Hyperspectral Microwave Atmospheric Sounding


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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)
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
The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines.
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 (8/8)
GeoMAS versus “Traditional” 60-GHz Bands
Why is an Array Needed??

- Other approaches using a single receiver:
  - 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

![Graph showing the advantage of an array approach over a single receiver approach in terms of effective bandwidth and noise reduction.](image)

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

Incorporating 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 detailed scattering
Global Profile Sets for Performance Assessments

MM5 characterized by high water content
NOAA88b characterized by high variability
GeoMAS Channels

(coverage of 10,000x10,000 km² area in 15 min is assumed)

- GeoMAS 118-GHz
  - 64 channels on the low-frequency side of the 118.75-GHz line
  \[ \Delta T_{\text{RMS}} = 0.2 \text{ K} \]
- GeoMAS 118-GHz + 183-GHz
  - 64 channels on the low-frequency side of the 118.75-GHz oxygen line
  - 16 channels within +/- 10 GHz of 183.83-GHz water vapor line
  \[ \Delta T_{\text{RMS}} = 0.25 \text{ K} \]
- “GeoMAS 88” (89-GHz + 118-GHz + 183-GHz)
  - 64 channels on the low-frequency 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
  \[ \Delta T_{\text{RMS}} = 0.15 \text{ K} \]

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

Temperature Retrieval Performance
GeoMAS versus “GeoAMSU”

~0.5K performance gap in boundary layer
Water Vapor Retrieval Performance
GeoMAS versus “GeoAMSU”

~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.

<table>
<thead>
<tr>
<th>Rain-rate Range (mm/h)</th>
<th>GeoMAS (mm/h)</th>
<th>STAR (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>4-8</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>8-16</td>
<td>6.0</td>
<td>6.8</td>
</tr>
<tr>
<td>16-32</td>
<td>10.2</td>
<td>10.6</td>
</tr>
<tr>
<td>32-64</td>
<td>16.9</td>
<td>17.9</td>
</tr>
</tbody>
</table>
Temperature Retrieval Performance
AIRS/AMSU/HSB Versus HyMAS 60-GHz

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

All Profiles

Cloudiest 30%

RMS Temperature Error (K) vs. Altitude (km)
Water Vapor Retrieval Performance
AIRS/AMSU/HSB Versus HyMAS 60-GHz

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

All Profiles

Cloudiest 30%

[Graphs showing RMS Water Vapor Error (percent) against Altitude (km) for All Profiles and Cloudiest 30% with lines and points for HyMAS 60 GHz and AIRS+AMSU+HSB datasets]
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 CO2 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 conference, September 2010

• “Improved All-Weather Atmospheric Sounding Using Hyperspectral Microwave Observations,” Blackwell, et al., IGARSS 2010

• Previous presentations available (AMS, URSI, and MicroRad)
GeoMAS Performance Superior, Even for Low Transmittance (High Water Content)

MM5 data set: 21417 cloudy, non-precipitating pixels over ocean

Number of Temperature retrieval error (relative to a priori) in 2-km layer nearest the surface

Number of pixels

Transmittance at 90 GHz

GeoMAS

STAR
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 nonhomogeneity 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

GeoSTAR¹
250kg, 350W

GeoMAS²
70kg, 50W

¹Lambrigtsen, et al., IGARSS 2008
## Comparison of GeoMAS and GeoSTAR

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

![Graph showing temperature retrieval performance with different line styles and markers, indicating RMS temperature error as a function of altitude for various data sets: HyMAS 60 GHz, HyMAS 118 GHz, AIRS+AMSUA+HSB, and AMSUA+HSB.](image-url)
Temperature Retrieval Performance
Water Vapor Retrieval Performance

![Graph showing water vapor retrieval performance](image)

- **HyMAS 60 GHz**
- **HyMAS 118 GHz**
- **AIRS+AMSUA+HSB**
- **AMSUA+HSB**

Altitude (km) vs. RMS Water Vapor Error (percent)
Water Vapor Retrieval Performance

![Graph showing water vapor retrieval performance](image)

- **HyMAS 60 GHz (mostly clear)**
- **HyMAS 60 GHz (mostly cloudy)**
- **AIRS+AMSUA+HSB (mostly clear)**
- **AIRS+AMSUA+HSB (mostly cloudy)**