Why Three Frequencies?

• Key Question: How can we better understand and predict cloud and precipitation variability, changes, and the role of interacting processes?
  • Advances in understanding the role of cloud processes are critical to reducing the uncertainty in precipitation and water cycle prediction -- a key component of the global climate system.
  • We seek to understand and sample the continuum of climatically important cloud regimes, globally, from heavy rain to light drizzle and snowfall. This includes deep convection, shallow cloud systems, frontal regimes, and orographic enhancement, recognizing the extreme importance of the ice phase.

• Frequency band properties:
  • Ku-band (13.4 GHz): Penetrates well through rain, no Mie scattering at high rain rates, poor sensitivity for clouds
  • Ka-band (35.6 GHz): Still penetrates through most rain, better sensitivity for clouds and light drizzle
  • W-band (94 GHz): Best sensitivity for clouds, dynamic range capped by Mie scattering for heavy rain, attenuates badly in rain

• To understand the complete picture in a cloud/precipitation system, we need all three frequencies

• Different properties of these three frequency bands can also provide additional information using multi-frequency retrievals
Example of 3 frequency radar view of a storm from CloudSat and GPM (no Doppler)

- CloudSat (W-band) and GPM (Ku/Ka-band) coincident data (+/- 15 min)
- By: J. Turk, P. Partain, E. Stocker
- Currently experimental product
- Can only can be produced when CloudSat and GPM are coincident.
- Time lag and track offsets complicate interpretation
- What we really want is three-frequencies at the same time in the same footprint!
Global-scale simulations using cloud-resolving model confirm our intuition and anecdotal experience that three-frequency radars have significant advantages over any single or two-frequency combination.
The GPM ground validation program and the ACE Science Working Group have successfully completed two joint projects where multi frequency cloud-precipitation radar data were acquired:

- **IPHEX/RADEX’14**, N. Carolina, May/Jun 2014

W. Petersen, M. Schwaller, J. Mace, R. Marchand, A. Barros, R. Houze, L. McMurdie and many other.

GPM exploits the multi frequency radar data to better constrain the validation of GPM retrievals.
ACE seeks to demonstrate and refine the definition of the radar for the ACE mission.

**APR-3** (S. Durden, PI, ESTO/AITT Program) is the first 3-frequency (Ku, Ka, W), scanning, Doppler, airborne radar. APR-3 was due for completion in June 2016, but was successfully demonstrated in OLYMPLEX/RADEX’15 onboard the NASA DC-8.
One example of the data acquired (preliminary calibration) is shown from a direct GPM/DPR underflight on Dec 3, 2015. APR-3 is an airborne proxy to **3CPR**.
Cylindrical parabolic antenna provides high gain and cross-track scanning capability at Ku-band (13.4 GHz), Ka-band (35.6 GHz) and W-band (94 GHz).

No need for heavy, lossy slotted waveguide arrays (as used in GPM).

Some issues to be addressed including:
- Reflector illumination over scan
- Pattern / pointing distortion due to feed point offsets

Feed technology exists for Ku and Ka bands:
- Ka-band TR 8-pack demo at JPL
- More recent Ka-band developments from GSFC / NGES (*Racette, et al*)

Focus on new technology required to enable W-band scanning.

NASA ESTO Instrument Incubator program funding development of sub-scaled reflector with electronically-scanned W-band feed array.
Evolution of an Instrument Concept

1999

Second Generation Precipitation Radar (PR-2)
- Ku/Ka-band Precipitation Radar
- First spaceborne precipitation radar concept using cylindrical parabolic reflector, active linear array feed

2009

Cloud Cross-track scanning Dual-frequency Doppler radar (C2D2)
- Ka/W-band
- Similar antenna configuration to PR-2
- First concept proposing W-band scanning

2013

Three-band Cloud and Precipitation Radar (3CPR)
- Ku/Ka/W-band
- Similar antenna configuration PR-2/C2D2
- Combines three active linear array feeds
- Scanning at all three bands
- Capable of simultaneous cloud / precipitation measurements
3CPR System Design

- Supports either:
  - ACE decadal survey mission concept (Ka- / W-band)
  - Cloud and Precipitation Processes Mission (CaPPM) concept. (Ku-, Ka-, W-band)

- **Most precious resources:**
  - Sampling time
  - Transmitted power

- Pulse-to-pulse beam agility and optimized timing enable optimization of performance WRT certain science requirements

- One point design was chosen for 3CPR system study
  - High-sensitivity nadir measurements
  - Significant swath at all three bands
  - Hardware is highly adaptable to changes in measurement priorities or resource limitations.

- Supports adaptive scan strategies and pulsed compression if required by application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (Ku/Ka/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflector Size</td>
<td>5 m x 3 m</td>
</tr>
<tr>
<td>Feed Array Length</td>
<td>2.5 / 2.87 / 2.87 m</td>
</tr>
<tr>
<td>Feed elements (each for TX / RX)</td>
<td>160 / 480 / 1152</td>
</tr>
<tr>
<td>Transmit Power (peak)</td>
<td>3200 / 1600 / 1267 W</td>
</tr>
<tr>
<td>Pulse length</td>
<td>1.5 µs</td>
</tr>
<tr>
<td>Scan angle (+/-)</td>
<td>4.5 / 12 / 3.5 degrees</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ku</th>
<th>Ka</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFOV (along x cross)</td>
<td>4 x 4</td>
<td>2 x 1.5</td>
<td>1 x 0.6</td>
</tr>
<tr>
<td>Clutter Free MDS dBZ</td>
<td>-5</td>
<td>-20</td>
<td>-35</td>
</tr>
<tr>
<td>Clutter Free hgt M</td>
<td>300</td>
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<td>300</td>
</tr>
<tr>
<td>Near Surface MDS dBZ</td>
<td>+12</td>
<td>-5</td>
<td>-20</td>
</tr>
<tr>
<td>Near Surface hgt M</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Doppler 0 SNR dBZ</td>
<td>+12</td>
<td>-5</td>
<td>-18</td>
</tr>
<tr>
<td>Doppler Prec. m/s</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Swath km</td>
<td>60</td>
<td>195</td>
<td>50</td>
</tr>
<tr>
<td>Max Scan Angle deg</td>
<td>4.5</td>
<td>12</td>
<td>3.5</td>
</tr>
<tr>
<td># Beams</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Polarization</td>
<td>FULL</td>
<td>LDR</td>
<td>LDR</td>
</tr>
</tbody>
</table>

Legend:
- **ACE**
- **IWSSM**
- **GPCM (Tent.)**
The element pattern used is the unit cell pattern from the W-band element in the picture above.

A linear array of unit cells 2.87m long feeds the reflector. The excitation and phase shifting is done per unit cell as shown in the figure to the right.

The spacing between unit cells is 5mm, making the effective spacing between elements 2.5mm.
Optimize antenna modeling until radiation pattern meets requirements for feed.

Using physical optics, calculation of induced current on the reflector surface.

Using the currents from the previous step, then calculate far field radiation pattern.

Thanks the combination of full MoM (Method of Moments) simulation techniques and PO (Physical Optics) we can simulate a reflector that is $950\lambda \times 1600\lambda$ in less than 7 minutes. In addition, the process is automated using matlab, so running variations is as simple and running a loop cycle.
Antenna Analysis using Hybrid Modelling

- Trades studies performed:
  - Feed element spacing
  - Phase shifter spacing
  - Phase shifter bits requirement
  - Reflector focal length
    - Drives both length of feed structure and short dimension of feed array
  - Errors due to feed offsets:
    - In a three-band system only one band can be on focal lines
    - Offset lead to beam distortion and along-track squint
      - Distortion shown to be acceptable
      - Effects of along-track squint can be removed by temporal shift of data
  - After trades were completed, full simulation of feed+reflector pattern was performed
Prototype SAT Component Designs

- PolyStrata W-band designs validated during two previous fabrication cycles during SBIR Phase II
  - Passive array tile module
  - Array tile module with 8x GaN MMICs
- We will leverage previous designs for IIP SAT.
  - Design modifications where necessary.
Fixed Beam 8x2 Active Array Demonstration

- Active fixed-beam SAT with
  - 16x 2 radiating elements
  - 8x 1 Watt TX channels
  - 16 RX channels (8 x H,V)
  - 3x 8-way combiners
  - Bias networks

- Used for preliminary demonstration of:
  - RF performance
  - Thermal design
  - Manufacturing approach
  - Assembly approach
3CPR Development Status

- First W-band Scanning Array Tile
  - 8x 1W transmitter channels with 5-bit phase control
  - 16 receiver channels 5-bit phase and 5-bit amplitude control
  - Channels are combined to three WR-10 waveguide ports (TX, RXV, RXH)
  - Includes DC biasing, serial phase/amplitude control interface
3CPR Development Status

- Instrument design trades are complete
  - Trades studies can continue as science requirements change
  - Expected requirements changes do not affect the design of the W-band arrays being developed
- Antenna designs are complete
  - Array parameters are fully defined
  - Parabolic surface defined
  - Feed+array analysis of chosen configuration has been completed
- MMIC design and fabrication is complete
  - GaN power amplifier and LNA, InP phase shifter / attenuator
- Scanning Array Tile development is in progress:
  - First Rev. 1 SAT has been delivered, four other are in assembly!
  - Testing and characterization of the first SAT will occur in the coming months
  - One more revision of the SAT will be built in 2016
- 64x2 element array + reflector demo in 2017
Thank you for your attention…questions?

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