# Hyperspectral Microwave Atmospheric Sounding

W. J. Blackwell, L. J. Bickmeier, R. V. Leslie, M. L. Pieper,
J. E. Samra, and C. Surussavadee[1]

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[1]C. Surussavadee is Head of the Andaman Environment and Natural Disaster Research Center, Phuket, Thailand

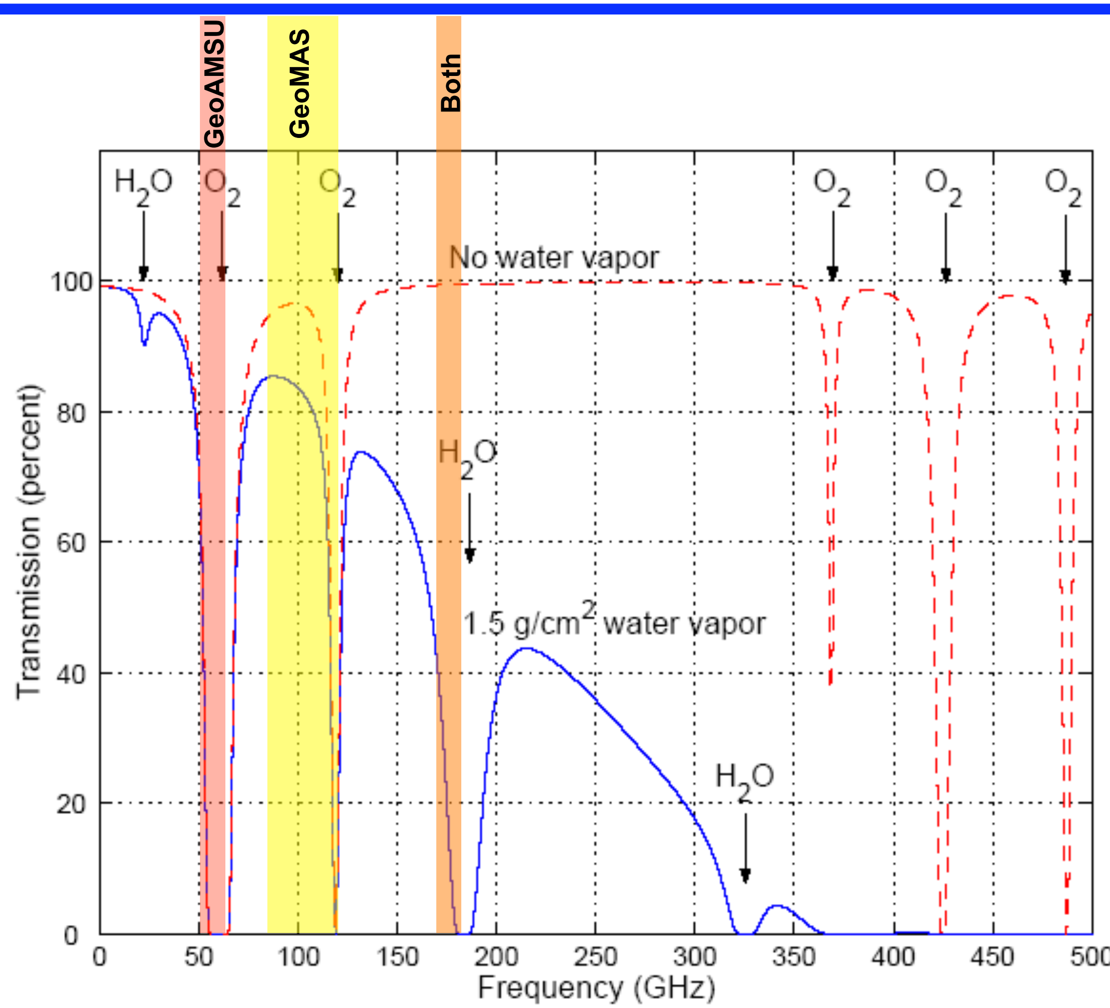
# Background/Overview

- “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)

# Outline

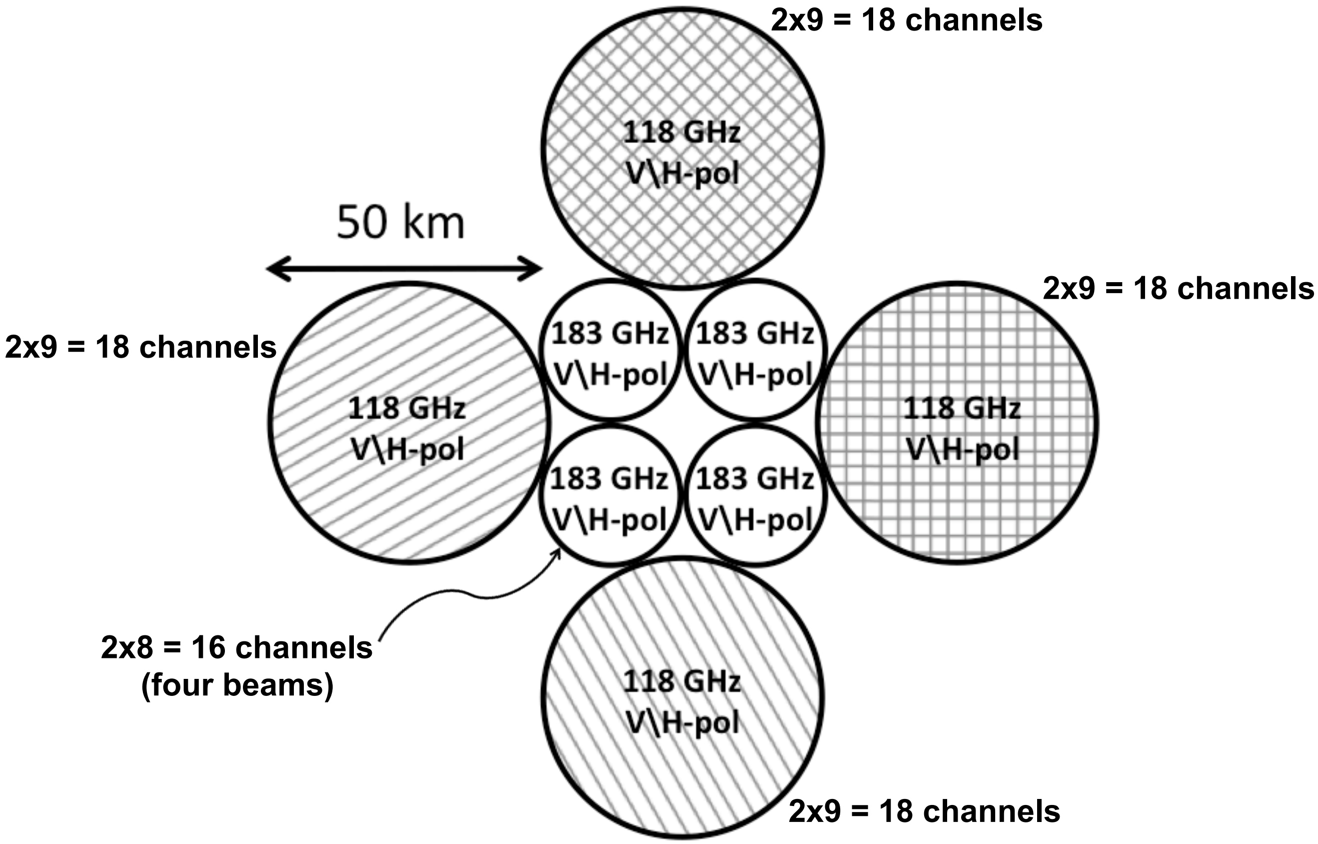
- Hyperspectral microwave sounding
  - "Spectral multiplexing" concept
  - Temperature weighting function analysis
- GEO performance comparisons
  - Precipitation and All-weather Temperature and Humidity (PATH)
  - GeoMAS (118/183 GHz): Geostationary Microwave Array Spectrometer
  - Compare with "GeoAMSU" synthetic aperture system
- LEO performance comparisons
  - HyMAS (60/183 GHz): Hyperspectral Microwave Array Spectrometer
  - Compare with AIRS + AMSUA + HSB
- Summary and path forward

# Atmospheric Transmission at Microwave Wavelengths



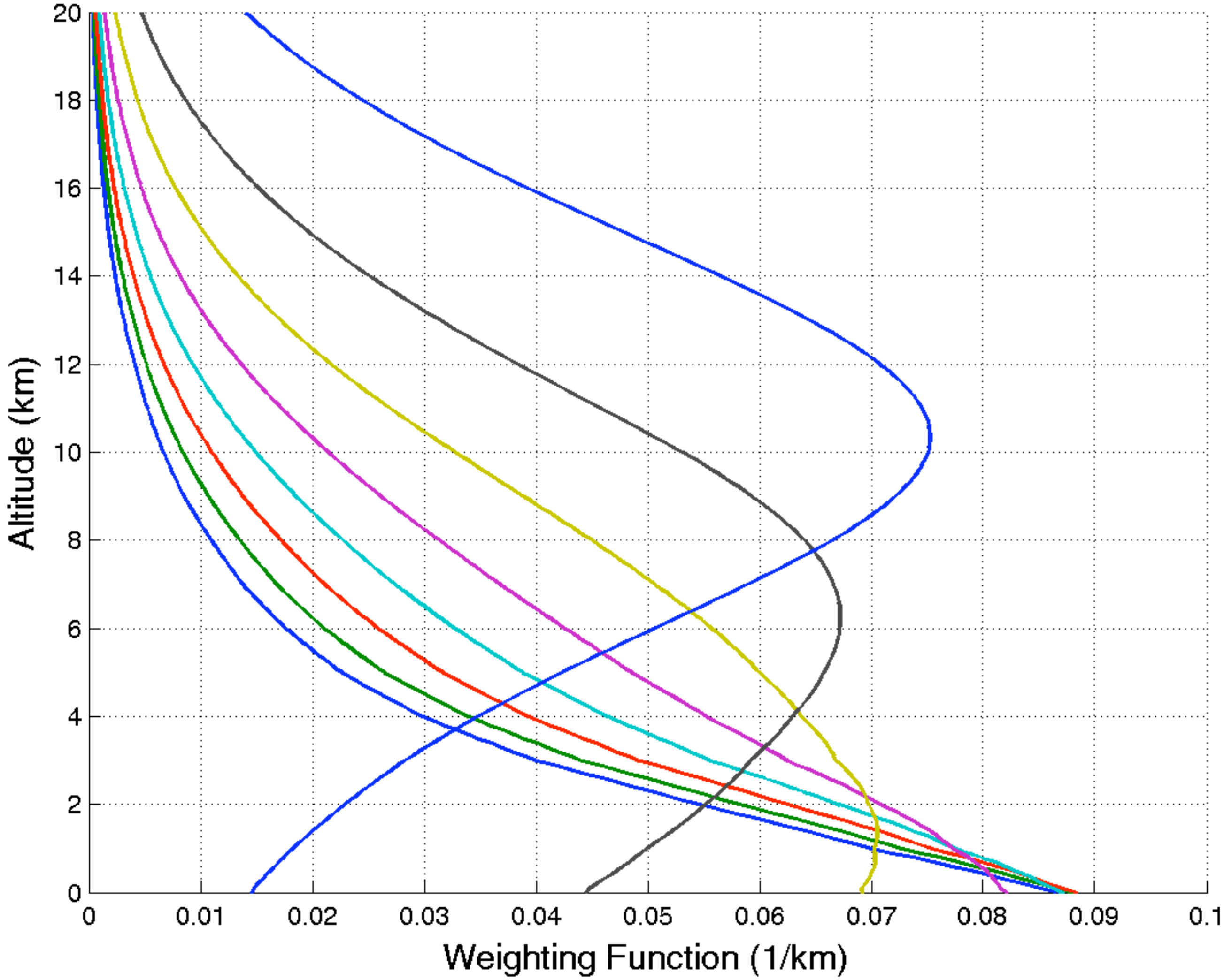

**The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines**

# Geostationary Microwave Array Spectrometer: Nominal GeoMAS Beam Layout

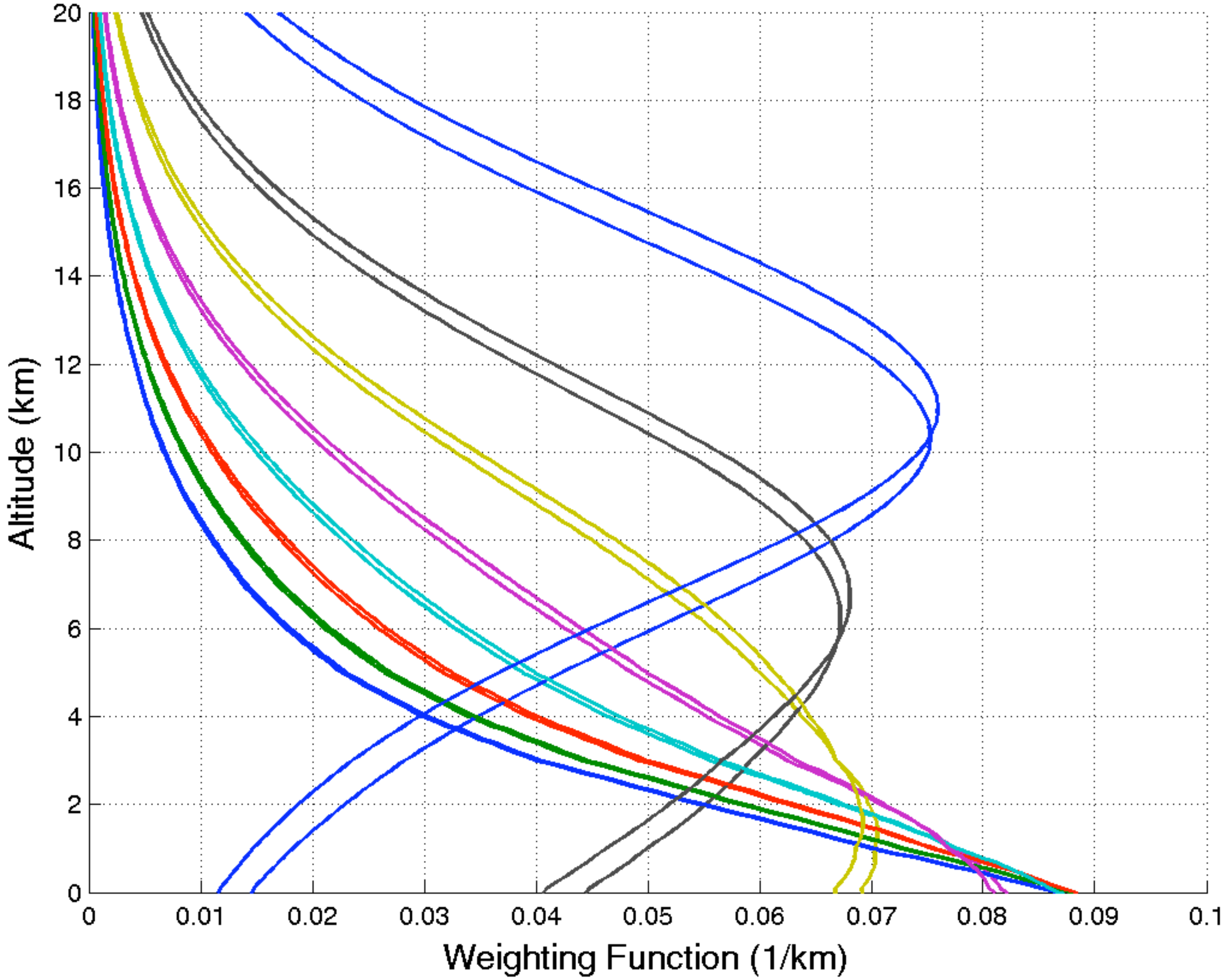



**Array microscans; every spot on the ground is measured by 88 channels**

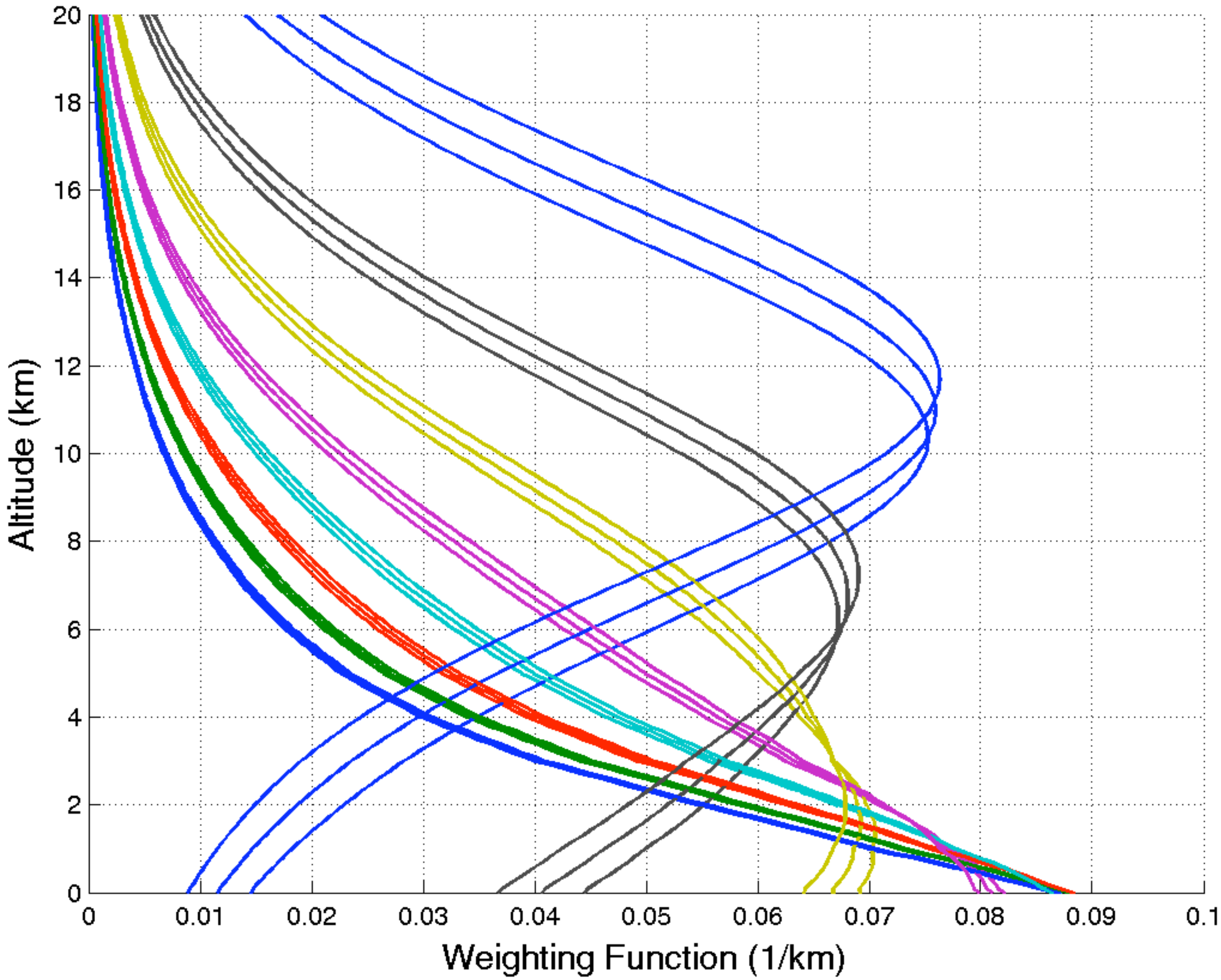
# Spectral Multiplexing Concept (1/8)



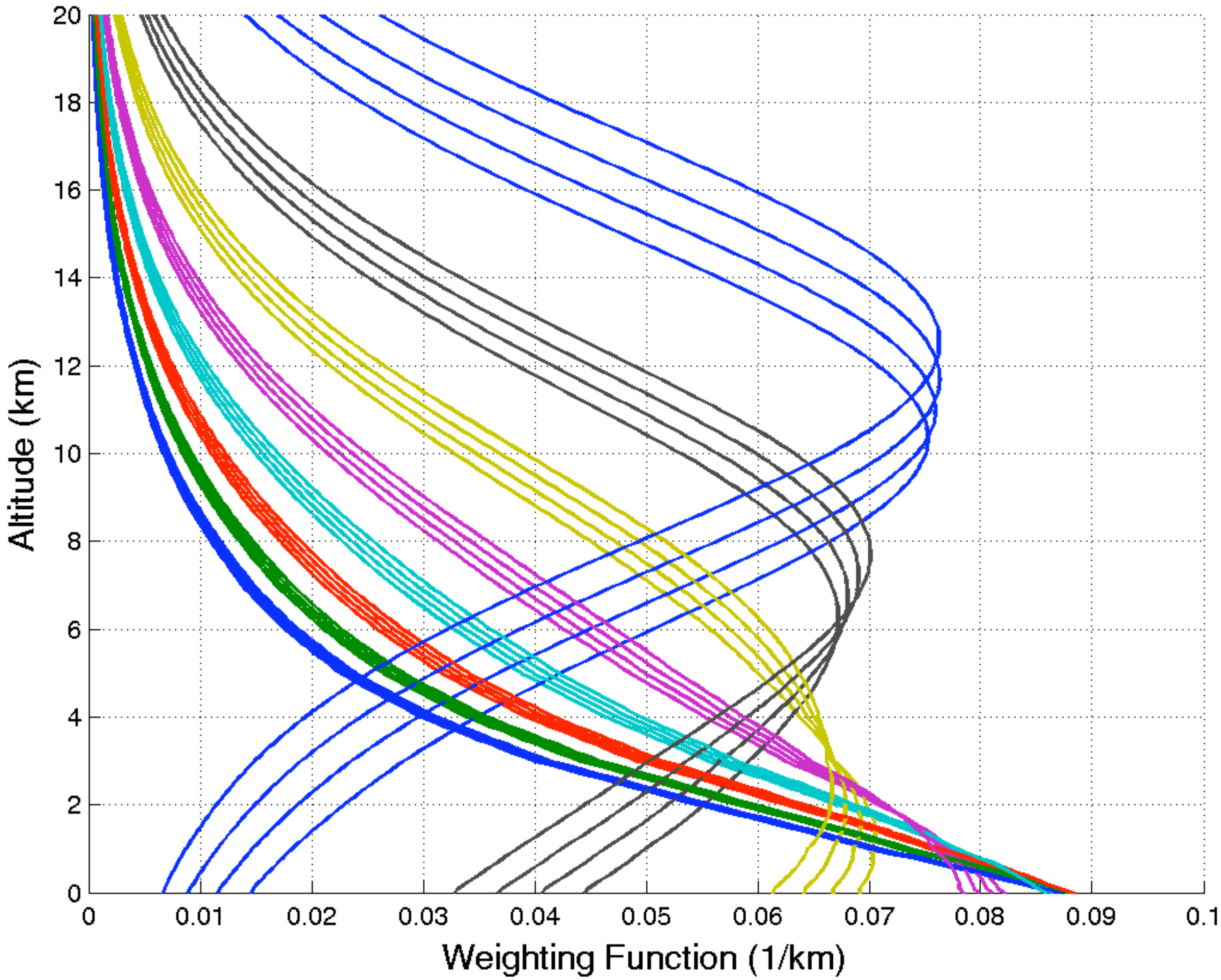
# Spectral Multiplexing Concept (2/8)



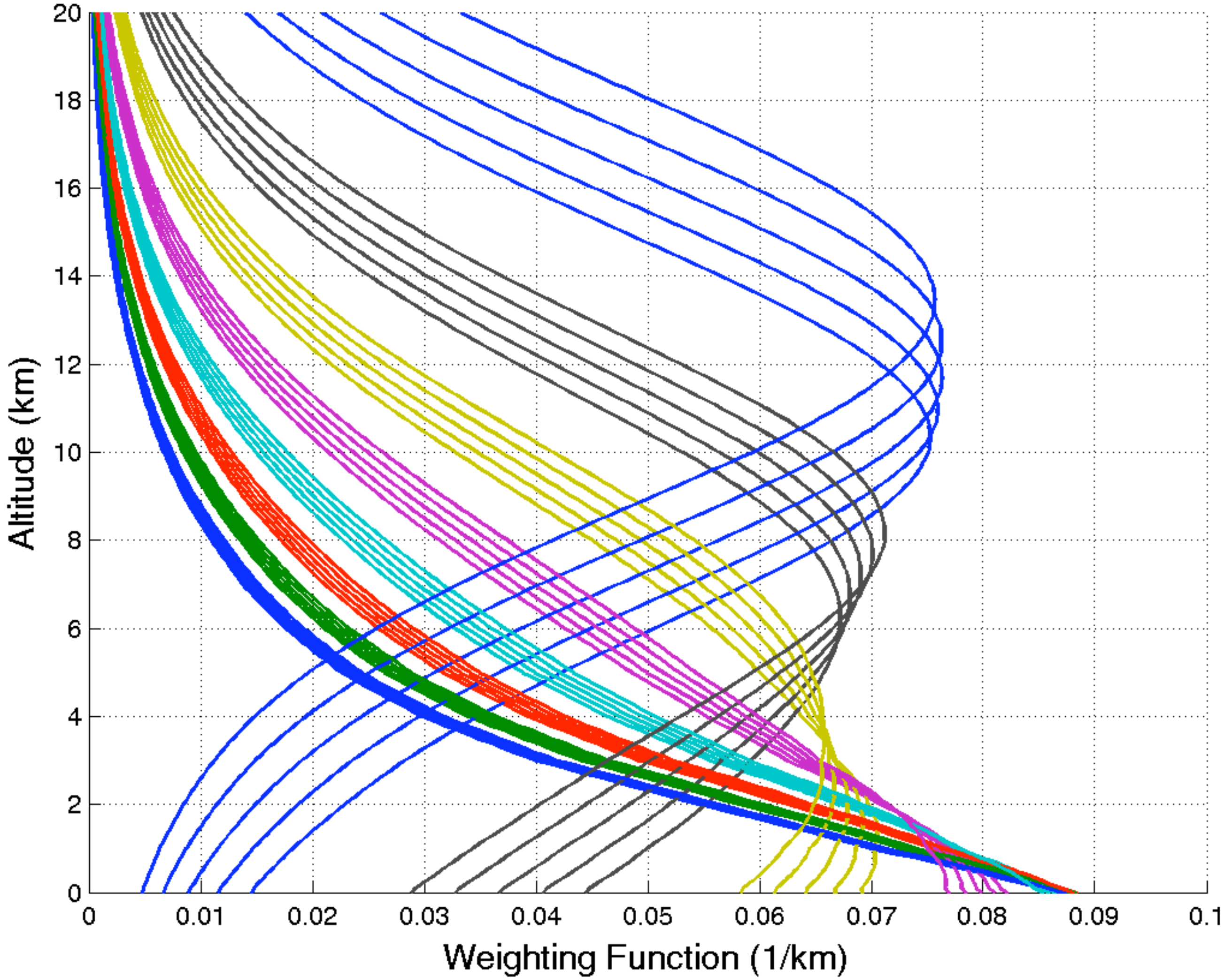
# Spectral Multiplexing Concept (3/8)



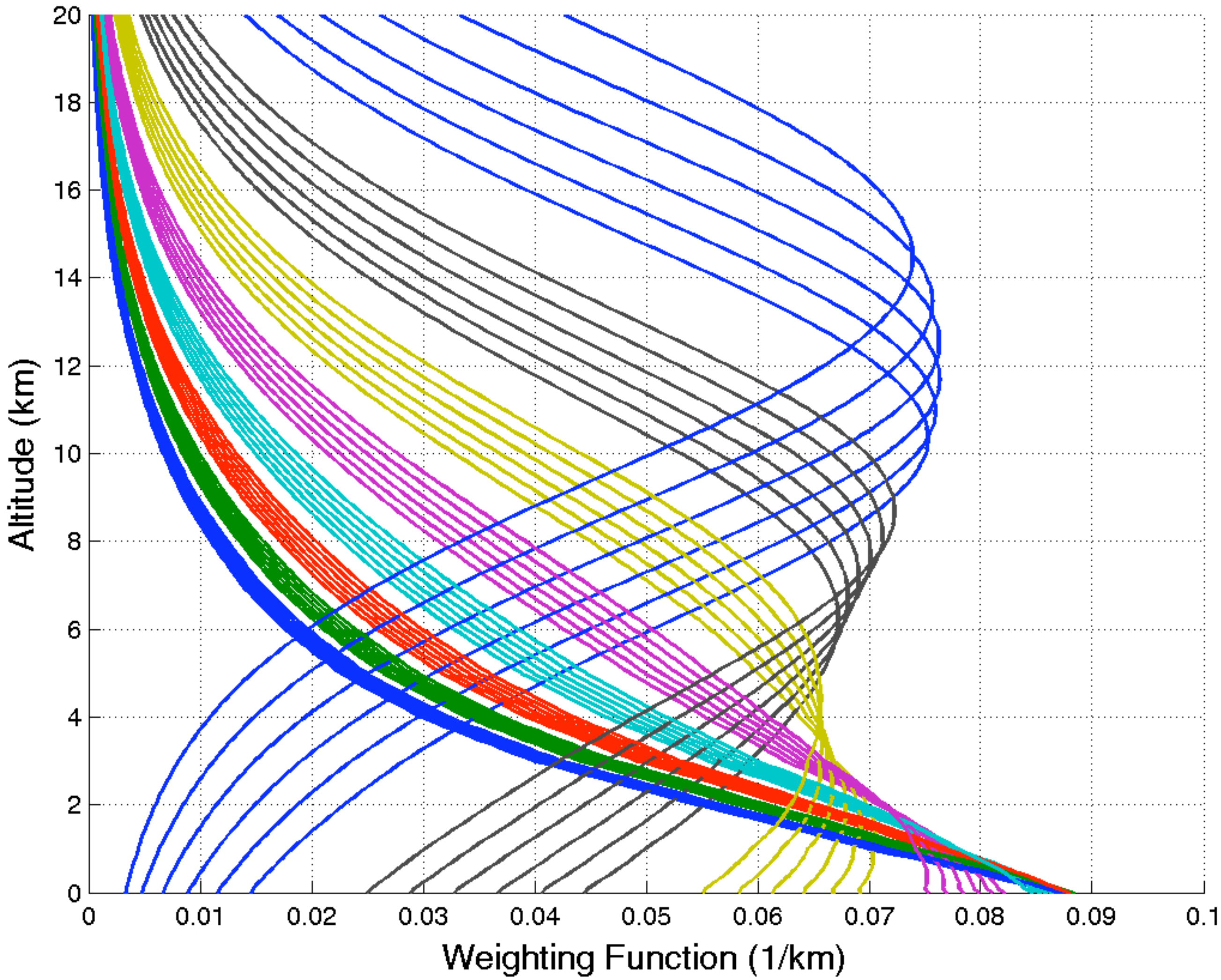
# Spectral Multiplexing Concept (4/8)



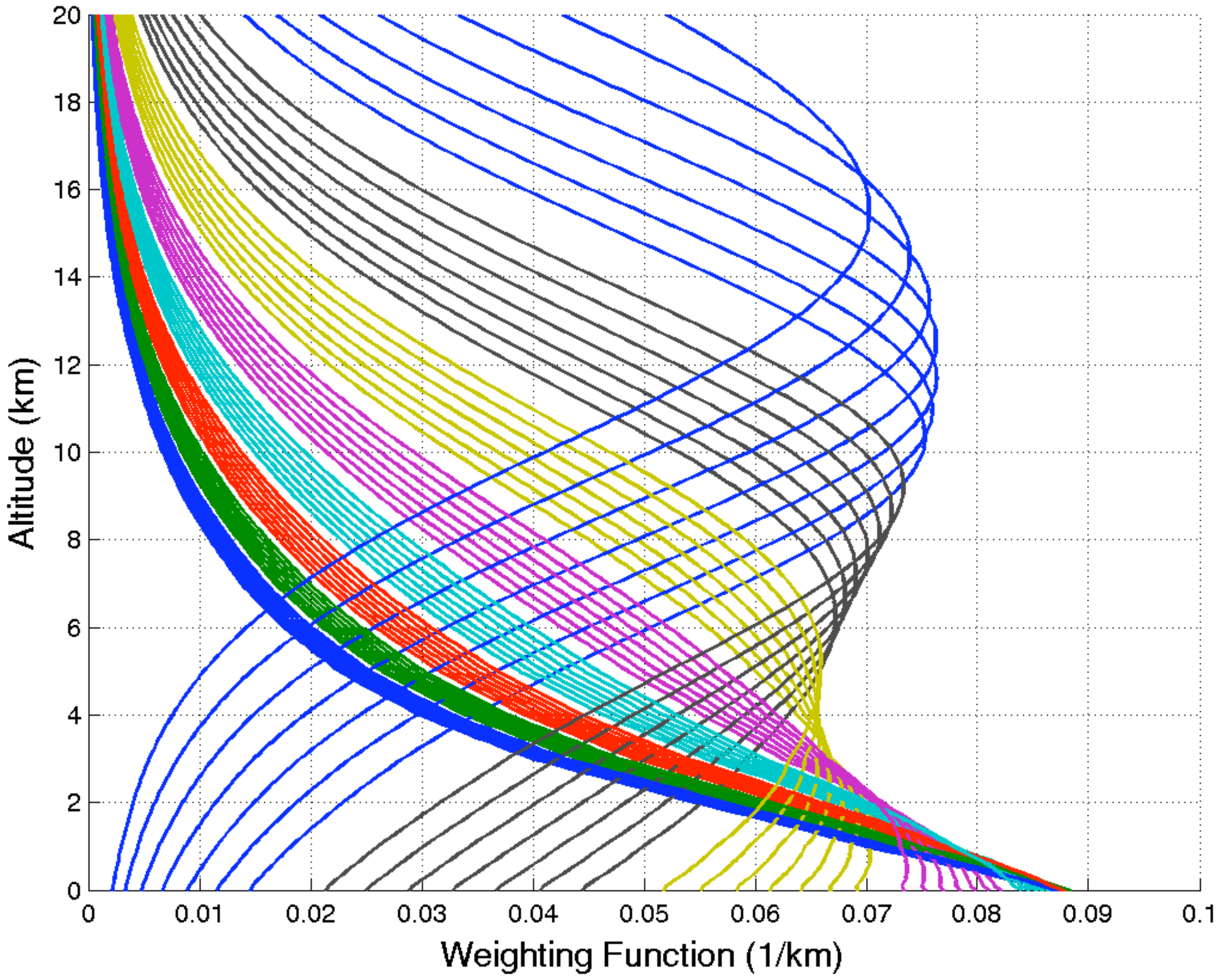
# Spectral Multiplexing Concept (5/8)



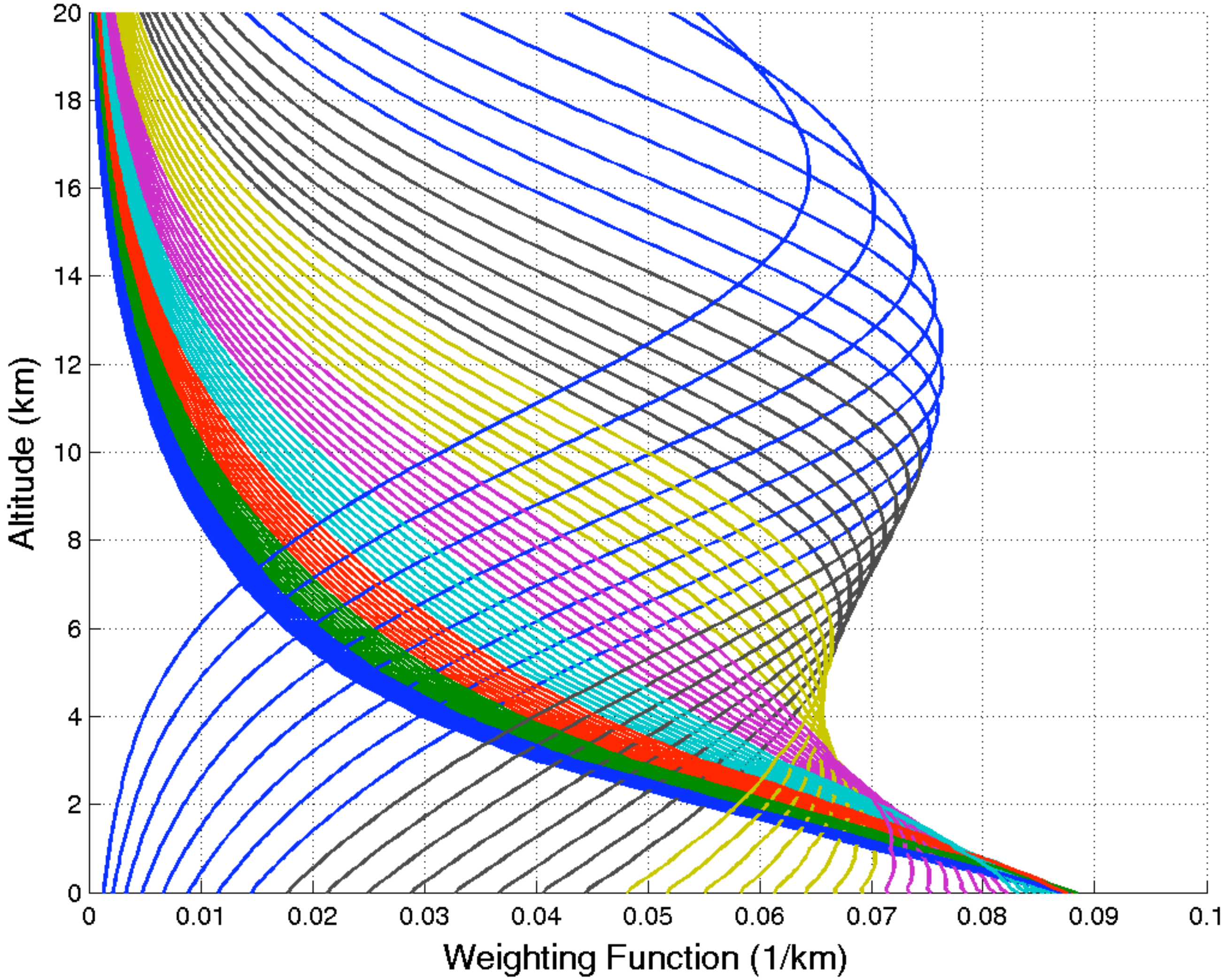
# Spectral Multiplexing Concept (6/8)



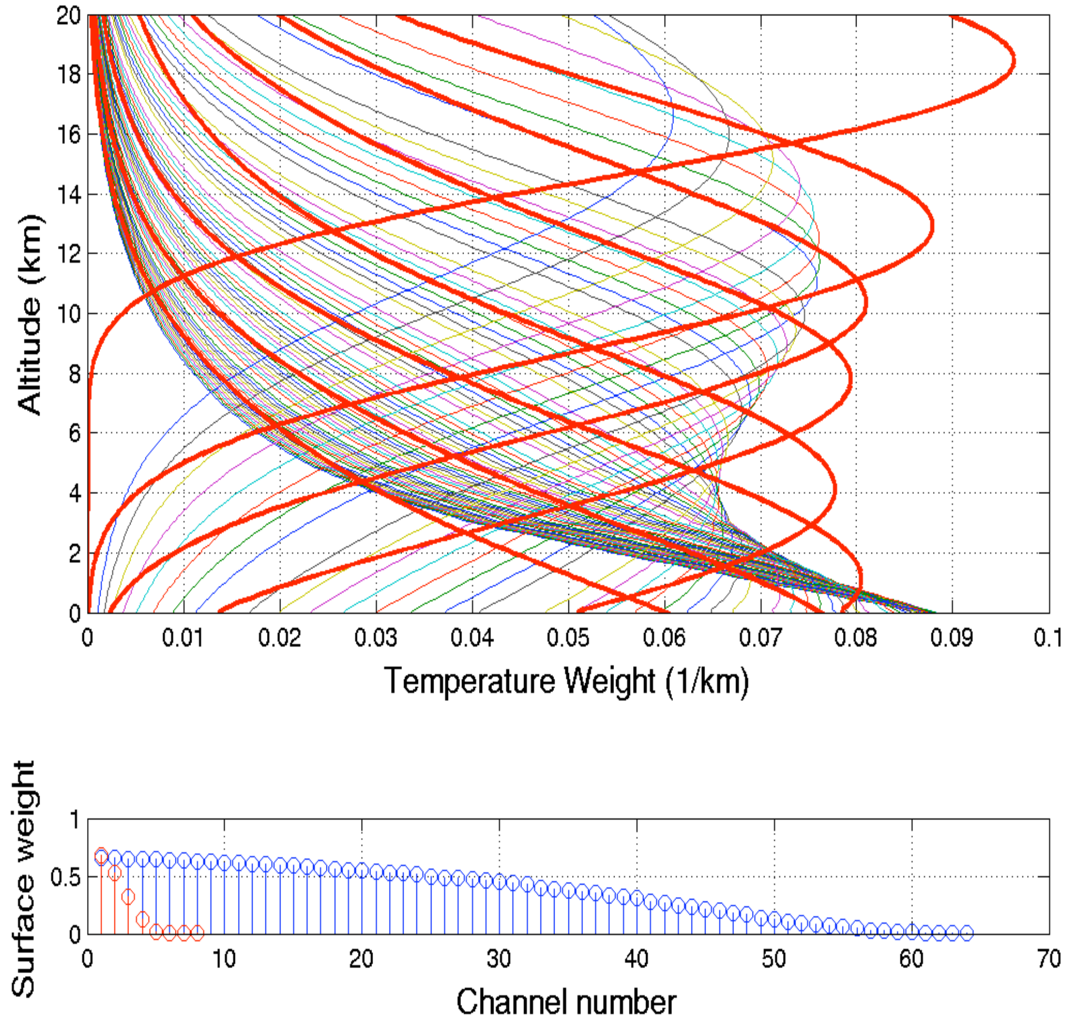
# Spectral Multiplexing Concept (7/8)



# Spectral Multiplexing Concept (8/8)

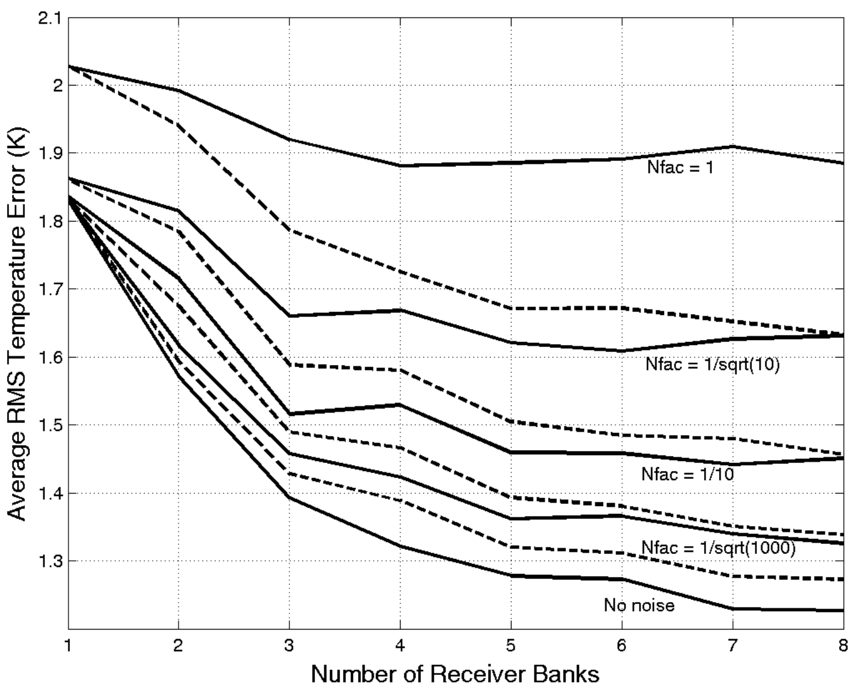


# GeoMAS versus "Traditional" 60-GHz Bands



# Why is an Array Needed??

- **Other approaches using a <u>single receiver</u>:**
  - **Simply sweep the receiver local oscillator (LO) to achieve many channels**
  - **Add a high-resolution digital backend to achieve many channels**
- **The array approach provides very large *effective bandwidth***




**Solid lines: Advantage due to channelization**
**Dashed lines: Advantage due to channelization AND noise reduction**

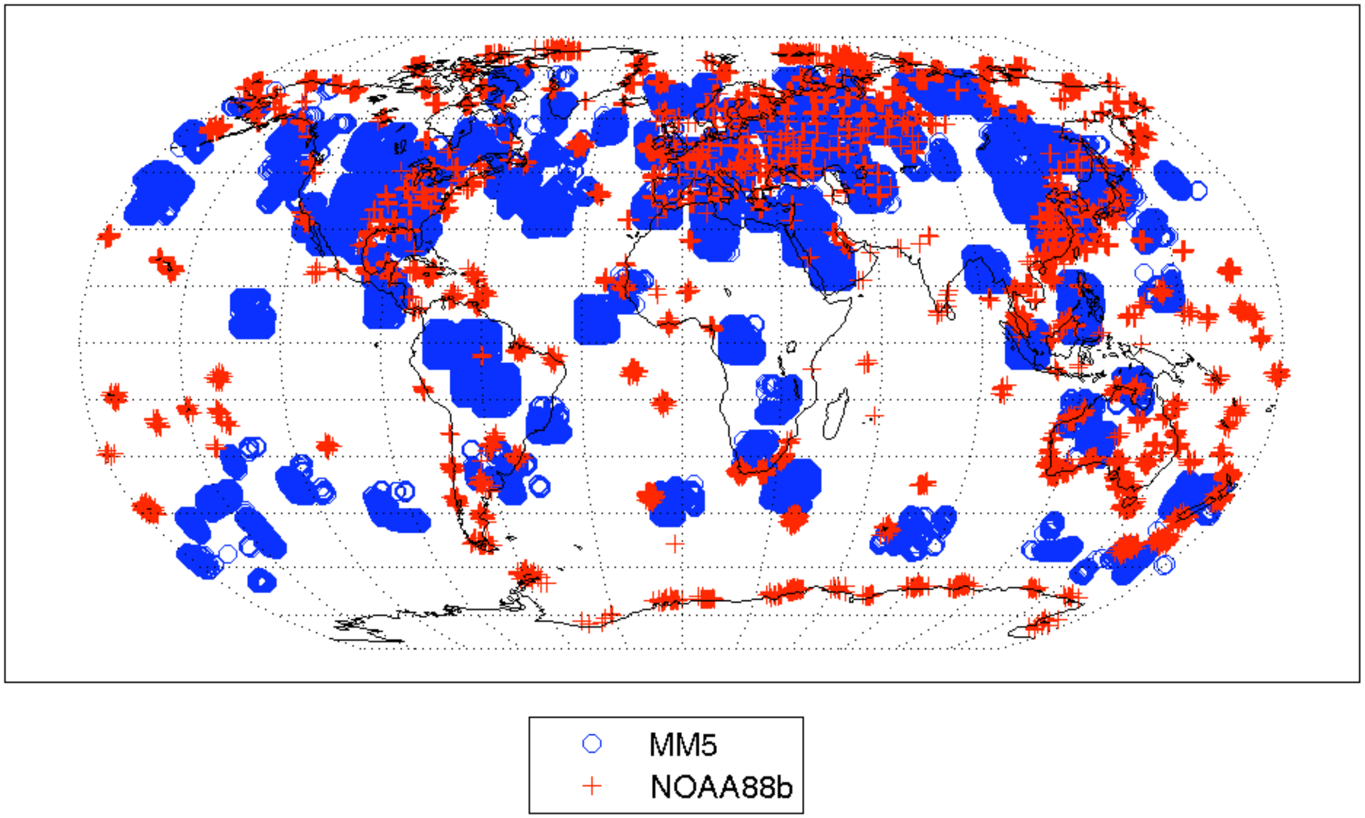
**Increasing integration time**

**118-GHz system**

# State-of-the-art Physical Models Used for Simulation Analyses

- Cloud-resolving atmospheric model (MM5)
- Ocean surface emissivity model
- Random land surface emissivity model
- Line-by-line transmittance model with <u>detailed scattering</u>

# 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

    $\Delta T_{RMS} = 0.2$ 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

    $\Delta T_{RMS} = 0.25$ 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

    $\Delta T_{RMS} = 0.15$ K

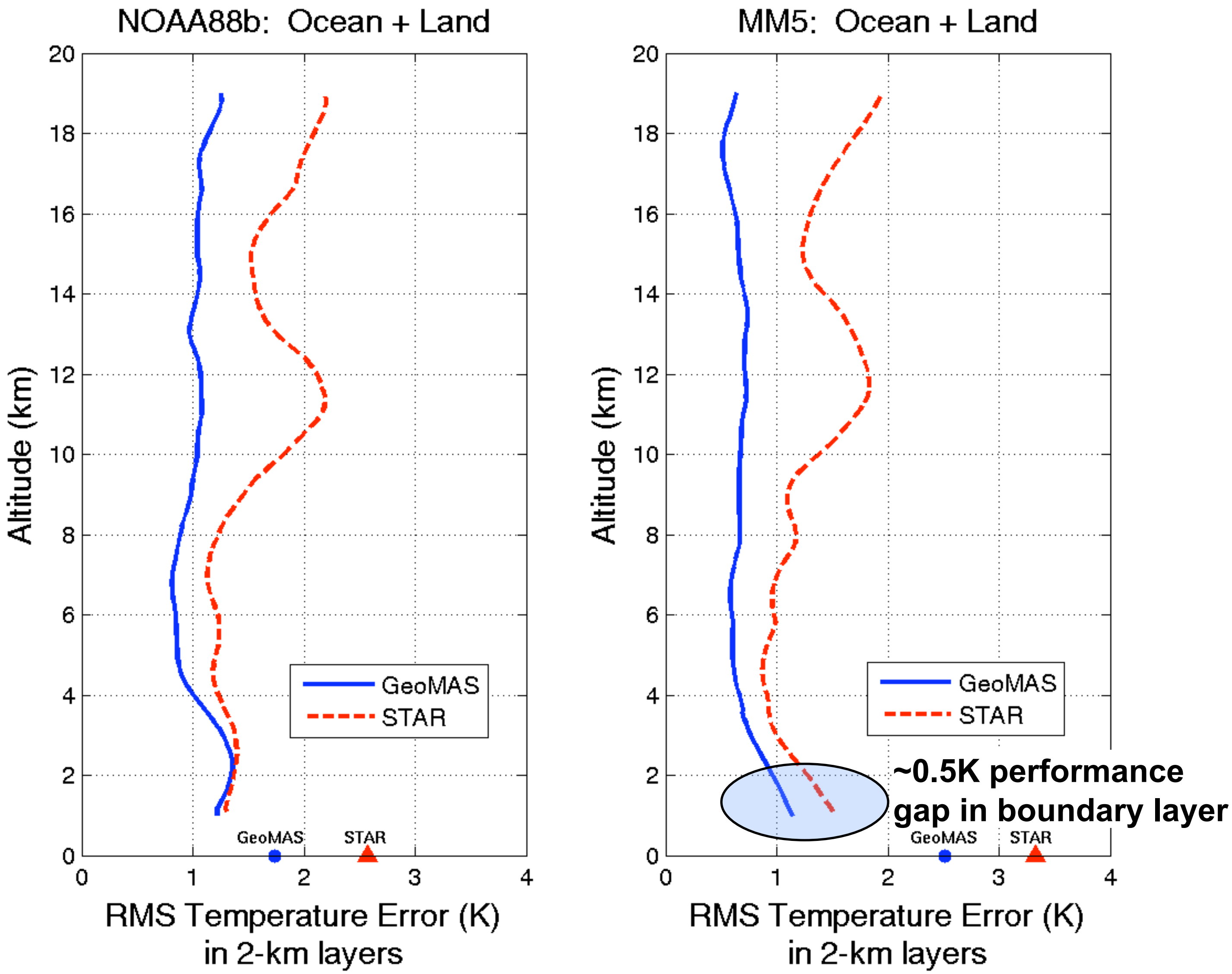
**Half the channels at each band are H-pol, the other half are V-pol**

# Synthetic Thinned Aperture Radiometer (STAR) Assumptions

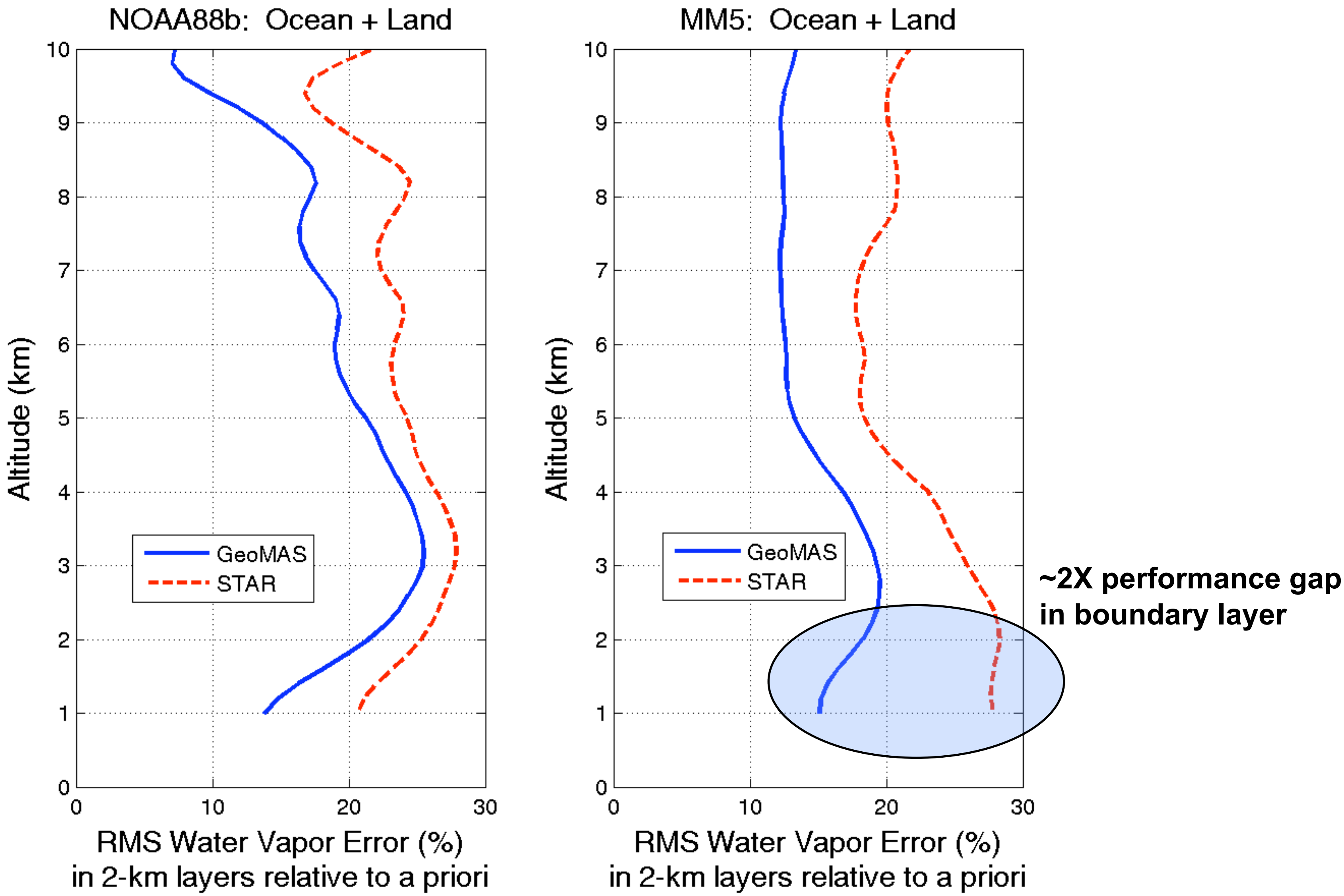
- Six oxygen channels (identical to AMSU-A):
  - 50.3, 52.8, 53.596, 54.4, 54.94, 55.5 GHz
  - $\Delta T_{RMS}$: 0.5, 0.35, 0.5, 0.35, 0.35, 0.35 K
- Four water vapor channels (three identical to AMSU-B):
  - 183.31 ± 1, 3, and 7 GHz; 167 GHz
  - $\Delta T_{RMS}$: 1, 0.71, 0.5, 0.71 K
- Fundamental receiver parameters ($T_{sys}$ and $\tau$) 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
# GeoMAS versus "GeoAMSU"



# Water Vapor Retrieval Performance
# GeoMAS versus "GeoAMSU"



# Precipitation Retrieval Performance: GeoMAS Superior for All Rain Rates

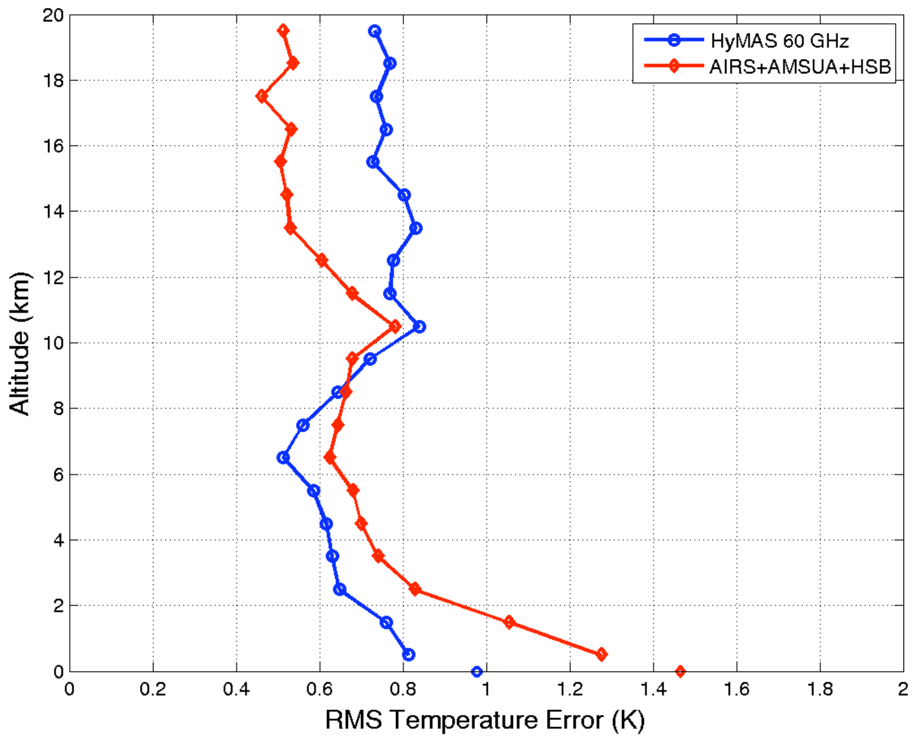
RAIN-RATE RETRIEVAL PERFORMANCE (RMS ERROR IN MM/H) FOR THE GEOMAS AND STAR SYSTEMS AT 25-KM SPATIAL RESOLUTION.

| 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 |

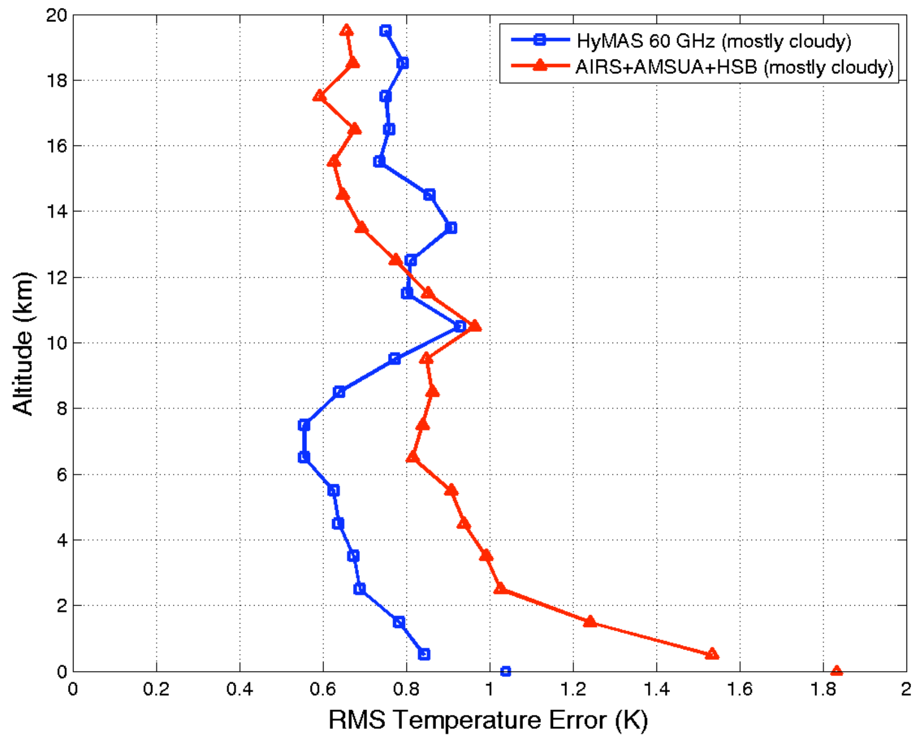
# Temperature Retrieval Performance AIRS/AMSU/HSB Versus HyMAS 60-GHz

## AIRS Level 2 Profile Database: Global, Non-frozen Ocean

### All Profiles



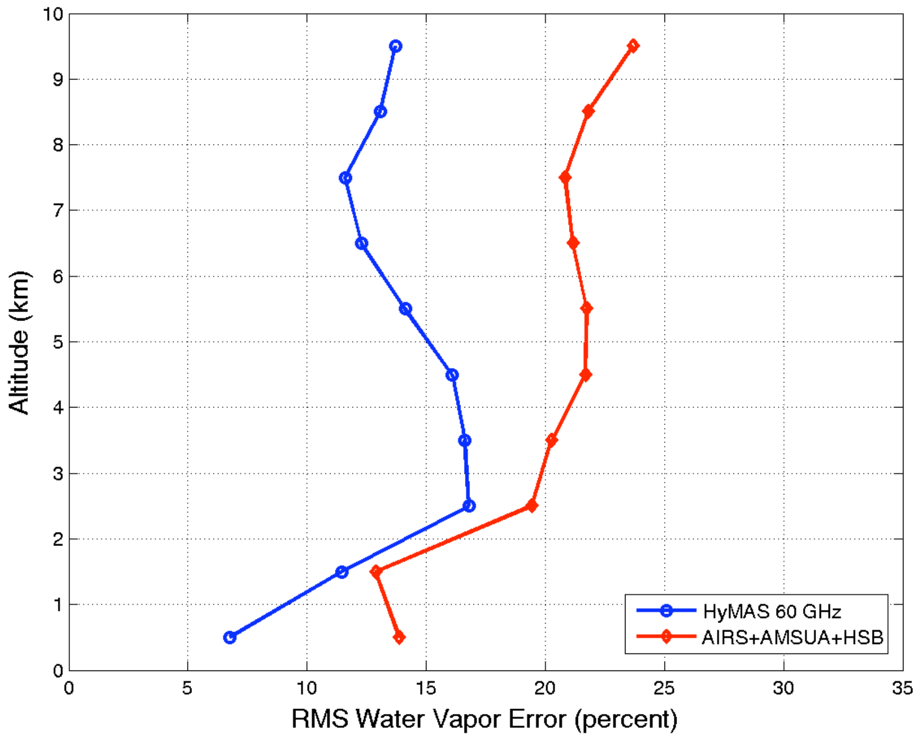

### Cloudiest 30%



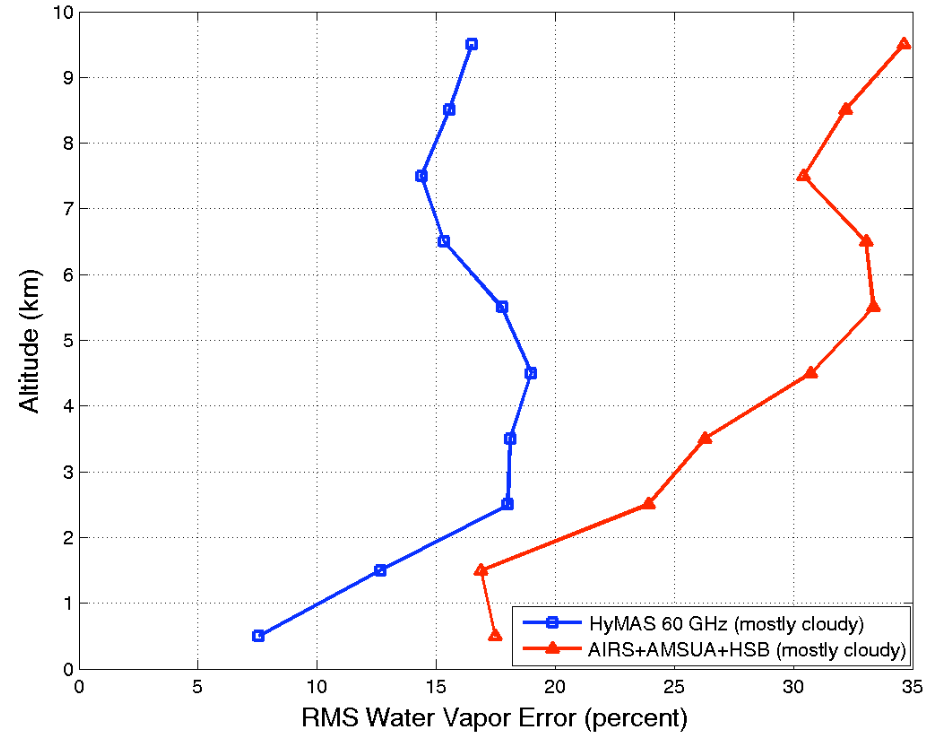
# Water Vapor Retrieval Performance AIRS/AMSU/HSB Versus HyMAS 60-GHz

## AIRS Level 2 Profile Database:  Global, Non-frozen Ocean

### All Profiles




### Cloudiest 30%



# Summary and Path Forward

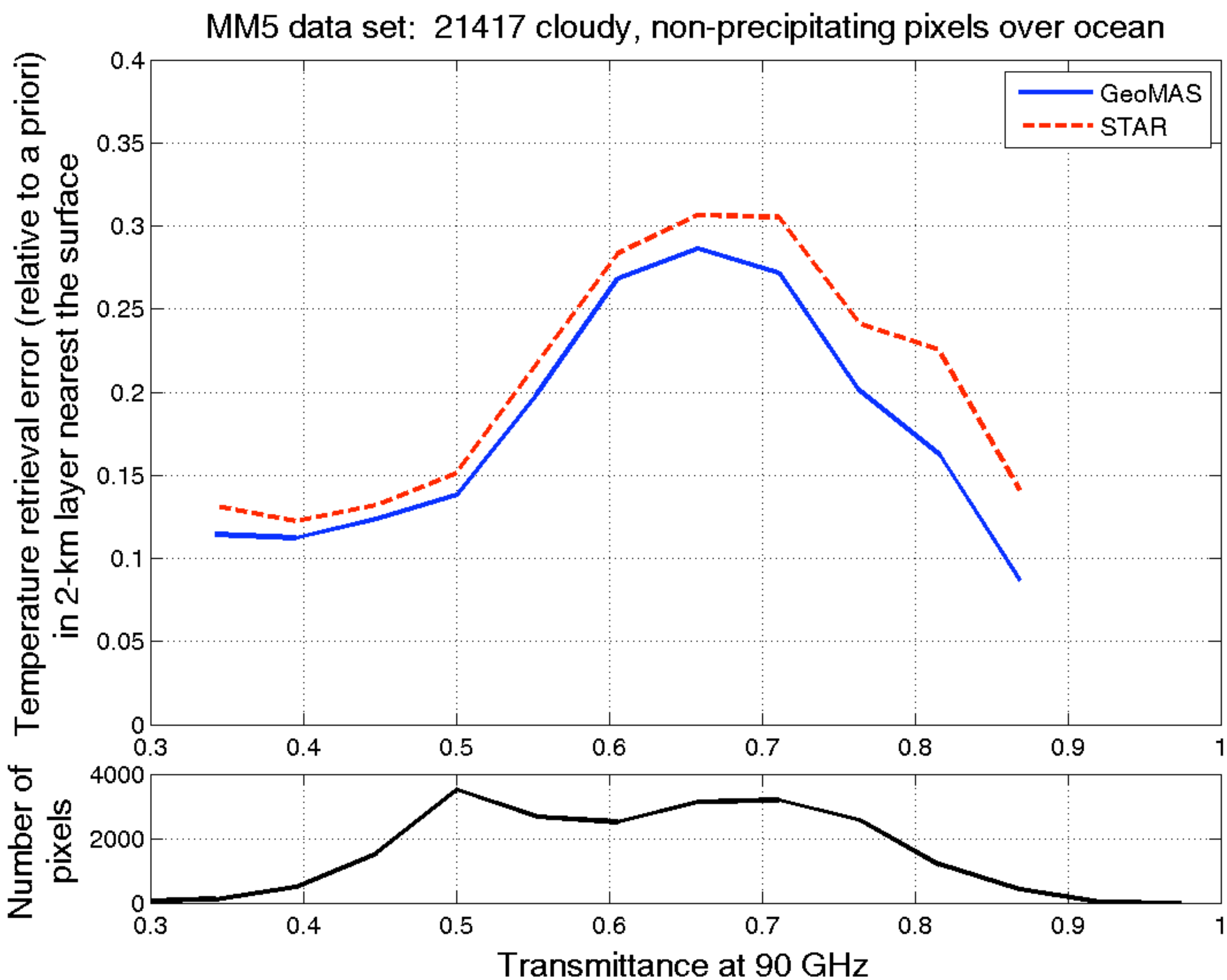
- Hyperspectral microwave sensors could change the landscape of atmospheric sounding (LEO and GEO)
- GeoMAS performance superior to current geostationary microwave state-of-the-art
  - Temperature, water vapor, and precipitation mapping
- HyMAS performance exceeds AIRS+AMSU, especially in clouds
- Hyperspectral microwave would provide advanced sounding capability
  - Complementary to hyperspectral IR (improved $CO_2$ retrievals expected)
  - Complementary to infrared ABI (rapid scan imaging of severe weather in tandem with ABI would provide quantum leap forward)
- Next steps
  - HyMAS/GeoMAS channel optimization; more channels; image sharpening
  - Detailed sensitivity studies (recent correlated error analyses promising)
  - Hardware demonstration (airborne prototype)

# More Information

- “Hyperspectral Microwave Atmospheric Sounding,” Blackwell, et al., under review (*IEEE TGRS*)
- “Scientific Arguments for a Hyperspectral Microwave Sensor,” Boukabara, et al., EUMETSAT confererence, September 2010
- “Improved All-Weather Atmospheric Sounding Using Hyperspectral Microwave Observations,” Blackwell, et al., IGARSS 2010
- Previous presentations available (AMS, URSI, and MicroRad)

# Backup Slides

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

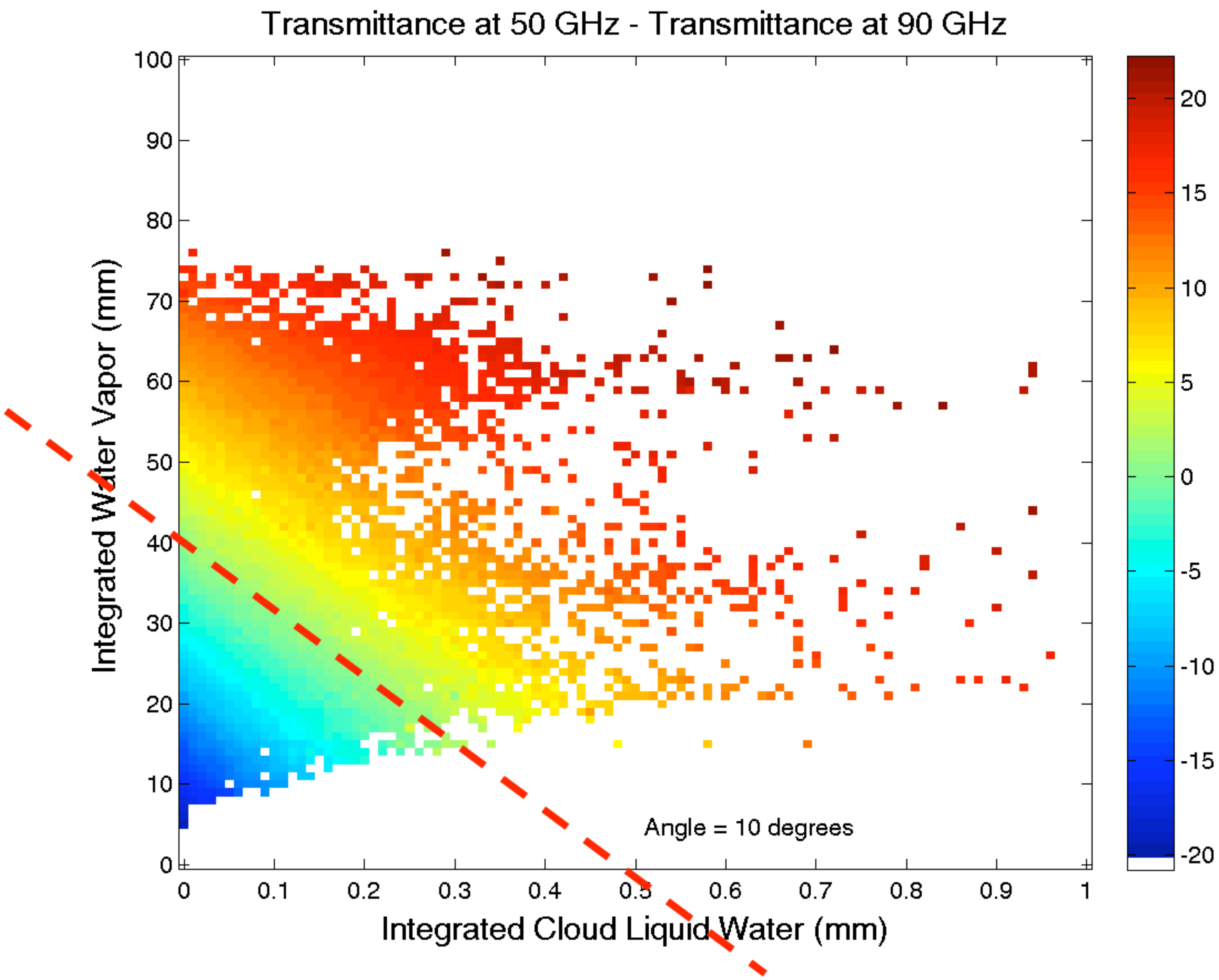


# Atmospheric Sounding

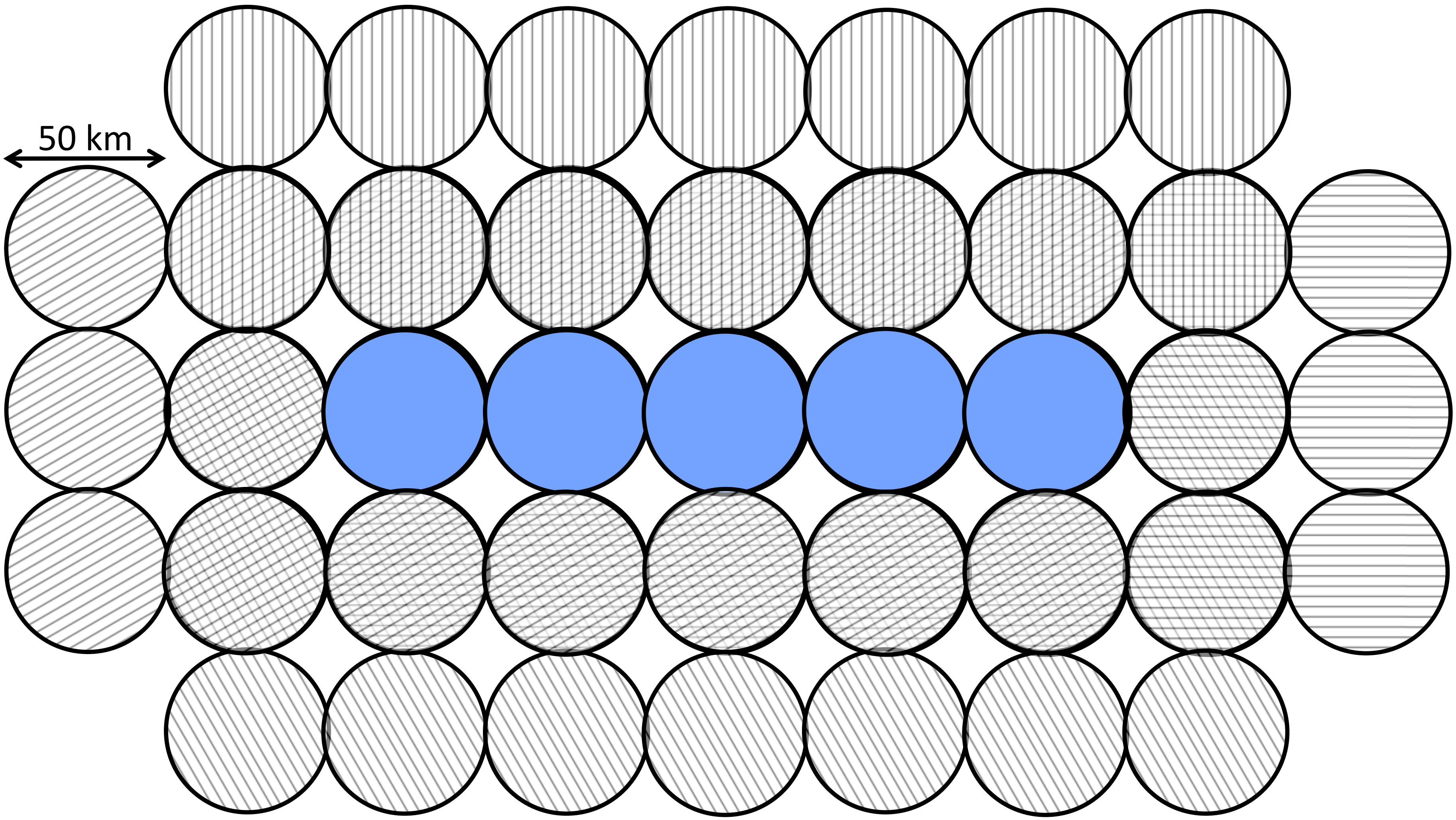
- Global all-weather observations of precipitation, temperature, and humidity are needed to drive weather forecast models
- These observations require space-based sensors measuring upwelling thermal radiance spectra
- Microwave observations are needed to provide cloud penetration
- Most weather develops over many hours so that existing multiple LEO sounders provide sufficiently frequent coverage
- Severe weather events are a critical exception, usually cloud shrouded; key observables vary within ~15 km and ~15 minutes

**These attributes motivate a geostationary microwave sensor**

# Transmittance Calculations in Clouds (Non-Precipitating Pixels)



# GeoMAS Beam Sampling
# Each Pixel is Eventually Sampled at All Freqs




Cross hatching indicates different frequency bands

Blue circles denote pixels that have been fully sampled

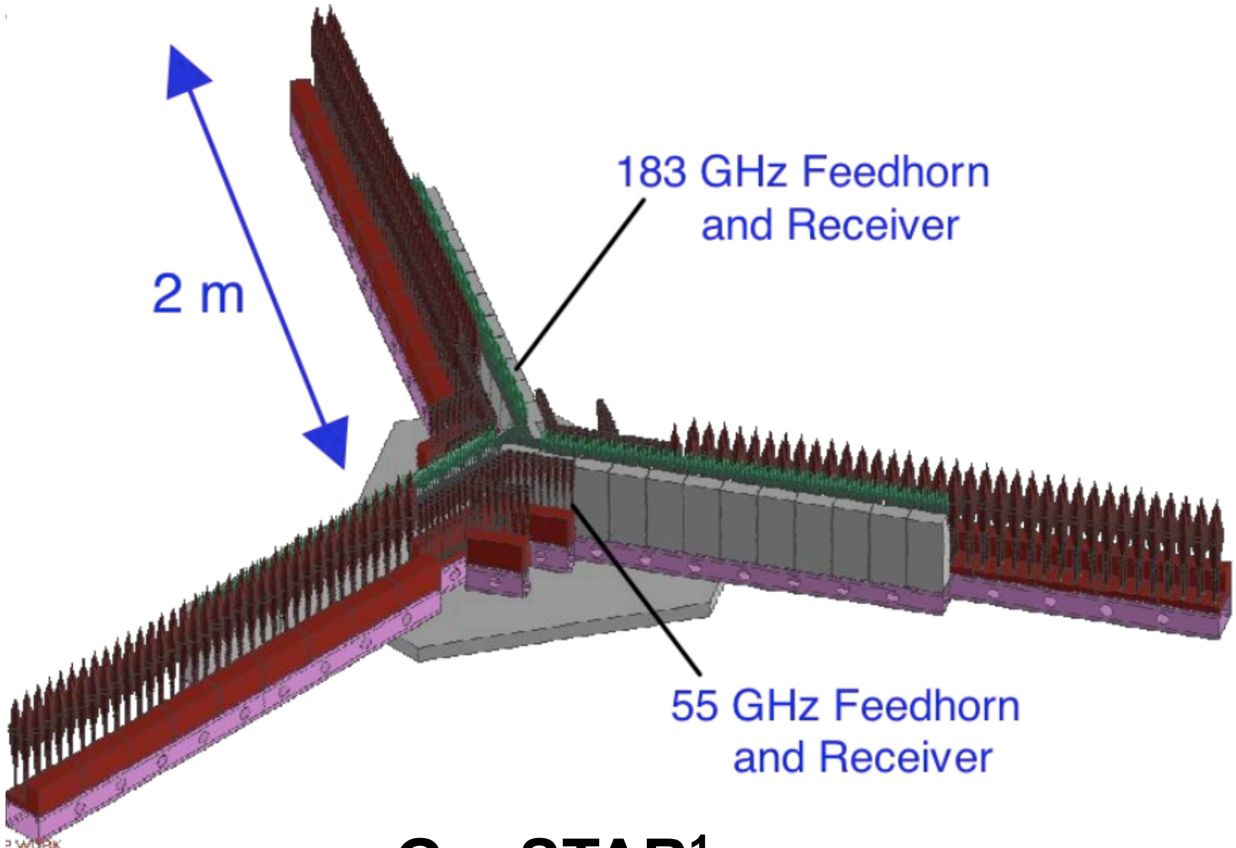
# Correlated Error Sources

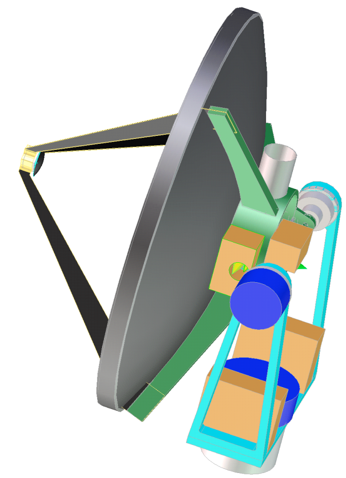
- Unknown array spatial misalignments
  - Small effect, due to broad beams, but non-negligible
  - Modeling included in our simulation study (slides to come)
- Spatial nonhomogeneities in scene
  - Clouds, surface, water vapor, etc.
  - Modeling included in our simulation study (slides to come)
- Forward model errors
  - Transmittance, cloud/microphysical, surface, etc.
  - Modeling included in our simulation study (slides to come)

# Significance of Performance Improvements

- Substantial advantage in the retrieval of sea surface temperature:
  - Better storm tracking and intensification prediction
  - More accurate long-term weather forecasts
- Marked advantage in atmospheric profile retrieval
  - Improved initialization of numerical forecast models
  - Areas in and around precipitation are most critical
- Synoptic coverage provided by LEO sounders sets "background error" that approaches 0.2K in mid troposphere
  - GEO soundings must be very accurate to positively impact current models
  - Sampling of diurnal variations in temperature and moisture are not provided by LEO observations

# Comparison of GeoSTAR and GeoMAS




**GeoSTAR[1]**
**250kg, 350W**

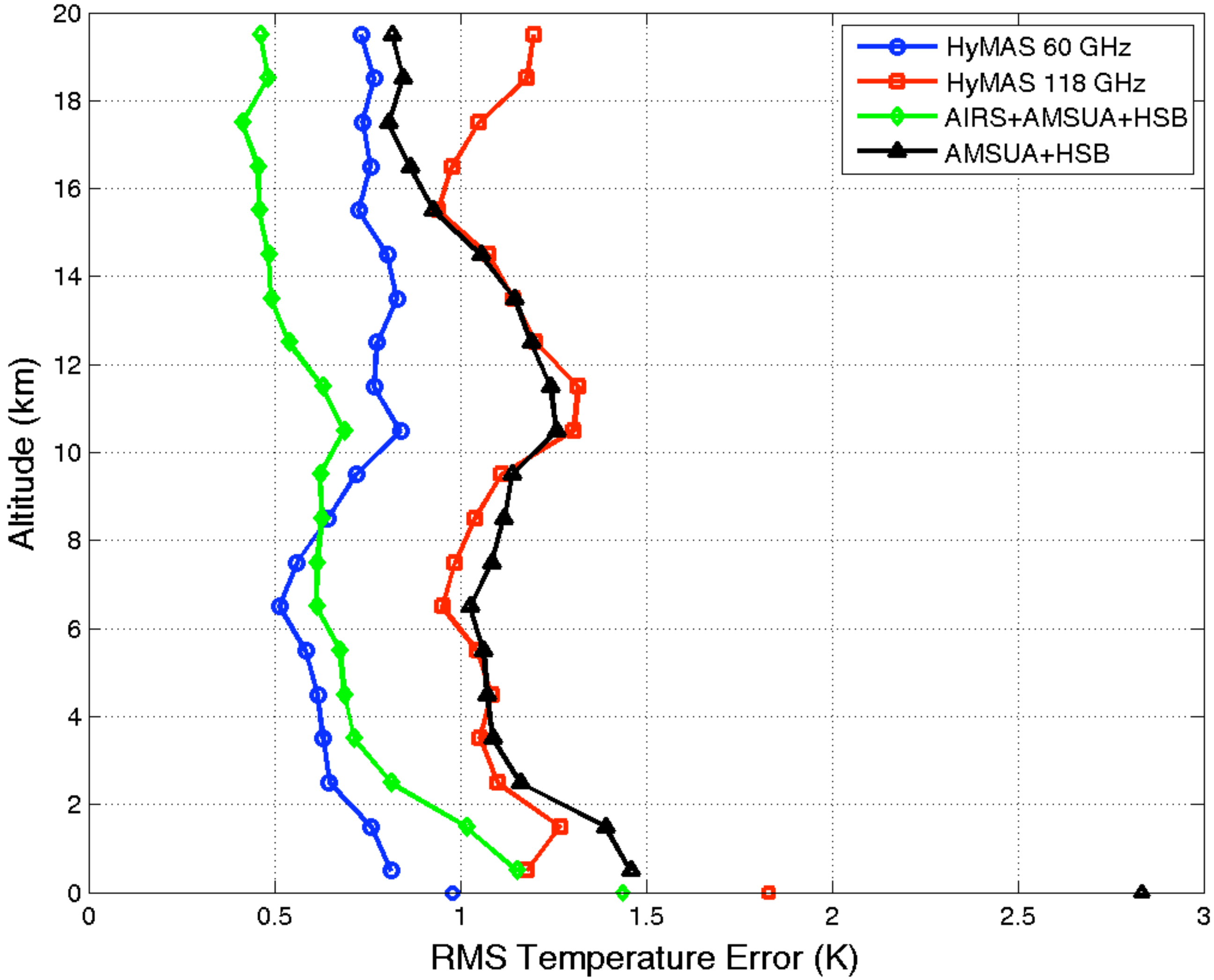
**GeoMAS[2]**
**70kg, 50W**

[1]Lambrigtsen, et al., IGARSS 2008
[2]Staelin, et al., GEM Working Group Report to GOES Program Office, 1997

# Comparison of GeoMAS and GeoSTAR

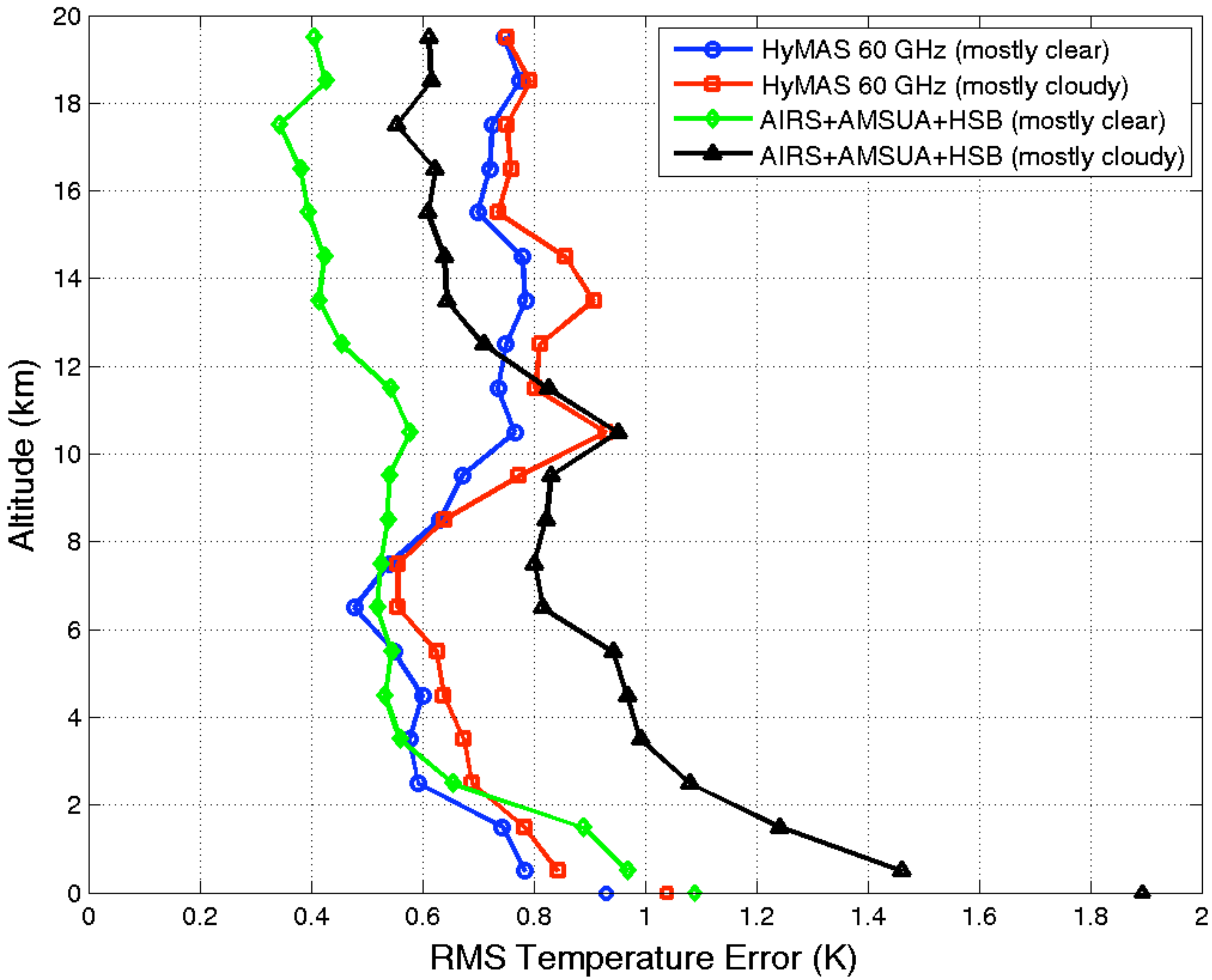
| | GeoMAS | STAR |
|---|---|---|
| Antenna feeds | 8 | ~900 |
| Receiver banks | 16 | ~900 |
| High-speed digitizers | 0 | ~1,800 |
| High-speed correlators | 0 | >600,000 |
| Mass (kg) and power (W) estimates | 70, 50 | 250, 350 |
| Channels | ~100 | ~10 |
| Temperature pixels @ 50 km | 40,000 | 40,000 |
| Water Vapor / Precip pixels @ 25 km | 160,000 | 160,000 |
| Nominal coverage time | 15 min | 15 min |
| Temp and water vapor performance exceeds 1.25 K / 25% RMS | YES | NO |
| Compatible with GOES ABI rapid scan imaging mode | YES | NO |
| Momentum impact to spacecraft | VERY LOW (tolerable) | NONE |
| Spaceflight heritage at similar freq. | AMSU/ATMS, SSMIS, MLS | NONE |

# Temperature Retrieval Performance

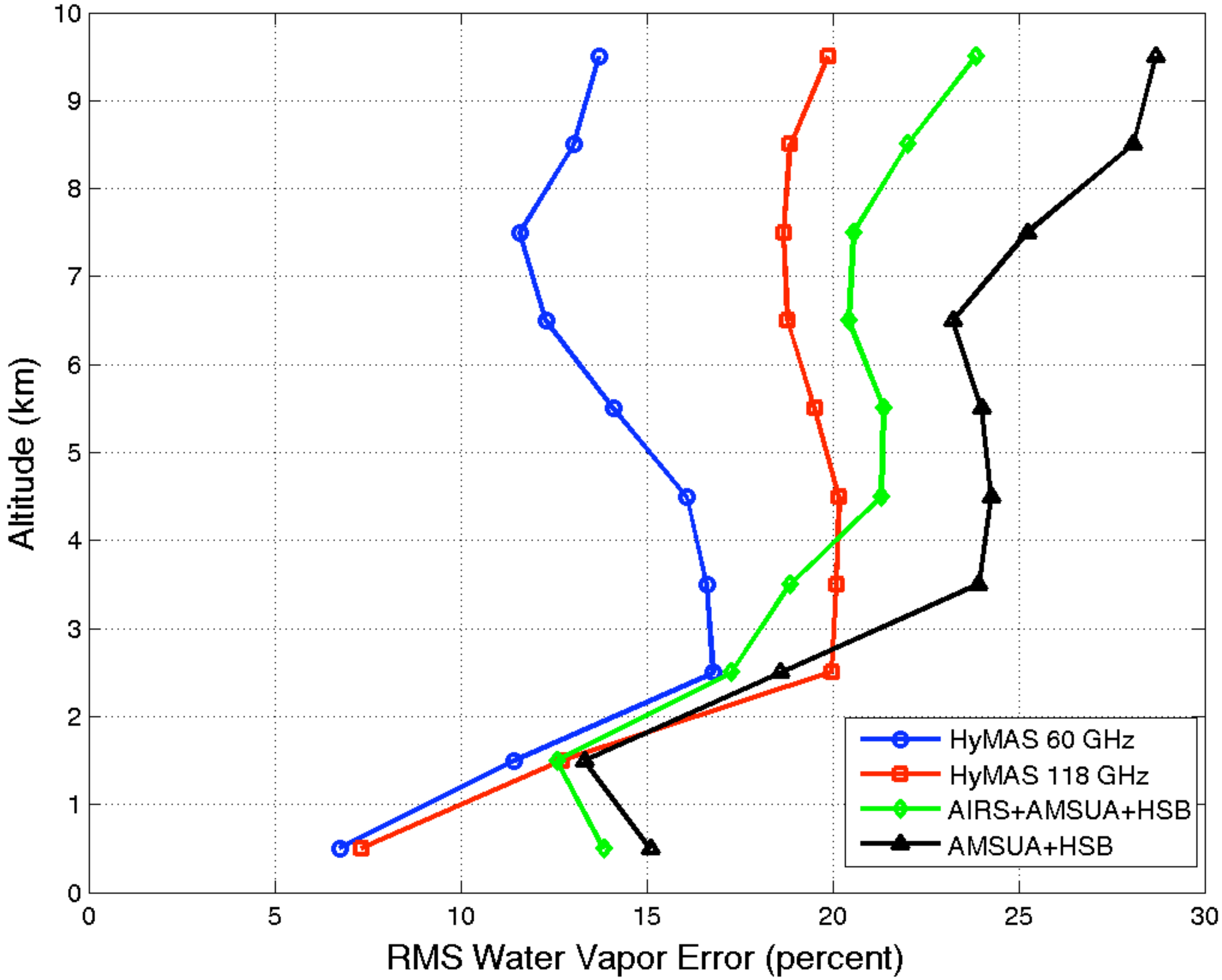



MIT Lincoln Laboratory

# Temperature Retrieval Performance



# Water Vapor Retrieval Performance



# Water Vapor Retrieval Performance