Wide-swath Shared-aperture Cloud Radar (WiSCR)

Earth Science Technology Forum
June 25, 2015

GSFC: Lihua Li, Paul Racette, Gerry Heymsfield, Matthew McLinden, Vijay Venkatesh, Michael Coon, Martin Perrine
NGES: Richard Park, Michael Cooley, Pete Stenger, Thomas Spence, Tom Retelny
Outline - WiSCR Objectives

• Science Motivations
  ➢ Science background
  ➢ ACE / CaPPM radar concept

• Tri-band Antenna Architecture Study
  ➢ Design trades
  ➢ Performance parameters

• Ka-band AESA T/R Module Development
  ➢ Module design
  ➢ MMIC development

• Advanced Doppler Radar Technologies
  ➢ Frequency diversity pulse pair Doppler technique
  ➢ Multi-channel waveform generation and frequency conversion modules with shared circuit to reduce SWaP

• 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.

• Decadal Survey (DS) Aerosol Cloud Ecosystem (ACE) calls for a dual frequency (Ka/W-band) radar while the more recent Cloud and Precipitation Process Mission (CaPPM) concept requires a tri-frequency imaging Doppler radar.
Dual- or Tri-band Radar Concept for ACE and CaPPM

- **IIP 2010 Achievements**
  - Demonstrated an efficient dual-frequency (Ka/W), shared aperture antenna architecture
    - Reflective/Reflectarray technologies
    - Sub-scale antenna
  - Developed Scalable Antenna Designs (7-17 sqm)
    - Dual-band (Ka/W) antenna
    - Ka-band AESA feed
    - Ka-band T/R module

- **ACE Technology Maturation Study (2013)**
  - Performed TRL assessment for Ka/W-band radar
  - Identified key areas to be advanced
  - Defined a pathway to space
Science Objectives Are Closely Tied to the Antenna Design and Associated Trades

Various antenna parameters must be balanced to meet mission objectives...

<table>
<thead>
<tr>
<th>Radar Parameter</th>
<th>Antenna Parameter/Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution</td>
<td>Aperture Size</td>
</tr>
<tr>
<td>Vertical Resolution</td>
<td>Tx Pulse Width</td>
</tr>
<tr>
<td>Field of View</td>
<td>Beam Steering</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>Dual-Polarization</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Size, Radiated Power, Efficiency, Noise Figure</td>
</tr>
<tr>
<td>Data Diversity</td>
<td>Multi-Band Antenna</td>
</tr>
</tbody>
</table>

AESA and T/R Module Experience, Technology Base & TRL

• X/Ku-band AESA & T/R module technology is high TRL
  - *NGES has extensive experience*

• Ka-band AESA & T/R module technology rapidly maturing
  - *Funded under ACE IIPs and demonstrated for various other programs/applications*

• W-band AESA technology emerging
  - *Funded under ACE IIPs and via other sources (e.g. DARPA)*

• GaN MMIC technology proliferating very fast at X, Ku, Ka, & W-bands
Key Parameters from the Tri-Band Antenna Study Design Budget [Assuming a 7 sqm main reflector]

<table>
<thead>
<tr>
<th></th>
<th>Ku</th>
<th>Ka</th>
<th>W Fixed Beam*</th>
<th>W AESA</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (dBZ @ Nadir)</td>
<td>0.0</td>
<td>-12.9</td>
<td>-34.4</td>
<td>-31.4**</td>
<td>For Ku &amp; Ka it assumes system dwells equally across swath. See below for W band **</td>
</tr>
<tr>
<td>Transmit Power (kW)</td>
<td>2.4</td>
<td>2.6</td>
<td>1.6</td>
<td>1.9</td>
<td>At antenna feed. 3-tier AESA Tx pwr</td>
</tr>
<tr>
<td>Antenna Gain (dBi)</td>
<td>49.8</td>
<td>58.3</td>
<td>67.7</td>
<td>66.7</td>
<td>Assumes 3 x 2.33 m antenna</td>
</tr>
<tr>
<td>Cross Track Resolution (km)</td>
<td>5.1</td>
<td>2.1</td>
<td>0.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Along Track Resolution (km)</td>
<td>3.4</td>
<td>1.4</td>
<td>0.7</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Cross Track Swath (± deg)</td>
<td>10.0</td>
<td>8.5</td>
<td>N/A</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>3.3</td>
<td>4.6</td>
<td>5.7</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Number of Integrated Pulses</td>
<td>151</td>
<td>29</td>
<td>725</td>
<td>642**</td>
<td>Constant CT Scan Rate</td>
</tr>
<tr>
<td>Duty (%)</td>
<td>1.56</td>
<td>1.56</td>
<td>1.56</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>Pulse Width (us)</td>
<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
<td>250 m resolution</td>
</tr>
<tr>
<td>Number of T/R Modules</td>
<td>128</td>
<td>288</td>
<td>N/A</td>
<td>384</td>
<td>4 channel Ka &amp; Ku module 8 channel W module</td>
</tr>
</tbody>
</table>

*Estimates assume the 7m² antenna architecture & CouldSat-style beam waveguide hardware

+ Greater swaths (e.g., +/- 17 deg) are supported with a minor adjustment in the assumed Ku band grid.

**AESA architecture permits flexible dwell times; dwelling longer in regions of interest is possible. This trade is most pronounced at W-band, where the beam width is most narrow. For reference, the sensitivity shown assumes dwelling on nadir only. A peak transmit power of 2W/site is assumed.

---

**Antenna Architectures Were Derived Based on Detailed Radar System Budgets**
Tri-Band Antenna Trade Study Assessment/Conclusions

Rich Trade Space
Enables tailoring for particular band(s) and/or requirements

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ku &amp; Ka Scanning, W Fixed</td>
<td>1A</td>
<td>1B</td>
<td>1B</td>
</tr>
<tr>
<td>Ka &amp; W Scanning</td>
<td>2A</td>
<td>2B</td>
<td>2B</td>
</tr>
<tr>
<td>Ku, Ka, W Scanning</td>
<td>3A</td>
<td>3B</td>
<td>3B</td>
</tr>
</tbody>
</table>

- 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-band architectures
  - Potential benefits in mitigating defocusing scan losses (Ka/W-band)

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-band architectures
  - Potential benefits in mitigating defocusing scan losses (Ka/W-band)
Objective Ka-Band T/R Module Design Development Path Overview

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
T/R Module RF Architecture
Supports Efficient T/R Functionality and Polarization Diversity

- Module front end architecture down-selected from 10 options
- Selected option provides best balance between system sensitivity, module cost and weight

~ 300 modules, each with 4 TR channels, form phase array line feed to reflector

Dual Pol
Radiator Feed (4X)

Beam Control (MFC MMIC)

Module In/Out

Dual Pol Duplexer

RX
TX/RX
RX
TX/RX
RX
TX/RX
RX
TX/RX
Ka-Band AESA and T/R Module Overview

System Performance Context: 4 Main Modes of Operation

1. Module 1D Scanning Radar
   Pulsed Modes
   - 1.65μS
   - 1.65μS
   - 0 to 80μS
   - 167 to 250μS
   - Switch Independently Between Rx Co-pol and X-pol
   - Duty Cycle held at 1.56%

2. Telemetry – Metadata Modes
   - Temperature, Current, Voltage
     - Trading whether at individual module or subarray level
   - Phase and Amplitude Control Read-back
     - Serial phase shift and attenuator commands are read back to beam steering control unit

3. Power Up/Down Modes
   - Standby
     - TR Module powered up without TR pulsing
   - All OFF Power Down
     - “zero” DC current draw

4. TR Head Count Mode (Health Check)

Antenna Beam Patterns
- Rx Pattern – Individual Module
- Tx Pattern – Individual Module
- Rx Pattern – All Modules
- Tx Pattern – All Modules

Other health check modes under consideration:
- Mutual Coupling Across Module Radiators
- Receive Noise Power Check at IF Receiver
Frequency Diversity Pulse Pair for Space-borne Doppler Measurement – Motivation

- Velocity folding and Doppler spectrum broaden due to spacecraft ground speed (7.6 km/s).
- Larger resolution volume could result in non-uniform filled beam and multi-scattering biases.
- Required $\sigma/2V_{\text{max}} < 0.3$ for good Doppler measurements ($v_{\text{max}} = \frac{\lambda \cdot \text{PRF}}{4}$).
- Approaches:
  - large antenna: reduce $\sigma$
  - higher PRF, stagger PRF: increase $V_{\text{max}}$

Unambiguous range & Doppler velocity versus PRF

Unambiguous Range (km) vs. PRF (kHz)

Unambiguous Velocity (m/s) vs. PRF (kHz)

$V_{\text{max}} = \frac{c\lambda}{8}$
# Techniques to Mitigate Range-Doppler Velocity Ambiguity

## Pulse Pairs

- **Traditional Pulse-pair (PP)**
- **Stagger PRF Pulse-pair (SRPP)**
- **Polarization Diverse Pulse-Pair (PDPP)**
- **Frequency Diverse Pulse-Pair (FDPP)**

## Table: Comparison of Techniques

<table>
<thead>
<tr>
<th></th>
<th>Pulse Pair</th>
<th>Dual-PRT Pulse Pair</th>
<th>Polarization Diversity Pulse Pair</th>
<th>Frequency Diversity Pulse Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>- Simple processing</td>
<td>- Mitigate velocity ambiguity</td>
<td>- Mitigate range/velocity ambiguity</td>
<td>- Mitigate range/velocity ambiguity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- High immunity to SNR</td>
<td>- Simple radar hardware</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>- Decorrelation due to spacecraft motion</td>
<td>- Decorrelation due to spacecraft motion</td>
<td>- Dual-pol Tx/Rx hardware</td>
<td>- Performance at low SNR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Poor channel isolation</td>
<td></td>
</tr>
</tbody>
</table>
Simulated Doppler Velocity Accuracy Versus Lag Time, Antenna Size and PRF

- Monte-Carlo based simulation
- Assuming scatter particle size distribution and use radar parameters to calculate backscattering power and phase
- Calculate Doppler velocity accuracy versus pulse pair lag time, antenna size, PRF, along track integration time et al.
- Preliminary results show potential to achieve ~1 m/s Doppler accuracy for Ka and W-band respectively for high SNR targets.
- More details are under study for low SNR cases.
- Rooftop test and airborne demonstration are planned.
Multi-Channel Tx Waveform Generation and Frequency Conversion Modules

Motivations:
- ACE/CaPPM radar requires multi-channel waveform generator and frequency conversion
- Use shared hardware to reduce SWaP
- Risk reduction for space

Objectives:
- Develop FPGA firmware based on a commercial module
- Support versatile waveform for pulse or pulse compression mode operation
- Develop compact, low power prototype frequency conversion module to reduce risk for space

Key challenging:
- Support up to 4 pulses and chirps per PRF cycle per channel
- Use minimum bandwidth for multi pulses
- Amplitude modulation for better channel isolation in spectrum
- Minimize SNR loss due to amplitude modulation

Status:
- Channel frequency mapping, firmware development
- Module design, simulation and part selection
Summary and Path Forward

• Tri-band, 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

• FDPP Doppler measurement technique development
  • Performance simulation
  • Roof-top test is under way
  • Airborne demonstration planned during the GPM ground validation campaign - Olympex flights (Nov-Dec, 2015)

• Multi-channel waveform generation and frequency conversion
  • Developed multi-channel waveform generation firmware
  • Carried out frequency conversion module design and simulation
  • Frequency conversion module layout underway
# 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><strong>Frequency (GHz)</strong></td>
<td>13.8</td>
<td>94</td>
<td>94</td>
<td>13.6</td>
<td>35</td>
<td>94</td>
</tr>
<tr>
<td><strong>Primary Target</strong></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><strong>Measurements</strong></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><strong>Retrieval Products</strong></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>
</tr>
<tr>
<td><strong>Orbit Altitude (km)</strong></td>
<td>402</td>
<td>720</td>
<td>400</td>
<td>407</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td><strong>Transmitter</strong></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><strong>Tx Peak Power (W)</strong></td>
<td>500</td>
<td>1820</td>
<td>1800</td>
<td>1012</td>
<td>146</td>
<td>2000</td>
</tr>
<tr>
<td><strong>Antenna Size (m)</strong></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>
</tr>
<tr>
<td><strong>Vertical Res. (m)</strong></td>
<td>250</td>
<td>500</td>
<td>500</td>
<td>250</td>
<td>250/500</td>
<td>250</td>
</tr>
<tr>
<td><strong>Horizontal Res. (km)</strong></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>
</tr>
<tr>
<td><strong>Cross Track Swath (km)</strong></td>
<td>245</td>
<td>Nadir</td>
<td>Nadir</td>
<td>245</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>Nadir Sensitivity (dBZ)</strong></td>
<td>18</td>
<td>-28</td>
<td>-35</td>
<td>17</td>
<td>12</td>
<td>-14.0</td>
</tr>
<tr>
<td><strong>Swath Sensitivity (dBZ)</strong></td>
<td>18</td>
<td>N/A</td>
<td>N/A</td>
<td>17</td>
<td>12</td>
<td>-11.0</td>
</tr>
<tr>
<td><strong>Doppler Capability</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Polarimetric Capability</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>LDR</td>
</tr>
</tbody>
</table>