Ka-band Technologies for Small Spacecraft Communications via Relays and Direct Data Downlink

CubeSat Workshop – 30th Annual AIAA/USU Conference on Small Satellites
NASA Glenn Research Center, Cleveland Ohio / James M. Budinger
Session VII Communications 07 August 2016
Outline

• Objectives
• Ka-band background
• Software defined radios
• Ka-band antennas
• Potential data return in Ka-band
• Summary
Ka-band Communications

OBJECTIVES
Objectives

- Develop affordable technologies to ease transition into Ka-band for significantly higher data rates with minimal impact on near Earth missions
  - Ka-band/multi-band **software defined radios (SDRs)** and standards for a range of space missions
  - **Portable waveforms** for SDRs to reduce cost of development and increase flexibility
  - **Electronically steered high gain antennas** to increase data return and eliminate mechanisms and vibration
  - Leverage **large and small business and university** capabilities to address unique needs of small spacecraft
NASA Ka-band Communications Infrastructure

KA-BAND BACKGROUND
TDRS Ka-band Single Access Service

• NASA’s Tracking and Data Relay Satellite (TDRS)
  – Three generations of spacecraft provide high bandwidth, low latency communications to multiple simultaneous mission spacecraft
  – S-band, Ku-band, and Ka-band Single Access (KaSA) and S-band Multiple Access services

• KaSA Service via large steerable antennas in auto-track mode
  – Return (from spacecraft) of mission data and spacecraft telemetry; \( G/T: 26.5 \text{ dB/K} \); 25.25-27.5 GHz
  – Forward (toward) command and control EIRP: 63.0 dBW; 22.55-23.55 GHz
  – Field of View ± 76.8° E-W; ± 30.5° N-S

Third Generation TDRS K, L, M
**NASA Near Earth Network (NEN)**

**Ka-band Tracking Terminal Examples**

- **WS-1**
  - White Sand Complex
  - 18 m
  - S-, X- and Ka-bands
  - Ka-band $G/T$ of 46 dB/k

- **AS-3**
  - Alaska Satellite Facility
  - 11 m
  - S- and X-bands operational
  - Provisions for Ka-band capability in ~2020
  - Expected Ka-band $G/T$ of 40 dB/k
Commercial Ka-band Tracking Terminal Example

- Comtech TCS 2.4m X/Y Tracking Terminal
  - Eliminates “keyhole” when spacecraft is overhead
- Ka-band operation
  - 25.5 to 27.0 GHz
  - G/T of 27 dB/K

### NASA Near-Earth Mission Frequency Spectrum and Typical Channel Bandwidths

#### Mission Links Via **TDRS Relays** (GHz)

<table>
<thead>
<tr>
<th>Space-Space</th>
<th>Forward Bandwidth</th>
<th>Return Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>• S-band</td>
<td>2.025-2.110</td>
<td>2.200-2.290</td>
</tr>
<tr>
<td>• Ku-band</td>
<td>13.775+.070</td>
<td>15.0034+.1125</td>
</tr>
<tr>
<td>• Ka-band</td>
<td>22.55-23.55</td>
<td>25.25-27.50</td>
</tr>
</tbody>
</table>

#### Mission Links Via **NEN Direct to Ground Links** (GHz)

<table>
<thead>
<tr>
<th>Space-Earth</th>
<th>Uplink/Command Bandwidth</th>
<th>Downlink/Telemetry Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>• S-band</td>
<td>2.025-2.110</td>
<td>2.200-2.290</td>
</tr>
<tr>
<td>• X-band Earth Science</td>
<td>N/A</td>
<td>8.025-8.400</td>
</tr>
<tr>
<td>• X-band Space Science</td>
<td>7.190-7.235</td>
<td>8.450-8.500</td>
</tr>
<tr>
<td>• Ka-band</td>
<td>N/A</td>
<td>25.50-27.0</td>
</tr>
</tbody>
</table>
SOFTWARE DEFINED RADIOS

STRS and Ka-band SDRs

SOFTWARE DEFINED RADIOS
• **Space Telecommunications Radio System (STRS) Architecture and Standard (NASA-STD-4009)**
  – Enables independence of applications from software defined radio platform/hardware
  – Reduces effort to develop, port and share applications waveforms and documentation via repository
  – Applicable to all categories of spacecraft from large platforms to SmallSats and CubeSats
  – Multiple vendors have STRS compliant SDRs or platforms in their product line
  – Others under development via partners and NASA SBIR/STTR Program
  – See [https://strs.grc.nasa.gov/](https://strs.grc.nasa.gov/)
SCaN Testbed on ISSs is Flying Multiple STRS-Compliant SDRs from 3 Vendors

**JPL/L-3 CE**
- S-band SDR; 6 MHz channel
- 10 Mbps Class
- L-band receive (GPS)
- Virtex II, Sparc Processor, RTEMs

**Harris**
- Ka-band SDR; 225 MHz
- >500 Mbps Class
- Virtex IV, PowerPC Proc, DSP (1 GFLOP), VxWorks
- STRS adopted for use in Harris AppSTAR™ software-defined payload architecture

**General Dynamics**
- S-band SDR; 6 MHz channel
- 10 Mbps Class
- Virtex II, ColdFire Processor (60 MIPS), VxWorks, CRAM (Chalcogenide RAM) Memory

✓ **SDRs offer economies-of-scale via common hardware, tailored to mission needs via STRS-compliant software**
SBIR/STTR Contracts for STRS-Compliant SDR Technologies

• SBIR-14 Commercialization Readiness Program
  – Software Defined Near Earth Space Transceiver (SD-NEST) [Space Micro]

• STTR-15 Phase I

• SBIR-16 Phase I Selections
  – OpenSWIFT-SDR for STRS [Tethers Unlimited]
  – Plug-In Architecture for Software-Defined Radios [Blue Sun]

• [Earlier SBIR SDR Contracts non-STRS Compliant]
  – https://www.nasa.gov/sites/default/files/files/SBIR_SDR.pdf

✔ Watch for the 2017 SBIR/STTR call for proposals in November 2016
Software-Defined Near Earth Space Transceiver (SD-NEST)

- SD-NEST
  - STRS-Compliant Multi-Band Transceiver
  - STRS Waveforms (From Legacy Repository)

- µSTDN-100 S-band Transceiver
  - NASA IRIS, LADEE Missions

- µXTx-100 / 200 X-Band Transmitter
  - NASA IRIS Mission

- Proton 400k Rad-Hard Processor
  - NASA MISSE-X Mission

- µKaTx-300 Ka-band Transmitter
  - NASA TESS Mission

- X/Ka Wideband Receivers (New Development)
Software-Defined Near Earth Space Transceiver (SD-NEST)

- **Frequency agile, multi-band transceiver**
  - Narrowband TT&C over any frequency S-, X- or Ka-bands
  - Wideband data return and forward over X-band (375 MHz) or Ka-band (>650 MHz)

- **Flexible waveform processing**
  - Low-power mode for TT&C alone
  - High-performance mode for high-rate mission data return (>1.2 Gbps)

- **STRS Operating Environment**
  - General-purpose processor available (e.g. P400K) for high-level control algorithms

- **Engineering Model Completion in FY17**
- **Seeking partners for contract option (with cost sharing) for proto-flight model**

![Diagram of the SD-NEST system with processor, modems, and power supply configurations.](attachment:diagram.png)

**Dimensions:**
- S-band Module: 4.9” x 8.8” x 9.2”
- X/Ka-band Module: 4.0” x 8.8” x 6.0”

**Connections:**
- TT&C; RS-422
- Mission Data; LVDS

**Diagram Side Notes:**
- Modern Board
- Synthesizer/Power Supply Slice
- Narrow Band Slice
- Wide Band Slice
Alternatives to Mechanically Deployed or Steered Antennas

KA-BAND ANTENNAS
Mechanically Steered High Gain Antenna Examples

**SCaN Testbed Ka-band and S-band Antenna Positioning System (APS)**

**Surrey Satellite X-band (COTS) and Ka-band (Under development) Antenna Pointing Mechanisms (APM)**

<table>
<thead>
<tr>
<th></th>
<th>SCan Testbed APS on ISS</th>
<th>SSTL X-APM</th>
<th>SSTL Ka-APM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>25.5 – 27.0 GHz</td>
<td>2.025-2.11 GHz</td>
<td>8.0 – 8.5 GHz</td>
</tr>
<tr>
<td>Gain</td>
<td>39.8 dBi</td>
<td>13 dBi</td>
<td>18 dBi</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>~46 cm</td>
<td>~25 cm</td>
<td></td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>57 cm x 30 cm x 71 cm</td>
<td>Ø 27.4 x 30 cm</td>
<td></td>
</tr>
</tbody>
</table>
GRC 3-D Printed Ka-band Faceted Dome Array – Concept and Prototype

- 36 Elements (16 at 30°, 16 at 15°, 4 at 0°)
- ~90 degree field of regard (~30° beamwidth)
- Probe Fed Elements 14.4 dBi, 256 MHz BW
SBIR/STTR SmallSat Antenna Technologies

Examples

• STTR-14 Phase II
  – Fully Printed Flexible 4x4 Element Graphene–Based Phased Array Antenna; [Omega Optics/U. Texas Austin]

• STTR-16 Phase I Selection
  – Deployable Ka-band Reflect Array Antenna; [Tyvak Nano-Satellite Systems/UCLA]

• SBIR-16 Phase I Selection
  – Space Environment Design and Testing; [Kymeta Government Solutions, Seattle, WA]

✔ Watch for the 2017 SBIR/STTR call for proposals in November 2016
Graphene Based, Flexible, Fully-Printed 2D-Scanning Phased Array – Omega Optics and Texas State University

• **Goal**
  – Develop a flexible ink-jet printed Graphene-based 4-bit 4x4 phased array antenna (PAA) at S-band

• **Development Approach**
  – Grow Graphene nano-flakes via CVD and incorporate into Graphene ink
  – Print multi-layer integrated circuits and interconnections on flexible substrates
  – Print Rx/Rx modules from Graphene transistors, phase shifters and amplifiers
  – Test a prototype printed PAA

• **Applications**
  – CubeSat and SmallSat antennas
  – Large deployable phased array antennas
  – Reconfigurable, deployable, conformal, and/or wearable active antennas

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Stage 2: Deploying

Stage 1: Rolled up and Stowed

Stage 3: Fully deployed

PAA on Face
Solar Cells on Back

Graphene flakes

Inkjet printed transistor

Multilayer interconnect

Printed Graphene PAA
Kymeta Government Solutions, Inc. (KGS)  
Meta-material Phased Array

**CubeSat Antenna**
- Frequency: Optimized for 27.0 GHz
- Gain: ~24 dBiC over scan volume
- Electronically steerable; ± 45° range
- Power: <5W

**SmallSat Antenna**
- Simultaneous transmit and receive out of same aperture for X, Ku, and Ka bands
- Capability at Q, V and W bands
- Technology creates potential for economical 6U, 12U, and larger form factors

**Maturity**
- Designed, built, tested, delivered
- Next steps: Modifications for space (SBIR Phase I), flight qualification testing and demonstration mission

**Maturity**
- Initial design target sets identified
- Early modeling and simulation complete
- Seeking a development partner to fund detailed design, build, and test
Current NASA Activities with Kymeta Meta-material Phased Array

KGS SBIR Phase I (GSFC)

• Seeks to space qualify CubeSat antenna
  – Define requirements
  – Hardware redesign
  – Antenna redesign
  – Thermal characterization

• All of which seek to make the SmallSat antenna space flight-qualifiable

Cubesat Antenna Measurements (GRC)

• Seeks to characterize the metamaterial-based technology beyond its design parameters gain insight into what it can do
  – Leverage antenna measurement systems and talent at GRC to obtain high quality pattern, polarization, power, and steering measurements.
  – Compare against other Ka-band antenna technologies for potential for use on CubeSat and SmallSat missions.
Boeing 256-Element Ka-Band Transmit Phased Array Antenna for GRC and ONR

Array Number of Elements: 256 Elements
Band: 25.5-27.5 GHz; > 1 GHz Bandwidth
Beam width: Nominal 5 degrees at -3dB
Gain (CP): 28 dBi
EIRP: Peak 36.5 dBW; 33 dBW @ 60 Degrees
Array Total DC Power: 90 Watts (per beam)
Dimensions: 19 cm x 10.2 cm x 6.5 cm
Mass: 1.8 kg

Limitations:
• Lab model over 10 year old design; many components obsolete
• Rad-hard Triquint GaAs MMIC design kit and foundry process retired
• “Brick” design is more expensive to manufacture than “tile” approach
Scalable Ka-band Active Phased Array Antenna (PAA) Design

- Space qualifiable tile PAA design
  - Based on Boeing Wideband Communication and RF Systems Group airborne product line
  - Tile packaging significantly reduces costs and offers higher efficiency than brick design
  - SiGe 0.15 um process; rad-hard by design MMICs to 300 krad (Si)

- Ka-band: 25.25 to 27.5 GHz
  - Right-or left-hand circular polarized

- Wide field of regard: ± 70°
  - LEO mission to GEO relay or direct to ground

- Easily scalable implementation
  - Select 64, 128 or 256 elements for EIRP of 24-, 30- or 36-dBW respectively
  - Range of user needs, budgets, SWaP constraints

- Potential for data rates up to 3.2 Gbps
  - Performance with DVB-S2 MODCOD to be validated
Boeing Ka-band Tile Array for SmallSats

- 25.5-27.0 GHz
- ± 70 degree FOR
- 24-, 30- or 36 dBW
- 22.9 cm x 17.8 cm x 9.6 cm
- 1.8 kg
- <150 W depending on # elements and drive level
- Rad-hard by design
- 8 year design life

Ka-band PAA Shown on Boeing 502M SmallSat Bus

- 10s to 100s Mbps data rates in affordable, modular PAA packages optimized for SmallSat missions
- Available with integrated beam controller, power supply and thermal management
Comparisons Via GEO Relay and Direct to Ground (DTG)

POTENTIAL DATA RETURN IN KA-BAND
## Potential Minimum Data Rates/Return Using Future Tile Phased Array Antenna

<table>
<thead>
<tr>
<th>Data Return via</th>
<th>Bandwidth</th>
<th>Future Boeing Ka-band Tile Phased Array Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>64 Element</td>
</tr>
<tr>
<td>TDRS, 26.5 dB/K</td>
<td>225 MHz</td>
<td>900 kbps</td>
</tr>
<tr>
<td>WS-1 Terminal</td>
<td>500 MHz</td>
<td>830 Mbps</td>
</tr>
<tr>
<td>18.3m, 46 dB/K</td>
<td>1.5 GHz</td>
<td>1.5 Gbps</td>
</tr>
<tr>
<td>AS-3 Terminal</td>
<td>500 MHz</td>
<td>520 Mbps</td>
</tr>
<tr>
<td>11m, 40 dB/K</td>
<td>1.5 GHz</td>
<td>940 Mbps</td>
</tr>
<tr>
<td>Comtech TCS</td>
<td>500 MHz</td>
<td>64 Mbps</td>
</tr>
<tr>
<td>2.4m, 27 dB/K</td>
<td>1.5 GHz</td>
<td>64 Mbps</td>
</tr>
</tbody>
</table>

- 1000 km, 98.5° mission, max ranges 38000 km, 2800 km, DVB-S2 MODCOD
- SmallSat DTG data rate ~70x higher than via TDRS; ~\textbf{38 Gb/10 minute pass}
- Large mission DTG data rate ~235x higher than via TDRS; ~\textbf{2Tb/10 minute pass}
• Affordable Ka-band communications technologies will enable a new generation of science and exploration missions through increased data return
  – Mission data return rates from 10s of Mbps to Gbps are feasible for range of small and large satellites

• NASA is working with industry and SBIR/STTR program to:
  – Develop STRS-compliant waveforms
  – Advance the technology readiness level of Ka-band SDRs
  – Develop and demonstrate Ka-band space-qualifiable electronically steered antennas
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THANK YOU!

For your kind attention