Antenna Technologies for Future NASA Exploration Missions

NASA’s plans for the manned exploration of the moon and Mars will rely heavily on the development of a reliable communications infrastructure on the surface and back to Earth. Future missions will thus focus not only on gathering scientific data, but also on the formation of the communications network. In either case, unique requirements become imposed on the antenna technologies necessary to accomplish these tasks. For example, surface activity applications such as robotic rovers, human extravehicular activities (EVA), and probes will require small size, lightweight, low power, multi-functionality, and robustness for the antenna elements being considered. Trunk-line communications to a centralized habitat on the surface and back to Earth (e.g., surface relays, satellites, landers) will necessitate wide-area coverage, high gain, low mass, deployable antennas. Likewise, the plethora of low to high data rate services desired to guarantee the safety and quality of mission data for robotic and human exploration will place additional demands on the technology.

Over the past year, NASA Glenn Research Center has been heavily involved in the development of candidate antenna technologies with the potential for meeting these strict requirements. This technology ranges from electrically small antennas to phased array and large inflatable structures. A summary of this overall effort is provided, with particular attention being paid to small antenna designs and applications. A discussion of the Agency-wide activities of the Exploration Systems Mission Directorate (ESMD) in forthcoming NASA missions, as they pertain to the communications architecture for the lunar and Martian networks is performed, with an emphasis on the desirable qualities of potential antenna element designs for envisioned communications assets. Identified frequency allocations for the lunar and Martian surfaces, as well as asset-specific data services will be described to develop a foundation for viable antenna technologies which might address these requirements and help guide future technology development decisions.
Outline of Presentation

• The Vision for Space Exploration
• Communications Architecture for Exploration
• Asset-Specific Communications Requirements
• Technology Development at Glenn Research Center
• Conclusions
A Bold Vision for Space Exploration

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014 (goal of 2012)
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

“It is time for America to take the next steps.

Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We’ll make steady progress – one mission, one voyage, one landing at a time.”

President George W. Bush – January 14, 2004
Communications Architecture
Assessment of Existing NASA Communications Capability

- Limited lunar coverage
- Existing Earth-based Tracking and Data Relay Satellite System (TDRSS) can presently provide limited Low Earth Orbit (LEO) and translunar backup systems for critical communications in lunar vicinity due to area coverage limitations
- Ground Networks (GN) can provide LEO and translunar short pass duration communications
- Large aperture Deep Space Network (DSN) antennas (26m, 34m, 70m) can provide excellent high-rate coverage in lunar vicinity
- Limited Mars communications data rates and numbers of connections
- Limited precision Mars navigation capability
Lunar Communications Assets

Lunar Reconnaissance Orbiter (LRO)

UHF&S-Band Tx/Rx to Moon
125 bps to 256 kbps

S-Band Tx/Rx direct to Earth
2.186 Mbps QPSK

Ka-Band Tx to Earth
>100 Mbps

VHF/UHF* Surface Comm.
(Data Rates: TBD)

S-Band* Surface Comm.
Tx/Rx relay to Earth
(Data Rates: TBD)

Ka-Band* Tx to Earth
(Data Rates: TBD)

* Probable communications frequencies
Mars Communications Assets

**Mars Reconnaissance Orbiter (MRO)**
- **UHF** Tx/Rx to Mars: 100 kbps - 1 Mbps
- **X-Band** Tx/Rx to Earth: 300 kbps
- **Ka-Band** Tx to Earth: 5 Mbps BPSK

**Arrival Date:** March 10, 2006

**Mars Odyssey**
- **UHF** Tx/Rx to Mars: 128 kbps
- **X-Band** Tx/Rx to Earth: 128 kbps

**Arrived October 24, 2001

**Mars Global Surveyor (MGS)**
- **UHF** Tx/Rx to Mars: 128 kbps
- **X-Band** Tx/Rx to Earth: 20 kbps
- **Ka-Band** Tx to Earth: 85 kbps (max)

**Arrived September 12, 1997

**Mars Express (ESA)**
- **UHF** Tx/Rx to Mars: 128 kbps
- **S-Band** Rx from Earth: up to 2 kbps
- **X-Band** Tx to Earth: 230 kbps

**Arrived December 25, 2003**
Asset-Specific Communications

Nominal Specifications
Surface Communications Architecture (~2030)

- Surface assets (e.g., nodes) communicate via each other and a centralized hub
- Surface Wireless Local Area Network (SWLAN) infrastructure to connect astronauts with rovers, probes, habitat, and each other
- Ad-hoc proximity networking amongst assets
- Access point (relay) towers to extend communication capabilities range
## Surface Communications Assets

<table>
<thead>
<tr>
<th>Data Services</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio*</td>
<td>8-64 kbps/channel</td>
</tr>
<tr>
<td></td>
<td>(at least 4 channels)</td>
</tr>
<tr>
<td>TT&amp;C*</td>
<td>&lt; 100 kbps</td>
</tr>
<tr>
<td>SDTV Video</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>HDTV Video</td>
<td>19 Mbps</td>
</tr>
<tr>
<td>Biomedical Control*</td>
<td>70 kbps</td>
</tr>
<tr>
<td>Biomedical Monitoring*</td>
<td>122 kbps</td>
</tr>
</tbody>
</table>

*Must be Reliable Links

Limited power/space availability
UHF/S-Band surface comm. frequencies

- **Reliable links require low BER**
- **Antennas should be small, efficient, and wideband/multiband to accommodate desired frequencies and data services in a restricted space.**
- **Multiband important for Software Defined Ratio (SDR) to reduce size, weight, and Power (SWaP)**
Surface Communications Assets

- Mobile Nodes with data-intensive mission requirements for surface-based exploration.
- Characterized by entities of moderate size and free to move about the lunar surface (e.g., rovers, pressurized vehicles, astronauts, robots)
- Tightly constrained by power, mass and volume.

- Smaller Nodes: support fixed and mobile nodes, and connect to the network by wired or wireless interface.
- Sensors, small probes, instruments and subsystems of very small size, limited power levels, and short range (~10 m) low data rate communications.

- Antennas should be low/self-powered, small, and efficient, and compatible with communication equipment that can provide high data rate coverage at short ranges (~1.5-3 km, horizon for the moon for EVA).

- Large, fixed nodes: Serves as base for surface activities.
- Centralized Hub/Habitat for immediate area coverage
- Transmission of data to surface and space assets
- Can support larger communication hardware and higher data rates over long distances.

- Smart/reconfigurable antennas, multibeam antennas, lightweight deployable antennas are viable technologies (10-30 Km)
Space Communications Assets

- Robotic Lunar Exploration Program (RLEP)
- Lunar Reconnaissance Orbiter (LRO) (RLEP-1)
- Crew Launch Vehicle (CLV)
- Crew Exploration Vehicle (CEV)

**Antenna Requirements:** Conformal, Reconfigurable or Multiband antennas, phased arrays

- Relay satellites (around the moon (e.g., LRO after its initial mission could be elevated to elliptical orbit for relay purposes); around Mars; etc.)
- Relay satellites (L1/L2)
- The intended orbit will drive the type of antenna technology.

**In Orbit:** Gimbaled dish (slew rate driven), reflectarrays, phased array antennas, deployable/inflatable arrays
## Antenna TechnologySummary

<table>
<thead>
<tr>
<th>Surface/ Surface Comm.</th>
<th>Potential Frequencies</th>
<th>Desirable Antenna Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA Suit</td>
<td>UHF/VHF S-band</td>
<td>• Miniature Antennas&lt;br&gt;• Multi-directional (to support mobility)&lt;br&gt;• Wearable Antennas&lt;br&gt;• Dipole/Monopole (omni-directional coverage)</td>
</tr>
<tr>
<td>Rovers</td>
<td>UHF/VHF S-band</td>
<td>• Miniature Antennas&lt;br&gt;• Omni antennas&lt;br&gt;• Phased Arrays (pitch/roll compensation)</td>
</tr>
<tr>
<td>Probes</td>
<td>UHF/VHF S-band</td>
<td>• Miniature Antennas&lt;br&gt;• Dielectric Resonator Antennas&lt;br&gt;• Wideband Antennas&lt;br&gt;• Solar Cell Integrated Antennas&lt;br&gt;• Retrodirective Antenna</td>
</tr>
<tr>
<td>Habitat/Surface Relays</td>
<td>HF (OTH Propagation) S-band X-band</td>
<td>• Deployable Antennas&lt;br&gt;• Multi-directional coverage (to support mobility)&lt;br&gt;• Smart/reconfigurable Antennas&lt;br&gt;• Multi-beam Antennas (to support connectivity to different nodes)</td>
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<td>S-band</td>
<td>• Phased Arrays</td>
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<tr>
<td></td>
<td>X-band</td>
<td>• Wideband/Multiband</td>
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<tr>
<td></td>
<td>Ku/Ka-band</td>
<td>• Conformal Antennas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Frequency Selective</td>
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<tr>
<td></td>
<td></td>
<td>Surface Antennas</td>
</tr>
<tr>
<td>Satellites</td>
<td>UHF</td>
<td>• Gimbaled Dish</td>
</tr>
<tr>
<td></td>
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<td>• Phased Arrays</td>
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<tr>
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<td>• Deployable Antennas</td>
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<tr>
<td></td>
<td>Ku/Ka-band</td>
<td>• Multi-Beam antennas</td>
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<tr>
<td></td>
<td></td>
<td>• High Gain</td>
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<td></td>
<td>• Solar Cell Integrated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antennas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Patch antennas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Retrodirective Antenna</td>
</tr>
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Technology Development at Glenn Research Center
Technology Readiness Level

- **TRL 9**: Actual system “flight proven” through successful mission operations
- **TRL 8**: Actual system completed and “flight qualified” through test and demonstration (Ground or Flight)
- **TRL 7**: System prototype demonstration in a space environment
- **TRL 6**: System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
- **TRL 5**: Component and/or breadboard validation in relevant environment
- **TRL 4**: Component and/or breadboard validation in laboratory environment
- **TRL 3**: Analytical and experimental critical function and/or characteristic proof-of-concept
- **TRL 2**: Technology concept and/or application formulated
- **TRL 1**: Basic principles observed and reported
Large Aperture Deployable Antennas
(X-, and Ka-Band: TRL 4)

Benefits
- Reduced mass (~1 kg/m²)
- Low fabrication costs
- High packaging efficiencies (as high as 50:1)
- Proven performance at S-Band & L-Band frequencies

Issues
- Stringent RMS surface accuracy requirements at high frequencies (i.e. Ka-Band)
- Development of reliable deployment mechanisms
- Thermal response
- Rigidization

Potential Applications
- Deep space relay station concept
- Backup satellite antenna systems
- Erectable surface communications relays
Large Aperture Inflatable Antennas

**Space Applications**

- Overhead photograph of 4- by 6-m inflatable reflector in GRC near field facility
- 4- by 6-m inflatable offset parabolic membrane antenna test in GRC near-field facility
- Deep-space relay station concept
- Backup 2-m inflatable Cassegrain reflector for ISS Ku-band system

**Surface Applications**

- 2.5-m inflatable membrane antenna in inflatable radome for ground applications
- Low-cost tracking ground station experiment in collaboration with Goddard Space Flight Center planned for May 2005

**Goals:**
- Develop large, lightweight reflector antennas with areal densities <0.75 kg/m², for Lunar, Mars, and deep-space relay exploration applications.
- Develop rigidization techniques (e.g., ultraviolet curing) to eliminate the need for makeup inflation gas.
- Demonstrate a ratio package to deploy volume greater than 1:75.
- Demonstrate quick deployment of large apertures for ground-based and planetary surface applications.
Large Aperture Deployable Antennas
(X-band: TRL 3)

Hybrid Inflatable Antenna

- Combines traditional fixed parabolic dish with an inflatable reflector annulus
- Redundant system prevents “all-or-nothing” scenarios
- Based on novel shape memory composite structure
- High packing efficiency

(1) Low cost fabrication and inflation of an annulus antenna
(2) Overall surface accuracy 1 mm
(3) Negligible gravity effects
(4) Elimination of large curve distortions across the reflector surface (i.e. Hencky curve)
Phased Array Antennas
(K-, and Ka-Band: TRL 9)

Benefits
• Electrically Steerable
• Conformal
• Graceful degradation
• Multi-Beam
• Fast Scanning/acquisition
• S-, X-, Ku-, K-, and Ka-Band

Issues
• Low MMIC efficiency (thermal management problems)
• Cost per module
• FOV (limited to +/- 60°)

Potential Applications
• CLV, CEV
• Robotic Rovers
• Satellite Systems
• Surface Communications

Boeing 91 Element Receive Array: H

Theory vs. Experiment 91 Element Boeing

Bit Error Rate

Relative Power - dB

Eb/N0 - dB

Azimuth - Degrees

0.01
0.1
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
100
1000
10000
100000
1000000
10000000
4
5
6
7
8
9
10
11
12
-60
-40
-20
0
20
40
60
0
-10
-20
-30
-40
-50
-60
Ferroelectric Reflectarray Development
(K-band: TRL 3)

Potential Applications
- Satellite Antenna Systems
- Ground-based Deep Space Network Array

Benefits
- High efficiency
- Zero manifold loss
- Electronically steerable
- Lightweight, planar reflector

EIRP (dBW)

Power Consumed (W)

~ 28 cm Active Diameter

19 GHz 615 Element Prototype

Gain (dB)

EIRP (dBW)

SQR of Number of Radiating Elements

Expected

Reflectarray

MMIC

Ferroelectric Reflectarray

Direct Radiating MMIC Array
Multi-beam Discrete Space Lens Arrays

- No manifold losses
- Capable of multiple beams
- Pseudo conformal

Collaboration with Dr. Z. Popovic
University of Colorado, Boulder.
Multi-Beam Antennas
(S-, Ka-band: TRL 4)

Potential Applications

- Smart Antenna Systems
- Ground-based Communications (i.e., Habitat, Relays)
- Satellite Constellations
TDRSS-C Antenna Development
(S-band: TRL 4)

- Next generation TDRSS to implement beamforming between S-band Single Access and Multiple Access antennas

- GRC responsible for antenna element design, construction and characterization of candidate antennas for next generation Multiple Access phased array

Potential Applications
- Satellite Antenna Systems
SMALL ANTENNAS (TRL 1-3)
Self-Powered Antennas  
(X-band: TRL 3)

- Integration of solar cell and local oscillator with antenna provides self-powering communications system package

Potential Applications
- Distributed sensors/probes
- Robotic rovers
- Astronaut EVA

![Diagram of X-band Integrated antenna/solar cell]
Miniaturized Reconfigurable Antenna For Planetary Surface Communications

**Program Goals**

- Develop electrically small (miniaturized) antennas with moderate bandwidths for planetary surface communications between remote sites sensors or orbiters.

- The technology is intended to enable low-risk sensing and monitoring missions in hostile planetary and/or atmospheric environments.

- These antennas are needed for Planetary and Moon Exploration and Monitoring Missions.

Collaboration with Dr. Jennifer Bernhard (University of Illinois)
Miniature Antennas
TRL 2

- Artificially manufacturable Metamaterials: Magnetic Photonic Crystals (MPC).

- These MPCs exhibit the following properties:

  (a) considerable slow down of incoming wave, resulting in frozen mode.

  (b) huge amplitude increase.

  (c) minimal reflection at the free space interface.

  (d) large effective dielectric constant, thus enabling miniaturization of the embedded elements

Collaboration with Dr. John Volakis and Mr. Jeff Kula (OSU)
Miniature Antennas
(S-, Ku-/Ka-band: TRL 3)

Benefits
• Provides optimal radiation patterns for surface-to-surface and surface-to-orbit communications at relevant frequencies without switches

Potential Applications
• Sensors/probes
• Robotic rovers
• Astronaut EVA

Surface-to-Surface

Surface-to-Orbit

Folded Hilbert Curve Fractal Antenna
Miniature Antennas
(S-band: TRL 3)

Benefits
• Performance comparable to an S-band dipole, but at less than 1/6 the size

Potential Applications
• Sensors/probes
• Robotic rovers
• Astronaut EVA

E-plane Pattern

H-plane Pattern

Compact Microstrip Monopole Antenna
NASA seeks to develop telemetry based implantable sensing systems to monitor the physiological parameters of humans during space flights.

A novel miniature inductor and pick-up antenna for contact-less powering and RF telemetry from implantable Bio-MEMS sensors has been developed.

**RF Telemetry System for an Implantable Bio-MEMS Sensor (TRL 3-4)**

- **Contact-less powering and telemetry concept**
- **Contact-less powering and telemetry application in biosensors**
- **Measured received relative signal strength as a function of frequency.** (a) Pick-up antenna at a height of 5 cm. (b) Pick-up antenna at a height of 10 cm.
Reconfigurable Antennas
For High Data Rate Multi-beam Communication
PI: Prof. Jennifer Berhard, U. Illinois, Grant # NAG3 2555

Target Technology:
Reconfigurable antenna elements capable of producing multiple beams, multiple frequencies, and array scan angles from broadside to horizon. Intended for inter-satellite, satellite-mobile and satellite-ground communication with a single array.

Antenna Elements:
Spiral microstrip patch antenna with reconfigurable switch elements activated by DC bias. Broadside to end-fire pattern reconfiguration by respective switch activation.

Measured patterns ($\varphi=0$) from 4x4 array in broadside and end-fire configurations

Reconfigurable antenna array (with 16 shorting wire switches)

Human/Rover Application

IC Compatible Prototype Square Element
For monolithic MEMS integrated fabrication
D-RATS Antenna Survey

The Desert Research And Technology Studies (D-RATS) is an informal partnership of individual teams from across the agency all working to solve the unique problems related to planetary surface exploration.
D-RATS Antenna Survey

D-GPS Beacon Receiver

5.8-GHz Video

Ultrawideband patch antenna (Green)

2.4-GHz Omni 802.11

GPS

900-MHz Emergency Stop

2.4-GHz Omni 802.11

GPS

SCOUT Rover Antenna Platform
D-RATS Antenna Survey

Spacesuit Antennas

Voice Repeater System
VHF Omni Antenna (1)
UHF Omni Antennas (3)
Reconfigurable transceivers and Software Defined Radios are the future of telecommunications
Conclusions

- By 2030, 1 Gbps deep space data rates desired. Choosing the proper antenna technology for future NASA exploration missions will rely on: data rate requirements, available frequencies, available space and power, and desired asset-specific services. Likewise, efficiency, mass, and cost will drive decisions.

- Viable antenna technologies should be scalable and flexible for evolving communications architecture.

- Enabling technologies include: large aperture deployable/inflatable antennas (reduce space/payload mass), multibeam antennas (reduce power consumption), reconfigurable antennas (reduce space), low loss phased arrays (conformal/graceful degradation), and efficient miniature antennas (reduce space/power).

- Efficient miniature antennas will play a critical role in future surface communications assets (e.g., SDR radios) where available space and power place stringent requirements on mobile communications systems at the envisioned UHF/VHF/S-band surface comm. frequencies (i.e., astronaut suits, probes, rovers).