New Techniques for High-Resolution Atmospheric Sounding

William J. Blackwell

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Outline

- Brief overview of MIT Lincoln Laboratory
- Introduction to space-based passive infrared and microwave atmospheric sounding
  - Motivation
  - Past, present, and future sounding systems
  - Mathematical background
- Algorithmic challenges of modern sounding systems
  - Retrieval of atmospheric temperature and moisture profiles using high-resolution IR sensors (1000's of channels)
  - Clouds impact approximately 95% of soundings (highly non-linear)
- Recent research and new approaches:
  - Algorithms: Neural Network Estimation; Stochastic Cloud Clearing
  - Sensors: Hyperspectral microwave sounding (GeoMAS) and constellation sensing (MicroMAS CubeSat mission)
- Summary and Final Thoughts

MIT Lincoln Laboratory is a DoD-Sponsored FFRDC* operated by MIT

Faculty 1000

Post-Doctoral and Graduate Students 7500

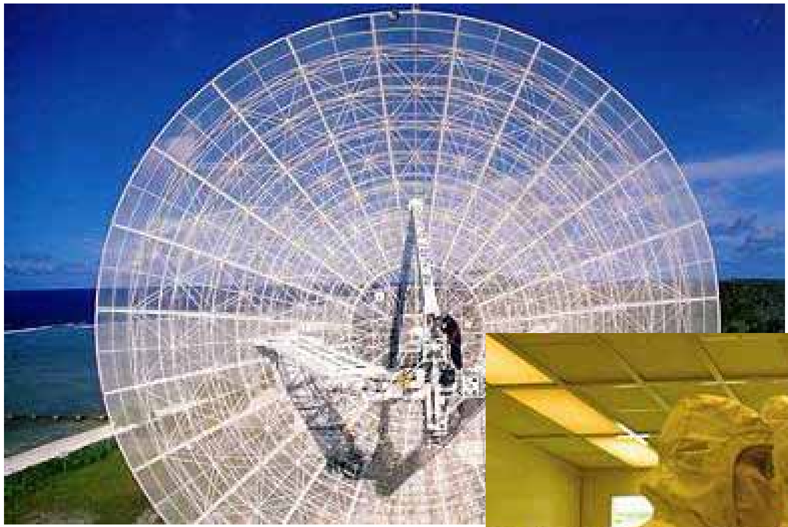
Undergraduate Students 4200

Technical Staff 2500

Support Staff 1500

*Federally-Funded Research and Development Center

Fundamental Mission — Technology in Support of National Security



Radar for ballistic missile defense and FAA

Transformational Communication Test Aircraft

Advanced lithography and microelectronics fabrication

MIT Lincoln Laboratory

Purpose

Technology in Support of National Security

Core Work Areas

Sensors ➔ Information Extraction ➔ Communications

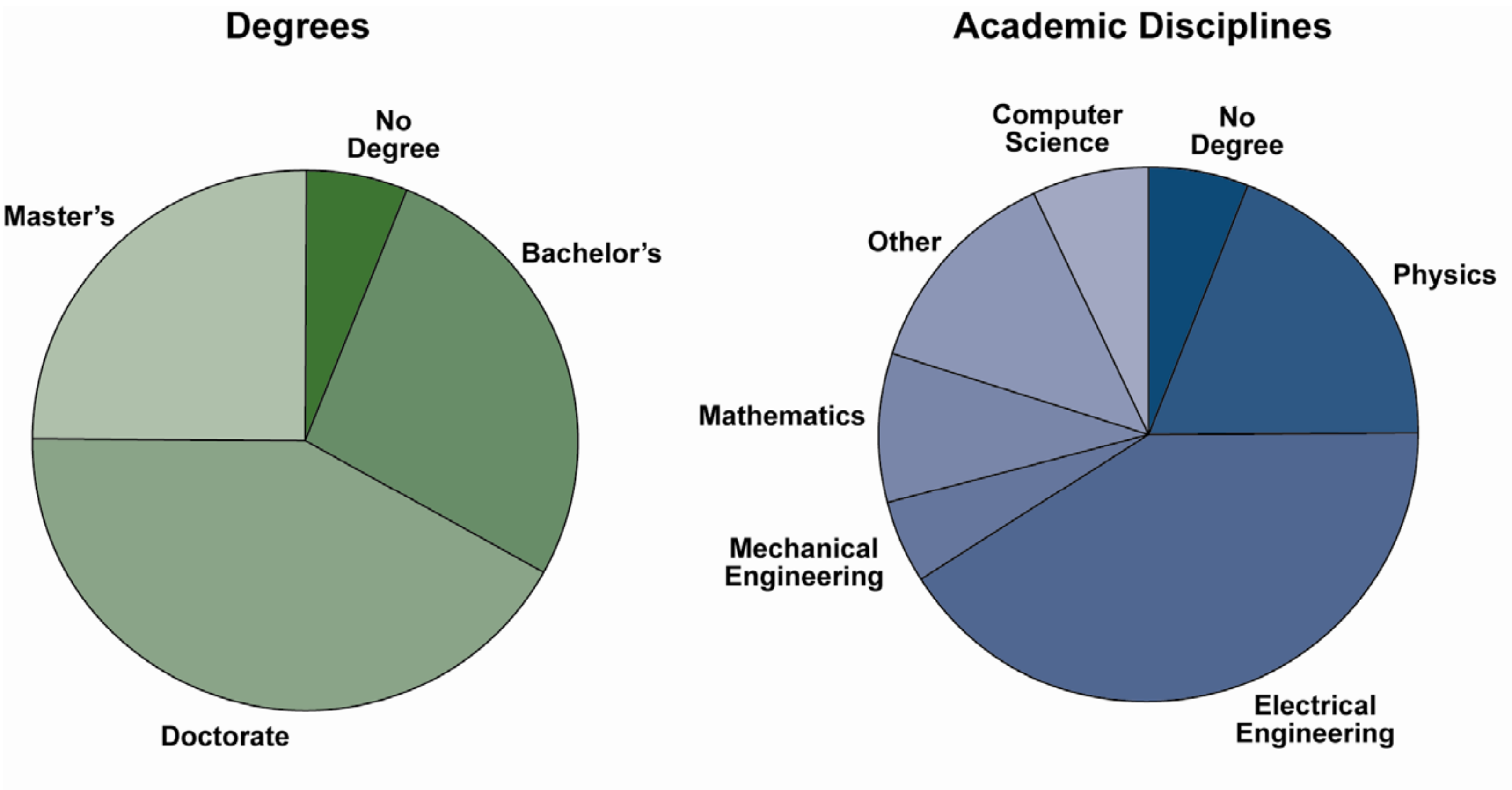
Integrated Sensing and Decision Support

(Secure – Countermeasure Resistant)

Current Mission Areas

- Communications and Information Technology
- Space Control
- Intelligence, Surveillance, and Reconnaissance Systems & Technology
- Advanced Electronics Technology
- Air and Missile Defense Technology
- Homeland Protection and Tactical Systems
- Non-DoD Air Traffic Control, NASA, NOAA

Composition of Professional Staff



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Meteorological Significance of Atmospheric Remote Sensing Data

- Nowcasting (assessing current atmospheric state)

- Initializing numerical weather prediction (NWP) forecasts
  - Increase forecast accuracy
  - Extend forecast duration
  - Biggest impact in Southern Hemisphere (little other data) and northern oceans plus their eastern coasts

- Precise climatological studies
  - Average atmospheric temperatures observed with ~0.02K relative accuracy, reducing aliasing in other global warming measurements which sample Earth nonuniformly
  - Geostationary satellites can observe at ~0.5-3 hr periods monitoring severe storms, while polar satellites provide synoptic data driving NWP models

Uses of the Infrared and Microwave Spectrum

- Temperature profile estimation
- Water vapor profile estimation
- Precipitation monitoring
- Sea surface temperature
- Snow and sea ice, flooding, surface emissivity
- Cloud-top pressure and temperature
  - Clouds are opaque at IR wavelengths
  - Non-precipitating clouds are transparent at MW wavelengths
- Trace constituents: O_3, CO, CH_4, N_2O, CO_2, etc.

Lincoln Laboratory's Role in Present and Future Sounding Systems

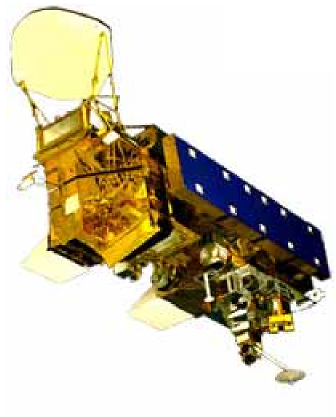
GOES

- Prototype demonstration
- Technology evaluation
  - ➢ Detector arrays
- Studies and analysis
  - ➢ Instrument point designs
  - ➢ Algorithm development and evaluation

POES

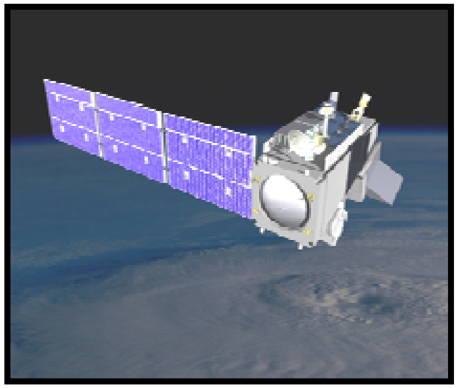
- Pre/Post-launch support
  - ➢ Calibration
  - ➢ Performance assessment
- On-orbit instrument evaluation
- Ground testing support

Aqua



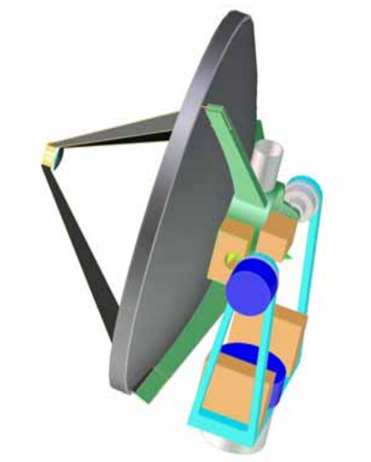
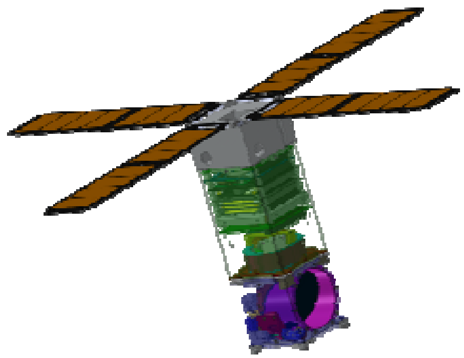
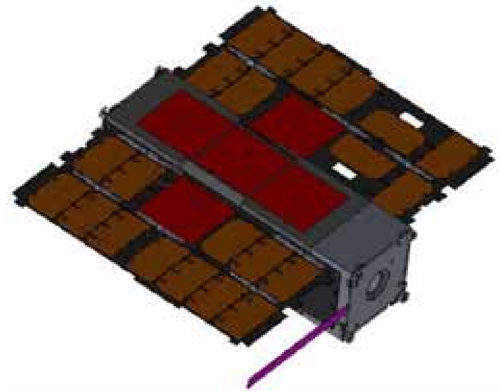
- Level 2 algorithm support
  - ➢ Neural network
  - ➢ Cloud clearing
- Performance validation
  - ➢ Radiosonde matchups
  - ➢ ECMWF comparisons

SNPP/JPSS



- Sensor development support
  - ➢ Modeling & simulation
  - ➢ Calibration & validation
  - ➢ Hardware testing
- Algorithm development and evaluation
  - ➢ Data fusion
  - ➢ Precipitation

Lincoln Laboratory's Role in Present and Future Sounding Systems

GeoMAS	MicroMAS	MiRaTA	NAST-M
			

GeoMAS

- Geostationary concept
- Hyperspectral microwave
  - ➢ Technology funded by NASA ESTO
- Excellent performance
  - ➢ All-weather
  - ➢ Precipitation
  - ➢ Temperature
  - ➢ Humidity

MicroMAS

- 3U CubeSat
  - ➢ 2013 launch (NASA)
  - ➢ 118-GHz spectrometer
- Scanning assembly
- One-year lifetime goal

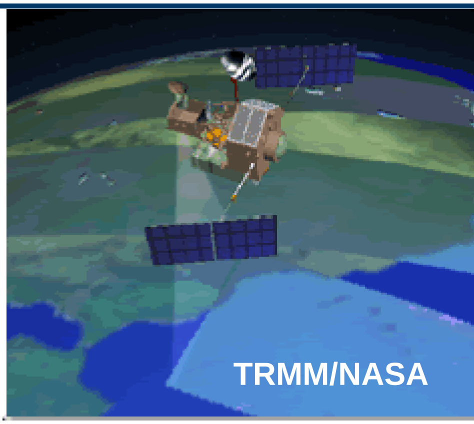
MiRaTA

- 3U CubeSat
  - ➢ Radiometer + GPSRO concept
  - ➢ Multi-band
- ATMS-like performance
- Proposal submitted

NAST-M

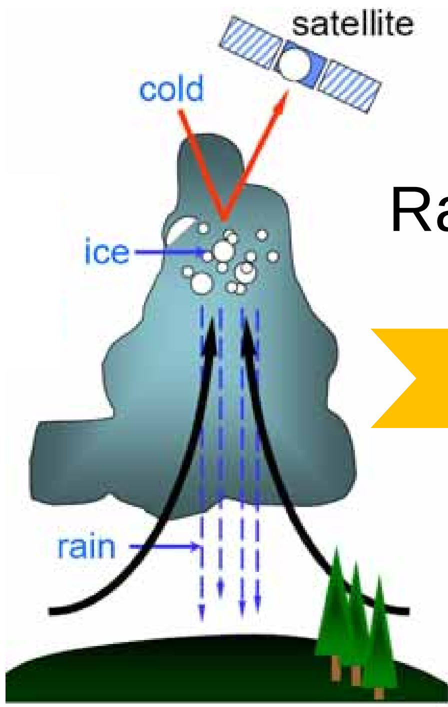
- Airborne instrument
  - ➢ SNPP cal/val
  - ➢ JPSS risk reduction
  - ➢ Technology validation
- Algorithm development and evaluation
  - ➢ Data fusion
  - ➢ Precipitation

Passive Microwave Radiation & Precipitation



Satellite microwave sensors can penetrate storm clouds and reveal precipitation with global coverage

NASA Goddard Laboratory of Atmospheres

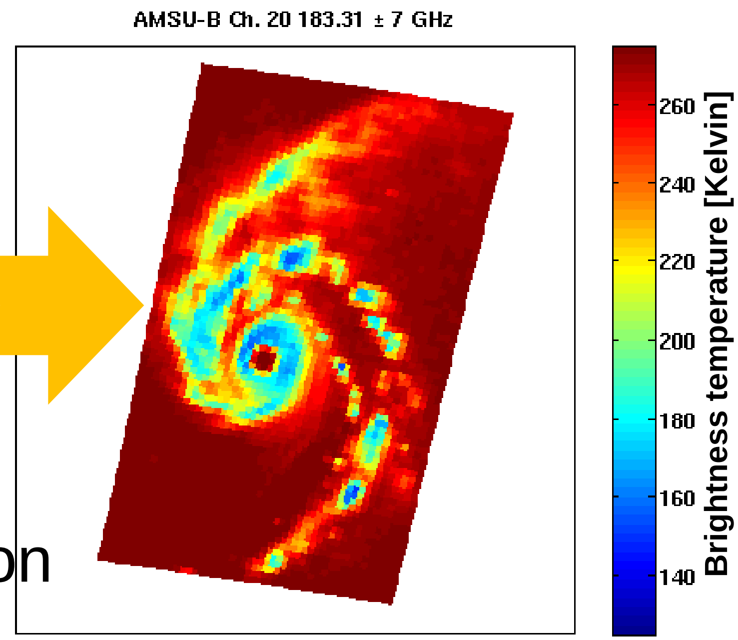


Radiance

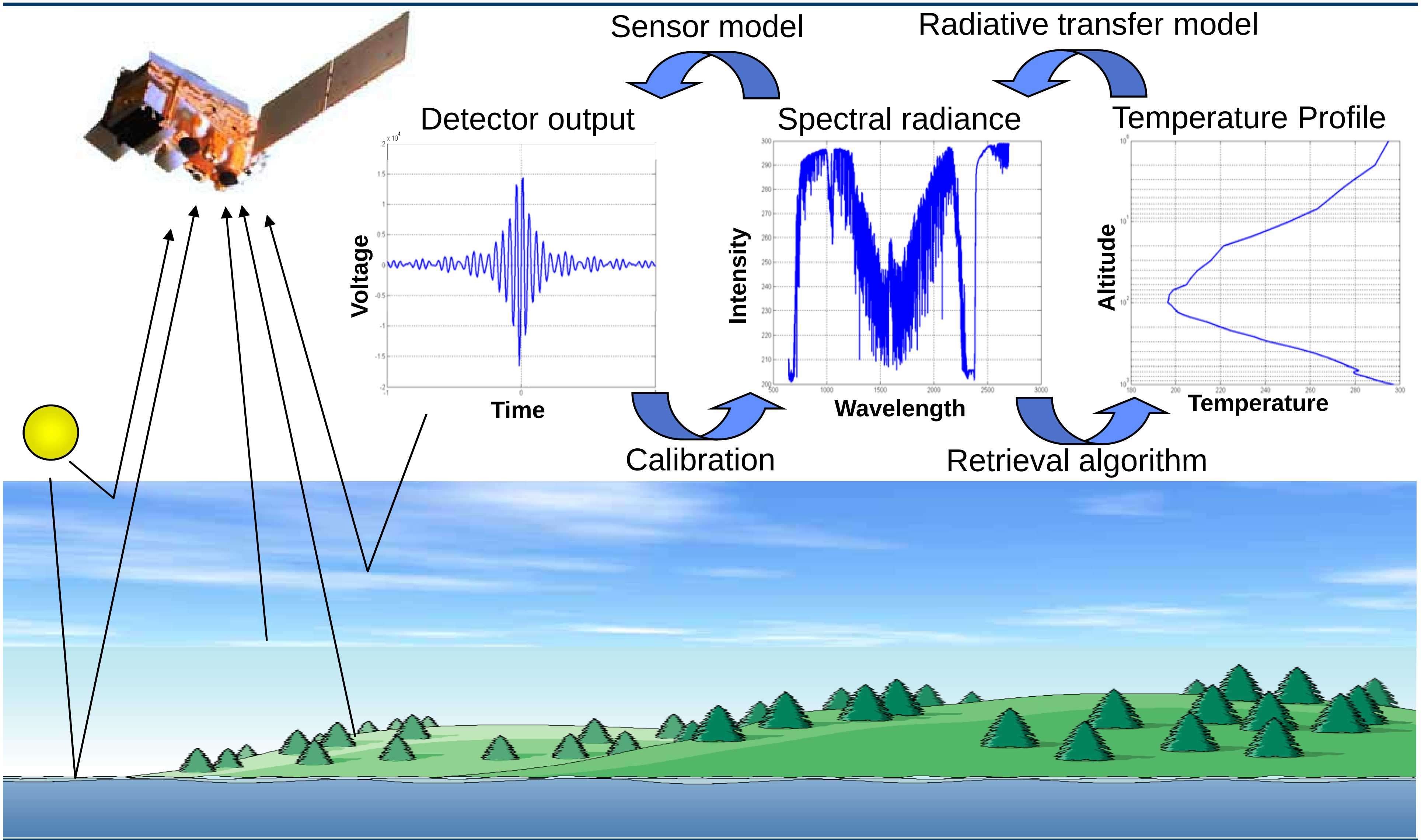
Precipitation Parameters

$$R = F\left(P\right)$$

"forward model"
or radiance simulation



Atmospheric Remote Sensing: Measurement Scenario



Retrieval of Geophysical Parameters from Radiometric Data

Variational (model-based) approach:

- A forward model relates the geophysical state of the atmosphere to the radiances measured by the sensor.

$$R = f\begin{pmatrix} X \equiv [T(\vec{r},t), W(\vec{r},t), O(\vec{r},t), \ldots] \\ \text{surface reflectivity, solar illumination, etc.} \\ \text{observing system (bandwidth, resolution, etc.)} \end{pmatrix} + \varepsilon$$

observation noise

- A "guess" of the atmospheric state is adjusted iteratively until modeled radiance "matches" observed radiance.

$$\gamma = \left\| R - R_{\text{obs}} \right\| + h(X)$$

"regularization" term

Statistical (regression-based) approach:

- An ensemble of radiance-state vector pairs is assembled, and a statistical relationship between the two is derived empirically.

$$\hat{X} = g(R_{\text{obs}}), \text{ where } g(\cdot) \text{ is } \underset{g(\cdot)}{\operatorname{argmin}} \left\| X_{ens} - g(R_{ens}) \right\|$$

Examples of $g(\cdot)$ include LLSE and neural network

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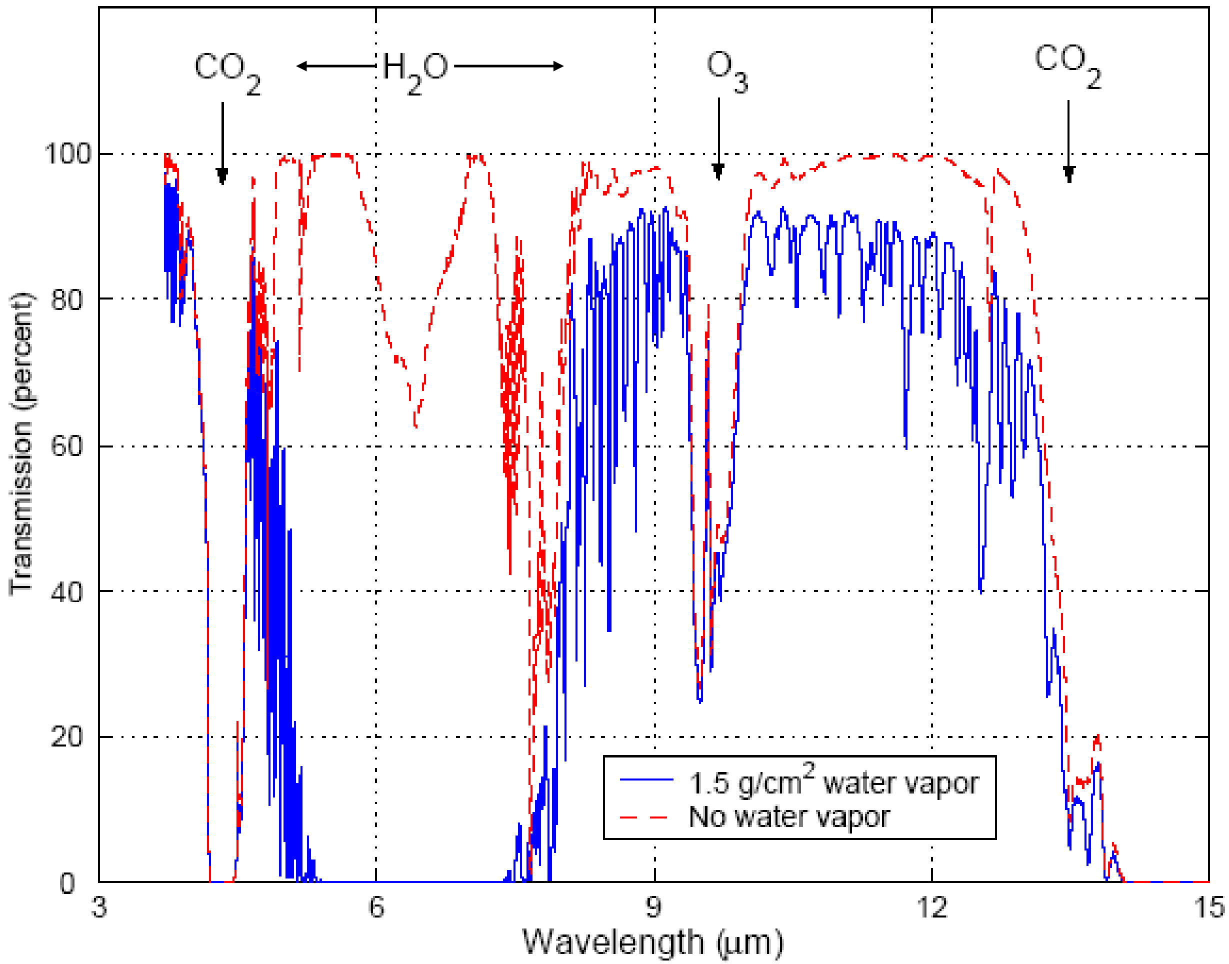
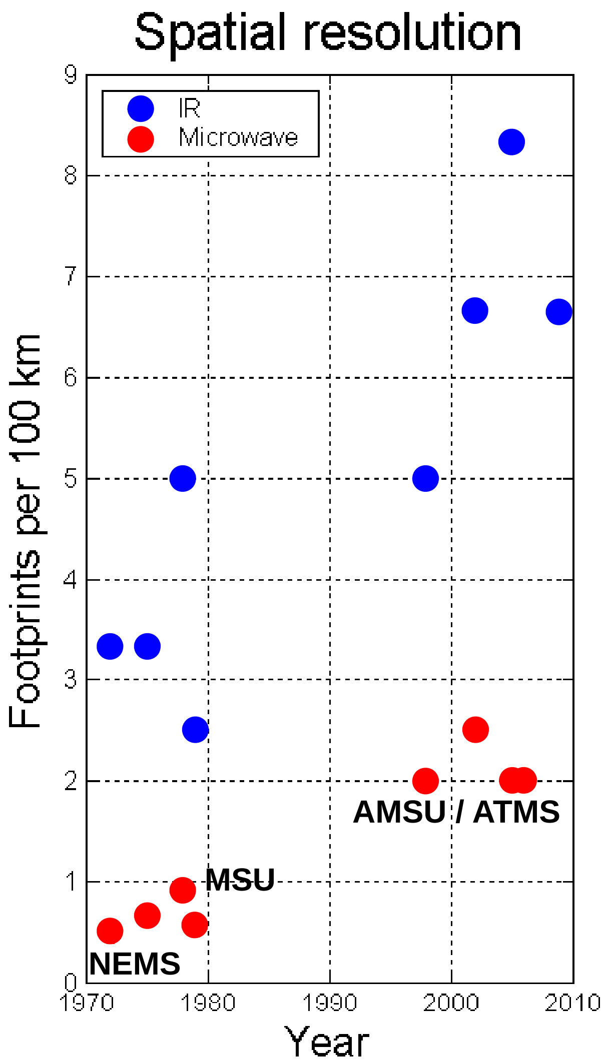
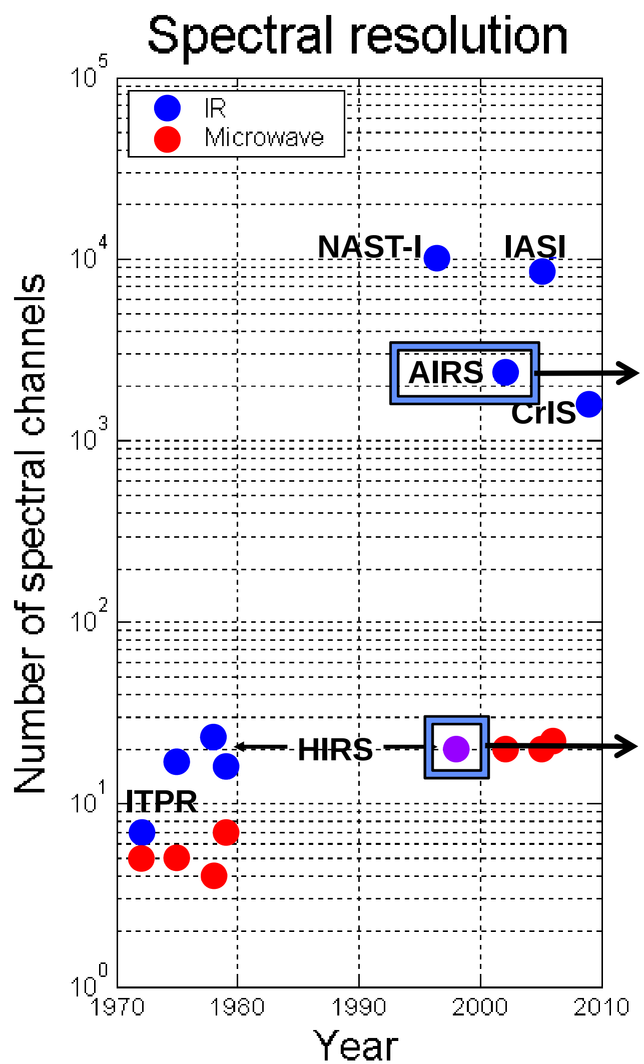
Atmospheric Transmission at Infrared Wavelengths



- The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines.

Recent Improvements In Measurement Resolution





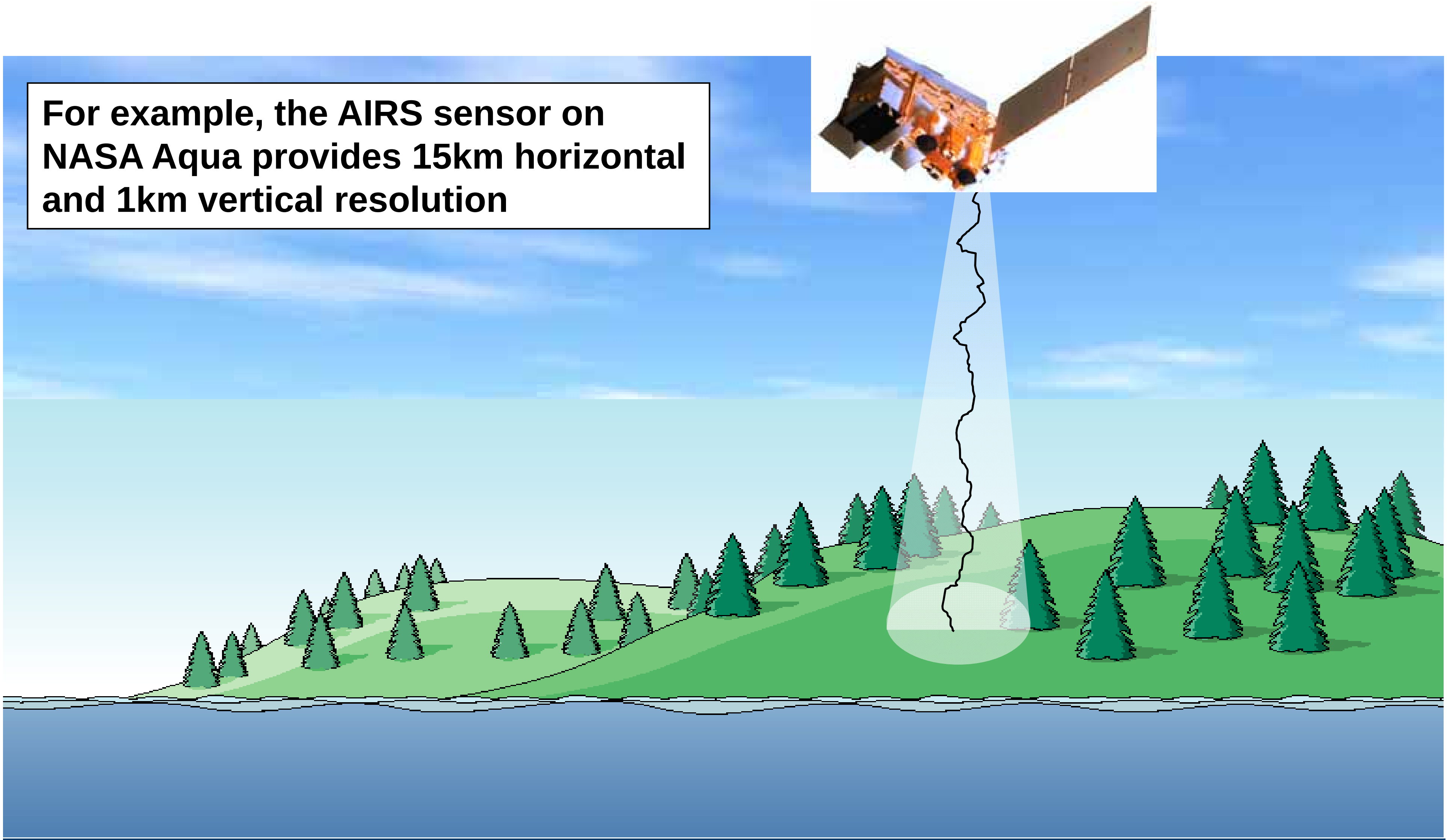
NASA Aqua Satellite Launched May 2002

AIRS:
Atmospheric InfraRed Sounder
2378 channels from 4-15 μm

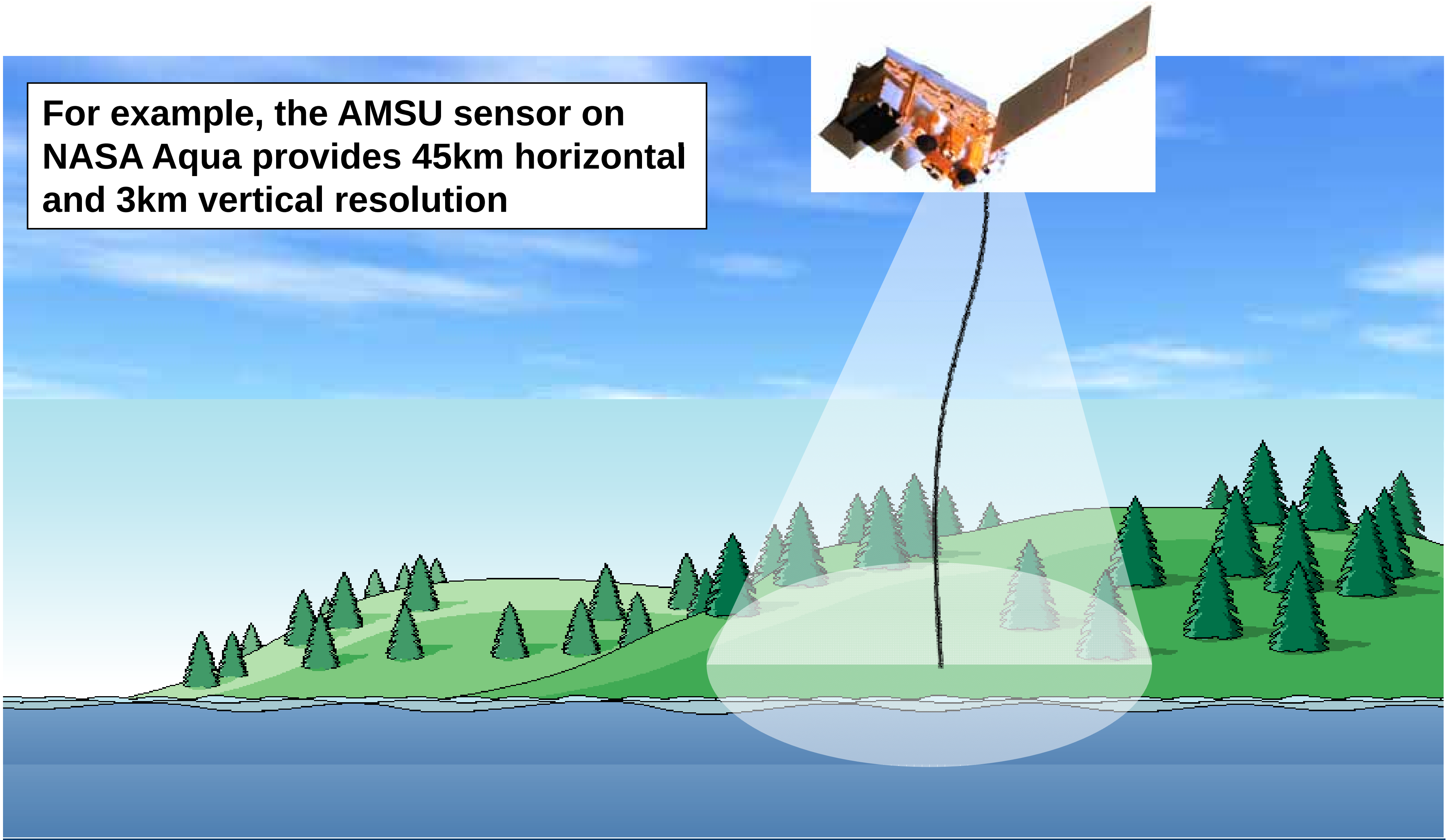
AMSU:
Advanced Microwave Sounding Unit
20 channels near 60- and 183-GHz

Passive Infrared Measurements Provide High Spatial Resolution

For example, the AIRS sensor on NASA Aqua provides 15km horizontal and 1km vertical resolution



Passive Microwave Measurements Provide Low Spatial Resolution, but Penetrate Clouds



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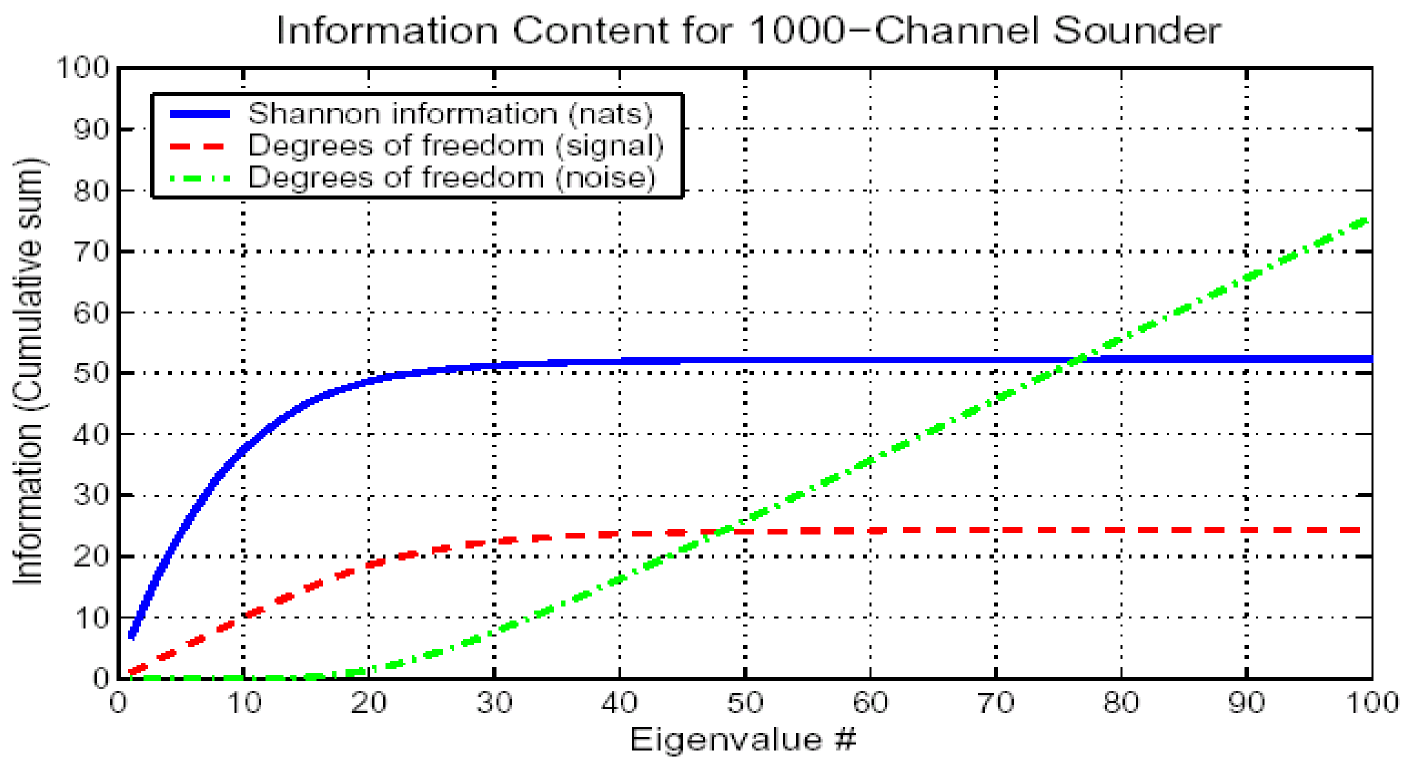
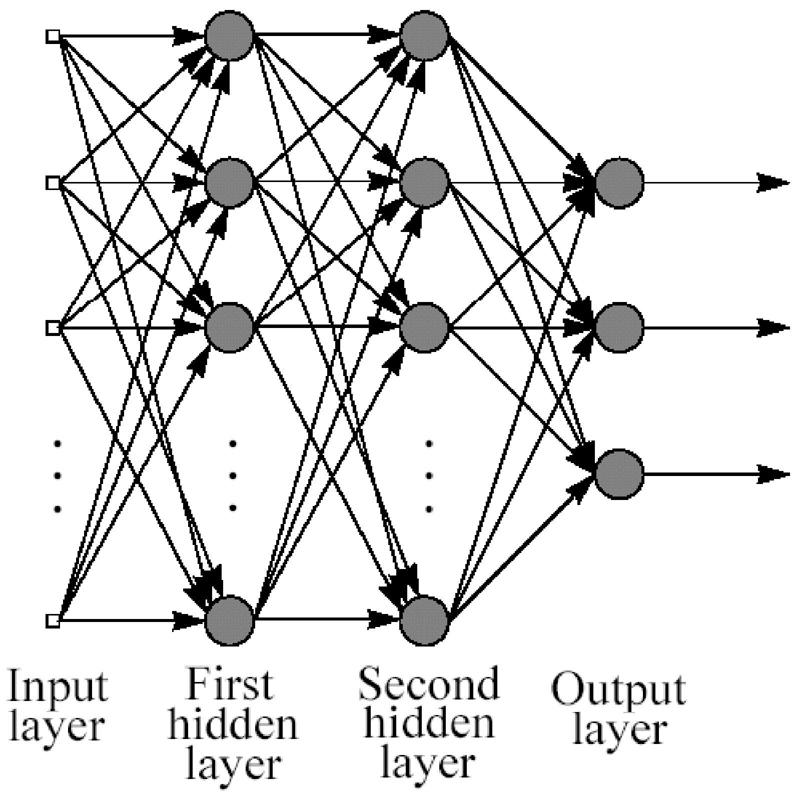
Hyperspectral Sounding Data is Highly Correlated



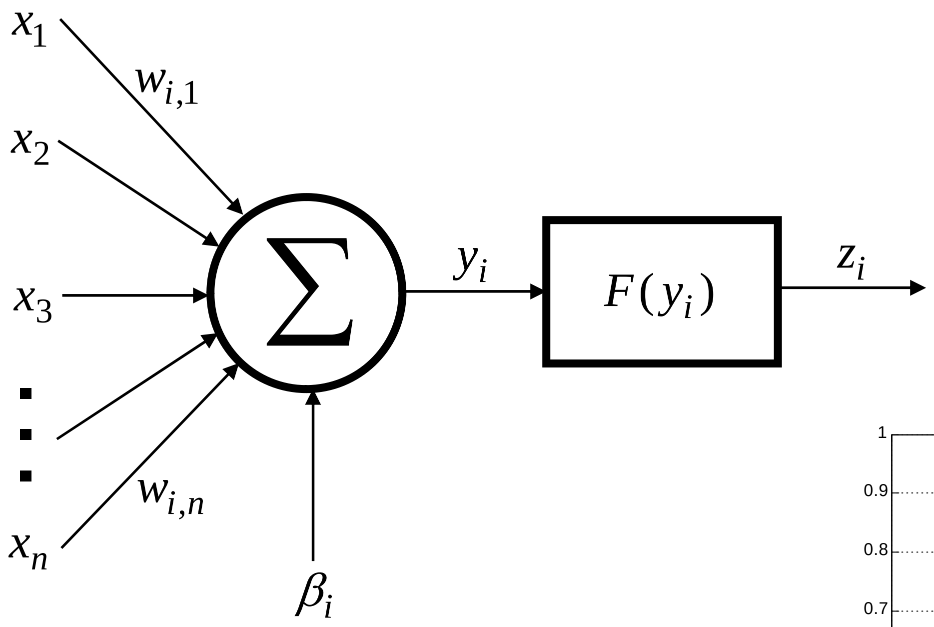
$$I = \frac{1}{2}\sum_i \log(1+\lambda_i) \qquad \mathrm{DOF_s} = \sum_i \frac{\lambda_i}{1+\lambda_i} \qquad \mathrm{DOF_n} = \sum_i \frac{1}{1+\lambda_i}$$

Multilayer Feedforward Neural Networks



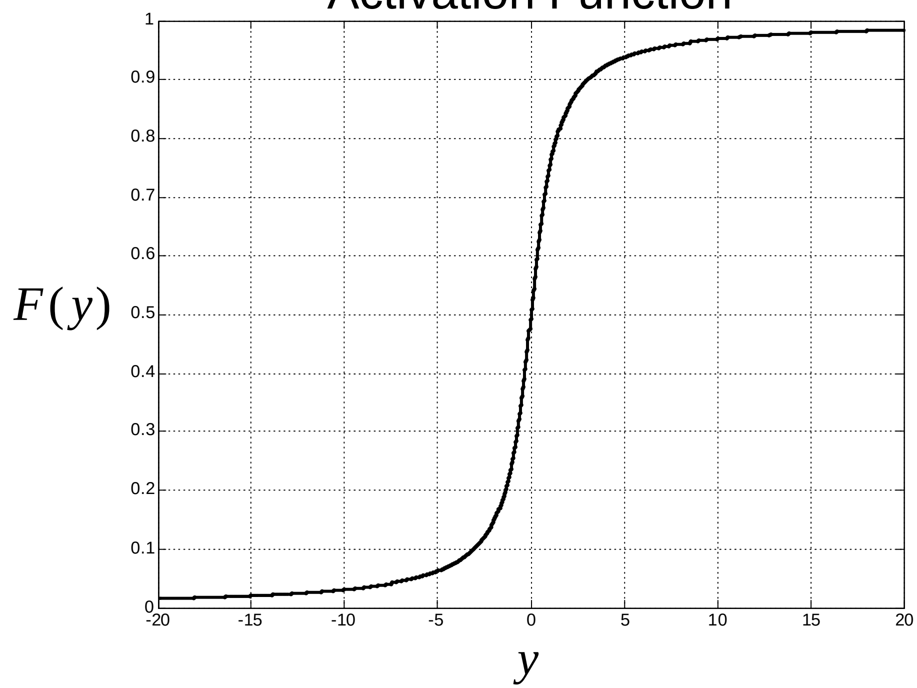
- Parameterized, nonlinear function
- Parameters (“weights” and “biases”) are found by numerically minimizing some cost function (usually SSE)
- Sophisticated methods for finding optimal weights exist (“back-propagation” of errors)

Perceptron



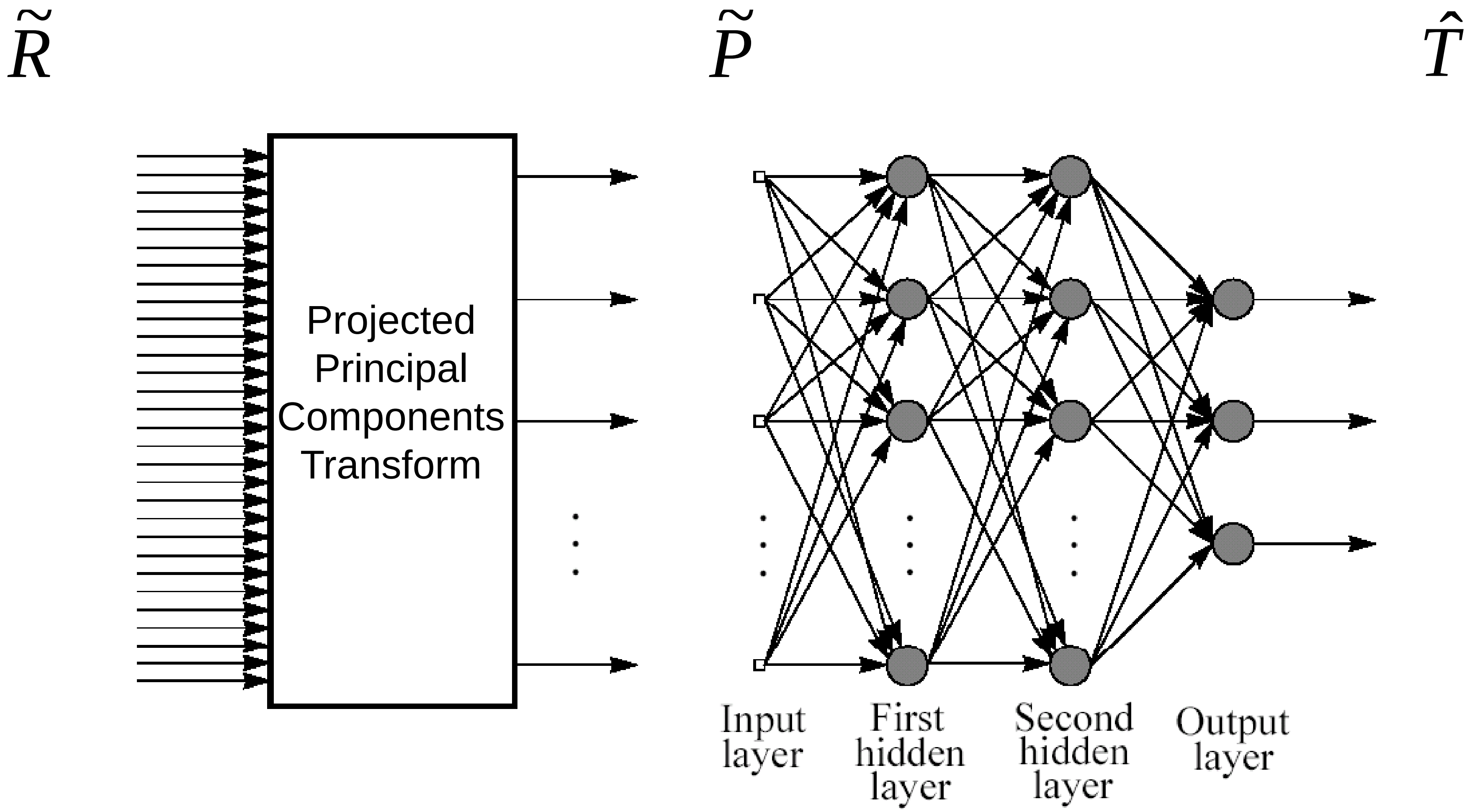
Differentiable activation functions typically used to facilitate gradient searches

“Activation Function”



Perceptron weights and biases are iteratively adjusted by “back propagation” of errors.

Combination of Radiance Compression and Neural Network



Cloud Clearing: Background and Prior Work

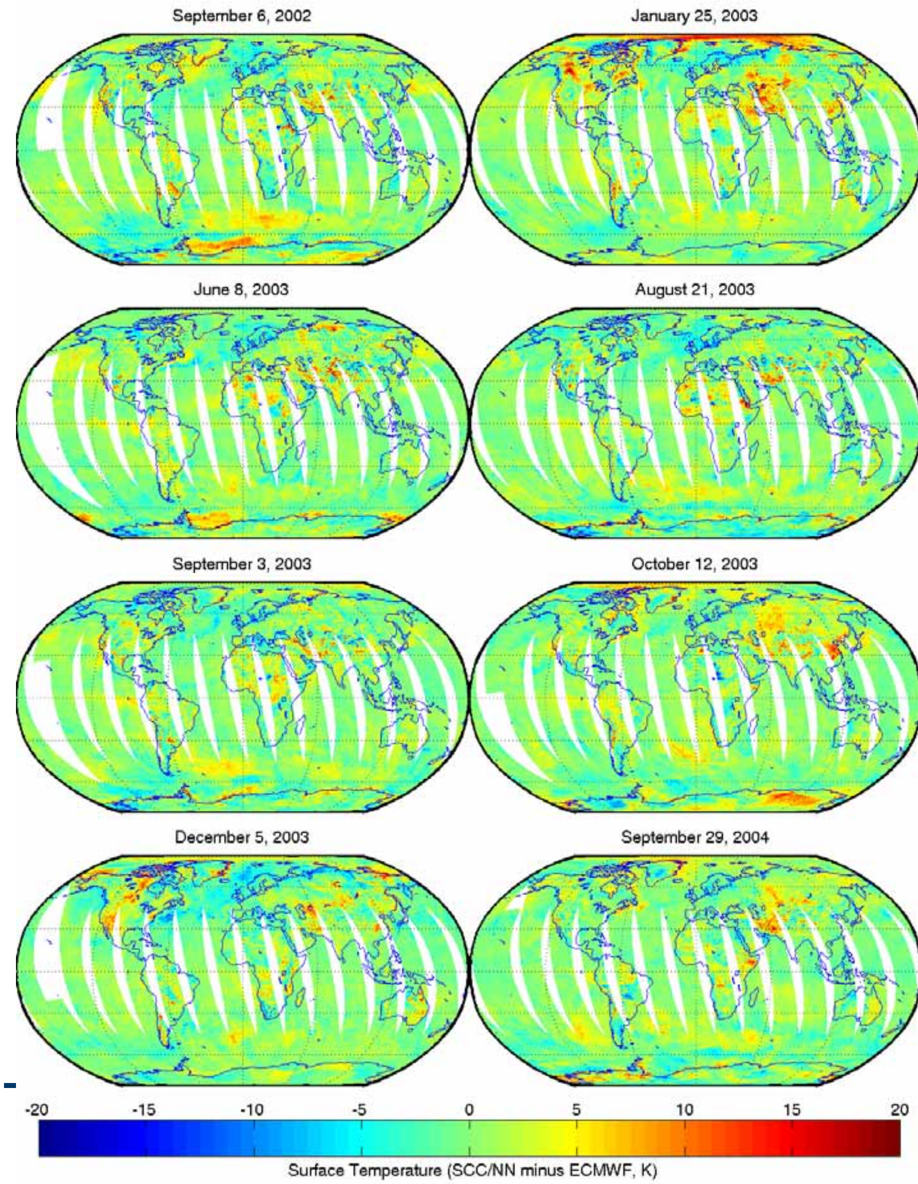
- **What is cloud clearing?**
  - **Cloudy radiances (or T_B) cause inaccurate retrievals**
  - **Cloud-cleared radiances: radiances which would have been observed if FOV contained no clouds**
- **Prior work on cloud clearing**
  - Ignore cloudy FOVs**: only ~5% of AIRS FOVs are clear!**
  - Physical cloud-clearing**: iterate between estimation of physical parameters and calculation of observed radiance**
  - Adjacent-pair clearing**: use adjacent FOVs which have different fractional cloud cover.**
  - Purely spatial processing**: restore 2-D temperature field from sparse cloud-clear samples**

Stochastic Cloud Clearing

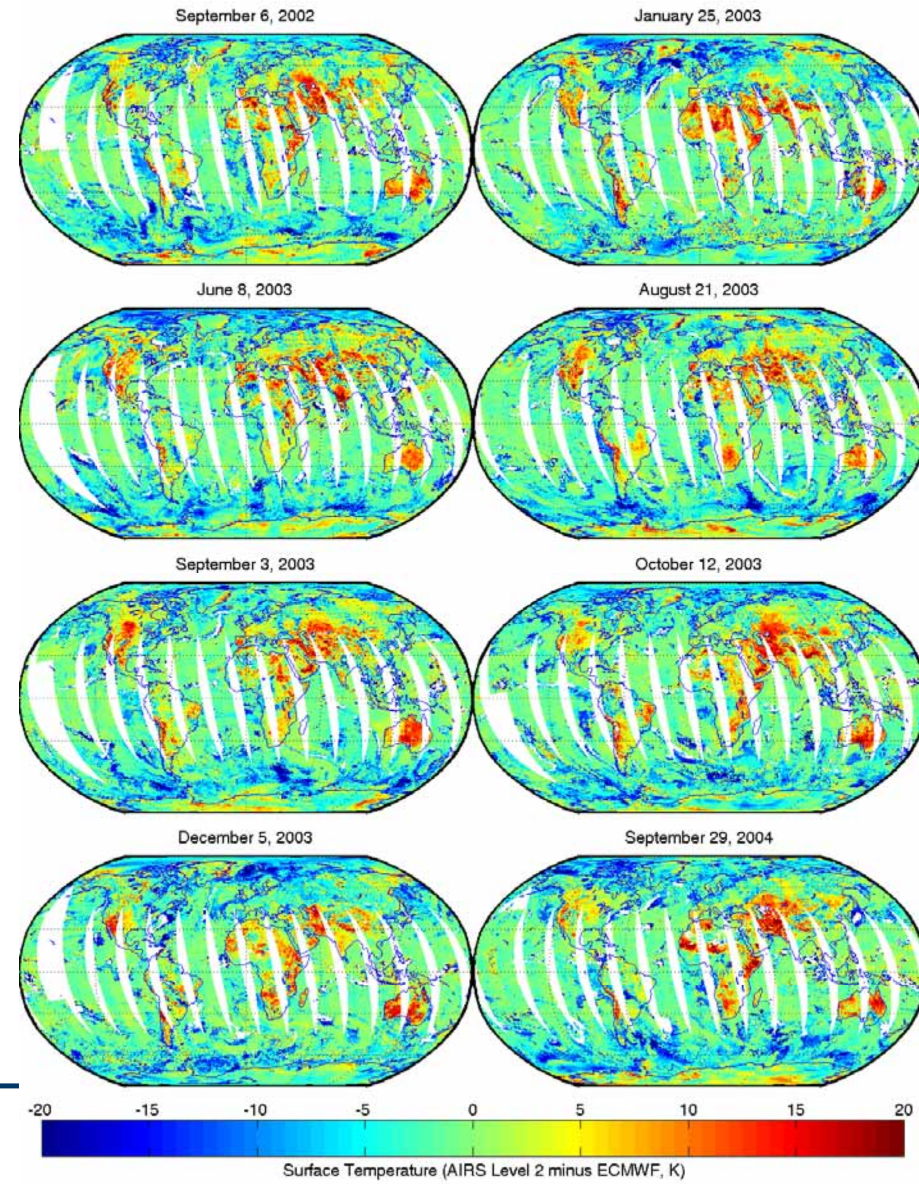
- **SC estimates cloud contaminations solely** *based on statistics* **without using any physical models**
- **Hyperspectral measurements may contain sufficient information about clouds in an obscured manner**
- Robust **and** stable **training is necessary**
- **Nonlinearity is accommodated using stratification (sea/land, latitude, day/night), multiplicative scan angle correction, etc.**
- **Advantages**
  - Simple**: SC does not need physical models (retrieval or radiative transfer).**
  - Fast**: Based on matrix addition and multiplication**

Surface Temperature Retrieval

SCC/NN

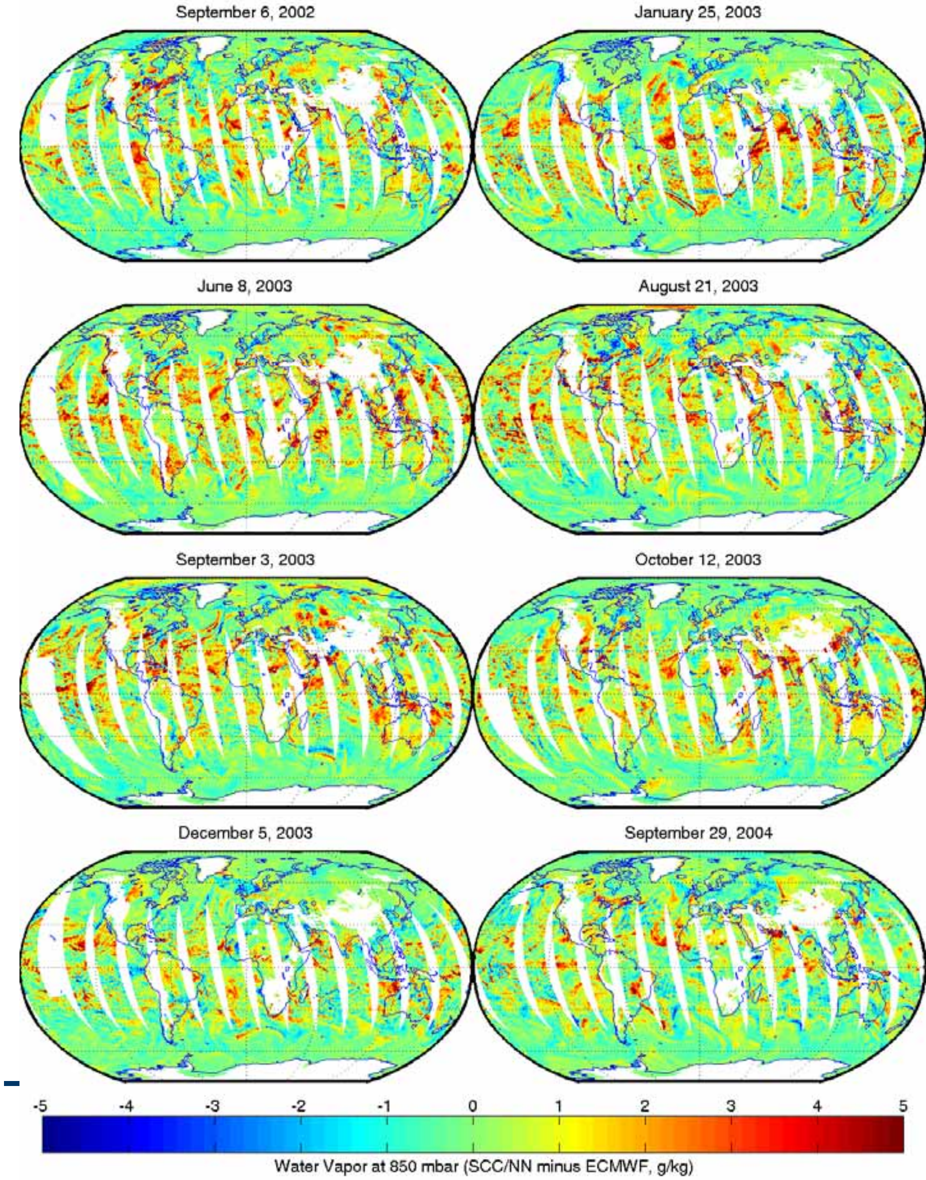


Version 5



Water Vapor at 850 mbar

SCC/NN



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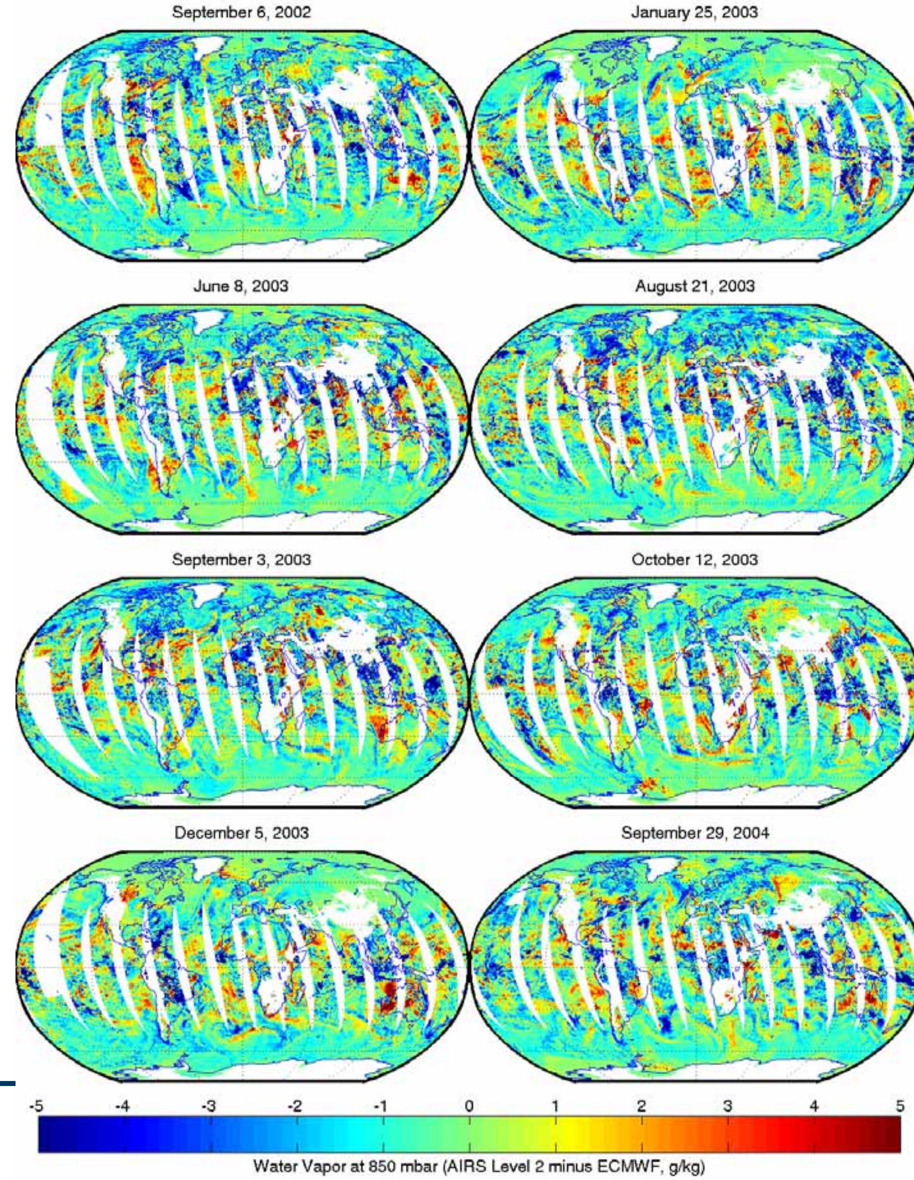
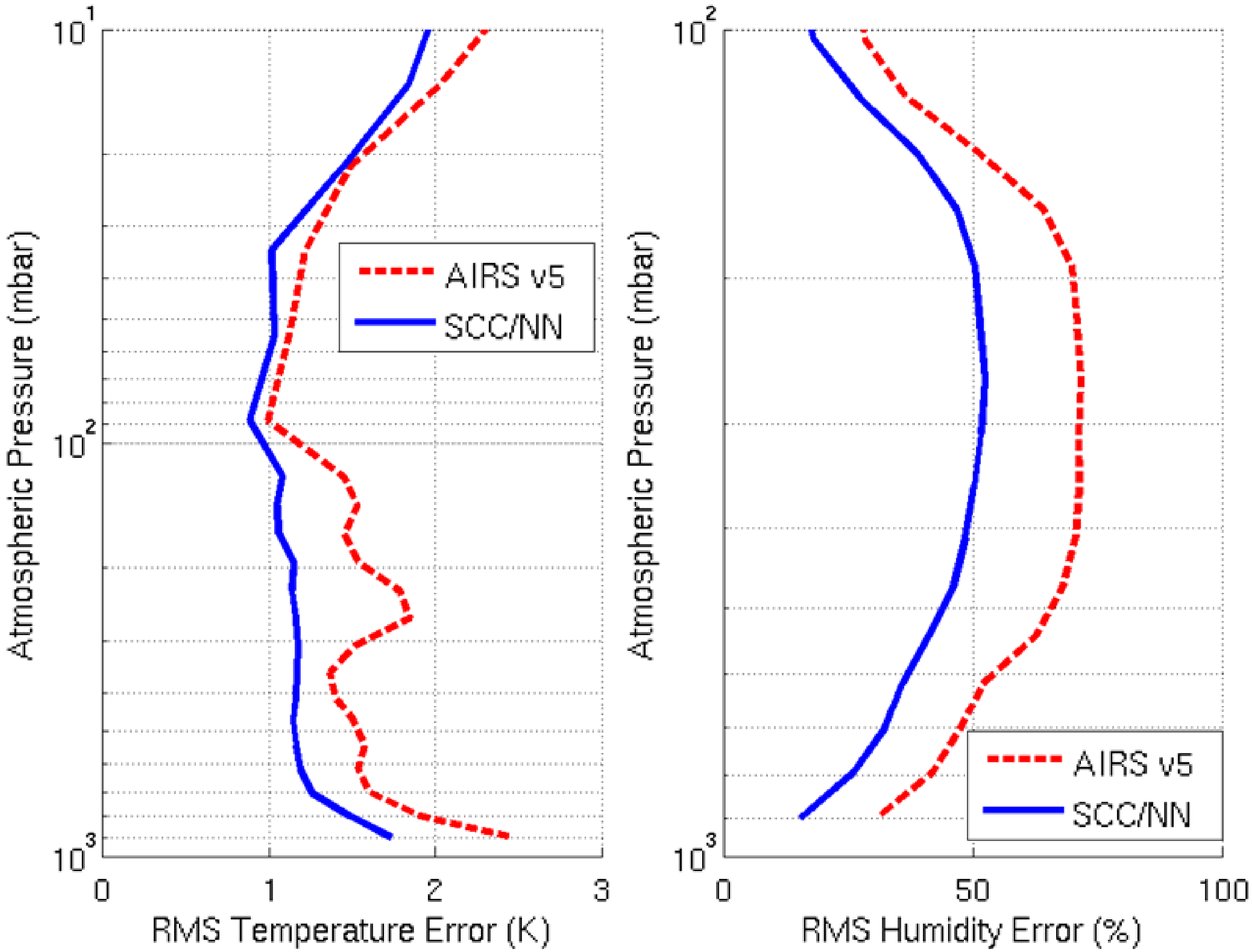
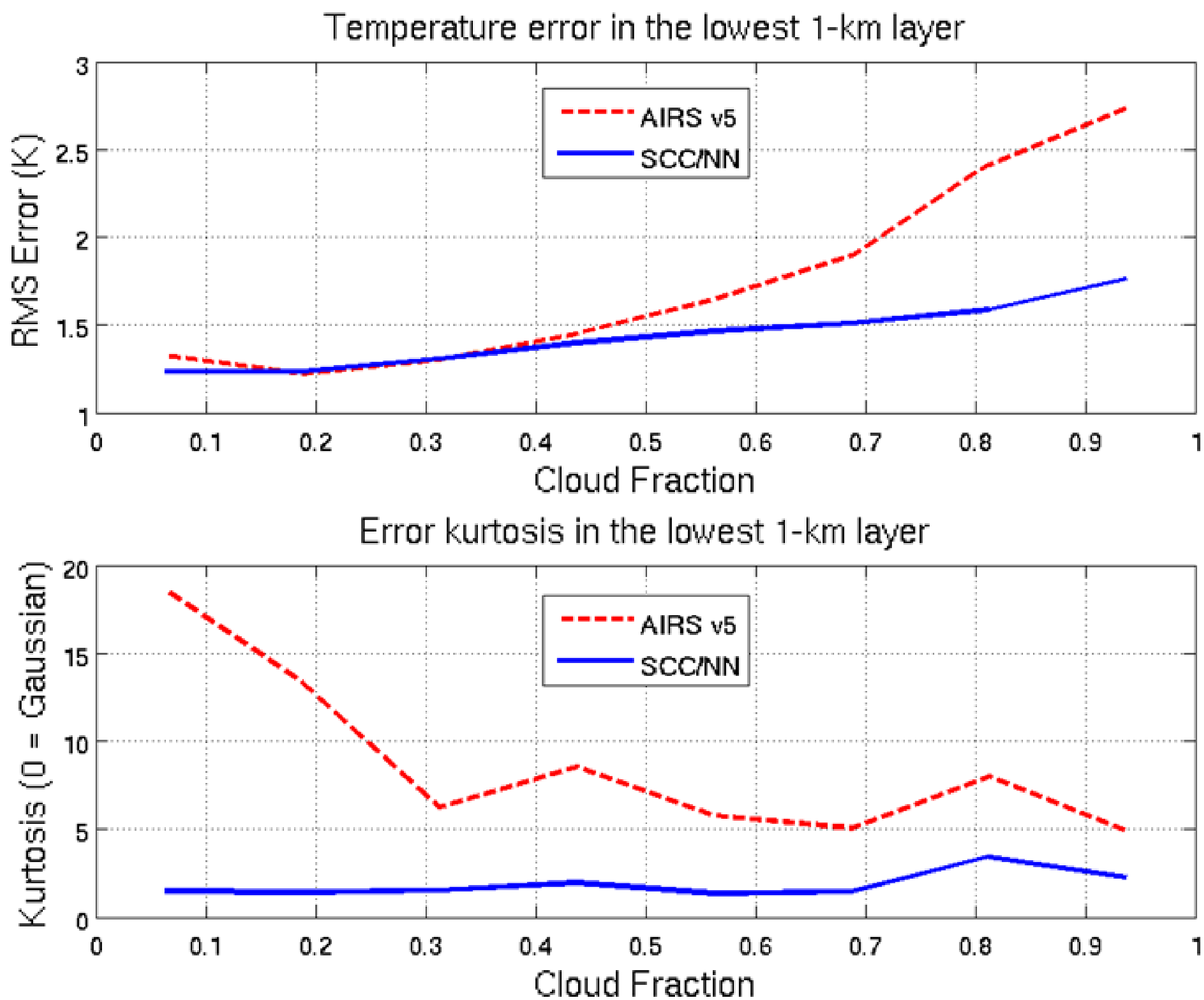


Global Comparisons with ECMWF



Performance Comparisons in Cloudy Cases



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Background/Overview

- "Hyperspectral" measurements allow the determination of the Earth's tropospheric temperature with vertical resolution exceeding 1km
  - ~100 channels in the microwave
- Hyperspectral infrared sensors available since the 90's
  - Clouds substantially degrade the information content
  - A hyperspectral microwave sensor is therefore highly desirable
- Several recent enabling technologies make HyMW feasible:
  - Detailed physical/microphysical atmospheric and sensor models
  - Advanced, signal-processing based retrieval algorithms
  - RF receivers are more sensitive and more compact/integrated
- The key idea: Use RF receiver arrays to build up information in the spectral domain (versus spatial domain for STAR systems)

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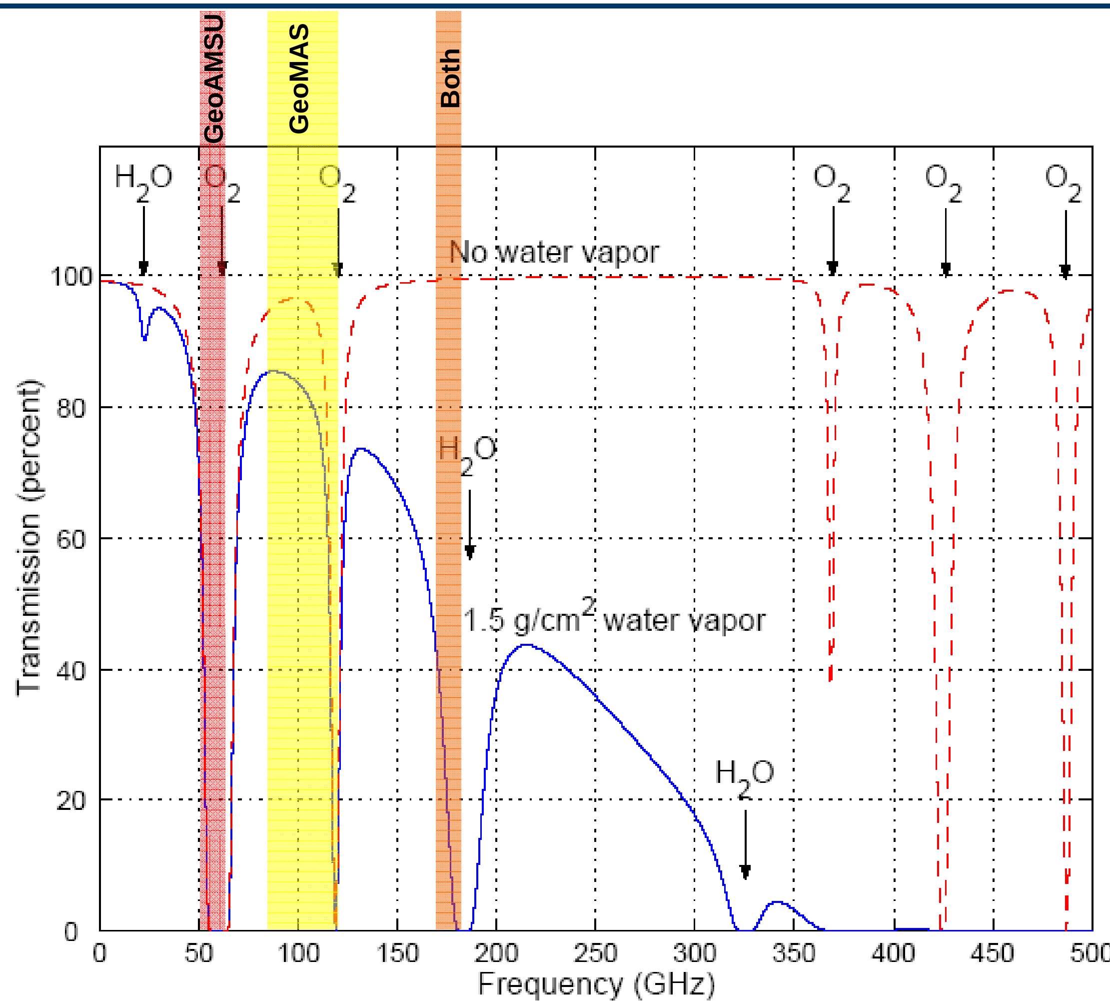
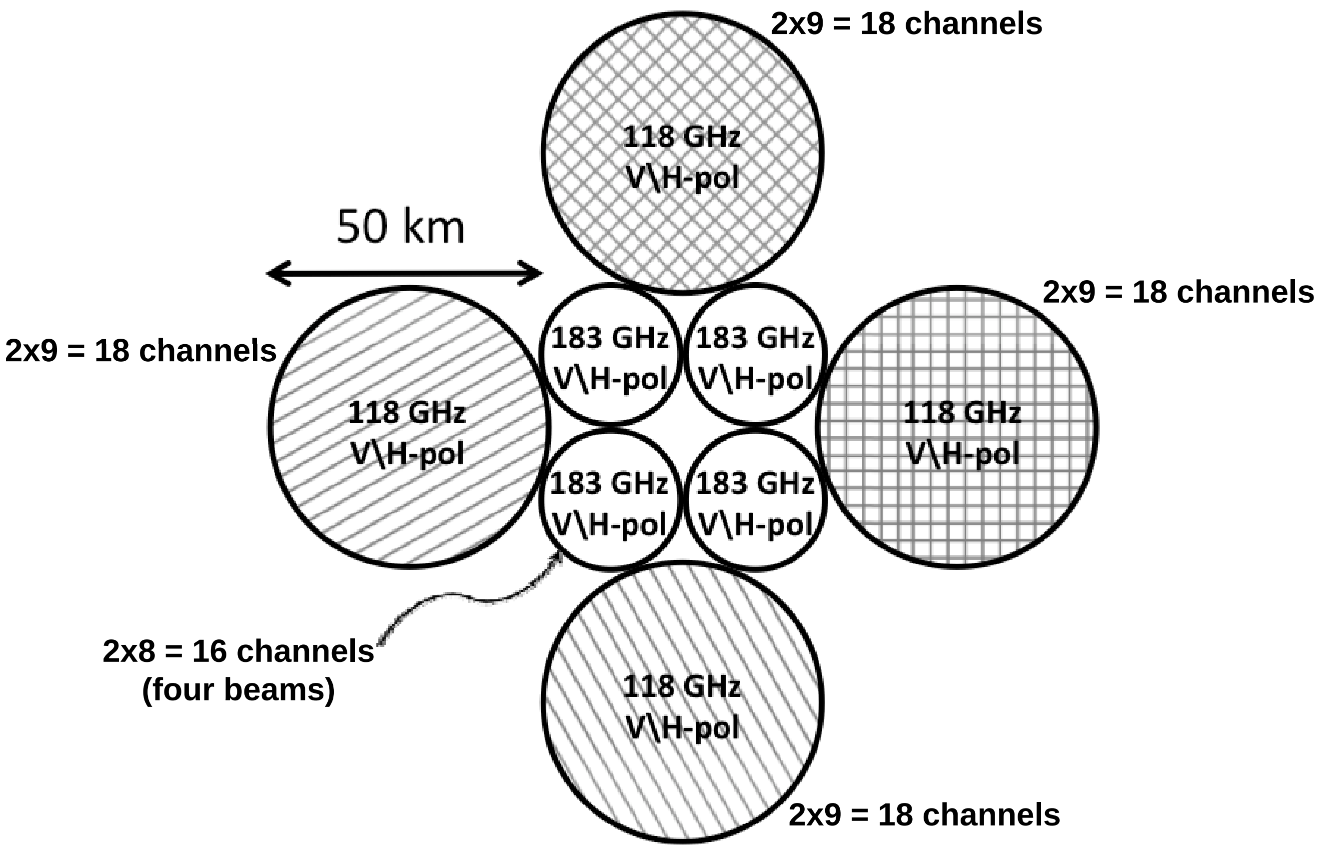
Atmospheric Transmission at Microwave Wavelengths



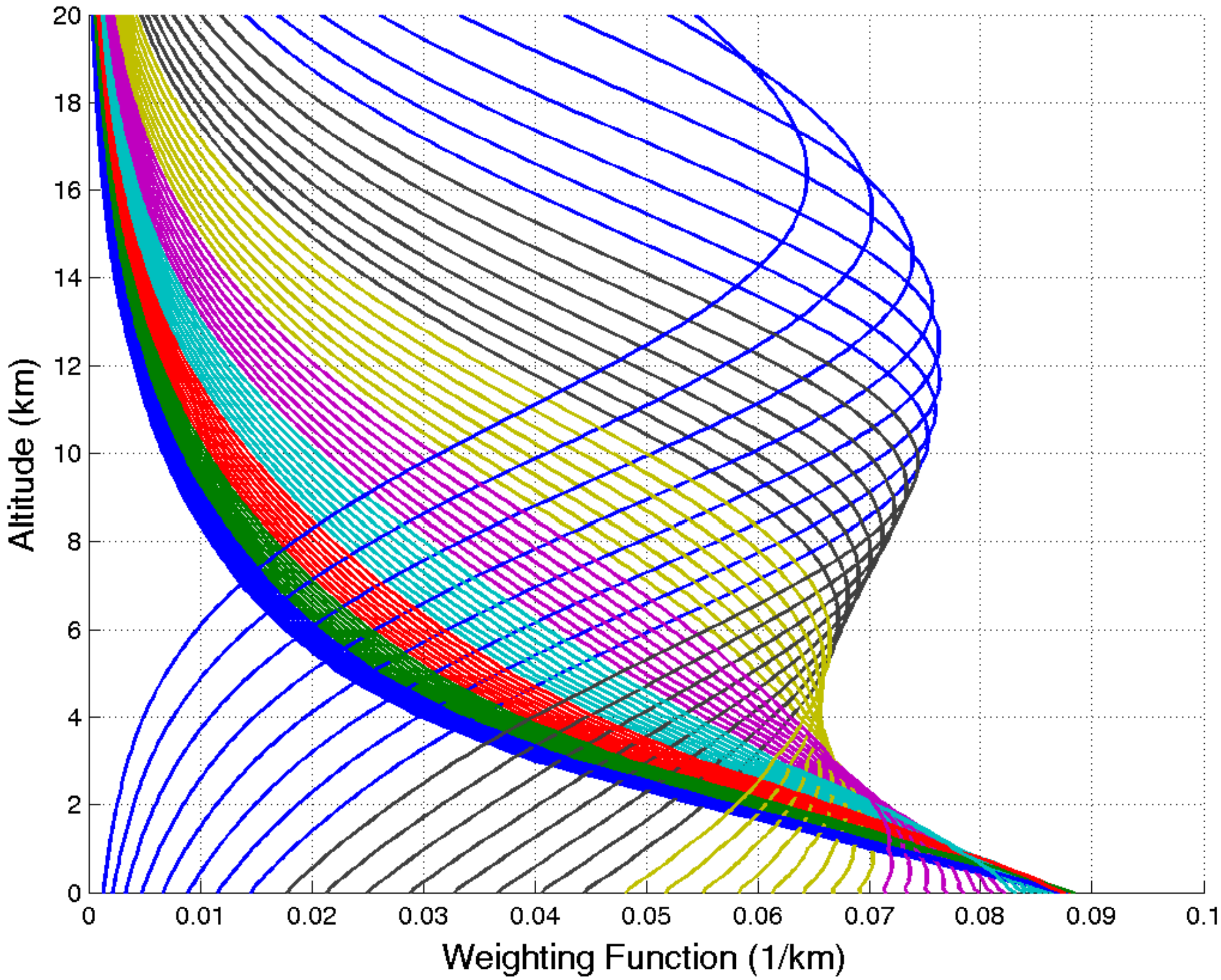
The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines

Geostationary Microwave Array Spectrometer: Nominal GeoMAS Beam Layout

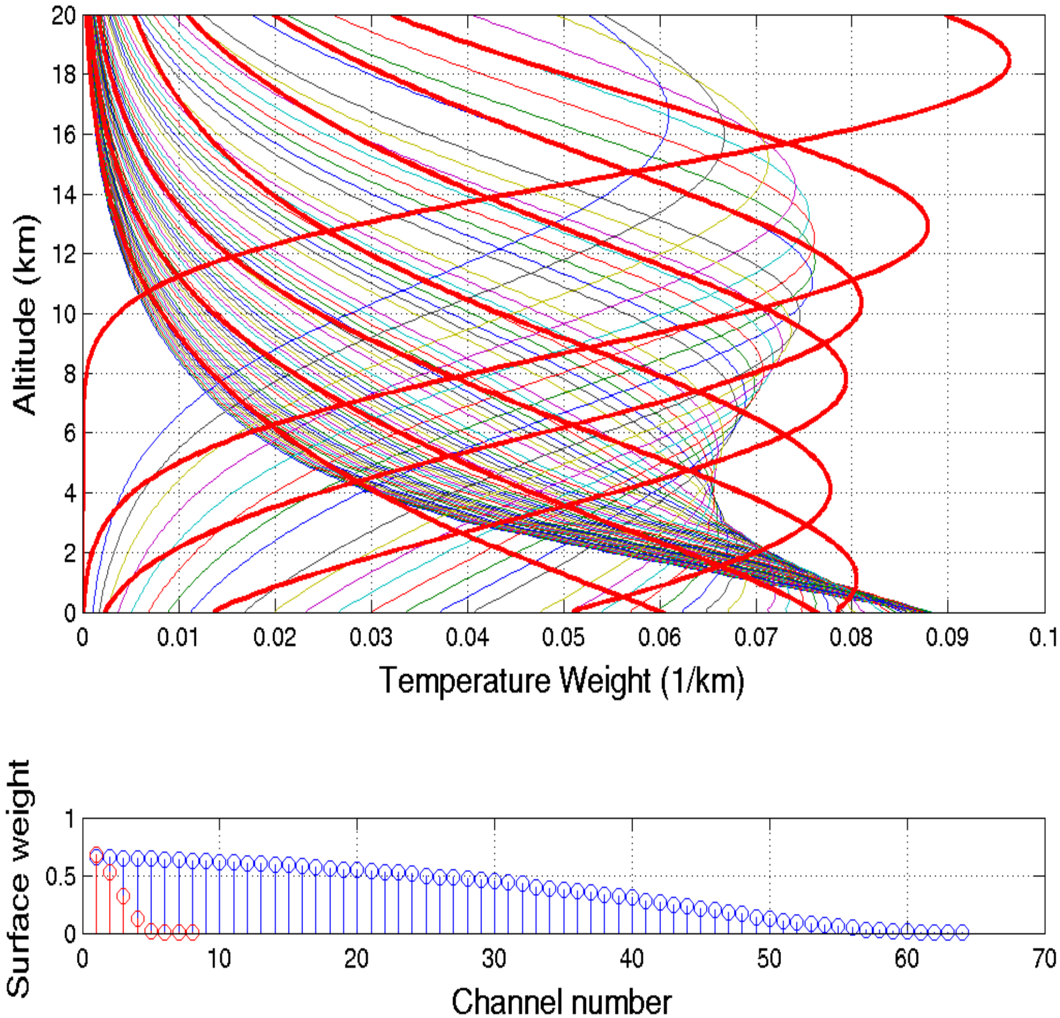


Array microscans; every spot on the ground is measured by 88 channels

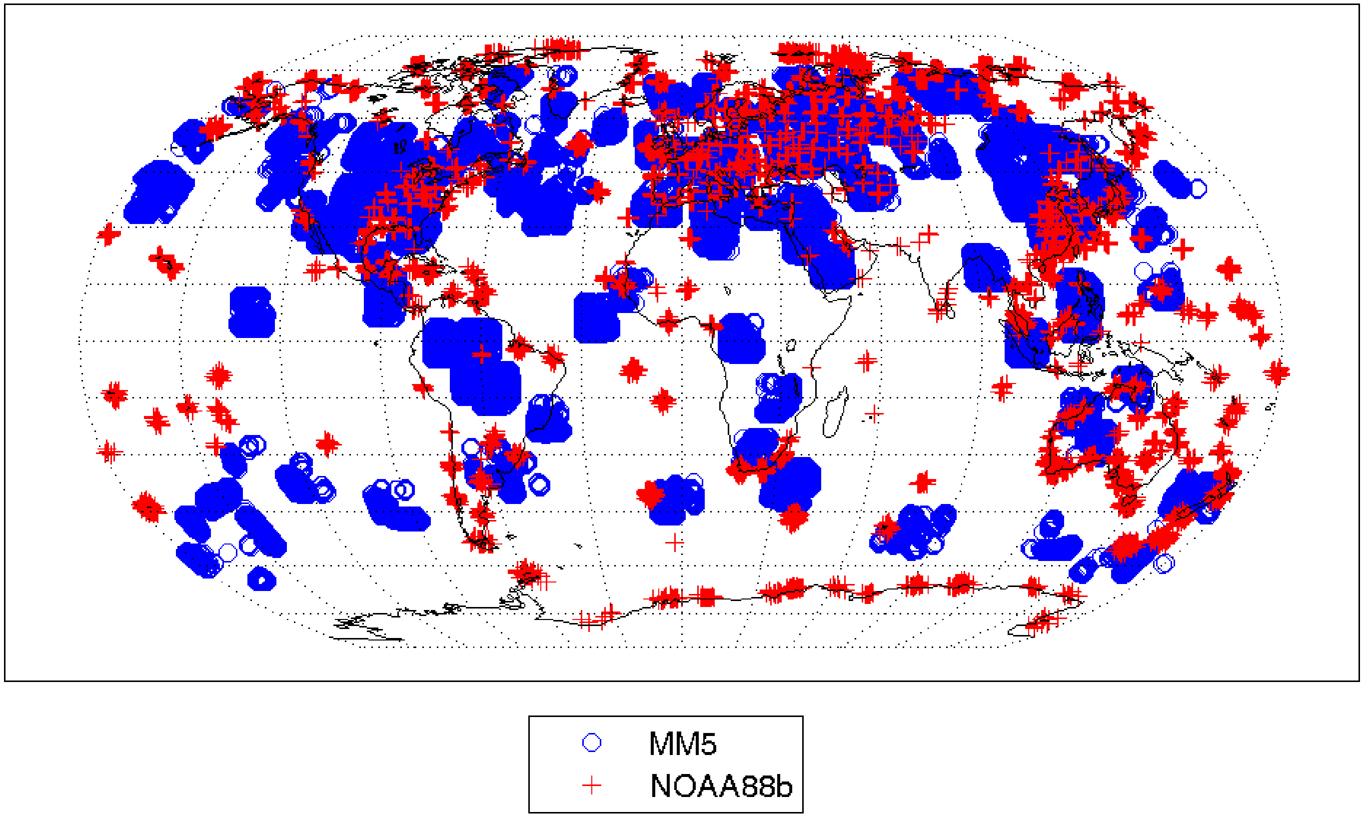
Spectral Multiplexing Concept



GeoMAS versus "Traditional" 60-GHz Bands



Global Profile Sets for Performance Assessments



MM5 characterized by high water content
NOAA88b characterized by high variability

GeoMAS Channels

(coverage of 10,000x10,000 km^2 area in 15 min is assumed)

- **GeoMAS 118-GHz**
  - 64 channels on the low-frequency side of the 118.75-GHz line

    ΔT_{RMS} = 0.2 K
- **GeoMAS 118-GHz + 183-GHz**
  - 64 channels on the low-freq side of the 118.75-GHz oxygen line
  - 16 channels within +/- 10 GHz of 183.83-GHz water vapor line

    ΔT_{RMS} = 0.25 K
- **"GeoMAS 88" (89-GHz + 118-GHz + 183-GHz)**
  - 64 channels on the low-freq side of the 118.75-GHz oxygen line
  - 16 channels within +/- 10 GHz of 183.83-GHz water vapor line
  - 8 channels at 89 +/- 0.5 GHz

    ΔT_{RMS} = 0.15 K

Half the channels at each band are H-pol, the other half are V-pol

Synthetic Thinned Aperture Radiometer (STAR) Assumptions

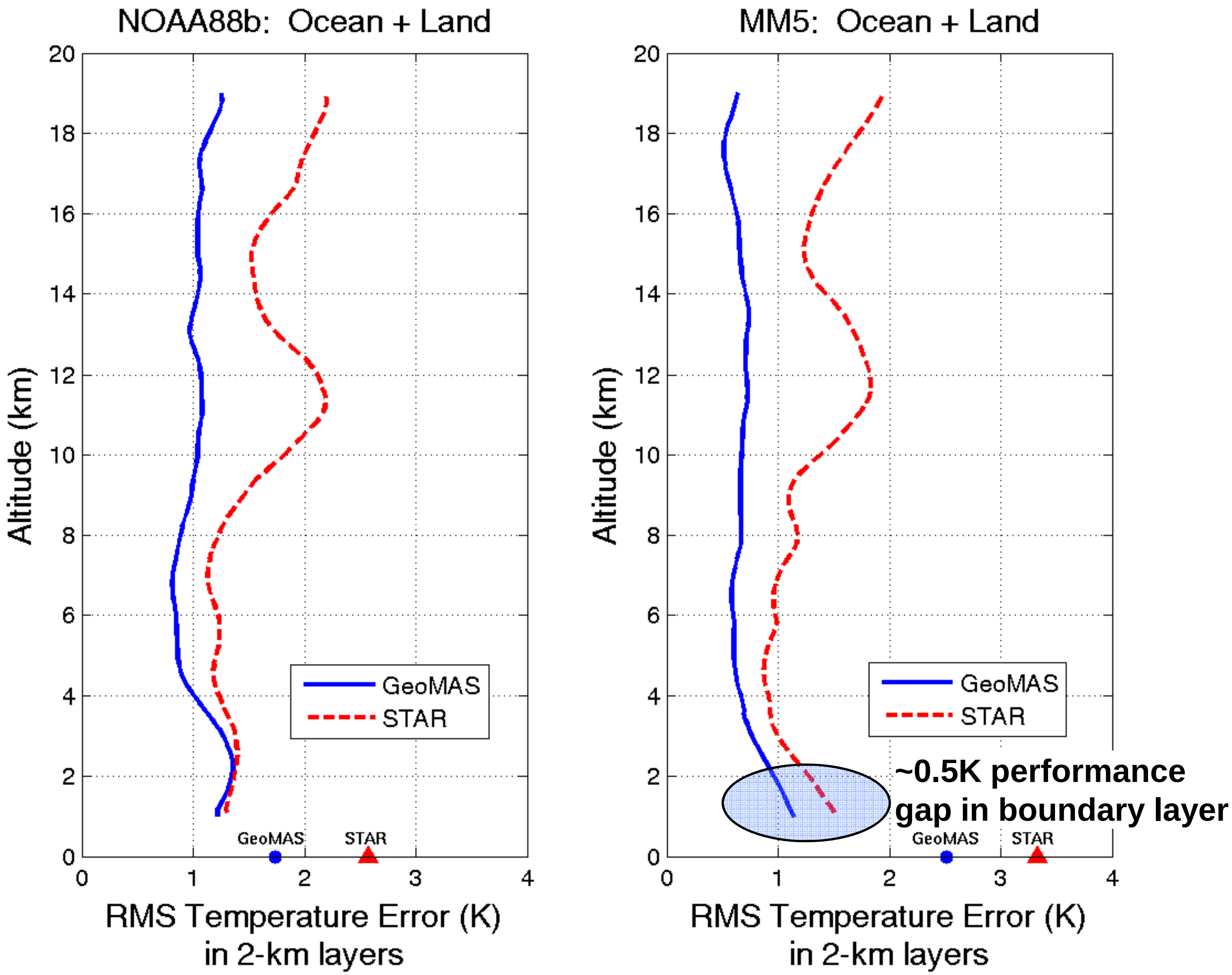
- **Six oxygen channels (identical to AMSU-A):**
  - **50.3, 52.8, 53.596, 54.4, 54.94, 55.5 GHz**
  - **ΔT_{RMS}: 0.5, 0.35, 0.5, 0.35, 0.35, 0.35 K**

- **Four water vapor channels (three identical to AMSU-B):**
  - **183.31 $\pm$ 1, 3, and 7 GHz; 167 GHz**
  - **ΔT_{RMS}: 1, 0.71, 0.5, 0.71 K**

- **Fundamental receiver parameters (T_{sys} and τ) identical to those used for GeoMAS**

B. Lambrigtsen, S. Brown, T. Gaier, P. Kangaslahti, and A. Tanner, "A baseline for the decadal-survey PATH mission," *Proc. IGARSS*, vol. 3, July 2008, pp. 338–341.

Temperature Retrieval Performance



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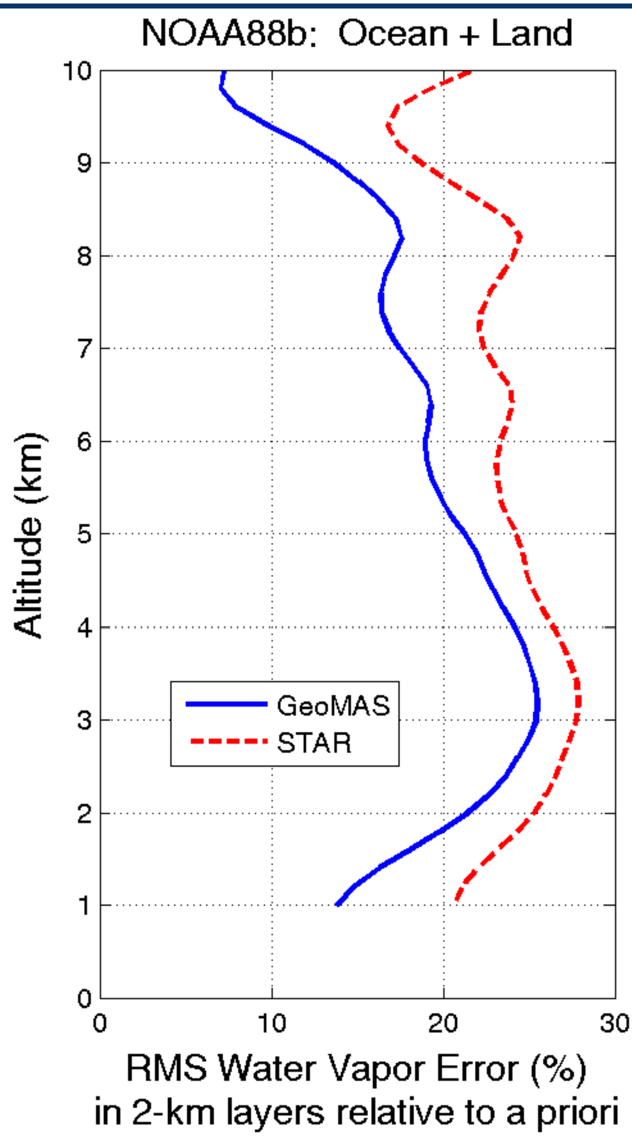
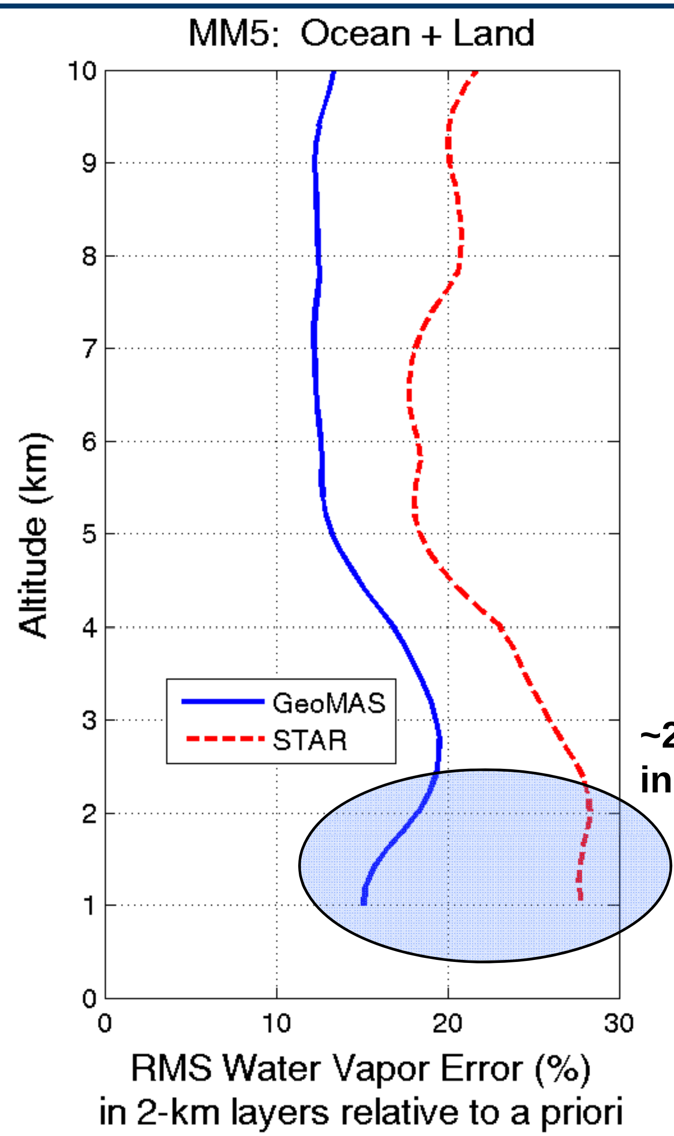
Water Vapor Retrieval Performance





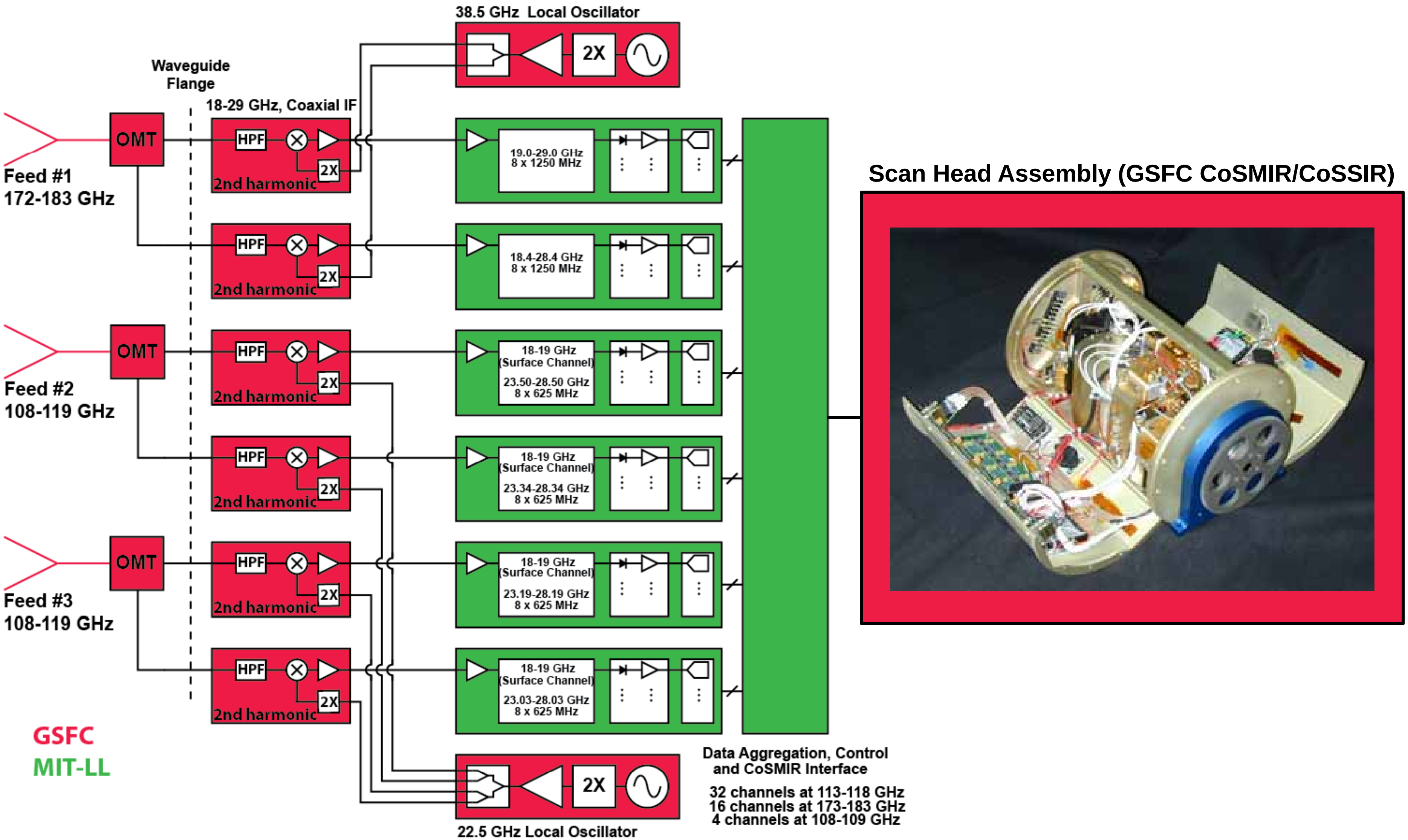
~2X performance gap in boundary layer

Precipitation Retrieval Performance: GeoMAS Superior for All Rain Rates

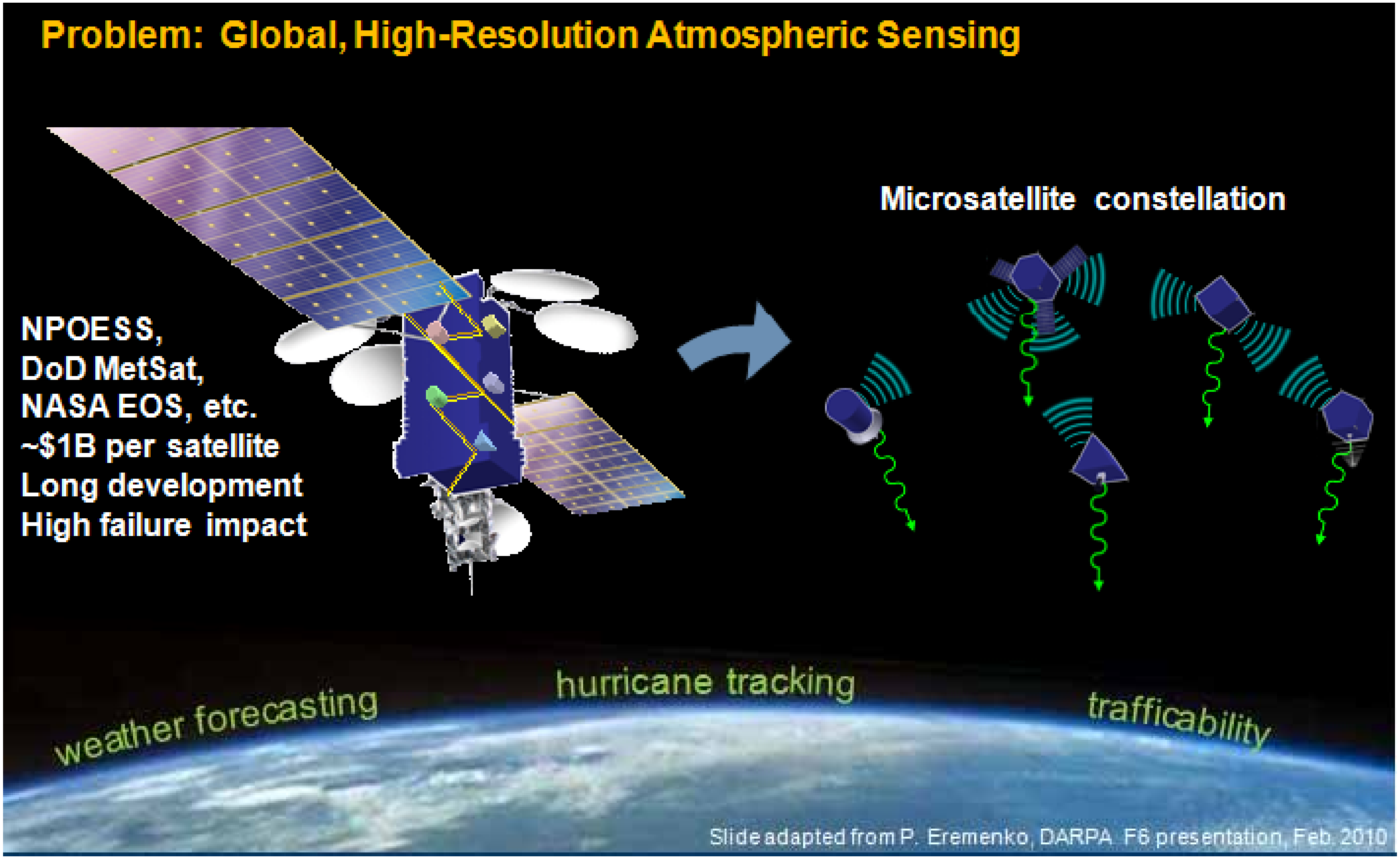
RAIN-RATE RETRIEVAL PERFORMANCE (RMS ERROR IN MM/H) FOR THE GEOMAS AND STAR SYSTEMS AT 25-KM SPATIAL RESOLUTION.

Rain-rate Range (mm/h)	GeoMAS (mm/h)	STAR (mm/h)
1-4	1.5	1.5
4-8	3.4	3.7
8-16	6.0	6.8
16-32	10.2	10.6
32-64	16.9	17.9

Hyperspectral Microwave Receiver Tech Demo Funded by NASA ACT



State-of-the-Art: Large, Monolithic Systems
Are Distributed Systems a Better Approach?



NASA Decadal Survey Interim Report June 2012

"<u>The nation's Earth observing system is beginning a rapid decline in capability as long-running missions end and key new missions are delayed, lost, or canceled. The projected loss of observing capability could have significant adverse consequences for science and society.</u> The loss of observations of key Earth system components and processes will weaken the ability to understand and forecast changes arising from interactions and feedbacks within the Earth system and limit the data and information available to users and decision makers. Consequences are likely to include slowing or even reversal of the steady gains in weather forecast accuracy over many years and degradation of the ability to assess and respond to natural hazards and to measure and understand changes in Earth's climate and life support systems."

Space News 1 June 2012

U.S. Air Force Spending $123.5M Weather Sat Funding on Tech Studies

"Air Force Col. Scott Larrimore, head of the Weather Systems Directorate at Air Force Space and Missile Systems Center in Los Angeles, said the Air Force will examine advanced electro-optical-infrared and microwave sensor technologies for the next-generation system. The service also will take a look at alternative mission architectures including a disaggregated approach in which sensors are dispersed among several small satellite platforms rather than loaded onto larger platforms, he said."

Recent Environmental Monitoring Initiatives: New Challenges and New Solutions

- **Spaceborne sensing needs are evolving:**
  - **High survivability**
  - **Flexible architectures**
  - **Rapid technology insertion**

- **The need for high resolution, SNR, and persistence is constant**

- **Budgets are shrinking, but sponsors are amenable to new ideas**

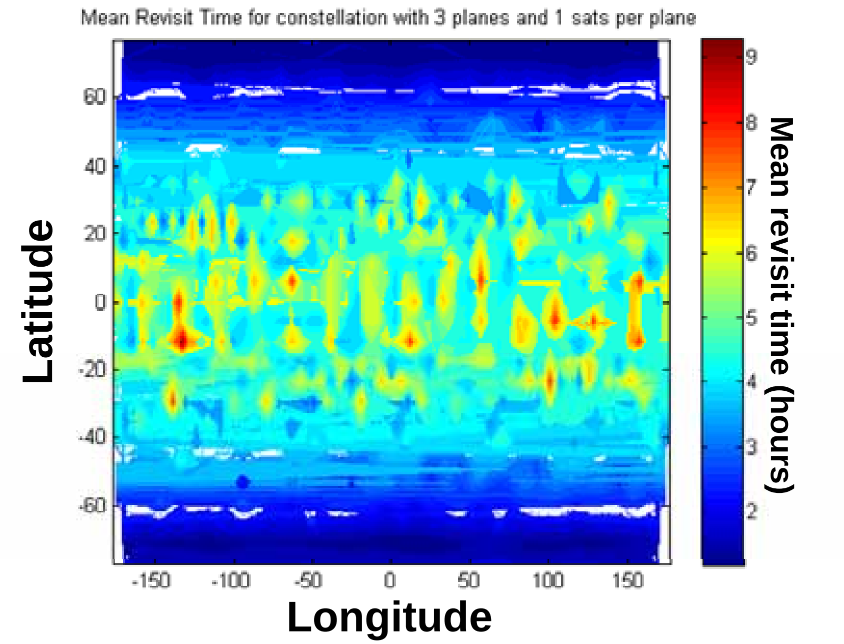
These Challenges Motivate Constellation Approaches

Passive Microwave Sensing is Particularly Well Suited

Architecture Studies Show Great Promise for Constellation Approaches

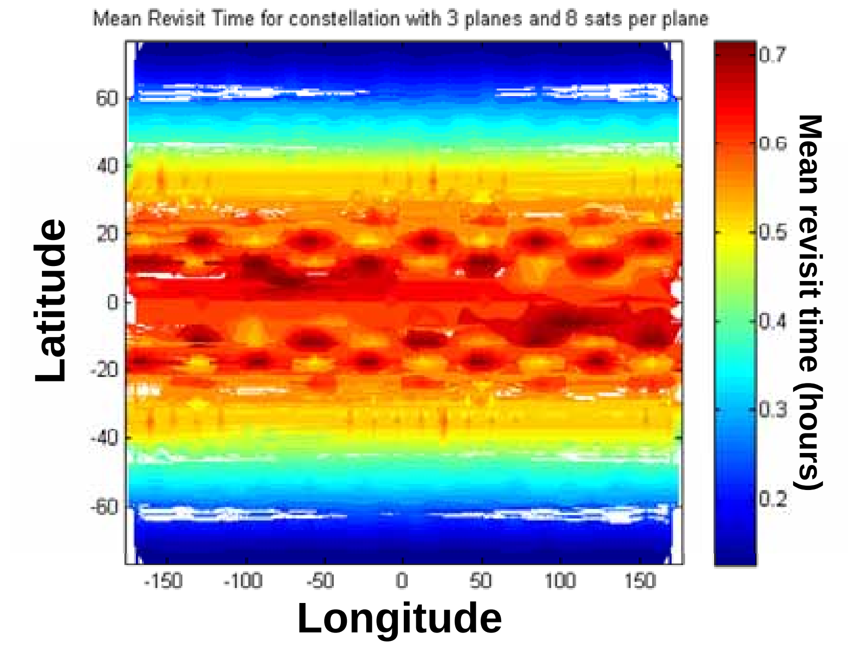
State-of-the-art
$500M system cost (w/ launch)

3 planes – 1 sat per plane



CubeSat constellation
$100M system cost (w/ launch)

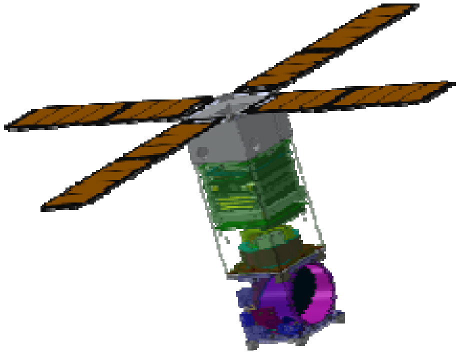
3 planes – 8 sat per plane



Better than 10X Revisit Rate Improvement in Tropics

Outline

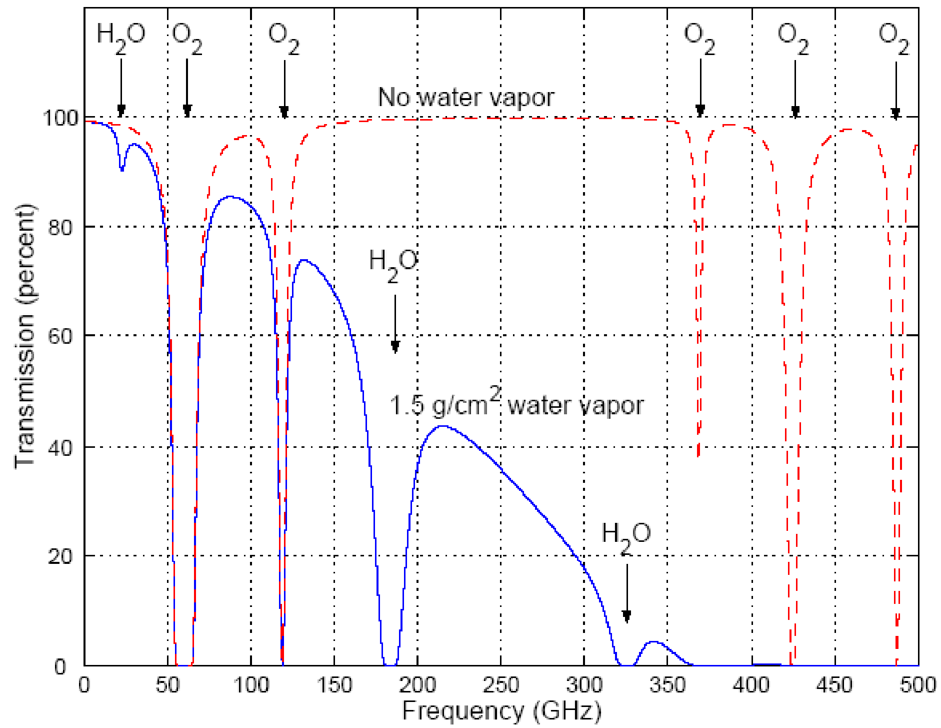
- **Introduction and Motivation**
- **Mission Objectives**
- **Spacecraft Subsystems**
  - **Structures**
  - **Avionics**
  - **Communications**
  - **Power**
  - **ADCS**
  - **Thermal**
- **Payload: 118-GHz Microwave Spectrometer**
- **Path Forward**



MicroMAS
3U CubeSat

Microwave Atmospheric Sensing

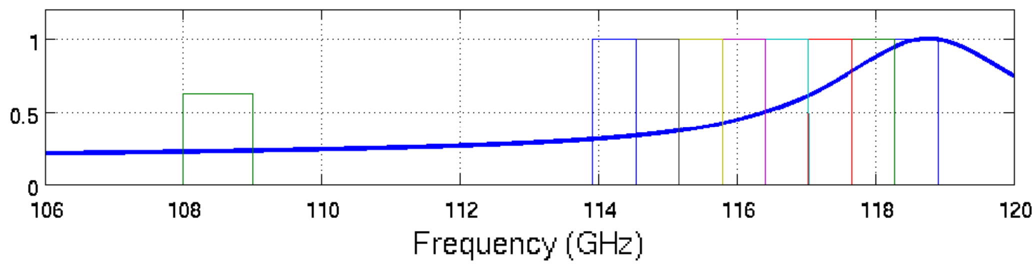
Cloud Penetration

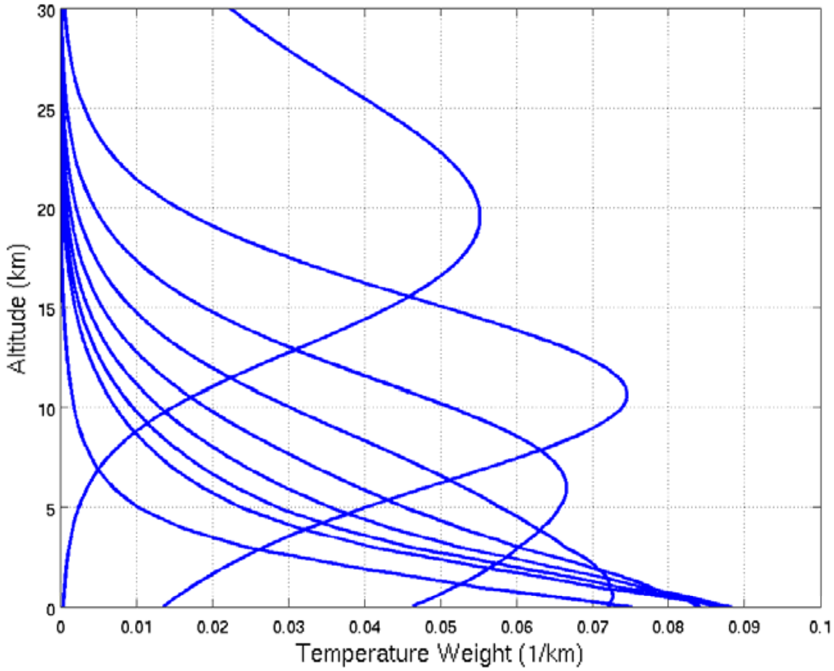


The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines

MicroMAS Channel Characteristics

Left edge	Center	Right edge	Bandwidth
113.9135	114.2260	114.5385	0.625
114.5375	114.8500	115.1625	0.625
115.1615	115.4740	115.7865	0.625
115.7855	116.0980	116.4105	0.625
116.4095	116.7220	117.0345	0.625
117.0335	117.3460	117.6585	0.625
117.6575	117.9700	118.2825	0.625
118.2815	118.5940	118.9065	0.625
108.0000	108.5000	109.0000	1.0000

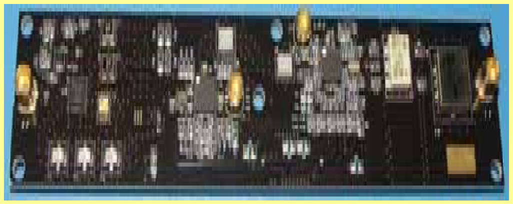




Approximately 1 rev/sec
1-degree sample spacing (Nyquist)
+/- 50-degree swath

Recent Work & Enabling Technologies

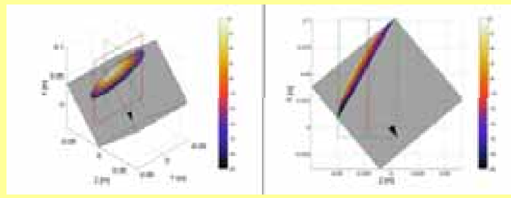
Ultra-compact receivers



MIT LL
UMass Amherst

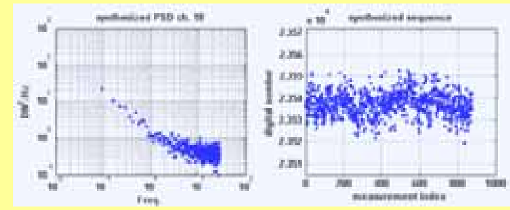
DoD 2011/2012

Multiband antenna systems



MIT LL
Northeastern U
UMass Amherst

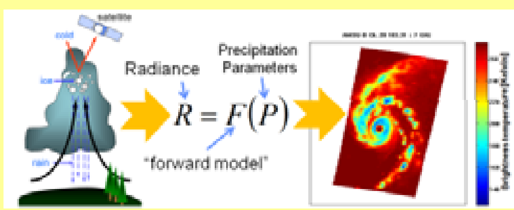
Novel calibration methods



MIT LL
MIT campus
Tufts U

NASA & NOAA

Geophysical retrievals and performance analysis

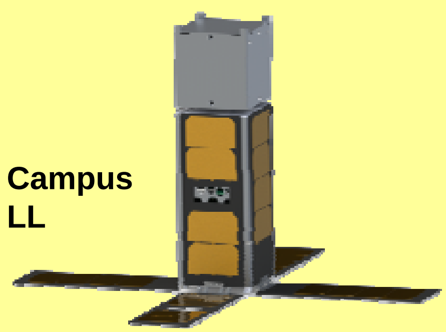


MIT LL
MIT Campus

NASA & NOAA

Nanosatellite Space Systems Engineering

MIT Campus
MIT LL

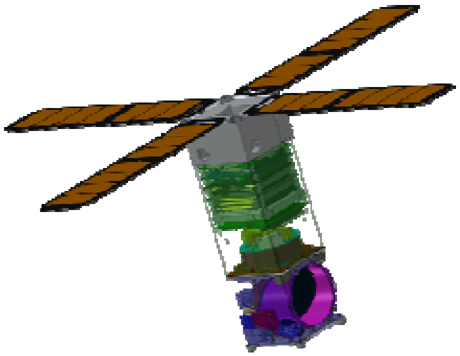


Beaver Works 2012+

MicroMAS Mission Objectives

Demonstrate Core Element of a Transformative Environmental Monitoring Architecture

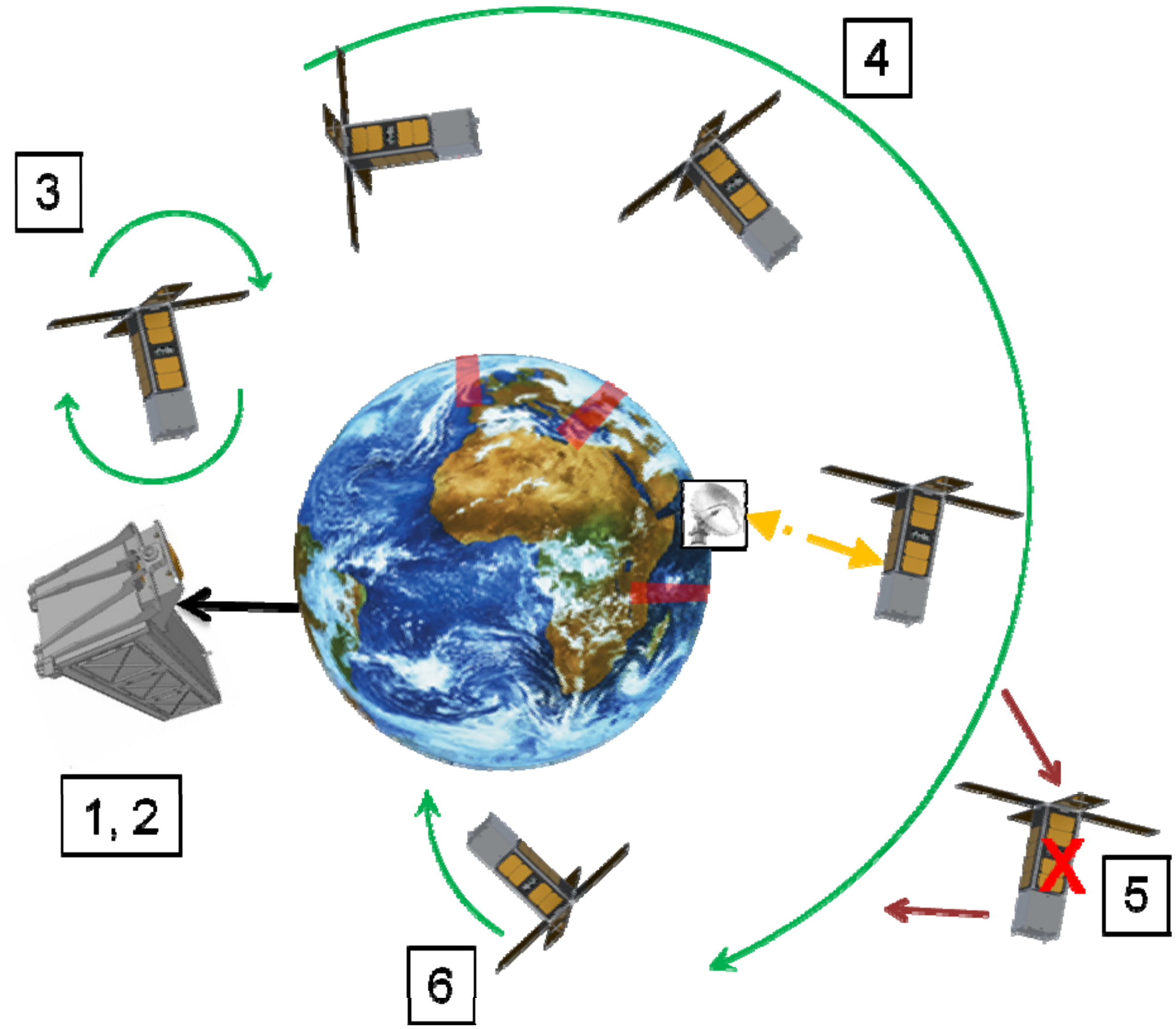
- Synoptic sensing with focus on hurricanes and severe weather
- Slightly inclined orbit; ~500-km orbit altitude
- 25-km pixel diameter at nadir (cross-track scan out to ±50°)
- Geolocation error less than 10% of pixel diameter
- 1 K absolute accuracy; 0.3 K sensitivity
- 1-year mission lifetime
- 20 kbps (avg) downlink
- 12 W (avg) power



3U CubeSat

MicroMAS Mission Overview

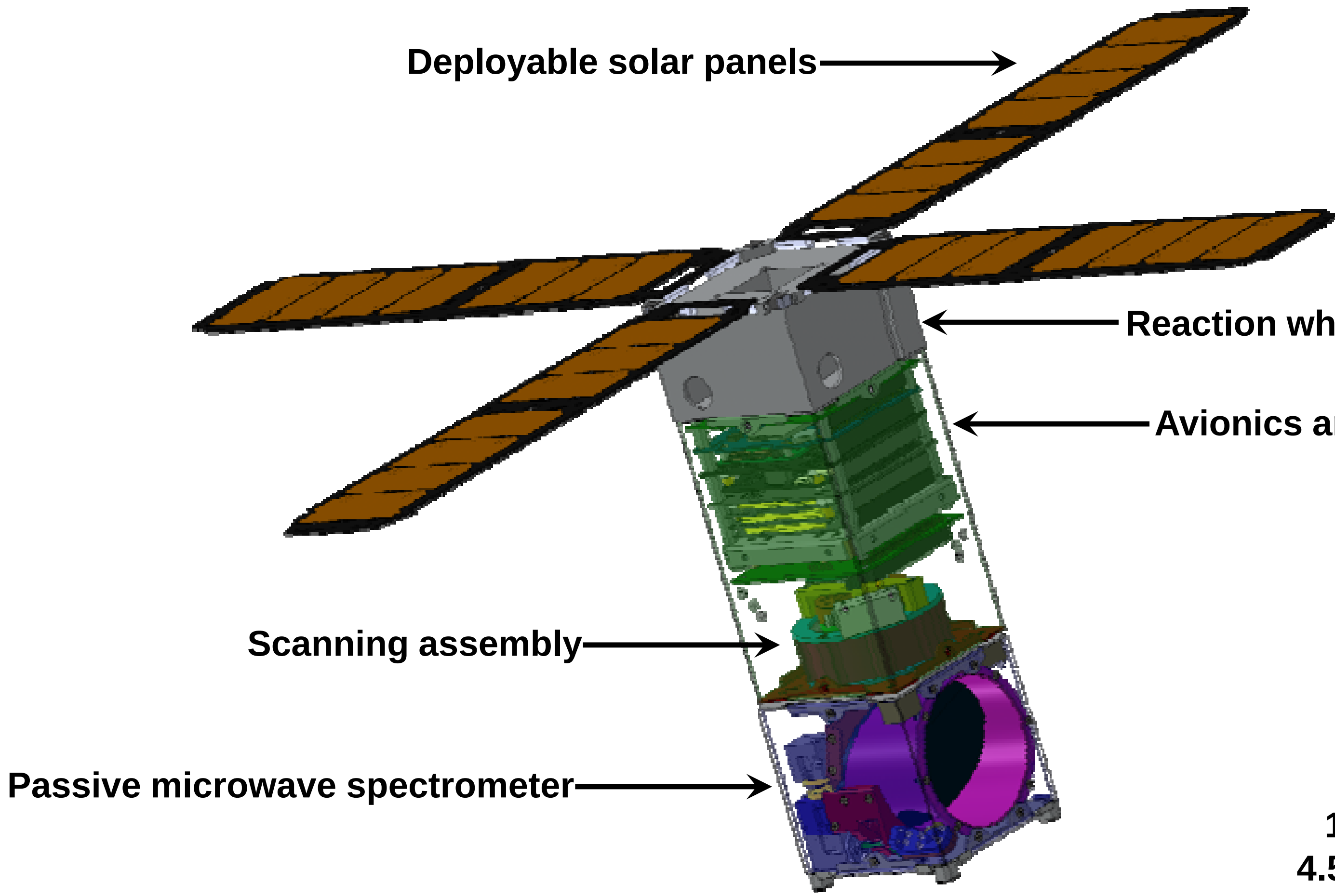
1	Mission Planning/Pre-Launch Integration
2	Launch as secondary payload
3	On-orbit deployment and initialization
4	Mission Ops - 6 months nominal
5	Fault Recovery/ Limited Ops
6	Mission Termination



MicroMAS Radiometer Objectives

- 8 channels near 118.75-GHz oxygen line
- 1 window channel
- Cross-track scan
- Spatial Nyquist sampling
- 2.4-degree FWHM antenna beam
- 95% beam efficiency
- 2 W (avg)
- 0.3 K NEDT
- 1 K calibration accuracy
- Noise diode, earth limb, and cold sky calibration

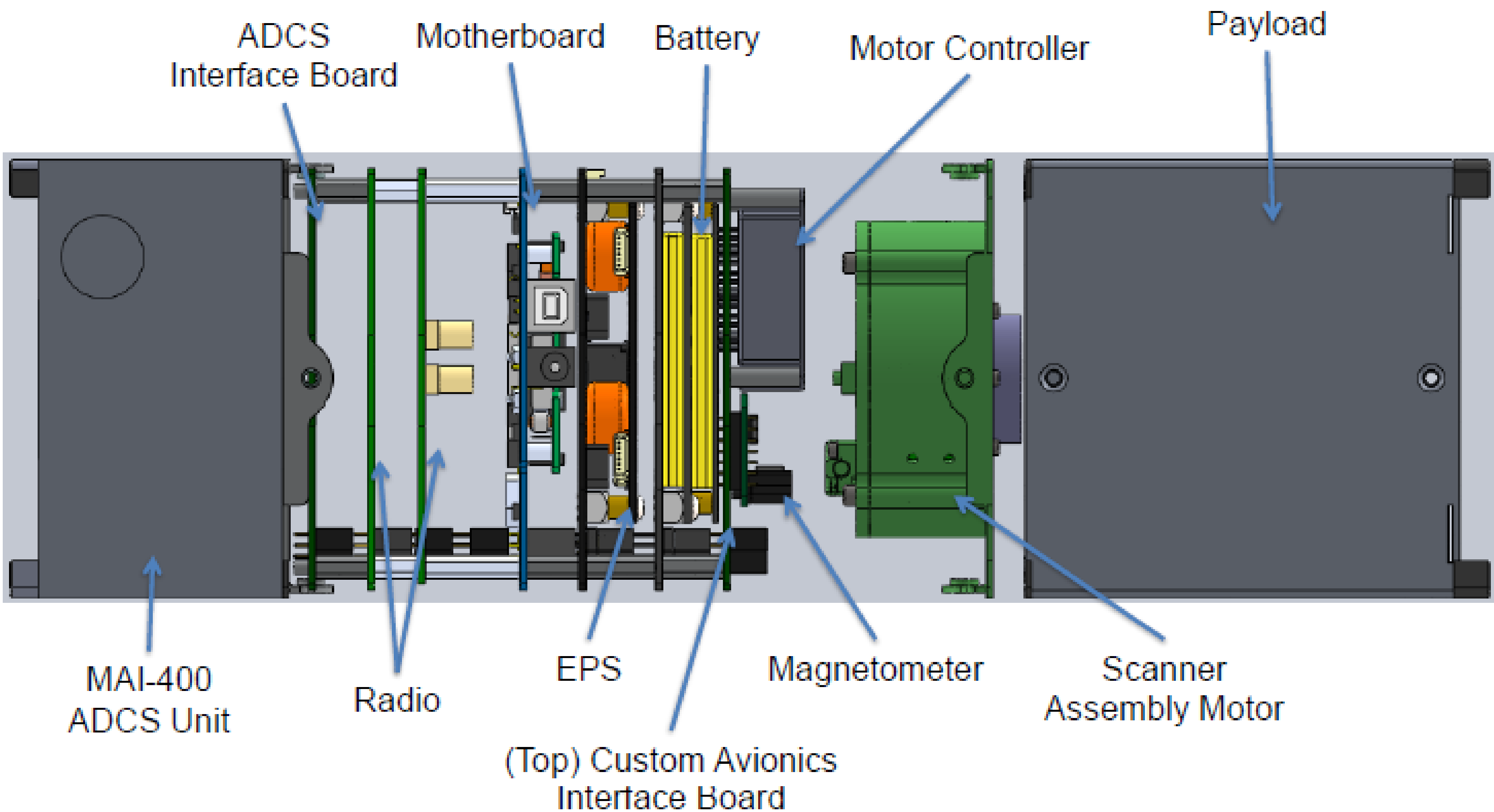
MicroMAS 3U Spacecraft



10x10x34 cm
4.5 kg, 12 W avg

Body-mounted solar panels not shown

MicroMAS Bus Design

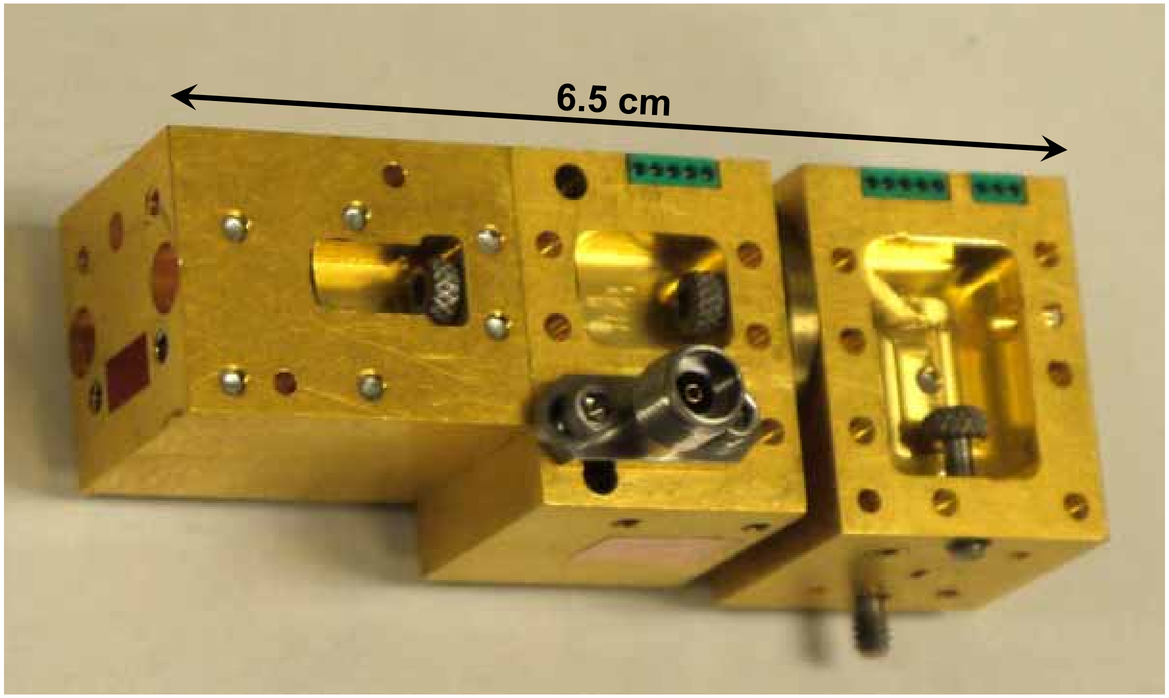


Spacecraft Bus Status

- **Engineering Development Model (EDM) complete in Oct 2011**
  - **Functional testing**
  - **Vibration testing**
  - **Thermal testing**
  - **TVAC testing**
  - **Air bearing testing**

- **Flight Model under development**
  - **Long-lead parts ordered**
  - **Program at CDR maturity with 10% margin on mass, power, and budget**

MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department

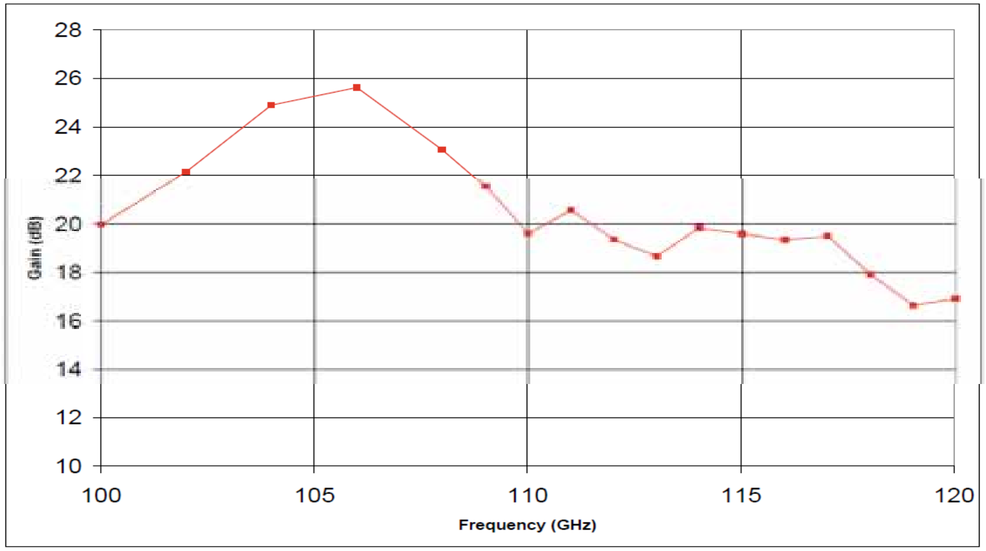


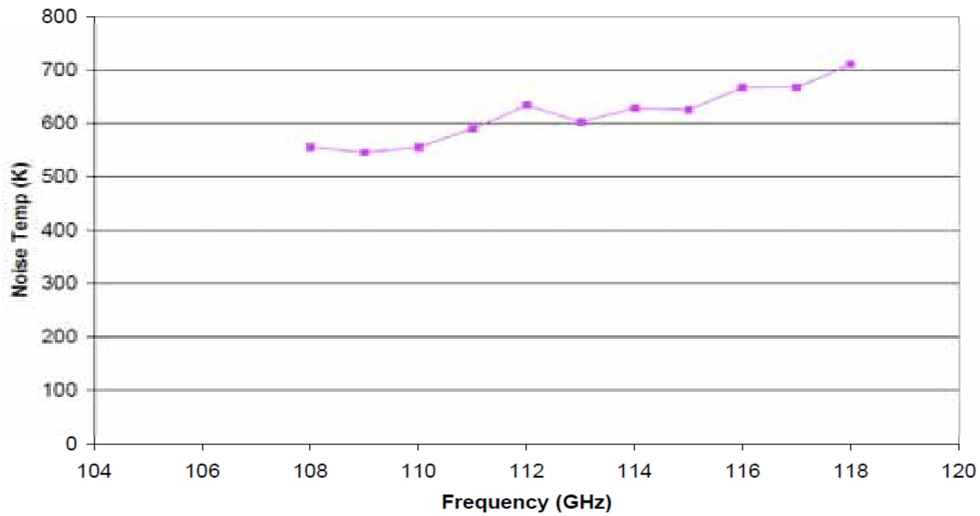
MicroMAS Tripler, Mixer, and RF Low-noise Preamplifer Modules

MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department

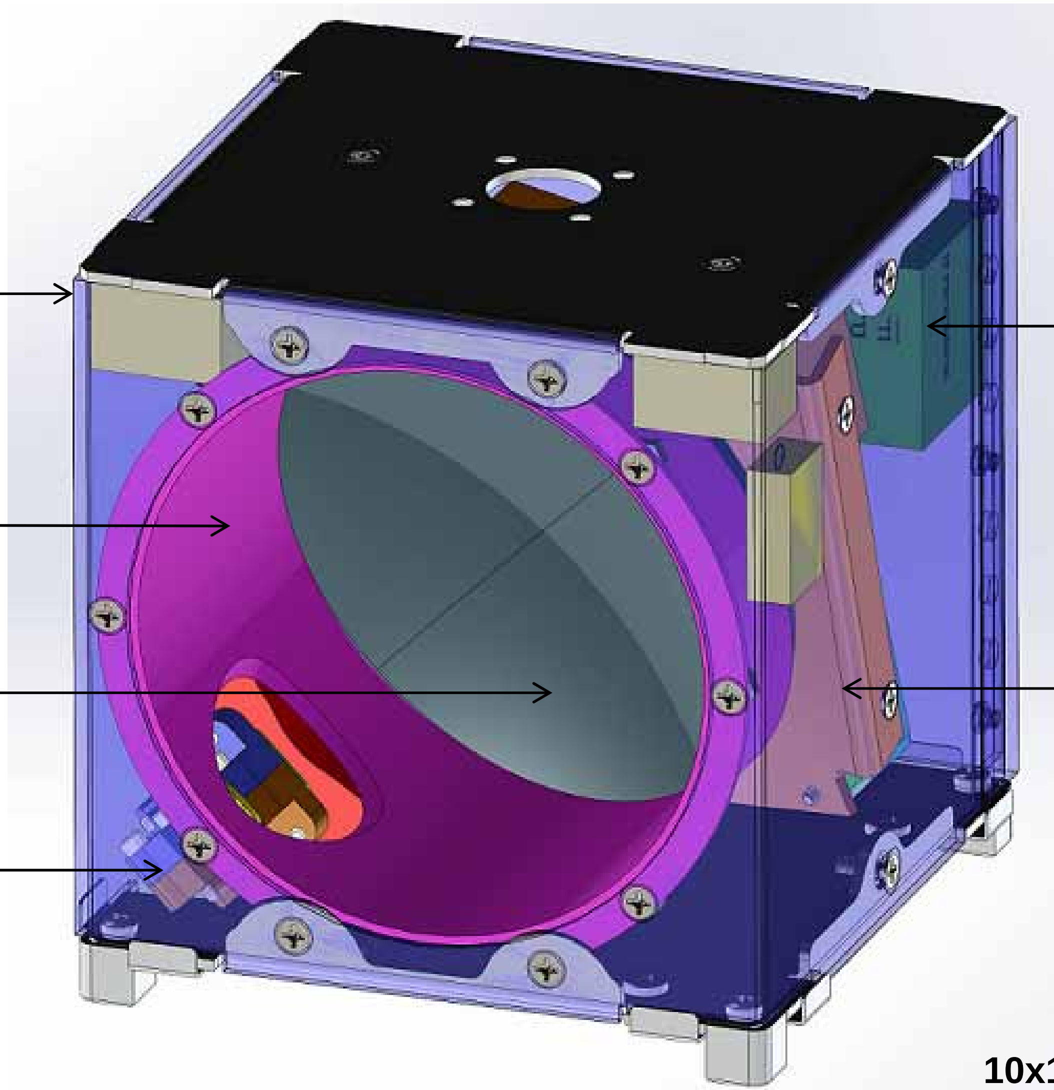
MicroMAS second stage
EM assembly

Fabrication of flight units underway



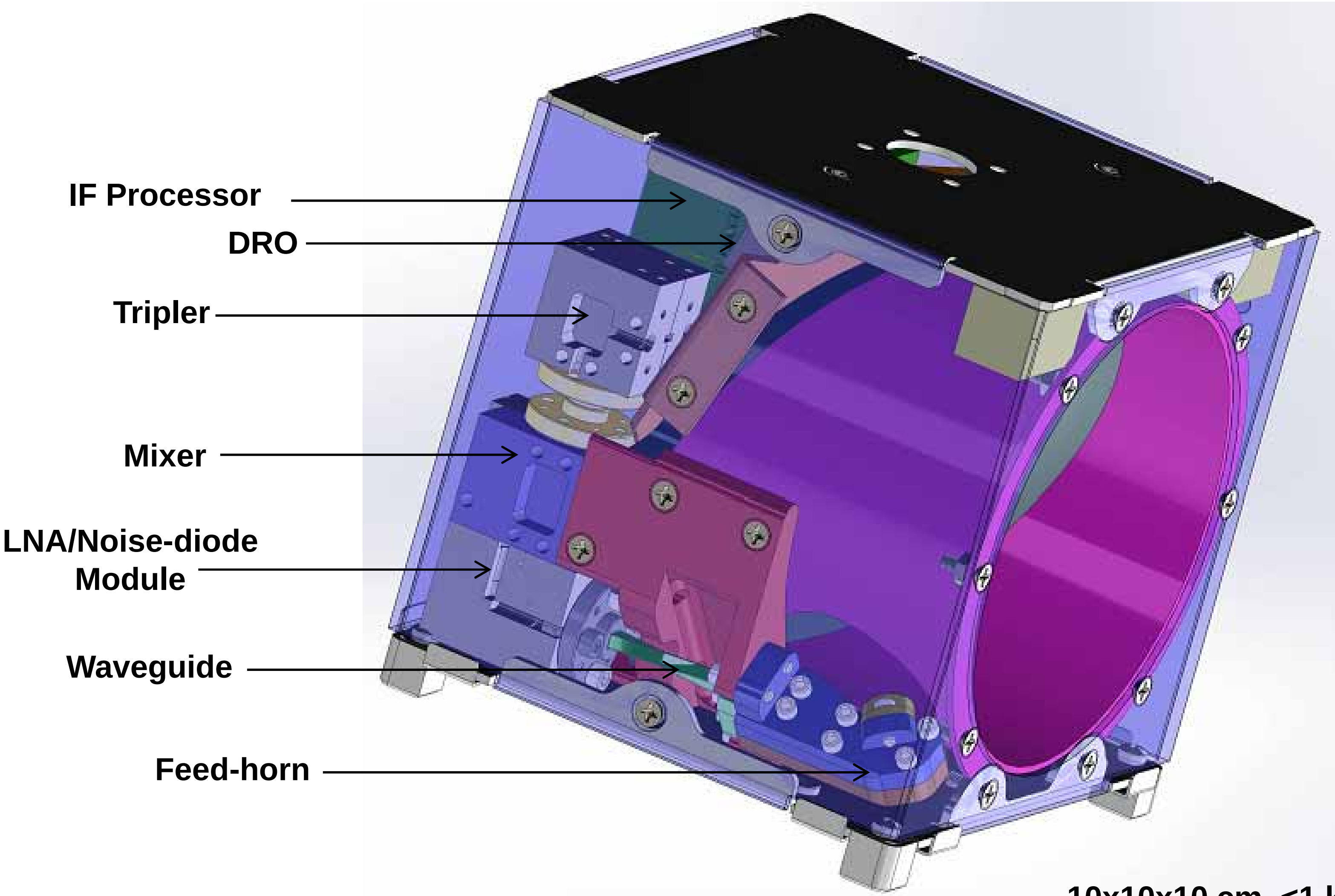


MicroMAS Payload (Front View)
118-GHz Spectrometer



10x10x10 cm, <1 kg, <2 W

MicroMAS Payload (Side View)
118-GHz Spectrometer



10x10x10 cm, <1 kg, <2 W

Path Forward

- **Launch to be provided in late 2013 / early 2014 by NASA**

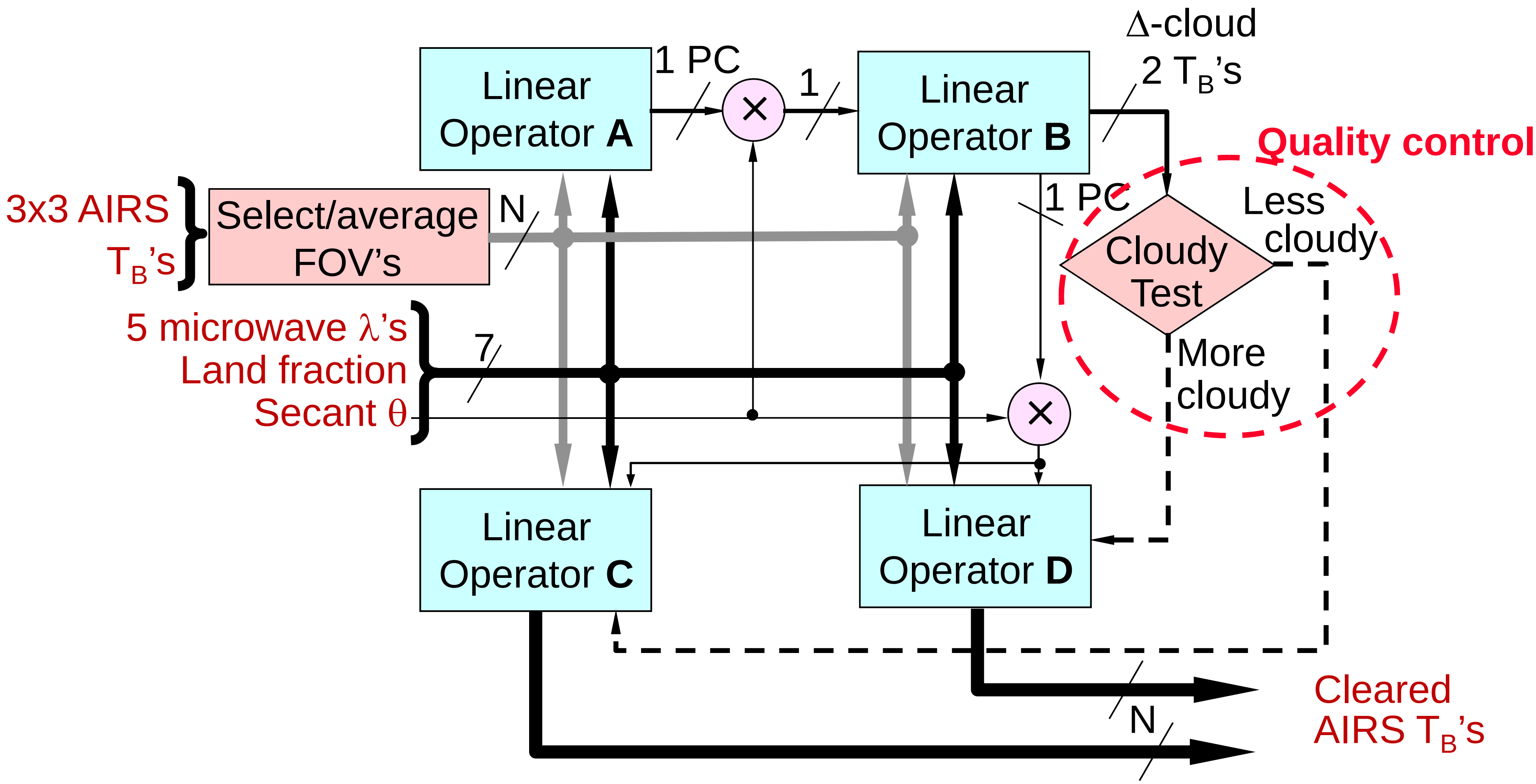
- **Concept demonstration illuminating new regions of architecture trade space for future Earth Science missions**
  - **All-weather sounding of highly dynamic phenomena, including convective storms, hurricanes, etc.**
  - **Studies of the hydrologic cycle**
    - **Vapor, liquid, ice; precipitation**
  - **Studies of the diurnal cycle**

Summary and Final Thoughts

- Earth atmospheric remote sensing is entering the era of "High Definition," improving forecasting and climate study:
  - Weather models now capable of resolving cloud and precipitation
  - Propagation models now capable of detailed scattering calculations
  - Advanced signal processing algorithms now capable of information extraction and fusion in high dimensional data sets
  - Microwave and infrared spectrometers observe with unprecedented accuracy, resolution, and revisit time
- Lincoln (and MIT campus) is active in all of these areas
  - Global data sets generated with MM5 cloud resolving models
  - TBSCAT radiative transfer codes
  - SCC/NN retrieval algorithm
  - AMSU/ATMS cal/val and precipitation retrieval
  - NAST-M airborne sensor
  - Advanced sensor concepts (GeoMAS, MicroMAS, and others)

Backup Slides

Block Diagram of SCC Algorithm

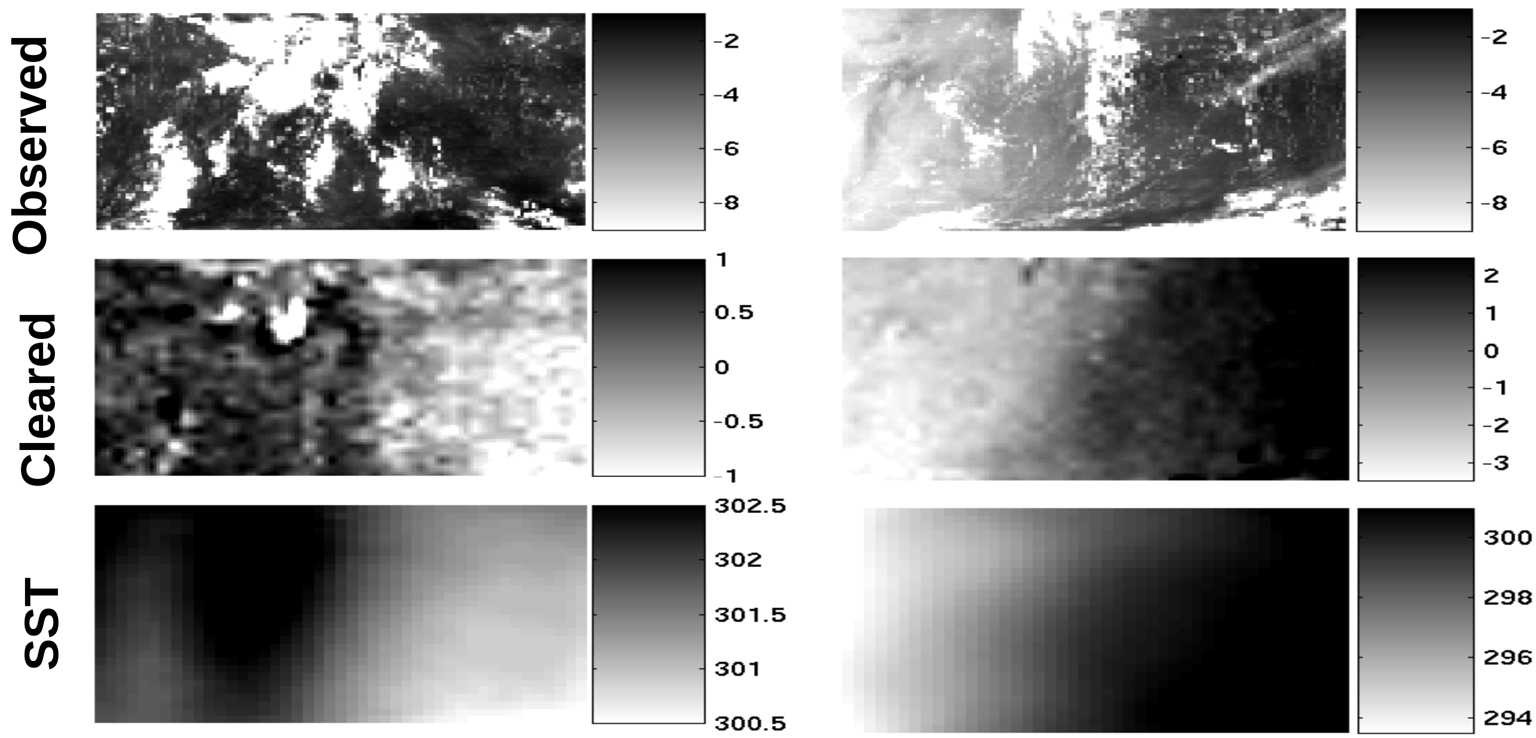


N = 2378 channels

Cho and Staelin, JGR (8/06)

Stochastic Cloud Clearing with AIRS/AMSU: Comparisons with Sea Surface Temperature

- **Angle-corrected TB images at window channels**



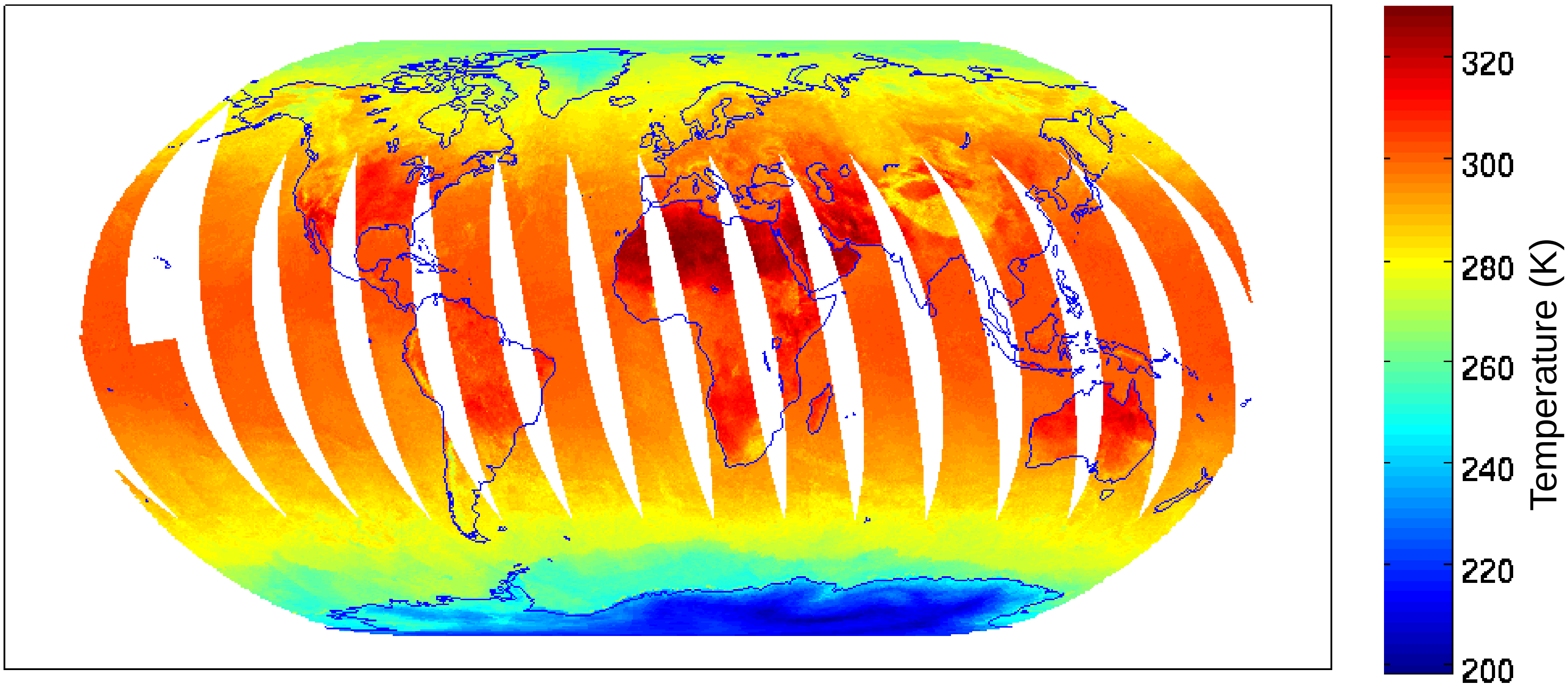
AIRS 2390.1cm^{-1}: near Hawaii   AIRS 2399.9cm^{-1}: near SW Indian Ocean

- **Clearing works well even if there is no hole (clear FOV)**

1951–2011
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Neural Network Retrieval of Global Temperature Profiles

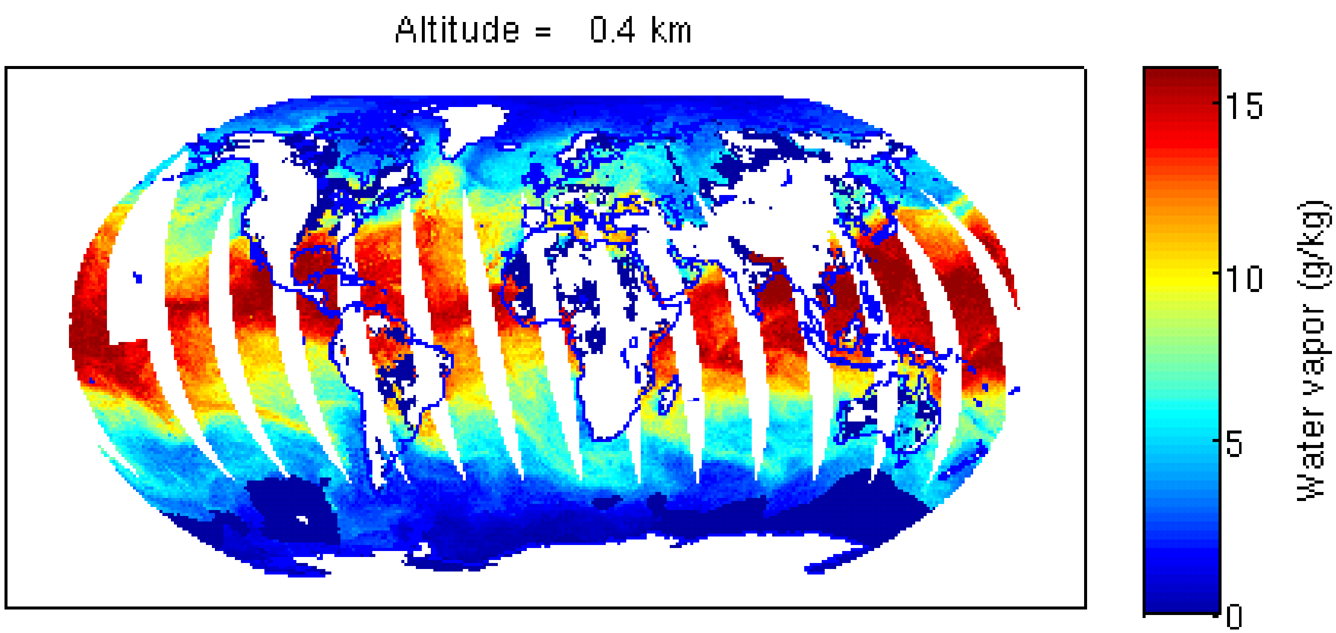
AIRS/AMSU (NASA Aqua)
Mosaic of Ascending Orbits on Sep 6, 2002



- **100X faster than state-of-the-art**
- **20% more accurate than state-of-the-art**
- **30% better yield than state-of-the-art**

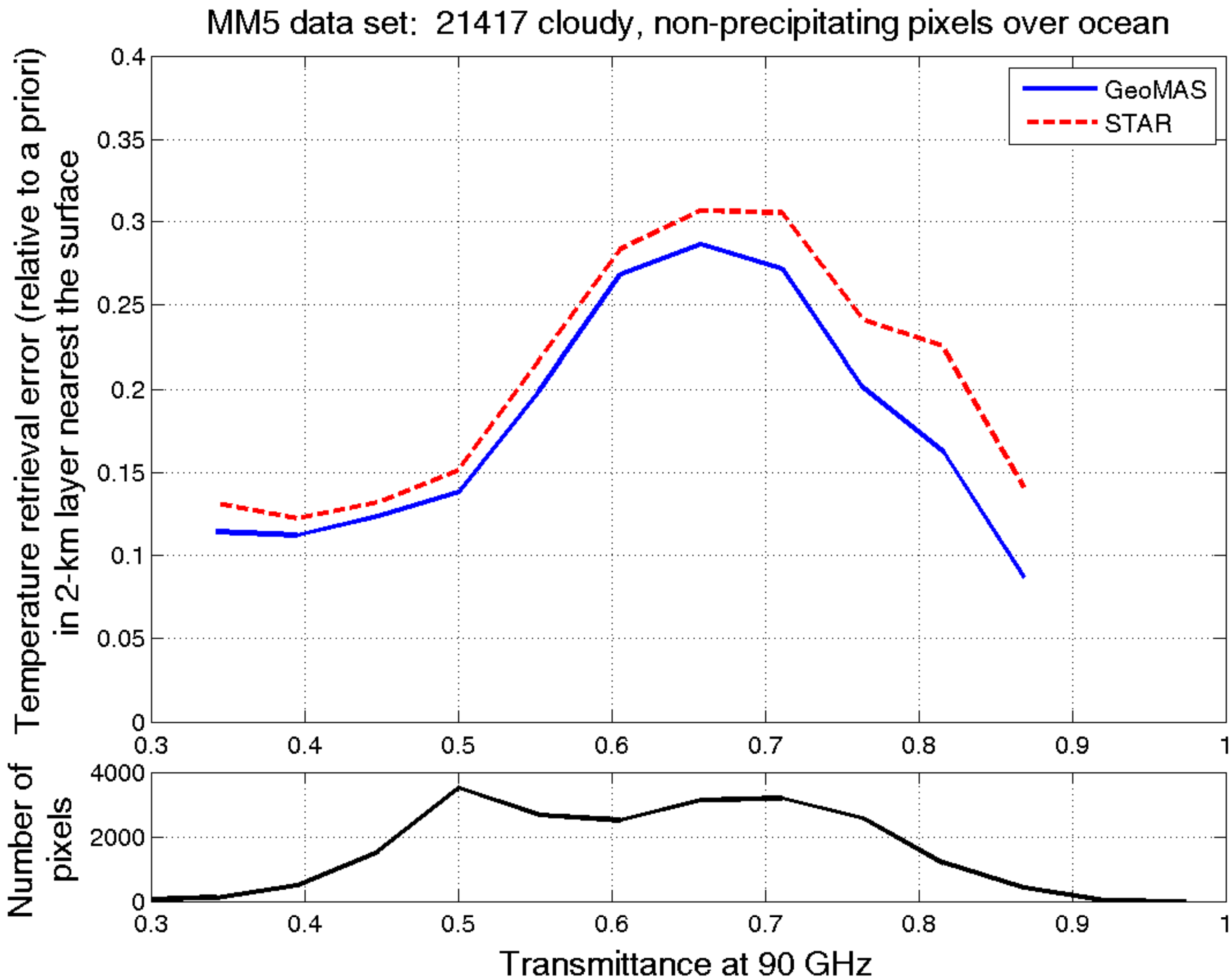
Neural Network Retrieval of Global Moisture Profile

AIRS/AMSU (NASA Aqua)
Mosaic of Ascending Orbits on Sep 6, 2002



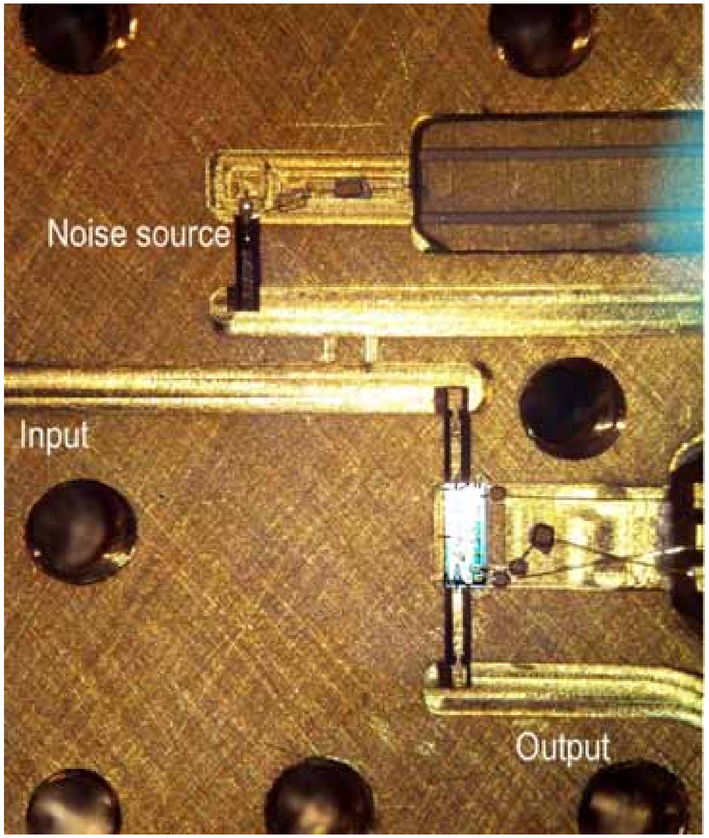
- **Water vapor is characterized by fine-scale structure**
- **Neural network retrieval captures this structure on a global scale**

GeoMAS Performance Superior, Even for Low Transmittance (High Water Content)

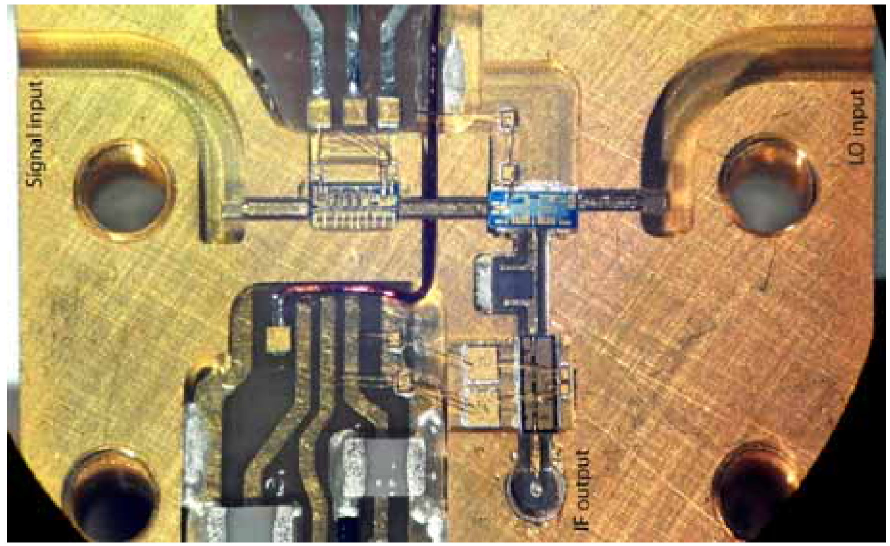


MicroMAS Receiver Engineering Model
UMass Radio Astronomy Department

First stage: RF preamplifier and noise diode
2.5 x 2 x 2 cm



Second stage: RF amplifier, mixer, and IF preamp
2.5 x 2 x 2 cm

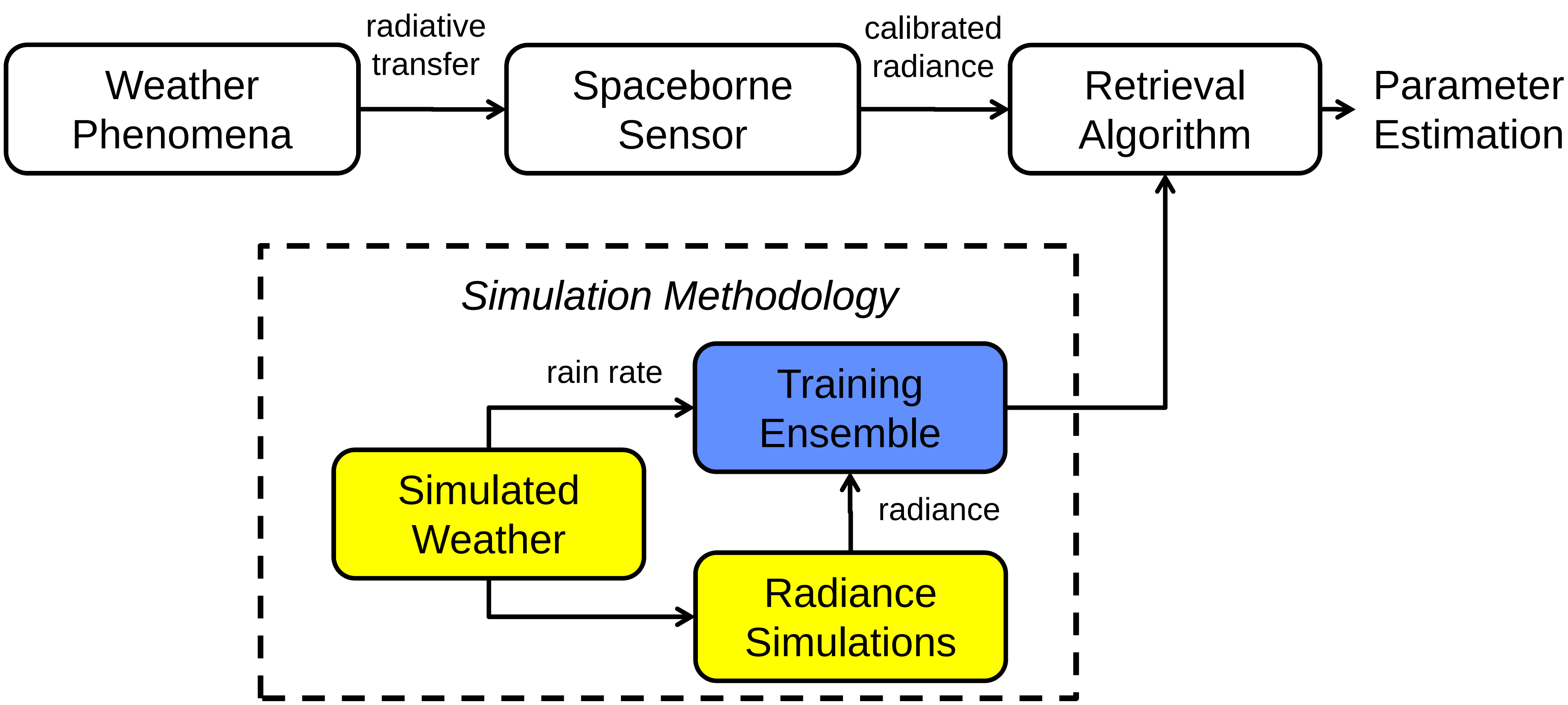


RF in: 108-119 GHz
IF out: 18-29 GHz

Outline

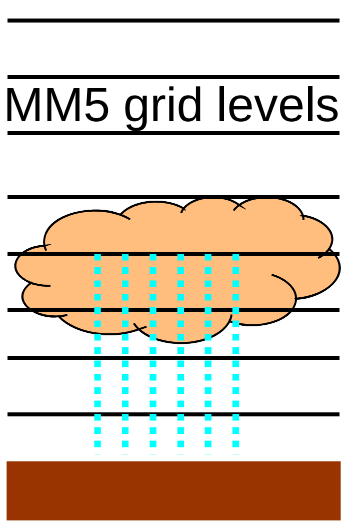
- Brief overview of MIT Lincoln Laboratory
- Introduction to space-based passive infrared and microwave atmospheric sounding
  – Motivation
  – Past, present, and future sounding systems
  – Mathematical background
- Algorithmic challenges of modern sounding systems
  – Retrieval of atmospheric temperature and moisture profiles using high-resolution IR sensors (1000's of channels)
  – Clouds impact approximately 95% of soundings (highly non-linear)
- **Recent research and new approaches:**
  – Algorithms: Neural Network Estimation; Stochastic Cloud Clearing
  – **Models: Atmospheric and radiative transfer**
  – Sensors: Hyperspectral microwave sounding (GeoMAS) and constellation sensing (MicroMAS CubeSat mission)
- Summary and Final Thoughts

Physical Models Needed for Simulations

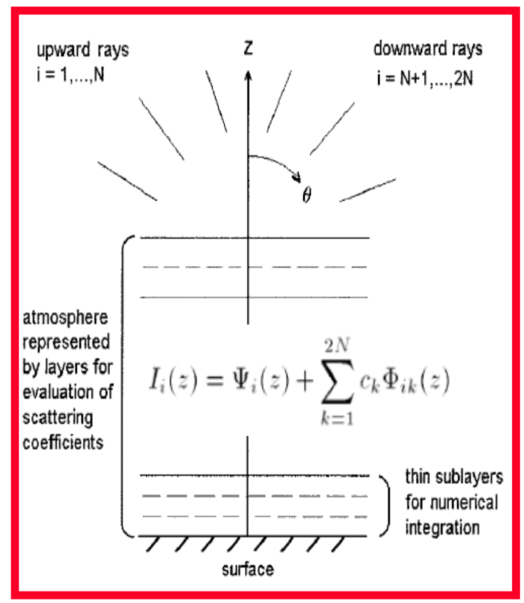


Simulation Methodology Validation

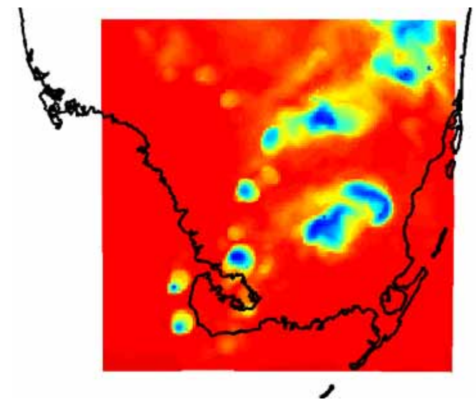
Cloud Resolving Model (CRM)

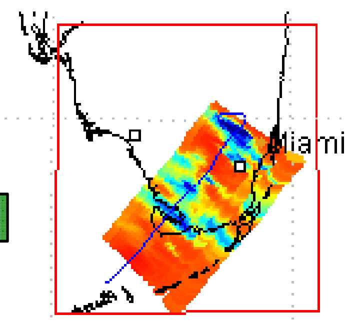


Radiative Transfer Algorithm (RTA)



Simulated Radiances





Airborne sensor measurements

- CRM = MM5 1-km saved every 15 min
- RTA = multiple-stream radiative transfer solution (TBSCAT or TBSOI)

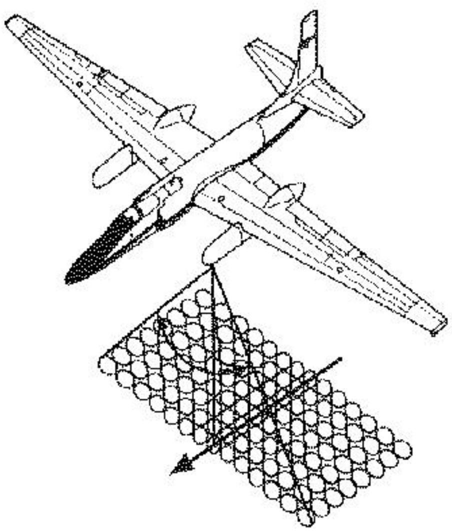
1951–2011
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

NPOESS Aircraft Sounder Testbed (NAST)

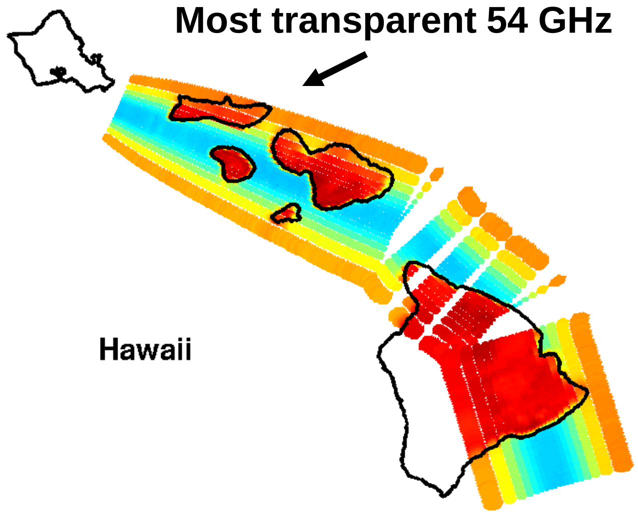
ER-2

Proteus

WB-57



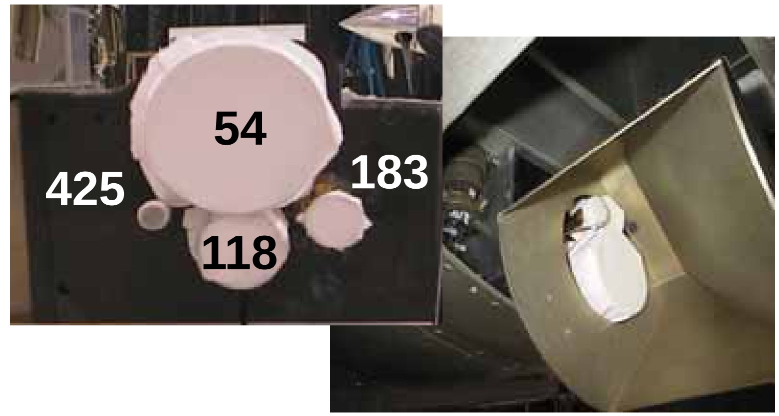
NAST-M Measurements
Most transparent 54 GHz

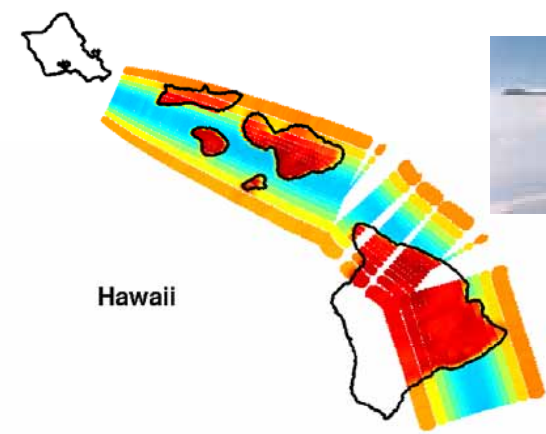


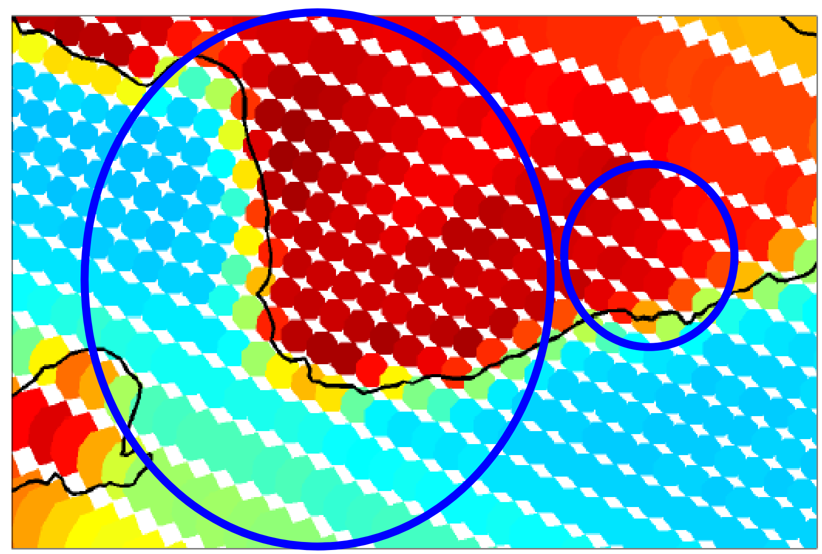
NAST- M (Microwave)

NAST-M Specifications

- Cruising altitude: ~17-20 km
- Cross-track scanning
- Scan angle: -65º to 65º
- 7.5º antenna beam width (FWHM)
- 2.5-km nadir footprint diameter
- Swath width of ~100 km
- Spectrometers at 54 GHz, 118 GHz, 183 GHz, and 425 GHz
- Nadir-viewing camera

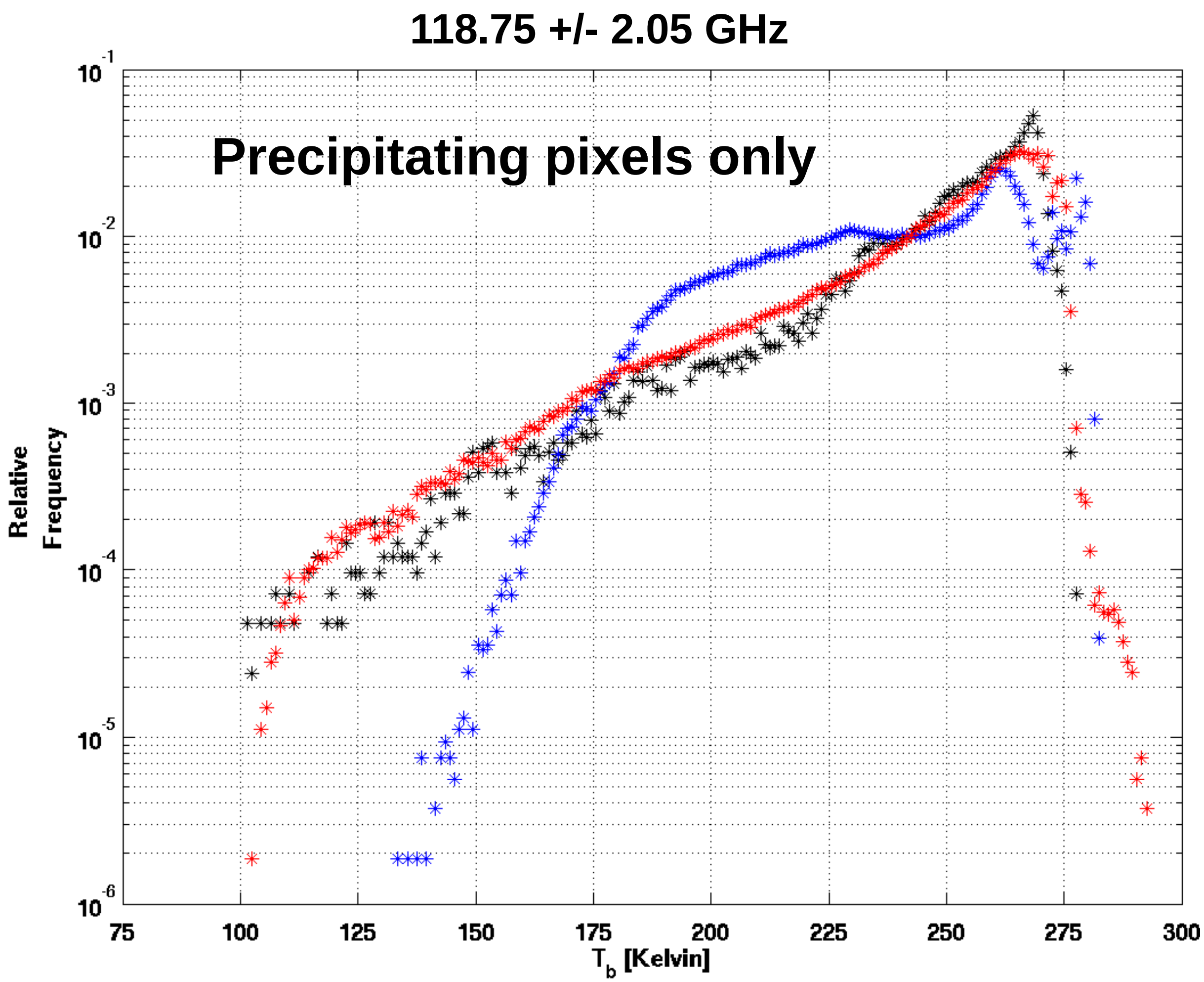






Methodology Validation

- * **Black asterisks are NAST-M observations from ten flights during the CRYSTAL-FACE 2002 deployment (41,670 pixels)**
- * **Blue asterisks are from the Suruss./Staelin methodology; (535,126 pixels from eight hours of MM5 simulation per day)**
- * **Red asterisks are the validated simulation methodology**



Surussavadee and Staelin, *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 10, Oct. 2006.