Millimeter- and Submillimeter-Wave Remote Sensing Using Small Satellites

NASA Goddard Space Flight Center

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Outline

- Motivation and science drive
- GSFC mm- and sub-mm-wave instruments
- Instrument study
- Candidate instrument architecture
- Small rocket technology (SMART)
- IceCube
- Conclusion
Motivation and science drive

- Cloud ice properties are fundamental controlling variables of atmospheric radiation and precipitation
- Large discrepancies in Ice Water Path (IWP) exist in Global Circulation Models
- Limited availability of data and poor assumptions about the cloud micro- and macro-physical properties of clouds are principle contributors to the discrepancy
- No ice cloud measurements currently exist for the intermediate altitudes
- mm- and submm-wave radiometry offers great potential to fill the measurement gap in the middle and upper troposphere
GSFC mm- and sub-mm-wave instruments

- **CoSMIR: Conical scanning mm-wave imaging radiometer**
  - Azimuth over Elevation dual axes gimbals for cross-track and conical scanning
  - 6 receivers, 9 channels at 50.3, 52.6, 89 (H&V), 165.5 (H&V), 183.3±1, 183.3±3, ±7
  - FOV: 4° beam width
  - Scan head: cylinder with 21.5 cm diameter and 28 cm length

- **CoSSIR: Compact scanning sub-mm-wave imaging radiometer**
  - 6 receivers, 12 channels at 183.3±1 ±3 ±7, 325±1.5 ±3.5 ±9.5, 448±1.4 ±3 ±7.2, 642 (H&V), 874

- **HyMAS: Hyperspectral Microwave Atmospheric Sounder**
  - Hyperspectral with 52 channels (in partnership with MIT-LL)
  - 6 receivers at 172-183 GHz (H&V), 2x108-119 (H&V)

- **GMI: GPM Microwave Imager**
  - Receiver Components:
    - Noise sources X-band—Ka-band
    - Mixers up to G-band
A small, compact sub-mm instrument has many opportunities in future NASA, NOAA and international missions.

GSFC developed design and analysis tools to evaluate size, weight, and power (SWaP) of sub-mm-wave instruments:
- Cross-track vs. Conical scan
- Spatial resolution, aperture size, and spatial resolution
- Receiver selection and number of channels

Scientifically-valuable sub-mm-instrument configuration fit within 30–50 kg mass, suitable for Earth-venture class opportunities.

<table>
<thead>
<tr>
<th>Projected Aperture</th>
<th>Scan Topology</th>
<th>Receptors</th>
<th># of Ch</th>
<th>Spatial Res. / Altitude</th>
<th>Power (W)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>448 V</td>
<td>640 V</td>
<td>360 km</td>
<td>61.2</td>
<td>107.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325 V</td>
<td></td>
<td>610 km</td>
<td>61.1</td>
<td>107.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>183 V</td>
<td></td>
<td>600 km</td>
<td>52.7</td>
<td>30.0</td>
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<td></td>
<td></td>
<td>183 V</td>
<td></td>
<td>600 km</td>
<td>61.1</td>
<td>41.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>193 V</td>
<td></td>
<td>600 km</td>
<td>54.0</td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>183 V</td>
<td></td>
<td>600 km</td>
<td>62.4</td>
<td>41.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>183 V</td>
<td></td>
<td>600 km</td>
<td>54.3</td>
<td>37.7</td>
</tr>
</tbody>
</table>

Conical Scan Instrument concept:
- Black Bodies (Calibration)
- Toroidal Reflector
- Space View Port
- Structural - Support Truss
- Rotating Electronics Assembly (REA)
- Common Payload Structure (CPS)
  - Drive Electronics
  - Static Electronics Assembly (SEA)
  - S/C interface
SMART is a Microsatellite prototype that enables focused science and technology missions with limited resources

- Demonstration of a point design instantiation of a modular, open systems architecture micro spacecraft prototype
- Miniaturized high-performance, power-efficient processing avionics for small expendable launch vehicles, and small orbiting spacecraft
- Modular, reconfigurable, and rapid architecture

- SMART core components are mostly COTS, and replaceable
- Payload mass capability: 30–50 kg
- Payload available power: 284–314 W
- Bus dissipated power: 45–75 W
## SCAMPER performance parameters

<table>
<thead>
<tr>
<th>Center frequency &amp; polarization</th>
<th>183 GHz V-pol</th>
<th>325 GHz V-Pol</th>
<th>642 GHz H-Pol</th>
<th>642 GHz V-Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF pass-band [GHz]</td>
<td>166-186</td>
<td>318-332</td>
<td>639-645</td>
<td>639-645</td>
</tr>
<tr>
<td>IF pass-band [GHz]</td>
<td>10-30</td>
<td>0.5-7</td>
<td>1-3</td>
<td>1-3</td>
</tr>
<tr>
<td>Number of channels</td>
<td>22</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vertical</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>Noise temperature [K]</td>
<td>1060 (SSB)</td>
<td>1540 (DSB)</td>
<td>4120 (DSB)</td>
<td>4120 (DSB)</td>
</tr>
<tr>
<td>NETD [K] @ $\tau_{\text{int}} = 7$ ms</td>
<td>0.64 (650 MHz BW)</td>
<td>0.49 (2 GHz BW)</td>
<td>1.18 (2 GHz BW)</td>
<td>1.18 (2 GHz BW)</td>
</tr>
</tbody>
</table>
New instrument technologies

- LNAs at 183 GHz and 325 GHz
  - Advantages
    - Improved noise temperature
    - Reduced power (mixer with higher conversion loss)
    - Single side-band detection (hyperspectral receivers)
  - Available technologies
    - 35 nm InP technology NGAS/JPL [Kangaslati et al., 2008] and BAE
    - SiGe technology Georgia Tech [Coen et al.]
    - Teledyne HBT InP

- Coupled noise source at 183 GHz
  - 9 dB ENR @ 200 GHz noise source developed at GSFC
  - Improving receiver calibration
  - Eliminates requiring view of clear sky

- Ultra Wide Band Spectrometer (UWS) developed by MIT-LL
  - 52-channel, 100 cm³ UWS developed for HyMAS (ESTO/ACT project)
IceCube: 874 GHz radiometer on a CubeSat

Objective
- Develop and validate a flight-qualified 874 GHz receiver for future use in ice cloud radiometer missions.

Operation Concept
- Orbit: LEO @ 350 km
- Duration: 28 days
- 15 orbits per day (31 mins pointed at Earth, 9 mins view of clear sky)

Technologies
- Sub-mm-wave 874 GHz receiver
  - 2nd Harmonic mixer
  - Frequency doubler & triplers
  - V-band multiplied LO with power modulation
  - IF with noise injection

Receiver performance
- Noise temperature < 6000 K
- NEDT < 0.1 K for 1 s integration time
- 2 K calibration error

(a) Conceptual drawing of IceCube (radiometer at top). (b) The 874 GHz CoSSIR. (c) First ever 874 GHz cloud measurements acquired by CoSSIR in 2008. CoSSIR measurements of ice clouds were used to successfully demonstrate retrieval of ice water path (IWP) and ice particle median mass-weighted ice particle size ($D_{me}$).
IceCube: receiver

2nd Harmonic Mixer
Coupler 20 dB
Isolator
BPF F= 6-12 GHz
LNA G= 19 dB
Gain Stages G= 38 dB
Detector

Video Amp

2x
3x

Noise Source
NS Ctrl

T3

DRO 24.3 GHz

PA

Ref Ctrl

437 GHz
145.7 GHz
72.8 GHz

T1 T2

T4

T5

ST 11401
14-bit ADC

Buffer

Signal Conditioning Circuit

Telemetry

Power Distribution Unit (PDU)

Receiver Interface Card

Switching Sequence

<table>
<thead>
<tr>
<th>Ant</th>
<th>A+N</th>
<th>Ref</th>
<th>R+N</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10 ms</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>40</td>
<td>1 sec</td>
</tr>
</tbody>
</table>

1 sec

Ant A+N Ref R+N

Ant A+N Ref R+N

Ant A+N Ref R+N

......

Ant A+N Ref R+N
## Conclusion

- Distributed satellite systems are required to retrieve IWP with 25% accuracy, to enable improved ice cloud modeling
  - Highly sensitive
  - Cost effective
  - Compact mm- and sub-mm-wave instrument with multiple channels

### Science capabilities

<table>
<thead>
<tr>
<th></th>
<th>SCAMPER</th>
<th>SSMIS</th>
<th>MHS</th>
<th>GMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud ice</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ice particle size</td>
<td>Yes</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
</tr>
<tr>
<td>Ice particle shape</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Limited</td>
</tr>
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### Instrument properties

<table>
<thead>
<tr>
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<th>MHS</th>
<th>GMI</th>
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</thead>
<tbody>
<tr>
<td>Frequencies [GHz]</td>
<td>183, 325, 642, 874</td>
<td>19, 22, 37, 91, 50-63, 183</td>
<td>89, 157, 183, 190</td>
<td>10, 18, 23, 36, 89, 165, 183</td>
</tr>
<tr>
<td>IF channels</td>
<td>28</td>
<td>24</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Dual-polar [GHz]</td>
<td>642</td>
<td>19, 37, 91</td>
<td>None</td>
<td>10.7, 18.7, 36.5, 89, 165.5</td>
</tr>
<tr>
<td>RF cal [GHz]</td>
<td>183</td>
<td>None</td>
<td>None</td>
<td>10.7, 18.7, 23.8, 36.5</td>
</tr>
</tbody>
</table>
Questions?
Distributed satellites
- Observations of ice clouds require frequently updated measurements by a distributed satellite system, due to a strong diurnal variation

Conically scanning/Cross track
- Polarization preservation

Radiometric stability
- Antenna is not exposed to open air

mm- and sub-mm-wave receivers housed in the compact scan head

Mass budget
- 41 kg

Power budget:?
## Backup: concept study table

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<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>400 km 800 km</td>
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</tr>
<tr>
<td>36.0 cm</td>
<td>Conical</td>
<td>183 V</td>
<td>325 V</td>
<td>448 V</td>
<td>640 V</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325 V</td>
<td>640 V</td>
<td>640 H</td>
<td>325 V</td>
<td>8</td>
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<tr>
<td></td>
<td></td>
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<td>640 V</td>
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<td></td>
<td></td>
<td>---</td>
<td>640 H</td>
<td>---</td>
<td>640 V</td>
<td>8</td>
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<td>640 H</td>
<td>640 V</td>
<td>9</td>
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<td></td>
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<td>---</td>
<td>640 V</td>
<td>874 V</td>
<td>874 V</td>
<td>3</td>
</tr>
<tr>
<td>19.8 cm</td>
<td>Conical</td>
<td>183 V</td>
<td>325 V</td>
<td>448 V</td>
<td>640 V</td>
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<tr>
<td></td>
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<td>325 V</td>
<td>640 V</td>
<td>640 H</td>
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<td>640 V</td>
<td>874 V</td>
<td>640 H</td>
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<td>640 V</td>
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<td>640 H</td>
<td>874 V</td>
<td>874 V</td>
<td></td>
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Backup: previous mm- and sub-mm-wave work

- CoSMIR: Conical scanning mm-wave imaging radiometer
  - Four receivers
  - 9 channels at 50.3, 52.6, 89 (H&V), 165.5 (H&V), 183.3±1, 183.3±3, ±7
- CoSSIR: Compact scanning sub-mm-wave imaging radiometer
- HyMASS:

CoSSIR nadir brightness temperature and retrieved IWP [K. F. Evans et al.]
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- Miniaturized high-performance, power-efficient processing avionics for small expendable launch vehicles, and small orbiting spacecraft.
- Modular, reconfigurable, and rapid architecture
Backup: Small rocket/spacecraft technology (SMART)

- SMART core components are mostly COTS, and replaceable
- Payload mass capability: 30–50 kg
- Payload available power: 284–314 W
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Backup: atmospheric sensing spectral regions