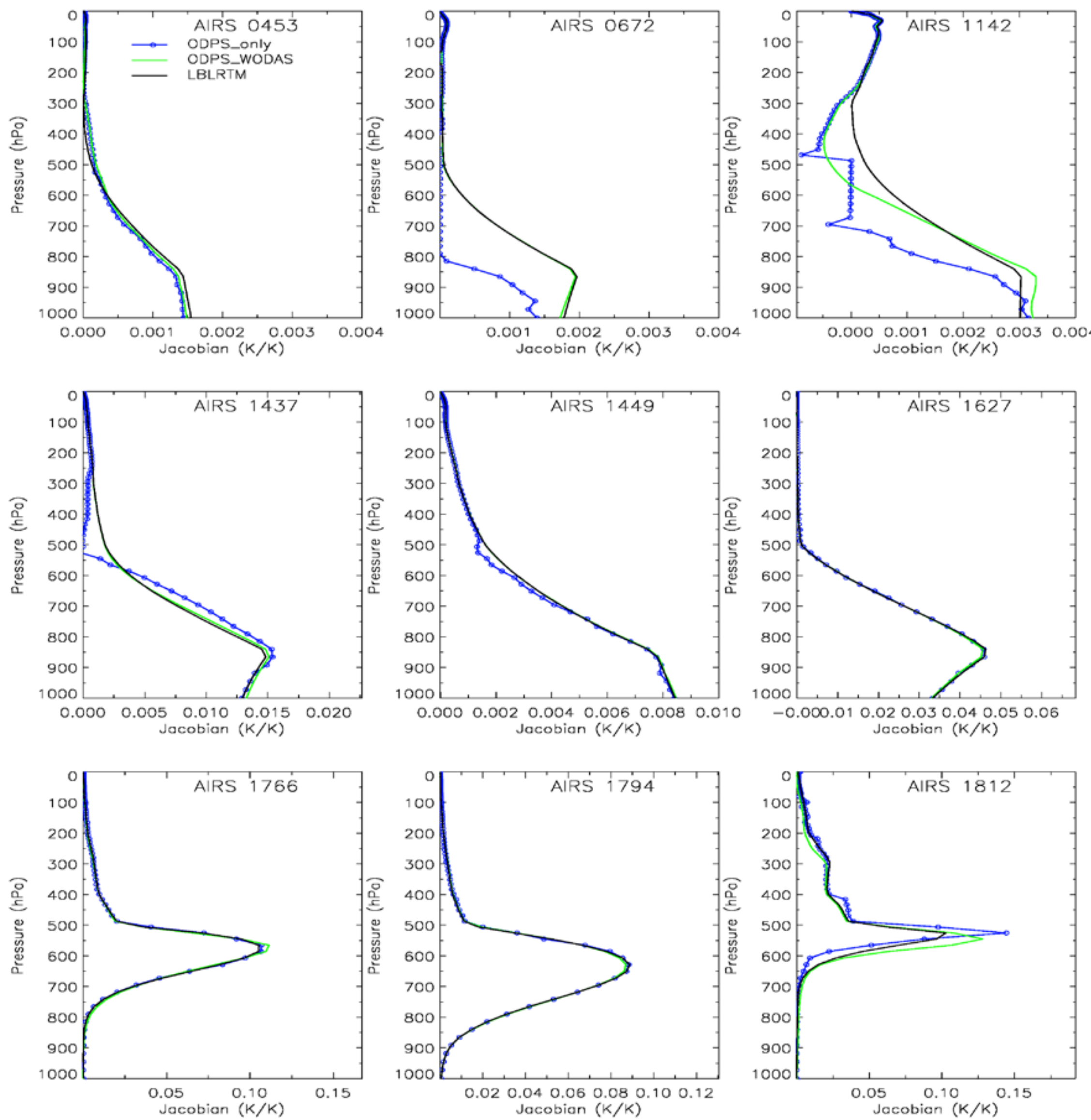
Training accuracy for IASI





ODPS vs ODAS

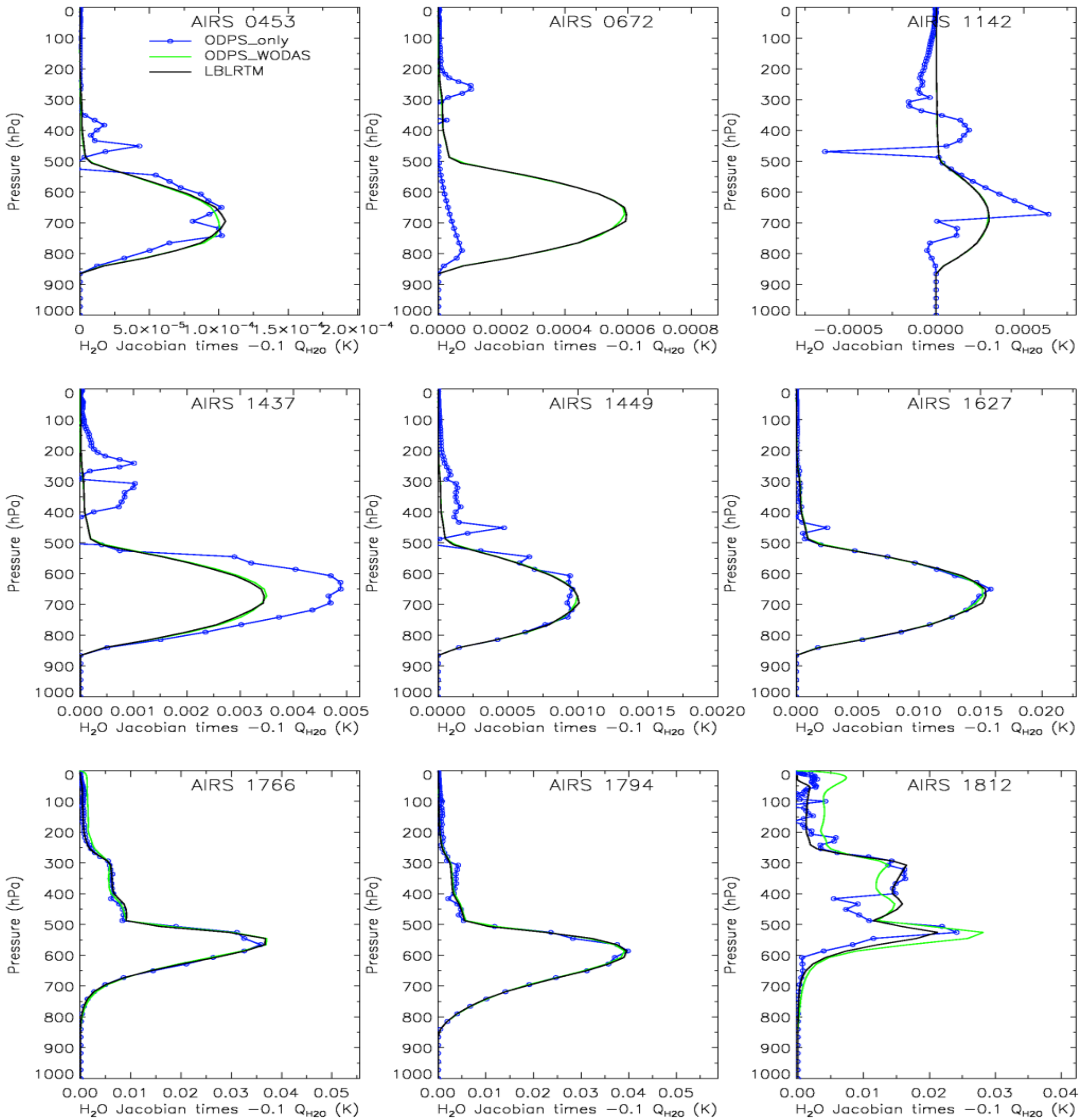
- In the ODPS transmittance model, the ODAS (OPTRAN) algorithm is used (optional) to compute water vapor line transmittances since it can provide better forward results and Jacobians for many IR channels.
- Preliminary results have shown positive NWP impacts from temperature related fields when the ODPS plus ODAS for H2O line is used, compared to the use of ODPS alone.



Temperature Jacobians

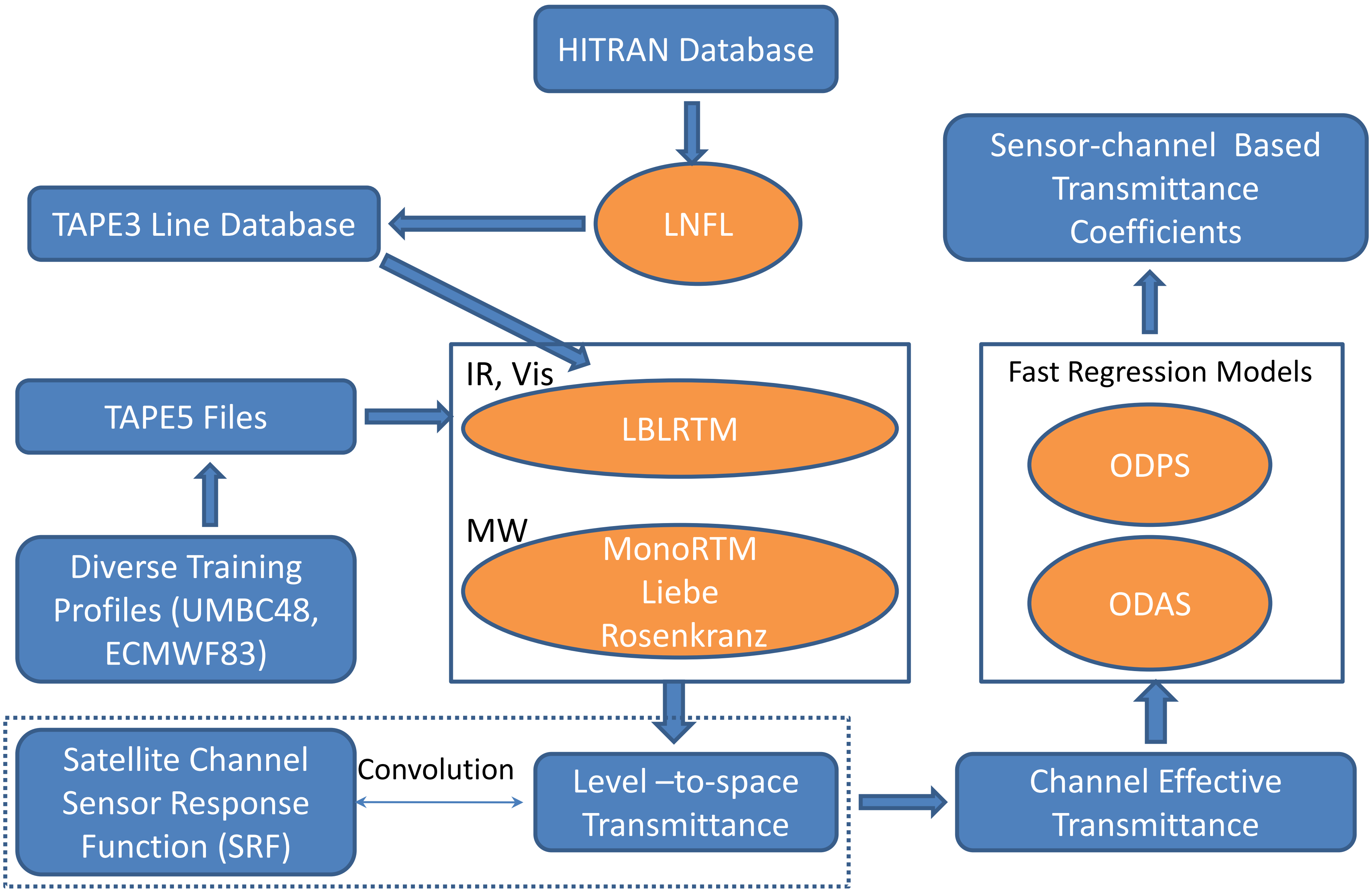
(Chen et al., 2010, JGR)

ODPS vs ODAS



Water Vapor Jacobian

CRTM Coefficients Training Process



Process of generating fast model IASI, CrIS coefficients

Run LBLRTM to generate the transmittance spectra on a constant wave number basis (0.001 cm^{-1}) from 600 to 2800 cm^{-1}.

↓ FFT

Fourier transform of the spectra to the interferogram space.

↓ Apodization Function

Convolution is done in the interferogram space by multiplying the Apodization functions.

↓ FFT^{-1}

Inverse Fourier transfrom of the products to spectra space, resampling the spectra on a constant wave number basis.

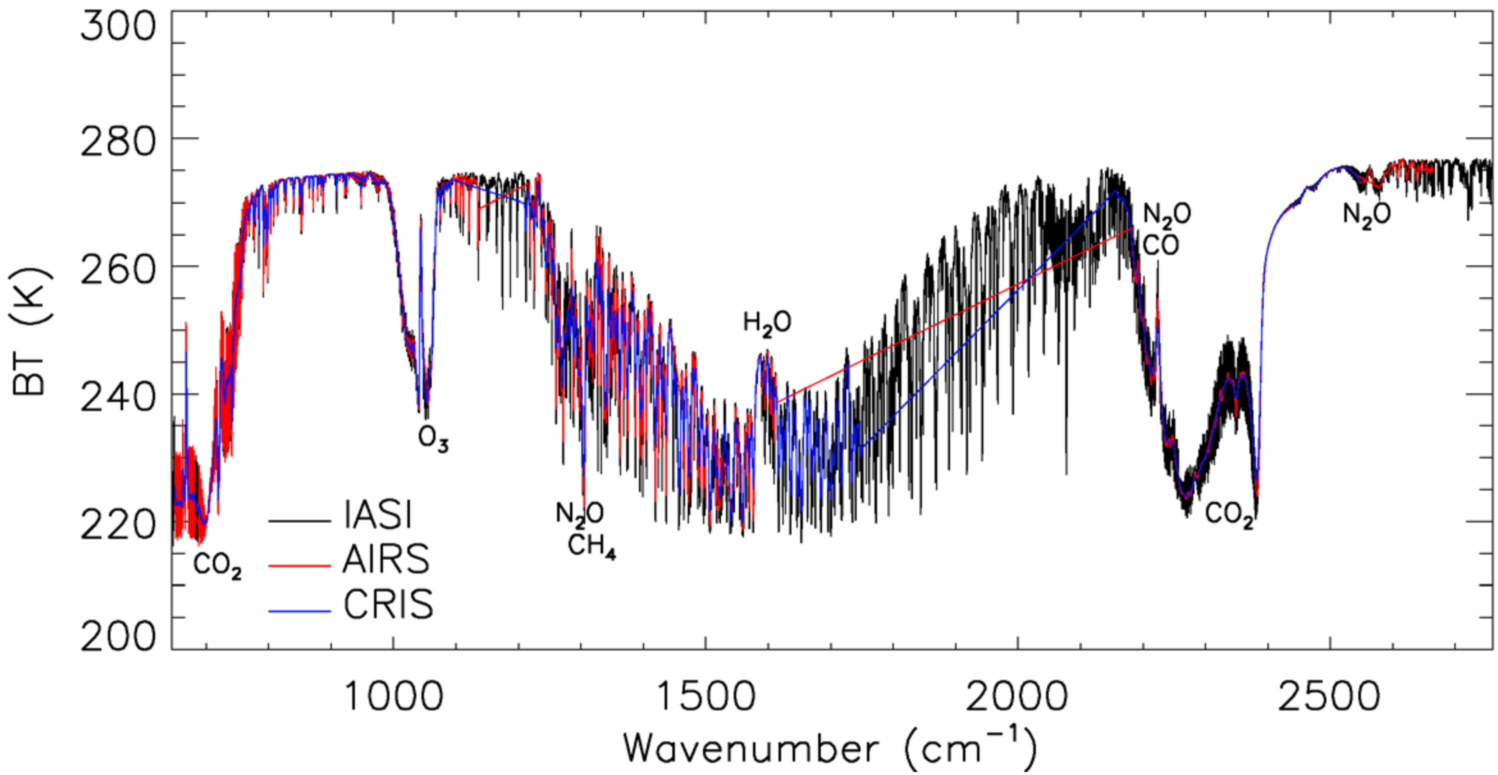
↓

Computing effective transmittance for dry, water vapor, and ozone and other gases.

↓

Training the transmittances with optical path transmittance algorithm.

CRTM Infrared Spectroscopy Corresponding to AIRS, IASI and CrIS



Variable gases: H_2O, CO_2, O_3, CO, CH_4, and N_2O, **Effective Transmittance**

$$\tau_{\nu,j}^{tot} = \tau_{\nu,j}^{wvcon}\tau_{\nu,j}^{fix}\left(\frac{\tau_{\nu,j}^{fix+CH_4}}{\tau_{\nu,j}^{fix}}\right)\left(\frac{\tau_{\nu,j}^{fix+CH_4+CO}}{\tau_{\nu,j}^{fix+CH_4}}\right)\left(\frac{\tau_{\nu,j}^{fix+CH_4+CO+N_2O}}{\tau_{\nu,j}^{fix+CH_4+CO}}\right)\left(\frac{\tau_{\nu,j}^{fix+CH_4+CO+N_2O+CO_2}}{\tau_{\nu,j}^{fix+CH_4+CO+N_2O}}\right)\times$$

$$\left(\frac{\tau_{\nu,j}^{fix+CH_4+CO+N_2O+CO_2+wv}}{\tau_{\nu,j}^{wvcon}\tau_{\nu,j}^{fix+CH_4+CO+N_2O+CO_2}}\right)\left(\frac{\tau_{\nu,j}^{fix+CH_4+CO+N_2O+CO_2+wv+O_3}}{\tau_{\nu,j}^{fix+CH_4+CO+N_2O+CO_2+wv}}\right)$$

Fast Transmittance Model for Stratospheric Sounding Unit (SSU)

- Stratospheric Sounding Unit data is a three-channel sensor in the CO_2 15 µm absorption band onboard NOAA series satellites (started from TIROS-N in 1978 and ended at NOAA-14 in 2006).
- The data in past 29 years is an unique near-global source on temperature for middle and upper stratosphere.
- The SSU data has been extensively used to study the temperature trends in the stratosphere, as well as their possible causes (e.g. Nash and Forrester, 1986; Ramaswamy et al., 2001; Shine et al., 2003; World Meteorological Organization (WNO), 1988, 2007; Liu and Weng, 2009).

SSU Sensor Response Function (SRF)

Different from a conventional sensor response function, the SSU SRF is a product of traditional broadband and the CO_2 cell absorption line responses.

High-frequency gas cell response

Filter function

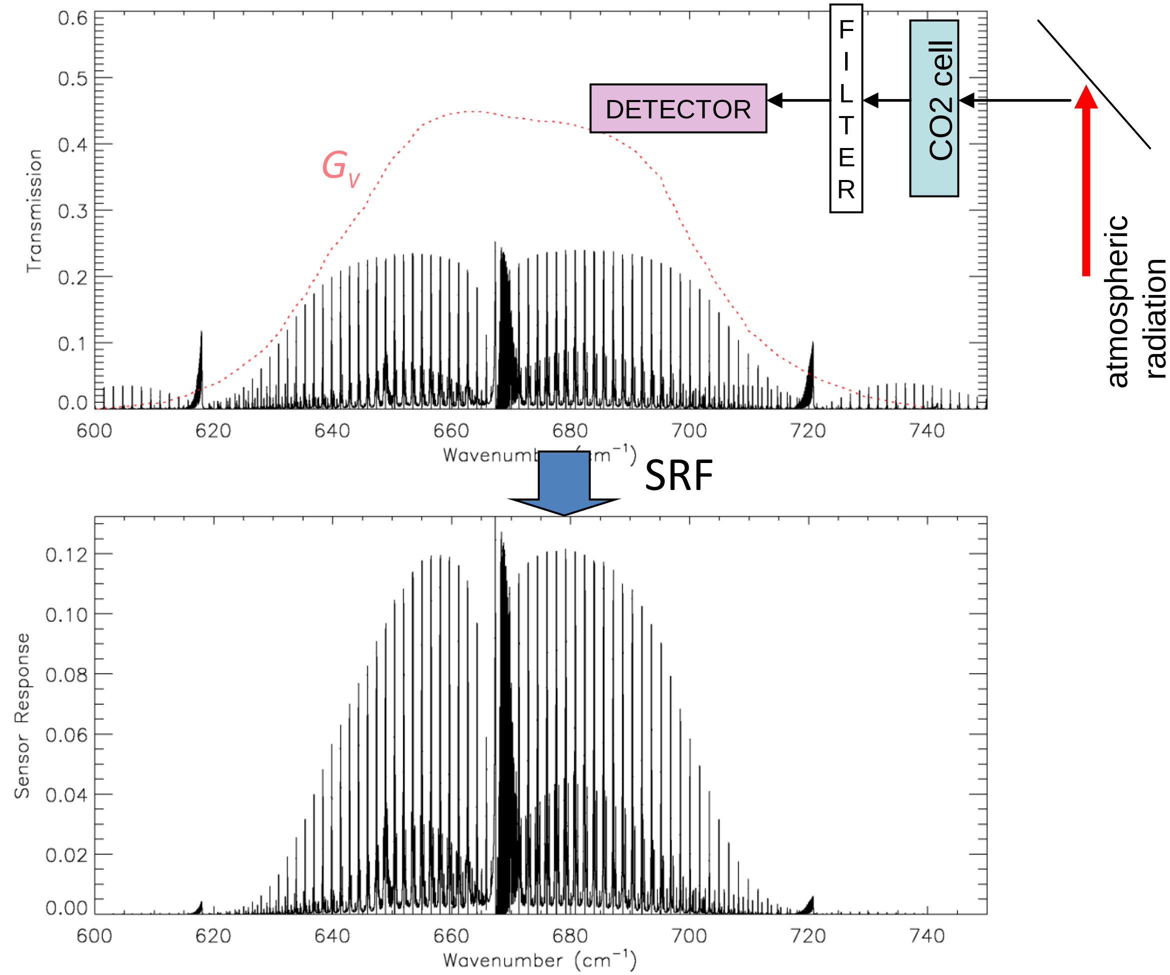
SSU SRF = $G_\nu H_\nu$

Two cell approximation (Brindley et al., 1998):

$$H_\nu = \tau_\nu^{low\ p\ cell} - \tau_\nu^{high\ p\ cell}$$

Transmittance of the low CO_2 pressure cell

Transmittance of the high CO_2 pressure cell



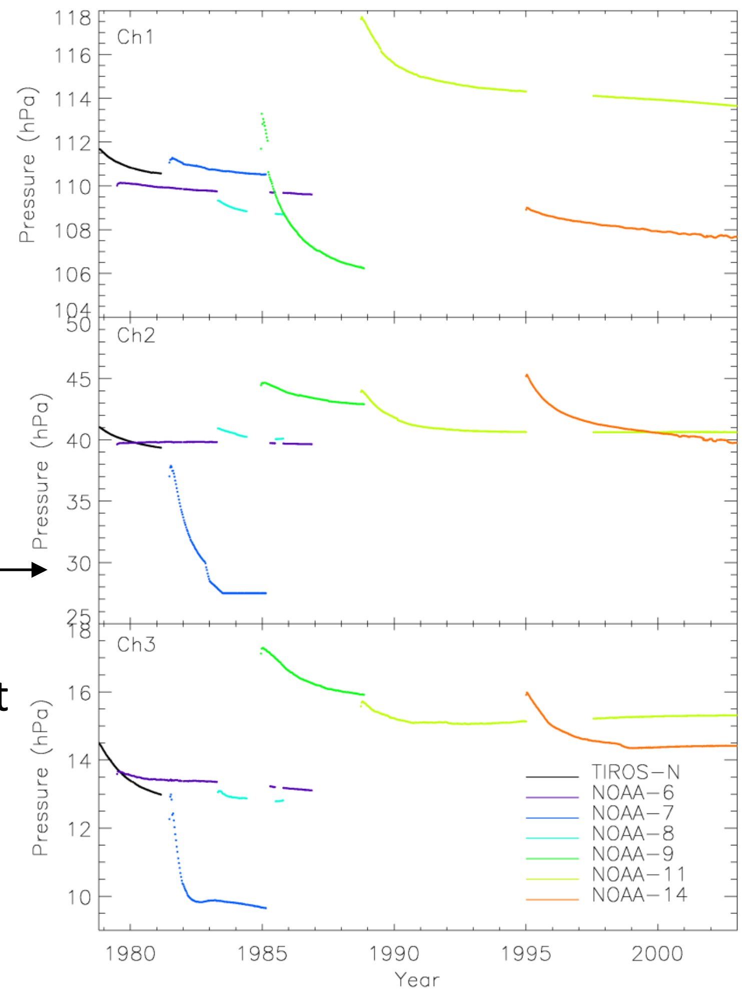
SSU Fast RT Model Taking CO_2 leaking into Account

- Based on the sensitivity studies, the fast RT model for SSU utilizes a spectral resolution of 5×10^{-4} cm^{-1}
- CO_2 and O_3 as variable gases.
- The fast model (implemented in CRTM version 2) takes account of the variations of the cell pressures:
    - Use a series of the transmittance coefficient sets for each sensor at different values of CO_2 cell pressure with corresponding SRF.
    - The transmittances at an arbitrary value of CO_2 cell pressure are obtained through interpolation from the transmittances computed at two adjacent CO_2 cell pressure nodes which bracket the desired value.

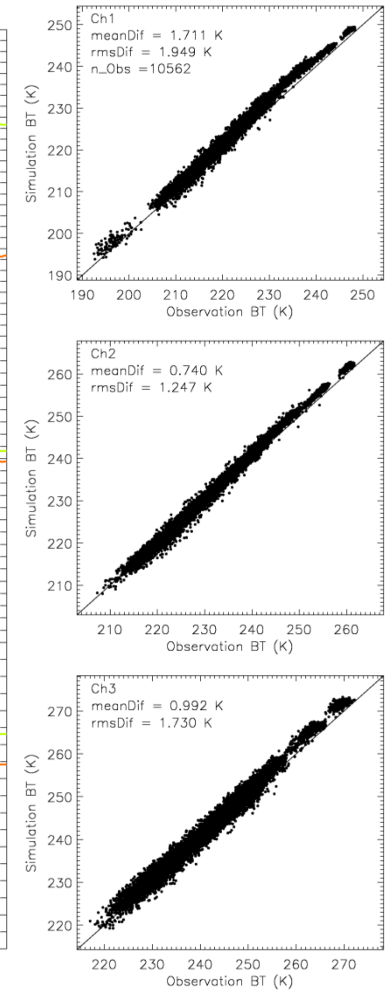
- It can also be used to address two important corrections in deriving trends from SSU measurements: CO_2 cell leaking correction, and atmospheric CO_2 concentration correction.

Fast Transmittance Model for SSU

- The SSU channel spectral response function (SRF) is a combination of the instrument filter function and the transmittance of a CO2 cell.
- The SRF varies due to the cell CO2 leaking problem.
- CRTM-v2 includes schemes to take the SRF variations into account (Liu and Weng, 2009; Chen et al. 2011)
- CO_2 and O_3 are variables gases



CO2 cell pressure variations, which causes SSU SRF variations.



CRTM simulations compared with SSU observations for SSU noaa-14.

Zeeman Effects in CRTM

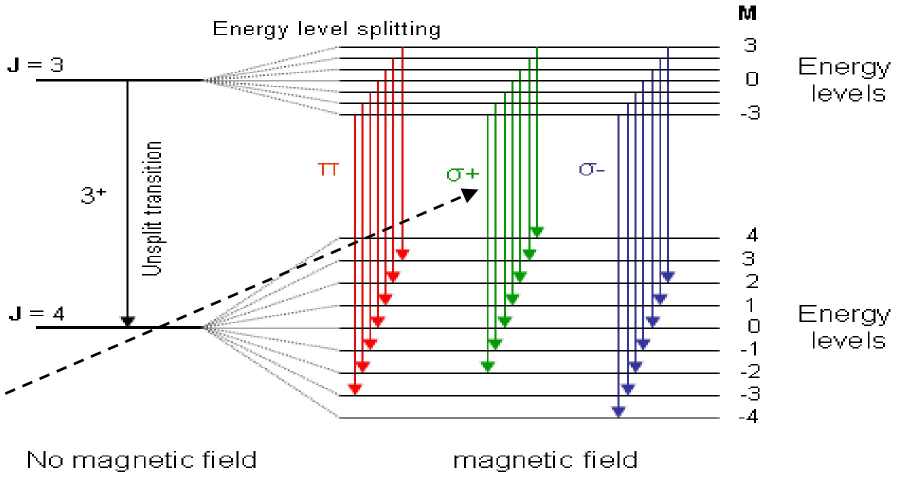
Energy level splitting:

In the presence of an external magnetic field, each energy level associated with the total angular momentum quantum number J is split into 2J+1 levels corresponding to the azimuthal quantum number M = -J, …, 0, …,J

Transition lines (Zeeman components) :

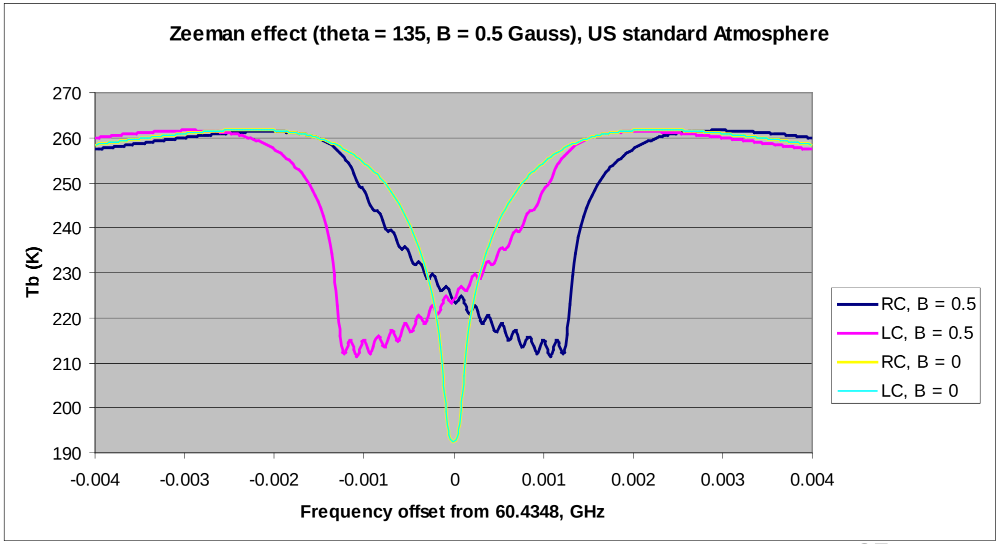
The selection rules permit transitions with ΔJ = ±1 and ΔM = 0, ±1. For a change in J (i.e. J=3 to J=4, represented by 3^+), transitions with

ΔM = 0 are called π components,
ΔM = 1 are called σ+ components and
ΔM = -1 are called σ- components.

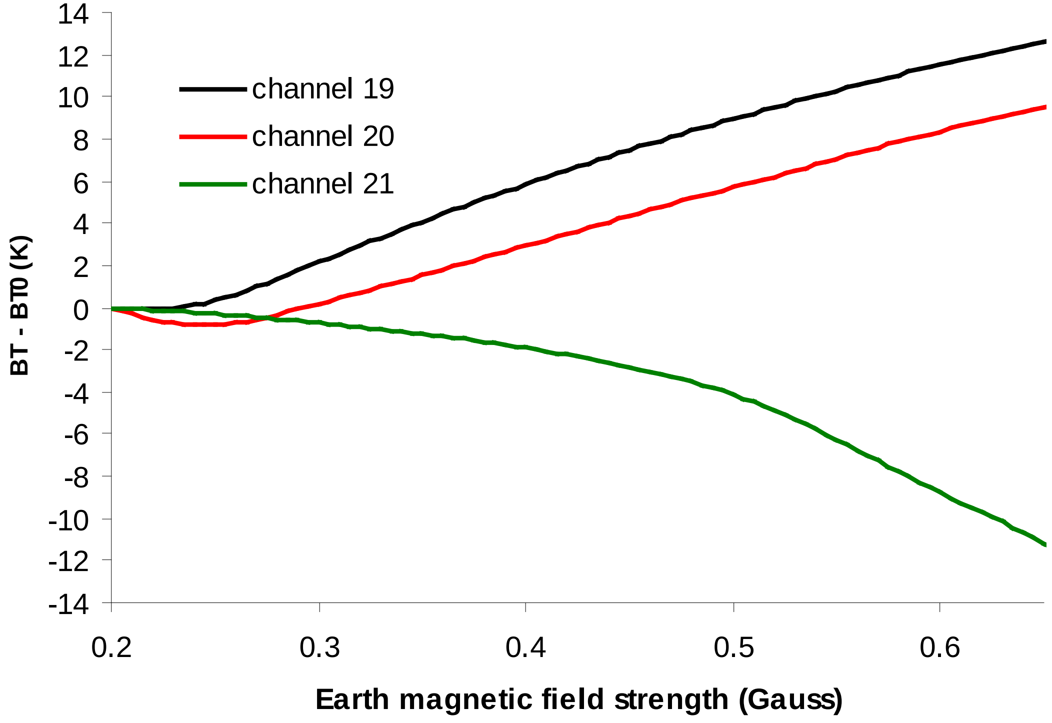


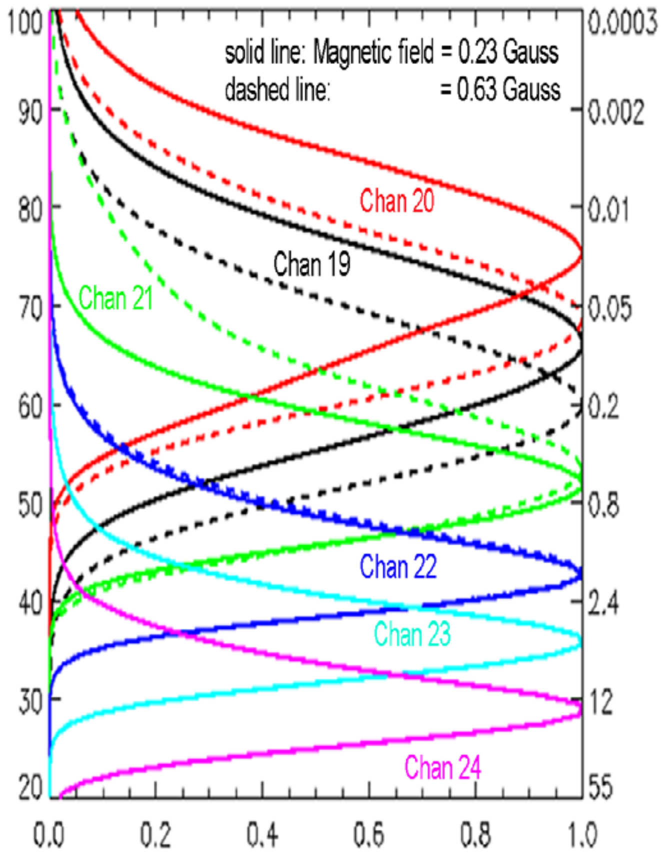
Polarization:

The three groups of Zeeman components also exhibit polarization effects with different characteristics. Radiation from these components received by a circularly polarized radiometer such as the SSMIS upper-air channels is a function of the magnetic field strength |**B**|, the angle θ_B between **B** and the wave propagation direction **k** as well as the state of atmosphere, not dependent on the azimuthal angle of **k** relative to **B**.



SSMIS Zeeman Splitting Related Errors





Fast Zeeman Absorption Model

(1) Atmosphere is vertically divided into N fixed pressure layers from 0.000076 mb (about 110km) to 200 mb. (currently N=100, each layer about 1km thick).

(2) The Earth's magnetic field is assumed constant vertically

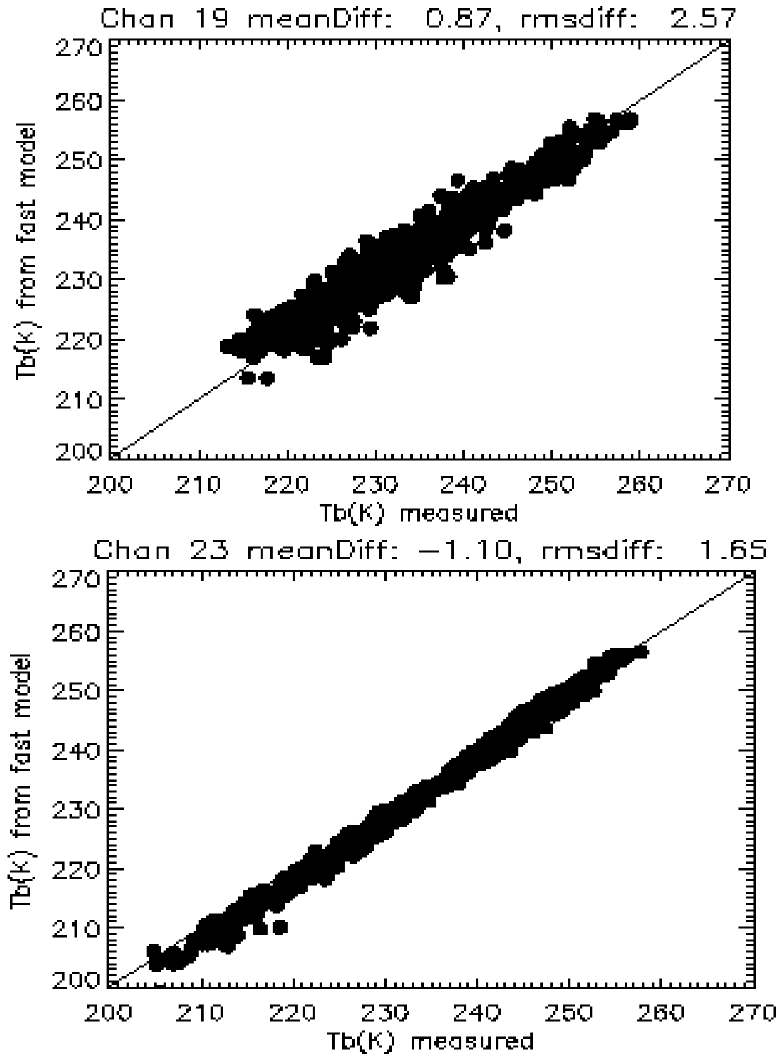
(3) For each layer, the following regression is applied to derive channel optical depth with a left-circular polarization:

$$\tau_i = \tau_{i-1} \exp(-OD_{lc,i} / COS(\theta)), \quad \tau_0 = 1$$

$$OD_{lc,i} = c_{i,0} + \sum_{j=1}^{m} c_{i,j} x_{i,j}$$

ψ – 300/T; T – temperature
B – Earth magnetic field strength
θ_B – angle between magnetic field and propagation direction

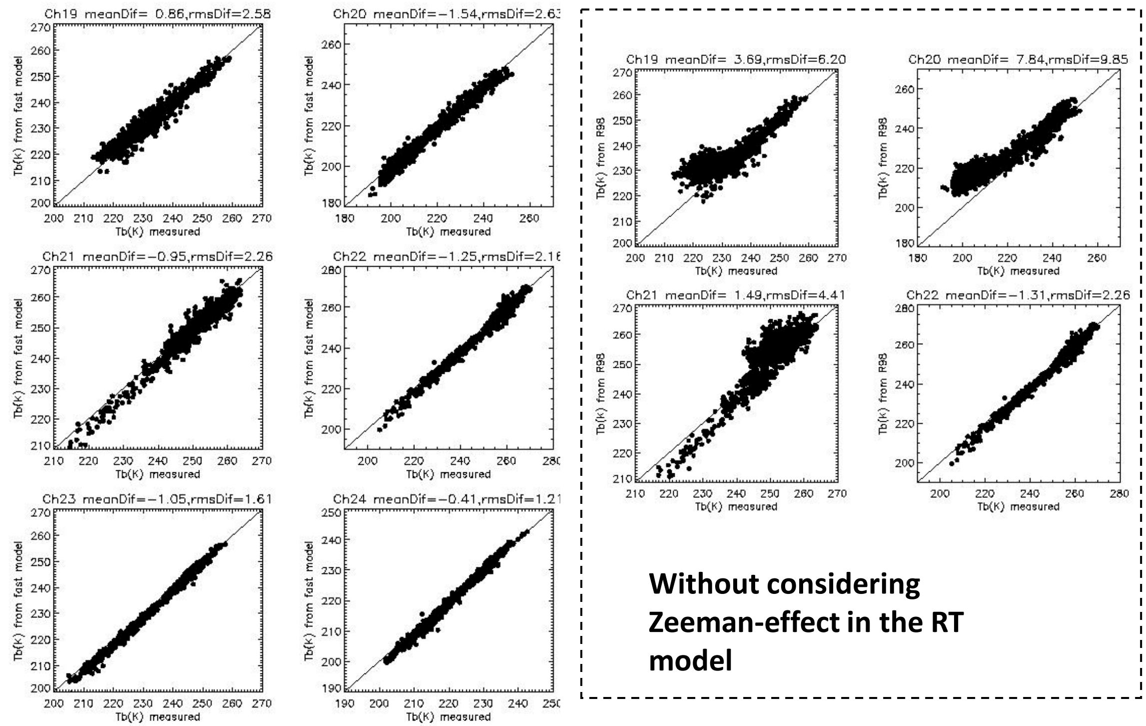
SSMIS UAS Simulated vs. Observed



(Han et al., 2007, JGR)

Fast Transmittance Model for SSMIS Upper Atmospheric Sounding (UAS) Channels

- Zeeman-splitting can have an effect up to 10 K on SSMIS UAS channels.
- The Doppler shift from Earth-rotation can have an effect up to 2 K on SSMIS UAS channels.
- Fast transmittance algorithms are implemented to take both effects into account.



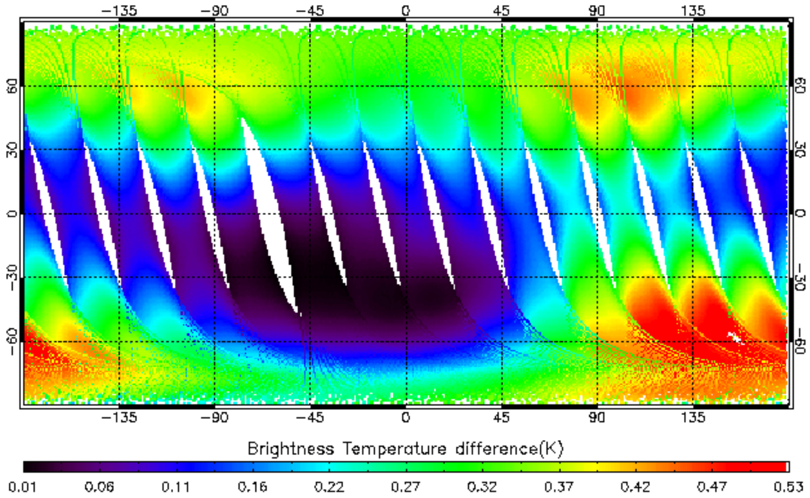
CRTM simulations compared to observations (SSMIS f16)

AMSU-A Channel-14 Brightness Temperature Differences Between RT Models w/o Zeeman-splitting Effect

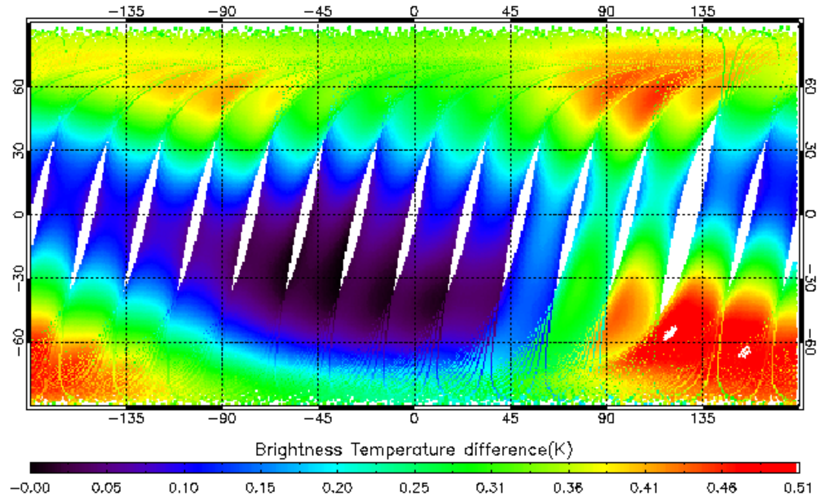
Model inputs:

B_e, θ_e, Φ_e – calculated using IGRF10 and data from AMSU-A MetOp-a 1B data files on September 8, 2007.

Atmospheric profile – US standard atmosphere applied over all regions.



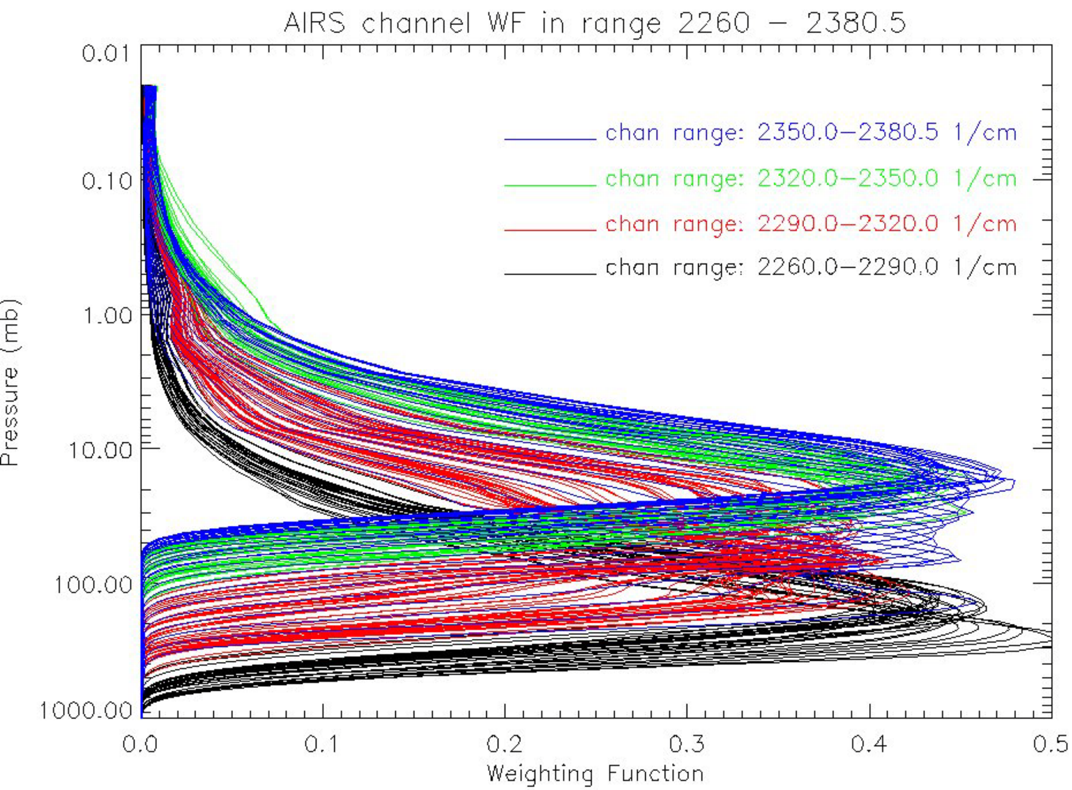
Ascending



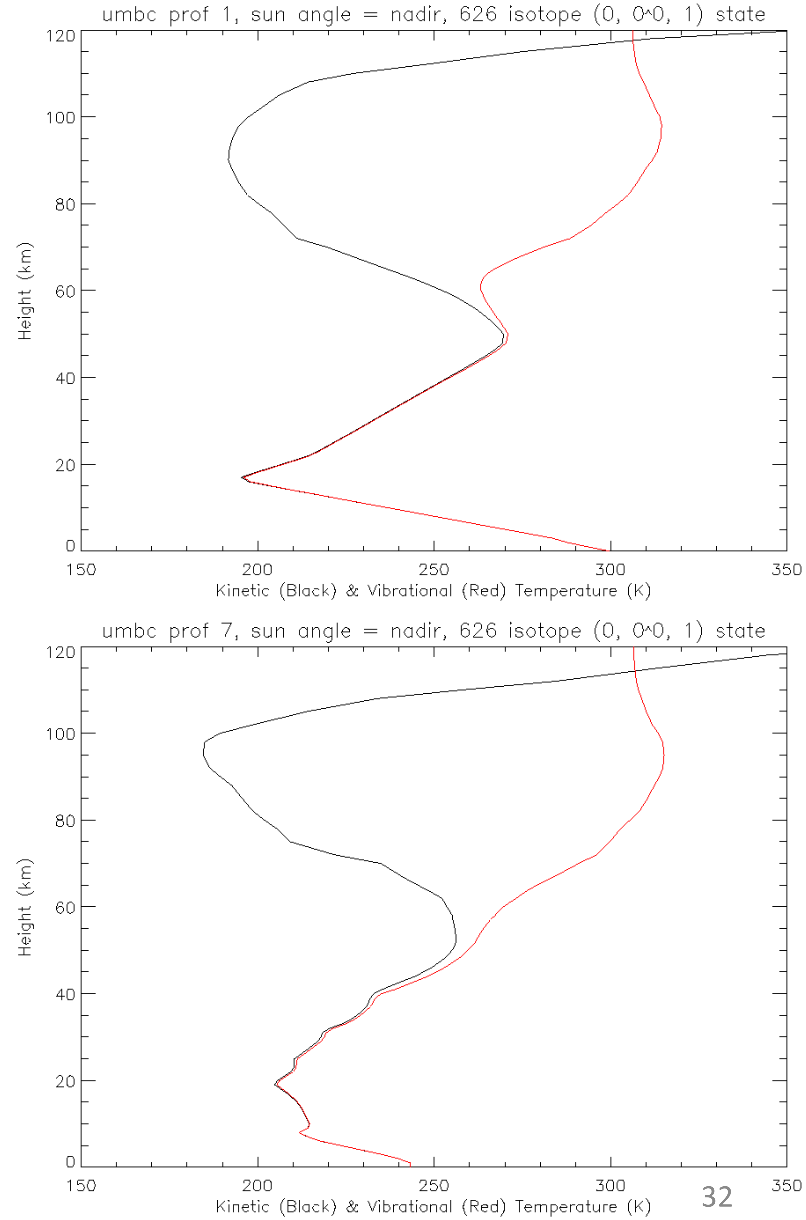
Descending

Non-Local Thermodynamic Equilibrium (NLTE) Module in CRTM

Weighting functions in shortwave region affected by NLTE



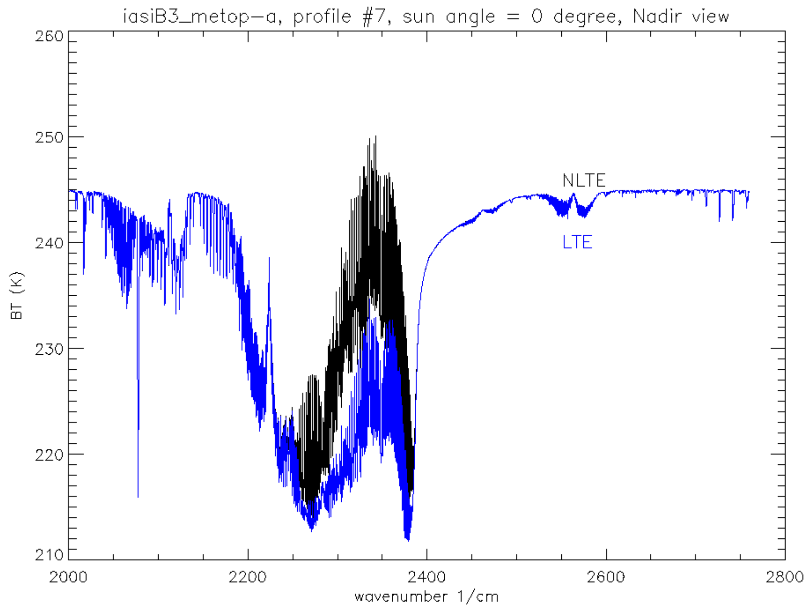
vibrational temperature



Non-Local Thermodynamic Equilibrium (NLTE) Module

$$R_{ch}^{NLTE} = R_{ch}^{LTE} + \Delta R_{ch}$$

$$\Delta R_{ch} = c_0 + \sum_{i=1}^{4} c_i x_i$$



Predictors:

x_1 - Solar angle

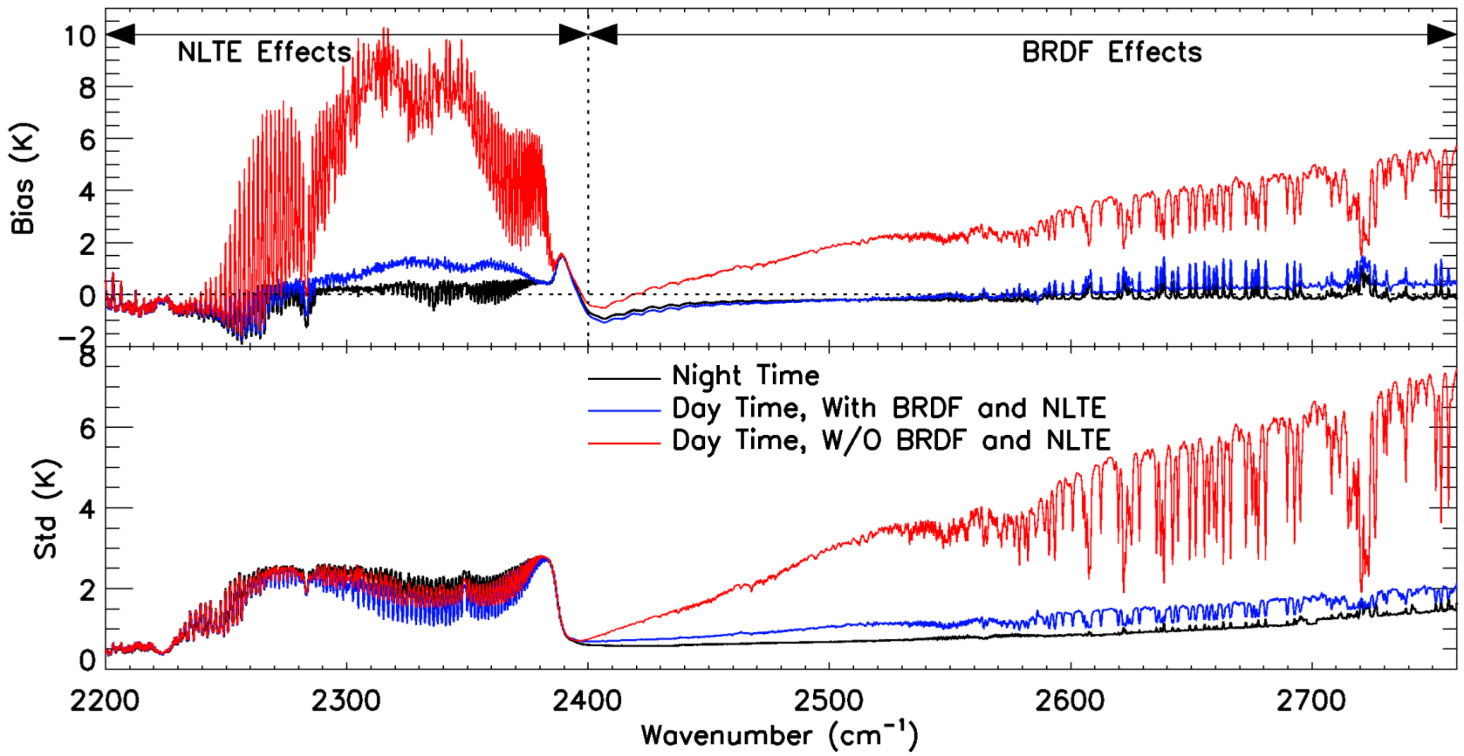
x_2 - Mean temperature from 0.005 To 0.2 mb

x_3 - Mean temperature from 0.2 To 52 mb

x_4 - Sensor zenith angle at the Earth surface

c_i - Regression coefficients, derived from LBLRTM and UMBC 48 profiles.

Validation of Ocean BRDF and NLTE Effects in CRTM by using IASI Data

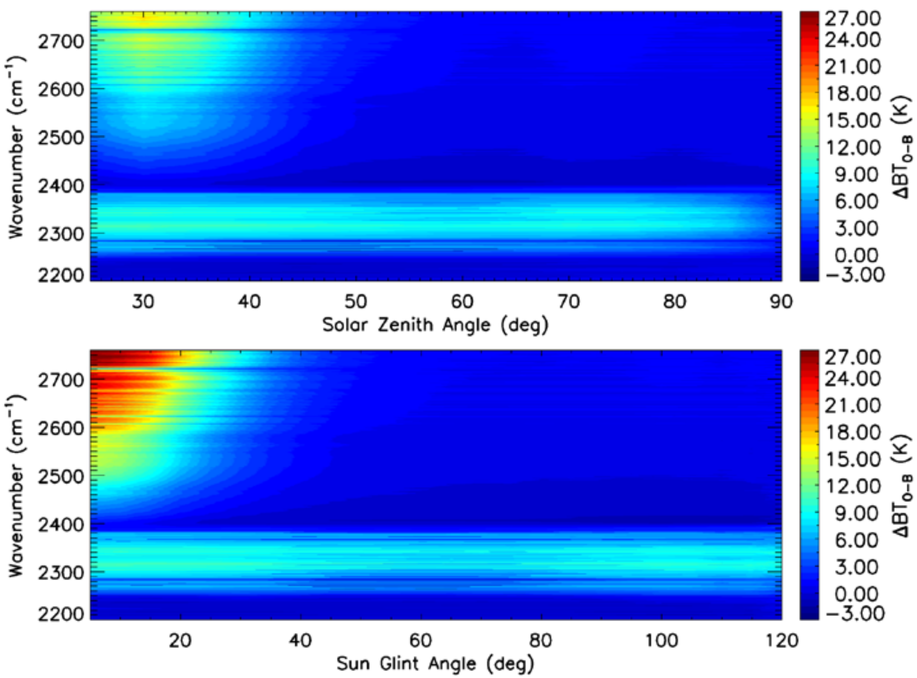


$$I = I_{em} + I_{sky} + I_{sun}$$

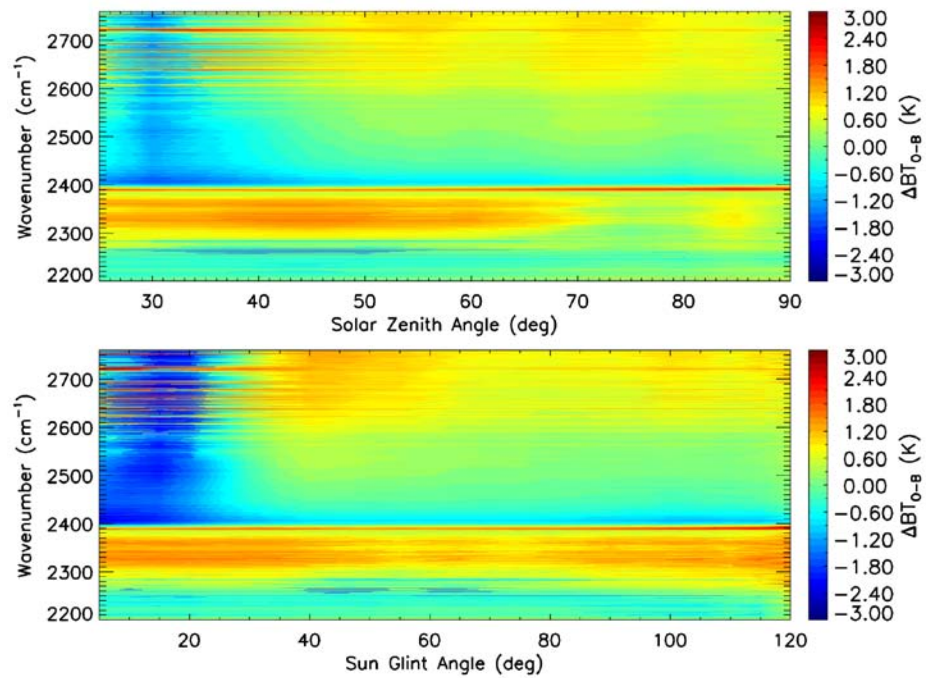
surface thermal emission	reflected down-welling thermal sky radiation	reflected sun radiation, also called sun-glint

Daytime Biases as a Function of Solar Zenith Angle and Sun Glint Angle

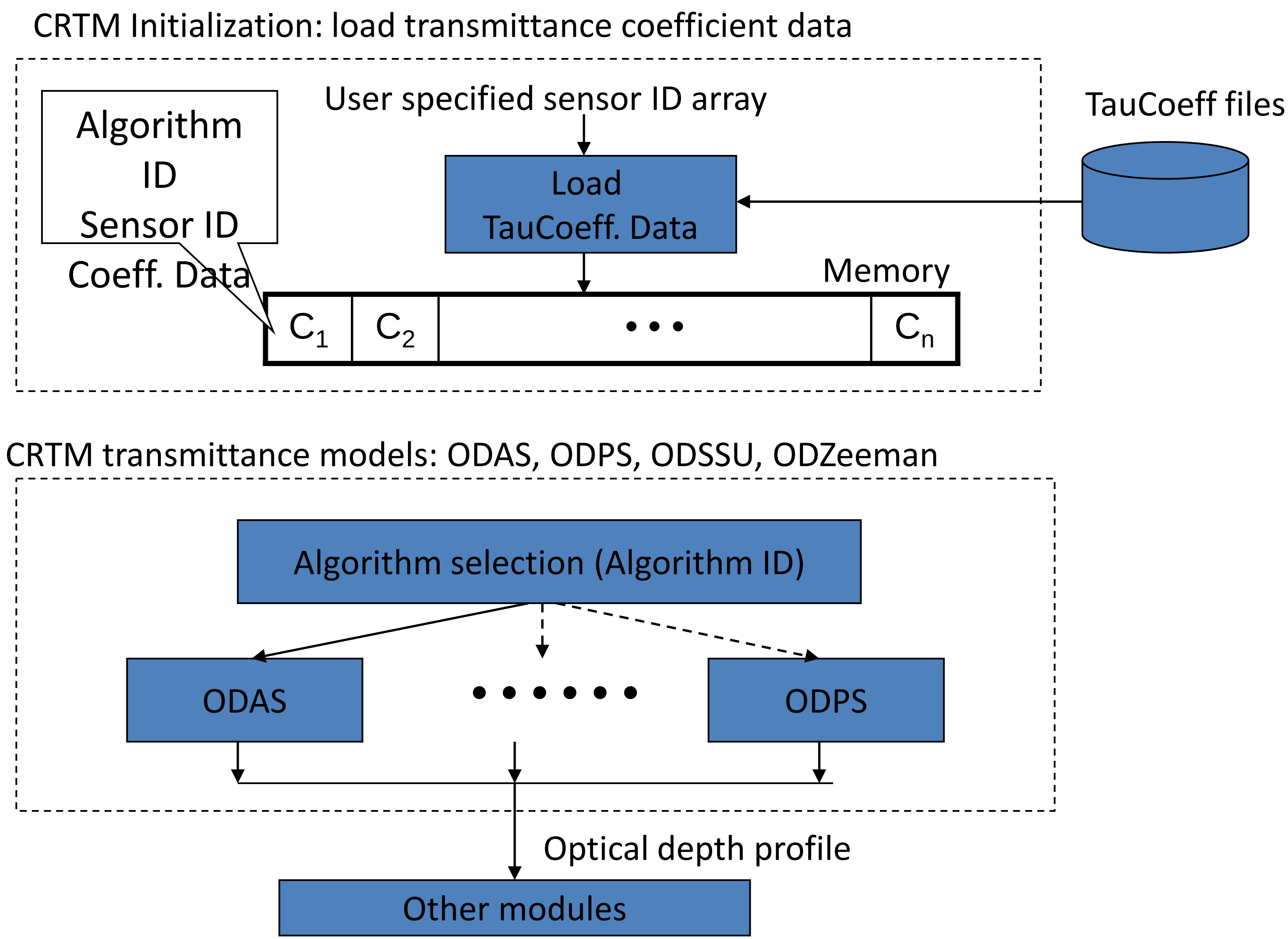
(CRTM v2.0.5 w/o BRDF and NLTE)



(CRTM v2.1 with NLTE)



Multiple Transmittance Algorithms Framework



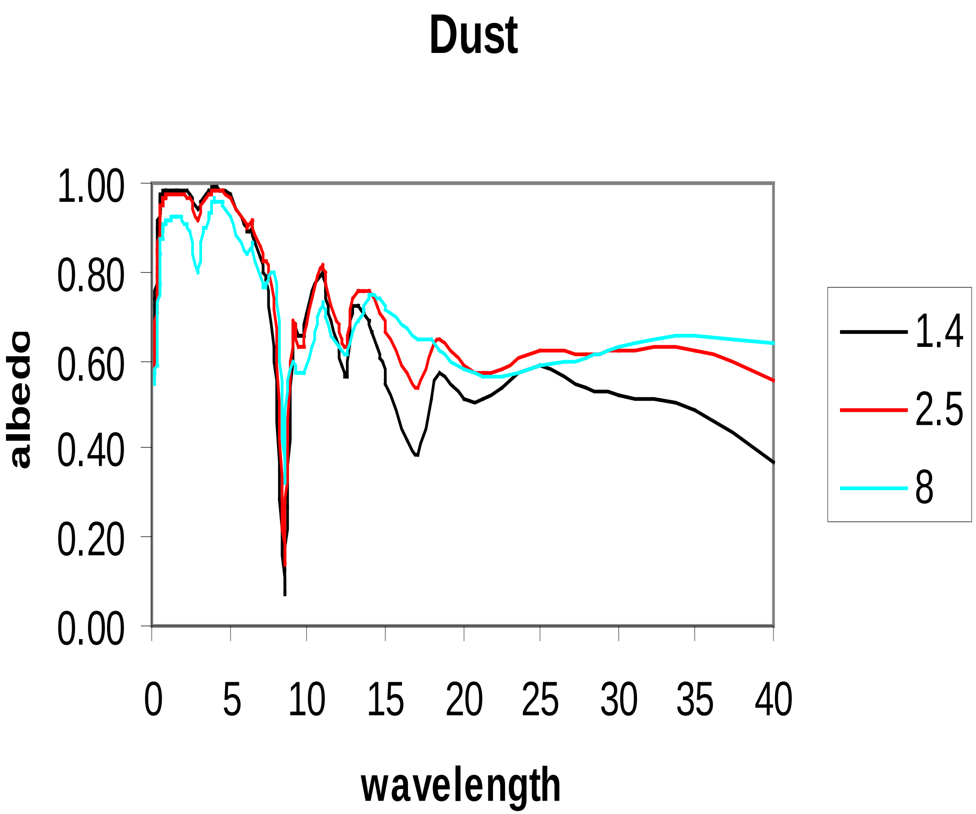
CRTM Aerosol Scattering Module

Goddard Chemistry Aerosol Radiation and Transport (GOCART) Aerosol Optical Model

1. Sulfur: DMS (Dimethyl sulfide), SO2, SO4, MSA (methanesulfonate)
2. Carbon: Hydrophobic BC/OC, hydrophilic BC/OC (water-like)
3. Dust: 8 bins: 0.1-0.18, 0.18-0.3, 0.3-0.6, 0.6-1, 1.0-1.8, 1.8-3.0, 3.0-6.0, 6.0-10.0 μm
4. Sea-salt: 4 bins: 0.1-0.5, 0.5-1.5, 1.5-5.0, 5.-10. μm

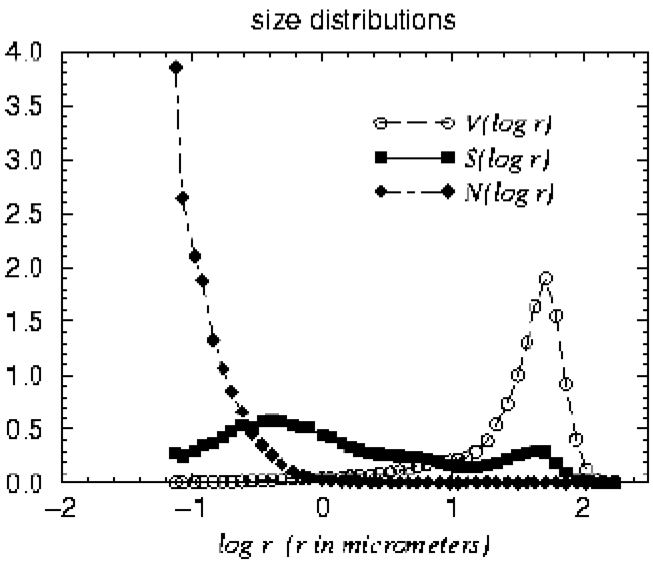
Lognormal size distribution, 35 size bins.

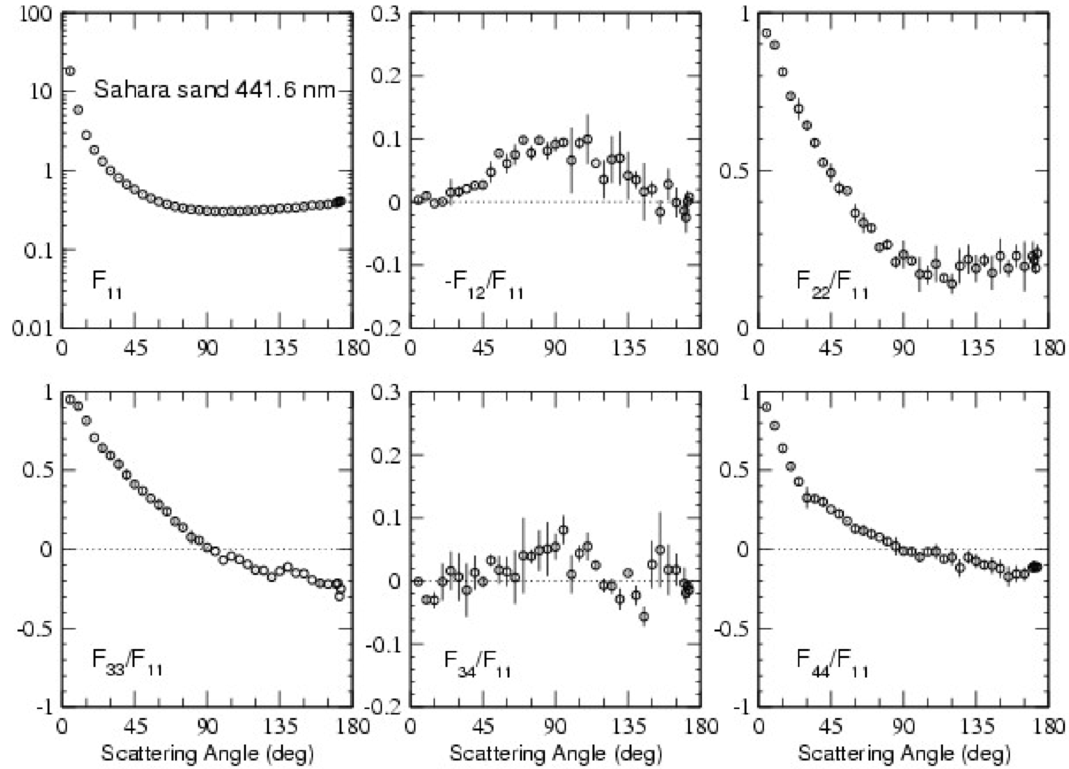
EPA Community Multiscale Air Quality (CMAQ) Aerosol Optical Model



Dust Aerosol Phase Matrix Elements

Sahara sand

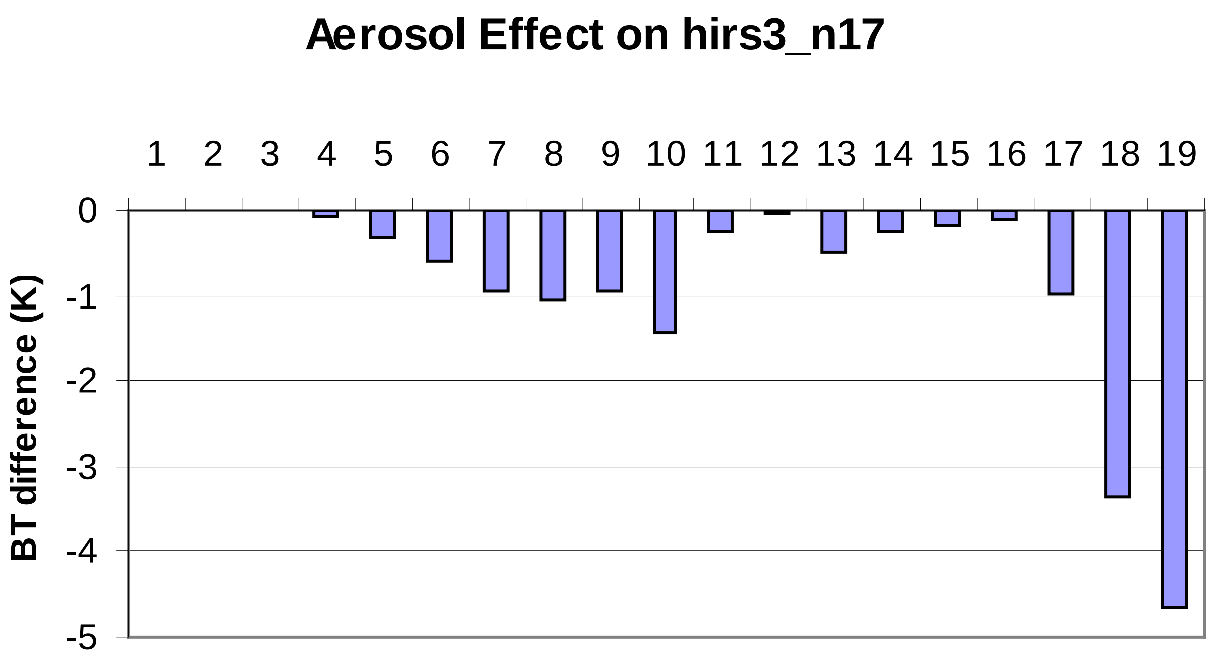




Phase functions

From Amsterdam Light Scattering Database

Aerosol Effect on NOAA-17 HIRS/3



0.1 g/m^2 OC aerosol at layer 63 (300 hPa)

0.1 g/m^2 Dust aerosol at layer 80 (592 hPa)

0.1 g/m^2 Dust aerosol at layer 82 (639 hPa)

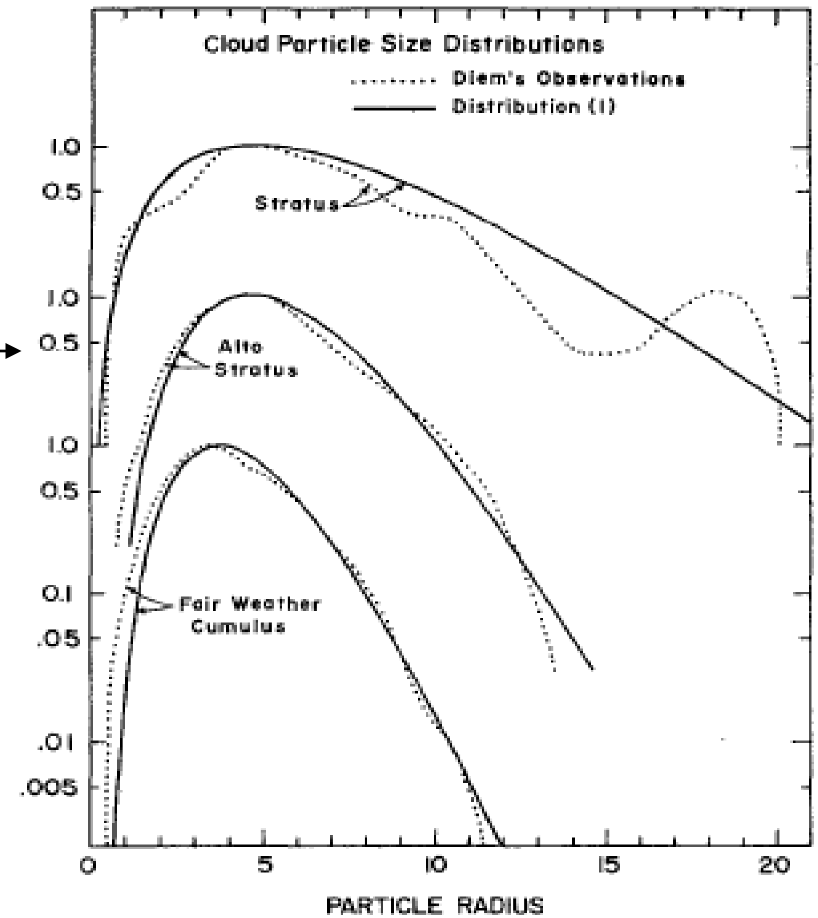
Cloud Particle Size Parameters

Gamma size distribution for small particle size:

$$f(r) = \frac{\Gamma(v)}{r_n} (r / r_n)^{v-1} e^{-r/r_n}$$

Hansen (1971)

For rain drops, snow, graupel/hail, Marshall-Palmer size distribution is used



Cloud Optical Parameter Module

- The 6 cloud types include water, ice, rain, snow, graupel and hail.

- Lookup table approach: the microphysical properties (extinction coefficient, single-scattering albedo, asymmetry factor, and Legendre phase function coefficients) of cloud particles are stored in lookup tables for IR and MW wavelengths based on widely-known publications (Simmer, 1994; Liou and Yang, 1995; Macke et al., 1996; Mishchenko et al., 2000; Baum et al., 2005, Yang et al., 2005). This table is searched with particle mean size and cloud water content (or mixing ratio). Note that the phase matrix elements are decomposed into a series of Legendre polynomials and the coefficients associated with the polynomials are also stored in the table.

- MW: the Mie theory is assumed in all calculations for spherical liquid and ice water cloud particles, and modified gamma size distributions (Simmer, 1994).

- IR (water cloud): spherical particles, Mie scattering, a modified gamma size distribution.

- IR (ice cloud): nonspherical hexagonal columns and with gamma size distribution, and the single-scattering properties of ice particles are computed from a composite method based on the finite-difference time domain technique, an improved geometric-optics method, and the Lorenz-Mie solutions for equivalent spheres (Fu et al., 1998; Yang et al., 2005).

Phase Function Model

- Rayleigh function: molecular scattering (1871)
- Henyey-Greenstein: approximate scattering (1941),for particles having finite size, no polarization.
- HG-Rayleigh scattering matrix, is a good approximation for cloud scattering in MW and aerosol scattering in IR.

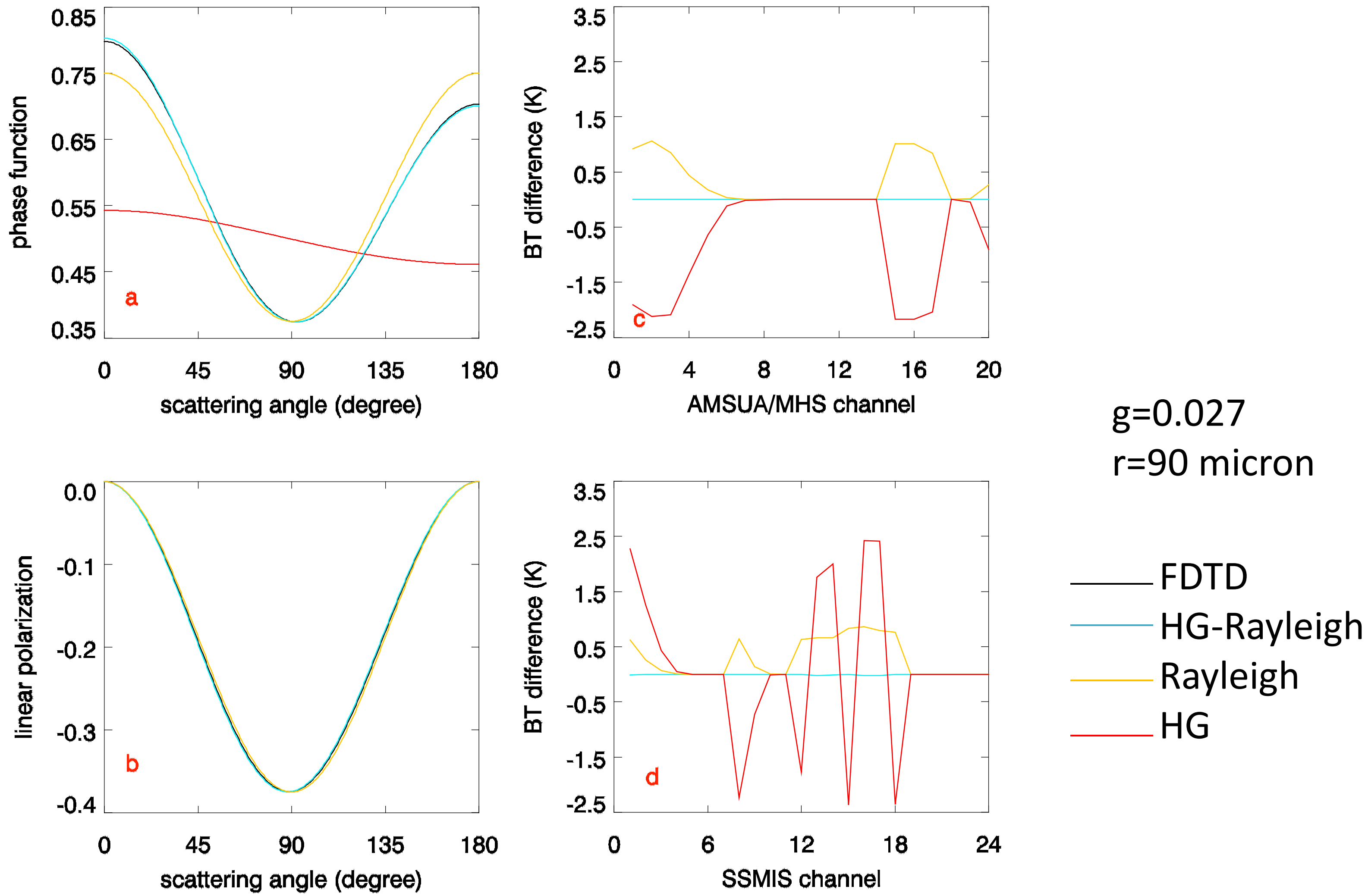
$$\mathbf{P}(\Theta, g) = C\frac{1-G^2}{(1+G^2-2G\cos\Theta)^{3/2}}\begin{bmatrix} 1+\cos^2\Theta & -1+\cos^2\Theta & 0 & 0 \\ -1+\cos^2\Theta & 1+\cos^2\Theta & 0 & 0 \\ 0 & 0 & \cos\Theta & 0 \\ 0 & 0 & 0 & \cos\Theta \end{bmatrix} \quad (1)$$

The normalization factor C and the asymmetry factor G used in HG part in HG-Rayleigh can analytically derived from

$$\int_0^{\pi} P(\Theta, g)\sin\Theta d\Theta = 1 \quad (2)$$ -----→ $$C = \frac{3}{8+3G^2}$$

$$\int_0^{\pi} \cos\Theta P(\Theta, g)\sin\Theta d\Theta = g \quad (3)$$ ---→ G=f(g)

Test HG-Rayleigh Scattering Matrix in CRTM



g=0.027
r=90 micron

(Liu and Weng, 2006, Applied Optics)

Radiative Transfer Solver

A vertically-stratified, plane-parallel and non-polarized atmosphere, the monochromatic radiative transfer equation

$$\mu \frac{dI(\tau;\mu,\phi)}{d\tau} = I(\tau;\mu,\phi) - \frac{\varpi}{4\pi}\int P(\tau;\mu,\phi;\mu',\phi')I(\tau;\mu',\phi')d\mu' d\phi' - \frac{\varpi}{4\pi}P(\tau;\mu,\phi;-\mu_{\otimes},\phi_{\otimes})F_{\otimes}e^{-\tau/\mu_{\otimes}} - (1-\varpi)B(T)$$

RT Solution under Clear-Sky Conditions $\varpi \approx 0$

$$I(\mu) = [r\int_0^{\tau_N} B(T)d\mathrm{T}_d(\tau',\mu_d) + r_{\otimes}\frac{F_{\otimes}}{\pi}\mathrm{T}_d(0,\mu_{\otimes}) + \varepsilon B(T_s)]\mathrm{T}_u(\tau_N,\mu) - \int_0^{\tau_N} B(T)d\mathrm{T}_u(\tau',\mu)$$

$$\mathrm{T}_u(\tau,\mu) = e^{-\tau/\mu} \qquad \mathrm{T}_d(\tau,\mu) = e^{-(\tau_N-\tau)/|\mu|}$$

$$I_{ch}(\mu) = (\bar{r}I_{ch}^{\downarrow}(\mu_d) + \bar{r}_{\otimes}\frac{\bar{F}_{\otimes}}{\pi}\mathrm{T}_{ch,d}(p_0,\mu_{\otimes}) + \bar{\varepsilon}B(T_{s,e}))\mathrm{T}_{ch,u}(p_N,\mu) + \sum_{i=1}^{N}(\mathrm{T}_{ch,u}(p_{i-1},\mu) - \mathrm{T}_{ch,u}(p_i,\mu))B(T_{i,e})$$

$$I_{ch}^{\downarrow}(\mu_d) = \sum_{i=1}^{N}(\mathrm{T}_{ch,d}(p_i,\mu_d) - \mathrm{T}_{ch,d}(p_{i-1},\mu_d))B(T_{i,e}) + I_{bg}T_{ch,d}(p_0,\mu_d)$$

Radiative Transfer Solver

RT Solution under Cloudy Conditions

$$\mu_i \frac{dI(\tau,\mu_i)}{d\tau} = I(\tau,\mu_i) - \varpi P(\mu_i,\mu_j) I(\tau,\mu_j) w_j - \varpi P(\mu_i,\mu_{-j}) I(\tau,\mu_{-j}) w_j - (1-\varpi) B(T)$$

$$-\mu_i \frac{dI(\tau,\mu_{-i})}{d\tau} = I(\tau,\mu_{-i}) - \varpi P(\mu_{-i},\mu_j) I(\tau,\mu_j) w_j - \varpi P(\mu_{-i},\mu_{-j}) I(\tau,\mu_{-j}) w_j - (1-\varpi) B(T)$$

$$\frac{d}{d\tau}\begin{bmatrix} \mathbf{I_u} \\ \mathbf{I_d} \end{bmatrix} = -\begin{bmatrix} \boldsymbol{\alpha} & \boldsymbol{\beta} \\ -\boldsymbol{\beta} & -\boldsymbol{\alpha} \end{bmatrix}\begin{bmatrix} \mathbf{I_u} \\ \mathbf{I_d} \end{bmatrix} - (1-\varpi) B(T) \begin{bmatrix} \mathbf{u}^{-1}\boldsymbol{\Xi} \\ -\mathbf{u}^{-1}\boldsymbol{\Xi} \end{bmatrix}$$

$$\alpha(\mu_i,\mu_j) = [\varpi\, P(\mu_i,\mu_j) w_j - \delta_{ij}] / \mu_i$$

$$\beta(\mu_i,\mu_{-j}) = \varpi\, P(\mu_i,\mu_{-j}) w_j / \mu_i$$

$$\mathbf{u} = [\mu_1, \mu_2, \ldots\ldots, \mu_N]_{diagnonal}$$

$$\boldsymbol{\Xi} = [1,1,\ldots,1]^T$$

μ_i : Gaussian quadrature points

w_i: Gaussian quadrature weights

$P(\mu_i,\mu_j), P(\mu_i,\mu_{-j})$

azimuth-averaged forward and backward phase matrix

$$P(\mu_i,\mu_j) = P(\mu_{-i},\mu_{-j})$$

$$P(\mu_{-i},\mu_j) = P(\mu_i,\mu_{-j})$$

Advanced Doubling-Adding (ADA) Method

Layer transmission and reflection

$$\mathbf{r}(\delta_0) = \delta_0 \boldsymbol{\beta} \qquad \mathbf{t}(\delta_0) = \mathbf{E} + \boldsymbol{\alpha}\delta_0 \qquad \delta = \delta_n = 2^n \delta_0$$

$$\mathbf{r}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{r}(\delta_i)\mathbf{t}(\delta_i) + \mathbf{r}(\delta_i)$$

$$\mathbf{t}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{t}(\delta_i)$$

Layer source function

$$\mathbf{S_u} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) - (B(T_2) - B(T_1))\mathbf{t} + \frac{B(T_2) - B(T_1)}{(1-\varpi g)\delta}(\mathbf{E} + \mathbf{r} - \mathbf{t})\mathbf{u}]\boldsymbol{\Xi}$$

$$\mathbf{S_d} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) + (B(T_2) - B(T_1))(\mathbf{E} - \mathbf{r}) + \frac{B(T_2) - B(T_1)}{(1-\varpi g)\delta}(\mathbf{t} - \mathbf{E} - \mathbf{r})\mathbf{u}]\boldsymbol{\Xi}$$

Vertical integration

$\mathbf{I_u}(n) = \varepsilon B(T_s)$ $\qquad \mathbf{R}(n)$ $\qquad$ the surface reflection matrix, loop k from n → 1

$$\mathbf{I_u}(k-1) = \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\,\mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\,\mathbf{I_u}(k)$$
$$= \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\,[\mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{I_u}(k)]$$

$$\mathbf{R}(k-1) = \mathbf{r}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\,\mathbf{R}(k)\mathbf{t}(k)$$

TOA radiance $\quad \mathbf{I_u} = \mathbf{I_u}(0) + \mathbf{R}(0)\,\mathbf{I}_{sky}$

ADA method remark

Numerically exactly
Analytical expressions replace the most complicated terms: source functions.
F90/F95 matrix and vector manipulation makes coding simple, also simple for tangent-linear and adjoint coding, good for code maintenance
Add a viewing angle in the streams for satellite radiance
Fast, about 60 times faster than the original double-adding method

Easy extension, for example:
Double the size of vector and matrix dimension and other minor change for the atmospheric residual polarization
Add a sun angle in the streams and add a loop over azimuthal-component for visible/UV radiance simulation

CRTM Baseline Solver +solar radiation

(Advanced Doubling-Adding, ADA)

1. Compute layer transmission and reflection (loop i from 0→ n-1)

baseline $\mathbf{r}(\delta_0) = \delta_0 \boldsymbol{\beta}$ $\quad \mathbf{t}(\delta_0) = \mathbf{E} + \boldsymbol{\alpha}\delta_0$ $\quad \delta = \delta_n = 2^n \delta_0$ $\quad \mathbf{t}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{t}(\delta_i)$

$$\mathbf{r}(\delta_{i+1}) = \mathbf{t}(\delta_i)[\mathbf{E} - \mathbf{r}(\delta_i)\mathbf{r}(\delta_i)]^{-1}\mathbf{r}(\delta_i)\mathbf{t}(\delta_i) + \mathbf{r}(\delta_i)$$

new $\mathbf{t} = (A_{22})^{-1}$ $\quad \mathbf{r} = A_{12}\mathbf{t}$ $\quad$ **where** $\exp(A\delta) = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$ **and A is the phase matrix.**

2. Compute layer source functions

$$\mathbf{S_u} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) - (B(T_2) - B(T_1))\mathbf{t} + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{E} + \mathbf{r} - \mathbf{t})\mathbf{u}]\boldsymbol{\Xi} + \frac{\varpi F_0}{\pi}\exp(-\bar{\tau}_{k-1}(\mu_0))[(\mathbf{E} - \mathbf{t}\exp(-\bar{\delta}(\mu_0))\Psi_u - \mathbf{r}\Psi_d]$$

$$\mathbf{S_d} = [(\mathbf{E} - \mathbf{t} - \mathbf{r})B(T_1) + (B(T_2) - B(T_1))(\mathbf{E} - \mathbf{r}) + \frac{B(T_2) - B(T_1)}{(1 - \varpi g)\delta}(\mathbf{t} - \mathbf{E} - \mathbf{r})\mathbf{u}]\boldsymbol{\Xi} + \frac{\varpi F_0}{\pi}\exp(-\bar{\tau}_{k-1}(\mu_0))[(\exp(-\bar{\delta}(\mu_0))E - \mathbf{t})\Psi_d - \mathbf{r}\exp(-\bar{\delta}(\mu_0))\Psi_u]$$

$$\begin{bmatrix} \Psi_d \\ \Psi_u \end{bmatrix} = -\frac{\varpi F_\lambda}{(1 + \delta_{0m})\pi}\begin{bmatrix} \boldsymbol{\alpha} + E/\mu_0 & \boldsymbol{\beta} \\ -\boldsymbol{\beta} & -\boldsymbol{\alpha} + E/\mu_0 \end{bmatrix}^{-1}\begin{bmatrix} \phi(\mu_i, \mu_0) \\ \phi(-\mu_i, \mu_0) \end{bmatrix}$$

3. Vertical integration

$$\mathbf{I_u}(n) = \varepsilon B(T_s) + \frac{F_\lambda \exp(-\bar{\tau}_N(\mu_0))}{(1 + \delta_{0m})\pi} R_s(\mu_0)$$

$\mathbf{R}(n)$ **the surface reflection matrix, loop k from n → 1**

$$\mathbf{I_u}(k-1) = \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ \mathbf{I_u}(k)$$
$$= \mathbf{S_u}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\ [\mathbf{R}(k)\mathbf{S_d}(k) + \mathbf{I_u}(k)]$$

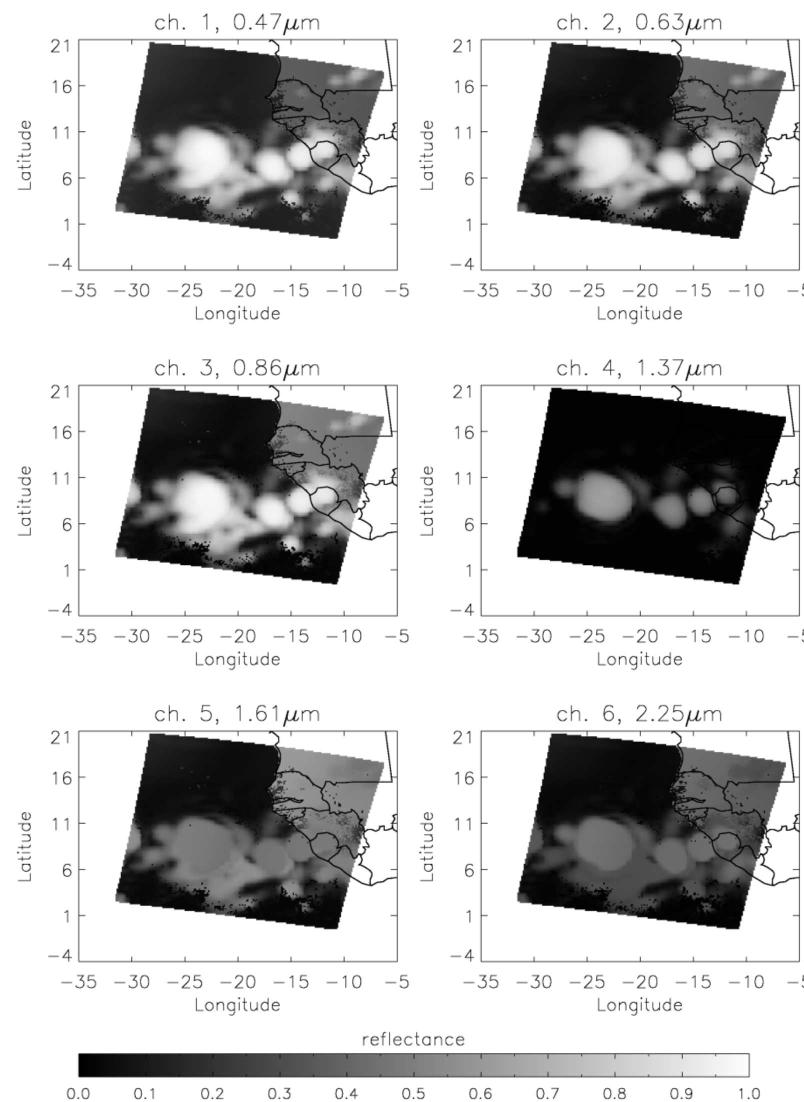
$$\mathbf{R}(k-1) = \mathbf{r}(k) + \mathbf{t}(k)[\mathbf{E} - \mathbf{R}(k)\mathbf{r}(k)]^{-1}\mathbf{R}(k)\mathbf{t}(k)$$

4. Final TOA radiance

$$\mathbf{R}adiance = \mathbf{I}_u(0) + \mathbf{R}(0)\mathbf{I}_{sky}$$

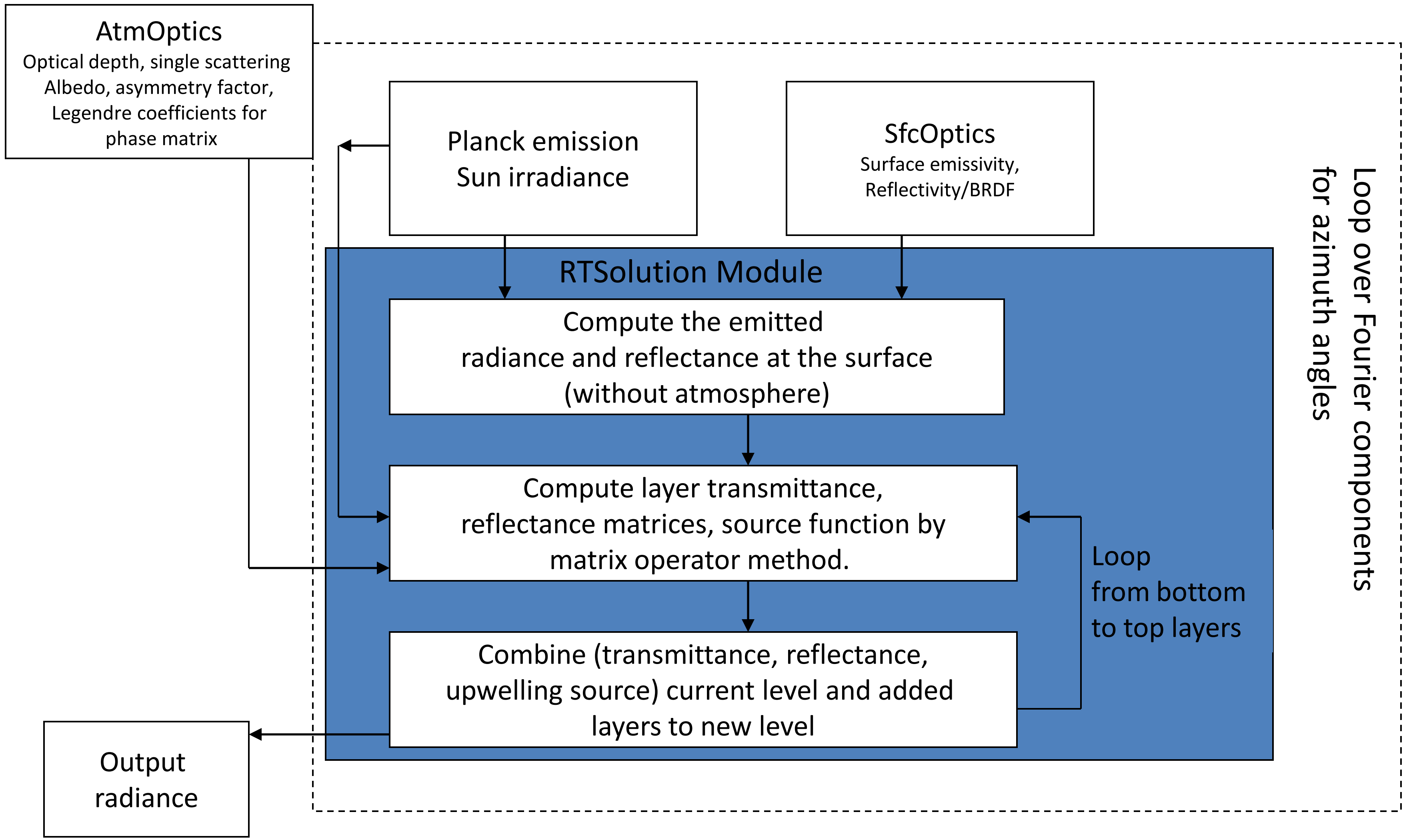
Components for Visible/UV Sensors

- MoleculeScatter module (new): compute molecule scattering optical properties
- Extension of AtmAbsorption module: compute molecule absorption for Vis/UV sensors
- Extension of CloudScatter and AerosolScatter modules: compute cloud and aerosol optical properties for Vis/UV sensors
- Extension of the Advanced Doubling-Adding (ADA) method: add integratione of the RT solution over Fourier components for azimuth angle



GOES-R ABI simulations with MODIS terra geometry parameters, GDAS data and GOCART aerosol data.

RT Solution for Cloud/Aerosol Scattering Environment: ADA with a Matrix Operator Method



(Liu and Weng, 2006, JAS; Liu 2010)

CRTM Surface Emissivity Module

Ocean Sea Ice Snow Canopy (bare soil) Desert

Microwave land emissivity model (NESDIS model) (Weng, Yan, Grody, 2001), desert microwave emissivity library (Yan and Weng, 2011), and improved NESDIS land surface emissivity model (Zheng et al., 2011); TELSEM, and CNRM databases

NPOESS Infrared emissivity database
IASI Land Infrared emissivity database
UWIREMIS database

Empirical snow and sea ice microwave emissivity algorithm (Yan and Weng, 2003; 2008)
Two layer snow emissivity model (Yan, Weng, Liang, 2010)
Fast multi-layer snow emissivity model (Liang, Weng, Yan, 2010)

FASTEM3 microwave emissivity model from (English and Hewison, 1998)
FASTEM4 microwave emissivity model (Liu, Weng, English, 2010)
FASTEM5
IR emissivity model (Wu and Smith, 1991; van Delst et al., 2001; Nalli et al., 2008)

CRTM URLs and Support Email

- CRTM software ftp site (Source code, Coefficients for each sensor, User guide, and Example programs):
  ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/

- CRTM support email list:
  listncep.list.emc.jcsda_crtm.support@noaa.gov

- CRTM trac page:
  https://svnemc.ncep.noaa.gov/trac/crtm

- CRTM repository (for checkouts, commits, etc)
  https://svnemc.ncep.noaa.gov/projects/crtm

- CRTM Announcement mailing list:
  https://lstsrv.ncep.noaa.gov/mailman/listinfo/ncep.list.emc.jcsda_crtm

- CRTM CWG mailing list:
  https://lstsrv.ncep.noaa.gov/mailman/listinfo/ncep.list.emc.jcsda_cwg

- CRTM Developers mailing list:
  https://lstsrv.ncep.noaa.gov/mailman/listinfo/ncep.list.emc.jcsda_crtm.developers

Summary

- CRTM is a fast and accurate model to compute satellite radiance and radiance derivatives for IR, MW, Visible and UV sensors.
- It includes advanced RT components to compute absorption, emission and scattering from various gases, clouds, aerosols and surfaces.
- It has been extensively validated against its base models and observations.
- The user interface and program structure are designed for easy use and future expansion.
- CRTM continues to update new components (NLTE, additional SOI RT solver) and to improve in computational efficiency, transmittance model and surface emissivity/reflection models (e.g. FASTEM5, and databases).

References

- •Carter, C., Q. Liu, W. Yang, D. Hommel, and W. Emery, 2002: Net heat flux, visible/infrared imager/radiometer suite algorithm theoretical basis document. Available on http://npoesslib.ipo.noaa.gov/u_listcategory_v3.php?35.
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