Radiative Transfer Models

Acknowledgments: This material has been prepared based on

- An Introduction to the JCSDA Community Radiative Transfer Model (CRTM) Yong Han NOAA/NESDIS JCSDA
- Introduction to radiative transfer, by Robert Hudson
- Radiation Transfer by Jean-Jacques Morcrette. Meteorological Training Course Lecture Series ECMWF, 2002
- http://www.star.nesdis.noaa.gov/smcd/spb/CRTM/
- A first course in atmospheric radiation. Grant W. Petty, 2004.

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Outline

- Basic concepts
- The role of a fast radiative transfer model in satellite data assimilation
- Radiative transfer (RT) equation applied
- CRTM main modules and user interfaces

What are Radiative Transfer Models?

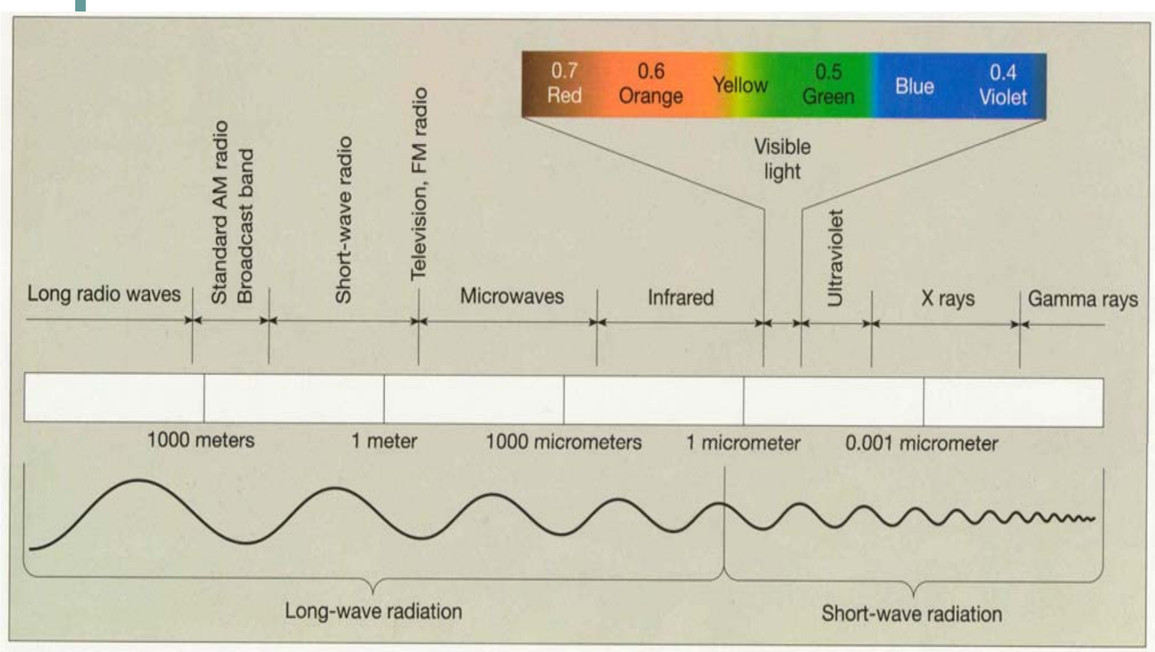
- Radiative transfer models are an important tool for many product retrieval strategies. Such models simulate the radiative transfer processes of the atmosphere at a given wavelength or spectral region for a given set of surface and atmospheric conditions. The radiative transfer model is thus used, for example, as a tool to compute an expected brightness temperature for cloud-free conditions.

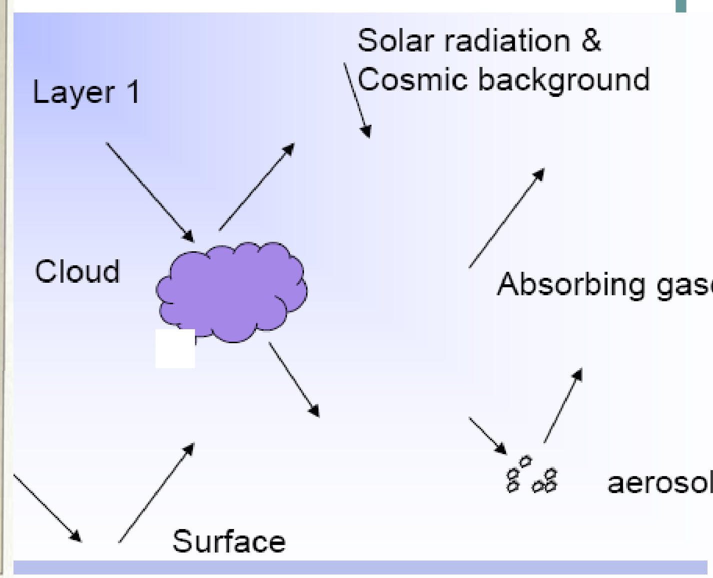
Basic concepts

- Compared to other processes, radiation transfer (RT) also stands as having a long history of theoretical developments.
- From the statistical and quantum mechanics at the end of the 19th and beginning of the 20th century, Boltzmann, Stefan, Wien, Planck and Einstein made pioneering advances in the spectral description of the radiation emitted by a black body.
- Afterwards, spectroscopic studies of the gases important for the radiative budget of the atmosphere, and the development of various approximations, made the calculation of the radiation transfer in the atmosphere a tractable problem.

Basic concepts

- We are dealing with EM waves, and are interested in a significant portion of the EM spectrum
- We are concerned with how gas molecules can emit and absorb energy (quantized)
- We know that some amount of energy is reflected and some is scattered, and need to represent how.





Spherical coordinates and solid angle

- Solid angle

$$d\omega = \sin\theta d\theta d\phi$$

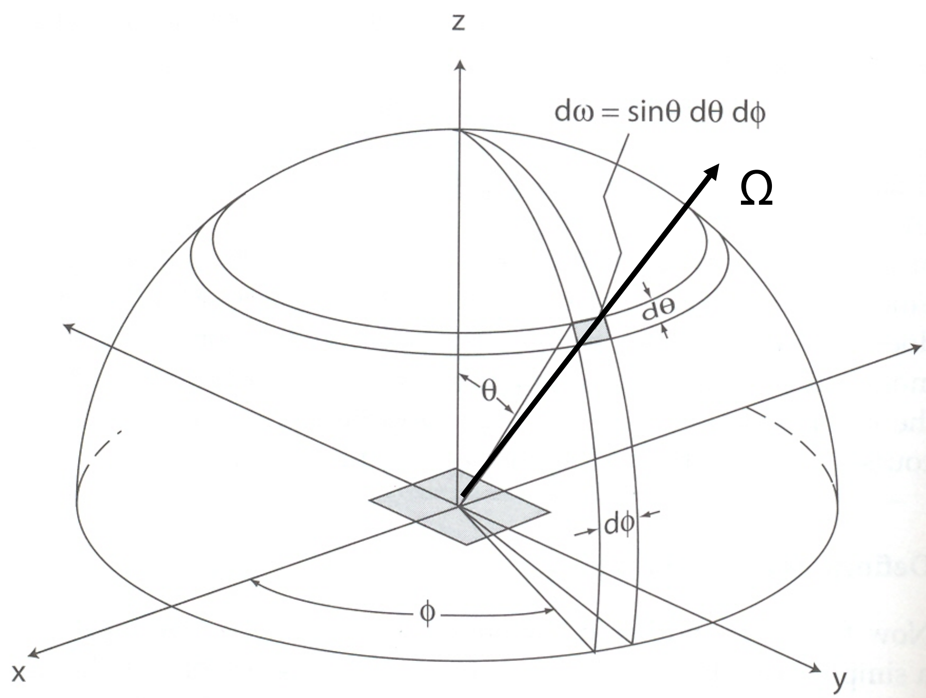


Fig. 2.4: The relationship between solid angle and polar coordinates.

From Petty, 2004

Fundamental variables

- Radiance

$$I_\lambda = \frac{\delta Q_R}{d\Omega dA dt}$$

Intensity: the flux of energy in a given direction per second per unit frequency range per unit solid angle per unit area perpendicular to the given direction

Brightness temperature T_B: the inverse of the black body emission

$$B_\lambda(T) = \frac{2hc^2}{exp(\frac{hc}{\lambda kT}) - 1}\lambda^{-5}$$

- Transmittance

$$\tau(s_1, s_2) = e^{-\int_{s_1}^{s_2} \beta_e(s)ds}$$

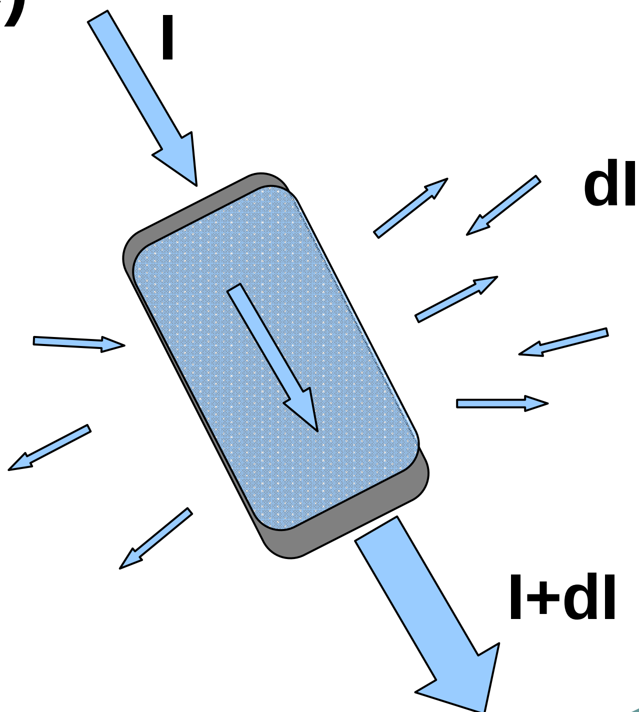
β_e is the monochromatic extinction coefficient (m^{-1})

So that, intensity at point s_2 will be

$$I_\lambda(s_2) = \tau(s_1, s_2) I_\lambda(s_1)$$

The Radiative Transfer equation

- We need to represent 3 main processes:
  - **Extinction (absorption + scatter)**
  - **Scattering (as a source)**
  - **Emission**



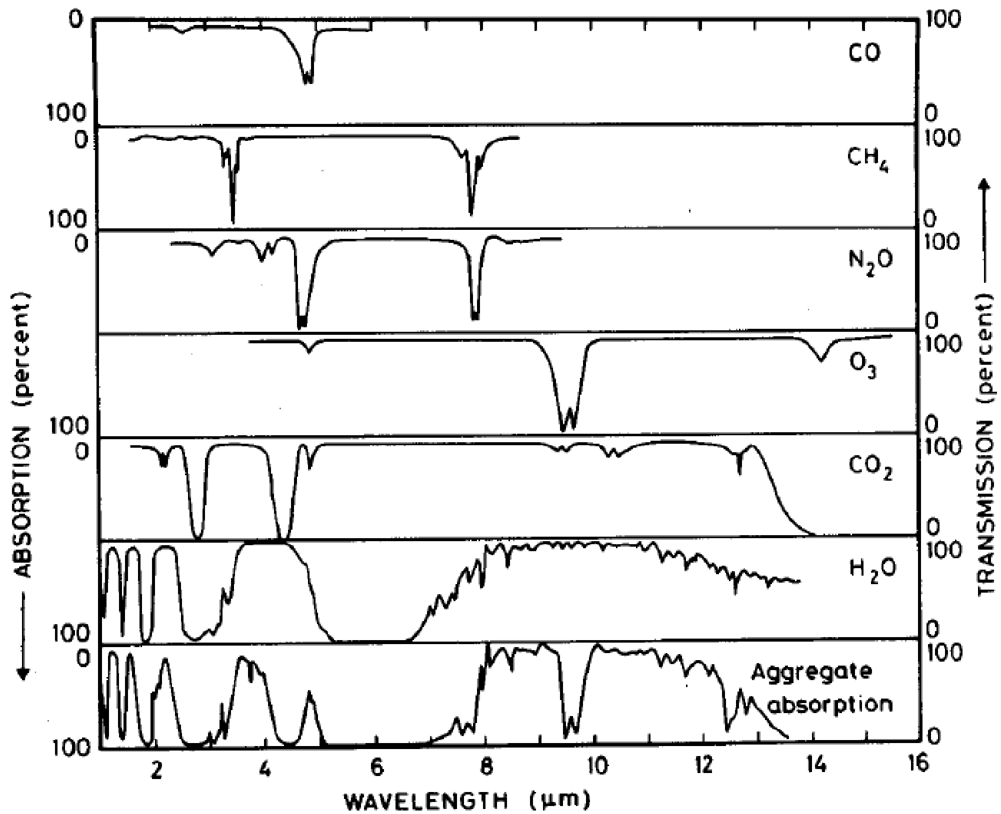
$$dI_{\lambda} = dI_{\lambda,ext} + dI_{\lambda,scat} + dI_{\lambda,emit}$$

Extinction: absorption + scattering

- Depends on the path, on the incident radiation and on the composition of the atmosphere

$$dI_{\lambda,ext} = -\beta_a I_\lambda ds - \beta_s I_\lambda ds$$

$$dI_{\lambda,ext} = -\beta_e I_\lambda ds$$



β_e is the monochromatic extinction coefficient (m^{-1})

Example: absorption in the IR

Scattering (as a source)

- It must be proportional to the scattering coefficient βs,
- Radiation passing through our infinitesimal volume from any direction Ω´ can potentially contribute scattered radiation in the direction of interest Ω
- These contributions from all directions will sum in a linear fashion

$$dI_{\lambda,scat} = \frac{\beta_s}{4\pi} \int_{4\pi} p(\Omega', \Omega) I_\lambda(\Omega') d\omega' ds$$

p(Ω´, Ω) is the normalized scattering phase function, i.e., the probability for a photon incoming from direction (Ω´) to be scattered in direction (Ω)

Emission

- It depends on T and varies with wavelength (Planck's function, has a continuous spectrum along λ, at all T)
- It peaks at a particular wavelength (Wien's law)
- At a fixed wavelength, a good absorber is also a good emitter (Kirchhoff's law). Absorption by gases is an interaction between molecules and photons and obeys quantum mechanics

$$dI_{\lambda,emit} = \beta_a B_{\lambda,T} ds$$

β_a is the monochromatic absorption coefficient (m^{-1})

Radiative Transfer equation

$$dI_\lambda = dI_{\lambda,ext} + dI_{\lambda,scat} + dI_{\lambda,emit}$$

$$dI_\lambda = -\beta_e I_\lambda ds + \frac{\beta_s}{4\pi}\int_{4\pi} p(\Omega',\Omega) I_\lambda(\Omega') d\omega' ds + \beta_a B_\lambda ds$$

- In terms of the optical depth σ $\quad d\sigma = -\beta_e ds$

$$\frac{dI_\lambda(\Omega)}{d\sigma} = -I_\lambda(\Omega) + (1-\tilde{\omega})B_\lambda + \frac{\tilde{\omega}}{4\pi}\int_{4\pi} p(\Omega',\Omega) I_\lambda(\Omega') d\omega'$$

single scatter albedo

$$\tilde{\omega} = \frac{\beta_s}{\beta_e} = \frac{\beta_s}{\beta_a + \beta_s}$$

- And using the plane parallel approximation

$$\mu\frac{dI_\lambda(\mu,\phi)}{d\sigma} = I_\lambda(\mu,\phi) - (1-\tilde{\omega})B_\lambda + \frac{\tilde{\omega}}{4\pi}\int_0^{2\pi}\int_{-1}^{1} p(\mu',\phi';\mu,\phi) I_\lambda(\mu',\phi') d\mu' d\phi'$$

$\mu = \cos\theta$

What is required to build a radiation transfer model?

- a formal solution of the radiation transfer equation
- an integration over the vertical, taking into account the variations of the radiative parameters with the vertical coordinate
- an integration over the angle, to go from a radiance to a flux
- an integration over the spectrum, to go from monochromatic to the considered spectral domain
- a differentiation of the total flux w.r.t. the vertical coordinate to get a profile of heating rate

In the context of data assimilation

$$J = \frac{1}{2}[(y_o - H(x))^T R^{-1}(y_o - H(x)) + (x - x_b)^T B^{-1}(x - x_b)]$$

- H(x) is the observation operator. It is applied to model variables (x) in order to derive or retrieve "observed" variables (y_o)
- An RT model is essentially H(x) and is needed to obtain radiances from model variables
- It can also be used to retrieve information about the model state variables from the radiance measurements.

What CRTM does?

- CRTM stands for “Community fast RT Model” and refers to the computational efficient algorithms that have been developed by several research groups to meet the requirements of the operational data assimilation system.
- It is used to simulate radiances and radiance gradients (or Jacobians) at the top of atmospheres for satellite and other space-based radiometers. It is a vital software used in numerical weather prediction model data assimilation systems .

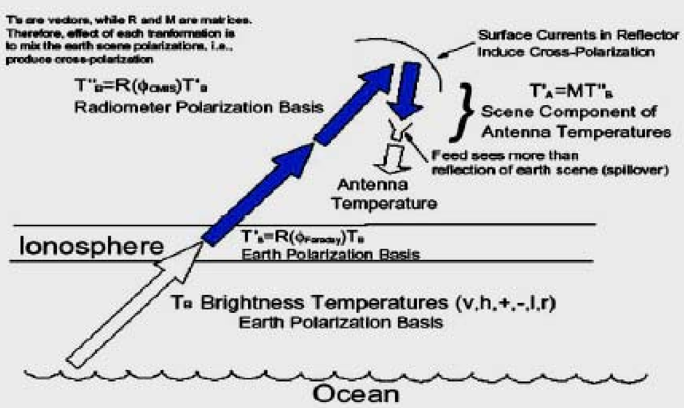
- Compute satellite radiances (Forward model)
- Compute radiance responses to the perturbations of the state variables (Tangent-linear model)
- Compute Adjoint (Adjoint model)
- Compute Jacobians (K-matrix model)

http://www.star.nesdis.noaa.gov/smcd/spb/CRTM/

NOAA Satellites and Information
National Environmental Satellite, Data, and Information Service

Office of Research and Applications — Sensor Physics Branch

JCSDA COMMUNITY RADIATIVE TRANSFER MODEL



What's New in CRTM

- **CRTM implementation:** CRTM was implemented into NCEP GFS gridpoint statistical interpolation system (GSI)
- **CRTM developments (August 10, 2006):** CRTM has an interface with SARTA. SARTA is a fast gas absorption model that works with the best accuracy with AIRS instrument. It also has trace gas absorption. Tangent linear and adjoint models are also developed for SARTA.

... More

Background	Science Components in CRTM					Archiving
Capability	Surface Models	Gas Absorption	Particle Scattering	Transfer Scheme	Advanced Scheme	Presentations
Overview	Microwave	OPTRAN	Cloud & Precip	Advanced Doubling&Adding	3D Monte Carlo	Briefings
Framework	Infrared	OSS	Aerosol	Successive Order of Interaction	Vector Discret Ordinate RT	CRTM User Guide
Team	Visible	SARTA	Molecule	Delta-4 Streams		
Linkage		Zeeman Effects		Discrete Ordinate Tangent Linear		

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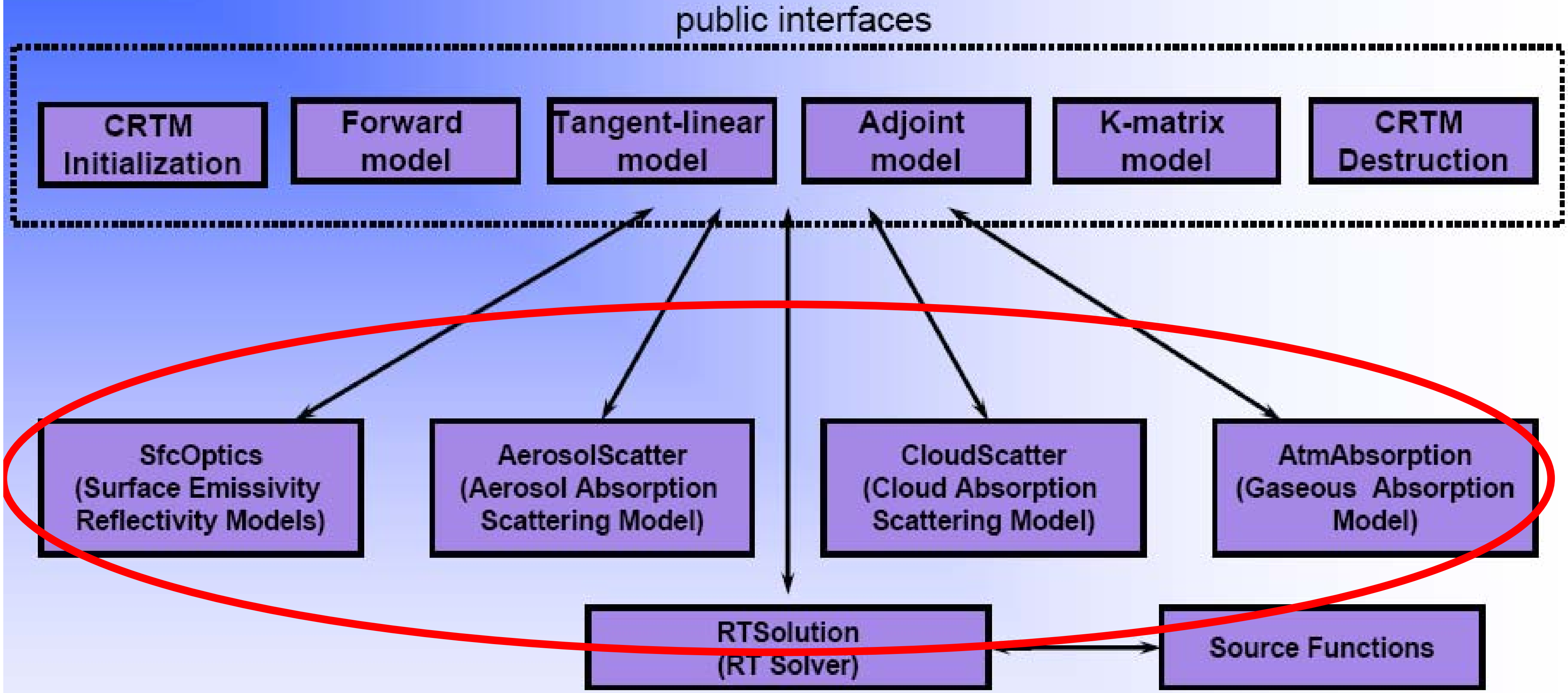
CRTM Major Modules



Supported Instruments (IR & MW)

TIROS-N to NOAA-18 AVHRR
TIROS-N to NOAA-18 HIRS
GOES-8 to 13 Imager channels
GOES-8 to 13 sounder channel 08-13
GOES-R ABI
Terra/Aqua MODIS Channel 1-10
METEOSAT-SG1 SEVIRI

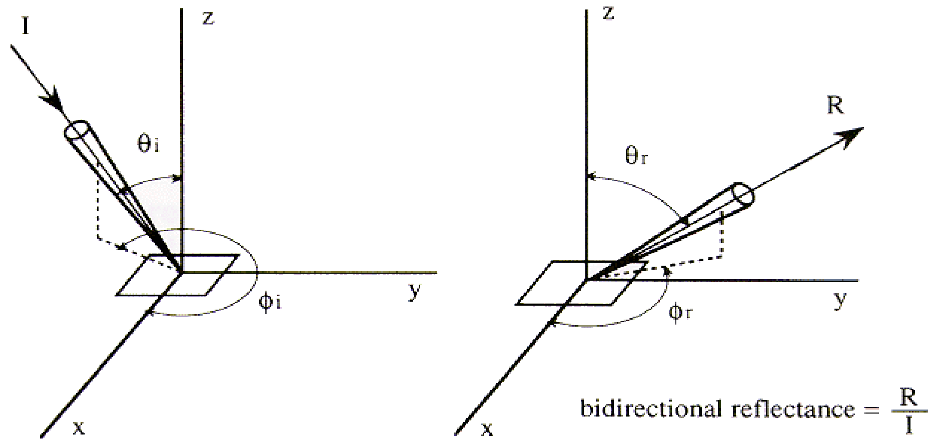
Aqua AIRS
Aqua AMSR-E
Aqua AMSU-A
Aqua HSB
NOAA-15 to 18 AMSU-A
NOAA-15 to 17 AMSU-B
NOAA-18 MHS
TIROS-N to NOAA-14 MSU

DMSP F13,15 SSM/T1
DMSP F14,15 SSM/T2
DMSP F16 SSMIS
NPP ATMS
Coriolis Windsat
METOP-A AMSUA, MHS, HIRS, AVHRR

CRTM modules

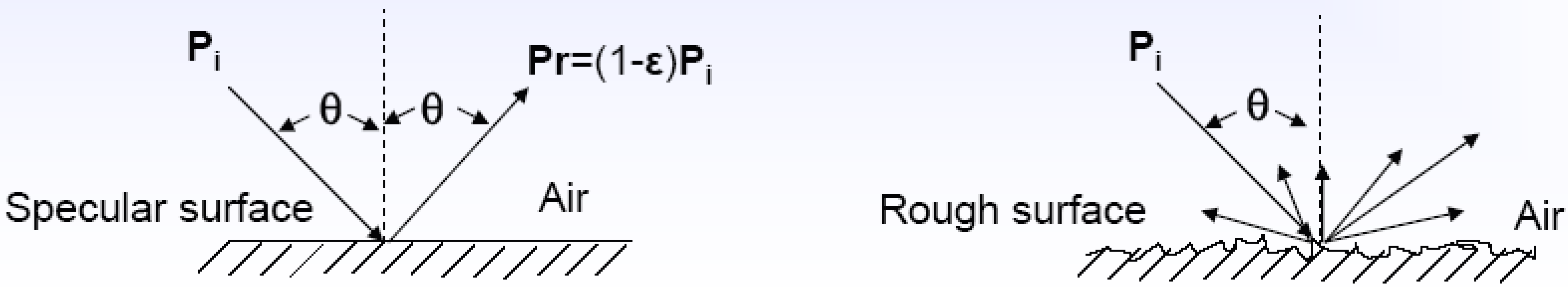
- **CRTM surface emissivity/reflectivity models** (relevant longitudes IR and MW)
  - Function of surface characteristics and T
  - Depends on incident radiation
- **CRTM Fast transmittance models**
- **CRTM absorption and scattering**
  - By clouds
  - By aerosols

Surface reflectivity

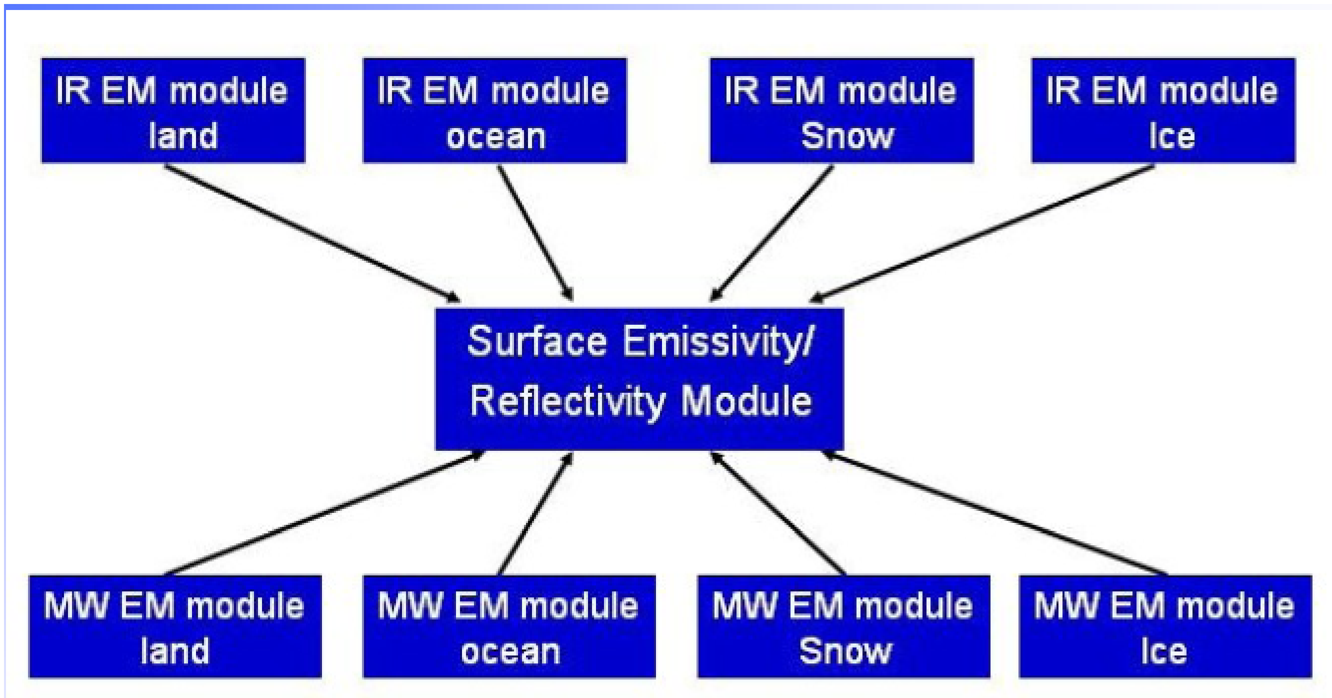


$$I^{\uparrow}{}_{\lambda}(\theta_r,\phi_r)=\int_0^{2\pi}\int_0^{\pi/2}\rho(\theta_i,\phi_i;\theta_r,\phi_r)I_{\lambda}^{\downarrow}(\theta_i,\phi_i)\cos\theta_i\sin\theta_i d\theta_i d\phi_i$$

CRTM assumes a specular reflection for MW sensors and Lambertian reflection for IR sensors, and uses relationship: $\rho(\theta)=1-\varepsilon(\theta)$ **(but** $\varepsilon(\theta)$ **is not limited to the two special cases)**



Surface emissivity



Technical characteristics

- Microwave emissivity
  - Over Land: NESDIS developed a microwave land emissivity model (Weng et al, 2001)
  - Over Ocean: Microwave Ocean Emissivity Model: FASTEM-1 (English and Hewison, 1998)
- Infrared emissivity:
  - From vis to IR wavelengths, the emissivity over land is derived from a look-up table, according to surface type and wavelength.

Surface Type	
Compacted soil	Grass scrub
Tilled soil	Oil grass
Sand	Urban concrete
Rock	Pine brush
Irrigated low vegetation	Broadleaf brush
Meadow grass	Wet soil
Scrub	Scrub soil
Broadleaf forest	Broadleaf(70)/Pine(30)
Pine forest	Water
Tundra	Old snow
Grass soil	Fresh snow
Broadleaf/Pine forest	New ice

Carter et al., 2002

CRTM modules

- **CRTM surface emissivity/reflectivity models** (relevant longitudes IR and MW)
  - Function of surface characteristics and T
  - Depends on incident radiation
- **CRTM Fast transmittance models**
- **CRTM absorption and scattering**
  - By clouds
  - By aerosols

RT solution under clear sky conditions

$$dI_\lambda = dI_{\lambda,abs} + dI_{\lambda,emit} = \beta_a (B_\lambda - I_\lambda) ds \qquad d\sigma = -\beta_a ds$$

$$\frac{dI_\lambda}{d\sigma} = -(B_\lambda - I_\lambda)$$

- The Schwarzchild's equation is the most fundamental description of radiative transfer in a nonscattering medium

$$I_\lambda(0) = \left[I_\lambda(\sigma') e^{-\sigma'} \right] + \int_0^{\sigma'} B_\lambda e^{-\sigma} d\sigma$$

We get the radiant intensity observed by the sensor that is stationed at σ =0, arriving from the far side of the path

Radiative transfer solution under clear sky conditions

$$I_\nu = \sum_{k=1}^{n} (\tau_{\nu,k-1} - \tau_{\nu,k}) B_\nu(T_k) + \varepsilon_\nu B_\nu(T_s)\tau_{\nu,n} + (1-\varepsilon_\nu)\tau_{\nu,n} I_s{}^{\downarrow}{}_\nu + \rho_\nu \tau_\nu(p_s, \theta_{sun})(F_{0,\nu}/\pi)\cos\theta_{sun}$$

(1) (2) (3) (4)

Transmittance at the kth level: $\tau_k = e^{-\sum_{j=1}^{k} \sigma_j / \cos(\theta)}$

σ_k – optical depth of the kth layer

(1) Contribution from the atmospheric absorbing gases;
(2) Contribution from surface emission attenuated by the atmosphere
(3) Surface reflected downwelling radiation from the atmosphere and space cosmic background attenuated by the atmosphere.

$$I^{\downarrow}{}_{s,\nu}(\theta_d) = \sum_{k=1}^{n} (\tau^{\downarrow}{}_{\nu,k}(\theta_d) - \tau^{\downarrow}{}_{\nu,k-1}(\theta_d)) B_\nu(T_k) + \tau^{\downarrow}{}_{\nu,n}(\theta_d) I_c$$

MW: θ_d – satellite zenith angle (specular surface reflection)
IR : θ_d – diffuse angle (Lambersian surface reflection)

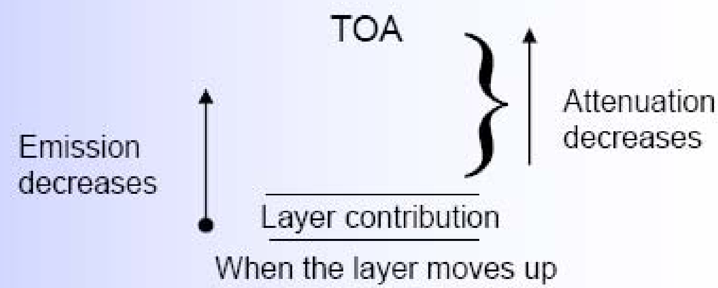
(4) Surface reflected solar radiation attenuated by the atmosphere

Weighting function

Weighting function:

$$w_k = (\tau_{\nu,k-1} - \tau_{\nu,k}) / (z_{k-1} - z_k)$$

or $$w_k = (\tau_{\nu,k-1} - \tau_{\nu,k}) / (\ln(p_k) - \ln(p_{k-1}))$$



(1) The atmosphere contribution (the first term of the RT solution in the previous slide) can be express as

$$I^{atm}{}_{\nu} = \sum_{k=1}^{n} \Delta z_k w_{k,\nu} B_{\nu}(T_k)$$

(a) The atmospheric contribution is the weighted sum of the source functions;
(b) The weighting function tells the relative importance of the contribution from each atmospheric layer.
(c) Weighting function does not depend on the layer thickness.

- W peaks at the level where absorption/emission is maximum

Weighting function

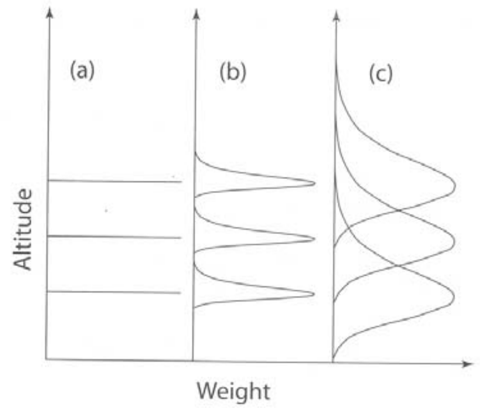
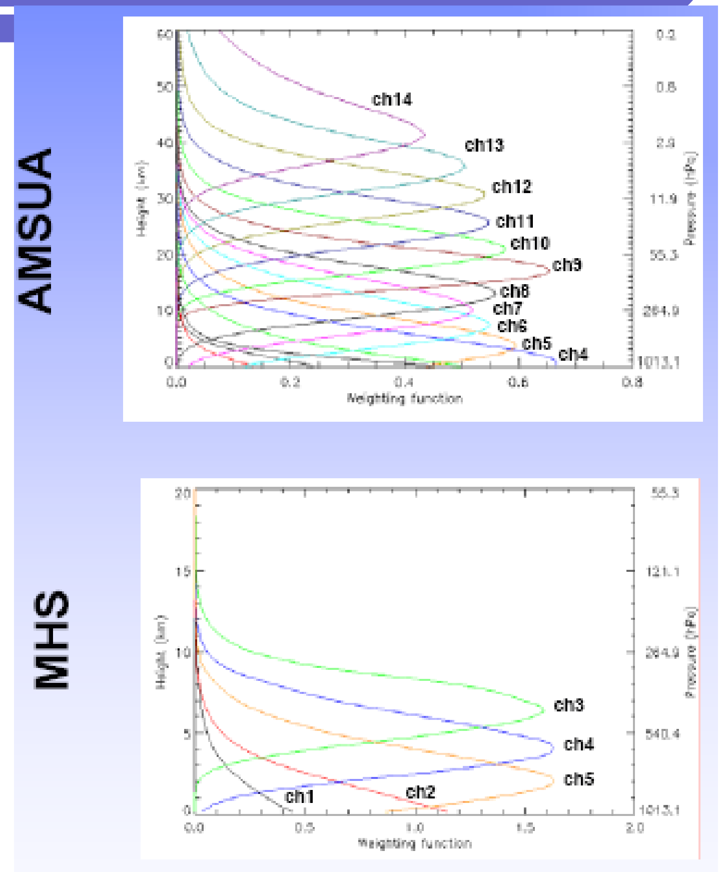


Fig. 8.4: Idealized satellite sensor weighting functions for atmospheric temperature profile retrievals. (a) Channel weighting functions resemble δ-functions; i.e., all emission observed by each channel originates at a single altitude. (b) Observed emission represents layer averages, but channel weighting functions do not overlap. (c) Realistic case, in which weighting functions not only represent layer averages but also overlap.

- Given any reasonable number of channels, there is always considerable overlap between adjacent WF

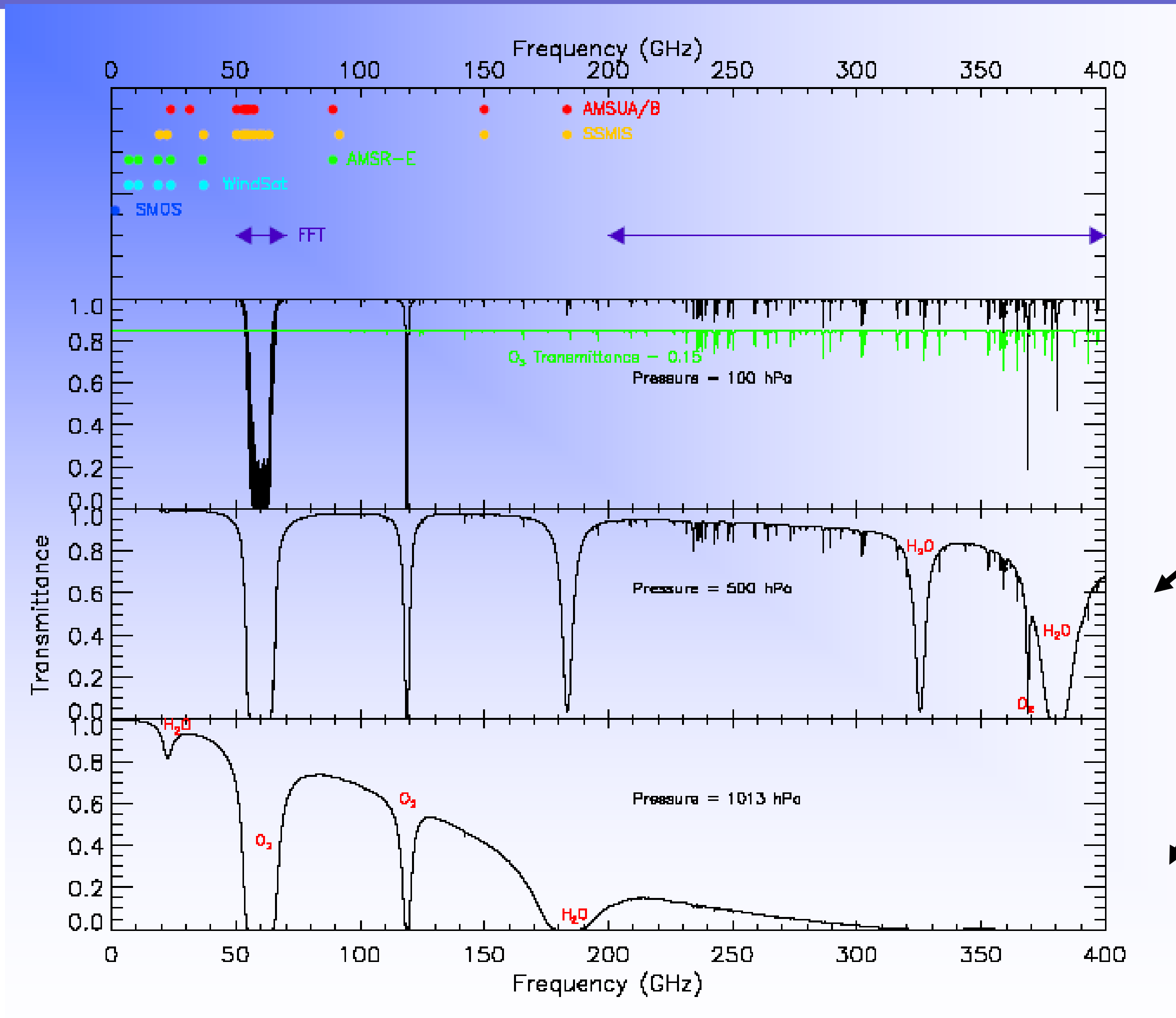


Computed with CRTM for US standard atmosphere over ocean surface

How does absorption take place?

- Line width:
  - In theory $\nu = \Delta E / h$ and lines are monochromatic
  - Actually, lines are of finite width, due to
    - **Natural broadening** (Heisenberg's principle)
    - **Doppler broadening**: because of the random translational motions of individual molecules in any gas, absorption and emission occurs at wavelengths that are Doppler-shifted relative to natural line position
    - **Pressure broadening**: Collisions between molecules randomly disrupt natural transitions between energy states, so that emission and absorption occurs at wavelengths that deviate from the natural line position

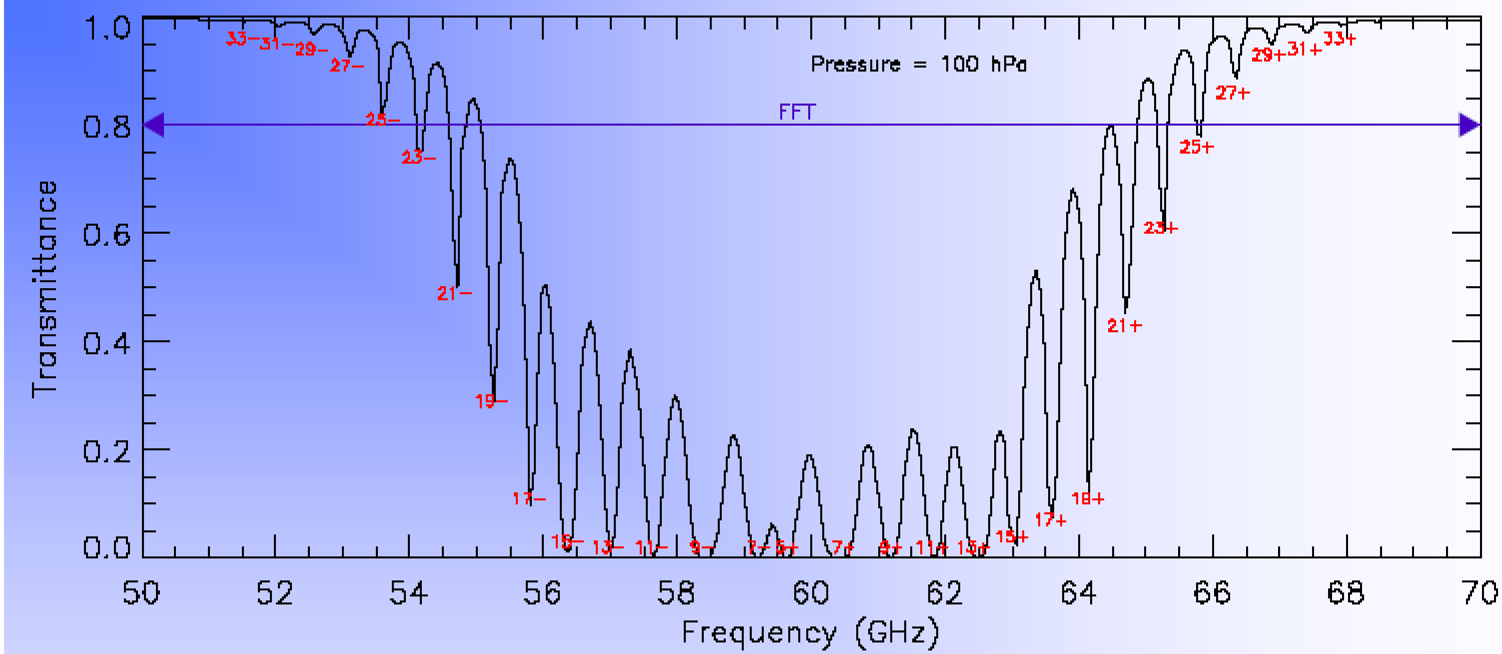
Microwave



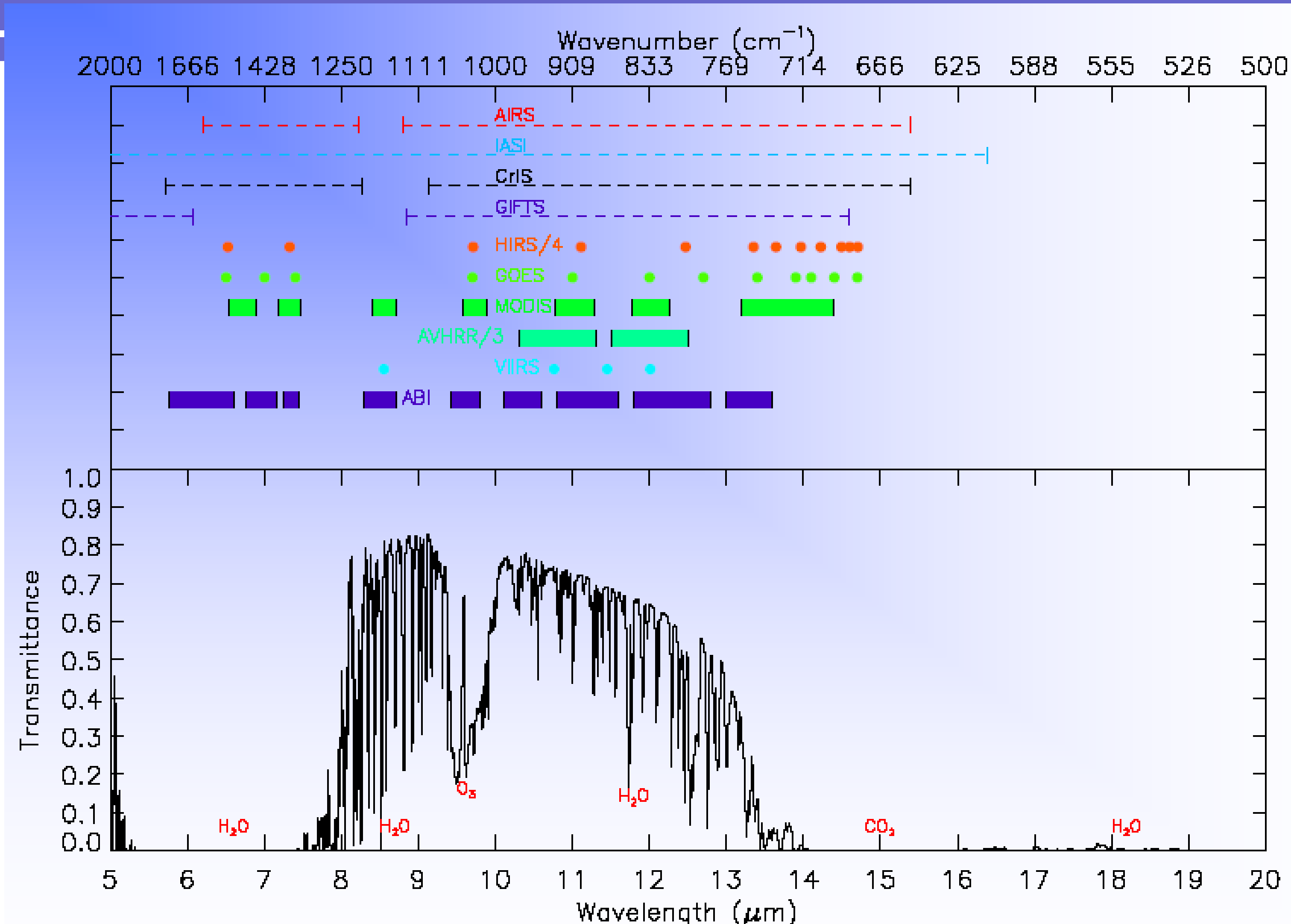
Pressure broadening

Microwave

MW O_2 transmittance near 60 GHz

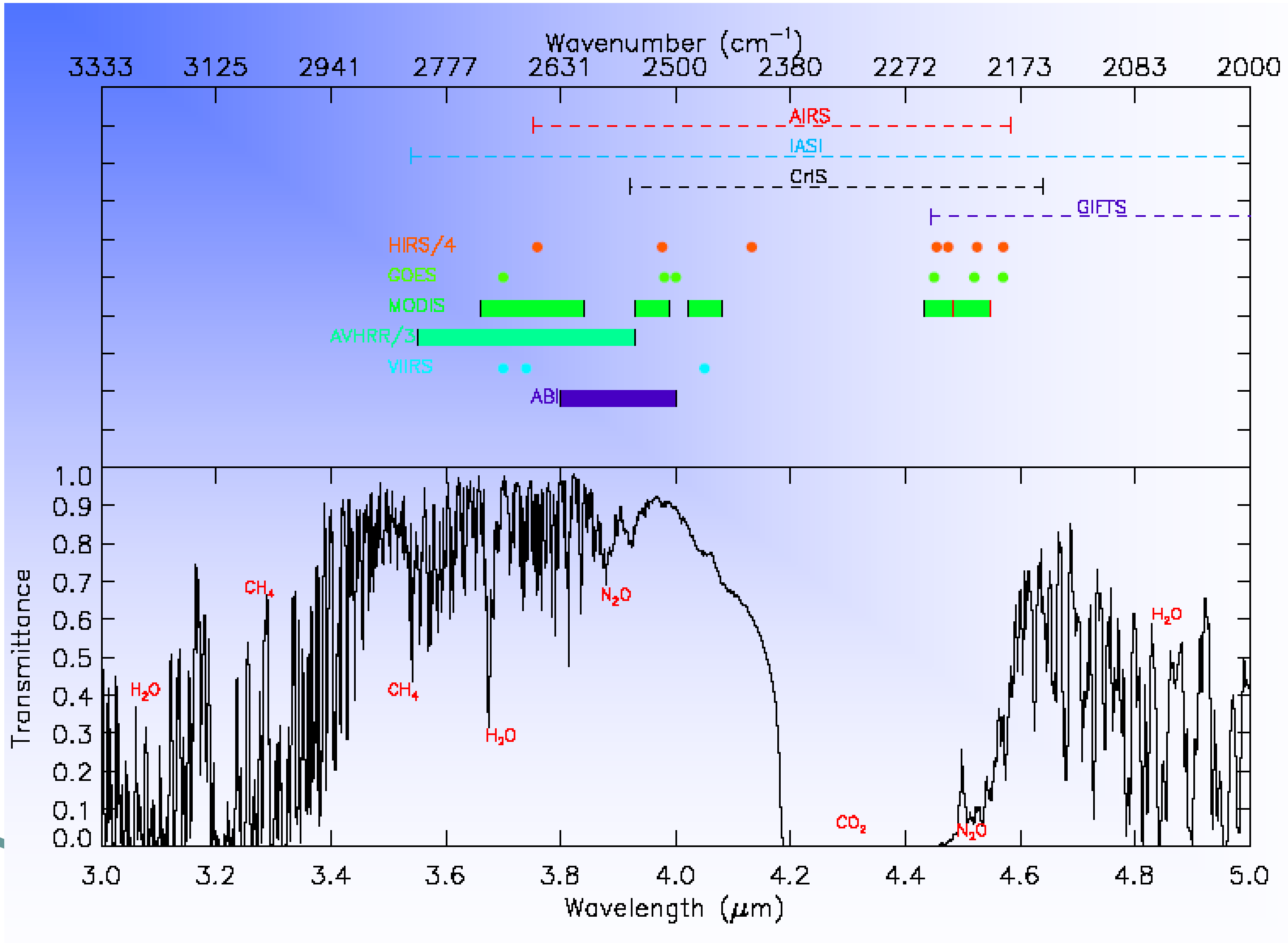


Infrared



Wavenumber (cm⁻¹)
2000 1666 1428 1250 1111 1000 909 833 769 714 666 625 588 555 526 500
AIRS
IASI
CrIS
GIFTS
HIRS/4
GOES
MODIS
AVHRR/3
VIIRS
ABI
Transmittance
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
H₂O
H₂O
O₃
H₂O
CO₂
H₂O
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Wavelength (μm)

IR total transmittance spectrum (2)



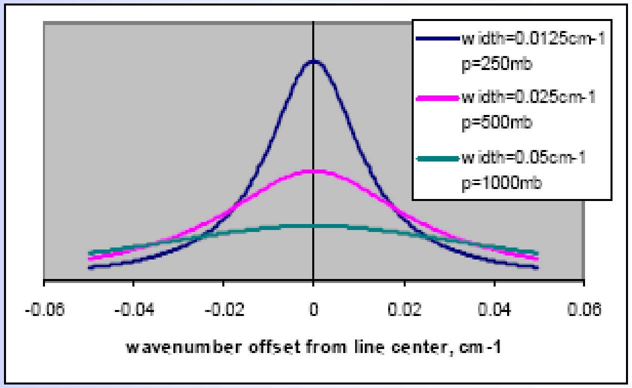
Fast approximation for transmittance calculations

- Under clear atmospheric conditions, radiative transfer modeling uses atmospheric absorption coefficients as the key input.
- The absorption varies with the atmospheric conditions in a complicated way and is often computed through the line-by-line (LBL) models.
- Although LBL models are accurate, they take considerable time to calculate transmittances for just a few atmospheres. To provide accurate transmittances in a timely fashion, the CRTM has generated and used fast approximation commonly known as OPTRAN for specific instrument channels.
- For atmospheric transmittance calculations, the gas absorption coefficients are predicted from the atmospheric parameters at fixed levels of the integrated absorber amount (Kleespies et al., 2004).
- This approach significantly reduces the coefficients which reside in computer memory and preserves the accuracy.

OPTRAN Basic idea

Why need fast algorithm:

In the atmosphere, the absorption line width α_L is about 0.05 cm^{-1} at 1000mb and 0.0125 cm^{-1} at 250 mb. So, e.g., for a sensor with 1 cm^{-1} passband, a large number of monochromatic radiance calculations are needed for channel radiance simulation:



From Goody

$$I_{ch} = \sum_{i=1}^{N} I_{\nu_i} \phi_{\nu_i}$$

← The channel's spectral response function (SRF)

Current operational systems can not handle such computation.

Solution: parameterize the optical depth $\sigma_{ch,k}$, defined as

$$\sigma_{ch,k} \equiv \ln(\tau_{ch,k-1} / \tau_{ch,k}) \quad \text{and} \quad \tau_{ch,k} \equiv \sum_{i=1}^{N} \tau_{\nu_i,k} \phi_{\nu_i}$$

Parameterization:

$$\sigma_{ch,k} = c_{0,k} + \sum_{i=1}^{n} c_{i,k} x_{i,k}$$

← Predictors, such as T and water vapor

The radiance is then computed with the regular RT equation without the need for spectral integration.

CRTM modules

- **CRTM surface emissivity/reflectivity models** (relevant longitudes IR and MW)
  - Function of surface characteristics and T
  - Depends on incident radiation
- **CRTM Fast transmittance models**

- **CRTM absorption and scattering**
  - By clouds
  - By aerosols

Basic ideas

- Scattering efficiency depends on size r, geometrical shape, and the real part of its refractive index
- Intensity of scattering depends on Mie parameter $\alpha = 2 \pi r / \lambda$
- molecules $r \sim 10^{-4}$ μm; $\alpha << 1$
  - Rayleigh scattering
- aerosols $0.01 < r < 10$ μm
- cloud particles $5 < r < 200$ μm, rain drops and hail particles up to 1 cm

CRTM absorption and scattering by clouds
(provide cloud optical parameters for RT solution)

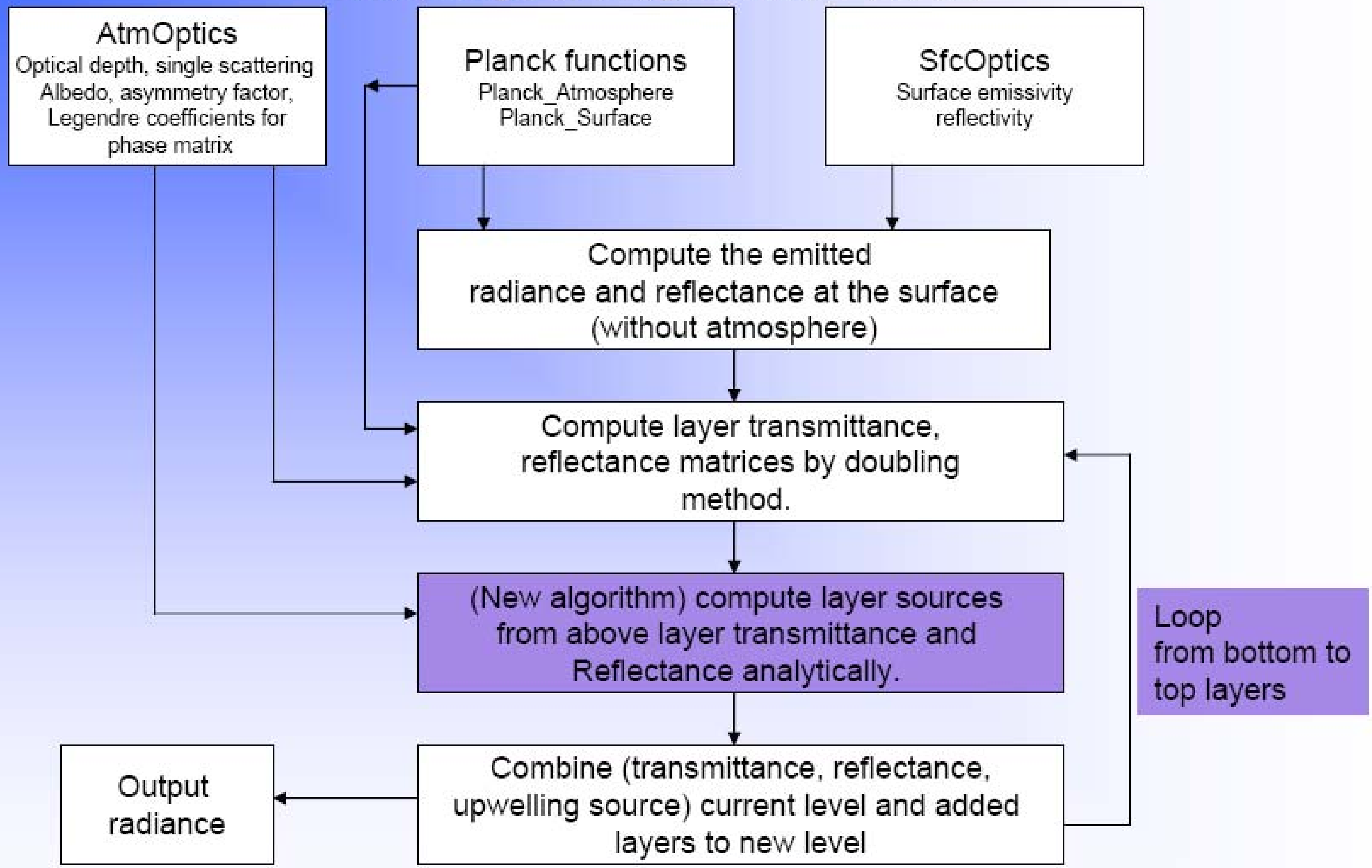
- CRTM treats several types of hydrometers including cloud ice, cloud liquid, snow and graupel and rain water (Simmer, 1994)
- Currently, cloud and precipitation optical parameters are calculated with general Mie theory using a distribution function. The parameters such as extinction efficiencies, single scattering albedo and phase matrix elements are pre-calculated and stored as a look up table (Liu et al., 2005). The table is searched with particle mean size, cloud water content (or mixing ratio).
- The non-spherical cloud ice particles are not processed in the current CRTM.

$$\frac{dI(\Omega)}{d\tau} = -I(\Omega) + (1-\tilde{\omega})B + \frac{\tilde{\omega}}{4\pi}\int_{4\pi} p(\Omega',\Omega)I(\Omega')d\omega'$$

CRTM absorption and scattering by aerosols
(provide aerosols optical parameters for RT solution)

- Aerosols are have strong interaction with electromagnetic waves from ultra-violet and visible to infrared wavelengths.
- CRTM aerosol optical module is based on the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model
- Major tropospheric aerosol components simulated: including sulfate, dust, black carbon (BC), organic carbon (OC), and sea-salt aerosols.
- Physical processes in the GOCART model:
  - Emissions of aerosols and their precursors Transport (advection, convection, BL mixing),
  - Chemistry (gas-to-particle conversion),
  - Dry deposition and settling
  - Wet deposition Hygroscopic growth as a function of RH.
- The concentrations of each type of aerosols are bin-size dependent for sea salt, dust particles, fixed sized black carbon, organic carbon, sulphate aerosols.

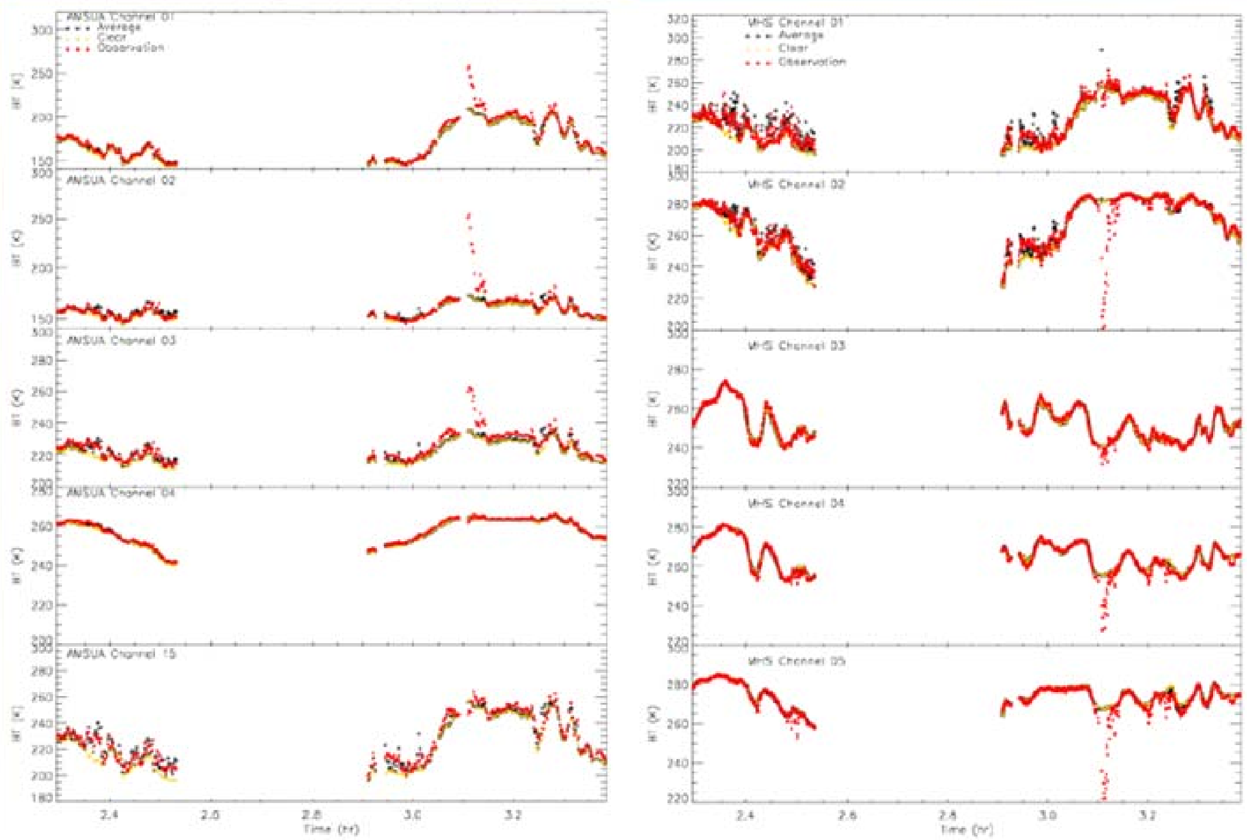
RT solution for cloud/aerosol scattering environment: Advanced Doubling-Adding Method (ADA)

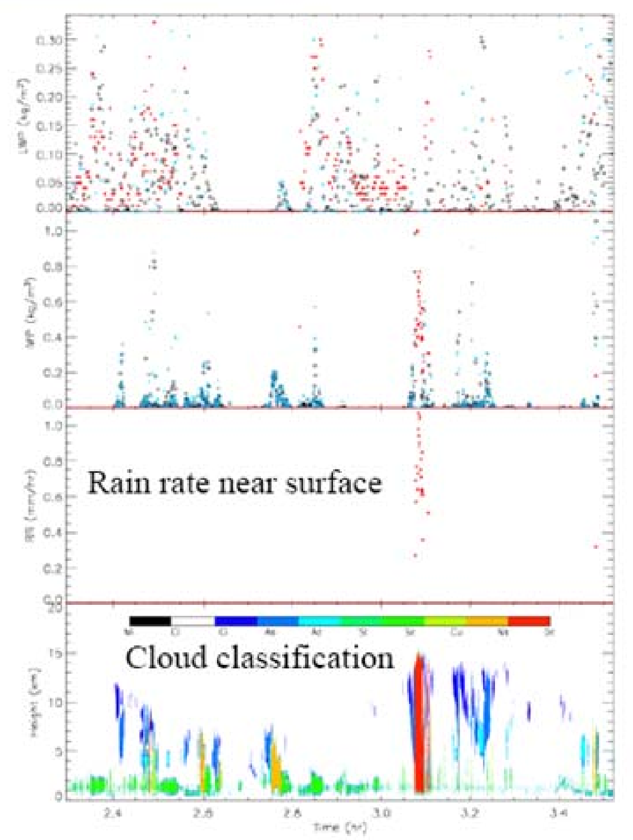


1.7 times faster then VDISORT; 61 times faster than DA
Maximum differences between ADA,VDISORT and DA are less than 0.01 K.

Liu and Weng, 2006

Time series of AMSU-A, MHS observations vs CRTM simulations using CloudSat data (non-precipitating weather)



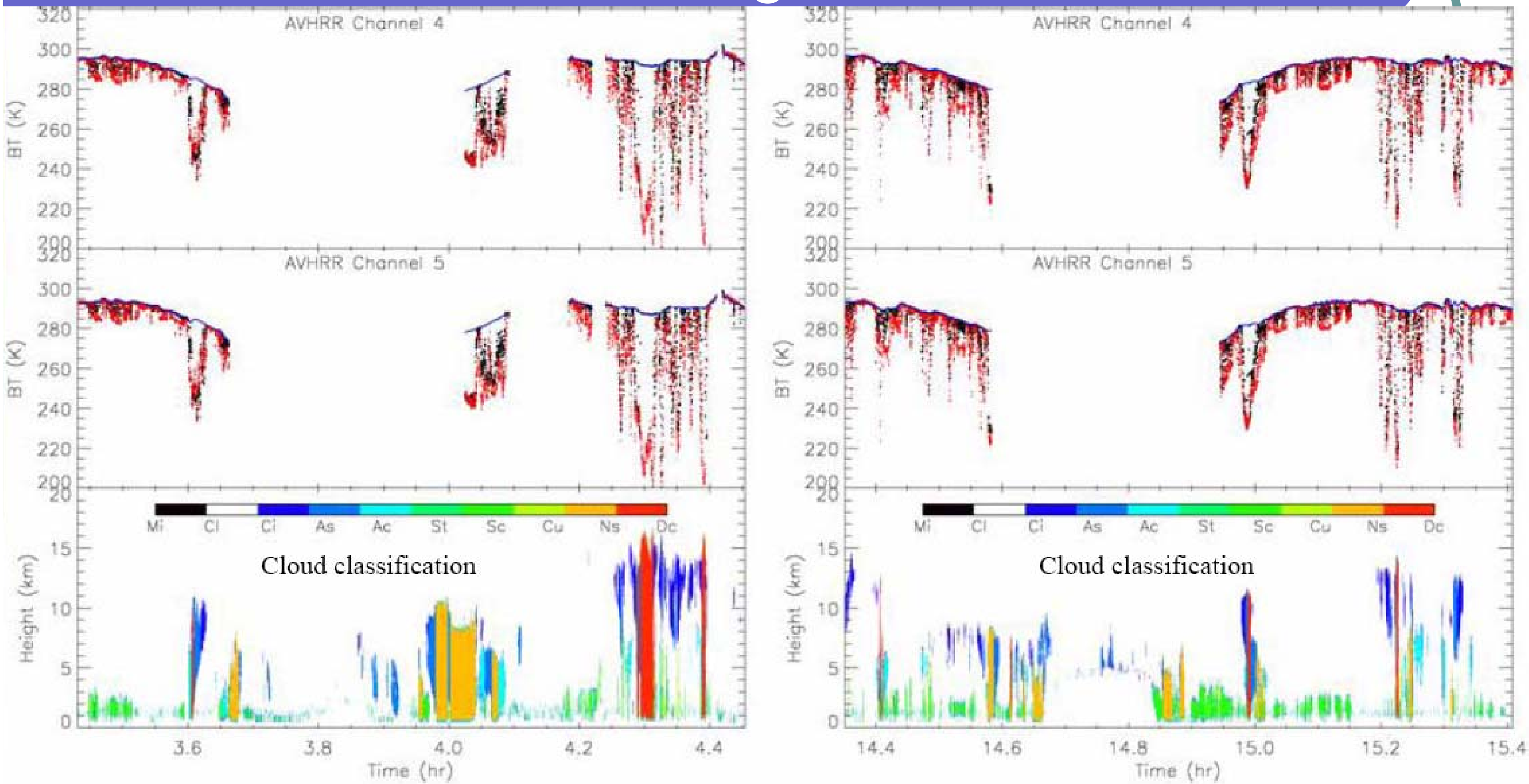


Model simulations with cloud component on (black) and off (yellow); AMSU-A and MHS observations (red), 07/27/2006
Model input: cloud liquid/ice content and particle size profiles from CloudSat

Upper two panels:
Red – AMSUA+MHS retrievals
Black – derived from CloudSat Radar

Large differences between Observations and simulations near 3.1 are due to CloudSat data that exclude precipitation.

Time series of AVHRR observations versus CRTM simulations using CloudSat data

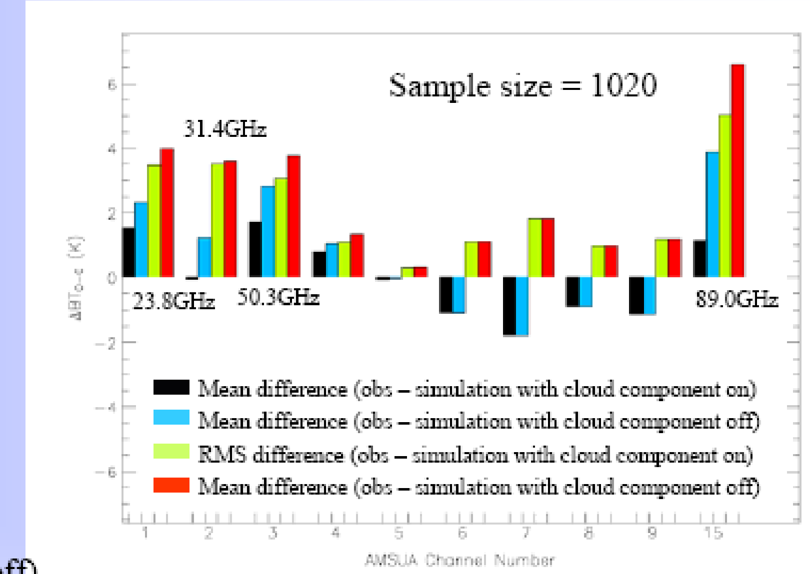


- Model simulations with cloud component on (black) and off (blue)
- AVHRR observations (red)
- Model input: cloud liquid/ice content and particle size profiles from CloudSat

Mean & RMS difference between AMSU-A, MHS & AVHRR observations and simulations under cloudy conditions

The differences between the observations and simulations are significantly reduced with the inclusion of modeling cloud absorption and scattering

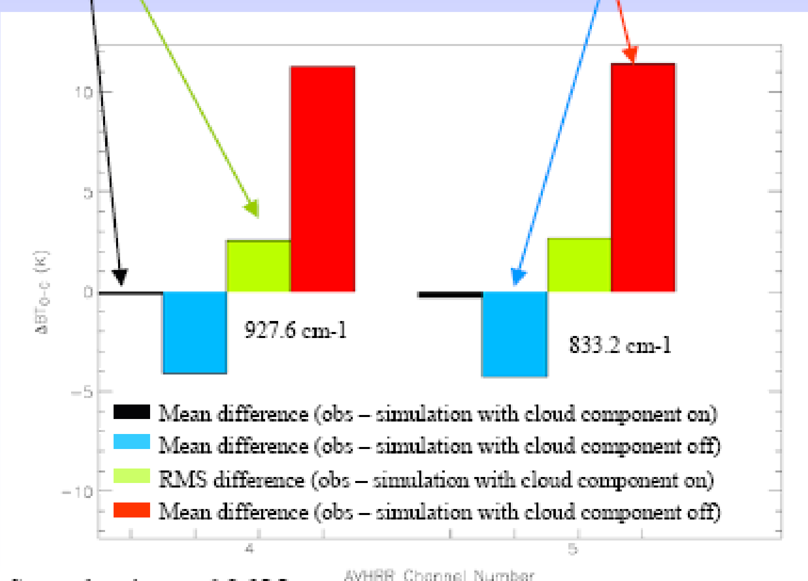
AMSU-A



Mean & RMS Diff. (obs. – simulation w. cloud on)

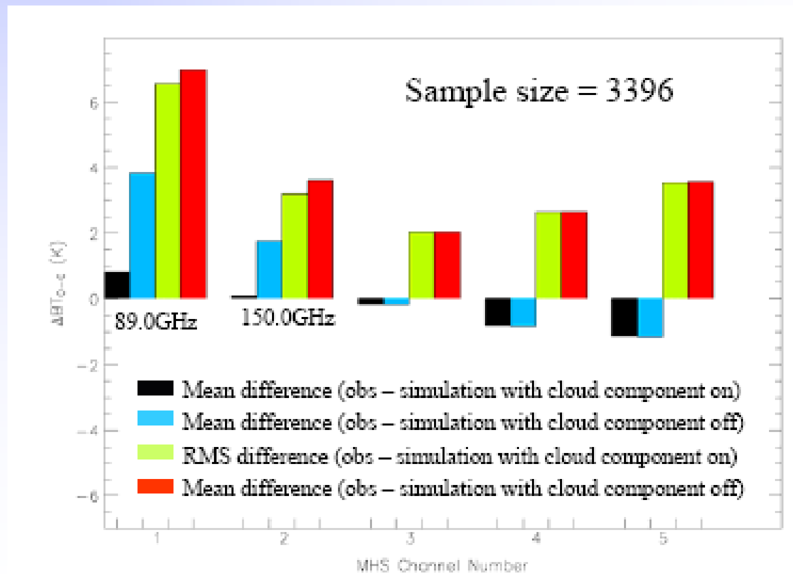
Mean & RMS Diff. (obs. – simulation w. cloud off)

AVHRR



Sample size = 10692

MHS



CRTM software characteristic:

- A set of Fortran subroutines and functions; users call CRTM from their application programs.
- There is a set of coefficient data that are loaded during CRTM initialization stage. These data are included in several files, some of which are sensor/channel independent and some are sensor/channel dependent.

CRTM User Interface (2)

- CRTM Calling procedure (an example):