Developments of JCSDA Community Radiative Transfer Model (CRTM)

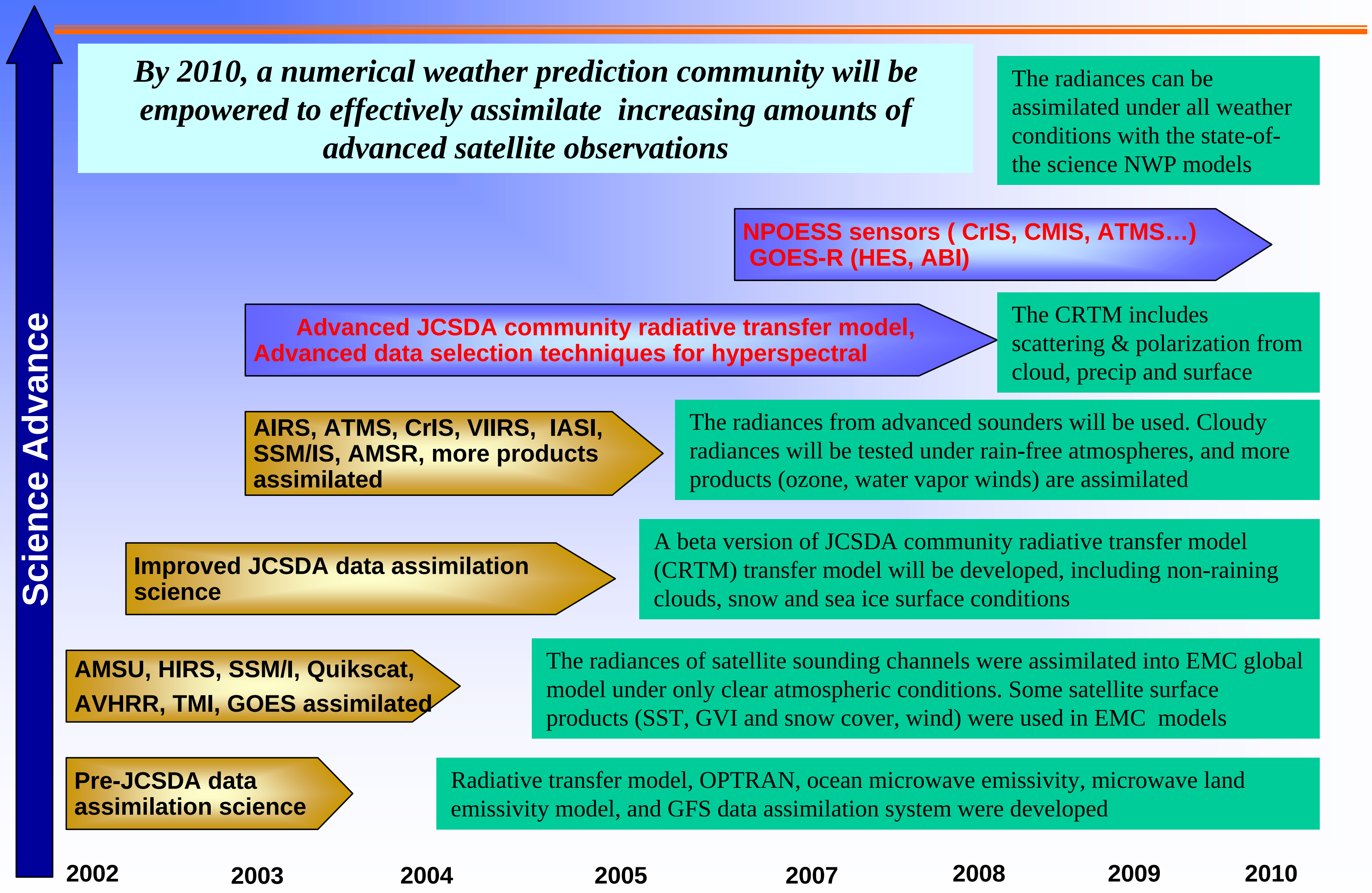
Fuzhong Weng
NOAA/NESDIS/Office of Research and Applications

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)



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

Requirements for Better RT Models

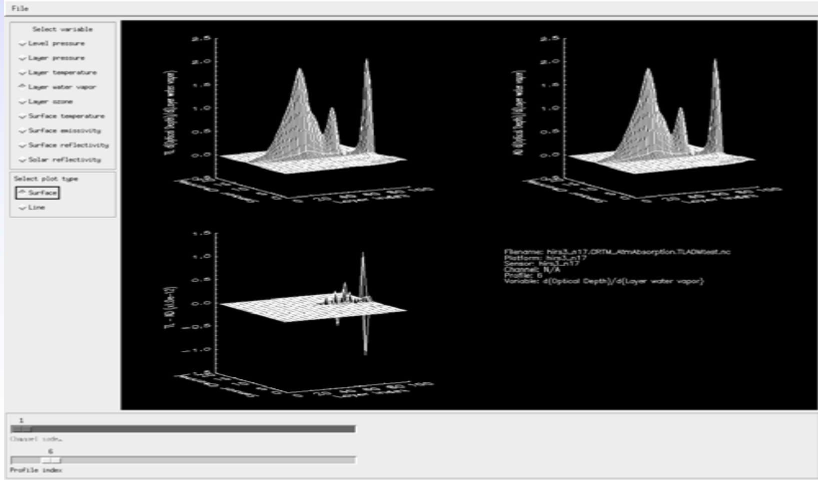
- Accelerated uses of satellite observations
  - Direct radiance assimilation (less dependent on product validation)
  - Unified satellite data assimilation infrastructure
- Advanced satellite instruments (NPOESS, GOES-R)
  - Interferometer sounding technology with a few thousand channels
  - Polarimetric 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

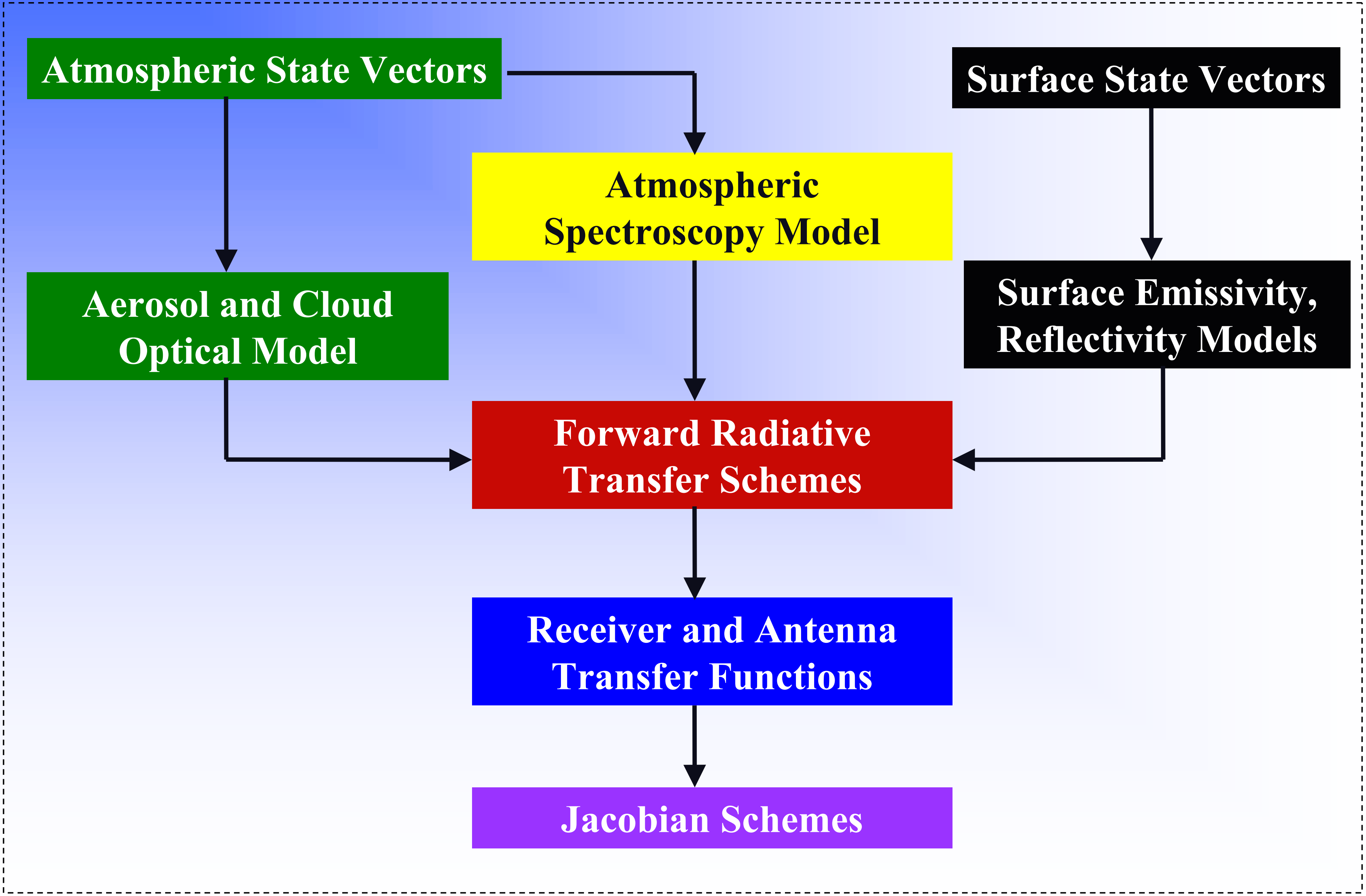
```
CRTM_Forward( Atmosphere,          &
              Surface,             &
              GeometryInfo,        &
              ChannelInfo,         &
              RTSolution )
```

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



Filename: hirs3_n17.CRTM_AtmAbsorption.TLADMtest.nc
Platform: hirs3_n17
Sensor: hirs3_n17
Channel: N/A
Profile: 6
Variable: d(Optical Depth)/d(Layer water vapor)

Community Radiative Transfer Model



Atmospheric State Vectors

Surface State Vectors

Atmospheric Spectroscopy Model

Aerosol and Cloud Optical Model

Surface Emissivity, Reflectivity Models

Forward Radiative Transfer Schemes

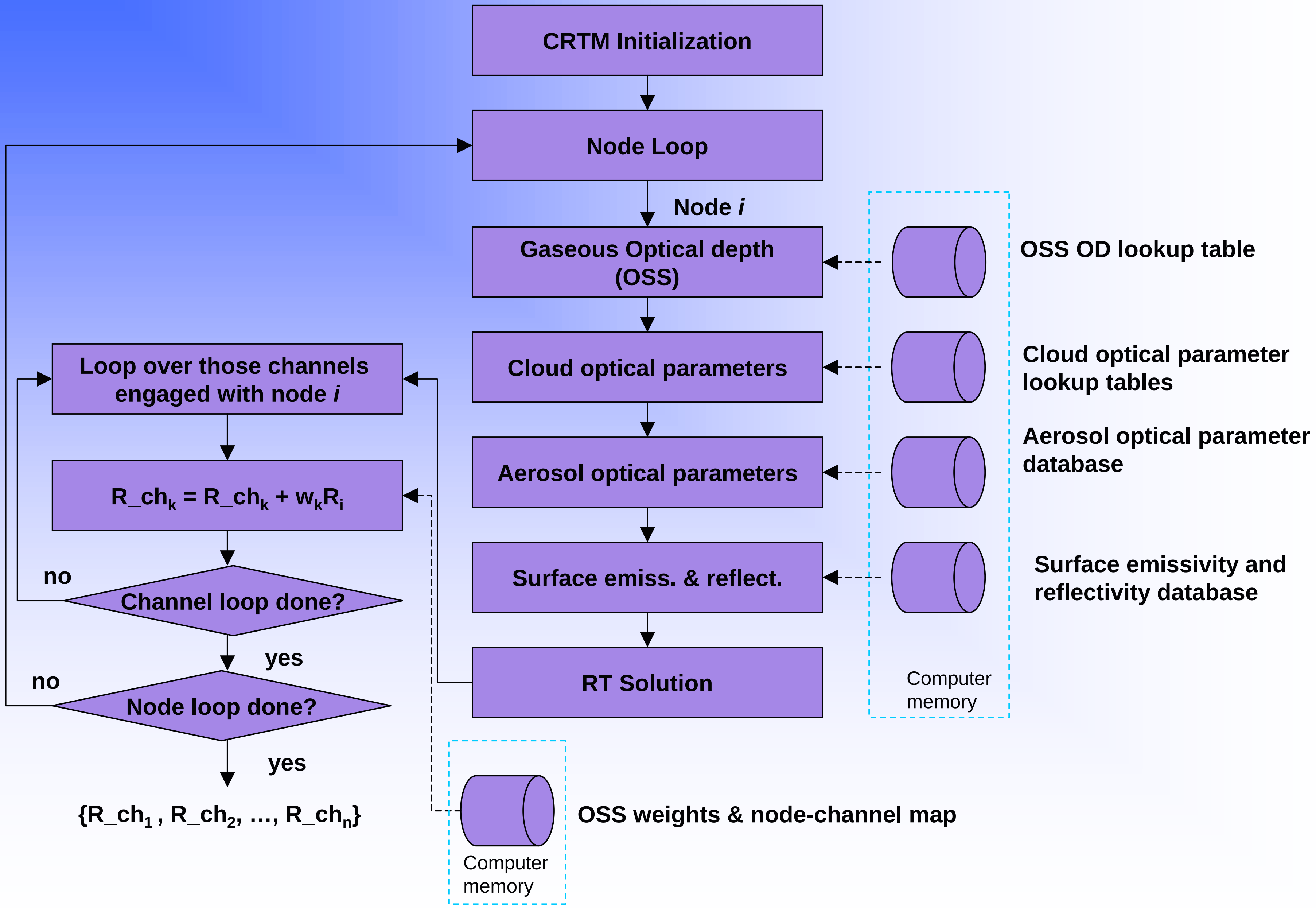
Receiver and Antenna Transfer Functions

Jacobian Schemes

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 polarmetric 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

Beta Version CRTM flowchart



CRTM Initialization

Node Loop

Node *i*

Gaseous Optical depth (OSS)

Cloud optical parameters

Aerosol optical parameters

Surface emiss. & reflect.

RT Solution

OSS OD lookup table

Cloud optical parameter lookup tables

Aerosol optical parameter database

Surface emissivity and reflectivity database

Computer memory

Loop over those channels engaged with node *i*

$R\_ch_k = R\_ch_k + w_k R_i$

Channel loop done?

no

yes

Node loop done?

no

yes

$\{R\_ch_1, R\_ch_2, \ldots, R\_ch_n\}$

OSS weights & node-channel map

Computer memory

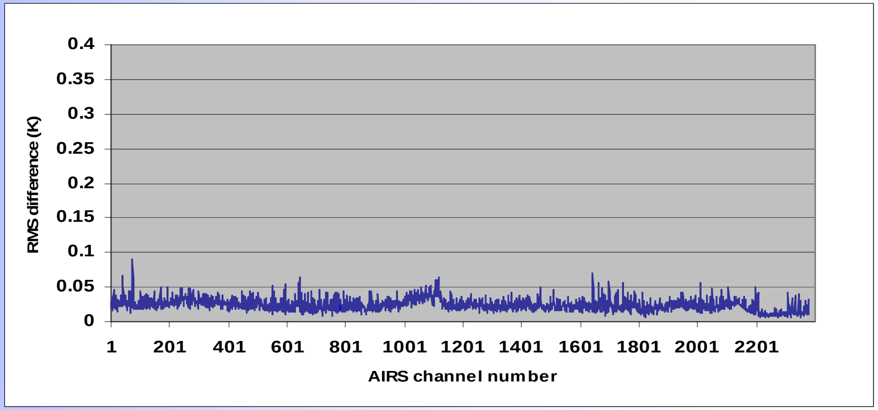
Fast Gaseous Absorption Model

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

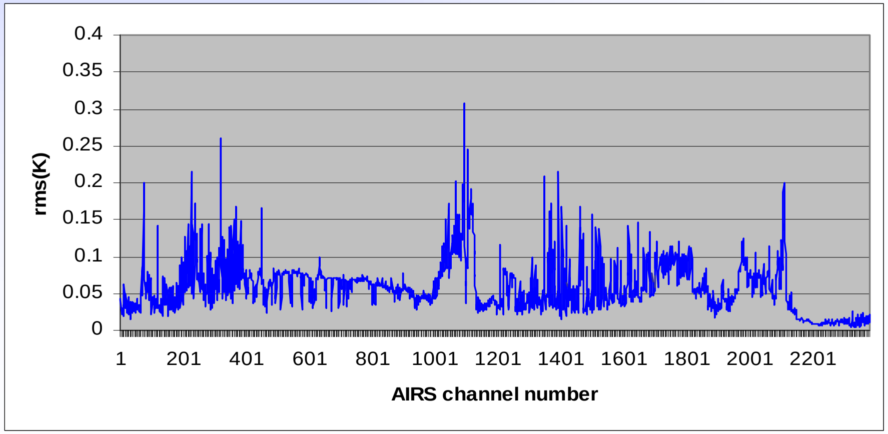
$$\overline{R} = \int_{\Delta\nu} \phi(\nu) R(\nu) d\nu \cong \sum_{i=1}^{N} w_i R(\nu_i); \qquad \nu_i \in \Delta\nu$$

- 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

OSS
Trained with ECMWF set
Tested with UMBC set



OPTRAN
Trained with UMBC set
Tested with ECMWF set



Provided by Y. Han (NESDIS) and J. Moncet (AER)

Computation & Memory Efficiency

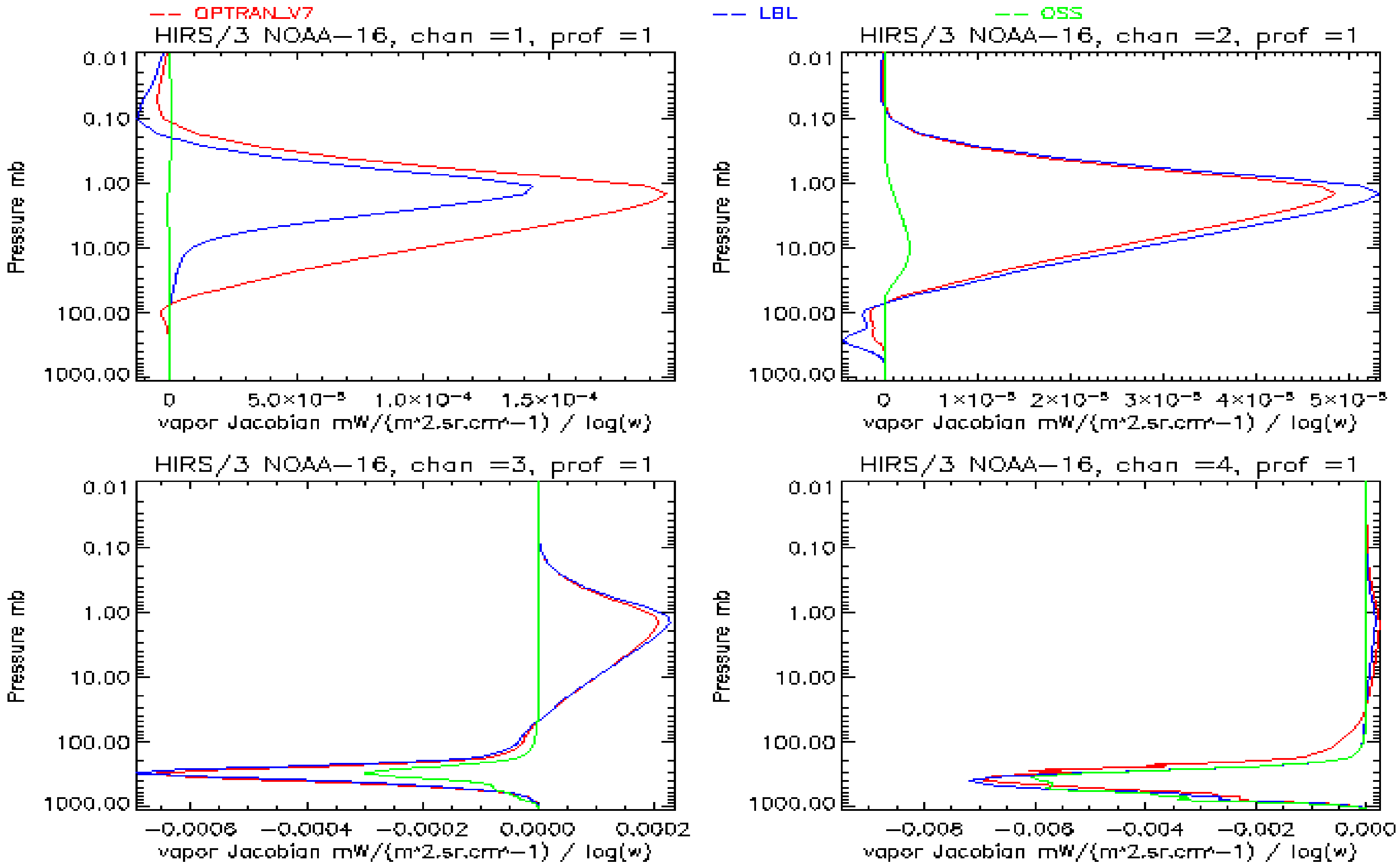
Time needed to process 48 profiles with 7 observation angles

	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

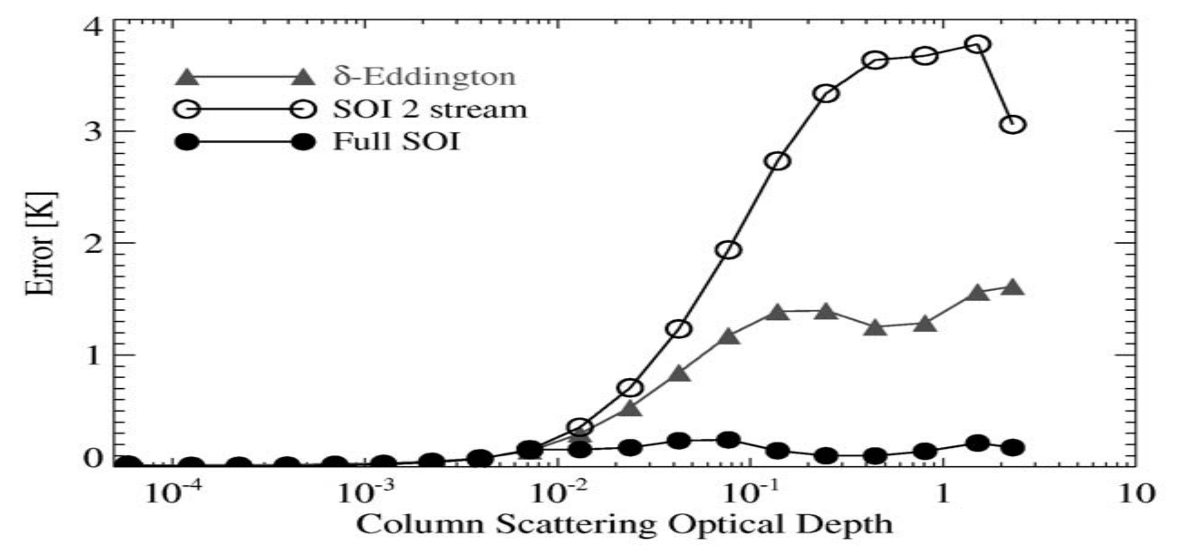
Memory resource required (Megabytes)

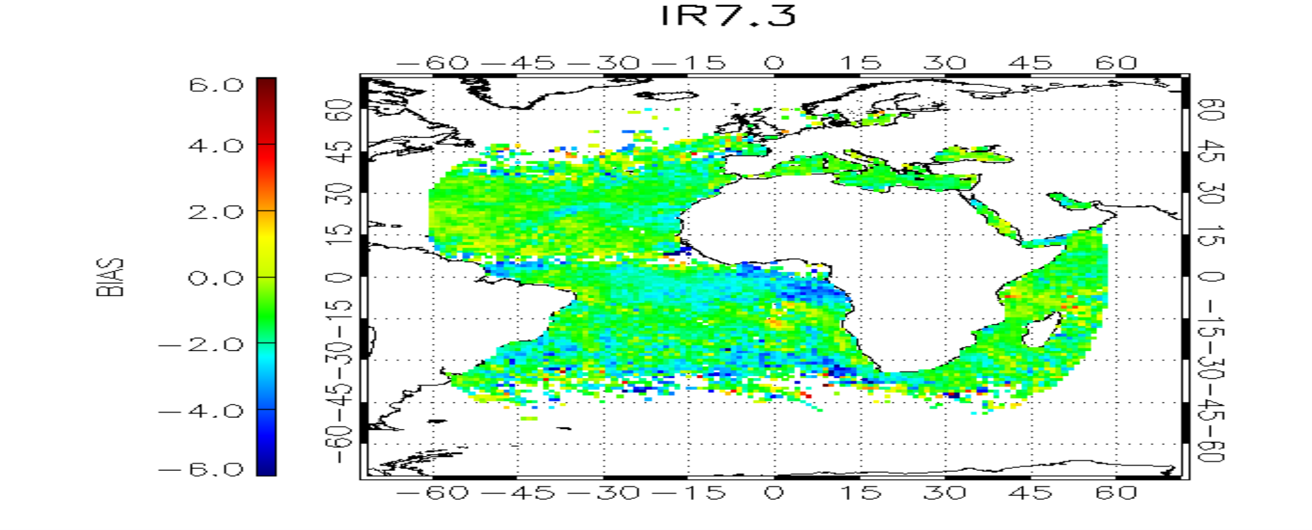
	OPTRAN-V7 single, double	OPTRAN-comp double precision	OSS Single precision
AIRS	33, 66	5	97
HIRS	0.26, 0.5	0.04	4

Water vapor Jacobians at weak absorption channels



Radiative Transfer Scheme: Successive Order of Iteration (SOI)

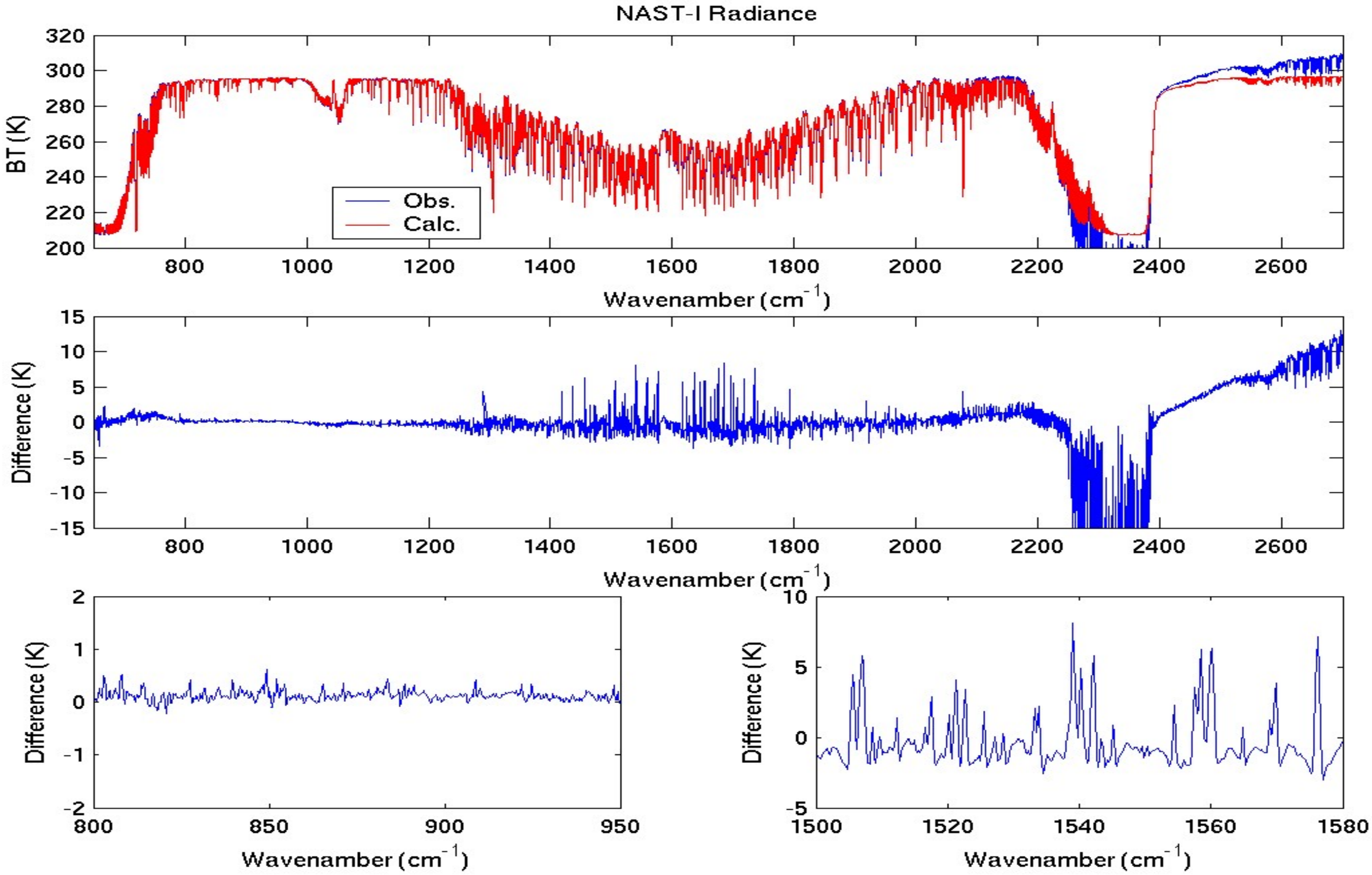




Provided by

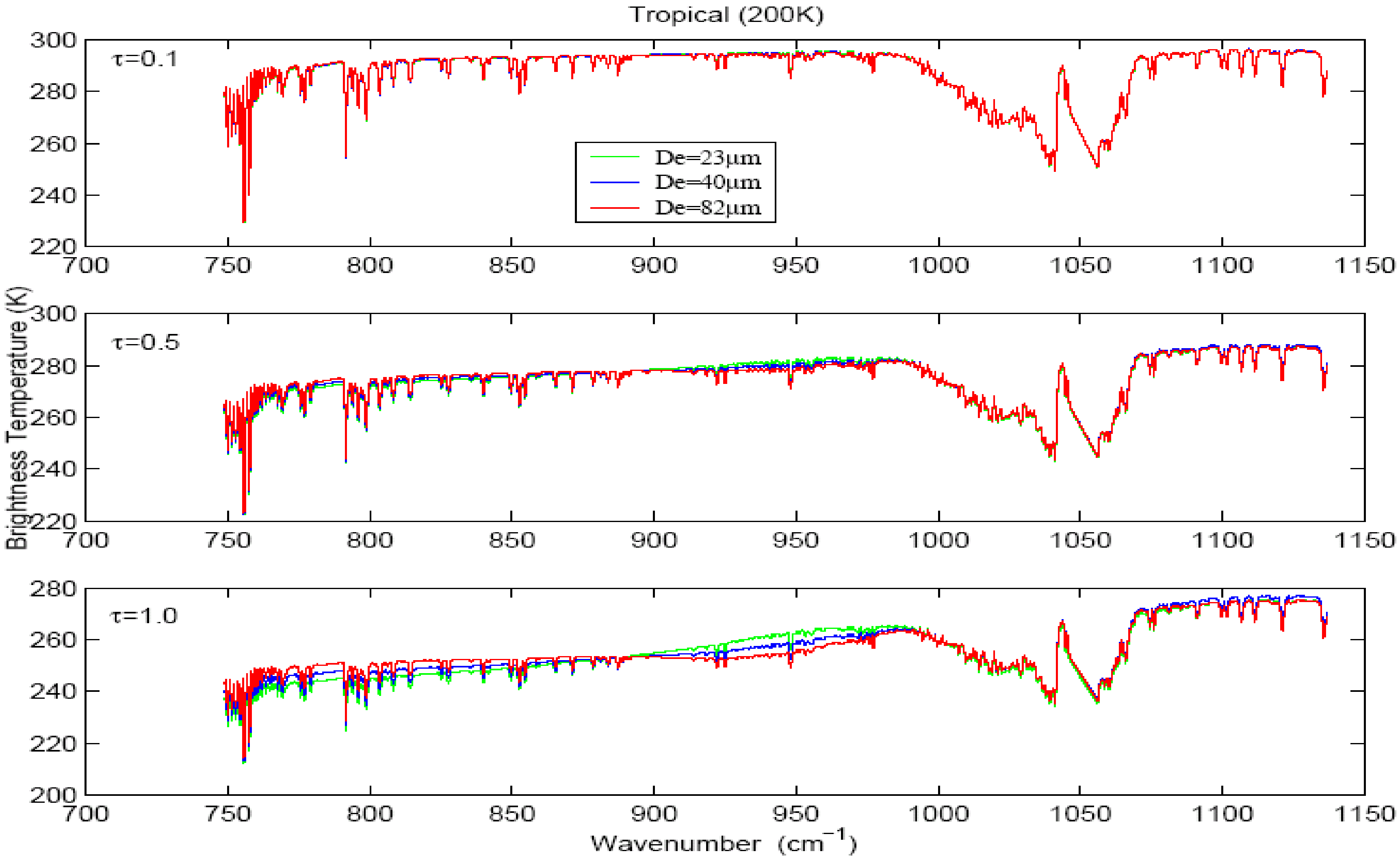
Bennartz et al

Principal Component Radiative Transfer



Provided by Xu Liu and Bill Smith

AIRS Sensitivity to Cirrus Clouds



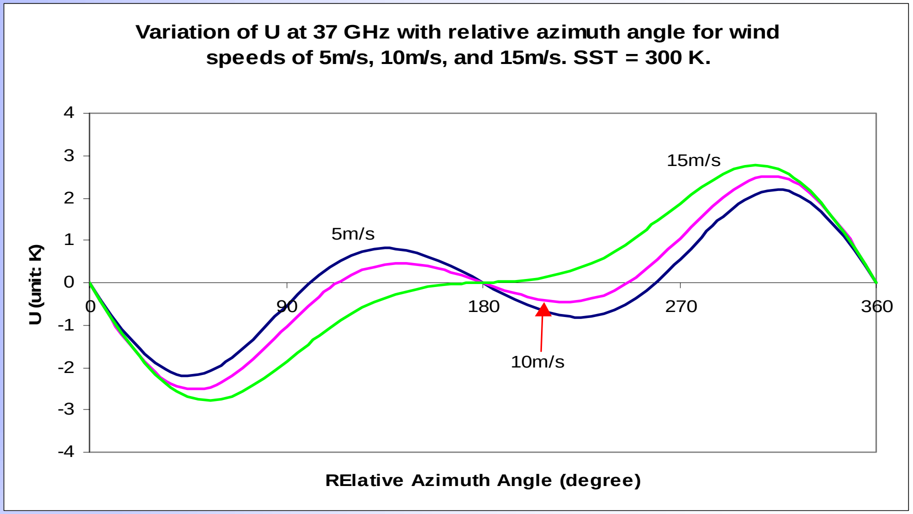
Provided by K.N. Liou and S. Ou

Oceanic Emission Model

Phenomenology.

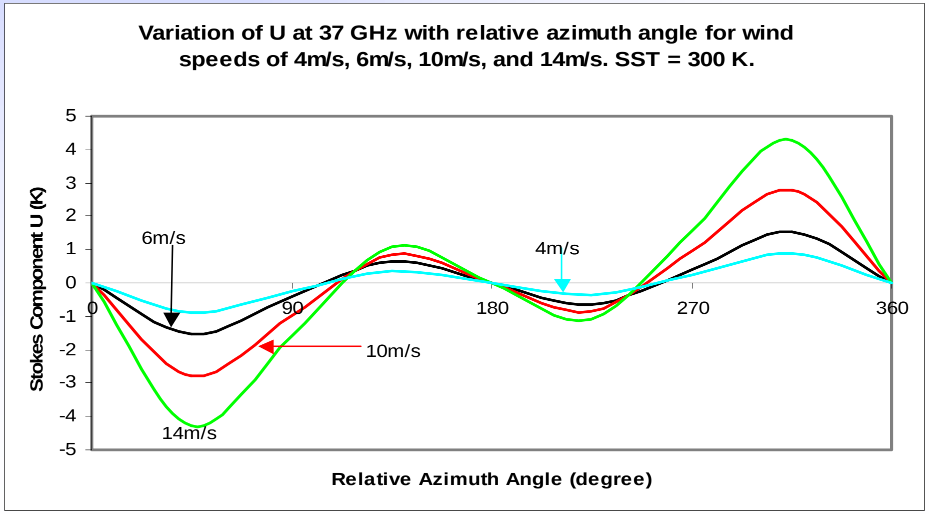
- Large gravity waves, whose wavelengths are long compared with the radiation wavelength.
- Small capillary waves, which are riding on top of the large-scale waves, and whose RMS height is small compared with radiation wavelength.
- Sea foam, which arises as a mixture of air and water at the wind roughened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

Two-scale Simulations



Variation of U at 37 GHz with relative azimuth angle for wind speeds of 5m/s, 10m/s, and 15m/s. SST = 300 K.

Aircraft Measurements



Variation of U at 37 GHz with relative azimuth angle for wind speeds of 4m/s, 6m/s, 10m/s, and 14m/s. SST = 300 K.

Canopy Scattering Model

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

d - leaf thickness

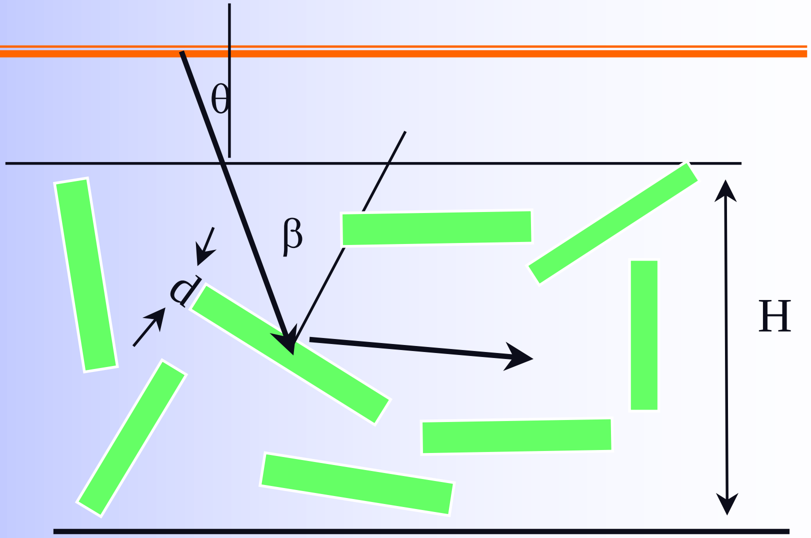
H - canopy height

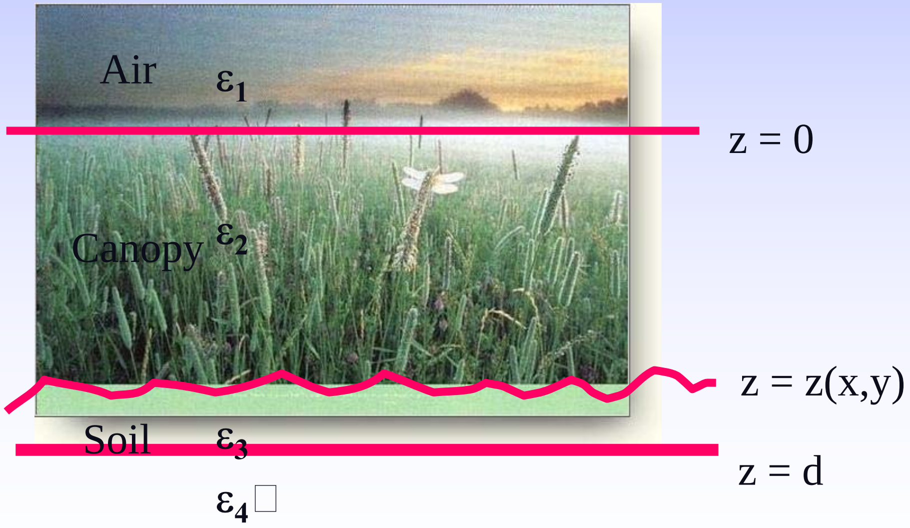
LAI - leaf area index

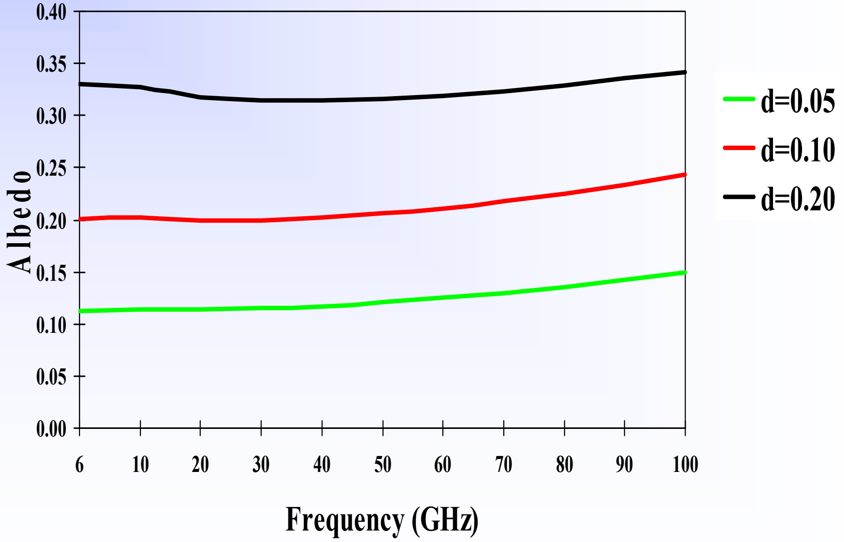
m_d - dry matter content

β – leaf orientation angle

θ – incident angle of EM wave

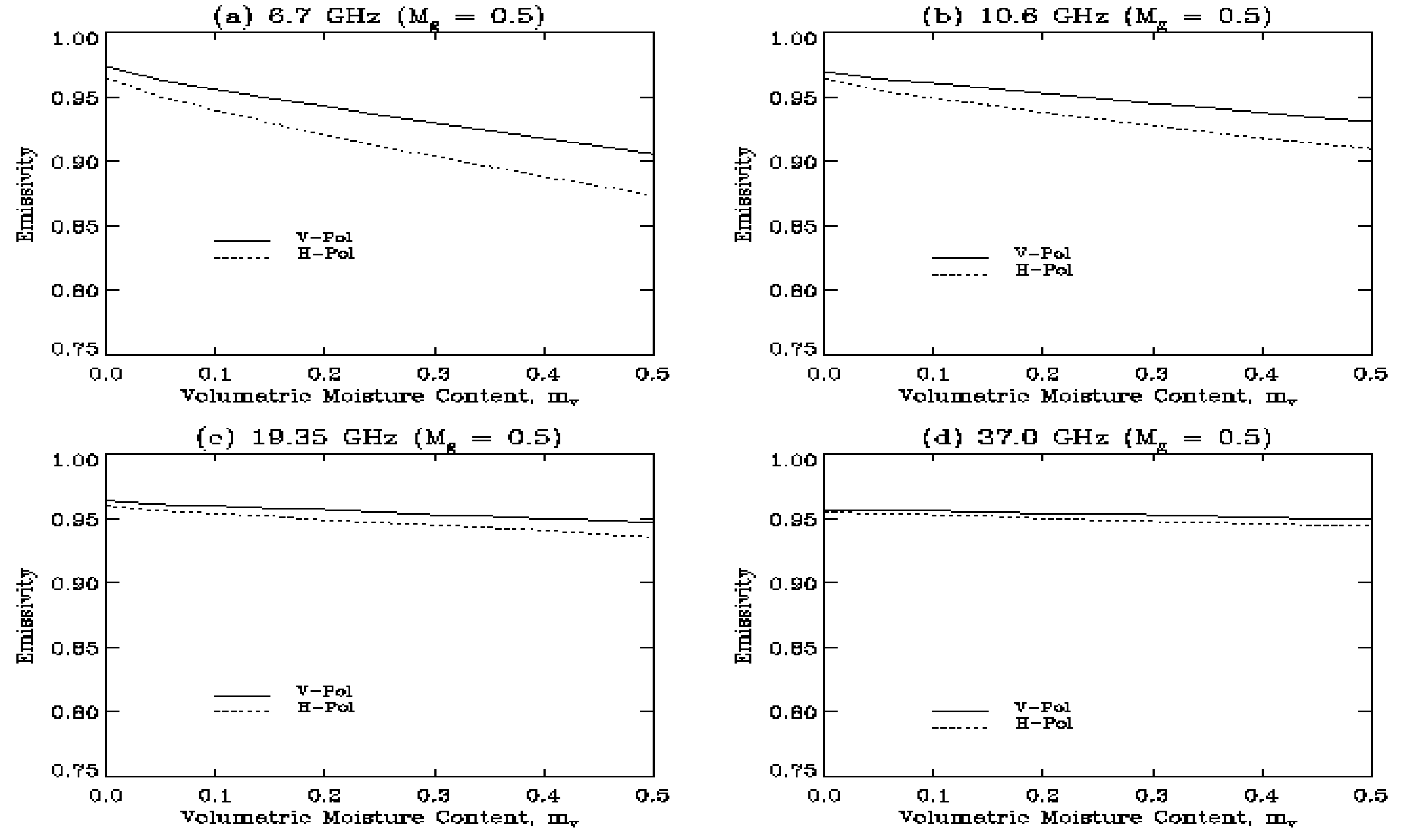






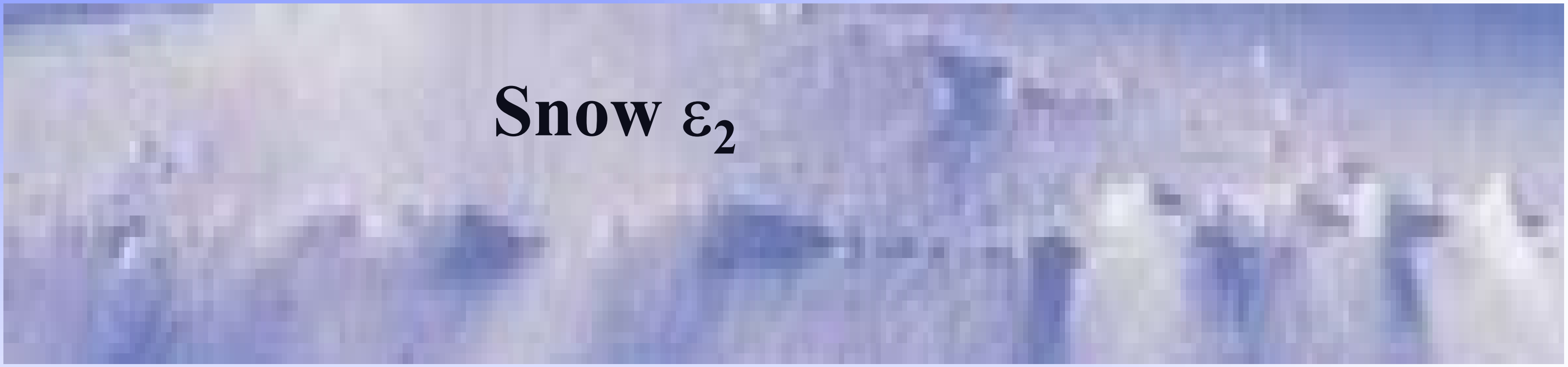
Emissivity-Soil Moisture

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

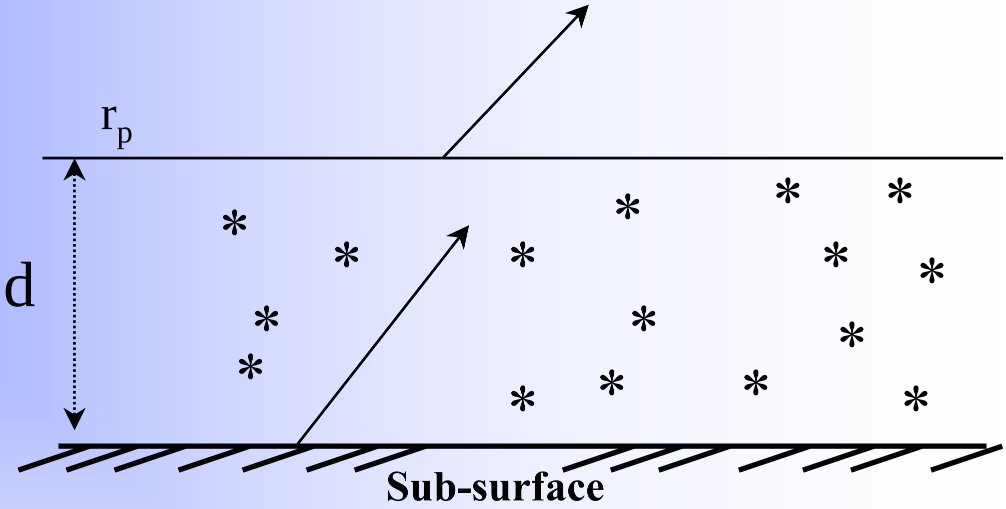
Strong fluactuation theory
(Tsang at al., 1985)

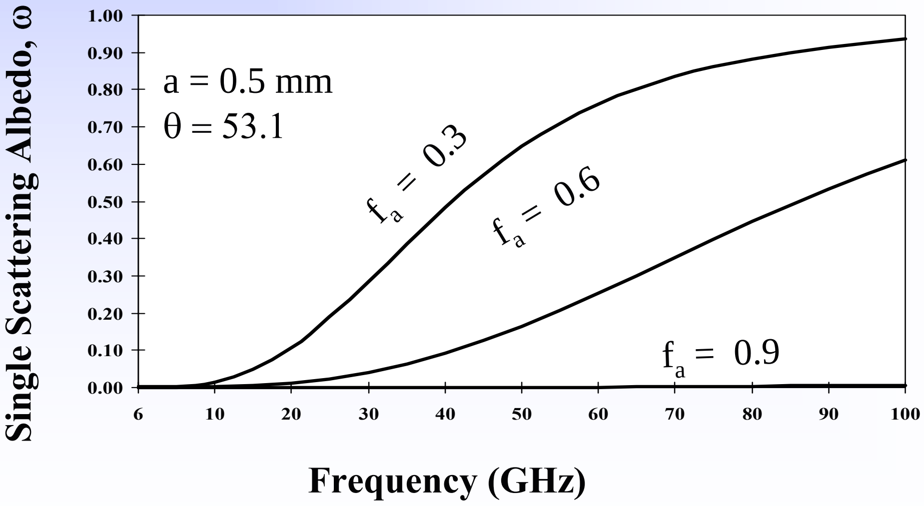
$$\varepsilon_{eff} = \frac{1+2f_a y}{1-f_a y} + i\frac{2f_a y^2(\kappa a)^3(1-f_a)^4}{(1-f_a y)^2(1+2f_a)^2}$$

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

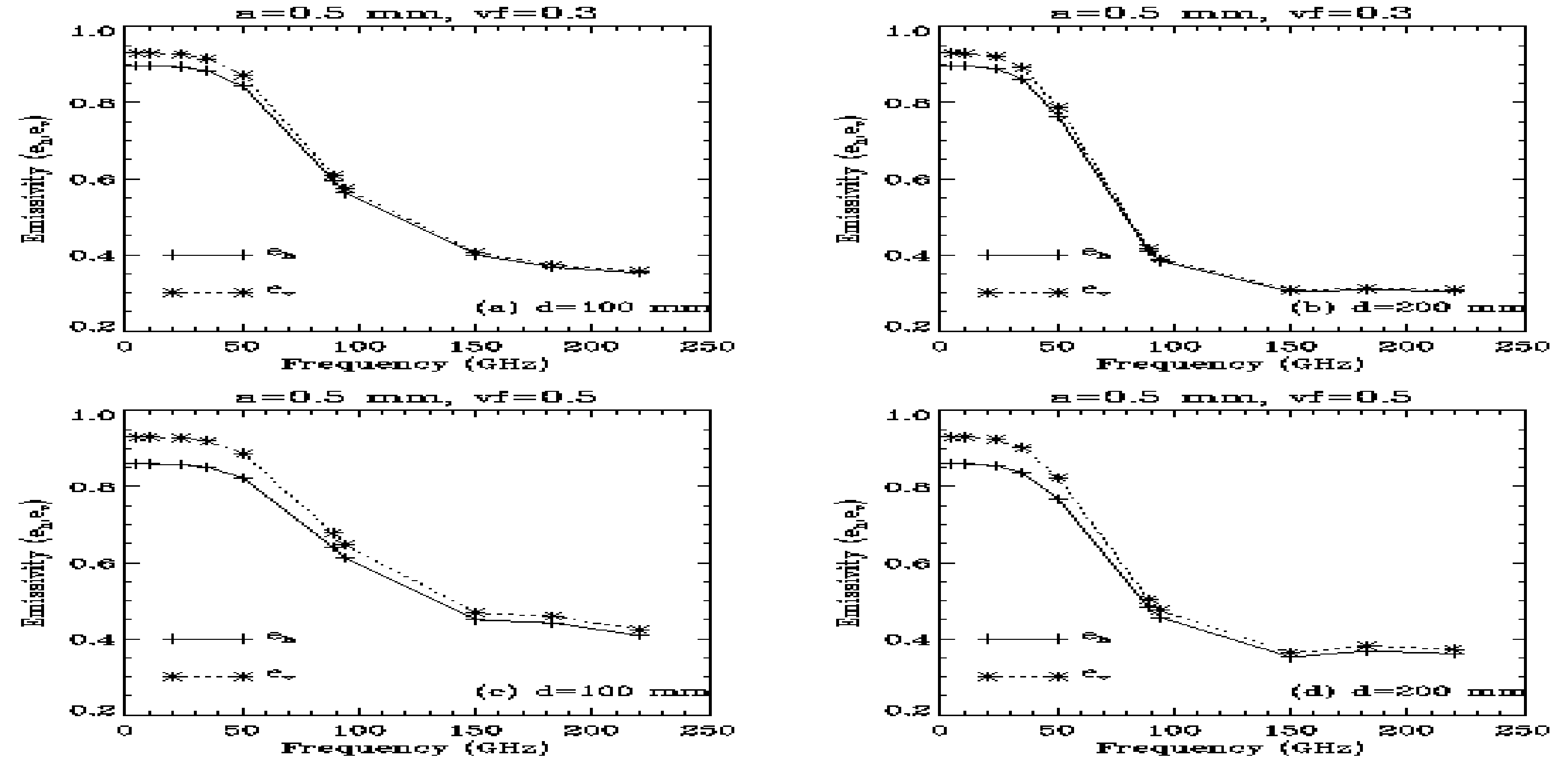
$$y = \frac{\varepsilon_s - \varepsilon}{\varepsilon_s + 2\varepsilon}$$

f_a - ice-volume fraction
d - snow depth
a - snow particle size





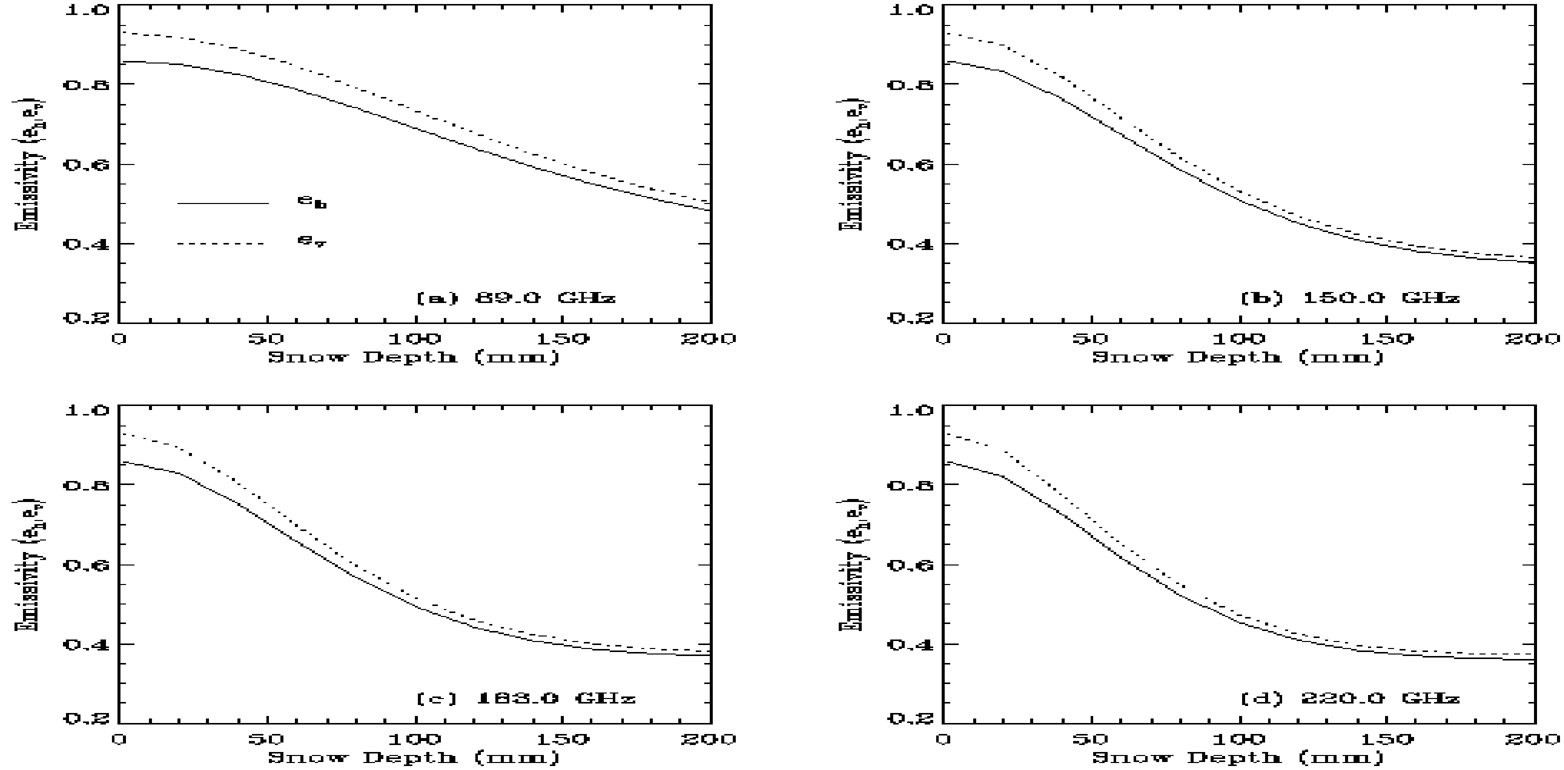
Snow Emissivity Spectra



Parameters:

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

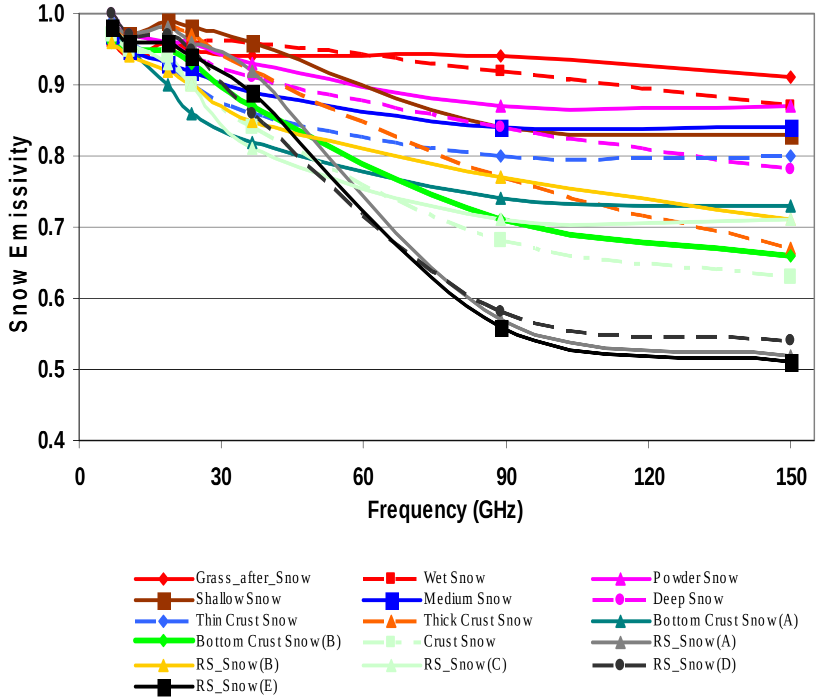
Emissivity vs. Snow Depth



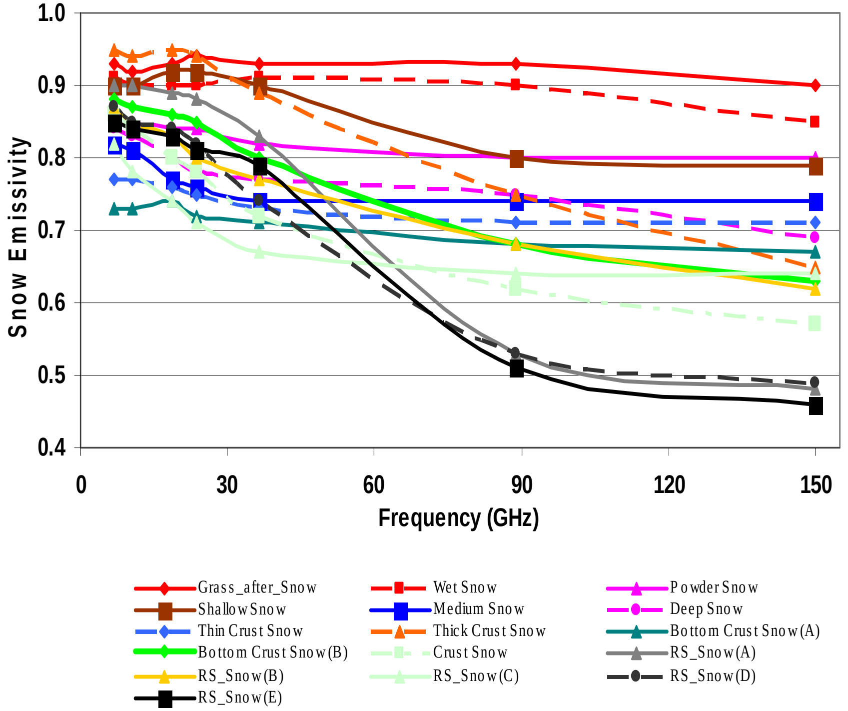
Need Improvements for:

- Snow stratification
- Melting/refrozen
- Metamorphosis process

Snow Microwave Emissivity Spectra



Snow V-POL Emissivity Spectra



Snow H-POL Emissivity Spectra

Analytic Jacobian

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

$$\frac{\partial \mathbf{I}_1(\mu)}{\partial x_s} = \sum_{j=1}^{4N} \mathbf{K}_L(\mu, j)\{B(T_s)\frac{\partial \boldsymbol{\varepsilon}}{\partial x_s} + \frac{\partial B(T_s)}{\partial x_s}\boldsymbol{\varepsilon} + \frac{\partial \mathbf{R}}{\partial x_s}\bar{\mathbf{E}}\mathbf{s}_L(\tau_L) + \frac{\partial \mathbf{R}_0}{\partial x_s}\frac{F_0}{\pi}\exp(-\tau_L / \mu_0)\bar{\boldsymbol{\Xi}}\}_j \qquad (1)$$

$$+\sum_{j=1}^{4N} \mathbf{K}_L(\mu, j)\{\frac{\partial \mathbf{R}}{\partial x_s}\bar{\mathbf{E}}\exp[\mathbf{A}_L(\tau_L - \tau_{L-1})]\,\mathbf{c}_L\}_j$$

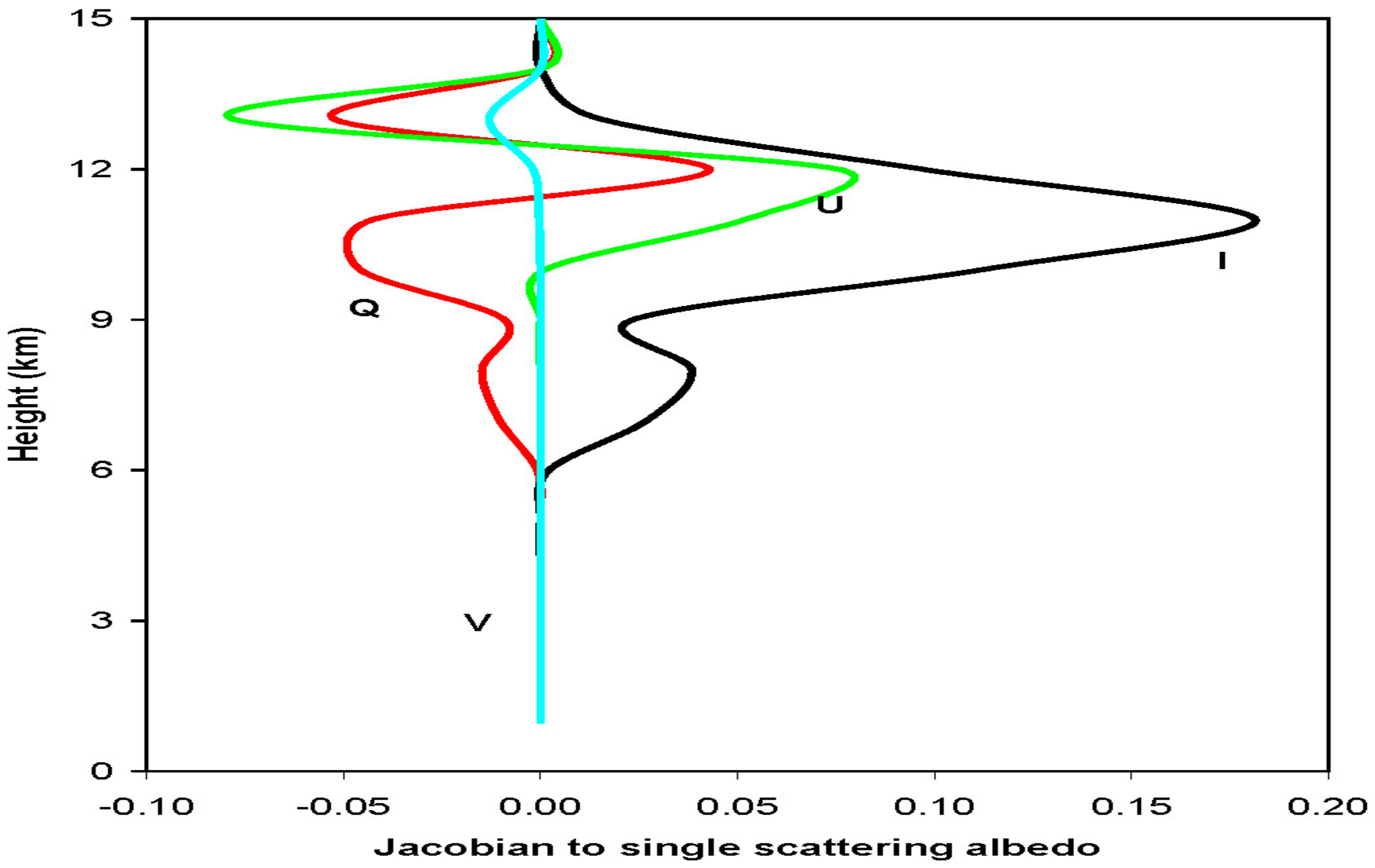
Jacobian to any atmospheric parameters is just a linear sum of the Jacobians to temperature, optical thickness, and phase function/matrix, for example, Jacobian to water vapor,

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

and Jacobian to cloud water,

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

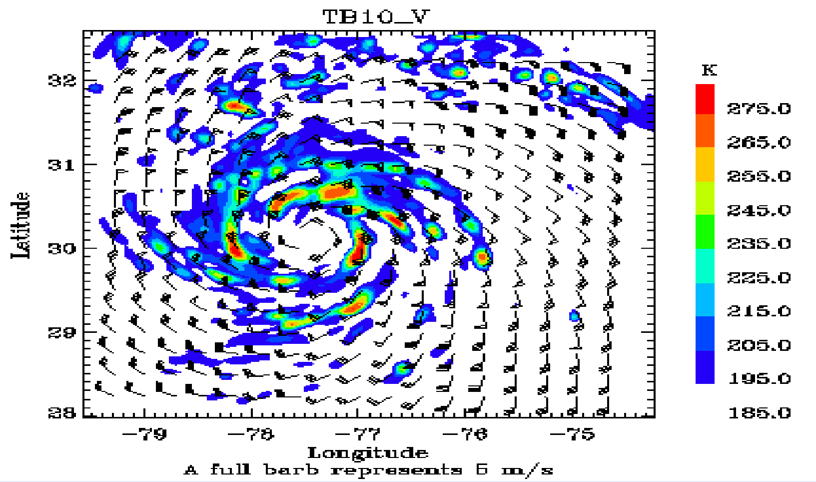
Stokes Jacobians at 0.67 micron Preparation for NPOESS/APS



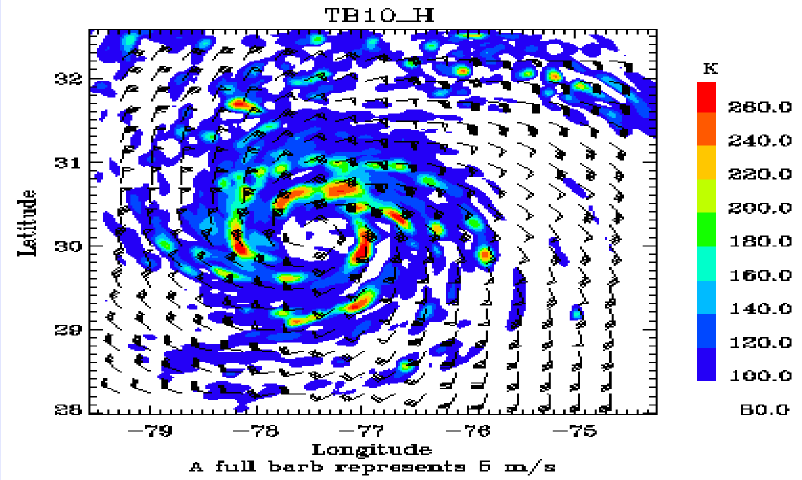
(Weng and Liu, 2003, JAS)

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

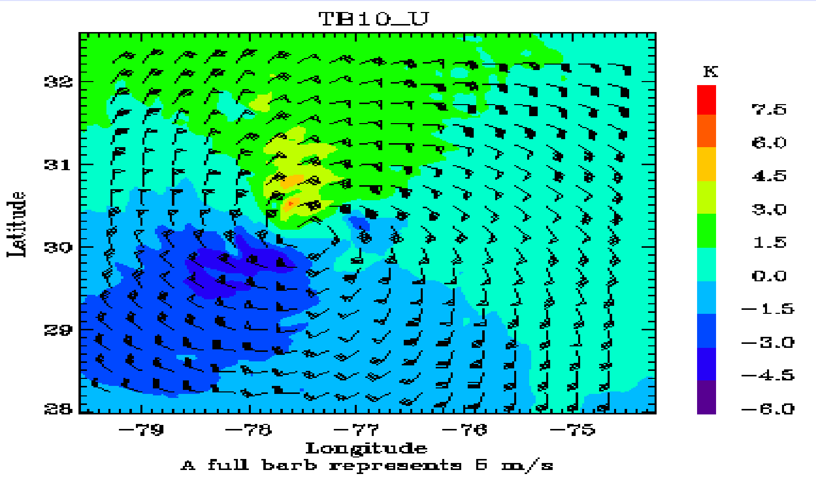
10.7_V



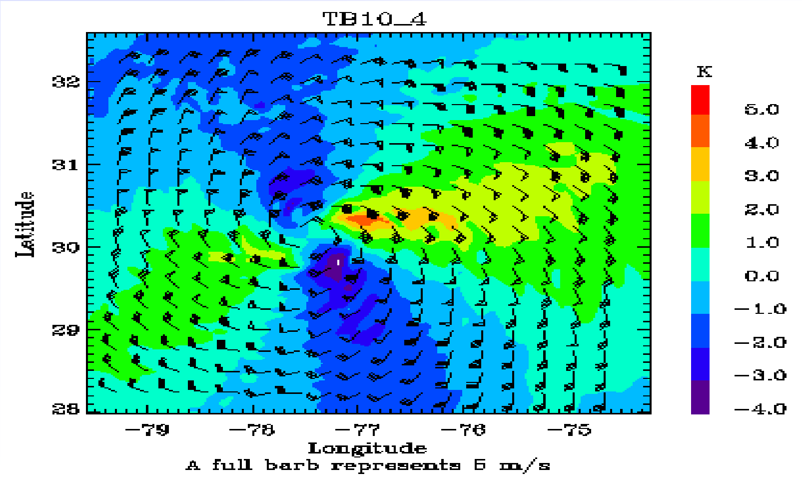
10.7_H



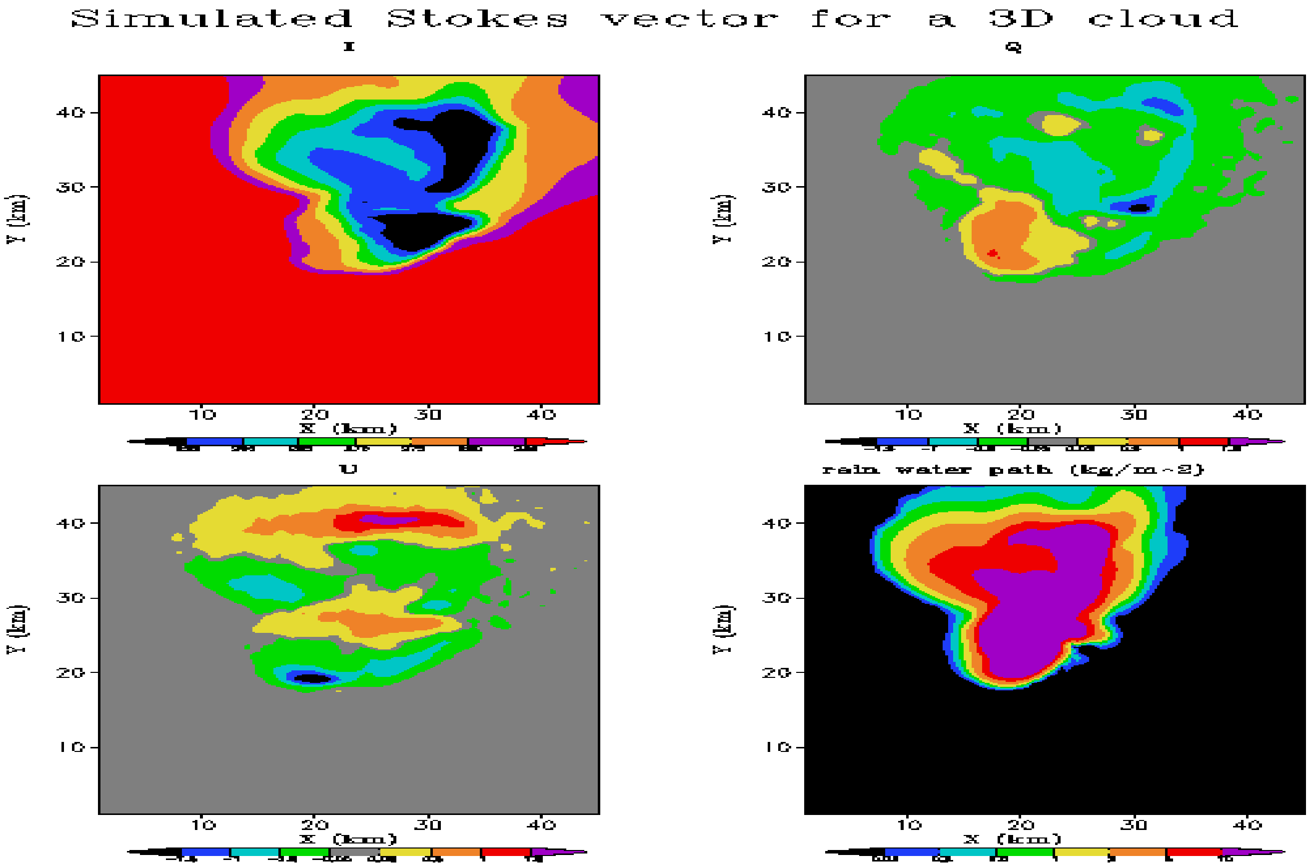
10.7_U



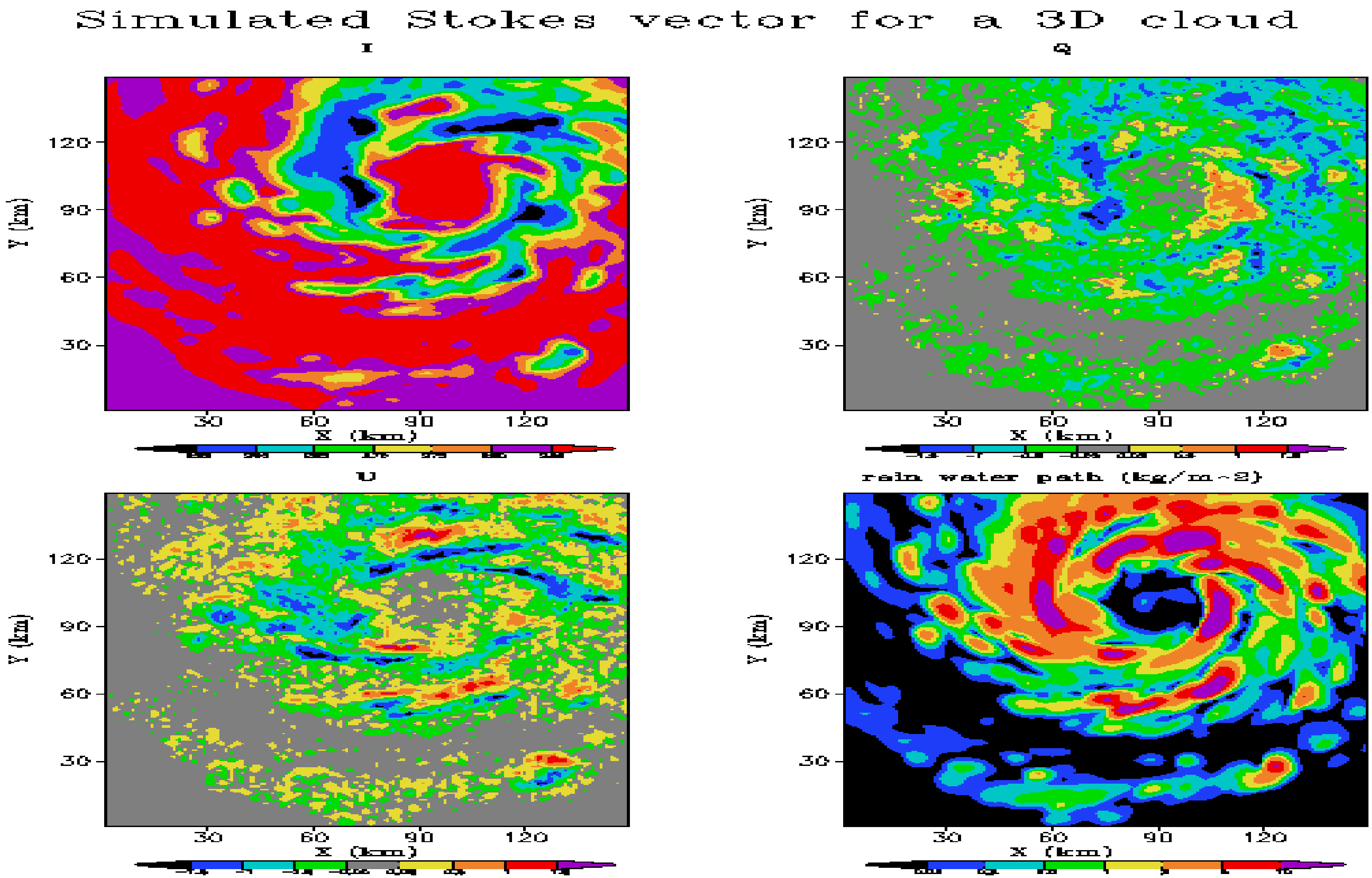
10.7_4



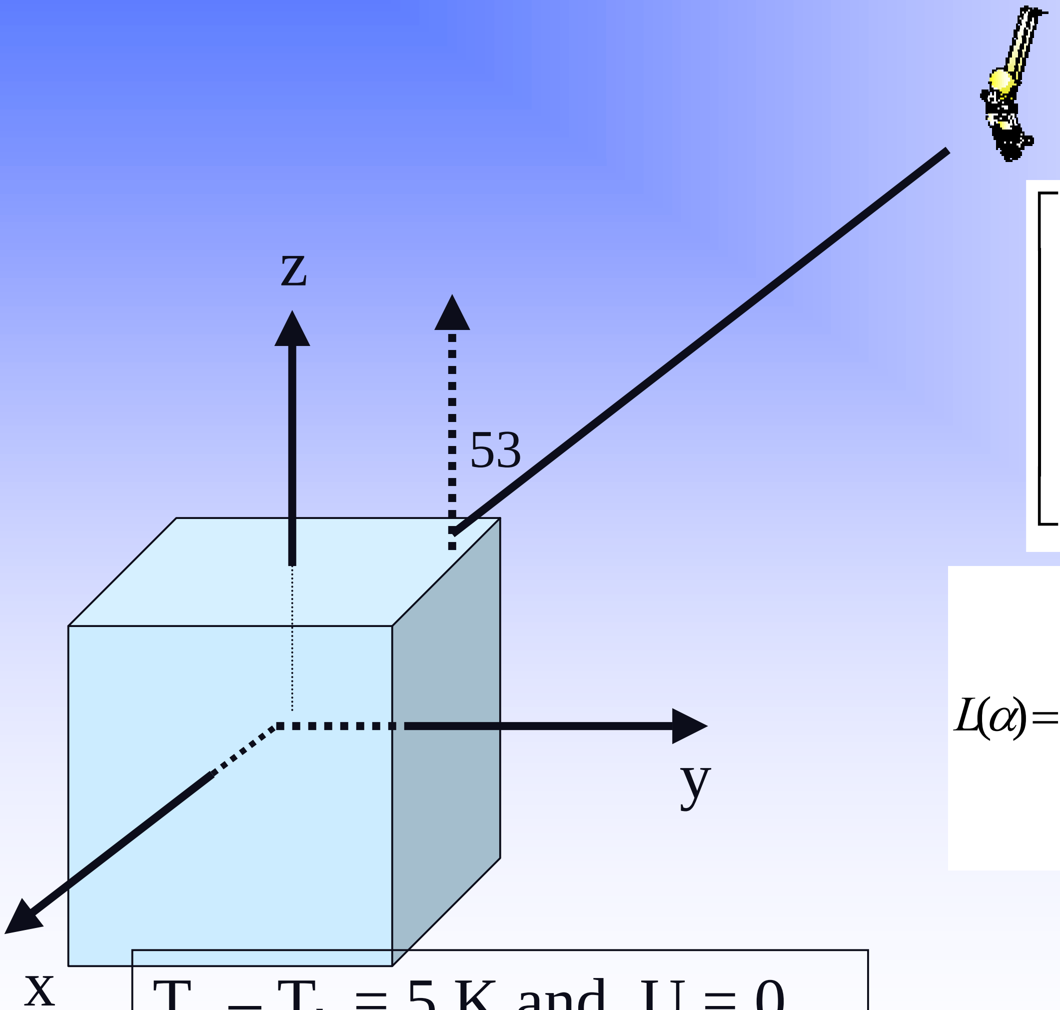
Polarimetric Signals from Clouds



3D Clouds Produce Third Stokes Component at 10.7 GHz



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



$$\begin{bmatrix} T_h \\ T_v \\ U \\ V \end{bmatrix}_{z-plan} = L(37^0) \begin{bmatrix} T_h \\ T_v \\ U \\ V \end{bmatrix}_{y-plan}$$

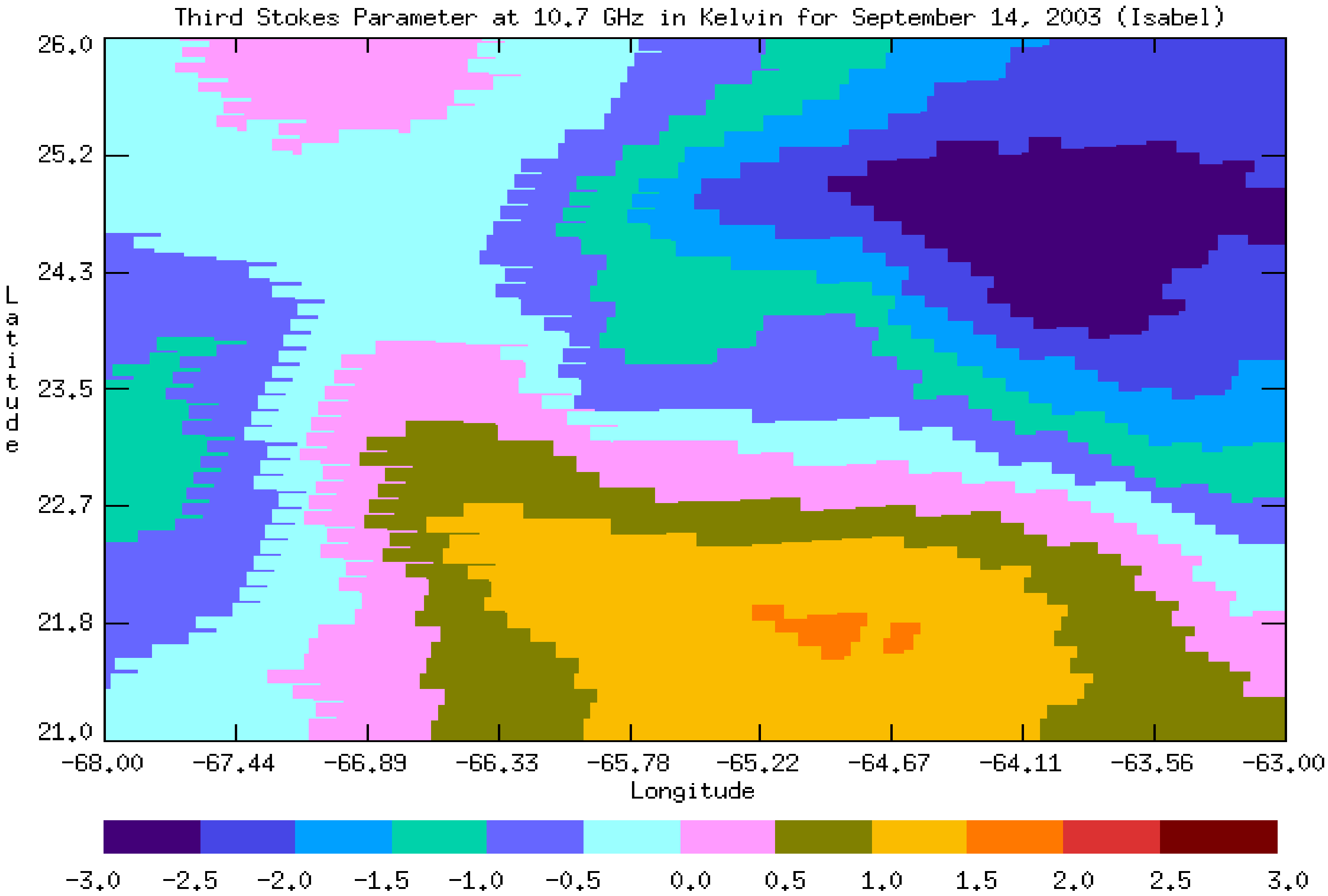
$$L(\alpha) = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & \sin\alpha\cos\alpha & 0 \\ \sin^2\alpha & \cos^2\alpha & -\sin\alpha\cos\alpha & 0 \\ -2\sin\alpha\cos\alpha & 2\sin\alpha\cos\alpha & \cos^2\alpha - \sin^2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$T_v – T_h$ = 5 K and U = 0, V= 0 in y-plan (53 degree)

➡

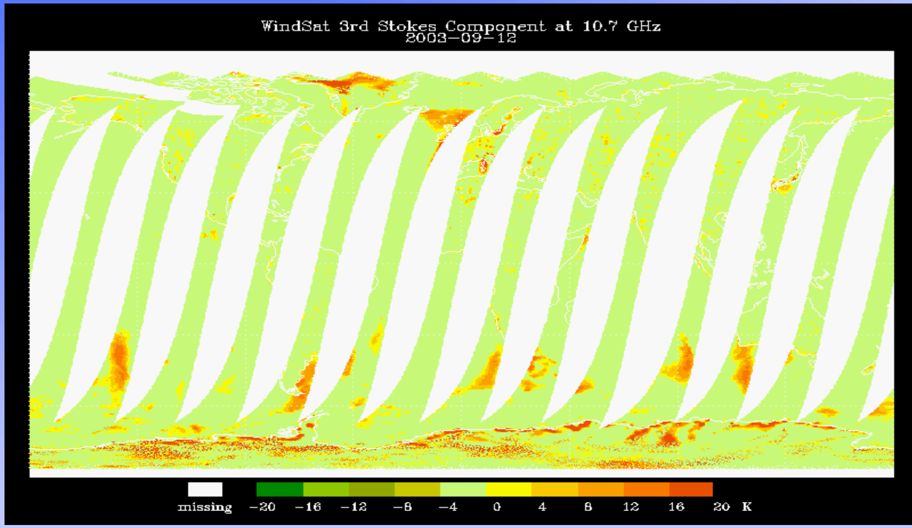
$T_v – T_h$ = 5 K and U = 4.8, V= 0 in z-plan

WindSat Measurements for Hurricane Isabel

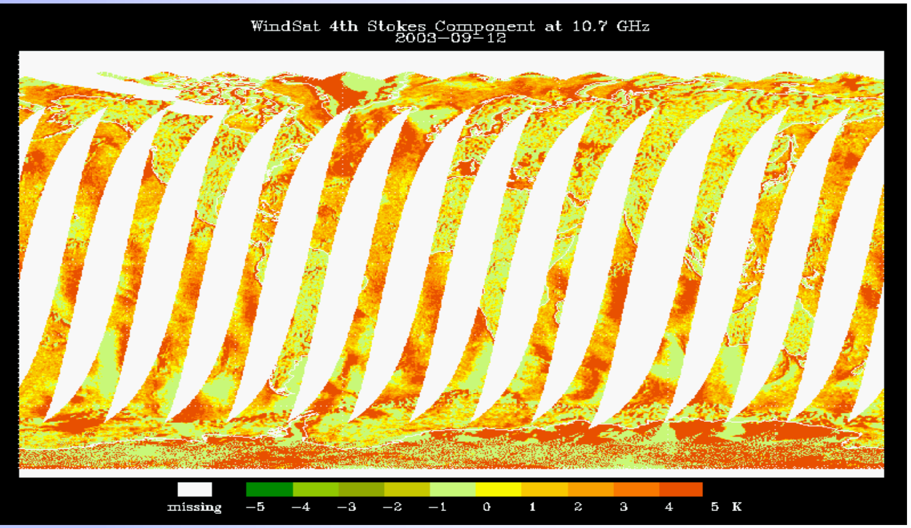


WindSat Measurements (3rd&4th Components)

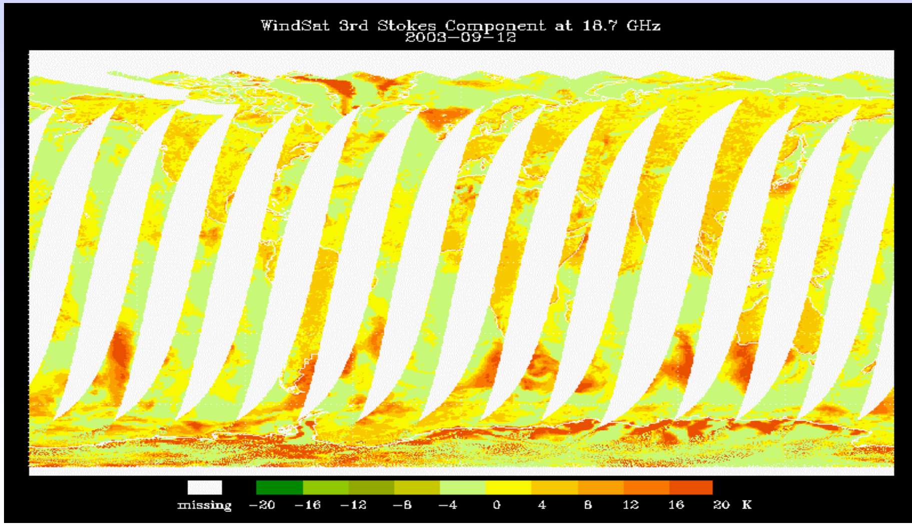
10.7 GHz TBU



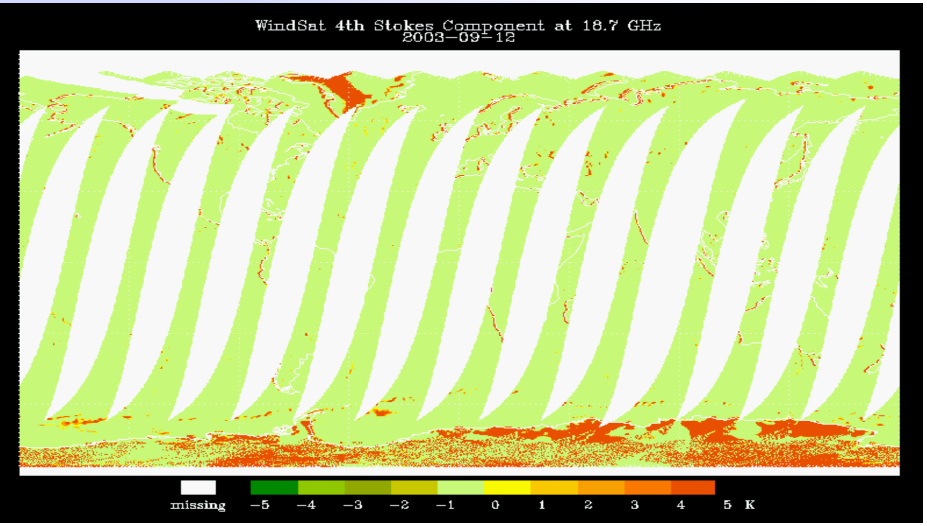
10.7 GHz TB4



18.7 GHz TBU

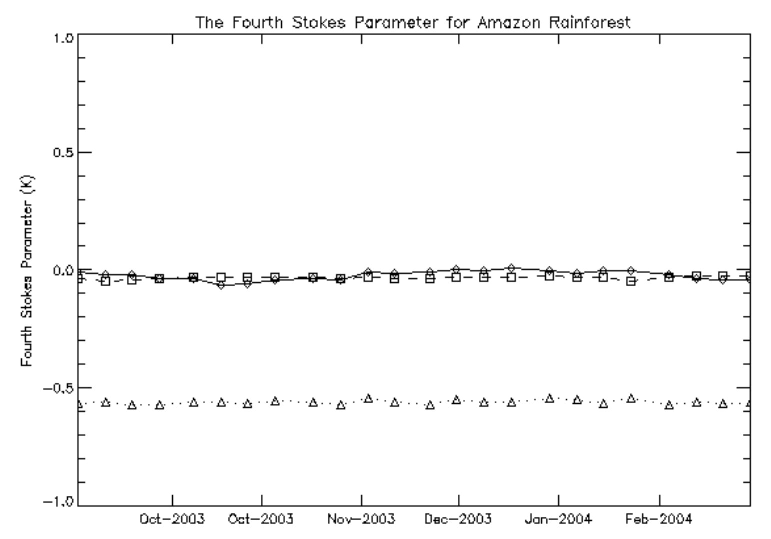


18.7 GHz TB4

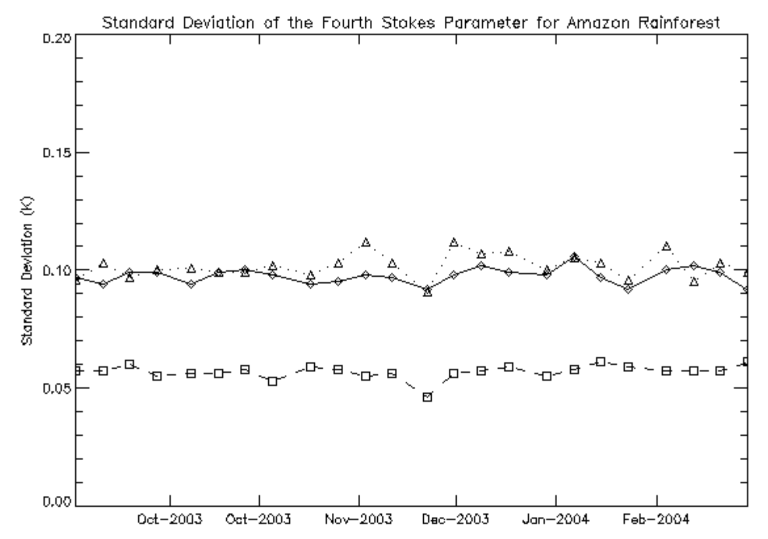


Vicarious Assessment of WindSat Measurements over Amazon

3rd Stokes component



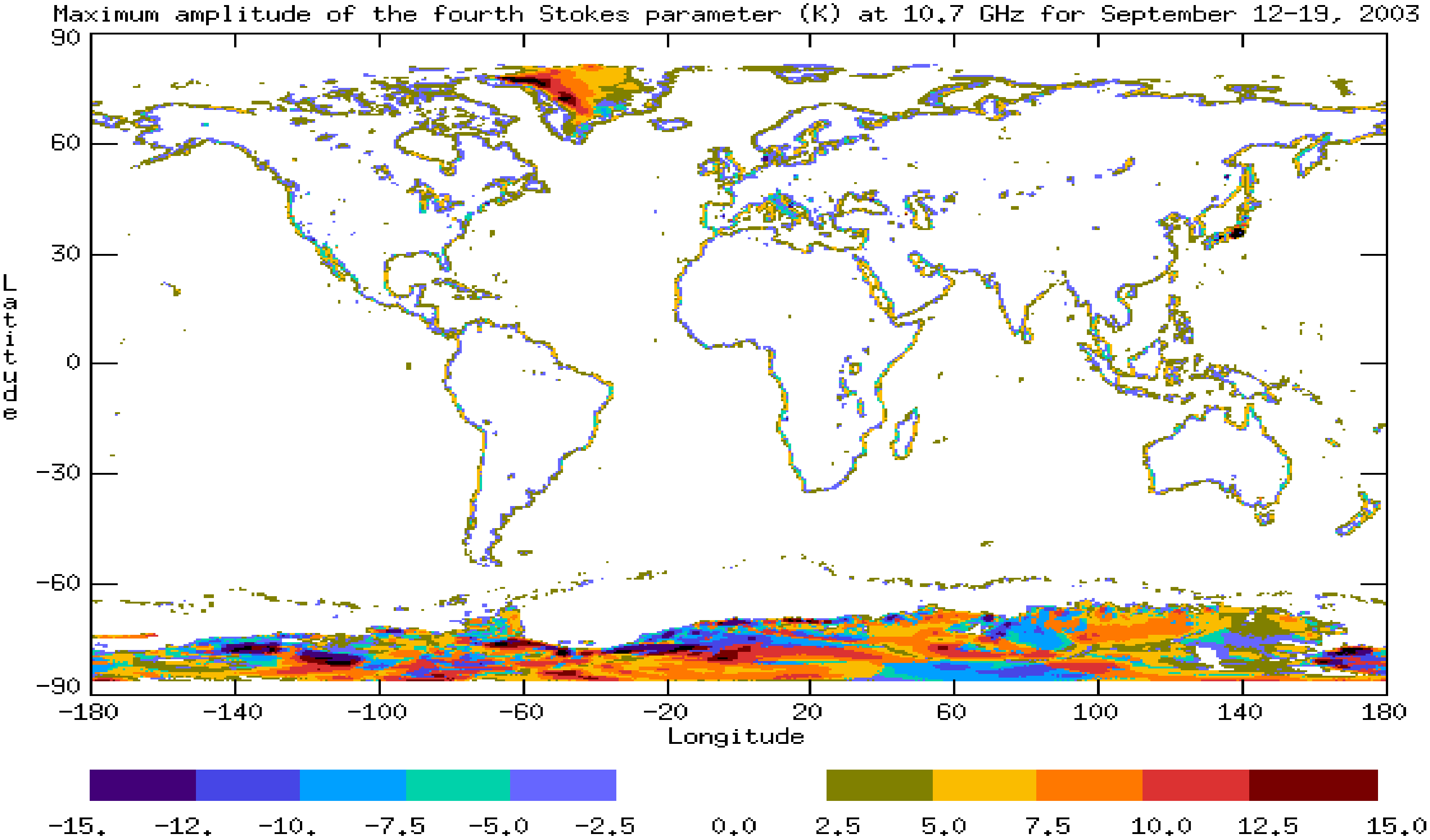
4th Stokes component



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 Radiavtive 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.

International TOVS Study Conference, 14th, ITSC-14, Beijing, China, 25-31 May 2005.
Madison, WI, University of Wisconsin-Madison, Space Science and Engineering Center,
Cooperative Institute for Meteorological Satellite Studies, 2005.