A Multi-frequency Wide-swath Spaceborne Cloud and Precipitation Imaging Radar

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Outline

• Science Motivations
   Science background
   Spaceborne atmospheric radar past, current and future

• Cloud and Precipitation Radar Design Trade
   Design trades
   Performance parameters

• Technology development at GSFC and NGES
   ACE Ka/W-band dual-frequency radar concept
   CaPPM Ku/Ka/W-band tri-frequency radar concept
   Dual or tri-frequency shared aperture antenna study
   Ka-band AESA development
   Radar digital receiver and processor

• Summary and Path Forward
Science Motivations

- Clouds and precipitation are among the greatest sources of uncertainty in climate change prediction. Global-scale measurements are critically needed.
- Multi-frequency radar with Doppler and imaging capability is crucial for improved understanding of the characteristics of clouds, precipitation, and their interaction.
  - Provide quantitative estimates of Ice Water Path (IWP), Liquid Water Path (LWP), particle size, and particle phase with much higher accuracy than single frequency radar measurements.
  - Doppler velocity provides information on vertical air motion, convective up- and down-draft, particle size and classification, and latent heat transportation etc.
- Decadal Survey (DS) Aerosol Cloud Ecosystem (ACE) calls for a dual frequency (Ka/W-band) radar.
- After the successful launch of GPM in 2014, a tri-frequency imaging Doppler radar concept as a CloudSat and GPM follow-on mission, Cloud and Precipitation Process Mission (CaPPM), is under development.
## Spaceborne Atmospheric Radar Past, Current and Future

<table>
<thead>
<tr>
<th></th>
<th>TRMM</th>
<th>CloudSat</th>
<th>EarthCare</th>
<th>GPM</th>
<th>ACE (GSFC/NGES)</th>
<th>CaPPM (GSFC/NGES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>13.8</td>
<td>94</td>
<td>94</td>
<td>13.6</td>
<td>35</td>
<td>94</td>
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<tr>
<td>Primary Target</td>
<td>Rain</td>
<td>Clouds</td>
<td>Clouds</td>
<td>Rain/Snow</td>
<td>Clouds</td>
<td>Clouds &amp; precipitation</td>
</tr>
<tr>
<td>Measurements</td>
<td>Reflectivity</td>
<td>Reflectivity</td>
<td>Reflectivity, Doppler</td>
<td>Reflectivity</td>
<td>Reflectivity, Doppler</td>
<td>Reflectivity, Doppler, &amp; Polarimetric (option)</td>
</tr>
<tr>
<td>Retrieval Products</td>
<td>Rain rate</td>
<td>IWC, LWC</td>
<td>IWC, LWC</td>
<td>Rain rate, particle size</td>
<td>IWC, LWC, particle size</td>
<td>IWC, LWC, particle size, rain rate, weather system dynamics</td>
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<td>Orbit Altitude (km)</td>
<td>402</td>
<td>720</td>
<td>400</td>
<td>407</td>
<td>420</td>
<td>420</td>
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<tr>
<td>Transmitter</td>
<td>SSPA Array</td>
<td>EIK</td>
<td>EIK</td>
<td>SSPA Array</td>
<td>SSPA Array</td>
<td>AESA</td>
</tr>
<tr>
<td>Tx Peak Power (W)</td>
<td>500</td>
<td>1820</td>
<td>1800</td>
<td>1012</td>
<td>146</td>
<td>2000</td>
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<tr>
<td>Antenna Size (m)</td>
<td>2.1</td>
<td>1.85</td>
<td>2.5</td>
<td>2.1</td>
<td>0.8</td>
<td>2.3x3.0 to 3.0x5.0</td>
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<td>Vertical Res. (m)</td>
<td>250</td>
<td>500</td>
<td>500</td>
<td>250</td>
<td>250</td>
<td>250</td>
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<td>Horizontal Res. (km)</td>
<td>5.2</td>
<td>1.4</td>
<td>0.8</td>
<td>5.2</td>
<td>5.2</td>
<td>2.0x1.5</td>
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<tr>
<td>Cross Track Swath (km)</td>
<td>245</td>
<td>Nadir</td>
<td>Nadir</td>
<td>245</td>
<td>120</td>
<td>120</td>
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<tr>
<td>Nadir Sensitivity (dBZ)</td>
<td>18</td>
<td>-28</td>
<td>-35</td>
<td>17</td>
<td>12</td>
<td>-14.0</td>
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<tr>
<td>Swath Sensitivity (dBZ)</td>
<td>18</td>
<td>N/A</td>
<td>N/A</td>
<td>17</td>
<td>12</td>
<td>-11.0</td>
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<tr>
<td>Doppler Capability</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Polarimetric Capability</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>LDR</td>
</tr>
</tbody>
</table>

*96th AMS Annual Meeting, January 13, 2016, Lihua Li, NASA GSFC*
System Design and Associated Trades Are Closely Tied to Science Objectives

Science Requirements and Priorities Including,

- Orbit altitude
- Radar sensitivity
- Spatial resolution
- Range resolution
- Swath width
- Matched beam
- Doppler accuracy
- Polarimetric operation

Radar Design Constraints

- Antenna size
- Primary power consumption
- Weight
- Data rate
- ...

Worse
Better
What Can We Do With Current and Near Future Technologies

• Active Electrically Scanned Array (AESA) for Different Scanning Modes
  - AESA feeds enable programmable scanning modes and footprint size.
  - Matched beam for nonhomogeneous and high dynamic targets, or non matched beams for better sensitivity for homogeneous targets.
  - Wider swath with lower sensitivity for precipitation, or narrow swath with higher sensitivity for clouds.
  - Longer dwell time at angles of interest for better sensitivity
• Programmable Waveform and Digital Receiver for Different Tx/Rx Pulse Sequence
  - Shorter pulse for better range resolution or longer pulse for better sensitivity
  - Frequency diversity pulses for more independent samples or Doppler measurements
• Pulse Compression for Better Sensitivity
• Radiometric Channels
Advanced Radar Technology Development at NASA GSFC and NGES

**NASA GSFC**
- TRMM and GPM science
- High altitude airborne radars cover frequencies from X, Ku, Ka to W-band
- NASA ESTO IIP2010 and IIP 2013
- Passive microwave and millimeter-wave remote sensing
- NASA GSFC and NGES Space Act Agreement since 2008

**NGES**
- World leading company for RF electronics and radar system development
- Delivered and flown over 100 space payloads
- Advanced radar technology including Active Electrically Scanning Array (AESA), antenna and back-end electronics
ACE Ka/W-band Dual-frequency Radar Concept (ESTO IIP 2010 project)

- Ka/W-band dual-frequency radar using a single one-dimension curved main reflector
- Ka-band AESA line feed for cross-track scanning
- W-band fixed nadir beam similar to CloudSat configuration
- Innovative reflector/reflectarray technology to achieve focus at W-band and cross-track scan at Ka-band
- Reflector/reflectarray enables co-located beams and reduces the loss due to feed displacement.
- Full scale design of antenna, Ka-band AESA T/R module, and the line feed.
- Designed, fabricated, and tested Ka-band high power amplifier MMIC for the AESA T/R module.
- Developed a subscale antenna using the reflector/reflectarray technology and carried out airborne demonstration with W-band CRS

GSFC/NGES ACE Cloud Radar using Reflector/Reflectarray Technology for wide swath Ka-band profiling

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Sub-scale Antenna Demonstration During IPHEX and OLYMPEX Campaigns

Sub-scale antenna in CRS canister in ER-2 tail cone

ER-2

20" 20"

W-Band Feed Horn
Feed Support Structure

Composite Reflector
Passive Ka-band Feed Array (includes azimuth manifold)
Tri-frequency Radar Concept for CaPPM (ESTO IIP 2013 project)

- Development of a tri-frequency radar concept
- Tri-band shared aperture antenna study
- Development of Ka-band Active Electrically Scanned Array (AESA) T/R module
- Development of radar back-end electronics, including waveform generation module, frequency conversion module and digital receiver/processor

ACE Technology Maturation Study (2013)
- Performed TRL assessment for Ka/W-band radar
- Identified key areas to be advanced
- Defined a pathway to space
Tri-frequency (Ku/Ka/W-band) Radar for Imaging Clouds and Precipitation

**Discriminating Features**

- Shared tri-frequency primary aperture
- Wide swath imaging at Ka-band (>120 km) and Ku-band (>250 km)
- W-band compatible with either fixed beam (similar to CloudSat / EarthCare) or AESA cross-track scanning beams
- Reflectarray enables co-located beams for tri-frequency with optional scanning W-band beam
- Programmable scanning mode
- Leverage high space readiness radar electronics from GSFC and NGES
- Technology Maturation Plan to achieve TRL 6 by 2017/2018

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CaPPM</th>
</tr>
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<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>13.48</td>
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<tr>
<td>Orbit Altitude (km)</td>
<td>395-420</td>
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<tr>
<td>Transmitter</td>
<td>SSPA</td>
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<tr>
<td>Tx Peak Power (W)</td>
<td>2000</td>
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<tr>
<td>Antenna Size (m)</td>
<td>3.0x2.3</td>
</tr>
<tr>
<td>PRF (Hz)</td>
<td>4700</td>
</tr>
<tr>
<td>Vertical Res. (m)</td>
<td>250</td>
</tr>
<tr>
<td>Horizontal Res. (km)</td>
<td>5.0x4.0</td>
</tr>
<tr>
<td>Cross Track Swath (km)</td>
<td>250</td>
</tr>
<tr>
<td>Nadir MDZ (dBZ)</td>
<td>1.0</td>
</tr>
<tr>
<td>Swath MDZ (dBZ)</td>
<td>4.0</td>
</tr>
<tr>
<td>Doppler Vel. Accuracy (m/s)</td>
<td>1.0</td>
</tr>
<tr>
<td>Polarization Option</td>
<td>Yes</td>
</tr>
</tbody>
</table>

7-17 m\(^2\) primary aperture with printed circuit reflectarray
Tri-frequency Antenna Trade Study

**Rich Trade Space**
Enables tailoring for particular frequency and/or requirements

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>1A</td>
<td>1B</td>
</tr>
<tr>
<td></td>
<td>Defocused Ku, Focused Ka, W RA on main.</td>
<td>Defocused Ku, Focused W</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>2B</td>
</tr>
<tr>
<td></td>
<td>Defocused Ka, Focused Ku via RA on sub. W RA on main.</td>
<td>Focused W via RA on sub. Focused Ka</td>
</tr>
<tr>
<td></td>
<td>3A</td>
<td>3B</td>
</tr>
<tr>
<td></td>
<td>Defocused Ku, Focused W via RA on sub.</td>
<td>Focused W via RA on sub. Focused Ka</td>
</tr>
<tr>
<td></td>
<td>3C</td>
<td>3D</td>
</tr>
<tr>
<td></td>
<td>Focused W via RA on sub. Focused Ku, Focused W via RA on sub.</td>
<td>Focused W via RA on sub. Focused W via RA on sub.</td>
</tr>
<tr>
<td></td>
<td>3E</td>
<td>3F</td>
</tr>
<tr>
<td></td>
<td>Focused Ku, Focused W via RA on sub. Focused Ka, Focused W via RA on sub.</td>
<td>Separate sub for Ku/Ka &amp; W via RA on both sub.</td>
</tr>
</tbody>
</table>

- **Tri-Band Capability**
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes

- **W-Band Cross Track Scanning?**
  - Fixed
  - Fixed
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes

- **Aligned Along Track Beams?**
  - Ka & W
  - Ka & W
  - All
  - None
  - All
  - None
  - Ka & W
  - All
  - All
  - All

- **Matched Cross-Track Beams Possible?**
  - Ku/Ka Only
  - Ku/Ka Only
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes
  - Yes

- **2-way Antenna Loss**
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku

- **3-dB Beam Width**
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku

- **2-way SLL**
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku
  - Ku

**Trade Study Summary**
- Identified, assessed 10 candidate architectures (3 classes)
- Down selected primary candidates from each class
- Leveraged IIP 2010 design tools and technologies
  - Reflectarray and reflector design/analysis tools
  - Low loss reflectarray element (including FSS properties)
  - Ka-band AESA and T/R module design
- Evaluated & traded various AESA and T/R module design approaches (Ku, Ka and W-band)
- Explored usage of reflectarrays for tri-freq. architectures
  - Potential benefits in mitigating defocusing scan losses (Ka/W-band)

**Surface Types**
- Acts as a solid reflector
- Acts as a reflectarray/FSS

**Parameter Diagrams**
- W beam waveguide
- Ku
- Ka
- W
- Ka
- Ku

1B shown
2B shown
3B shown
Ka-Band AESA T/R Module Development

Integrated circulator, MMIC and ASIC development currently under development…

- Held PDR, CDR, FDR for LNA and Key MFC MMIC Circuits
- 3 Design Options For Circulator
- ASIC Requirements for control and telemetry concept
Spaceborne Digital Receiver and Processor

• Hardware and firmware evaluation through airborne Xilinx Virtex-5 based digital receiver and processor

• NASA GSFC SpaceCube 2.0
  • Developed for International Space Station (ISS) and future space mission
  • 3U CPCI architecture
  • Xilinx Virtex-5 FPGA
  • Compact size (7”x5”x8”)

• NGES
  • 6U modules include all radar backend electronic and processor functions
  • Hi-Rel design for space application
  • Xilinx Virtex-5 FPGA
  • TRL 6 by 2017
Summary and Path Forward

• Technologies for a dual- or tri-frequency spaceborne cloud and precipitation radar are under development at NASA GSFC and NGES.

• Dual- or tri-frequency, shared-aperture antenna study
  • Evaluated 3 classes and 10 candidate architectures
  • Down selected to primary candidates supporting final mission requirements
  • Addresses various band combinations with options for W-band fixed beam and scanning
  • Includes application of proven reflectarray technologies

• Ka-band AESA T/R module development
  • Module RF and mechanical design
  • MMIC and circulator development approaching fab
  • GaN HPA MMIC design verification test underway

• W-band compatible with either fixed nadir beam or AESA scanning beam
  • Leverage high TRL CloudSat technologies
  • Compatible with AESA cross-track scanning design

• Ku-band AESA technology is mature

• Continue to enhance the Technology Readiness Level (TRL) for space
Thank You!

Developing technologies for the next generation spaceborne atmospheric radars