Prospects for All-Weather Microwave Radiance Assimilation

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Why Develop All-Weather Microwave Assimilation?

Potential capabilities include:

- Short-term prediction of mesoscale convection for warnings with high specificity
- Tracking of latent heat exchange within precipitation
- Improved accuracy of cloud and radiation products
- Extended thermodynamic information (water vapor and temperature fields) within frontal regions

Toward a Demonstration of GEM Radiance Assimilation

Maximum *a posteriori* estimation minimizes the following cost function *J* :

$$J=\left(x-x^{b}\right)B^{-1}\left(x-x^{b}\right)+\left(h\left[x\right]-y\right)^{T}R^{-1}\left(h\left[x\right]-y\right)$$

The basic linear solution:

$$x^{a}=x^{b}+\left[B^{-1}+H^{T}R^{-1}H\right]^{-1}H^{T}R^{-1}\left(y-h\left[x^{b}\right]\right)$$

Tangent linear approximation *H* for non linear observation operator *h* :

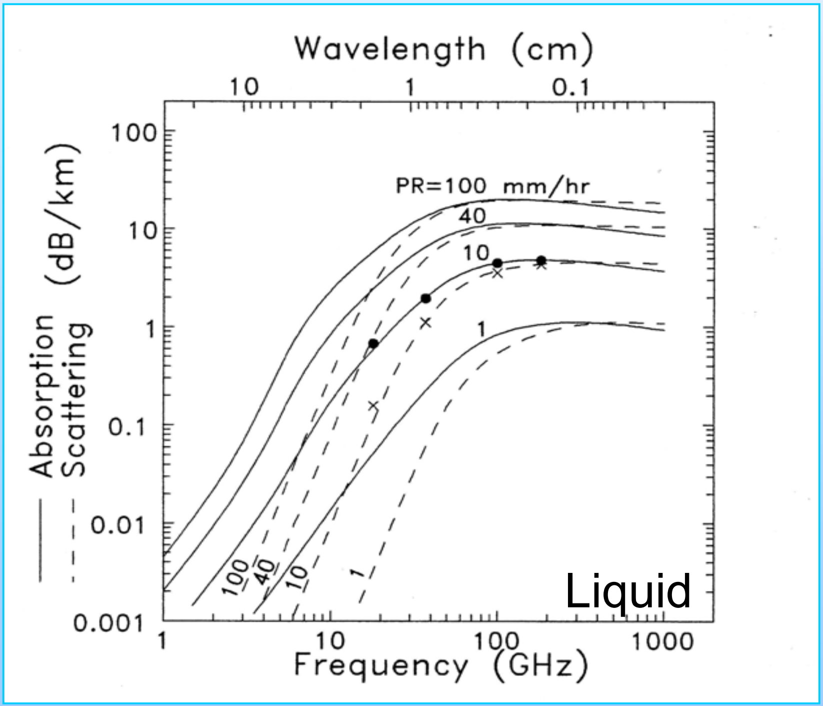
$$H=\frac{\partial h}{\partial x}$$

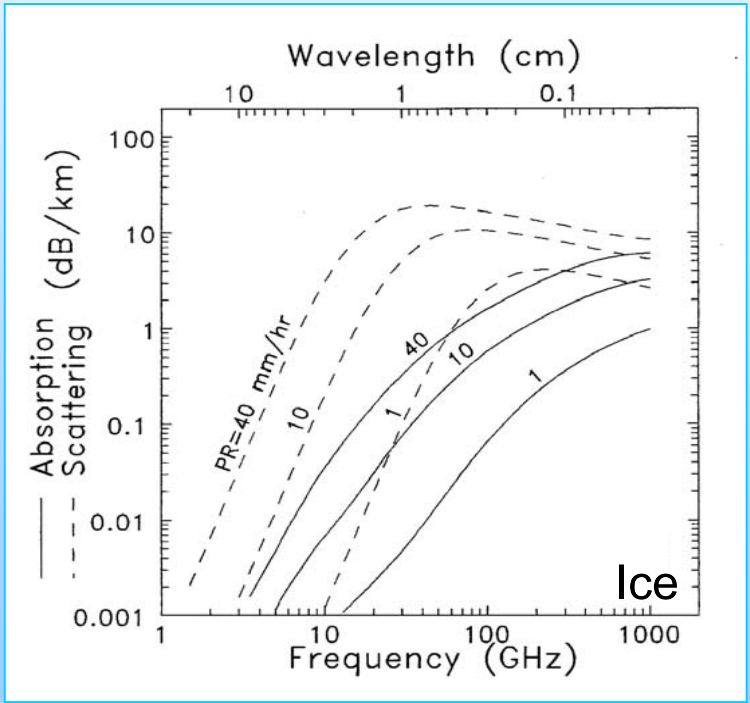
The state vector X can include precipitation distribution parameters e.g., 4 parameters per hydrometeor phase for a Gamma distribution, At 5 phases => up to 20 hydrometeor parameters at each level

Effects of Hydrometeors on Microwave Signatures

- Strong impact by raincells on signatures above ~50 GHz
- Scattering predominantly caused by frozen hydrometeors
- Signatures even for non-precipitating clouds at higher frequencies

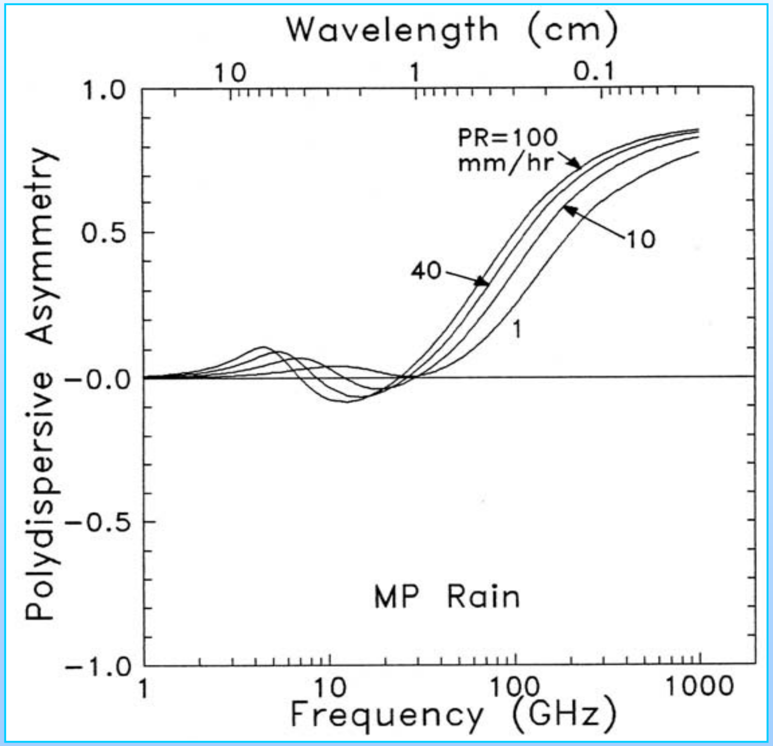
⇨ **Scattering and absorption by hydrometeors needs to be considered in radiance assimilation both to extend soundings into cloudy regions and couple models to raincell occurrence.**

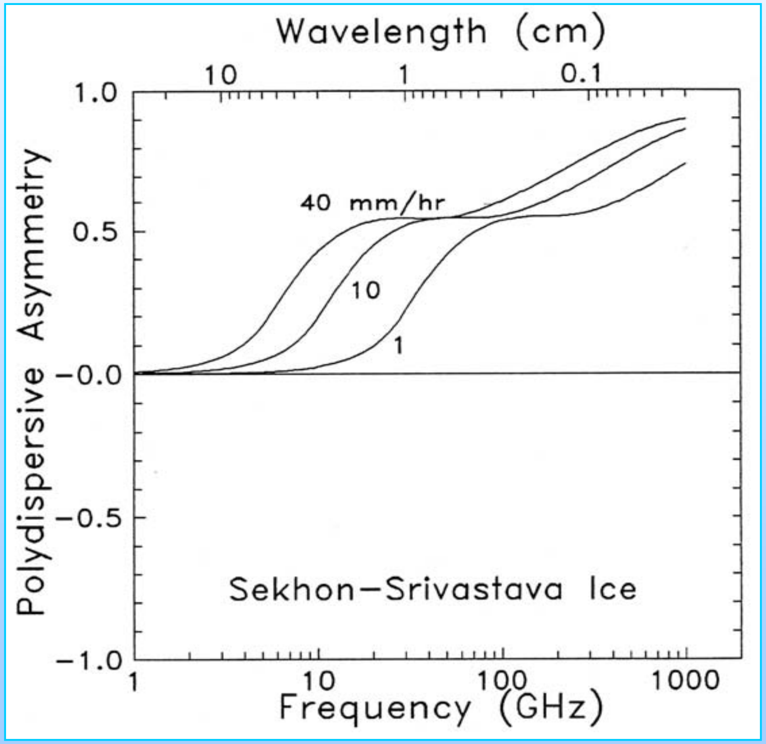




Effects of Hydrometeor Scattering on Microwave Signatures

- Scattering asymmetry and phase matrix determine angular redistribution of radiance
- Scattering asymmetry parameters varies significantly over frequency and size distribution parameter space

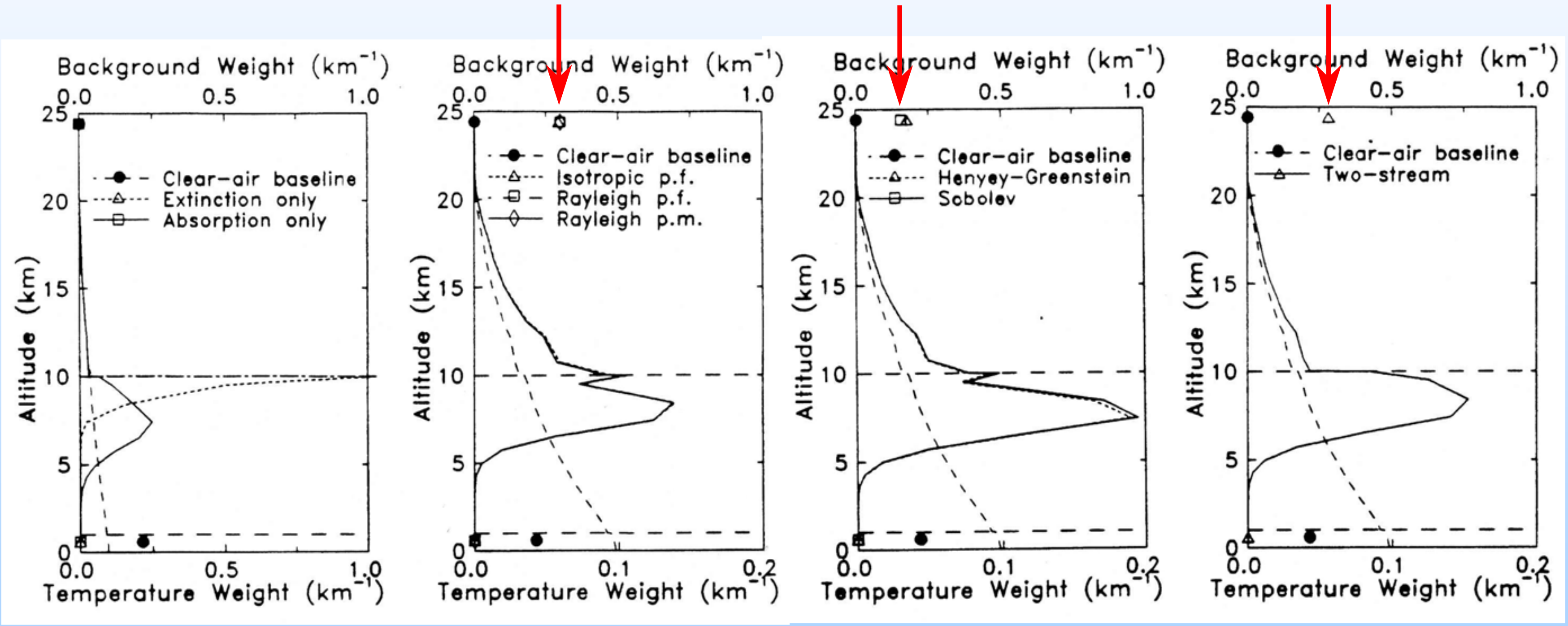




(Janssen, Ch 3, 1992)

Effects of Hydrometeor Scattering on Microwave Signatures (cont'd)

- Accuracy of phase matrix approximations impacts raincell top albedo
- Neglect of multiple streams radiance (i.e., two-stream model) overestimates raincell albedo



Multiple streams of radiance with an appropriate phase matrix approximation need to be incorporated in forward RT models.

Fast Scattering-based Jacobian Technique

- Planar stratified atmosphere
- Liebe MPM 87 & 93 gaseous absorption model
- Polydispersive Mie solution for five phase of water:
  - Cloud (liquid)
  - Rain (liquid)
  - Graupel (liquid/frozen mixture)
  - Snow (frozen)
  - Cloud Ice (frozen)
- Henyey-Greenstein hydrometeor phase matrix
- Discrete-ordinate layer-adding solution
- Incremental response to changes in bulk absorption and scattering coefficients and temperature
- Efficiency compatible with satellite data streams
- Applicable for arbitrary wavelengths

Practical Implications
(Radiation Jacobian)

# Layers	# Streams	CPU Rate (GHz)	Calculation Time (ms)
60	8	1.8	4.2

Recourses:

1. Further simplified treatment of non-scattering layers (acceleration factor ~ 2-3x)
2. Parallel processing 2.8 GHz 100-nodes (acceleration ~ 200x)
3. Statistical: ~10% scattering cloud cover (acceleration ~10x)

=> **~1 usec** per channel-profile (anticipated)

NPOESS CMIS data rate: ~30 channels every ~12 msec

=> **~400 usec** per channel-profile

Algorithm Complexity & Scaling

Product:	T_B	$\frac{\partial T_B}{\partial \beta_i}$
Number of operations:	$\sim N \cdot M^3$	$\sim (3 \div 5) N \cdot M^3$

N = Number of layers   M = Number of streams

Voronovich, A., A.J. Gasiewski, and B.L. Weber, "A Fast Multistream Scattering-Based Jacobian for Microwave Radiance Assimilation," submitted for publication in *IEEE Trans. Geosci. Remote Sensing*, October 2003.

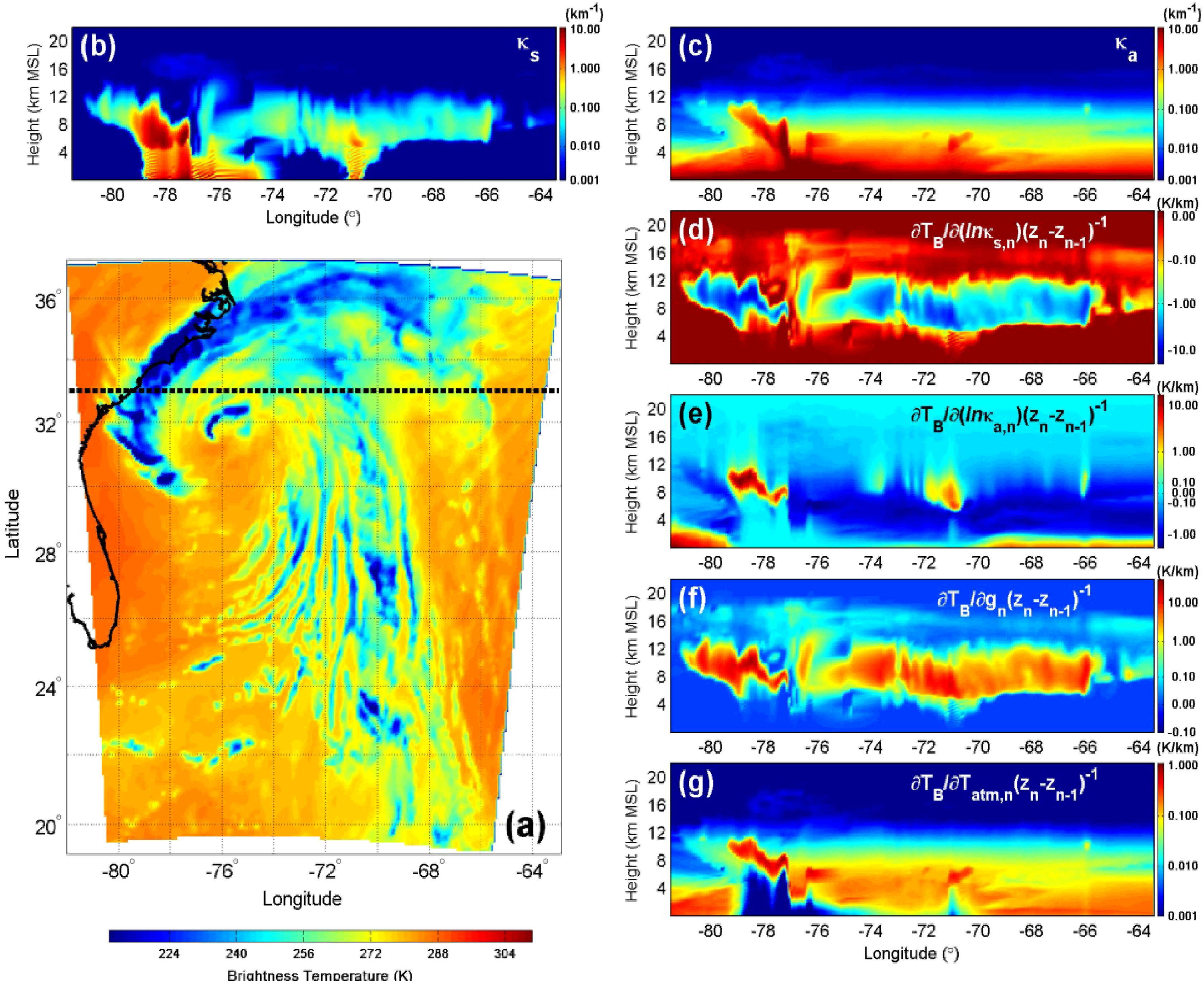
NWP Precipitation Dynamics

- 24-Hr simulation for 166 GHz
- Hurricane Bonnie, August 26, 1998, 0000-1130 UTC
- MM5/MRT Reisner 5-phase simulations with 6-km innermost nested grid
- Fast DO Radiative Jacobian with 60 vertical levels
- Jacobian cross-sections for 33^o latitude slices
- 15-minute time increments

MM5/DO Hurricane Bonnie 183.3101 - 17GHz 26 August 1998 00:15 UTC

φ_s

T_B



φ_a

$\frac{\partial T_B}{\partial \varphi_S}$

$\frac{\partial T_B}{\partial \varphi_A}$

$\frac{\partial T_B}{\partial g}$

$\frac{\partial T_B}{\partial T}$

NWP Precipitation “Locking”

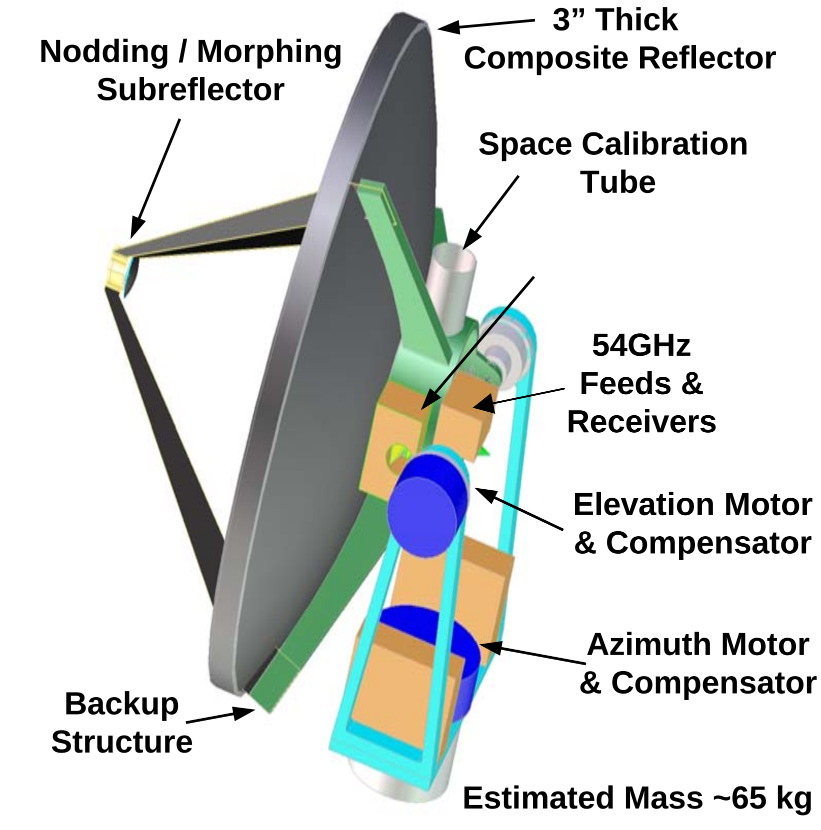
- To realize “locking” of an NWP model onto precipitation, observations are needed at time and space scales of order ~5-15 km and ~15 minutes.
- Locking is analogous to phase-locked loop in electrical engineering wherein linear phase differencing is achieved only when oscillator and signal remain within same phase cycle.
- Similarly, linear NWP model updates can be achieved providede that the cloud and precipitation state does not decorrelate between satellite observations.

The sampling needs for all-weather microwave assimilation using near-term NWP models (especially regional models) are well satisfied by a large-aperture geosynchronous microwave sounder.

GMSWG* Concept Summary

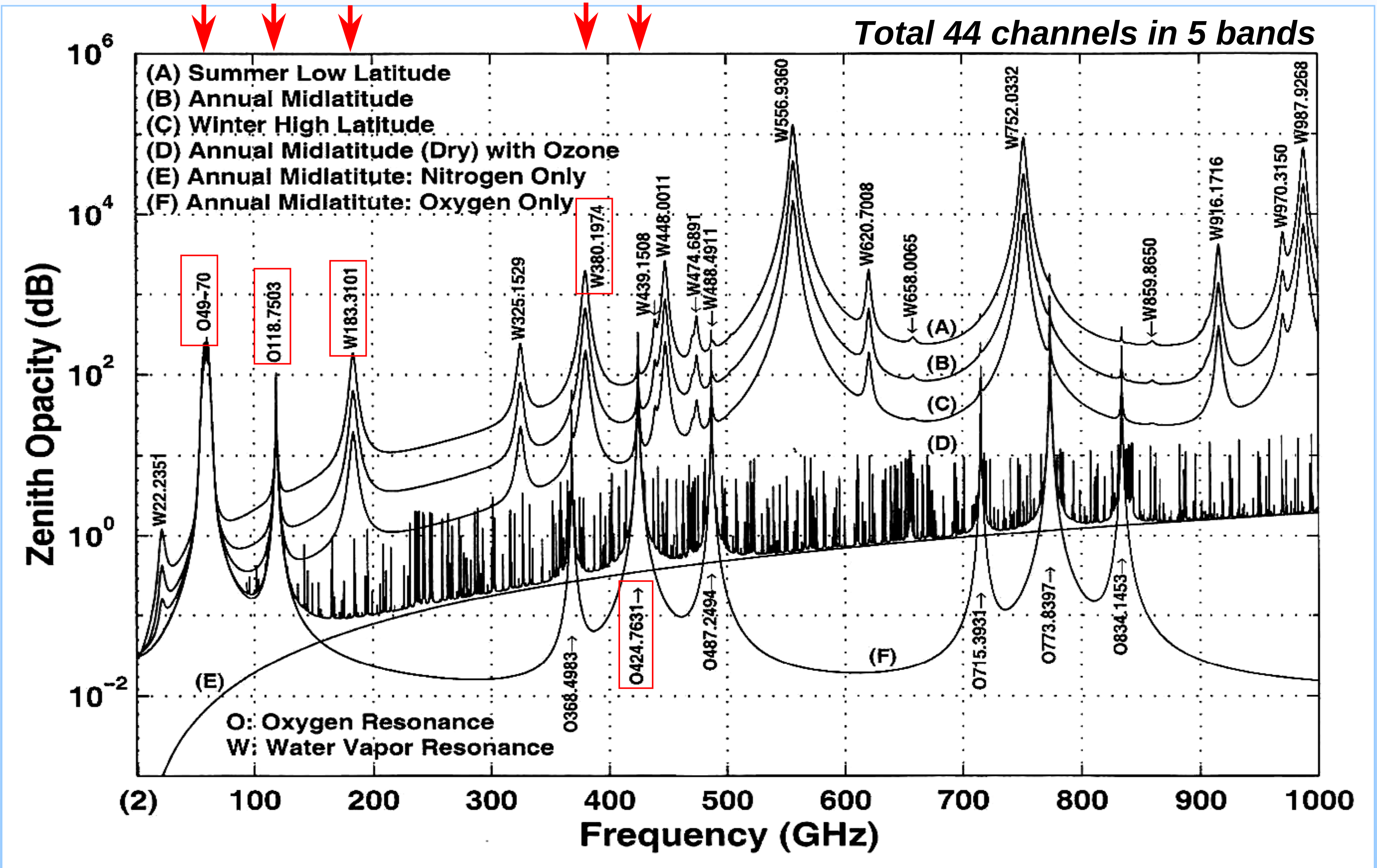
GEosynchronous Microwave (GEM) Sensor

- Baseline system using 54, 118, 183, 380, and 424 GHz with ~2 m diameter Cassegrain antenna.
- ~16 km subsatellite resolution (~12 km using oversampling) above 2-5 km altitude at highest frequency channels.
- The 380 and 424 GHz channels selected to map precipitation through most optically opaque clouds at sub-hourly intervals. (Gasiewski, 1992)
- Temperature and humidity sounding channels penetrate clouds sufficiently to drive NWP models with hourly data.
- Estimated 2004 costs: $34M non-recurring plus ~$32M/unit.



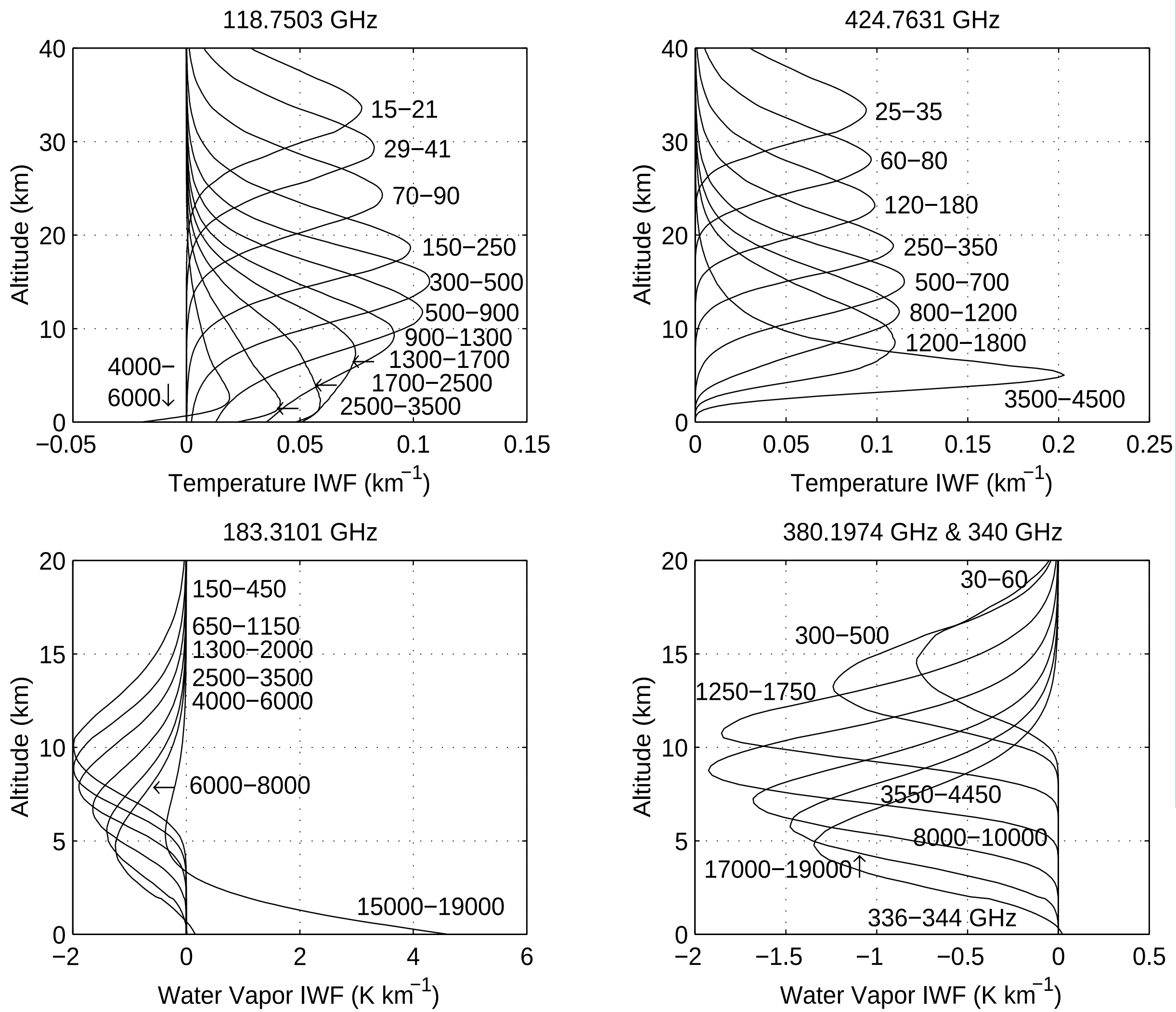
** Geosynchronous Microwave Sounder Working Group, Chair: D.H. Staelin (MIT)*

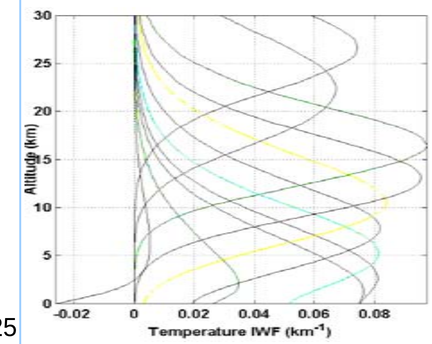
GEM Spectral Selection



GEM Vertical Response

- Clear Air -



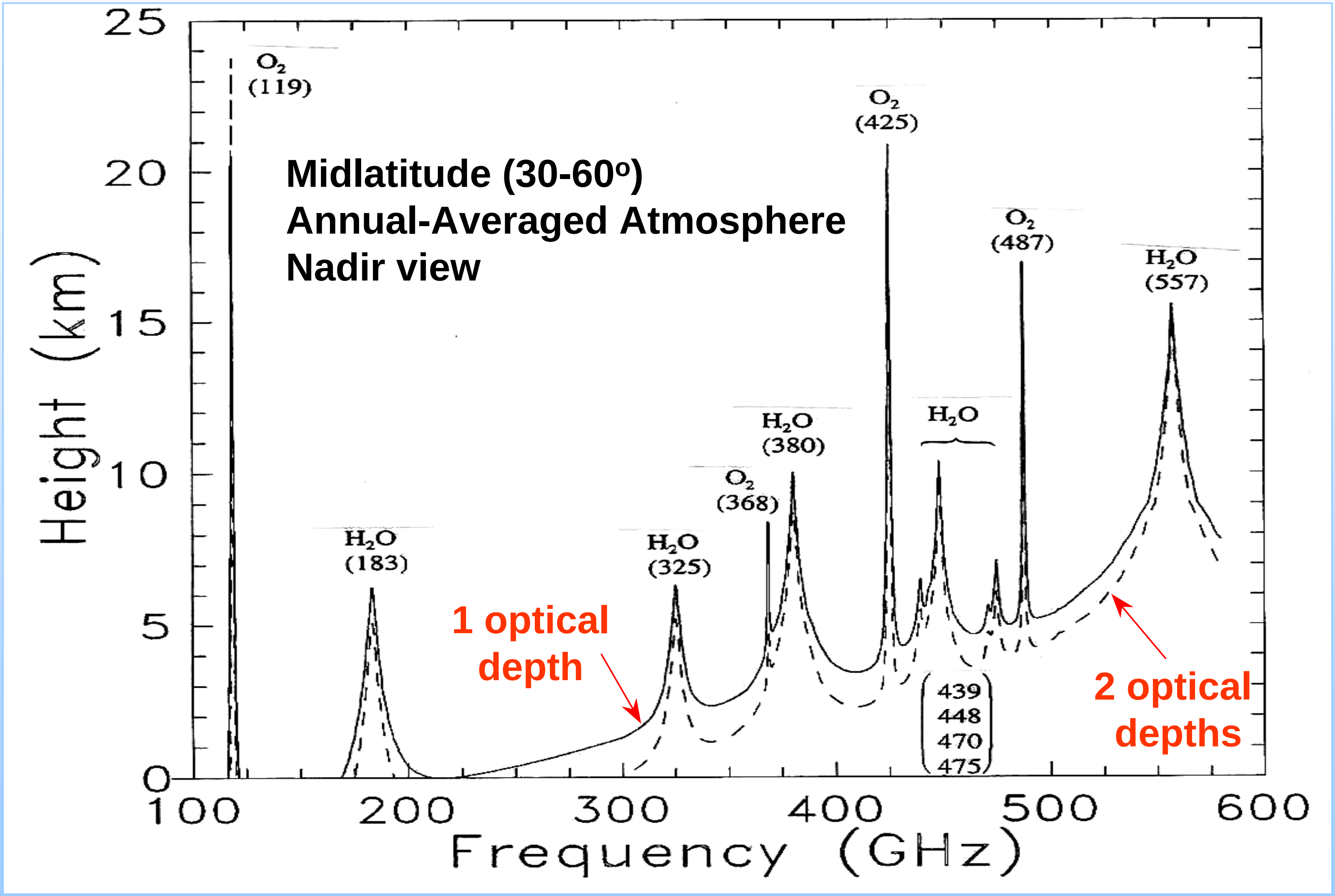


AMSU
5-MM

Klein & Gasiewski,
JGR-ATM,
July 2000

GEM Probing Depths

- Clear Air -



GEM Sensitivity & Scan Mode

- **<u>Regional</u> (1500 x 1500 km^2) : ~15 minutes**

Band (GHz)	3-dB IFOV (km, SSP)	Deconvolved Resolution (km, SSP)	ΔT_{RMS} (K)	ΔT_{RMS} Required (K,SNR=100)
50-56	138.6	~104	0.04-0.1	0.1-0.6
118.705	60.2	~45	0.07-0.9 ~	0.1-0.6
183.310	41.9	~31	0.06-0.2	0.3-0.6
380.153	20.5	~16	0.03-3.4 *	0.3-0.5
424.763	16.4	~12	1.0-9.5 *	0.4-0.6

Assumptions:

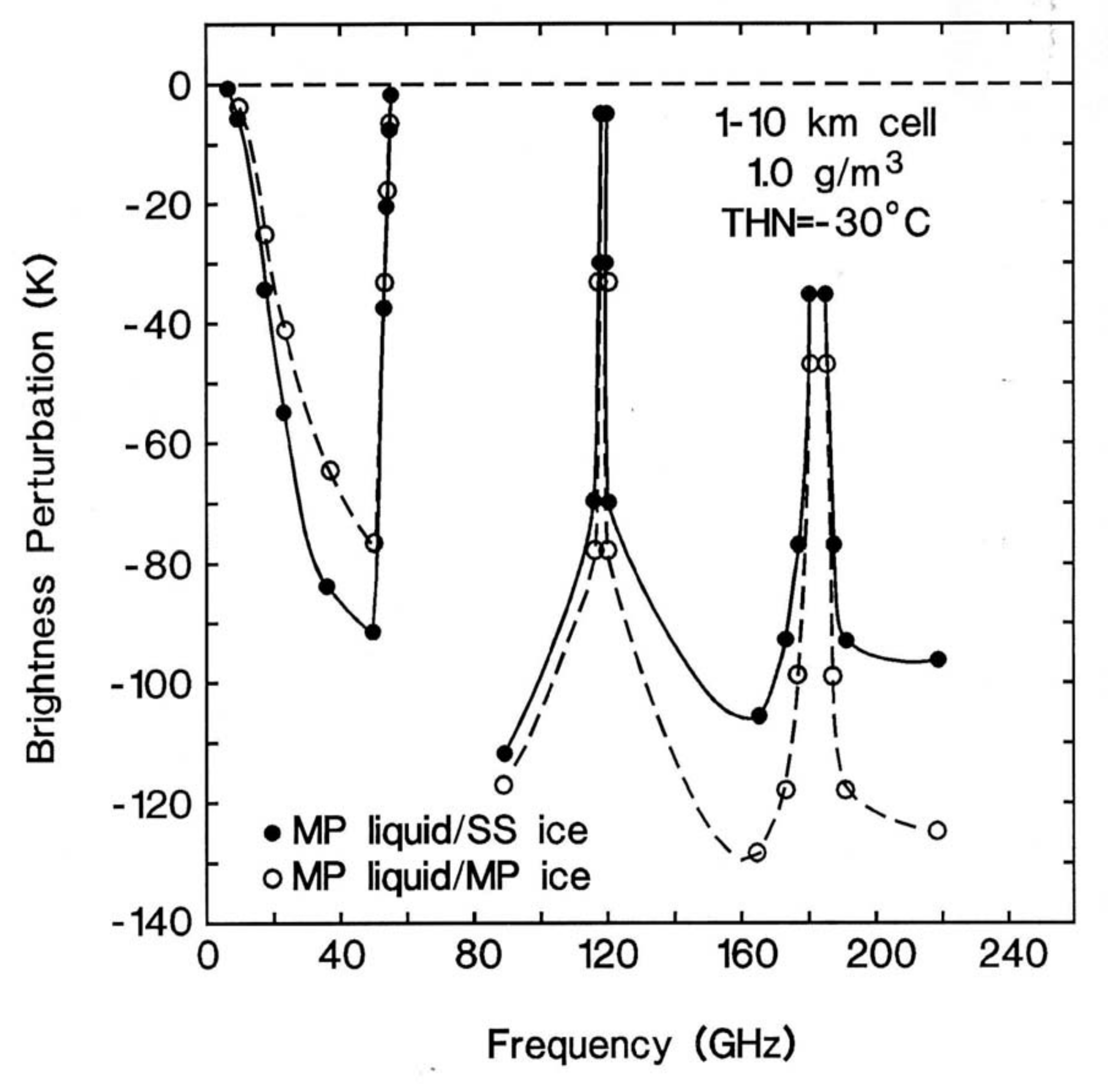
- **Averaging (downsampling) of beams to fundamental deconvolved resolution.**
- *** Further reductions in ΔT_{RMS} achievable via additional downsampling and/or time averaging.**

- **<u>CONUS</u> imaging time (3000 x 5000 km^2) : 90 minutes**

Downlink rate ~45 kb/sec at ~17 msec sample period

SMMW Spectral Modes

RT Model Calculations



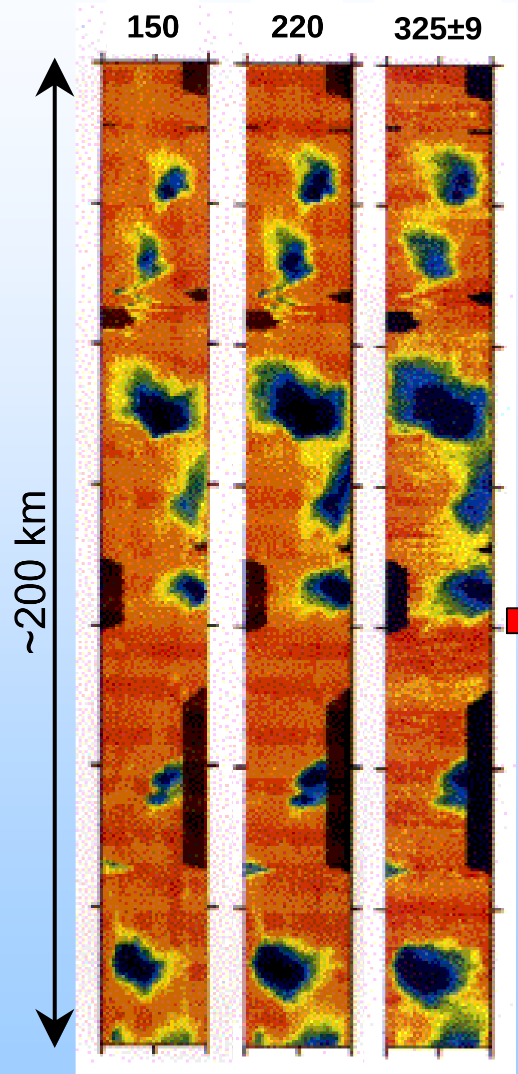
Iterative Model Calculations Over Convection

Effect of Ice Particle Size Distributions

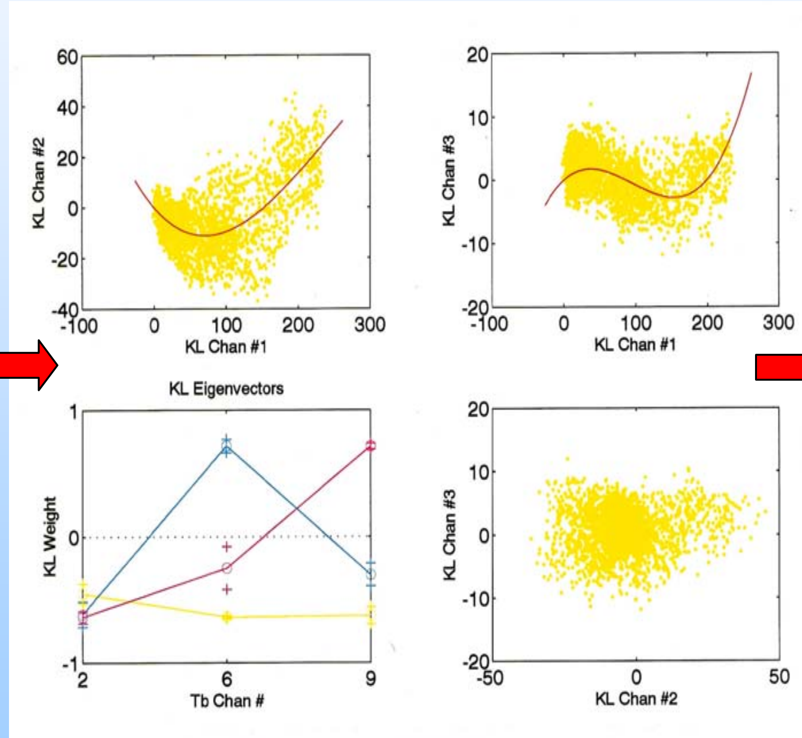
Gasiewski, *TGARS* September 1992

SMMW Degrees of Freedom

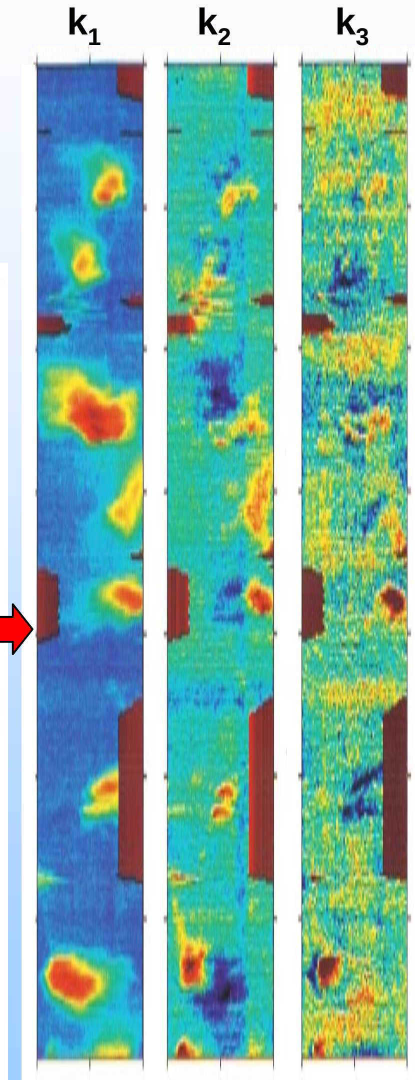
- Maritime Convective Precipitation -



Nonlinear Karhunen-Loeve (KL) mode decomposition: MIR 150, 220, & 325±9 GHz channels

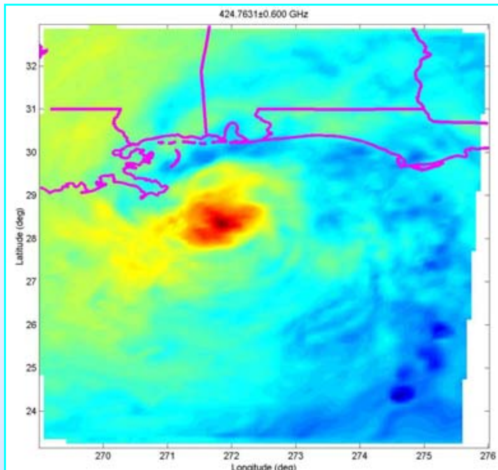


(Gasiewski 1996, unpublished)

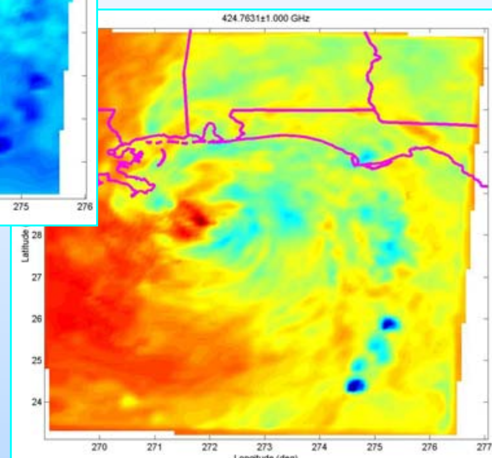


GEM Simulated Imagery

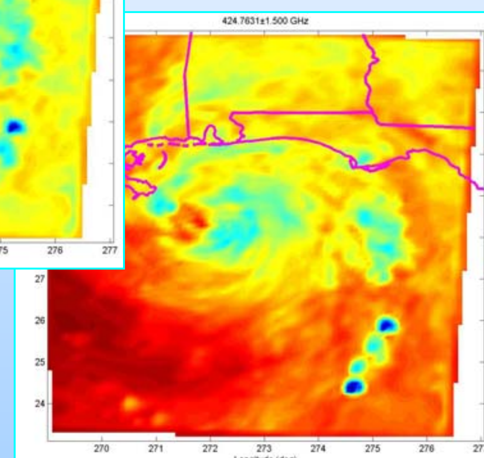
Spectral Response



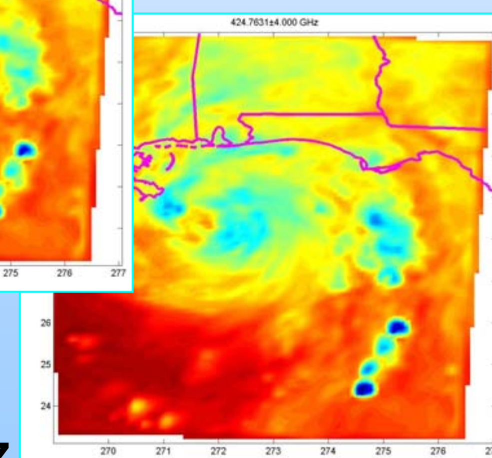
+/-0.6 GHz



+/-1.0 GHz



+/-1.5 GHz



424.763+/-4.0 GHz

Opaque ↔ **Transparent**

Hurricane Opal 1995

MM5/MRT
Reisner 5-phase

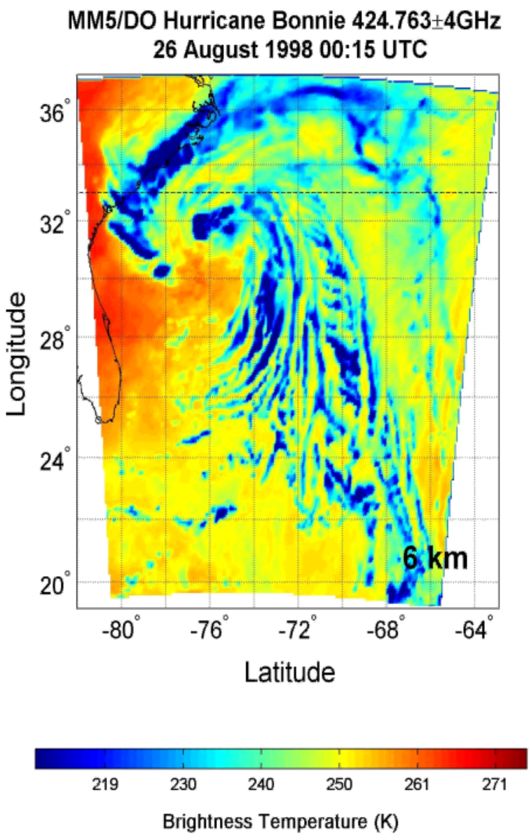
GEM Response to Precipitation

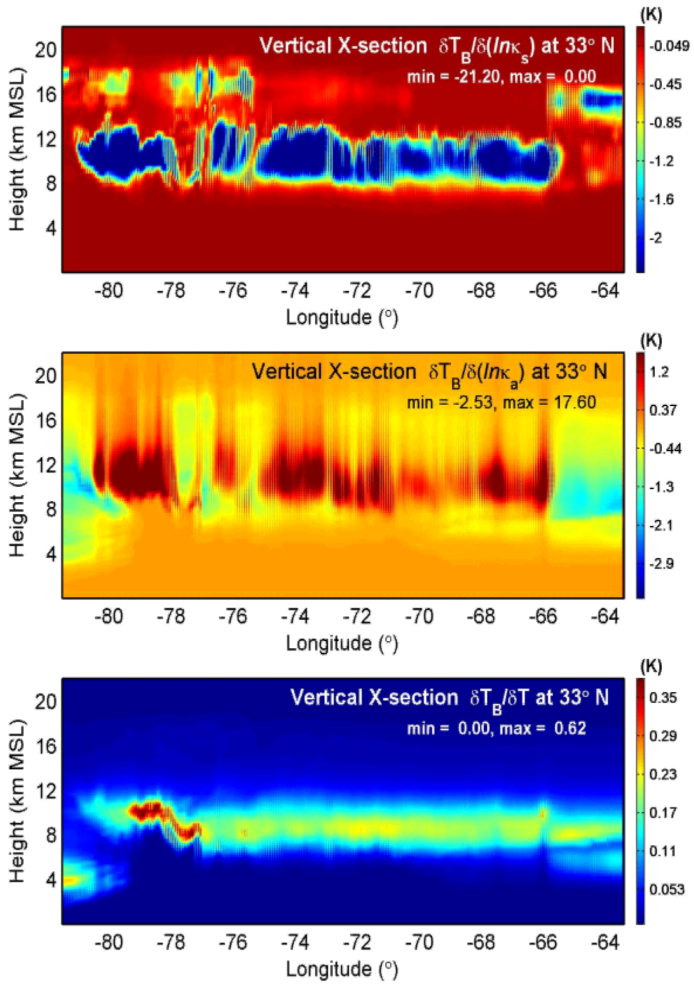
- Simulation of 183±17 GHz and 424.763±4 GHz channels
- Hurricane Bonnie, August 26, 1998, 0900 UTC
- MM5/MRT Reisner 5-phase simulations with 6-km innermost nested grid
- Fast DO Radiative Jacobian with 50 vertical levels
- Jacobian cross-sections shown for 33^{o} latitude slices
- 15 minute and 3 hour time intervals

MM5 24-Hr Simulation of GEM Imagery

Hurricane Bonnie   August 26, 1998   424±4 GHz

15 min time steps





$$\frac{\partial T_B}{\partial \alpha_S}$$

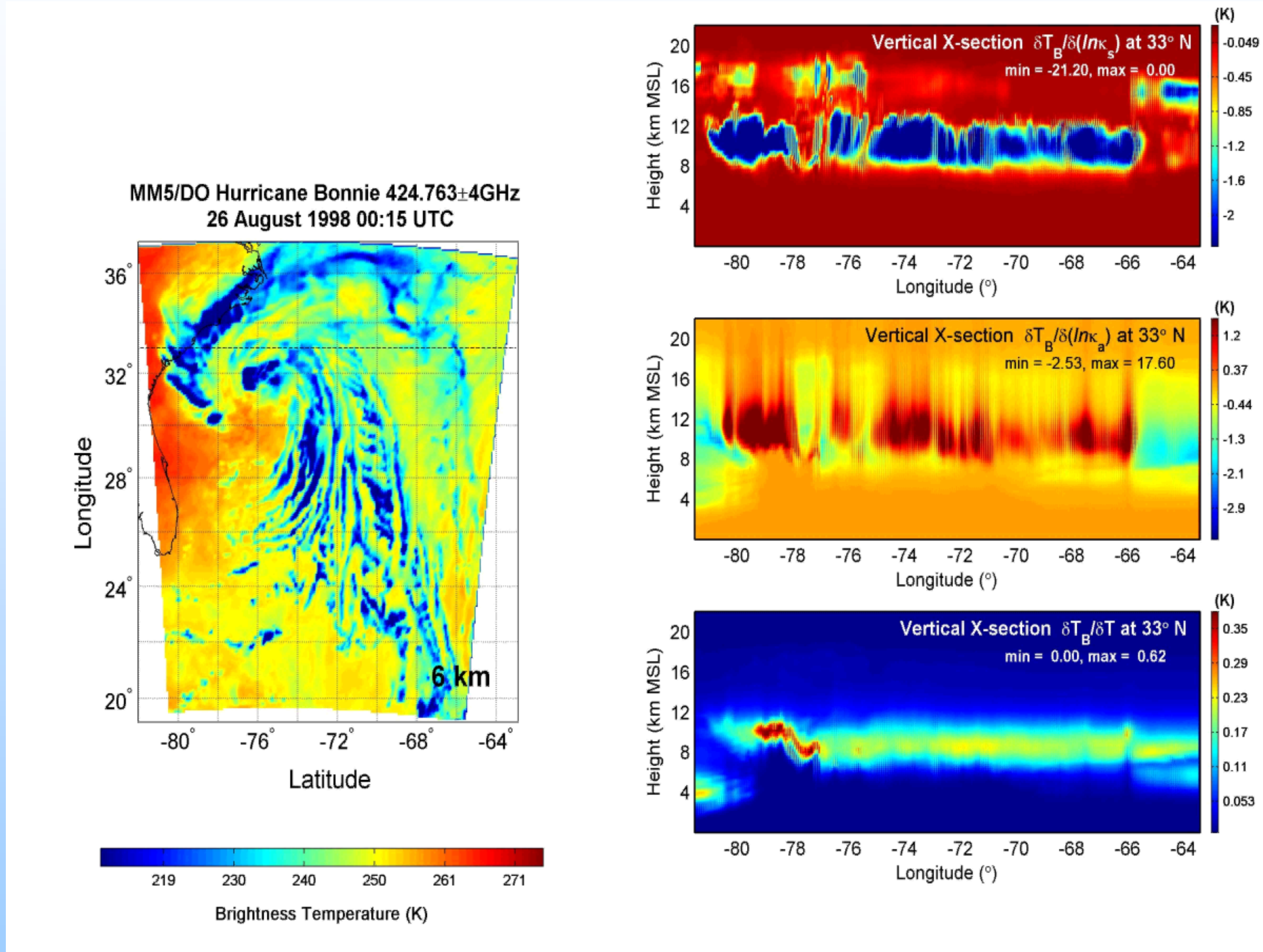
$$\frac{\partial T_B}{\partial \alpha_A}$$

$$\frac{\partial T_B}{\partial T}$$

MM5 24-Hr Simulation of GEM Imagery

Hurricane Bonnie   August 26, 1998   424±4 GHz

3 hour time steps



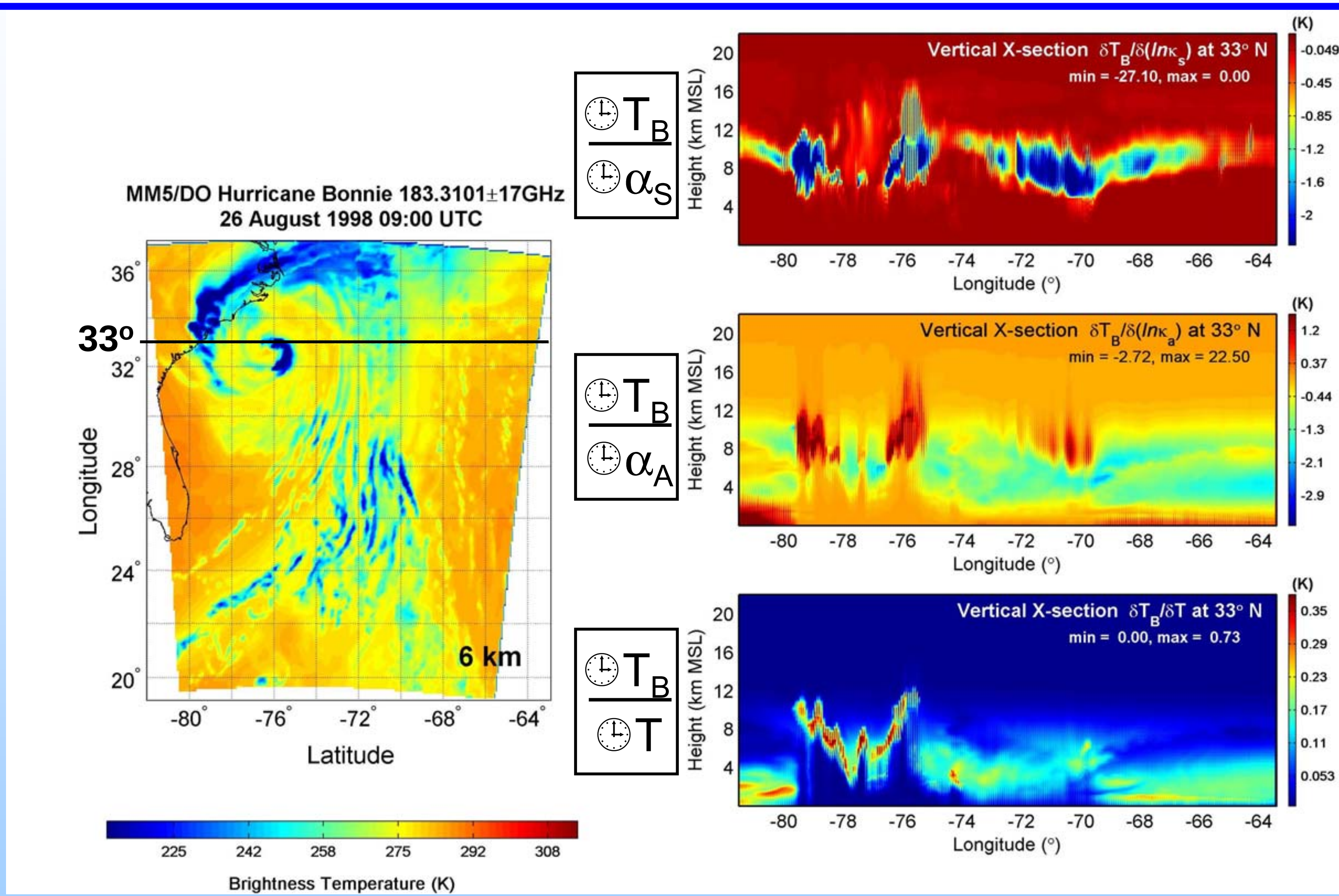
$\frac{T_B}{\alpha_S}$

$\frac{T_B}{\alpha_A}$

$\frac{T_B}{T}$

GEM Response to Precipitation

Jacobian Cross-sections at 183±17 GHz

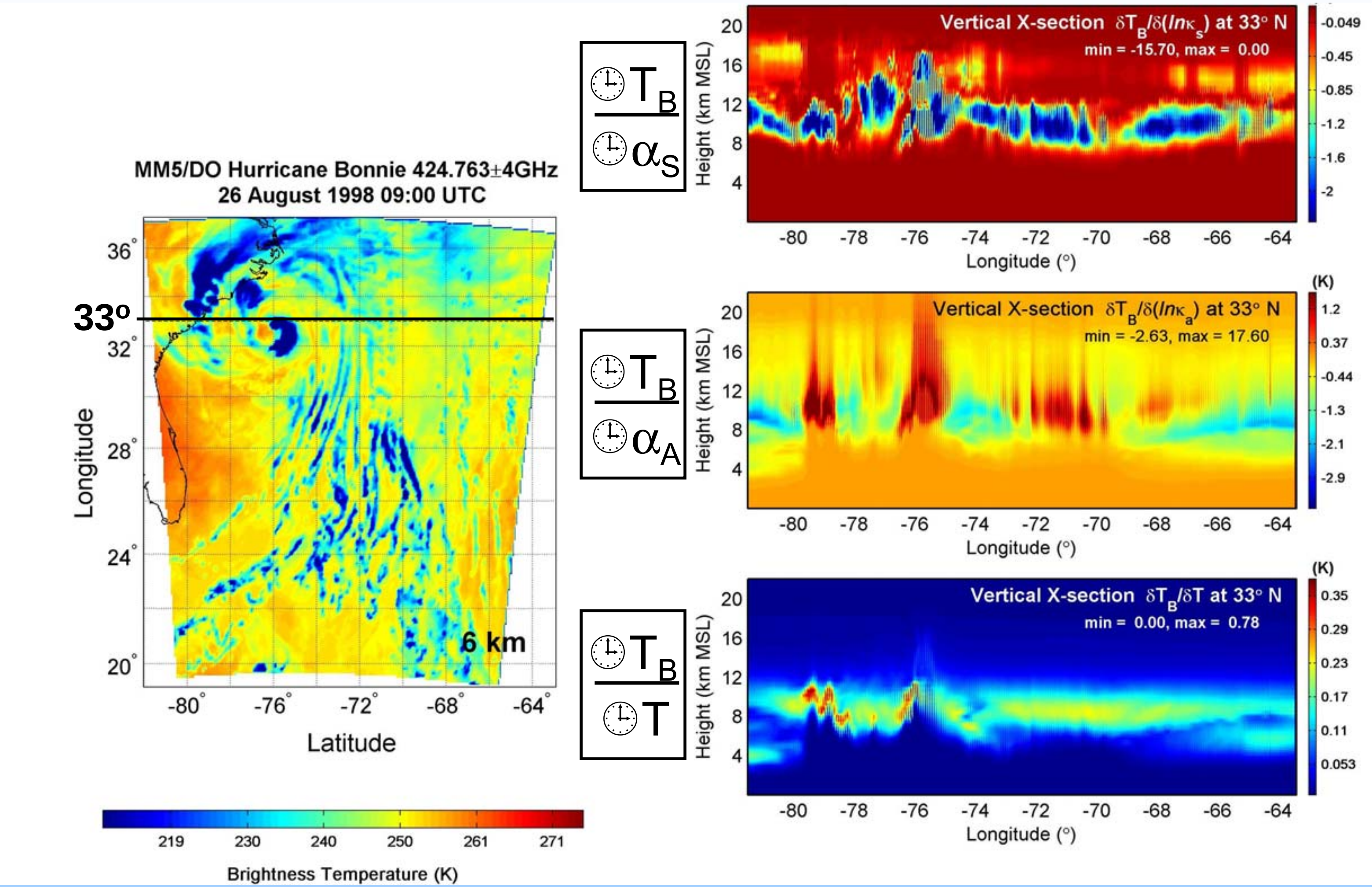


Hurricane Bonnie, August 26, 1998, 0900 UTC

MM5/MRT Reisner 5-phase with DO RT model at 183.310 ± 17 GHz

GEM Response to Precipitation

Jacobian Cross-sections at 424±4 GHz

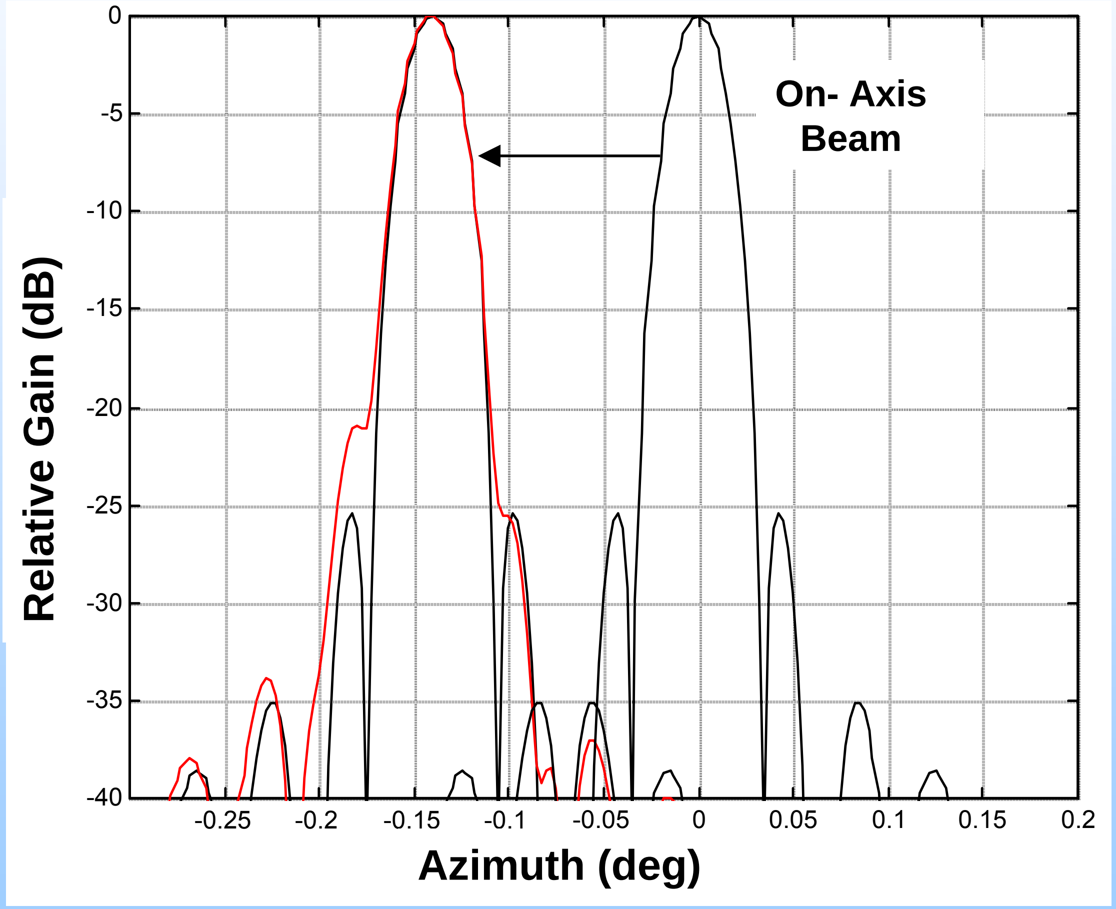


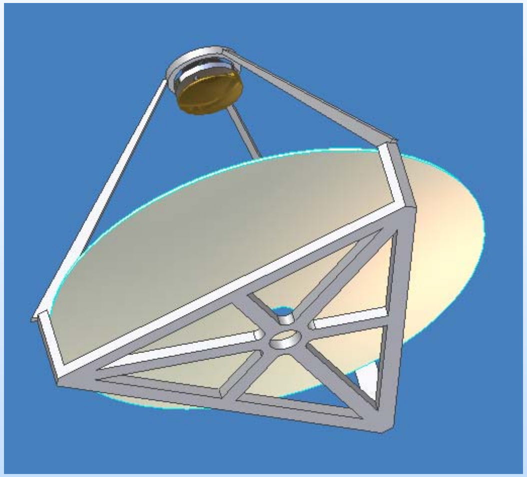
Hurricane Bonnie, August 26, 1998, 0900 UTC
MM5/MRT Reisner 5-phase with DO RT model at 424.763 ± 4 GHz

GEM Antenna Studies

Main Beam Microscanning

5 beam scan (0.14º) at 424 GHz from tilting/decentering subreflector and 2-m reflector (MIT/Lincoln Labs)

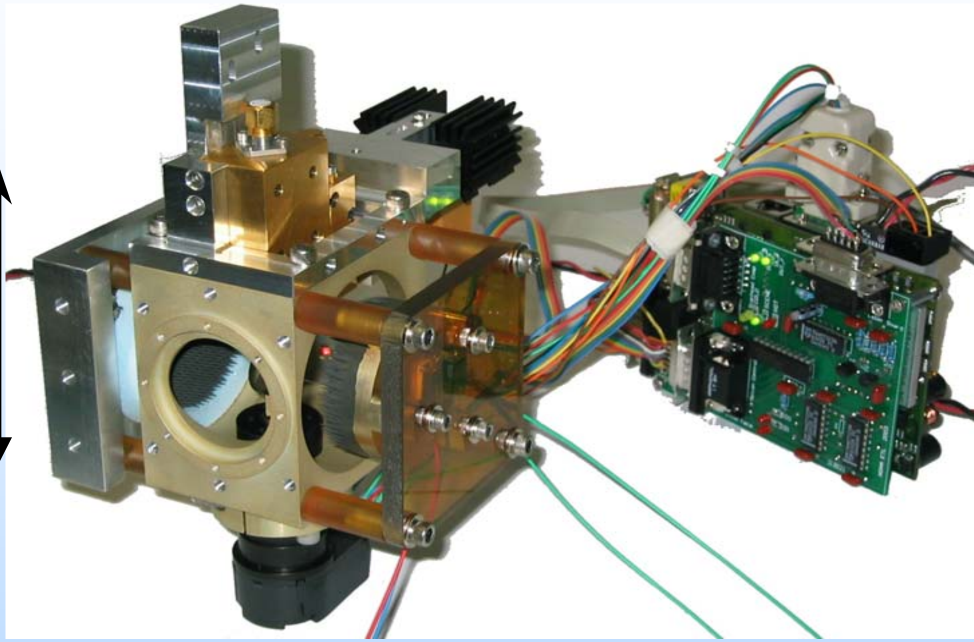


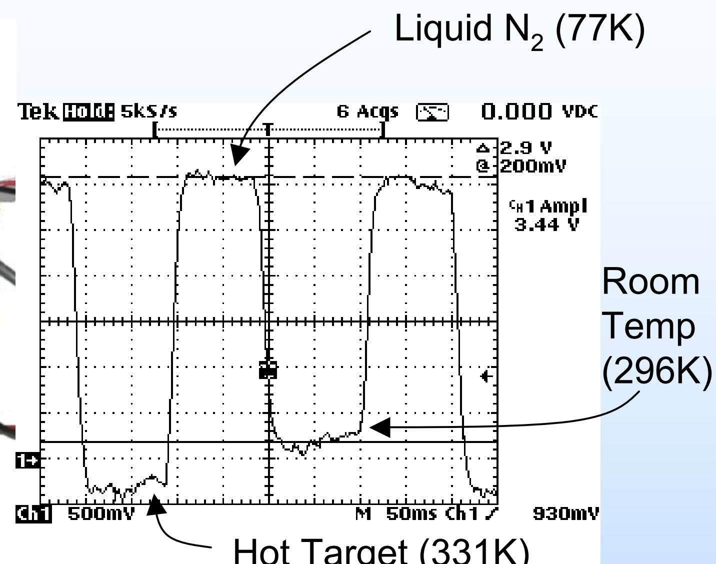


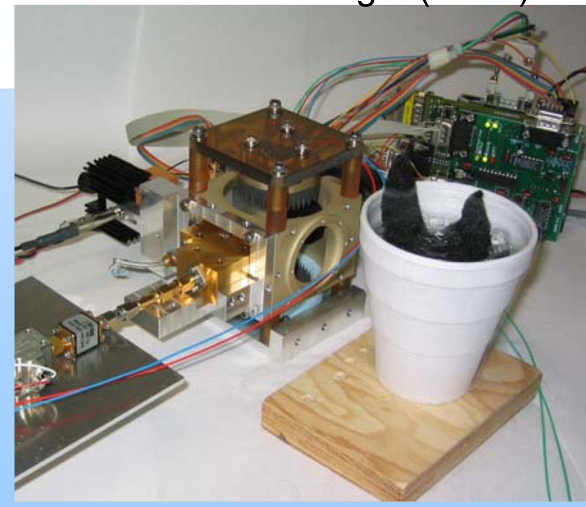
Concept design of GEM antenna with tilting/decentering subreflector (Ball ATC)

PSR/S 380 GHz Spectrometer

~10 cm







500 MHz wide IF band
Centered at 10.65 GHz

$\Delta T = 3.1$ K ➡ $T_{sys} \sim 4900$ K

GEM Mass, Power, Slew, Data Rate

2-meter System – MIT/LL Study

Total Mass
~66 kg

Moving Mass
~53 kg
(momentum compensated)

Main Reflector Max Slew Rate
~0.1°/sec

Power
~125-150 W

Data
~64 kbps

Component	Number	Weight (kg)	Weight (lb)
Main reflector	1	15.00	33.07
Subreflector	1	0.07	0.15
Strut	3	0.97	2.14
Subreflector support structure	1	1.78	3.92
Subreflector nodding actuator	1	1.00	2.20
Antenna shape-sensing hardware	1	1.00	2.20
Back structure collar	1	3.53	7.78
Back structure vanes	3	4.75	10.47
Rotary calibration optic	1	0.25	0.55
Rotary optic drive motor	1	0.70	1.54
RF feedhorns	5	1.50	3.31
Calibration bodies	2	2.00	4.41
Instrument mounting structure	1	2.00	4.41
Space tube	1	0.60	1.32
Receivers	5	18.00	39.68
Dichroic	1	0.25	0.55
Subtotal		**53.40**	**117.72**
Elevation structure & mechanisms	1	6.35	14.00
Azimuth structure & mechanisms	1	6.40	14.11
Total		**66.15**	**145.83**

Summary

- Microwave NWP assimilation of precipitation likely possible over mesoscale-sized regions with ~15 min update. Longer update intervals progressively inhibit ability to “lock” the NWP model onto precipitation evolution, especially at raincell-scale grid sizes.

- GEM will be a cost-effective AMSU-like sounder/imager but with time-resolved observations of precipitation – complementary to geostationary infrared, with new spectral degrees of freedom.

- RT modeling, retrieval simulations, and radiance assimilation studies (OSSEs) for GEM and other geo-microwave systems are in progress.