Nanosatellite Communications at MIT

Kerri Cahoy, Ryan Kingsbury
kcahoy@mit.edu
kingryan@mit.edu

Ground Stations for Nanosatellites Workshop
April 23, 2013
• MicroMAS comm. plan, ground stations  
  – L3Com Cadet, Wallops

• MIT campus ground stations  
  – UHF/VHF and S-band

• Distributed Satellite System (Mothercube)  
  – E-space Payload Telemetry System, OSAGS

• General needs
MicroMAS Overview

Launch a Single Satellite to Demonstrate the Core Element of a Transformative Sensing Architecture

- All-weather measurements of atmospheric temperature and precipitation
- High resolution 118-GHz spectrometer
- Dual-spinning 3U CubeSat
MicroMAS Objectives

- Focus on hurricanes + severe weather
- 500-km orbit altitude
- 25-km pixel diameter at nadir (cross-track scan out to ±50°)
- 1 K absolute accuracy
  - 0.3 K sensitivity
- Geolocation error less than 10% of pixel diameter
- 20 kbps (avg) downlink
- 12 W (avg) power
- One year mission lifetime
- 2014 launch by NASA
MicroMAS Status

- L3Com Cadet modem
- Wallops ground station, SRI?
- Single? monopole tape antenna
- Preliminary HFSS simulations
- Assembling ground station emulator
  - USRP, CC1101 eval board
MIT Campus Ground Stations

• UHF/VHF Station
  – MIT Radio Society is assembling a “standard” ham band UHF/VHF station
  – Two AZ-EL steerable Yagi antennas
  – Undergoing final integration this spring
  – Located at W1MX station on Walker Memorial

• S-Band Station
  – Green Building 5.5 m dish
  – A much bigger project...
Green Dish: Ancient History

• 5.5 meter (18 ft) dish

• Originally installed for weather radar research

• Pedestal is World War 2 surplus SCR-584

• Two rounds of modifications
  – Bigger dish, radome (~1965)
  – Computer control (~1985)
SCR-584 Pedestal
Green Dish: Recent History

- MIT Radio Society gained access to the dish ~2005
  - Completed minor repairs, “changed oil”
  - Managed to slew the dish
  - Added offset CP feeds for 2304 MHz and 1296 MHz

- Primary feed is not useful
  - RG-48/U waveguide (2.6 – 4.0 GHz)
  - Badly corroded due to loss of N₂ purge

- Semi-functional, but certainly not reliable
  - Concerns about state of drive train (planetary gears, bearings, etc.)
  - Ancient drive electronics (amplidyynes)
• Initial evaluation of dish by experts from Haystack, MIT Lincoln Lab, contractors

• Consensus
  • Robust hardware, internal inspection required
  • Drive train components (gears & bearings) could be expensive to replace
  • Try to get another SCR-584 to scavenge

• Where to find another SCR-584?
SCR-584 Found!
OSAGS Heritage

- OSAGS = Open System of Agile Ground Stations

- Ground stations originally successfully used to support the MIT HETE-2 mission
  - High Energy Transient Explorer (Oct. 2000)

- NASA SBIR with Espace to upgrade ground stations
  - Collaboration NASA ARC
  - Software defined radio
  - Available for nanosatellites and CubeSats
## Ground Station Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink Frequency</td>
<td>2.025 – 2.120</td>
<td>GHz</td>
</tr>
<tr>
<td>Downlink Frequency</td>
<td>2.200 – 2.300</td>
<td>GHz</td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>2.3</td>
<td>m</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>31</td>
<td>dBi</td>
</tr>
<tr>
<td>Polarization</td>
<td>RHCP</td>
<td>-</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>15.44</td>
<td>dBW</td>
</tr>
<tr>
<td>Data Rate</td>
<td>&lt; 3.5</td>
<td>Mbits/sec</td>
</tr>
<tr>
<td>G/T</td>
<td>6.9</td>
<td>dB/K</td>
</tr>
</tbody>
</table>
Upgrades in 2010-2011

• New:
  – 2.3 m antennas
  – Counterweights
  – Feed and feed arms
  – Diplexers (BPF)
  – LNA
  – 4 Ettus USRP2 SDR transceivers (redundancy)
• Reuses HETE-2 power amplifiers
• Can support several missions
  – 5 MHz NTIA S-band BW limit
  – Handles up to 3.5 Mbits/sec
• Remotely configurable
S-Band Payload Telemetry System

- PTS = Payload Telemetry System
- RF Board + Digital Processing Board
  - 2 inputs, 2 outputs
  - Half-duplex

<table>
<thead>
<tr>
<th></th>
<th>Uplink</th>
<th>Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2.025-2.120 GHz</td>
<td>2.20-2.30 GHz</td>
</tr>
<tr>
<td>Data Rate</td>
<td>0.01 – 0.1 Mbps</td>
<td>0.01-1.0 Mbps</td>
</tr>
<tr>
<td>Power</td>
<td>2.0 W</td>
<td>3.6 W</td>
</tr>
<tr>
<td>Output Power</td>
<td>N/A</td>
<td>1.0 W</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK, QPSK, OQPSK, CPFSK</td>
<td></td>
</tr>
<tr>
<td>Standby Power:</td>
<td>0.75W</td>
<td></td>
</tr>
<tr>
<td>Dimensions (LxWxH):</td>
<td>90.17mm x 95.89mm x 35mm</td>
<td></td>
</tr>
<tr>
<td>Mass:</td>
<td>0.094kg</td>
<td></td>
</tr>
</tbody>
</table>
Additional HF/VHF Rx Capability

- Takes GPS clock input

<table>
<thead>
<tr>
<th></th>
<th>HF Rx</th>
<th>VHF Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>100 kHz – 10 MHz selectable</td>
<td>60 MHz – 1 GHz selectable</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>100 kHz – 10 MHz selectable</td>
<td>100 kHz – 10 MHz selectable</td>
</tr>
<tr>
<td>Sampling</td>
<td>14 bits I / Q up to 20 Ms/s</td>
<td>14 bits I / Q up to 20 Ms/s</td>
</tr>
<tr>
<td>Adjustable RF Gain</td>
<td>0 – 40 dB</td>
<td>0 – 44 dB</td>
</tr>
<tr>
<td>RF inputs</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Power</td>
<td>1 W from 6 V supply</td>
<td>2.2 W from 6 V supply</td>
</tr>
</tbody>
</table>
General Needs at MIT

• MicroMAS
  – Ground station emulator
  – Testing, testing, testing
  – Mission data handling design from DICE?

• Licensing process ambiguity / schedule risk

• Green dish refurbishment
  – Grease monkey / gear head
  – New drive controls, feed system
Acknowledgements

- Utah State University
- SRI
- Haystack Observatory
- MIT Lincoln Lab
- MIT Radio Society
- Aurora Flight Sciences
- E-Space
- Dr. Sara Seager
Backup Slides
• Ground stations originally successfully used to support the MIT HETE-2 mission
  – High Energy Transient Explorer (Oct. 2000)

• NASA SBIR with Espace to upgrade ground stations
  – Collaboration NASA ARC
  – Software defined radio
  – Available for nanosatellites and CubeSats
## GS Link Budget Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamwidth</td>
<td>3.5</td>
<td>degrees</td>
</tr>
<tr>
<td>Efficiency</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>Back-lobe Gain</td>
<td>-30</td>
<td>dB</td>
</tr>
<tr>
<td>System Noise Temp</td>
<td>290</td>
<td>K</td>
</tr>
<tr>
<td>LNA Gain</td>
<td>0</td>
<td>dB</td>
</tr>
<tr>
<td>Antenna to LNA Loss</td>
<td>1</td>
<td>dB</td>
</tr>
<tr>
<td>LNA to Receiver Loss</td>
<td>0</td>
<td>dB</td>
</tr>
<tr>
<td>Pointing Loss*</td>
<td>1</td>
<td>dB</td>
</tr>
</tbody>
</table>

*pointing 30% of main lobe beamwidth
Frequency Licensing

- 2.2—2.3 GHz S-band
- Gov’t. rights to spectrum
- Two approaches
  - DD-1494 with gov’t. sponsor
  - FCC Commercial Experimental License
- Foreign ground stations
  - OSAGS has established representatives at Singapore and Cayenne (France)
# Link Budget

**Detailed link budget**

## MicroMAS Link Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Units</th>
<th>Worst Case</th>
<th>Best Case</th>
<th>Worst Case</th>
<th>Best Case</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP</td>
<td></td>
<td>dBW</td>
<td>0.00</td>
<td>0.00</td>
<td>15.44</td>
<td>15.44</td>
<td>0 dB is power output for Espace PTS radio.</td>
</tr>
<tr>
<td>Transmitter Power</td>
<td>P</td>
<td>dBW</td>
<td>0.00</td>
<td>0.00</td>
<td>15.44</td>
<td>15.44</td>
<td></td>
</tr>
<tr>
<td>Transmitter Line Loss</td>
<td>L_t</td>
<td>dB</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>TBR: Attenuation and length of cable needed for accurate calculation (Assume negligible for now)</td>
</tr>
<tr>
<td>Transceiver Antenna Gain (net)</td>
<td>G_t</td>
<td>dBi</td>
<td>1.00</td>
<td>7.40</td>
<td>31.68</td>
<td>31.68</td>
<td>TBR: Downlink transmit antenna gain is the requirement for onboard patch antennas. Antenna design is underway.</td>
</tr>
<tr>
<td>Equiv. Isotropic Radiated Power</td>
<td>EIRP</td>
<td>dBW</td>
<td>1.00</td>
<td>7.40</td>
<td>47.12</td>
<td>47.12</td>
<td></td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>G_r</td>
<td>dB</td>
<td>31.68</td>
<td>31.68</td>
<td>6.00</td>
<td>10.00</td>
<td>See SMAD eq. (13-36b)</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>GHz</td>
<td>2.25</td>
<td>2.25</td>
<td>2.08</td>
<td>2.08</td>
<td>Downlink Frequency: 2.25 GHz, mid point of 2.2 - 2.3 GHz range of OSAGS ground stations. Uplink Frequency is 2.075 GHz. Mid point of 2.05 - 2.10 GHz for OSAGS ground stations.</td>
</tr>
<tr>
<td>Receive Antenna Diameter</td>
<td>D_r</td>
<td>m</td>
<td>2.30</td>
<td>2.30</td>
<td>0.05</td>
<td>0.05</td>
<td>2.3 m diameter for OSAGS from Espace-OSAGS-PTS-Slides-2-21-2012.pdf from Francois Martel.</td>
</tr>
<tr>
<td>Receive Antenna efficiency</td>
<td>η</td>
<td>n/a</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>General Assumption</td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>G_r</td>
<td>dB</td>
<td>31.68</td>
<td>31.68</td>
<td>6.00</td>
<td>10.00</td>
<td>See SMAD eq. (13-36b)</td>
</tr>
<tr>
<td>Free Space Loss</td>
<td>S</td>
<td>km</td>
<td>2,076.00</td>
<td>500.00</td>
<td>2,076.00</td>
<td>500.00</td>
<td>Based on Max Range from STK Analysis (Assuming a cutoff of Eb/N0 &gt; 7.5, or Elevation &gt; 5°)</td>
</tr>
<tr>
<td>Transmitter Antenna Pointing Loss</td>
<td>L_{tp}</td>
<td>dB</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.50</td>
<td>Assumed based on conversations with OSAGS engineer.</td>
</tr>
<tr>
<td>C/I</td>
<td>dB</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>Best: Assumed 0 to match STK simulation. Worst: Based on 3 years of atmospheric attenuation research prior to CASTOR program (CASTOR link budget)</td>
</tr>
<tr>
<td>Atmospheric Loss (H2O and O2 losses)</td>
<td>L_{at}</td>
<td>dB</td>
<td>-0.34</td>
<td>-0.34</td>
<td>-0.34</td>
<td>-0.34</td>
<td>Based on 3 years of atmospheric attenuation research prior to CASTOR program (CASTOR link budget)</td>
</tr>
<tr>
<td>LOS due to Rain</td>
<td>L_{los}</td>
<td>dB</td>
<td>-2.00</td>
<td>-0.01</td>
<td>-2.00</td>
<td>-0.01</td>
<td>Based on 3 years of atmospheric attenuation research prior to CASTOR program (CASTOR link budget)</td>
</tr>
<tr>
<td>Depolarization Loss</td>
<td>L_{dp}</td>
<td>dB</td>
<td>-0.15</td>
<td>0.00</td>
<td>-0.15</td>
<td>0.00</td>
<td>“derived from generic communication knowledge” (CASTOR link budget). TBR: Plan to Close loop with PTS Designer</td>
</tr>
<tr>
<td>Total Additional Losses</td>
<td>L_{t}</td>
<td>dB</td>
<td>-4.49</td>
<td>-0.05</td>
<td>-6.99</td>
<td>-0.95</td>
<td>Current MicroMAS design uses two patch antennas, one for uplink and one for downlink.</td>
</tr>
</tbody>
</table>

## Data Rate

- **Data Rate**: 694,444.00 bps, 25,600.00 bps.
- **Original data downlink calculations were done with 115,200 bps, but MicroMAS will need as high a data rate as possible.**

## Boltzmann’s Constant

- **Boltzmann’s Constant**: 10 log(J/K) dBW/Hz*K = 228.00 dB.

## System Noise Temperature

- **Antenna Noise Temperature**: 290.00 K
- **Receiver Noise Temperature**: 0.00 K
- **System Noise Temperature**: 290.00 K

## Noise Power

- **E_b/N0**: 7.91 dB
- **E_b/N0 required**: 7.50 dB
- **Margin**: 0.41 dB

8/12/2012 CubeSat Developers Workshop - Cahoy 26
S-Band CubeSat Antenna Design

• Two custom patch antennas
  – Uplink, downlink
  – Truncated corners – RHC
  – Probe feed
    • SMA – coax – PTS board
  – Dielectric RT Duroid 5880
    • Thickness 1.57 mm
    • ε_r = 2.2
  – Mount on nadir facing body panels
### S-Band CubeSat Antenna Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uplink Antenna</th>
<th>Downlink Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>47 mm</td>
<td>43 mm</td>
</tr>
<tr>
<td>Corner Truncation</td>
<td>5.4 mm</td>
<td>4.9 mm</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.088 GHz</td>
<td>2.27 GHz</td>
</tr>
<tr>
<td>Return Loss</td>
<td>-21.2 dB</td>
<td>-16.02 dB</td>
</tr>
<tr>
<td>Gain</td>
<td>7.20 dBi</td>
<td>7.45 dBi</td>
</tr>
<tr>
<td>Half-Power Angle</td>
<td>85 deg</td>
<td>84 deg</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>38 MHz</td>
<td>35 MHz</td>
</tr>
<tr>
<td>Mass</td>
<td>11.2 g</td>
<td>11.08 g</td>
</tr>
<tr>
<td>Price</td>
<td>$350</td>
<td>$350</td>
</tr>
</tbody>
</table>