



Developments of JCSDA Community Radiative Transfer Model (CRTM)

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NOAA/NESDIS/Office of Research and Applications

Acknowledgements: *Yong Han (ORA), Paul van Delst (CIMSS/EMC), Mark Liu (QSS), Larry McMillin (ORA), Jean-Luc Moncet (AER), Ralf Bennartz (UWisc), Al Gasiewski (ETL), K.N Liu (UCLA), Ben Ruston (NRL), Andy Jones (CIRA), Xu Liu (NASA/Langley), Bill Smith (HU), and Eric Wood (PU)*

Also see 6.1 (Bennartz), 6.2 (Moncet), 6.3 (Liu), A37 (van Delst)

**The 14th International TOVS Study Conference, Beijing, China
May 25-31, 2005**

JCSDA Road Map (2002 - 2010)

Science Advance

By 2010, a numerical weather prediction community will be empowered to effectively assimilate increasing amounts of advanced satellite observations

The radiances can be assimilated under all weather conditions with the state-of-the science NWP models

**NPOESS sensors (CrIS, CMIS, ATMS...)
GOES-R (HES, ABI)**

**Advanced JCSDA community radiative transfer model,
Advanced data selection techniques for hyperspectral**

The CRTM includes scattering & polarization from cloud, precip and surface

**AIRS, ATMS, CrIS, VIIRS, IASI,
SSM/IS, AMSR, more products
assimilated**

The radiances from advanced sounders will be used. Cloudy radiances will be tested under rain-free atmospheres, and more products (ozone, water vapor winds) are assimilated

**Improved JCSDA data assimilation
science**

A beta version of JCSDA community radiative transfer model (CRTM) transfer model will be developed, including non-raining clouds, snow and sea ice surface conditions

**AMSU, HIRS, SSM/I, Quikscat,
AVHRR, TMI, GOES assimilated**

The radiances of satellite sounding channels were assimilated into EMC global model under only clear atmospheric conditions. Some satellite surface products (SST, GVI and snow cover, wind) were used in EMC models

**Pre-JCSDA data
assimilation science**

Radiative transfer model, OPTRAN, ocean microwave emissivity, microwave land emissivity model, and GFS data assimilation system were developed

2002 2003 2004 2005 2007 2008 2009 2010

Requirements for Better RT Models

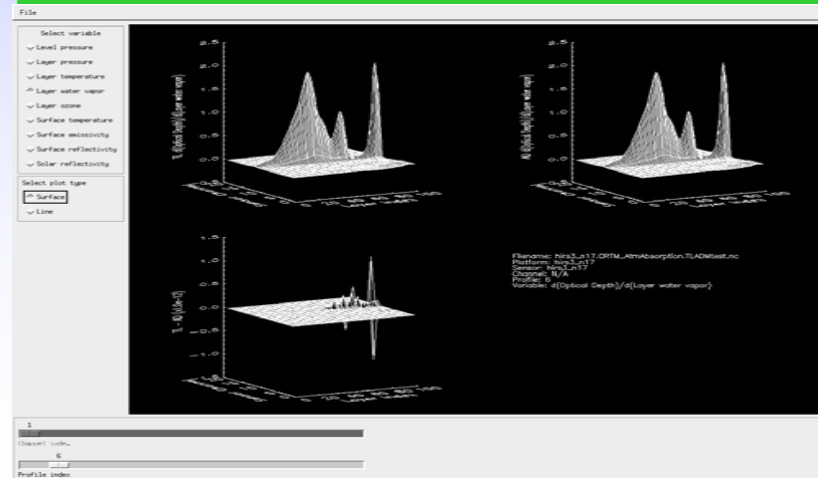
- Accelerated uses of satellite observations
 - Direct radiance assimilation (less dependent on product validation)
 - Unified satellite data assimilation infrastructure
- Advanced satellite instruments (NPOESS, GOES-R)
 - Interferometer sounding technology with a few thousand channels
 - Polarimetric from visible to microwave
 - Uses of channels sensitive to surface
 - Inclusion of spectral response functions/field of views
- NWP specific drivers
 - Speed, accuracy and storage
 - Radiances/Jacobians
 - Coupling with forecast modeling

The CRTM Framework

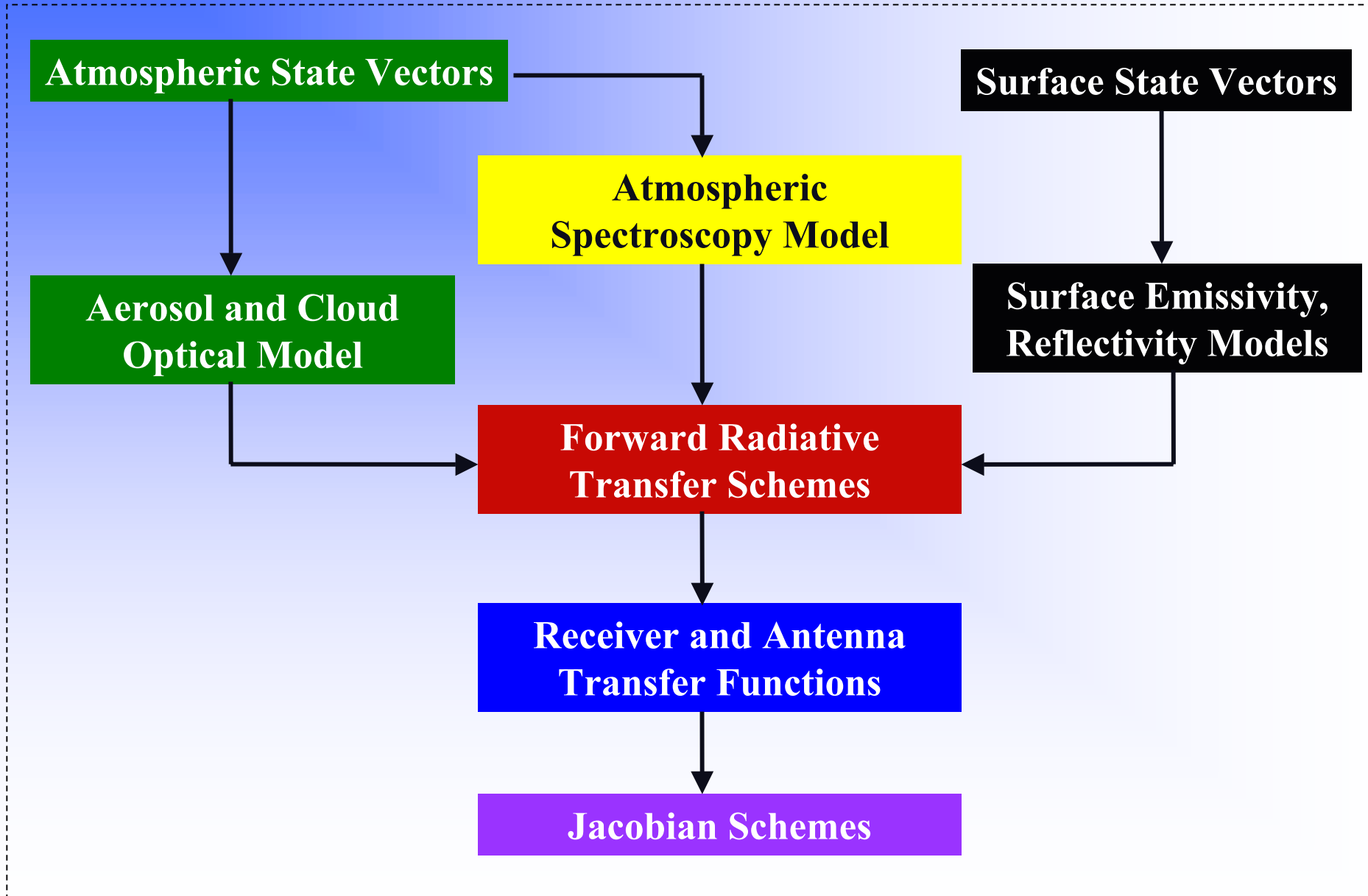
- The radiative transfer problem is split into various components (e.g. gaseous absorption, scattering etc). Each component defines its own structure definition and application modules to facilitate independent development.
- Minimize or eliminate potential software conflicts and redundancies.
- Components developed by different groups can “simply” be dropped into the framework.
- Faster implementation of new science and algorithms
- There are User and Developer interfaces, Shared Data interface, Test Software, Utilities/Feedback

```
CRTM_Forward( Atmosphere, &  
              Surface, &  
              GeometryInfo, &  
              ChannelInfo, &  
              RTSolution )
```

```
CRTM_K_Matrix( Atmosphere, &  
              Surface, &  
              RTSolution_K, &  
              GeometryInfo, &  
              ChannelInfo, &  
              Atmosphere_K, &  
              Surface_K, &  
              RTSolution )
```



Community Radiative Transfer Model



Community Contributions

- Community Research: Radiative transfer science
 - AER. Inc: Optimal Spectral Sampling (OSS) Method
 - NRL – Improving Microwave Emissivity Model (MEM) in deserts
 - NOAA/ETL – Fully polarimetric surface models and microwave radiative transfer model
 - UCLA – Delta 4 stream vector radiative transfer model
 - UMBC – aerosol scattering
 - UWisc – Successive Order of Iteration
 - CIRA/CU – SHDOMPPDA
 - Langley/Hampton Univ – principal component radiative transfer
 - Princeton Univ – snow emissivity model improvement
 - NESDIS/ORA – Snow, sea ice, microwave land emissivity models, vector discrete ordinate radiative transfer (VDISORT), ocean polarimetric, scattering models for all wavelengths
- Core team (ORA/EMC): Smooth transition from research to operation
 - Maintenance of CRTM (OPTRAN/OSS coeff., Emissivity upgrade)
 - CRTM interface
 - Benchmark tests for model selection
 - Integration of new science into CRTM

Fast Gaseous Absorption Model

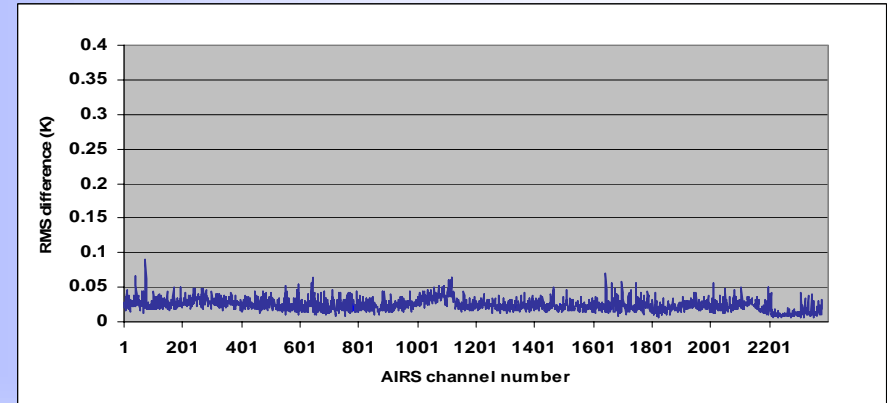
OSS

- OSS (Optimal Spectral Sampling) method (Moncet and Uymin, 2003; Moncet *et al.* 2001) models the channel radiance as

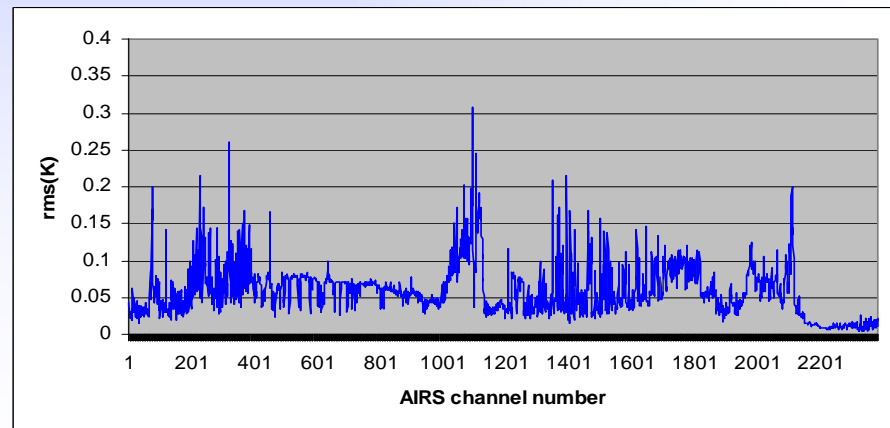
$$\bar{R} = \int_{\Delta\nu} \phi(\nu)R(\nu)d\nu \cong \sum_{i=1}^N w_i R(\nu_i); \quad \nu_i \in \Delta\nu$$

- Wavenumber ν_i (nodes) and weights w_i are determined by fitting “exact” calculations (from line-by-line model) for globally representative set of atmospheres (training set)
- Monochromatic RT (using look-up tables of absorption coefficients for relevant species stored at the selected nodes)
 - Maximum brightness temperature error with current LUT < 0.05K in infrared and <~0.01K in microwave

Trained with ECMWF set Tested with UMBC set



OPTRAN Trained with UMBC set Tested with ECMWF set



Computation & Memory Efficiency

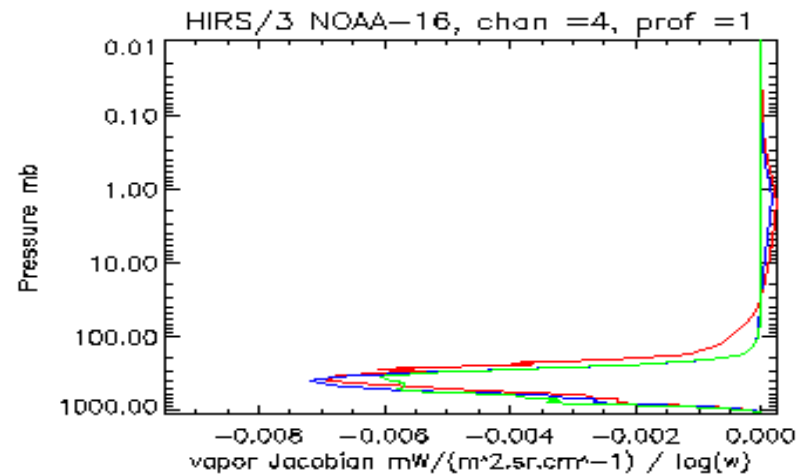
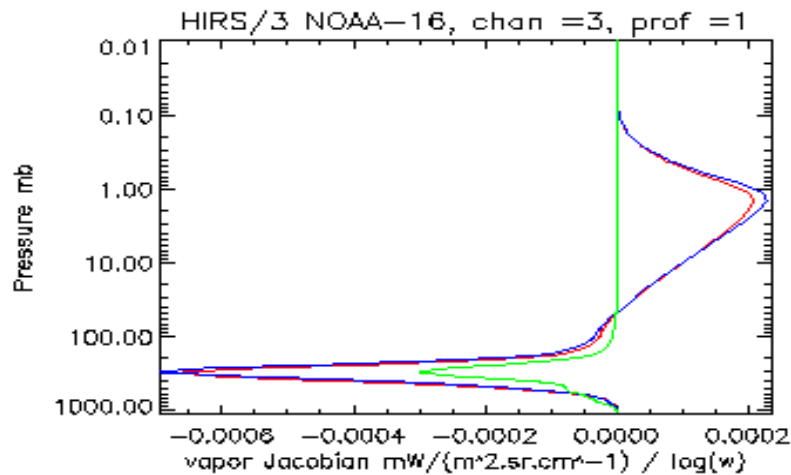
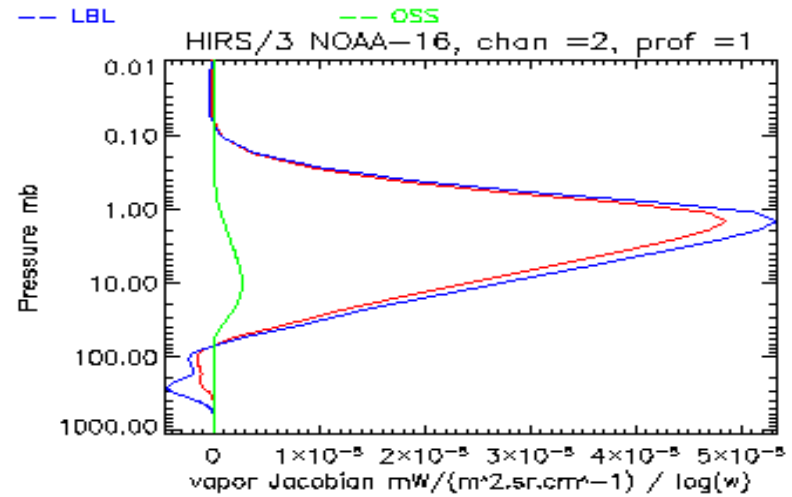
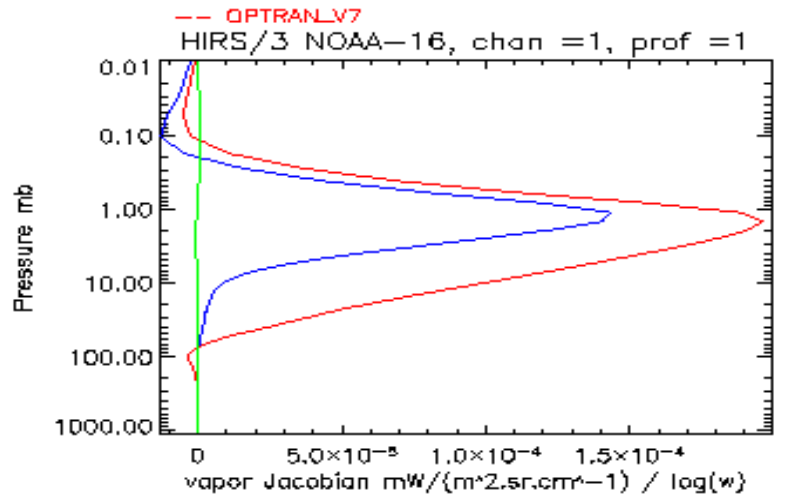
Time needed to process 48 profiles with 7 observation angles

	OPTRAN-V7 Forward, Jacobian+Forward	OPTRAN-comp Forward, Jacobian+Forward	OSS Jacobian+Forward
AIRS	7m20s, 22m36s	10m33s, 35m12	3m10s
HIRS	4s, 13s	5s, 17s	9s

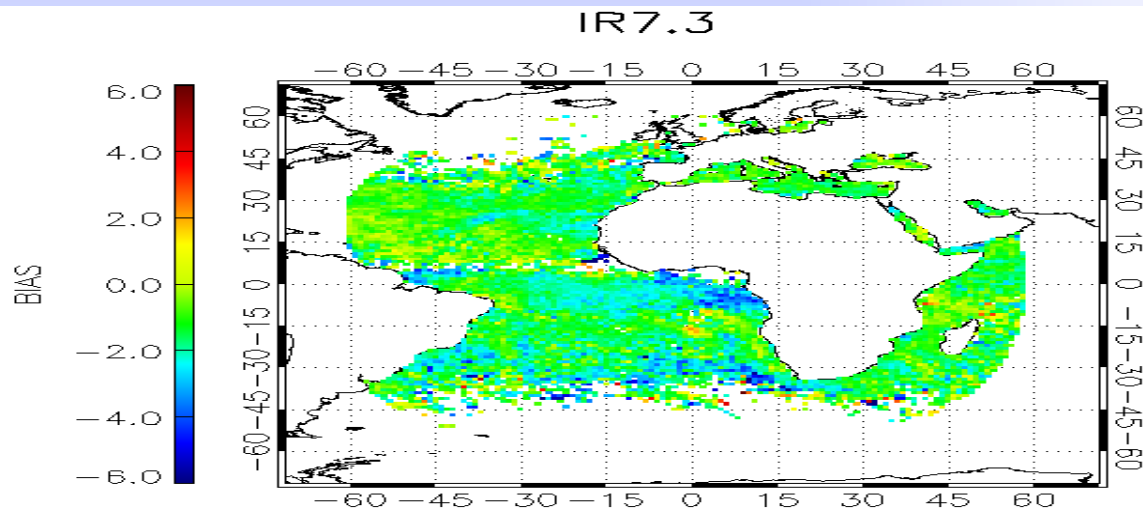
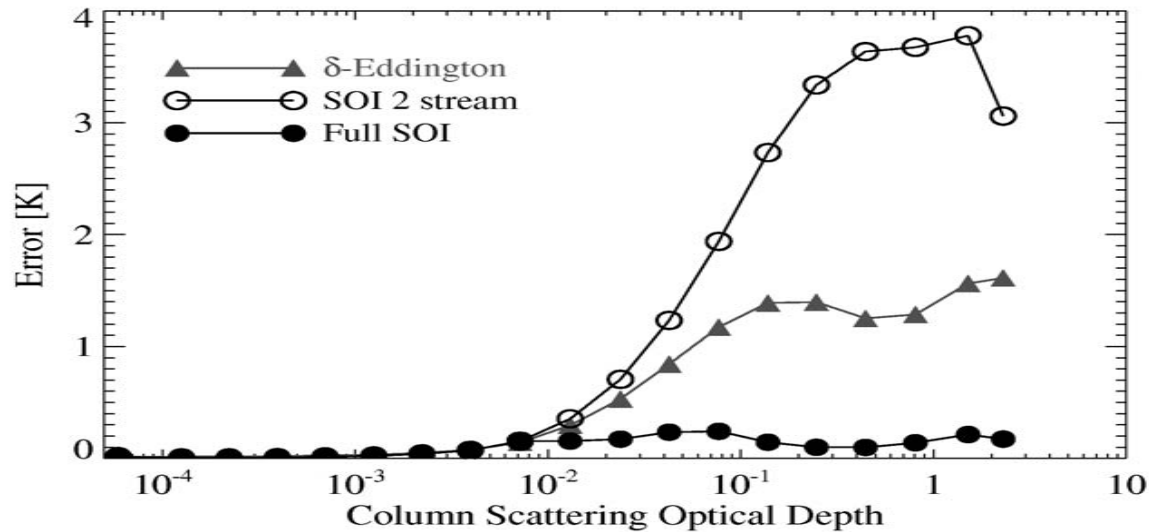
Memory resource required (Megabytes)

	OPTRAN-V7 single, double	OPTRAN-comp double precision	OSS Single precision
AIRS	33, 66	5	97
HIRS	0.26, 0.5	0.04	4

Water vapor Jacobians at weak absorption channels

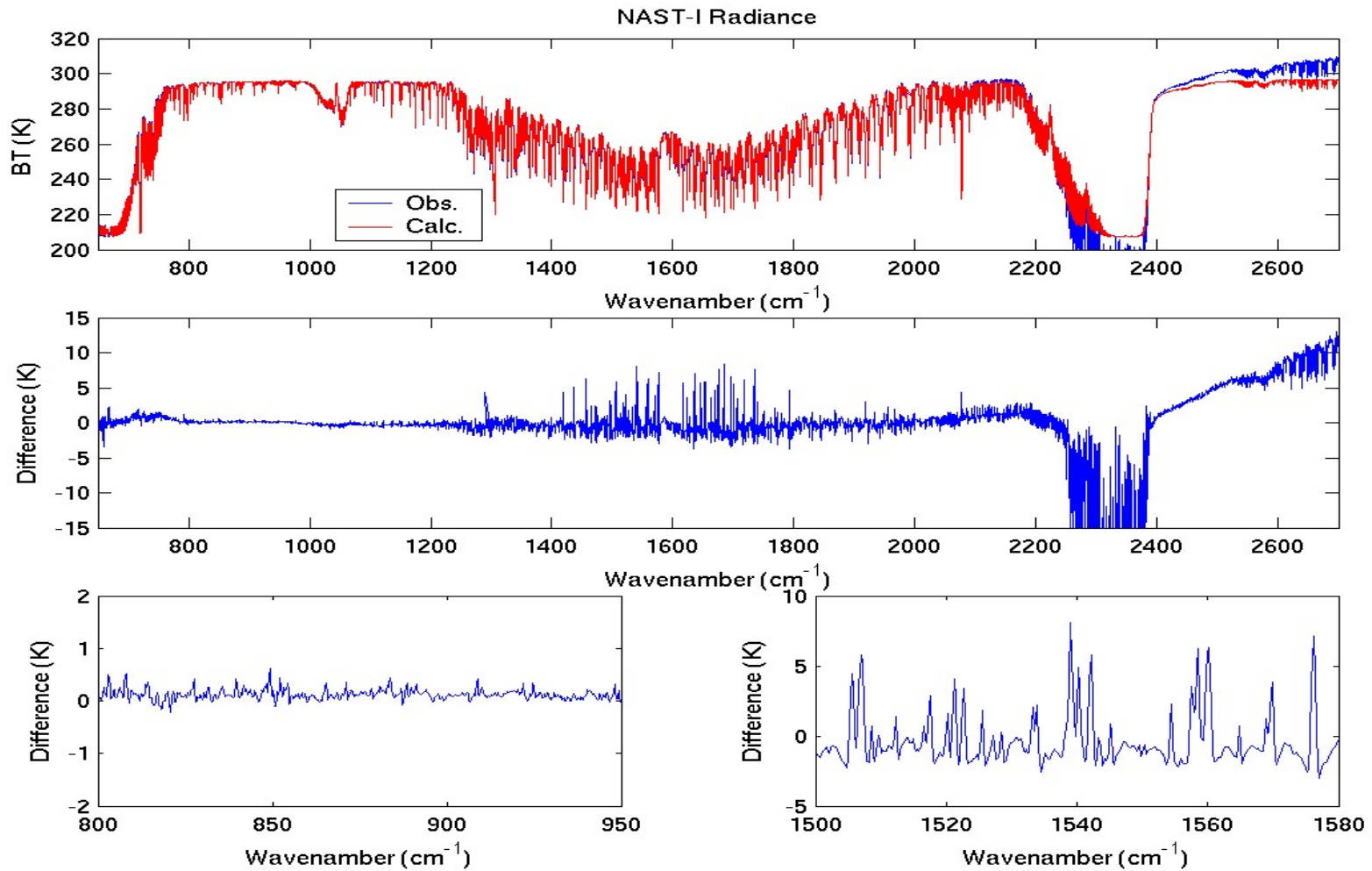


Radiative Transfer Scheme: Successive Order of Iteration (SOI)



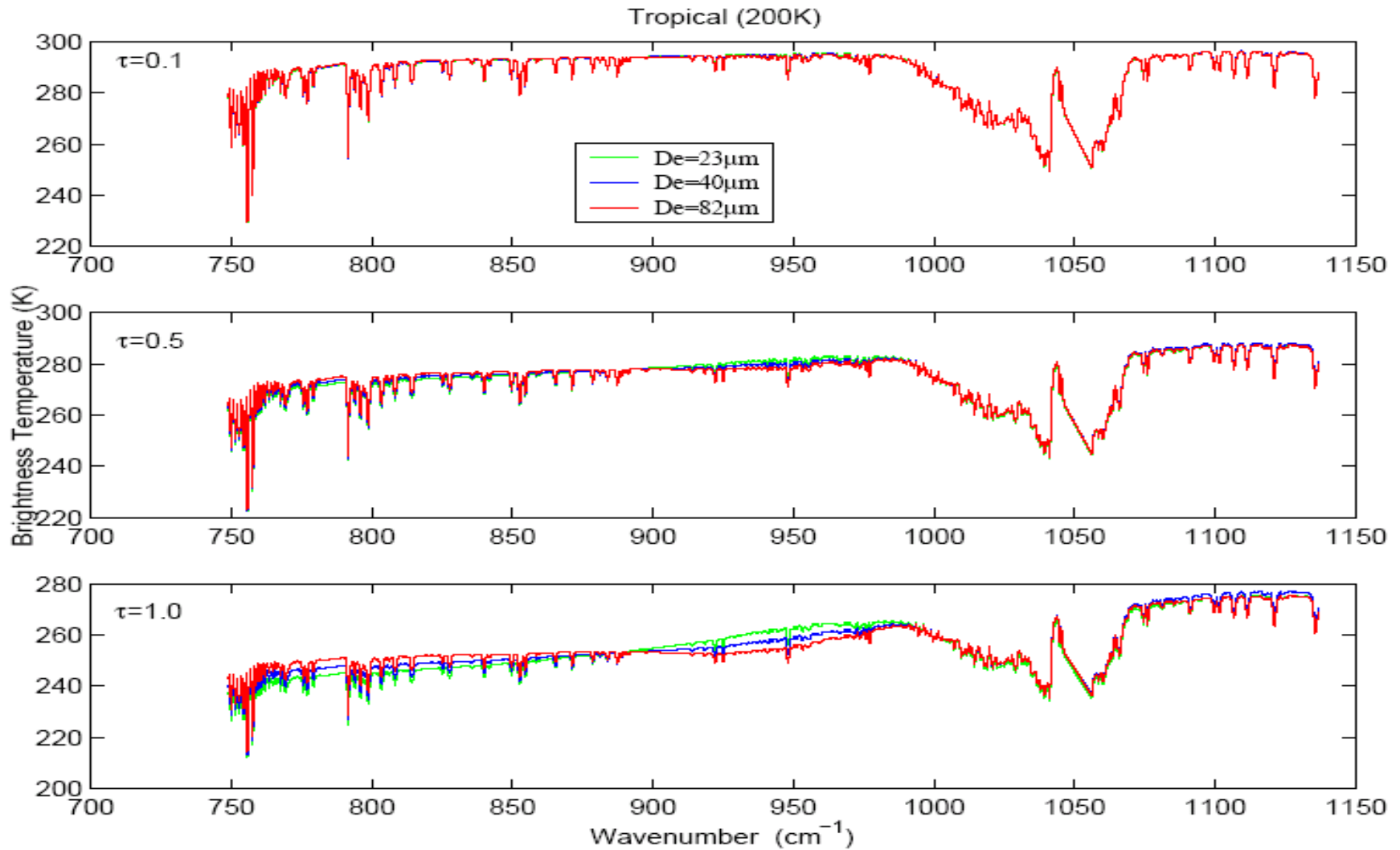
Provided by
Bennartz et al

Principal Component Radiative Transfer



Provided by Xu Liu and Bill Smith

AIRS Sensitivity to Cirrus Clouds



Provided by K.N. Liou and S. Ou

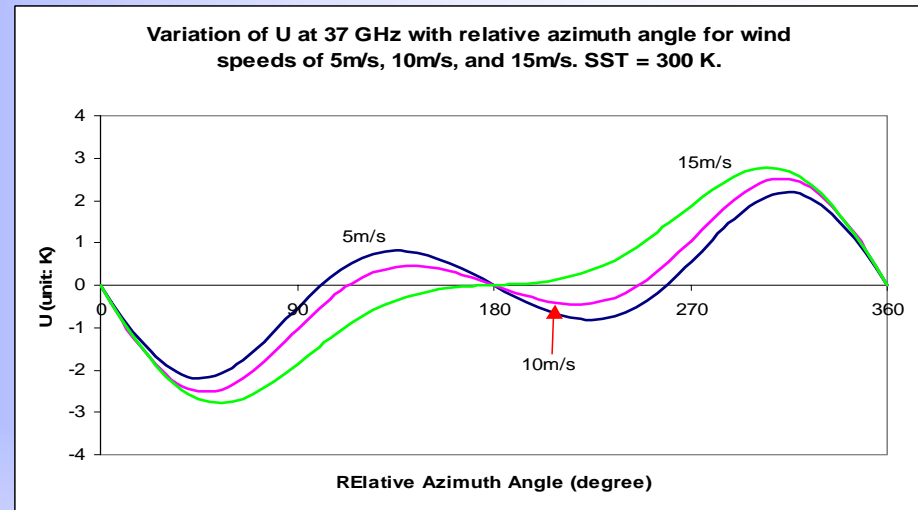
Oceanic Emission Model

Phenomenology.

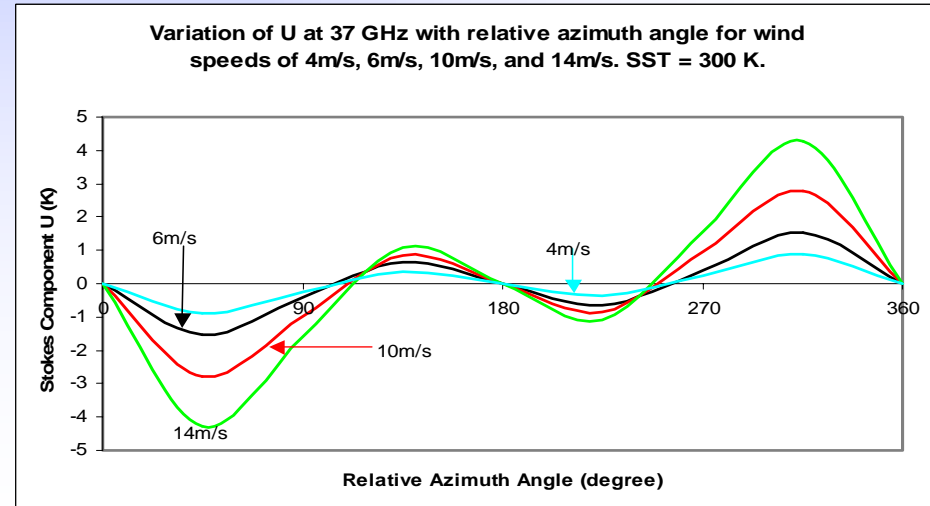
- Large gravity waves, whose wavelengths are long compared with the radiation wavelength.
- Small capillary waves, which are riding on top of the large-scale waves, and whose RMS height is small compared with radiation wavelength.
- Sea foam, which arises as a mixture of air and water at the wind roughened ocean surface, and which leads to a general increase in the surface emissivity.



Two-scale Simulations



Aircraft Measurements



Canopy Scattering Model

Methodology: geometric optics is applied because the leaf size is typically larger than wavelength

d - leaf thickness

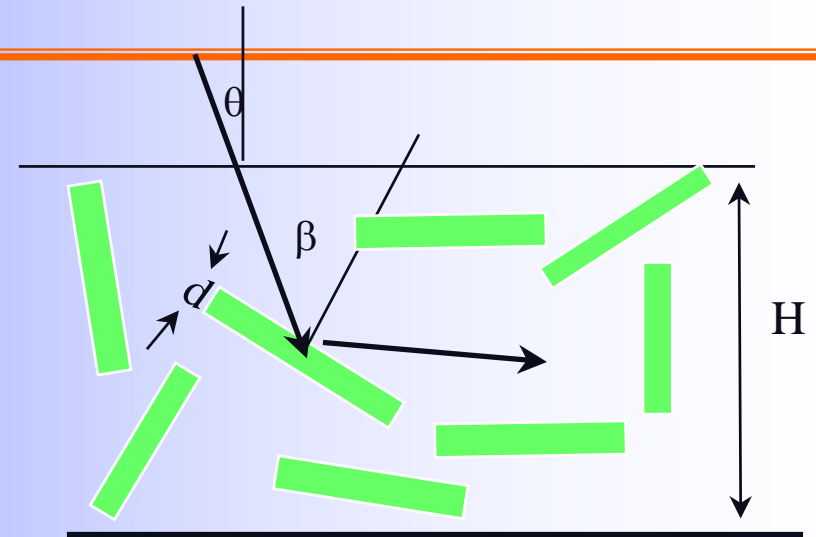
H - canopy height

LAI - leaf area index

m_d - dry matter content

β - leaf orientation angle

θ - incident angle of EM wave

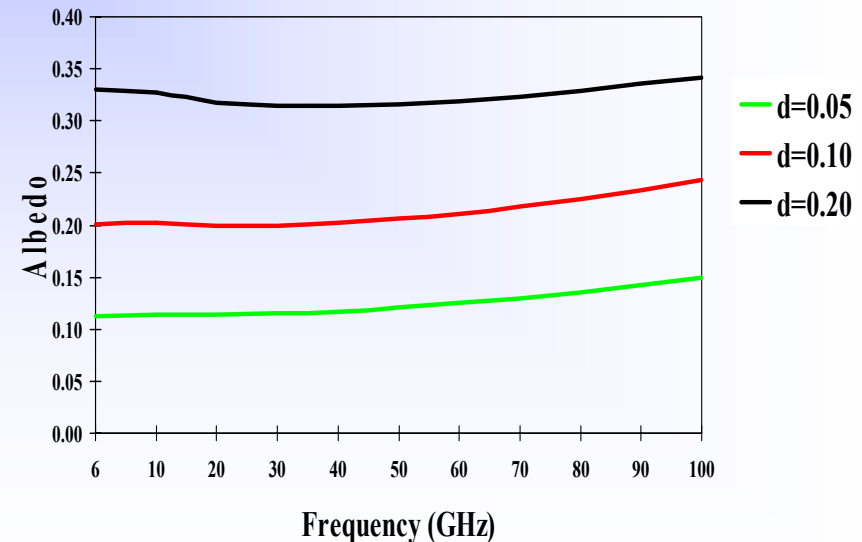


$z = 0$

$z = z(x, y)$

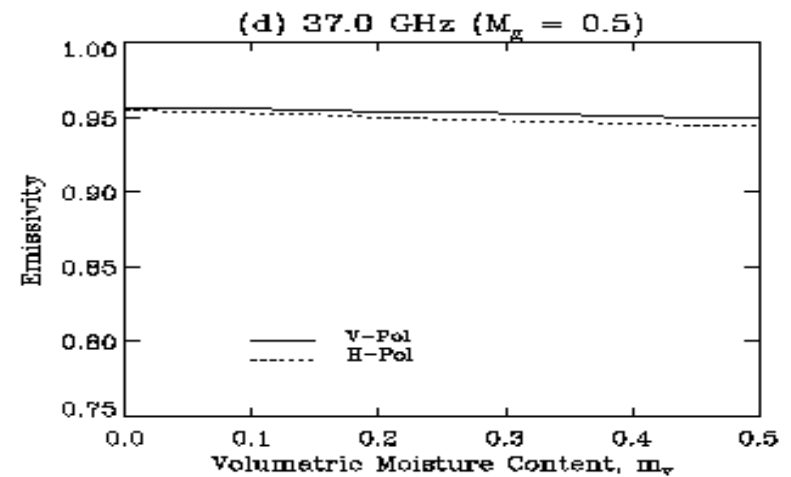
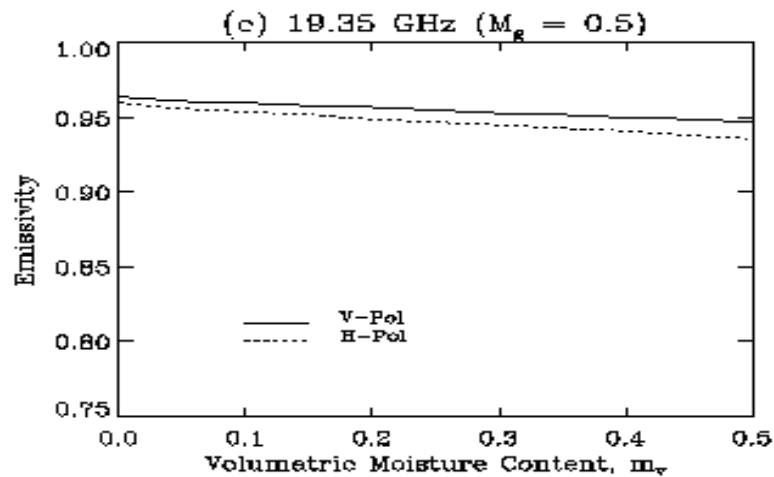
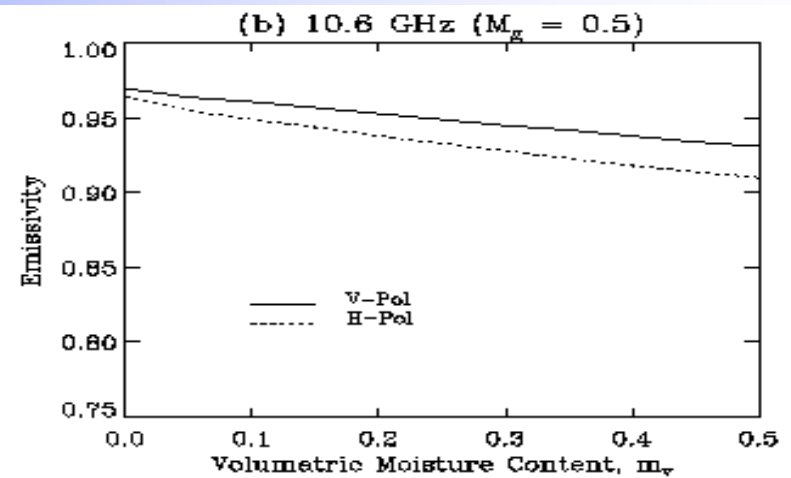
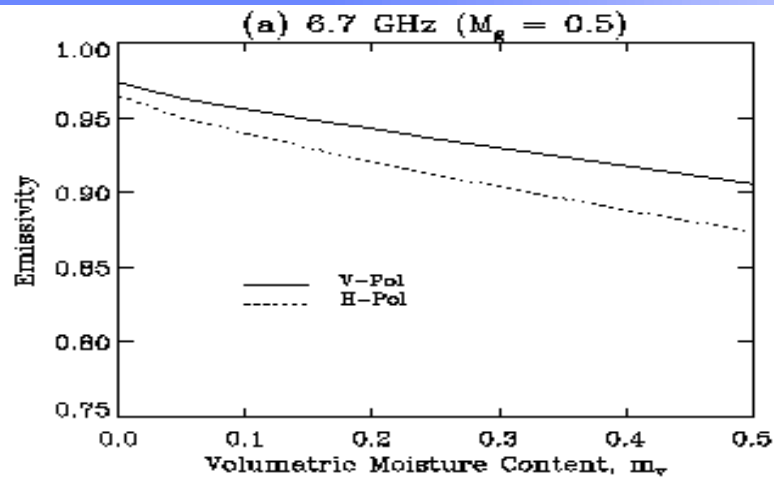
Soil ϵ_3
 ϵ_4 □

$z = d$



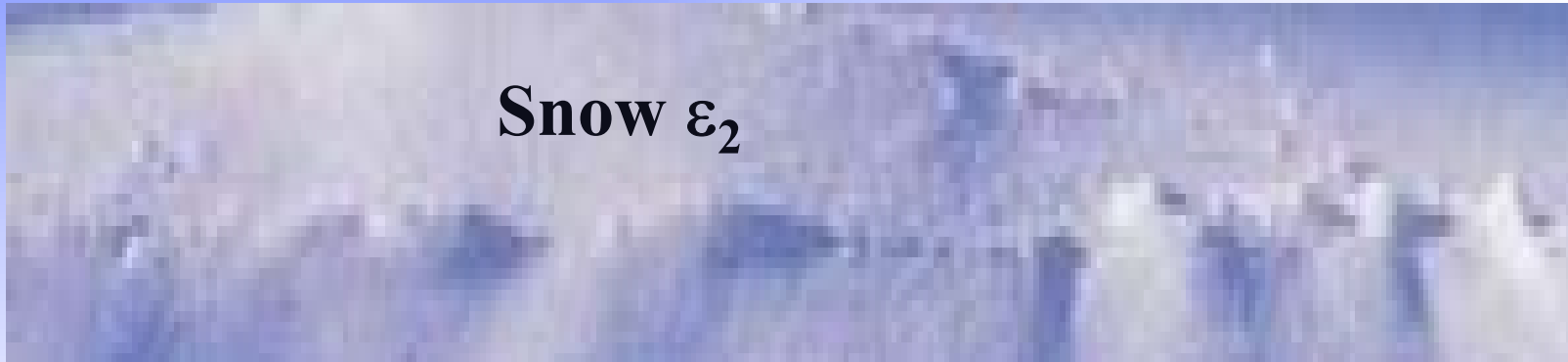
Emissivity-Soil Moisture

with canopy



Snow Emissivity Model

Air ϵ_1



Snow ϵ_2

Subsurface ϵ_3

- Dielectric constant within snow is perturbed and a function of volume fraction of scattering particles
- Reflection occurs at interface

Optical Properties of Dense Medium

Strong fluctuation theory
(Tsang et al., 1985)

$$\epsilon_{eff} = \frac{1 + 2f_a y}{1 - f_a y} + i \frac{2f_a y^2 (\kappa a)^3 (1 - f_a)^4}{(1 - f_a y)^2 (1 + 2f_a)^2}$$

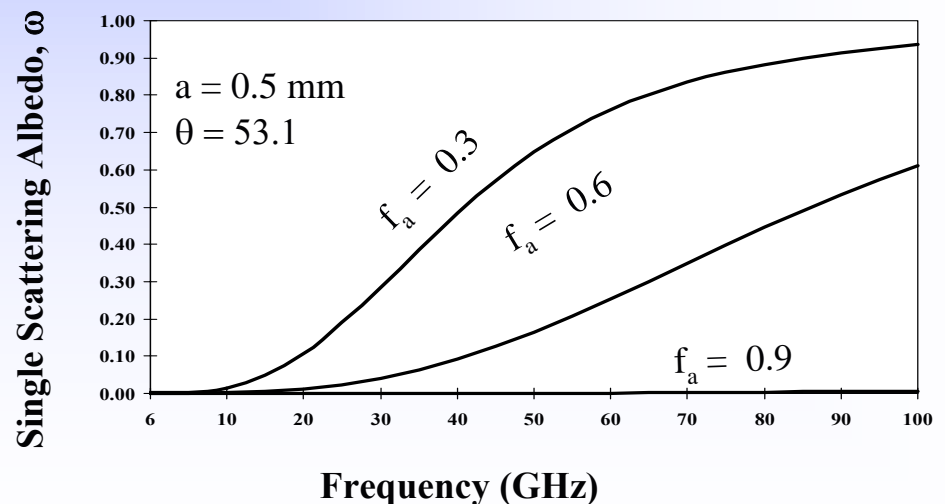
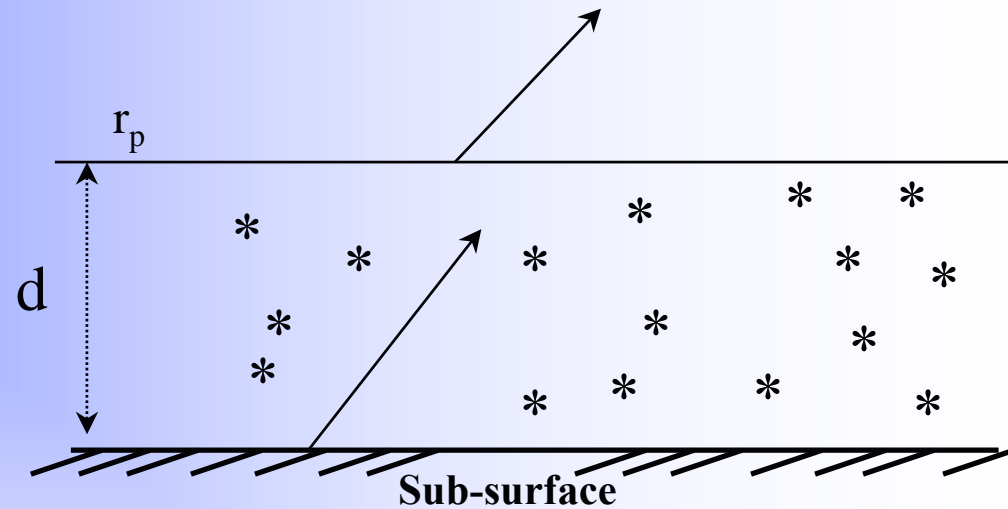
$$\kappa = \sqrt{3(1 - \omega)(1 - \omega g)}$$

$$y = \frac{\epsilon_s - \epsilon}{\epsilon_s + 2\epsilon}$$

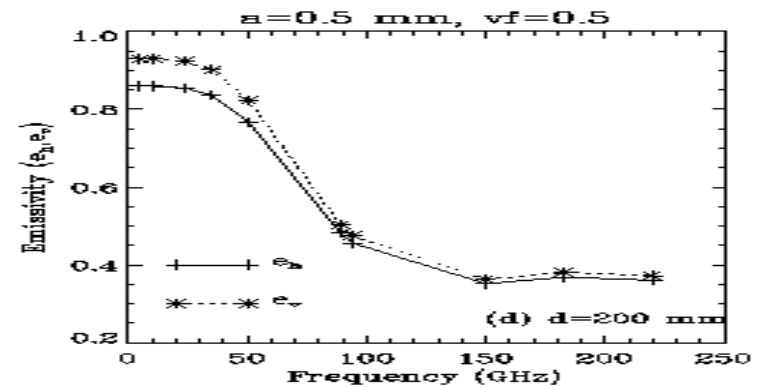
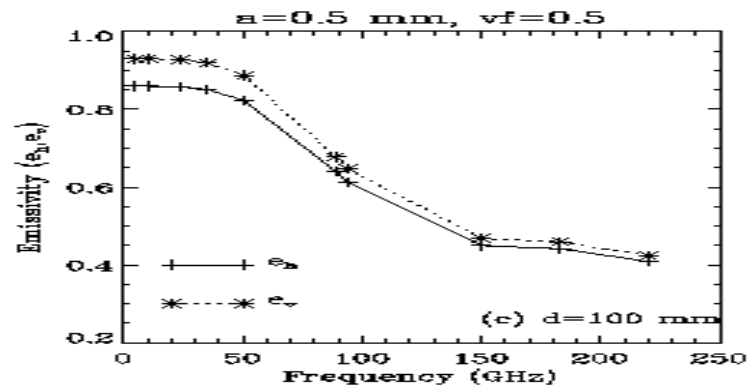
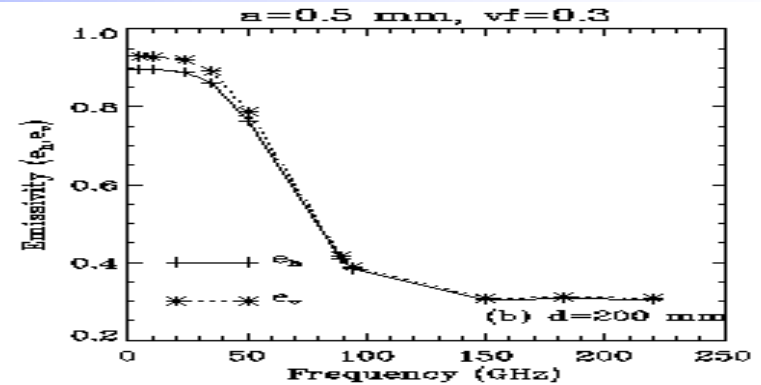
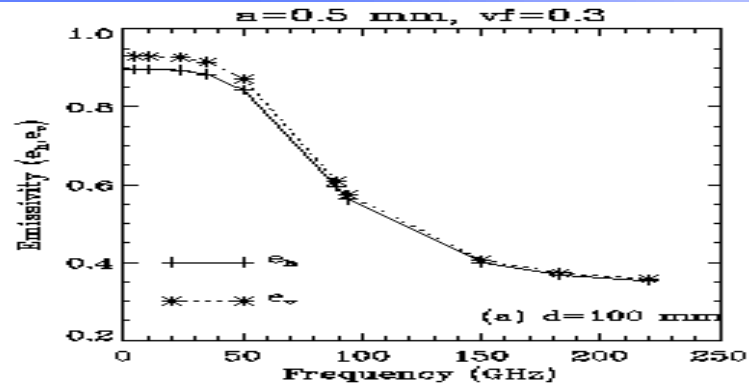
f_a - ice-volume fraction

d - snow depth

a - snow particle size



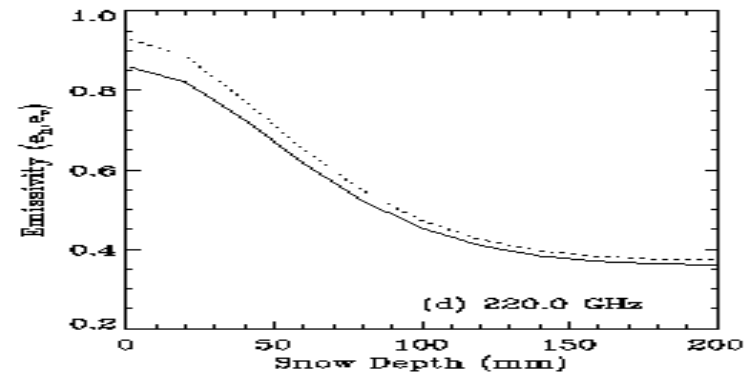
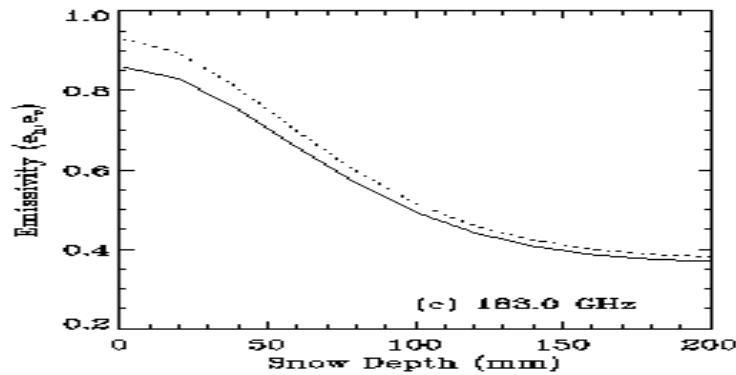
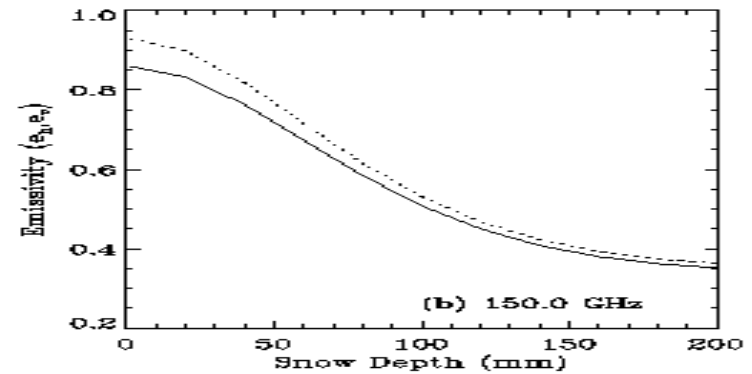
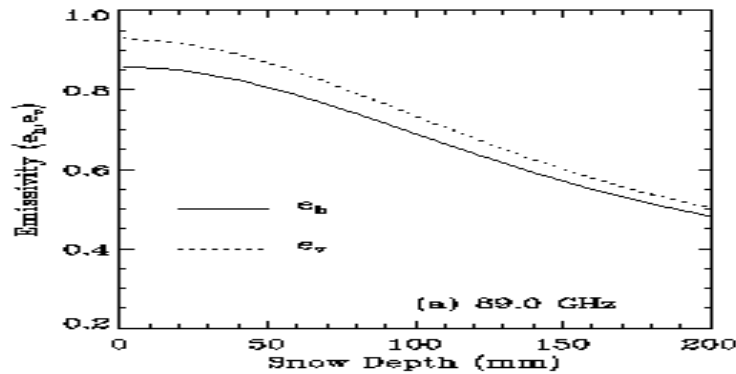
Snow Emissivity Spectra



Parameters:

- Snow depth
- Volume fraction
- Grain size/bulk density

Emissivity vs. Snow Depth

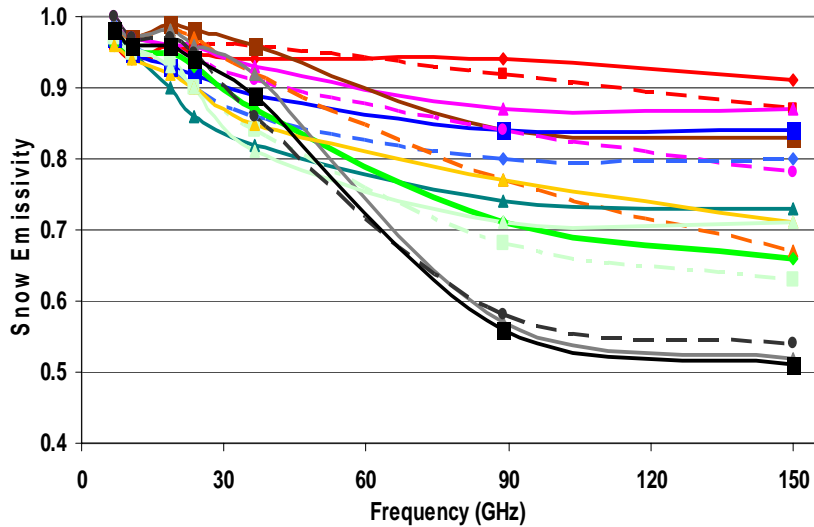


Need Improvements for:

- Snow stratification
- Melting/refrozen
- Metamorphosis process

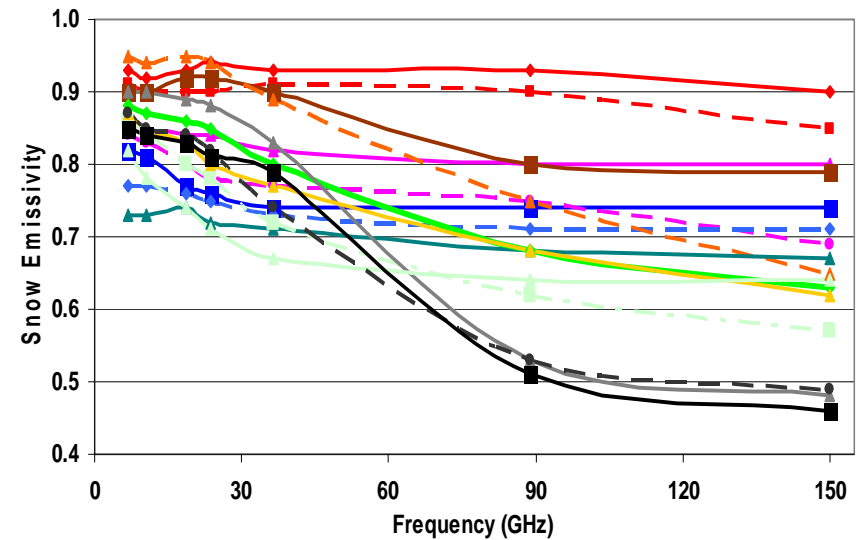
Snow Microwave Emissivity Spectra

Snow V-POL Emissivity Spectra



- Grass_after_Snow
- Shallow Snow
- Thin Crust Snow
- Bottom Crust Snow (B)
- RS_Snow (B)
- RS_Snow (E)
- Wet Snow
- Medium Snow
- Thick Crust Snow
- Crust Snow
- RS_Snow (C)
- Powder Snow
- Deep Snow
- Bottom Crust Snow (A)
- RS_Snow (A)
- RS_Snow (D)

Snow H-POL Emissivity Spectra



- Grass_after_Snow
- Shallow Snow
- Thin Crust Snow
- Bottom Crust Snow (B)
- RS_Snow (B)
- RS_Snow (E)
- Wet Snow
- Medium Snow
- Thick Crust Snow
- Crust Snow
- RS_Snow (C)
- Powder Snow
- Deep Snow
- Bottom Crust Snow (A)
- RS_Snow (A)
- RS_Snow (D)

Analytic Jacobian

Jacobian to surface parameters (e.g. surface temperature, soil moisture) can be written as (Weng and Liu, 2003, JAS):

$$\begin{aligned} \frac{\partial \mathbf{I}_1(\mu)}{\partial x_s} = & \sum_{j=1}^{4N} \mathbf{K}_L(\mu, j) \left\{ B(T_s) \frac{\partial \boldsymbol{\varepsilon}}{\partial x_s} + \frac{\partial B(T_s)}{\partial x_s} \boldsymbol{\varepsilon} + \frac{\partial \mathbf{R}}{\partial x_s} \bar{\mathbf{E}} \mathbf{s}_L(\tau_L) + \frac{\partial \mathbf{R}_0}{\partial x_s} \frac{F_0}{\pi} \exp(-\tau_L / \mu_0) \bar{\boldsymbol{\Xi}} \right\}_j \\ & + \sum_{j=1}^{4N} \mathbf{K}_L(\mu, j) \left\{ \frac{\partial \mathbf{R}}{\partial x_s} \bar{\mathbf{E}} \exp[\mathbf{A}_L(\tau_L - \tau_{L-1})] \mathbf{c}_L \right\}_j \end{aligned} \quad (1)$$

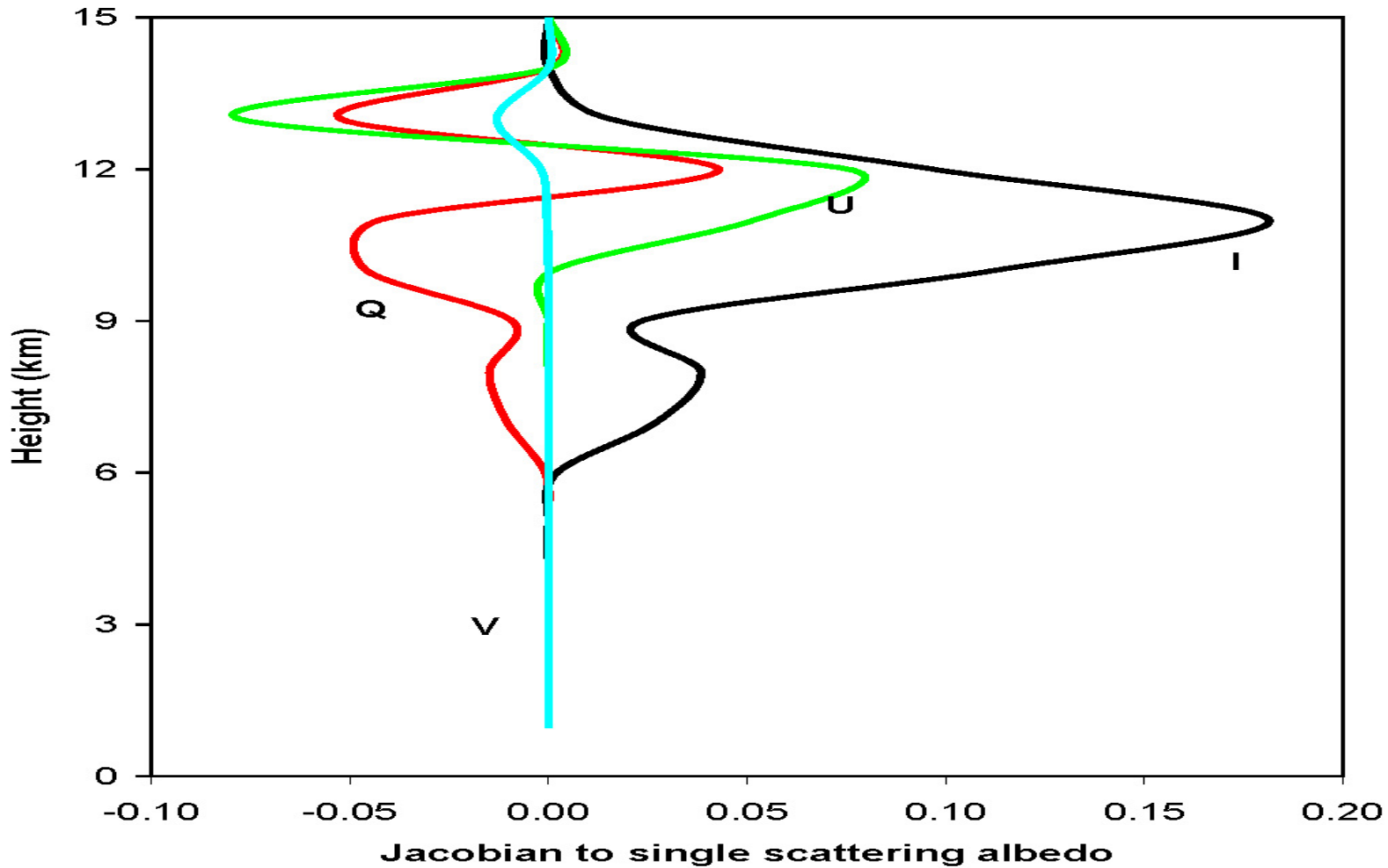
Jacobian to any atmospheric parameters is just a linear sum of the Jacobians to temperature, optical thickness, and phase function/matrix, for example, Jacobian to water vapor,

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial q_l} = \frac{\partial \tau_l}{\partial q_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\partial \varpi_l}{\partial q_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} = \kappa_l^{abs} \left[\frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} - \frac{\varpi_l}{\tau_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} \right] \quad (2)$$

and Jacobian to cloud water,

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial w_l} = \frac{\partial \tau_l}{\partial w_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\partial \varpi_l}{\partial w_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} = \frac{\tau_l - \kappa_l^{abs} q_l}{w_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \tau_l} + \frac{\varpi_l \kappa_l^{abs} q_l}{w_l \tau_l} \frac{\partial \mathbf{I}_1(\mu)}{\partial \varpi_l} \quad (3)$$

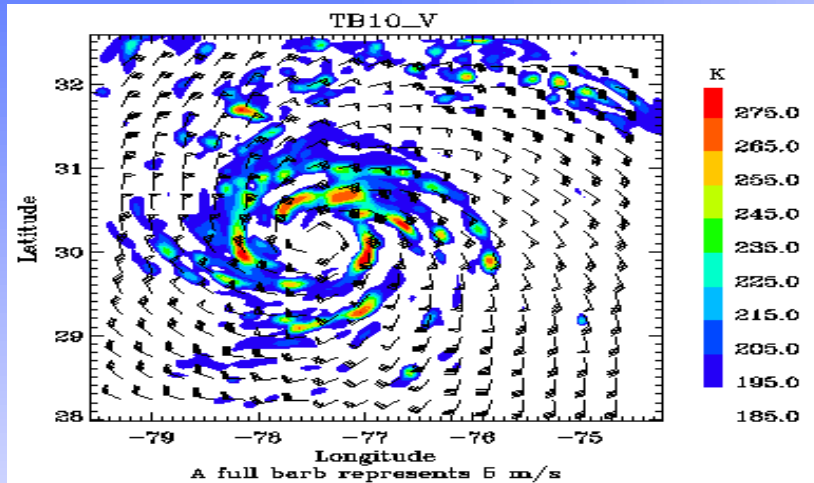
Stokes Jacobians at 0.67 micron Preparation for NPOESS/APS



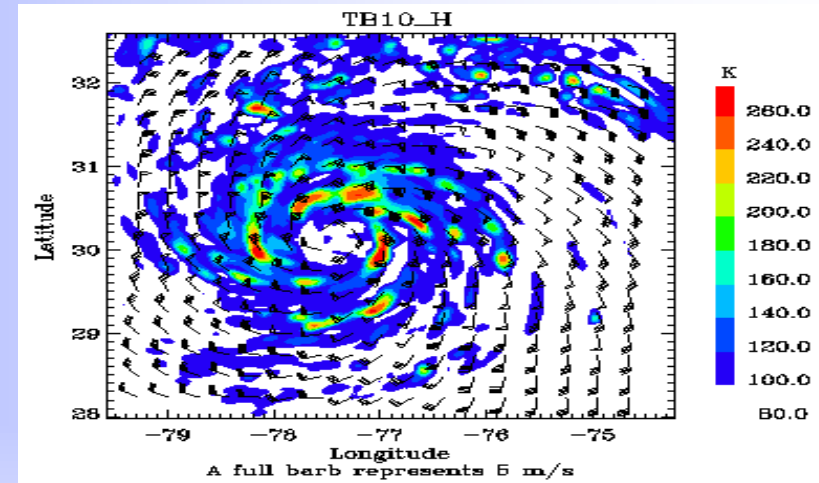
(Weng and Liu, 2003, JAS)

Stokes Radiance Simulations at Microwave Wavelength, Preparation for NPOESS/CMIS

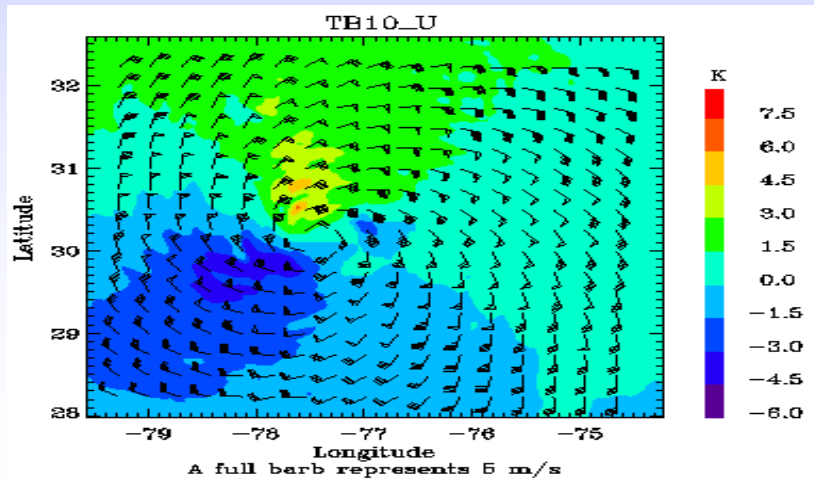
10.7_V



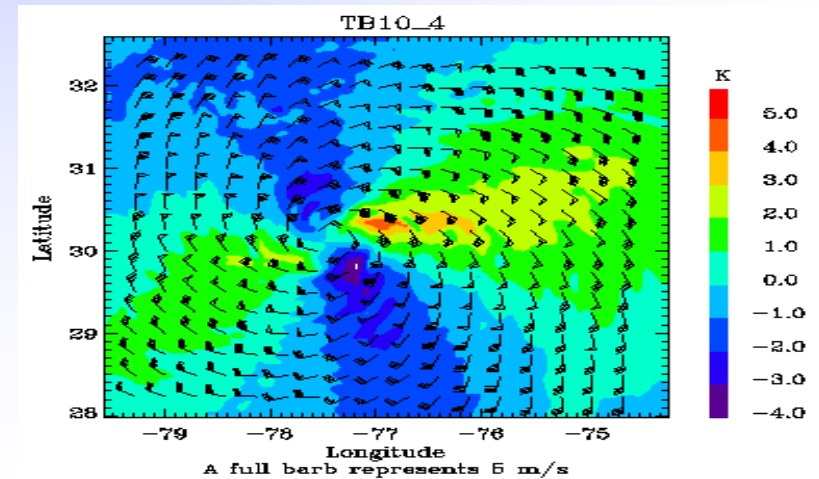
10.7_H



10.7_U

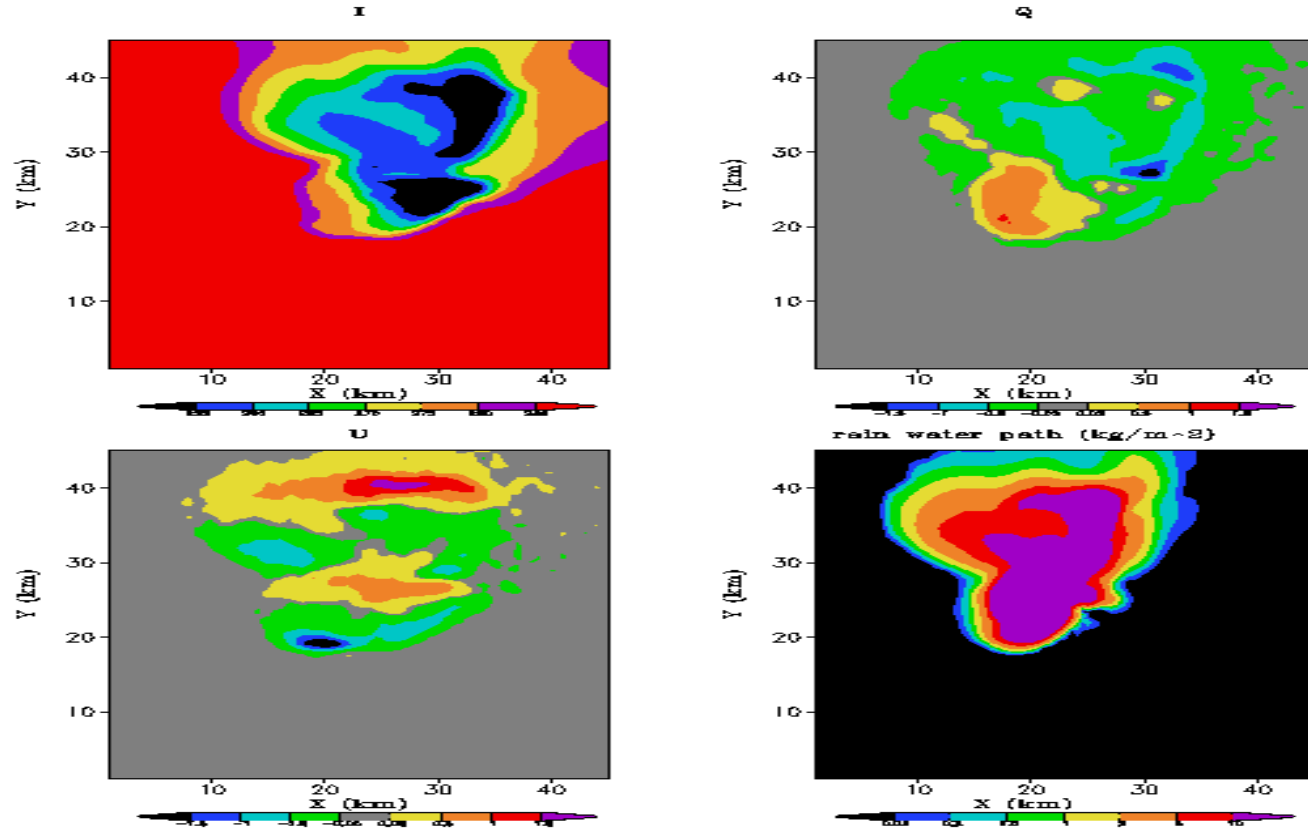


10.7_4



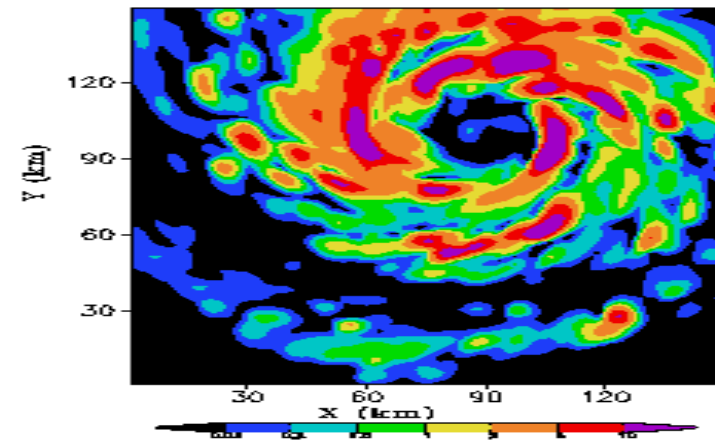
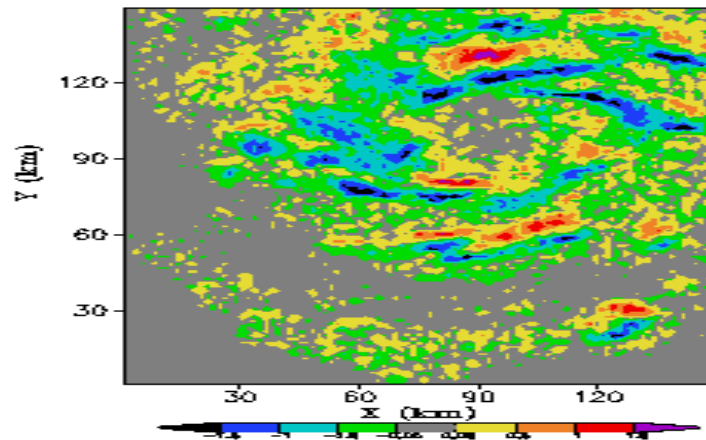
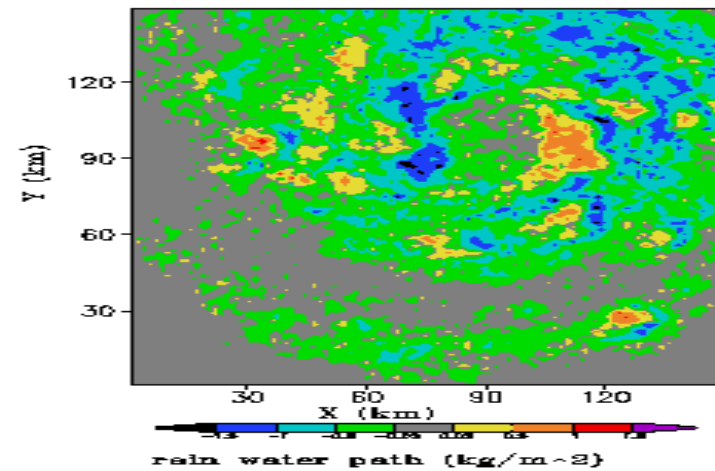
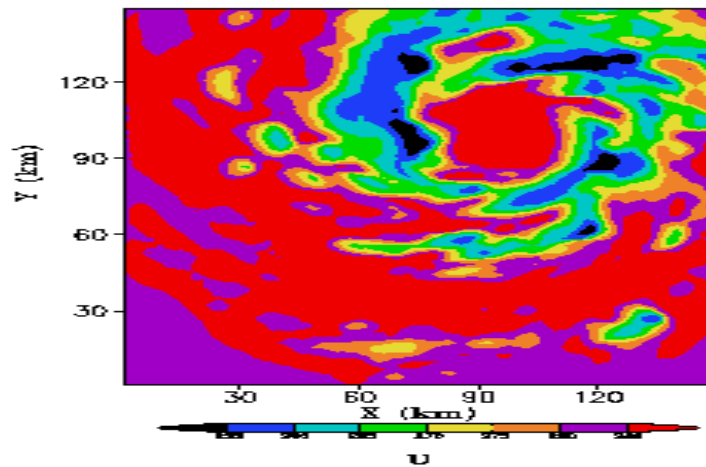
Polarimetric Signals from Clouds

Simulated Stokes vector for a 3D cloud

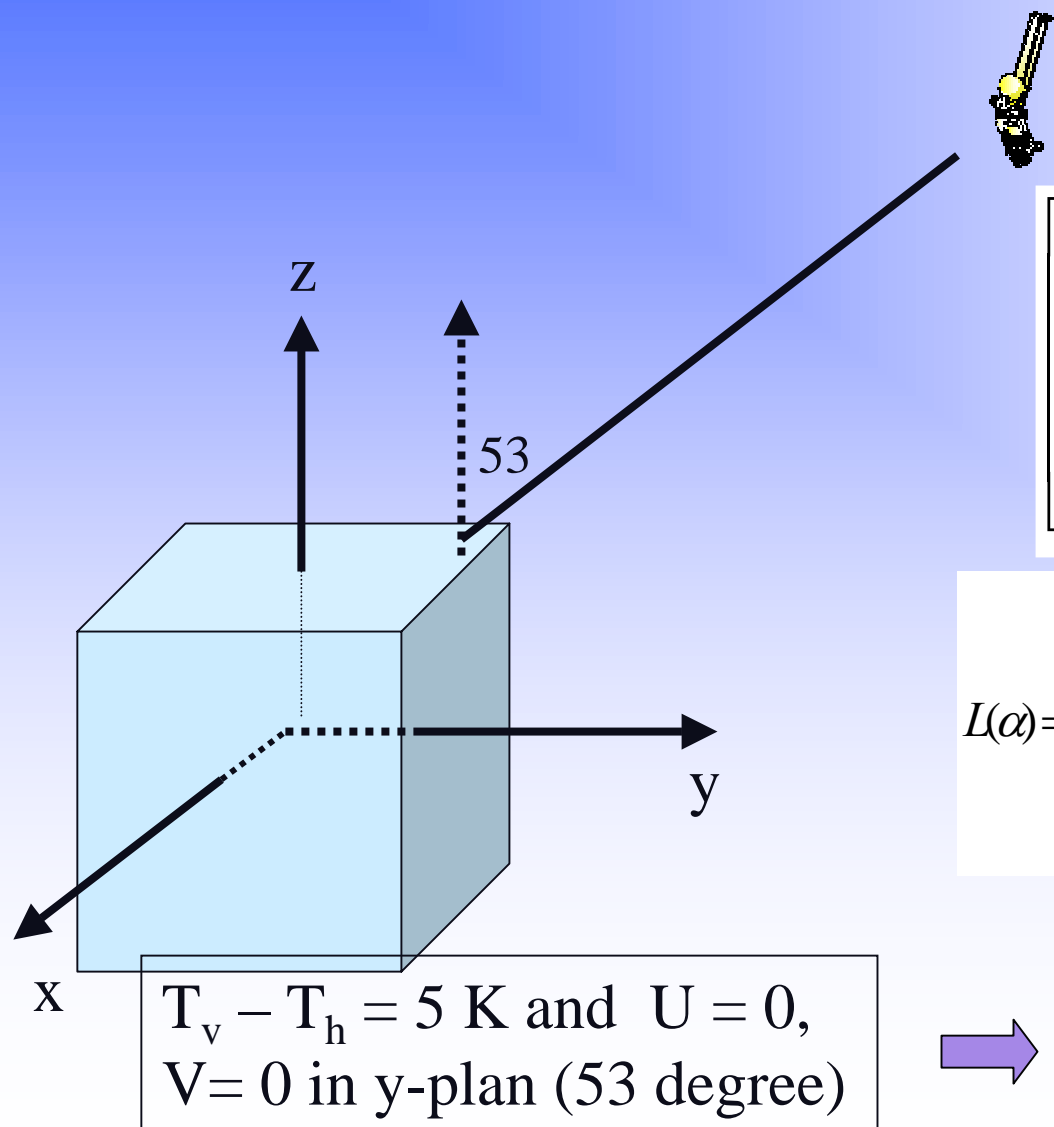


3D Clouds Produce Third Stokes Component at 10.7 GHz

Simulated Stokes vector for a 3D cloud



Polarimetric Signals from Finite Clouds: Physical Process of 3D Effects

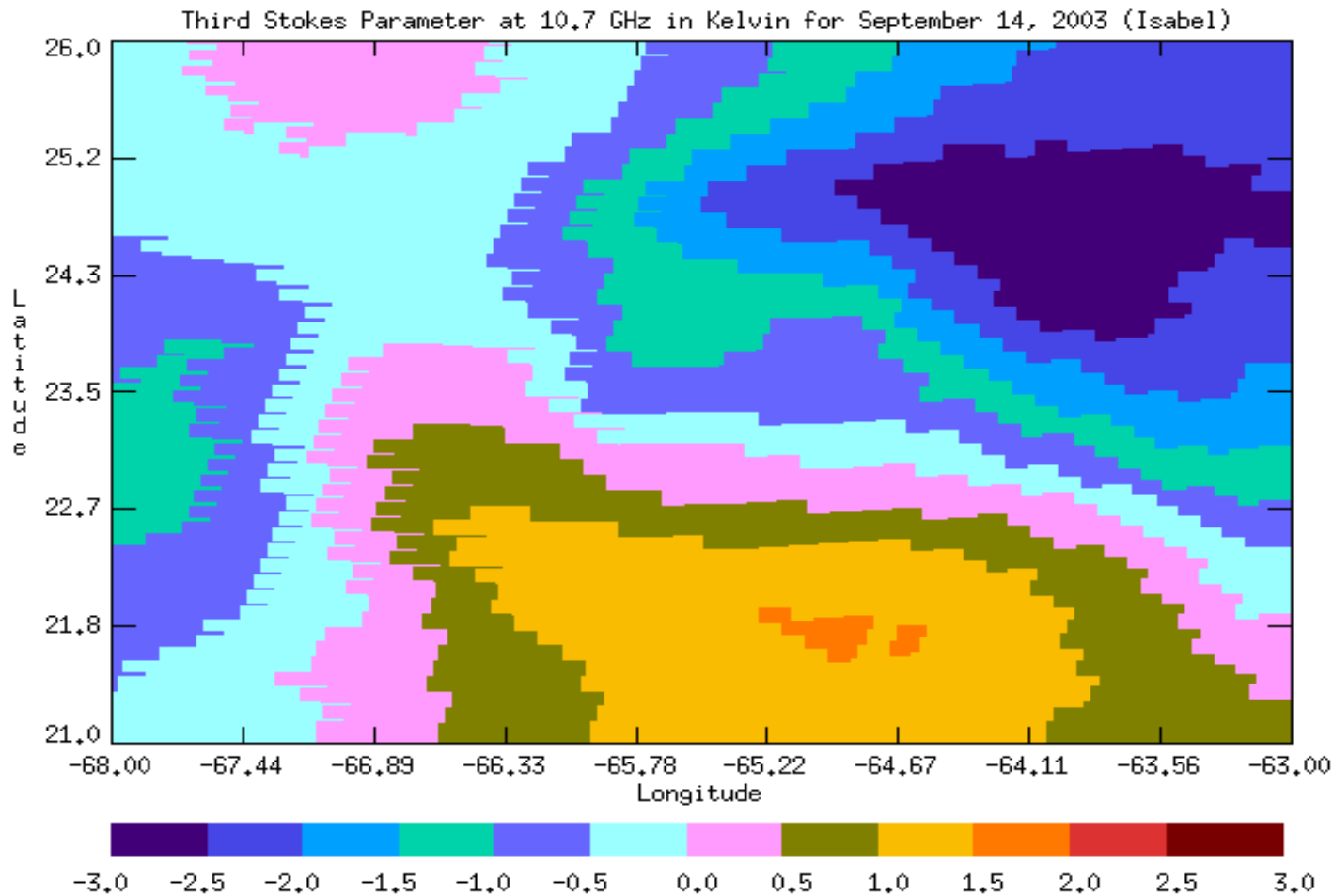


$$\begin{bmatrix} T_h \\ T_v \\ U \\ V \end{bmatrix}_{z\text{-plan}} = L(37^\circ) \begin{bmatrix} T_h \\ T_v \\ U \\ V \end{bmatrix}_{y\text{-plan}}$$

$$L(\alpha) = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & \sin\alpha\cos\alpha & 0 \\ \sin^2\alpha & \cos^2\alpha & -\sin\alpha\cos\alpha & 0 \\ -2\sin\alpha\cos\alpha & 2\sin\alpha\cos\alpha & \cos^2\alpha - \sin^2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_v - T_h = 5 \text{ K and } U = 4.8, V = 0 \text{ in } z\text{-plan}$$

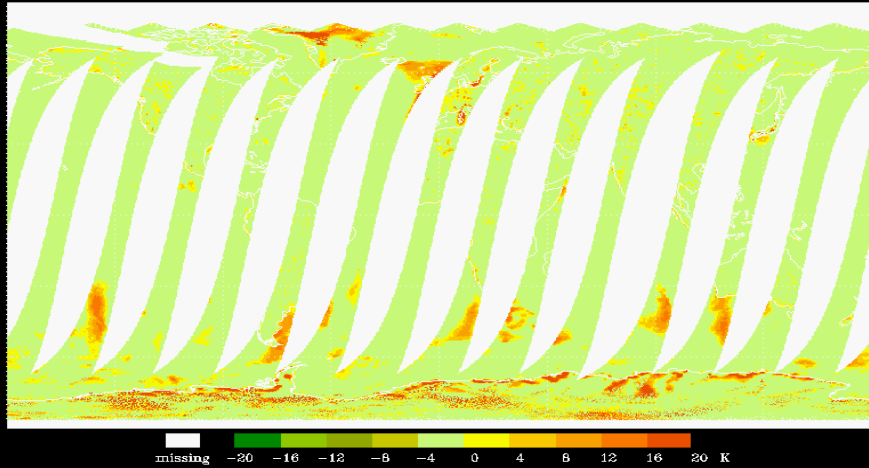
WindSat Measurements for Hurricane Isabel



WindSat Measurements (3rd & 4th Components)

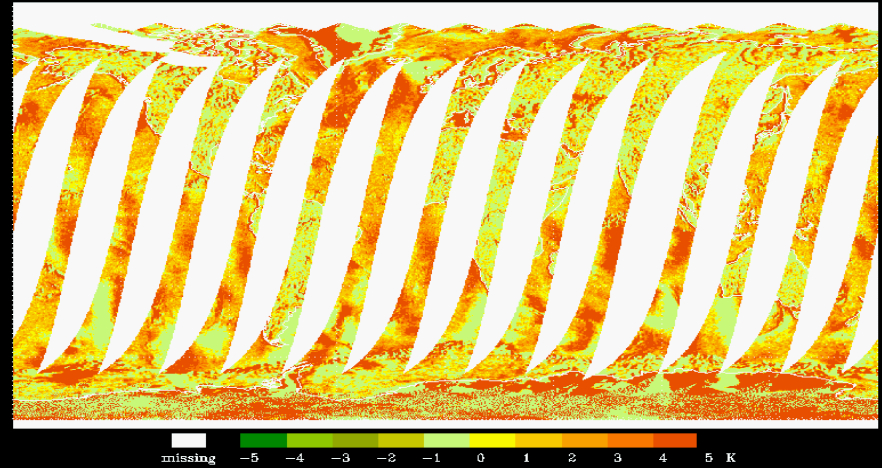
10.7 GHz TBU

WindSat 3rd Stokes Component at 10.7 GHz
2003-09-12



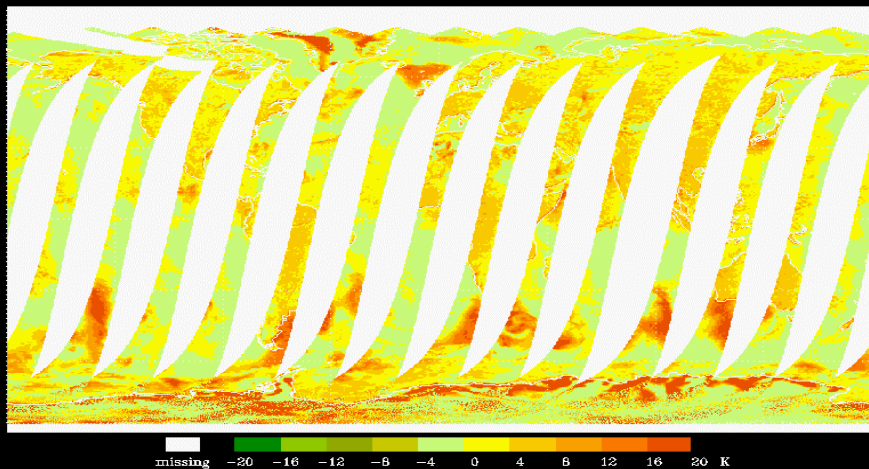
10.7 GHz TB4

WindSat 4th Stokes Component at 10.7 GHz
2003-09-12



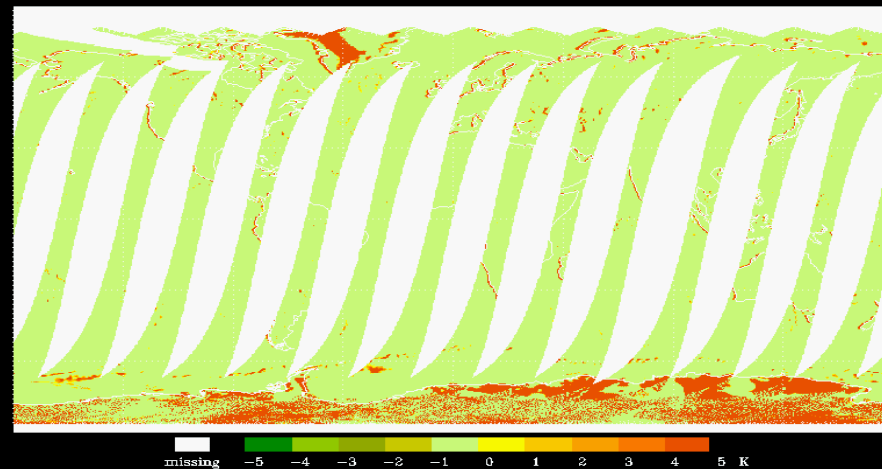
18.7 GHz TBU

WindSat 3rd Stokes Component at 18.7 GHz
2003-09-12



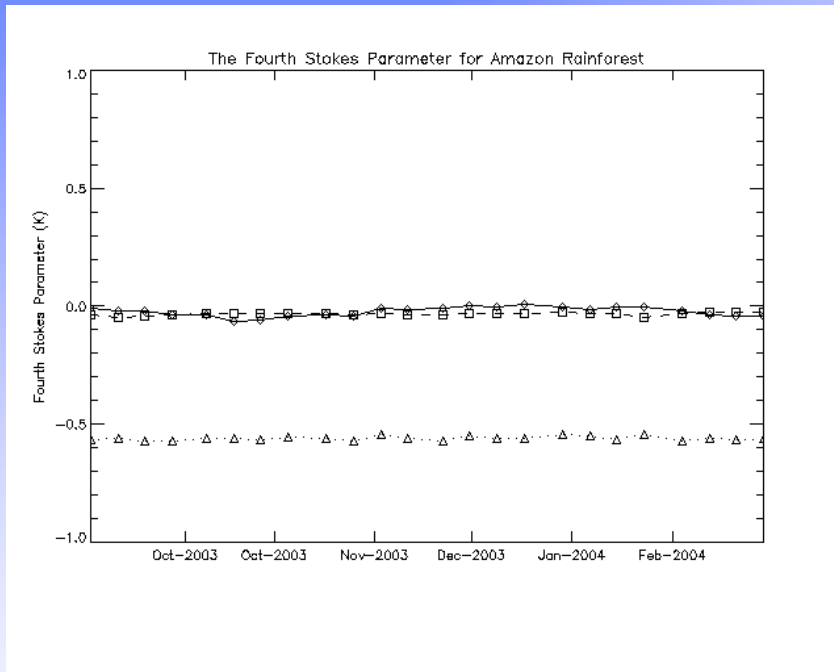
18.7 GHz TB4

WindSat 4th Stokes Component at 18.7 GHz
2003-09-12

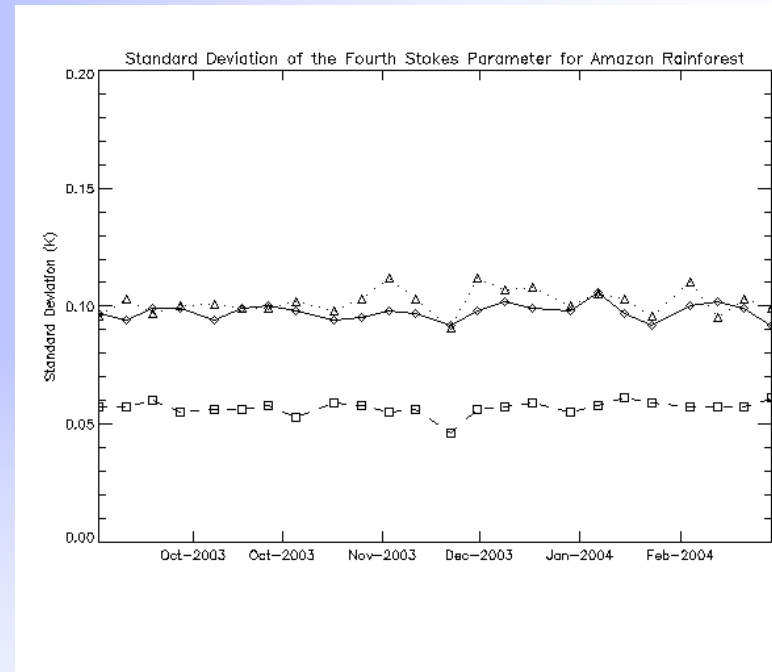


Vicarious Assessment of WindSat Measurements over Amazon

3rd Stokes component



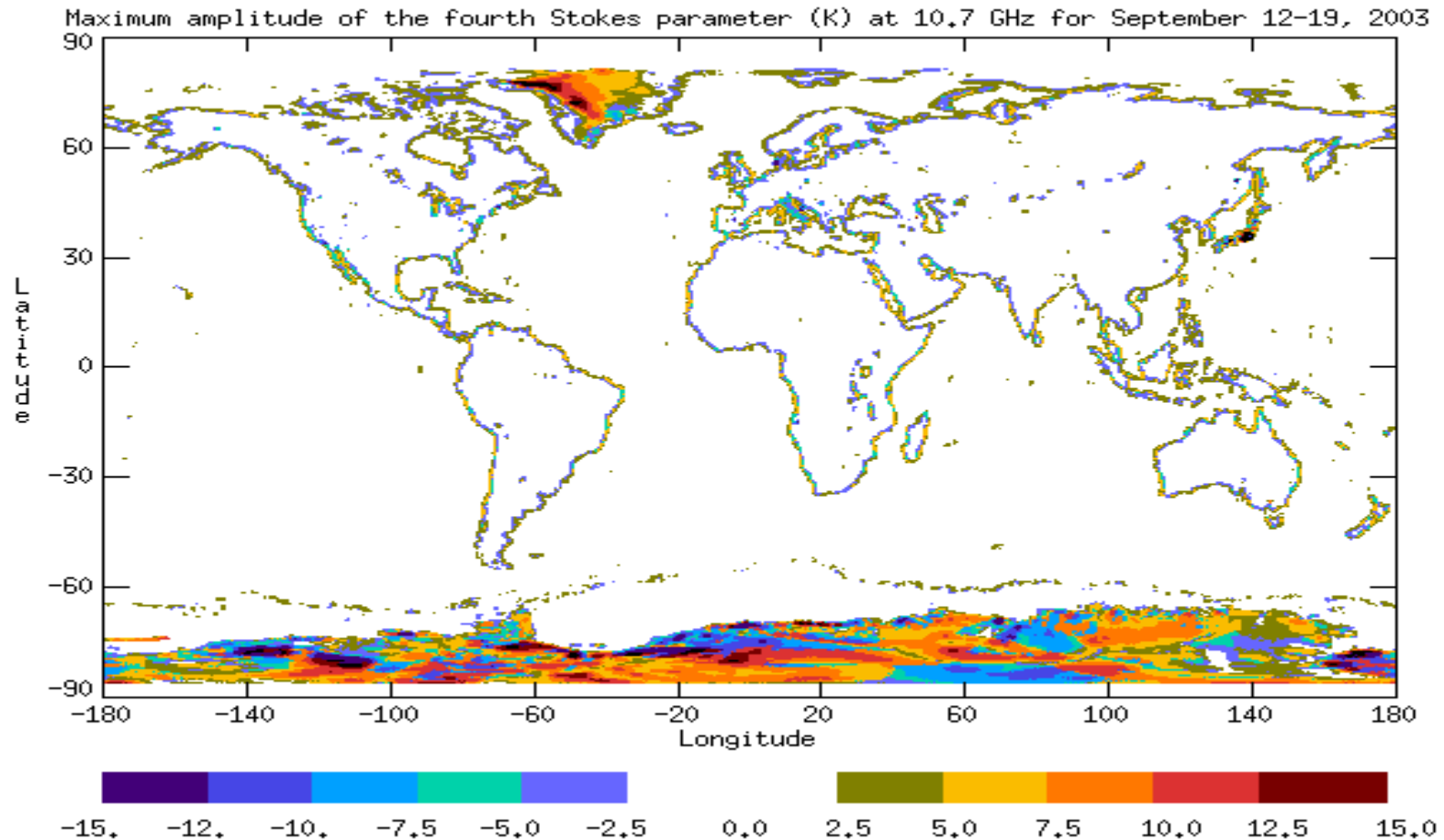
4th Stokes component



Time series of the mean 3rd and 4th Stokes parameters over Amazon rainforests.

the line with diamond, triangle and square corresponds to 10.7, 18.7 and 37 GHz, respectively

WindSat Measurements over Snow-Covered Surfaces



Summary

- The Community Radiative Transfer Model (CRTM) is being developed through the JCSDA satellite data assimilation program
- The CRTM includes vital components required for direct assimilations of current and future operational satellite radiances and will allow for uses of satellite data under all weather conditions in NWP models
- The CRTM is a framework with all interfaces to link university research and is accelerating the transition of new radiative transfer science into US operational NWP data assimilation systems (NASA and DoD are planning to use the same CRTM)

Outstanding Issues

- Lack of schemes for diagnosing the hydrometeors associated with sub-grid convection
- Lack of high quality dataset to validate CRTM under cloudy conditions
- Consistent assumptions in cloud microphysics from visible, infrared and microwave wavelengths used in CRTM with NWP models
- Limited access to operational forecast models outputs
- Surface scattering/emission related to dense medium materials
- Inclusion of spatial inhomogeneity of clouds and precipitation in CRTM
- Infrared emissivity over deserts
- Sea ice emissivity modeling at microwave frequencies

2005

**Dr. Larry McMillin is retiring from NOAA/NESDIS after
34 years of service!!**

Dr. Larry McMillin has been dedicated to develop
OPTRAN to make it possible to assimilate satellite
radiances in US global weather forecast model.

