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

Space Communications and Navigation

CubeSat Workshop – 30th Annual AIAA/USU Conference on Small Satellites
NASA Glenn Research Center, Cleveland Ohio / James M. Budinger
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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
• 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 \( \pm 76.8^\circ \text{ E-W}; \pm 30.5^\circ \text{ N-S} \)
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

<table>
<thead>
<tr>
<th>Mission Links</th>
<th>Via TDRS Relays (GHz)</th>
<th>Via NEN Direct to Ground Links (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Space-Space</strong></td>
<td><strong>Forward</strong></td>
<td><strong>Bandwidth</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• S-band</td>
<td>2.025-2.110</td>
<td>0.028</td>
</tr>
<tr>
<td>• Ku-band</td>
<td>13.775+.070</td>
<td>0.065</td>
</tr>
<tr>
<td>• Ka-band</td>
<td>22.55-23.55</td>
<td>0.065</td>
</tr>
<tr>
<td><strong>Space-Earth</strong></td>
<td><strong>Uplink/Command</strong></td>
<td><strong>Bandwidth</strong></td>
</tr>
<tr>
<td>• S-band</td>
<td>2.025-2.110</td>
<td>0.085</td>
</tr>
<tr>
<td>• X-band Earth Science</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>• X-band Space Science</td>
<td>7.190-7.235</td>
<td>0.045</td>
</tr>
<tr>
<td>• Ka-band</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- **Overlap**
- **Up to 4x**
SOFTWARE DEFINED RADIOS

STRS and Ka-band SDRs
• **Space Telecommunications Radio System (STRS) Architecture and Standard** ([NASA-STD-4009](https://strs.grc.nasa.gov/))
  - 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](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)

STRS Waveforms
(From Legacy Repository)

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

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

- SD-NEST STRS-Compliant Multi-Band Transceiver
  - NASA IRIS Mission

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

![Diagram of SD-NEST components]

- **Key Specifications**
  - CPU, STRS OE, Modem, Wideband FPGA, X/Ka-band Module
  - Narrowband FPGA, S-band Module, Synthesizer/Power

- **Physical Dimensions**
  - Modem Board: 4.9” x 8.8” x 9.2”
  - Narrow Band Slice: 4.0” x 8.8” x 6.0”

- **Timeline**
  - Engineering Model Completion in FY17
  - Seeking partners for contract option (with cost sharing) for proto-flight model
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><strong>Frequency</strong></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><strong>Gain</strong></td>
<td>39.8 dBi</td>
<td>13 dBi</td>
<td>18 dBi</td>
</tr>
<tr>
<td><strong>Antenna diameter</strong></td>
<td>~46 cm</td>
<td>~25 cm</td>
<td>~30 cm</td>
</tr>
<tr>
<td><strong>Overall Dimensions</strong></td>
<td>57 cm x 30 cm x 71 cm</td>
<td>Ø 27.4 x 30 cm</td>
<td>TBD</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
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.
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>64 Element</th>
<th>128 Element</th>
<th>256 Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDRS, 26.5 dB/K</td>
<td>225 MHz</td>
<td>900 kbps</td>
<td>3.5 Mbps</td>
<td>14 Mbps</td>
</tr>
<tr>
<td><strong>WS-1 Terminal</strong></td>
<td>500 MHz</td>
<td>830 Mbps</td>
<td>1.1 Gbps</td>
<td>1.1 Gbps</td>
</tr>
<tr>
<td>18.3m, 46 dB/K</td>
<td>1.5 GHz</td>
<td>1.5 Gbps</td>
<td>2.9 Gbps</td>
<td>3.3 Gbps</td>
</tr>
<tr>
<td><strong>AS-3 Terminal</strong></td>
<td>500 MHz</td>
<td>520 Mbps</td>
<td>990 Mbps</td>
<td>1.1 Mbps</td>
</tr>
<tr>
<td>11m, 40 dB/K</td>
<td>1.5 GHz</td>
<td>940 Mbps</td>
<td>1.9 Gbps</td>
<td>3.1 Gbps</td>
</tr>
<tr>
<td><strong>Comtech TCS</strong></td>
<td>500 MHz</td>
<td>64 Mbps</td>
<td>230 Mbps</td>
<td>500 Mbps</td>
</tr>
<tr>
<td>2.4m, 27 dB/K</td>
<td>1.5 GHz</td>
<td>64 Mbps</td>
<td>250 Mbps</td>
<td>820 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; ~38 Gb/10 minute pass
- Large mission DTG data rate ~235x higher than via TDRS; ~2Tb/10 minute pass
Summary and Co-Authors and Contributors

CLOSING COMMENTS
Summary

• 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!