Consideration of the On-board Calibration of Interferometric Synthetic Aperture Microwave Radiometer: Using Geostationary Interferometric Microwave Sounder (GIMS) for Example

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Outline

• Synthetic aperture radiometer overview
  – Real Aperture Vs. Synthetic Aperture

• GIMS overview
  – System concept
  – Demonstrator development

• GIMS calibration consideration
  – Overview of calibration for real aperture and synthetic aperture radiometer
  – Ground-based Calibration & Imaging Results

• Conclusion
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Microwave radiometry: sounder & imager

**Sounders:**
- AMSU-A/B, MHS, etc
- Cross-track scan
- 53GHz, 183GHz

**Imagers:**
- SSMI/S, TMI, GMI, AMSR2, etc
- Conical scan
- C/X band - 183GHz
The spatial resolution of passive microwave sensors

- Spatial resolution of passive sensors: totally determined by the antenna aperture size.
- Spatial resolution of active sensors: can be improved by range compression, and aperture synthesis.
How to improve the spatial resolution of the passive microwave sensors?

- **Real aperture technologies:**
  - large deployable antennas (low frequency)
  - Large reflector antennas (high frequency)
Synthetic Aperture Radiometry

- **Synthetic Aperture Radiometer** (interferometric radiometer, synthetic thinned array radiometer):
  - Using **thinned array** to replace the **real aperture**
  - Measuring the Fourier transform of the brightness temperature distribution

MIRAS/SMOS/ESA, Y-shape thinned array
Applications of Interferometric Synthetic Aperture Radiometer

• **Soil Moisture & Ocean Salinity: L band**
  - SMOS
  - Chinese Salinity Mission
  - WCOM

• **Geostationary Microwave Atmospheric Sounding: millimeter and sub-millimeter wave band**
  - GeoSTAR, NASA/JPL
  - GAS, ESA
  - GIMS, CAS/NSSC
<table>
<thead>
<tr>
<th>Synthetic Aperture: Y-shape stationary array</th>
<th>Synthetic Aperture: Rotating Y-shape array</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GeoSTAR (JPL/NASA)</strong></td>
<td><strong>GAS (ESA)</strong></td>
</tr>
<tr>
<td>From 2000~</td>
<td>From 2002~</td>
</tr>
</tbody>
</table>

![Synthetic Aperture: Y-shape stationary array](image1)

![Synthetic Aperture: Rotating Y-shape array](image2)

Frequency bands: 53 GHz, 183 GHz.
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GIMS Concept

- GIMS (Geostationary Interferometric Microwave Sounder)
  - Fourier Relationship: TB (Spatial Domain) ↔ VF (Spatial Frequency Domain)
  - Timeshared Sampling in SF Domain with Rotating Thinned Circular Array

Number of antenna units: \( N \)
Number of instantaneous VF samplers: \( \frac{N(N-1)}{2} \)
Full-disk Coverage & 3D Sounding

- Interferometric Synthetic Aperture Radiometry: Full-Disk Coverage
- Rotating Circular Thinned Array with 70 antenna units: Fast Imaging Capability (5mins/channel)
- 50-56GHz Sounding Channels: 3D Atmospheric Temperature Profiling

Simulated GiMS Observation (Ch. 5)
Fast Imaging ➔ Tracking the evolution of TCs

Dynamic Target (FNL+WRF+RTTOV) Simulated GIMS Observation (Full-disk, 30km res, 5mins)

- 30-mins duration
- 5-min imaging period,
- 10s image refresh based on kalman-filtering & interpolation processing

GIMS development roadmap

2006~2008:
Two-element Interferometer

2008~2012:
28-element GIMS-I Demonstrator

2014~2017:
Dual-mode microwave humidity/temperature sounder concept

Point Source Fringe test

GIMS-I Field Imaging Results

Cheng Zhang, Hao Liu, Ji Wu, etc, Imaging Analysis and First Results of the Geostationary Interferometric Microwave Sounder Demonstrator, IEEE Transactions on Geoscience and Remote Sensing 01/2015; DOI:10.1109/TGRS.2014.2320983
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Calibration of traditional total power radiometers

- Two-point calibration

\[ v = aT + b \]

- Receiver gain
- Receiver noise temperature
- Loss before the first LNA, including antenna, isolator, switch, etc..
- Detector bias
Calibration Considerations for Synthetic Aperture Radiometers (1)

- (1). Calibration is done on Visibility Functions, not on TB

\[ T = a_0 V_0 + a_1 V_1 + a_2 V_2 \cdots + a_n V_n + b \]

\[ V_{ij}(u, v) = \sqrt{D_i D_j} \int \int_{\xi^2 + \eta^2 \leq 1} \frac{T_B(\xi, \eta) - T_r}{\sqrt{1 - \xi^2 - \eta^2}} \cdot F_{n,i}(\xi, \eta) F_{n,j}^*(\xi, \eta) \cdot \tilde{r} \left( -\frac{u\xi + v\eta}{f_0} \right) \cdot e^{-j2\pi(u\xi+v\eta)} d\xi d\eta \]
Calibration Considerations for Synthetic Aperture Radiometers (2)

- (2). Short baselines is much more important than the long baselines
  - The value of the VF decrease very quickly from several tens K to $10^{-3}$ K with the baselines length

TB distribution in spatial domain

![TB distribution image]

VF samples in spatial frequency domain

![VF samples image]

$$T = a_0 V_0 + a_1 V_1 + a_2 V_2 + \cdots + a_n V_n + b$$
Calibration Considerations for Synthetic Aperture Radiometers (3)

- (3). In-orbit Calibration approach
  - Inter-channel Amplitude Calibration
    - Noise injection
    - Two-point calibration
  - Inter-channel phase alignment:
    - Correlated Noise Injection
    - Redundant calibration
  - Antenna pattern calibration:
    - flat target response
  - Other issues:
    - Backward Noise coupling
    - IQ imbalance
    - Fringe-washing effects
    - Imaging algorithm error

\[ T = a_0 V_0 + a_1 V_1 + a_2 V_2 \ldots \ldots + a_n V_n + b \]
GIMS Calibration Approach

- **Amplitude:**
  - two-point calibration

- **Phase:**
  - Self-calibration

\[
\phi_{ab\_0} + \phi_{ab\_180} = 2(\alpha_a - \alpha_b)
\]

\[
\phi_{ab} + \phi_{bc} + \phi_{ca}
= \phi_{id} + \alpha_a - \alpha_b + \phi_{id} + \alpha_b - \alpha_c + \phi_{id} + \alpha_c - \alpha_a
= \phi_{id} + \phi_{id} + \phi_{id}
\]
GIMS-II Demonstrator Calibration & Imaging Test

• Calibration
  ① Two-point Calibration of 70-element Receiving Channels
  ② Redundant phase calibration: point source imaging

• Imaging Tests
  ① Point Source: evaluation on spatial resolution
  ② Building
  ③ Solar transit
  ④ Imaging on Targets with changing temperature
  ⑤ Cold sky imaging: NEDT evaluation

• Restriction of On-ground Tests
  – Aliasing: no cold sky background > 18 degree
  – Near Field: D>600 wavelength → Farfield > 5km。
  – Calibration: No Cold Sky reference, Redundant Phase calibration in Near field
  – Environment effects: temperature variation, wind, solar illumination, etc
End-to-end Two-point Calibration（70-elements）

- Two calibration source + one target source
Mean NEDT of 70 receivers: 0.686K

Mean TB of 70 receivers measurements: 276.48 K
STD: 0.65K
Redundant Phase Self-Calibration

Noise Source

Phase correction - A

Rotation angle (deg)

Phase (deg)

1 & 3  6 & 8  4 & 5

14 & 15  16 & 17  11 & 12  20 & 21
Point Source Imaging (spatial resolution)

<table>
<thead>
<tr>
<th>Window Type</th>
<th>Spatial Resolution</th>
<th>Equiv. On-Track Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Window</td>
<td>$(6.817+4.941)*1e^{-4}*180/\pi=0.067^\circ$</td>
<td>42.1 km</td>
</tr>
<tr>
<td></td>
<td>$(20.83-8.943)*1e^{-4}*180/\pi=0.068^\circ$</td>
<td>42.7 km</td>
</tr>
<tr>
<td>Guassian Window</td>
<td>$(5.941+7.942)*1e^{-4}*180/\pi=0.080^\circ$</td>
<td>50.0 km</td>
</tr>
<tr>
<td></td>
<td>$(21.83-7.942)*1e^{-4}*180/\pi=0.080^\circ$</td>
<td>50.0 km</td>
</tr>
</tbody>
</table>
Building imaging

Rectangular-window

2-mins imaging time

5-mins imaging time

Rectangular-window

5-mins imaging time (blackman window)
Solar transit

Aliasing free field of view evaluation

<table>
<thead>
<tr>
<th></th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-side grating-lobe</td>
<td>$\pm \arcsin[(0.2074+0.1123)/2] = \pm 9.198^\circ$</td>
</tr>
<tr>
<td>Right-side grating-lobe</td>
<td>$\pm \arcsin[(0.1336+0.1849)/2] = \pm 9.163^\circ$</td>
</tr>
</tbody>
</table>
Continuous Imaging Tests on Thermal Sources with Changing Temperature

• Continuous Observation 110-mins
  – Hot Source (∼20°C → 60°C, switch-off)
  – Blackbody (illuminated by an heater, switch-off)
Perspectives (1)

- 53/183GHz Joint-demonstration with ESA
  - 2015.01.30: PDR, ESTEC, Noordwijk, the Netherlands
  - 2015.12.08: DDR, NSSC, Beijing, China
  - 2017.11.09: TRR, Omnisys, Gothenburg, Sweden
Perspectives (2)

- Improved GIMS Design with deployable sub-array structure

- 50GHz
- Physical dimension Da=7.91m
- Equivalent dimension: Db=14.82m
- Ground resolution: 24km
- Antenna elements: 8*15=120
Thanks!