Technology Development for a Wide-swath Shared-aperture Cloud Radar (WiSCR)

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Outline

• Why Multi-band Wide-swath Imaging Radar?
• Tri-band Imaging Radar Concept
• Ka-band AESA T/R Module Development
  ➢ Module design
  ➢ MMIC development
  ➢ Integrated Circulator
  ➢ ASIC
• Advanced Radar Backend Electronic Technologies
  ➢ Frequency diversity pulse pair Doppler measurement technique
  ➢ Multi-channel waveform generation and frequency conversion modules
• Summary and Path Forward
Why Multi-band and Wide-swath Imaging Radar?

- Clouds and precipitation are among the greatest sources of uncertainty in climate change prediction. Global-scale measurements are critically needed.
- Multi-band 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 et al.

- Decadal Survey 2007 Aerosol Cloud Ecosystem (ACE) - Ka/W-band radar.
- A tri-band imaging Doppler radar concept, Cloud and Precipitation Process Mission (CaPPM), as CloudSat and GPM follow-on mission.
- Decadal Survey 2017 white paper inputs.
Dual- or Tri-band Radar Concept for ACE and CaPPM

• IIP 2010 Achievements
  - Demonstrated an efficient dual-band (Ka/W), shared aperture antenna architecture
    › Reflector/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
Tri-band (Ku/Ka/W-band) Radar for Imaging Clouds and Precipitation

Discriminating Features

• Shared tri-band primary aperture
• Wide swath imaging at Ka-band (>120 km) and Ku-band (>250 km)
• 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 NGMS
• Technology Maturation Plan to achieve TRL 6 within 2 years of funding initiative (after current IIP)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CaPPM</th>
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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></td>
</tr>
<tr>
<td>Transmitter</td>
<td>SSPA</td>
</tr>
<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>
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<tr>
<td>PRF (Hz)</td>
<td>4700</td>
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<tr>
<td>Vertical Res. (m)</td>
<td>250</td>
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<tr>
<td>Horizontal Res. (m)</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>
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<tr>
<td>Polarization Option</td>
<td>Yes</td>
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</table>
Objective Ka-Band T/R Module Design
Development Path Overview

Integrated circulator, MMIC and ASIC development currently under development…

- First pass success demonstrated on all MMIC designs
- 3 Design Options For Circulator
- ASIC design and fab complete, testing underway
T/R Module RF Architecture
Supports Efficient T/R Functionality and Polarization Diversity

= Transmit Path
= Receive Path

Module In/Out

Transmit Pre-driver and, Receiver post LNA MMICs

Phase and attenuation control for beam steering and side-lobe control

Dual Pol Duplexer

RX
TX/RX
RX
TX/RX
RX
TX/RX
RX
TX/RX

Dual Pol Radiator Feed (4X)

~ 300 modules in azimuth, each with 4 TR channels in elevation direction, form phase array line feed to reflector
Ka TR Module Mechanical Layout

• Hermetic Design
• Low Temperature Co-fired Ceramic (LTCC)

Overall Size: 1.9" x 2.6" x 0.19" (without connectors)
Ka TR Module Component Layout

- **Regulators/Resistor Networks**
- **Pre Tx driver and post Rx MMIC**
- **DC Bias Regulator**
- **HexFETs (2)**
- **HPA/LNA (4)**
- **Front End Cavities**
- **Module Controllers (2)**
- **Resistor Networks/Caps**
- **Integrating Circulators (4)**
MMIC Device Development Test Articles

GaN HPA Device Verification Test

GaAs MMIC wafer and test
- GaAs MMICs including MFC, TR, LNA/switch
- MMIC wafer built
- Test results agree with design well

GaAs MMICs – Reticle shown

Power Out (dBm) vs Frequency (GHz)
- Packaged Sample 1
  - 37.7 dBm min. goal

PAE (%) vs Frequency (GHz)
- Packaged Sample 1
  - 25% min. goal

Pre-Tx/Post-Rx TR MMIC

Pre-Tx/Post-Rx MFC MMIC

Breakouts And Cal Structures

LNA MMICs

Packaged Sample 1

37.7 dBm min. goal
# Summary of Measured MMIC Data @ 25C

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>GOAL</th>
<th>Measured</th>
<th>Comments</th>
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<tbody>
<tr>
<td><strong>GaN HPA MMIC</strong></td>
<td></td>
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<tr>
<td>HPA Tier 1 Pout</td>
<td>37.8 dB</td>
<td>38.5 dB</td>
<td>DVT Complete on 3 units</td>
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<tr>
<td>HPA Efficiency</td>
<td>25 %</td>
<td>31%</td>
<td></td>
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<tr>
<td><strong>GaAs LNA MMIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNA Gain</td>
<td>28.6 dB,</td>
<td>27.3 dB</td>
<td></td>
</tr>
<tr>
<td>DC Current @ 1.5v</td>
<td>18 mA</td>
<td>18 mA</td>
<td></td>
</tr>
<tr>
<td>LNA Noise Figure</td>
<td>2.5 dB</td>
<td>2.9 dB</td>
<td>Recover system SNR with Tx power margin</td>
</tr>
<tr>
<td><strong>GaAs TR MMIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tx Driver Pout</td>
<td>26.5 min pulsed</td>
<td>27.0 dB CW,</td>
<td>CW, should increase pulsed</td>
</tr>
<tr>
<td>DC Current @ 6v</td>
<td>307 mA @ P1dB</td>
<td>366 mA@ P1dB</td>
<td></td>
</tr>
<tr>
<td>Receive Gain</td>
<td>21.7 dB</td>
<td>21.2 dB</td>
<td>Gain margin in entire chain exists to mitigate</td>
</tr>
<tr>
<td>Rx Pout and DC Current</td>
<td>-3.5 dB min</td>
<td>0.5 dB</td>
<td>12 mA</td>
</tr>
<tr>
<td><strong>GaAs MFC MMIC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tx Pre Driver Pout and DC Current</td>
<td>11.6 dBM 61.2 mA</td>
<td>12.7 dBM</td>
<td>60 mA</td>
</tr>
<tr>
<td>Rx Gain</td>
<td>-4 dB @ 9mA</td>
<td>-4 dB @ 12 mA, 9 mA</td>
<td>Gain margin in entire chain exists to mitigate</td>
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<tr>
<td>Rx Pout and DC Current</td>
<td>-7.8 dBM 9 mA</td>
<td>-1 dBm</td>
<td>9 mA</td>
</tr>
<tr>
<td>RMS Attenuator Error</td>
<td>0.5 dB</td>
<td>0.5 dB</td>
<td>Calibrated</td>
</tr>
<tr>
<td>RMS Phase Shifter Phase Error</td>
<td>1.7 deg</td>
<td>1.7 deg</td>
<td>Linearized</td>
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</tbody>
</table>
Development of Integrated Circulator
RF Performance of Junction at Reference Planes

Ka Band Test Using “Top Hat” Magnet Configuration

HFSS Model Detail
- Ferrite Puck
- Stripline Transition
- Ceramic Cavity & Via Details

Assembled Part
-0.8 dB Coupon Target

1018_WD_90mil Insertion Loss Paths
-0.8 dB Coupon Target

Insertion Loss
F freq (GHz)
-3.2 -3.3 -3.4 -3.5 -3.6 -3.7 -3.8
-2.5
-2.0
-1.5
-1.0
-0.5
0

S11,S22,S33
S21,S32,S13
S12,S23,S31

1018_WD_90mil Return Loss Paths

Return Loss
F freq (GHz)
-30 -25 -20 -15 -10 -5 0 5 10

Return Loss
F freq (GHz)
-30 -25 -20 -15 -10 -5 0 5 10

Isolation
F freq (GHz)
-30 -25 -20 -15 -10 -5 0 5 10

-20 dB Coupon Target

Model (Ref plane @ coax-SL transition)
Path 1 of 3
Path 2 of 3
Path 3 of 3
Power Controller ASIC

- Key features
  - Bias Sequencing
  - Conditioned voltages
  - Timing control of pulsed DC power for radar modes
  - Temp sensor to monitor module temperature

![Diagram of Power Controller ASIC](image)

- GaN HPA bias gating drive signals
- Temperature Sense
- Sequence Protect*
- Ready
- Level shift
- DAC
- -4.5 V Ref.
- +1.5 V
- -5 V
- +5 V
- Gate voltage divider network
- GaN HPA Gate Bias
- Driver and post LNA GaAs MMIC gating bias
- LNA bias gating and Polarization Switch selection
- Drive signals
- Transmit Receive Enable Control Inputs
- GaN HPA gate voltage Control inputs
- Over temp warning
- Temp sense
- Temperature Sense
- Over temp warning
- Temp sense
- LNA bias gating and Polarization Switch selection
- Drive signals
Ka-band AESA T/R Module Recent Accomplishments

- Tested samples of LNA/Switch, MFC and TR GaAs MMICs
- Completed HPA Design Verification Testing (DVT)
- Completed module package design and now in fabrication
- Completed ASIC design, fab and preliminary functional test
- Completed circulator development
- All module components parts are on hand or on order
- Implementing module assembly tooling, test fixture and test equipment items
- Complete module functional test plans
Frequency Diversity Pulse Pair Airborne Demonstration

**Challenges of Doppler Measurement from Space:**

- Velocity folding and spectrum broaden due to spacecraft ground speed and up- and down draft
- $\sigma/2V_{\text{max}} < 0.3$ for good Doppler measurements
- Approaches:
  - large antenna: reduce $\sigma$
  - higher PRF, stagger PRF: increase $V_{\text{max}}$

**FDPP Algorithm**

- Frequency Diversity Pulse Pair (FDPP) utilizes alternate pair of pulses with slightly different center frequencies.
- Programmable time interval between the pulses to extend the Doppler Nyquist range without causing range ambiguity.
- Integration of equal number of pair $f_1/f_2$ and pair of $f_2/f_1$ to cancel the range dependent phase

**FDPP Implementation on 94 GHz CRS**

- Waveform implementation
- Digital receiver configuration
- Olympic Mountain Experiment (OLYMPEX)/Radar Definition Experiment (RADEX)
  - Objectives: GPM cal/val and ACE algorithm study
  - Location: Olympic Peninsula of Washington State
FDPP Data Analysis

- Conv. Dop 1: f1, f1 pair
- Conv. Dop 2: f2, f2 pair
- Order 1: f1, f2 pair
- Order 2: f2, f1 pair
- FDPP: sum of Order 1 and Order 2

Preliminary analysis
- FDPP works well for ocean surface return
- Indicates coherent Doppler phase for cloud region with relative high SNR. Working progress on improving the results.
• FDPP results were compared with traditional pulse-pair velocity estimates.

• Based on simulation predictions, a high SNR target (i.e. surface echo) was isolated for quantitative comparison.

• Preliminary analysis showed excellent fidelity for the FDPP estimates for surface return.
Multi-channel Waveform Generation and Frequency Conversion Modules

• FPGA Based Multi-channel Waveform Generator
  • Support multi-channel simultaneous versatile transmit waveform and timing signal generation
  • Based on GSFC high TRL SpaceCube processor card
  • Adding high-speed DACs for waveform generation and I/O interface
  • Completed schematic design and board layout
  • Prototype unit ready for fabrication

• PCB Based Multi-channel Frequency Conversion Module
  • Support multi-band, multi-channel transmission and receive
  • Shared common circuits and parts to reduce SWaP
  • Prototype module built
  • Test on airborne radar underway
Summary and Path Forward

• Technologies for dual- or tri-band spaceborne cloud and precipitation radar under development at NASA GSFC and NGMS.

• Dual- or tri-band, shared-aperture antenna
  • Trade study and concept design
  • Identified primary candidates supporting all variant of final mission requirements
  • Addresses various band combinations with options for W-band fixed beam and scanning
  • Includes application of proven reflectarray technologies

• Ku-band AESA technology is mature

• Ka-band AESA T/R module development
  • Module RF and mechanical design
  • MMIC, circulator and ASCI design, fabrication and test
  • GaN HPA MMIC design and verification test
  • LTCC in fabrication

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

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

Developing technologies for the next generation spaceborne atmospheric radars