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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.

Antenna Technologies for Future NASA Exploration Missions

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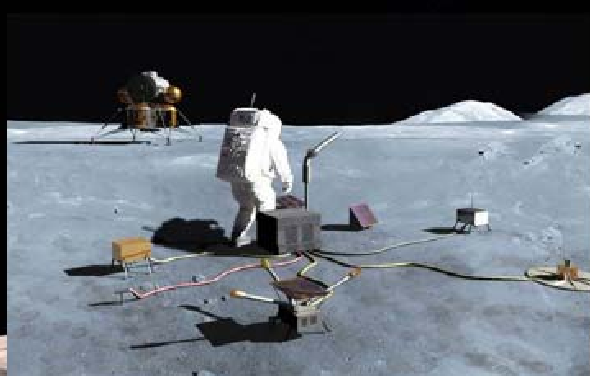
Small Antennas and Novel Metamaterials
White Plains, NY
March 6-8, 2006

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"

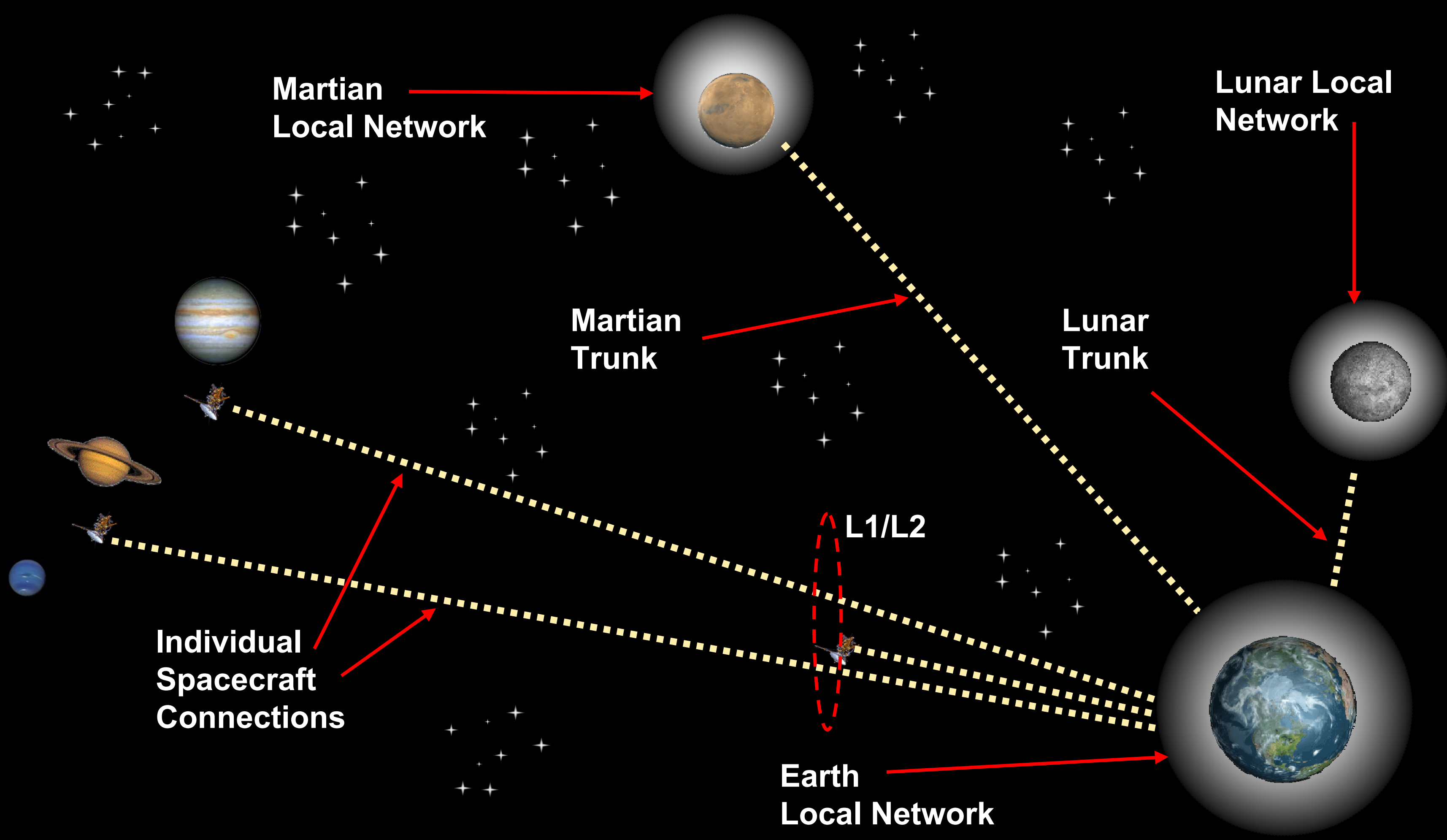
President George W. Bush – January 14, 2004

Communications Architecture

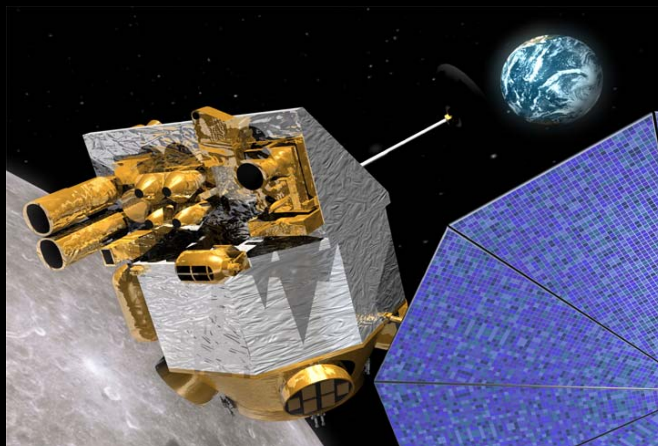
Assessment of Existing NASA Communications Capability

- 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

Top Level Conceptual Communication Architecture ~2030



Lunar Communications Assets



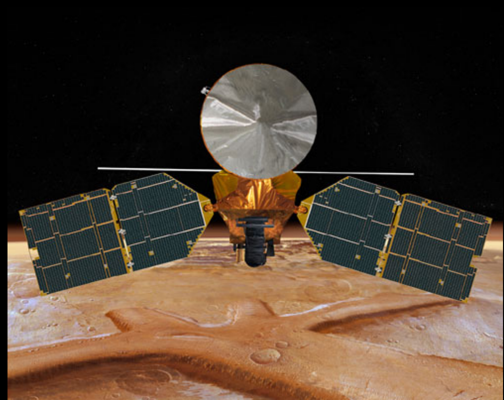
Lunar Reconnaissance Orbiter (LRO)

Robotic Lunar Lander

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

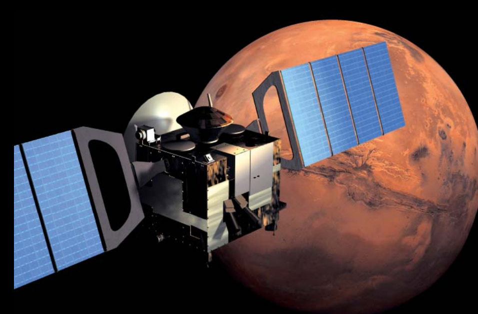
UHF	**Tx/Rx to Mars** *128 kbps*
X-Band	**Tx/Rx to Earth** *128 kbps*

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)

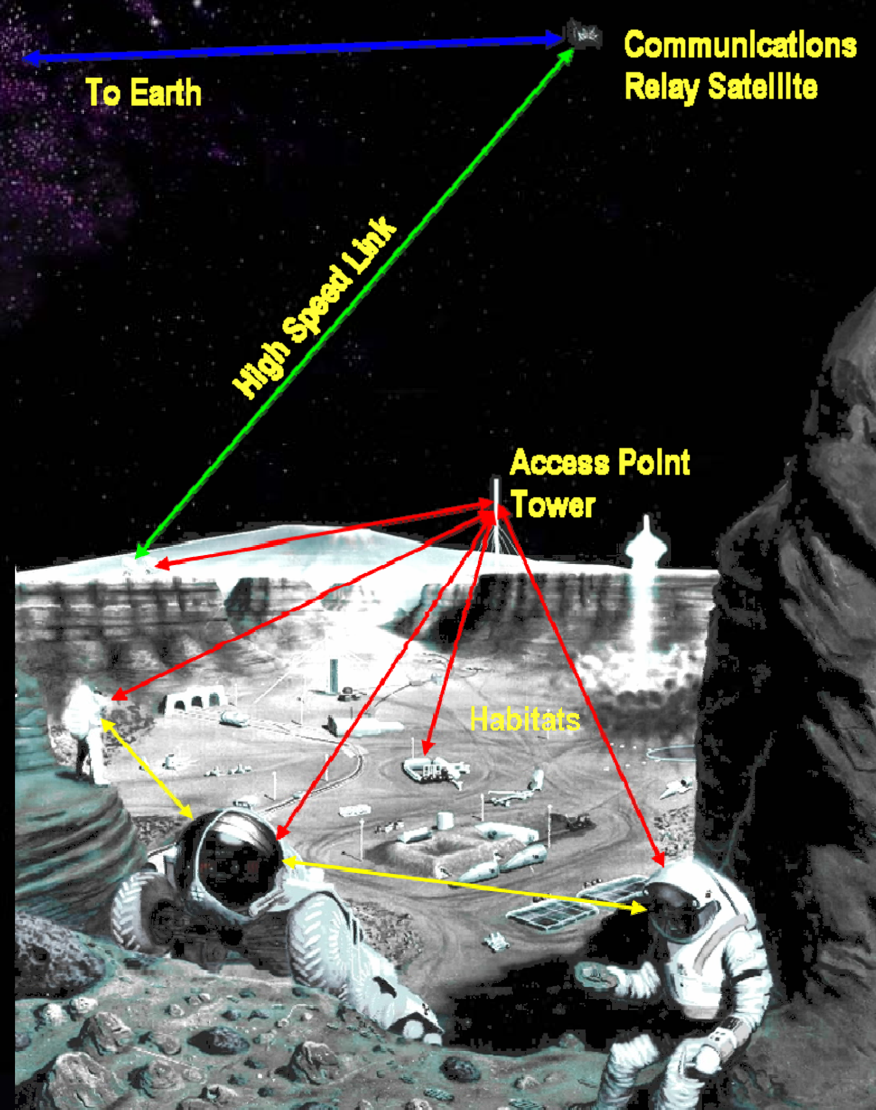
UHF	**Tx/Rx to Mars** *128 kbps*
S-Band	**Rx from Earth** *up to 2 kbps*
X-Band	**Tx to Earth** *230 kbps*

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

Astronaut EVA Suit

Data Services	
Audio*	8-64 kbps/channel (at least 4 channels)
TT&C*	< 100 kbps
SDTV Video	6 Mbps
HDTV Video	19 Mbps
Biomedical Control*	70 kbps
Biomedical Monitoring*	122 kpbs

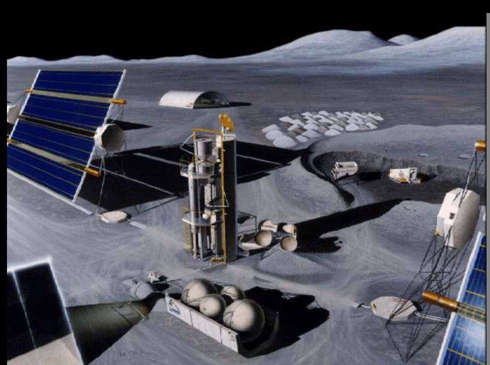
*Must be Reliable Links

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



Habitat

- 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.

➢ ***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).***

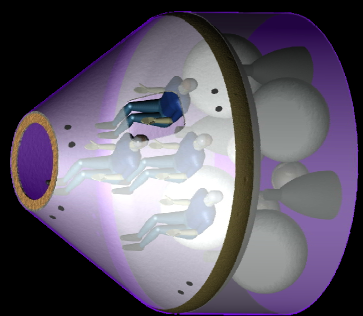
- Small Nodes: support fixed and mobile nodes, and connect to the network by wired or wireless interface.
- Sensors, small probes, instruments and subsystems of very small size, limited power levels, and short range (~10 m) low data rate communications.

➢ ***Antennas should be low/self-powered, small, and efficient.***

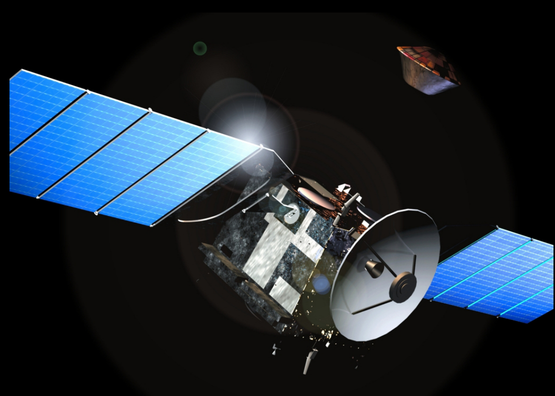
- Large, fixed nodes: Serves as base for surface activities.
- Centralized Hub/Habitat for immediate area coverage
- Transmission of data to surface and space assets
- Can support larger communication hardware and higher data rates over long distances.

➢ ***Smart/reconfigurable antennas, multibeam antennas, lightweight deployable antennas are viable technologies (10-30 Km)***

Space Communications Assets



Crew Exploration Vehicle (CEV)



Satellite Systems

- 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 Technology Summary

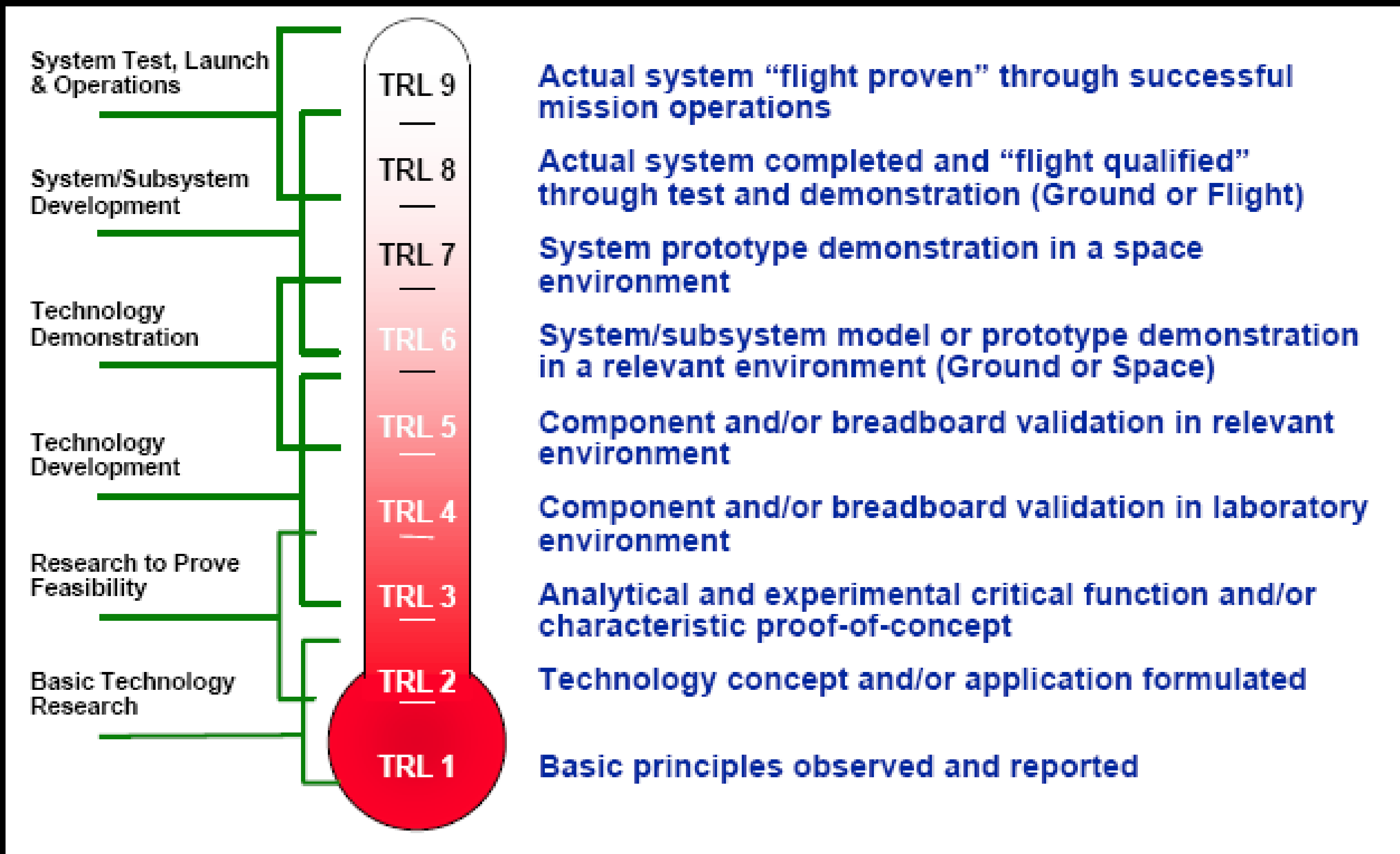
Surface/ Surface Comm.	Potential Frequencies	Desirable Antenna Technologies	
EVA Suit	UHF/VHF S-band	• Miniature Antennas • Multi-directional (to support mobility) • Wearable Antennas	• Dipole/Monopole (omni-directional coverage)
Rovers	UHF/VHF S-band	• Miniature Antennas • Omni antennas	• Phased Arrays (pitch/roll compensation)
Probes	UHF/VHF S-band	• Miniature Antennas • Dielectric Resonator Antennas • Wideband Antennas	• Solar Cell Integrated Antennas • Retrodirective Antenna
Habitat/Surface Relays	HF (OTH Propagation) S-band X-band	• Deployable Antennas • Multi-directional coverage (to support mobility) • Smart/reconfigurable Antennas	• Multi-beam Antennas (to support connectivity to different nodes)

Antenna Technology Summary

Surface/Orbit Comm.	Potential Frequencies	Desirable Antenna Technologies
CEV	S-band X-band Ku/Ka-band	• Phased Arrays • Wideband/Multiband • Conformal Antennas • Frequency Selective Surface Antennas
Satellites	UHF S-band X-band Ku/Ka-band	• Gimbaled Dish • Phased Arrays • Deployable Antennas • Multi-Beam antennas • High Gain
Rovers	UHF S-band	• Miniature Antennas • Phased Arrays
Probes	UHF	• Miniature Antennas • Solar Cell Integrated Antennas • Patch antennas • Retrodirective Antenna

Technology Development at Glenn Research Center

Technology Readiness Level



Large Aperture Deployable Antennas
(X-, and Ka-Band: TRL 4)

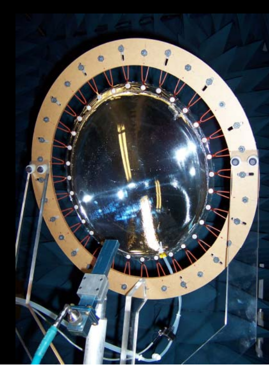
Benefits
- Reduced mass (~1 kg/m^2)
- Low fabrication costs
- High packaging efficiencies (as high as 50:1)
- Proven performance at S-Band & L-Band frequencies

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

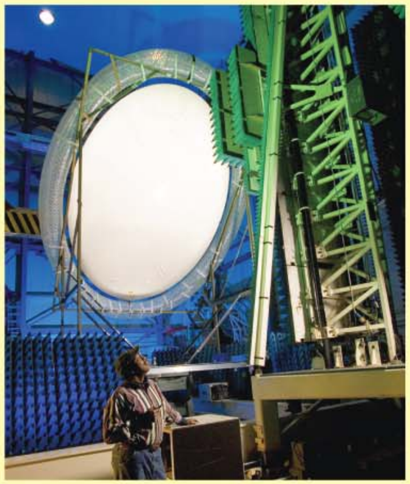
2.5 m "Beach Ball" Antenna


4 x 6 m offset parabolic

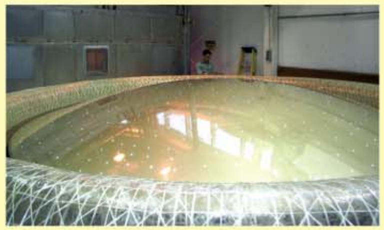

0.3 m Parabolic Antenna

Large Aperture Inflatable Antennas

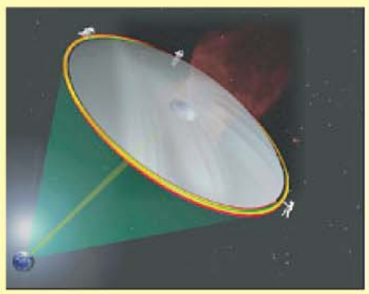
Space Applications



4- by 6-m inflatable offset parabolic membrane antenna test in GRC near-field facility

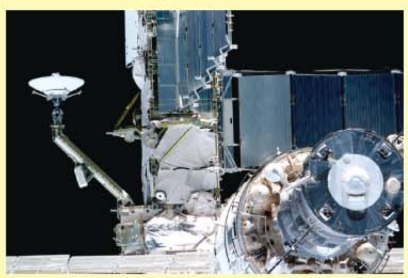


4- by 6-m inflatable offset parabolic membrane antenna inflation test (human in the background)



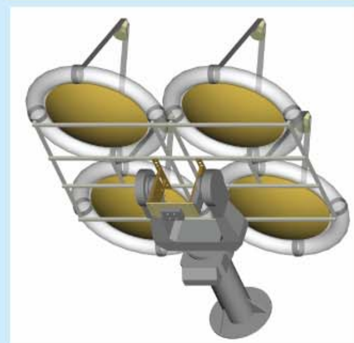
Deep-space relay station concept

Overhead photograph of 4- by 6-m inflatable reflector in GRC near field facility



Backup 2-m inflatable Cassegrain reflector for ISS Ku-band system

Surface Applications



Low-cost tracking ground station experiment in collaboration with Goddard Space Flight Center planned for May 2005

2.5-m inflatable membrane antenna in inflatable radome for ground applications

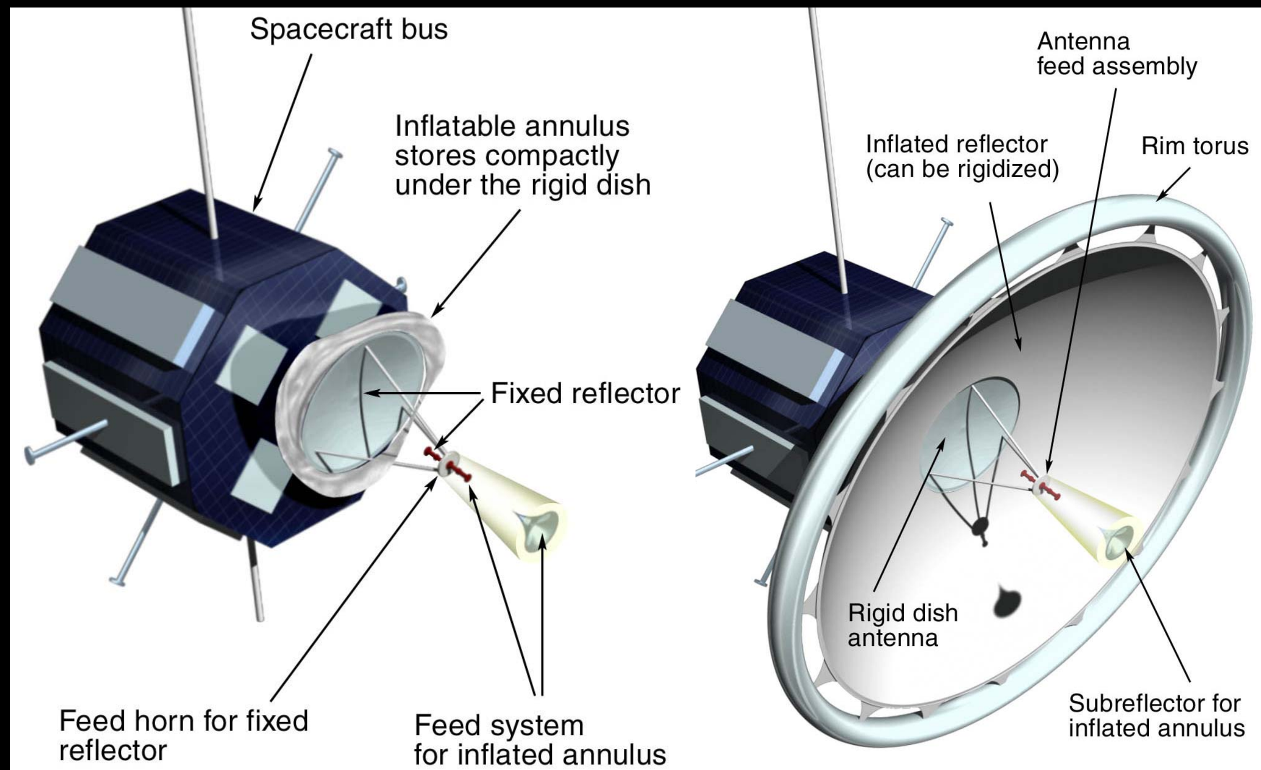
Goals:

- Develop large, lightweight reflector antennas with areal densities <0.75 kg/m^2, 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

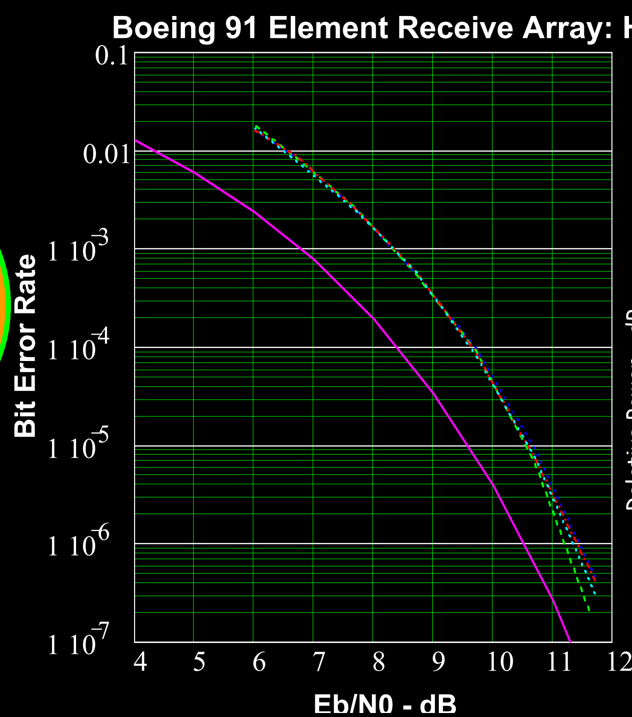
- Combines traditional fixed parabolic dish with an inflatable reflector annulus
- Redundant system prevents “all-or-nothing” scenarios
- Based on novel shape memory composite structure
- High packing efficiency

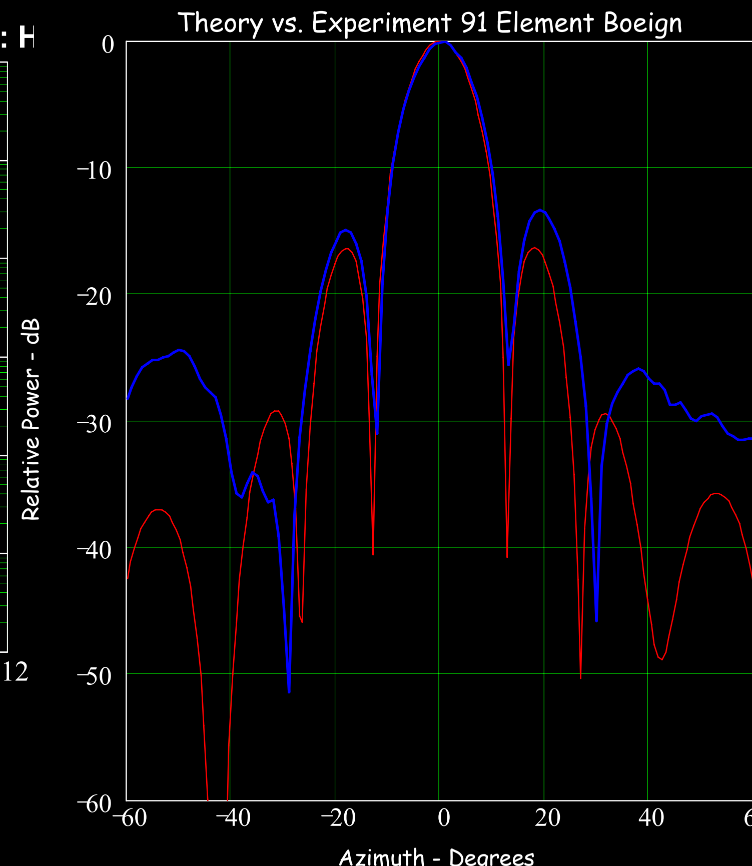


JHU/APL under NASA Grant

(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)



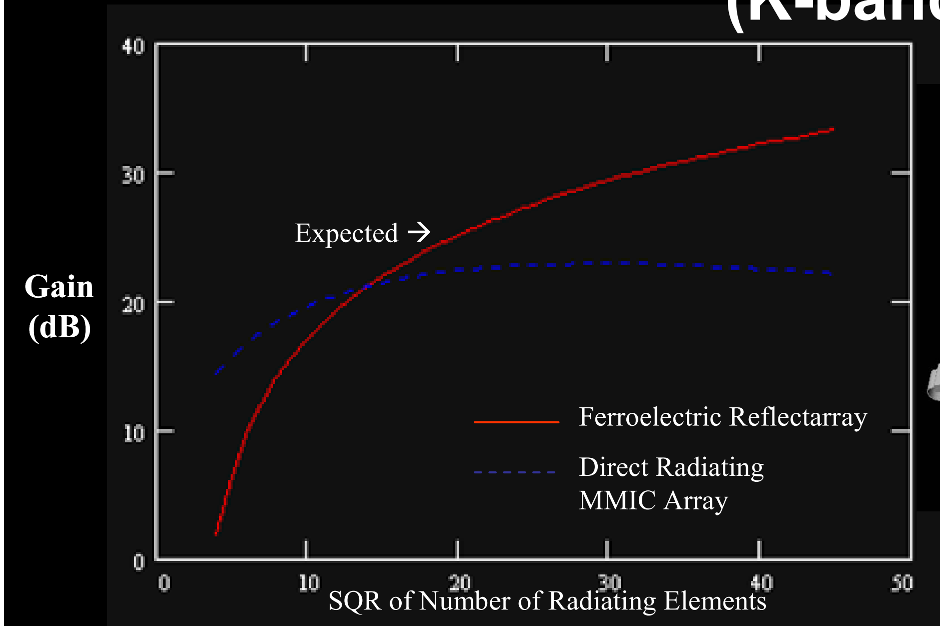


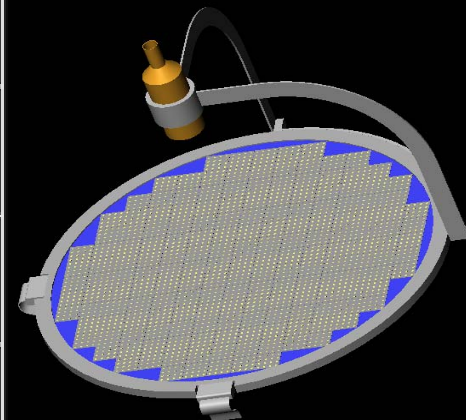
Benefits
- Electrically Steerable
- Conformal
- Graceful degradation
- Multi-Beam
- Fast Scanning/acquisition
- S-, X-, Ku-, K-, and Ka-Band

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

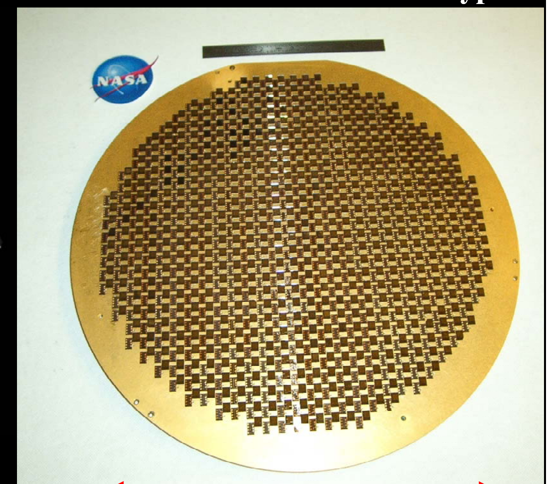
Potential Applications
- CLV, CEV
- Robotic Rovers
- Satellite Systems
- Surface Communications

Ferroelectric Reflectarray Development
(K-band: TRL 3)

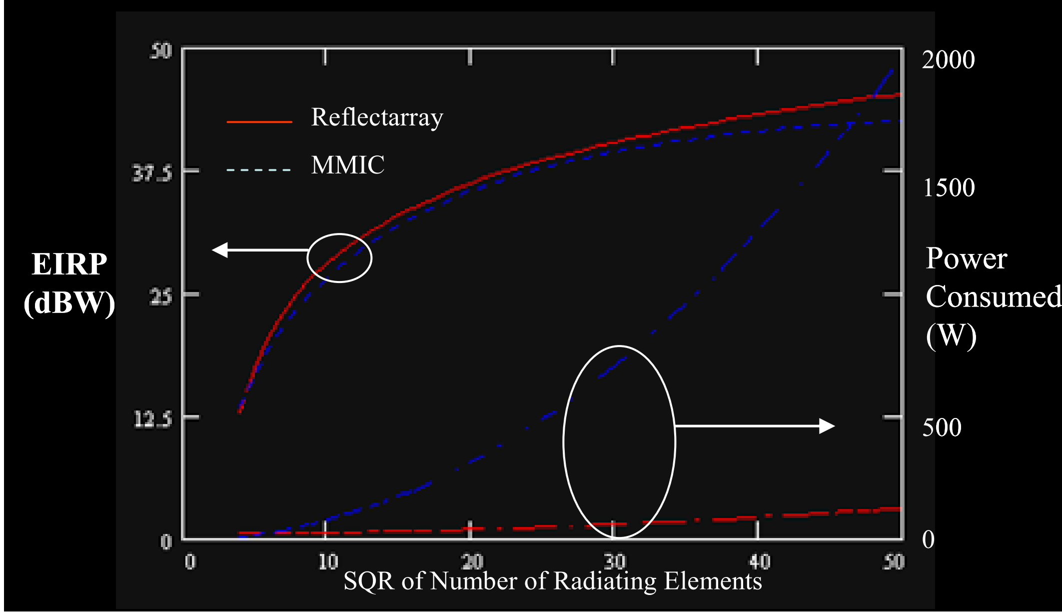




19 GHz 615 Element Prototype

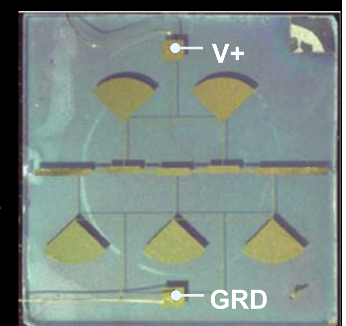


≈ 28 cm Active Diameter



Benefits

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

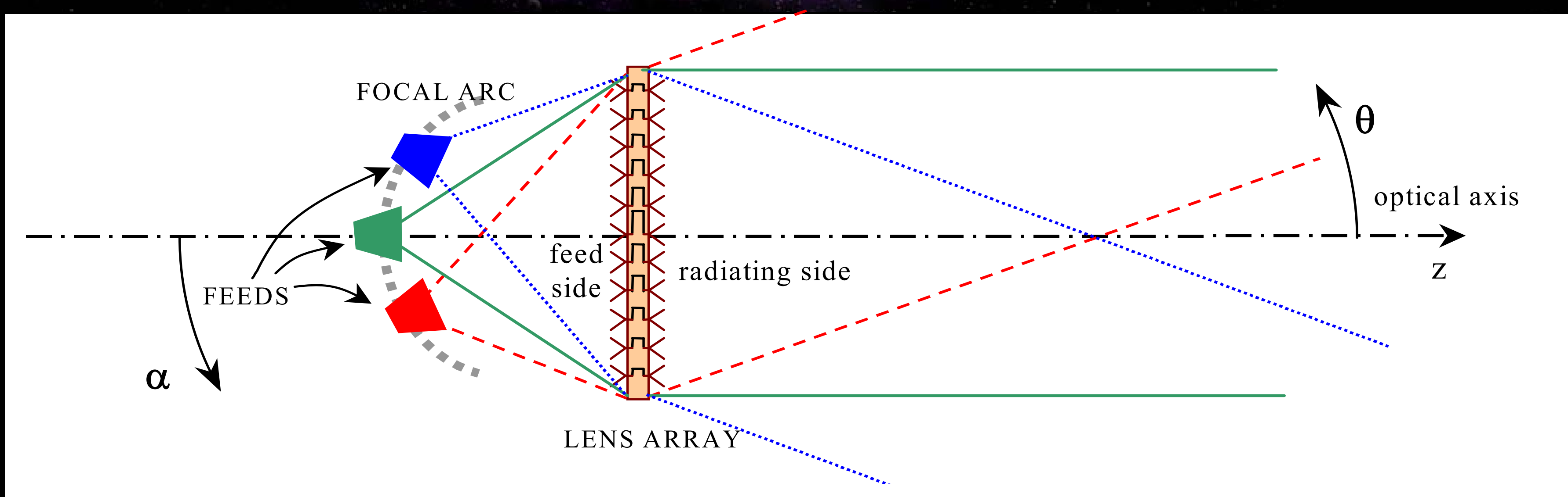


Potential Applications

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

Multi-beam Discrete Space Lens Arrays

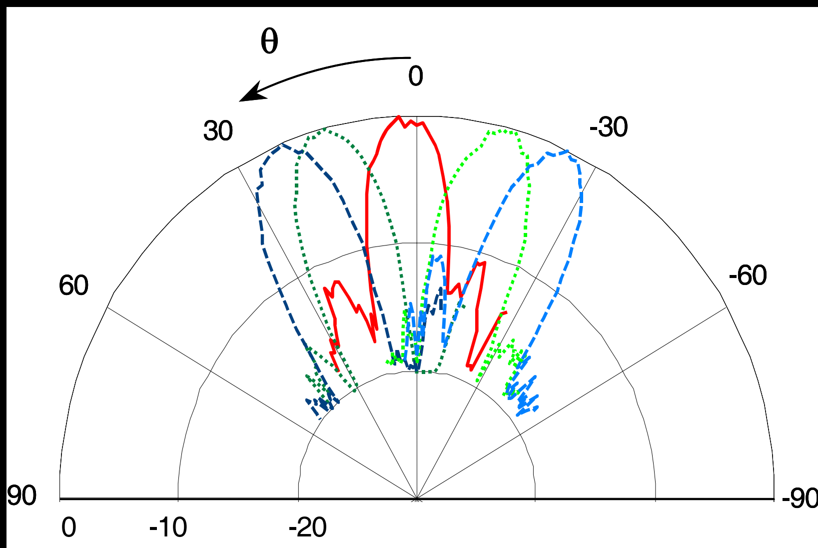
- No manifold losses
- Capable of multiple beams
- Pseudo conformal

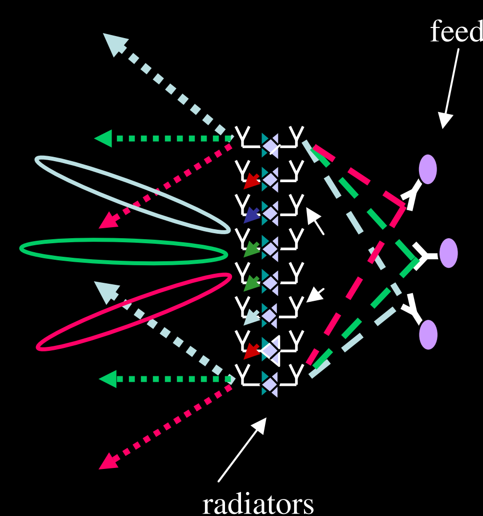


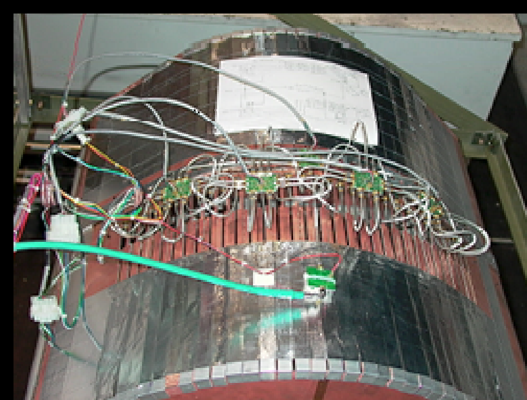
Collaboration with Dr. Z. Popovic
University of Colorado, Boulder.

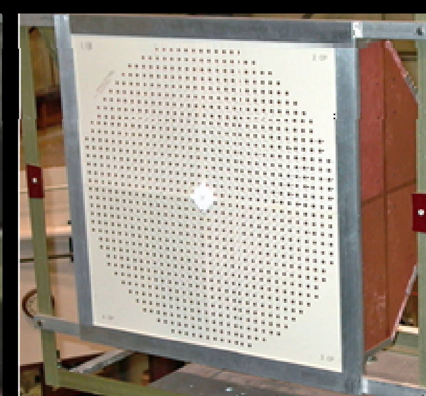
Multi-Beam Antennas

(S-, Ka-band: TRL 4)







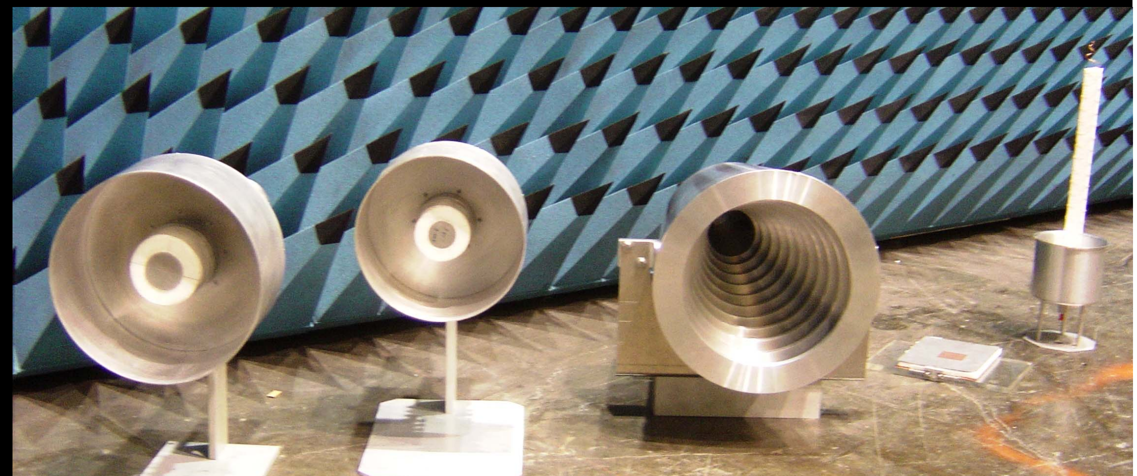


Potential Applications

- 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

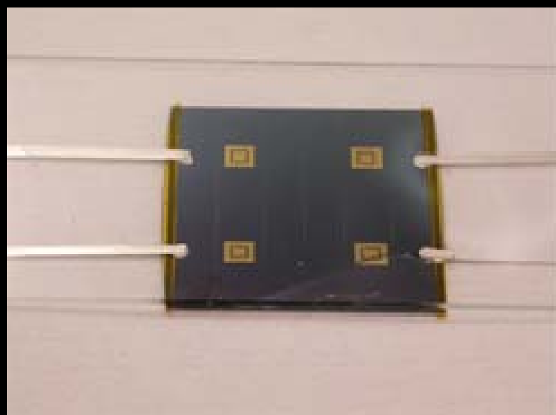


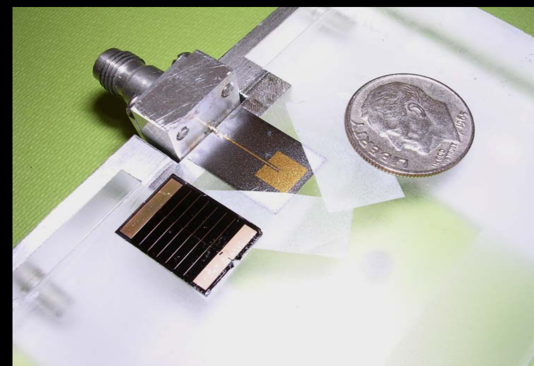
Specification	Bandwidth 2.0 – 2.3 GHz WB 2.2 – 2.3 GHz NB	Directivity >15 dBi Peak	Directivity at ± 20 deg. > 10 dBi	Axial Ratio < 5 dB ± 20 deg. LHCP,RHCP	Pol. Isolation < -20 dB	Return Loss < -20 dB Port Isolation < -10 dB	Mounting Footprint (Diameter)
Cup-Waveguide (Wideband)	NB Meets WB MEETS	Meets	Meets	Meets LHCP, RHCP	Meets	Meets	Meets 11.5 in
Cup-Waveguide (Narrowband)	NB Meets	Meets	Meets	Meets LHCP, RHCP	Meets	Meets	Meets 10.6 in
Horn	NB Meets	Meets	Meets	Meets LHCP, RHCP	Meets	Meets	DNM* 14.5 in
Helix	NB Meets	Meets	Meets	Meets LHCP	NA	Meets	Meets 6.0 in
Cup-Patch	WB Meets	Meets	Meets	Meets LHCP, RHCP	Meets	Meets	Meets 12.5 in

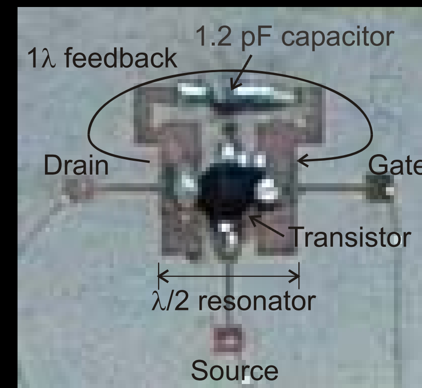
Potential Applications
- Satellite Antenna Systems

SMALL ANTENNAS
(TRL 1-3)

Self-Powered Antennas
(X-band: TRL 3)







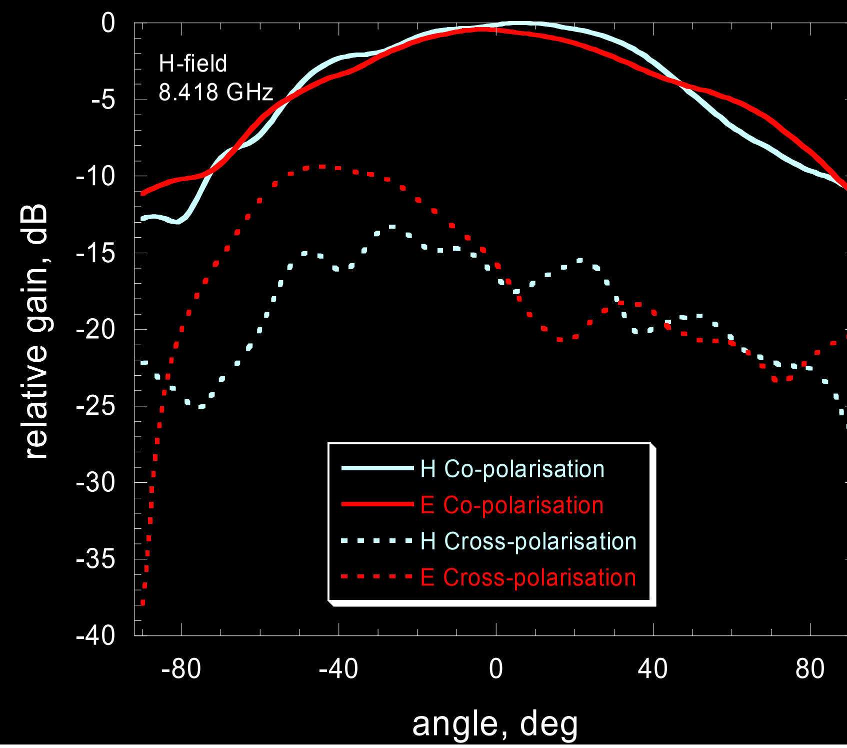
Local Oscillator

X-band Integrated antenna/solar cell

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

<u>Potential Applications</u>

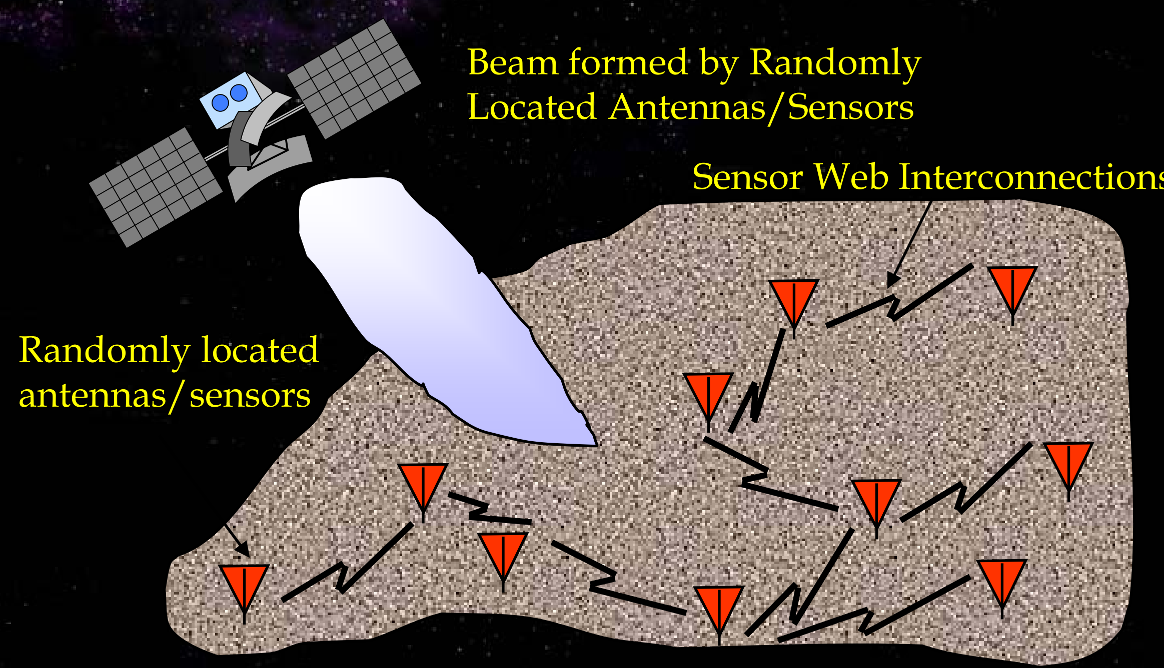
- Distributed sensors/probes
- Robotic rovers
- Astronaut EVA



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

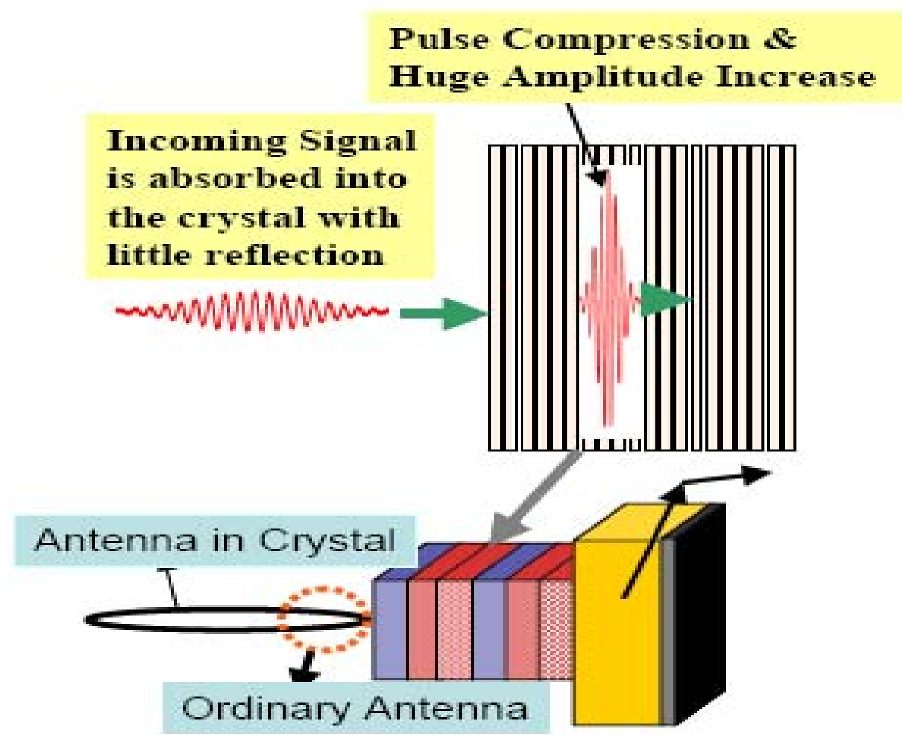
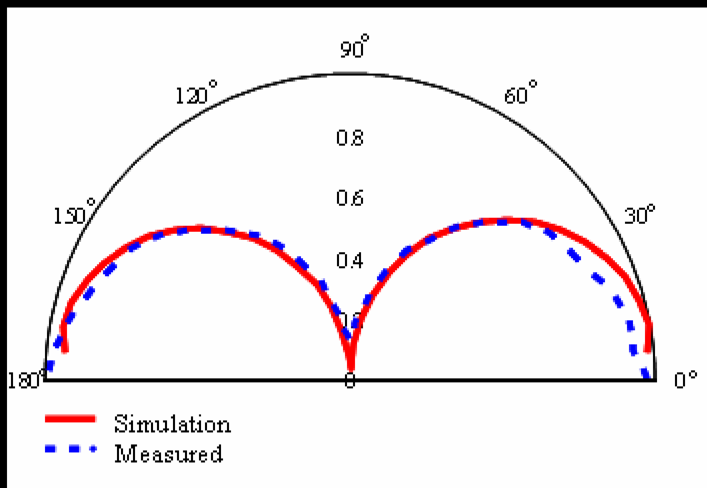


Fig. 1. MPC stack design and related benefits, including unidirectionality.

Collaboration with Dr. John Volakis and Mr. Jeff Kula (OSU)

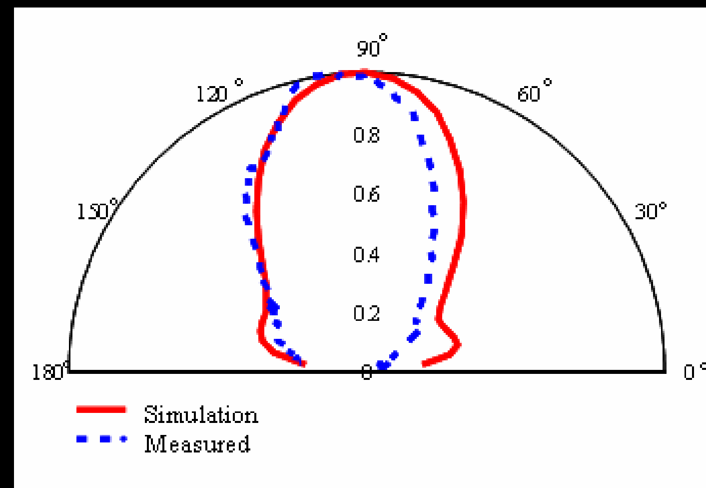
Miniature Antennas
(S-, Ku-/Ka-band: TRL 3)

S-Band



Surface-to-Surface

Ku/Ka-Band



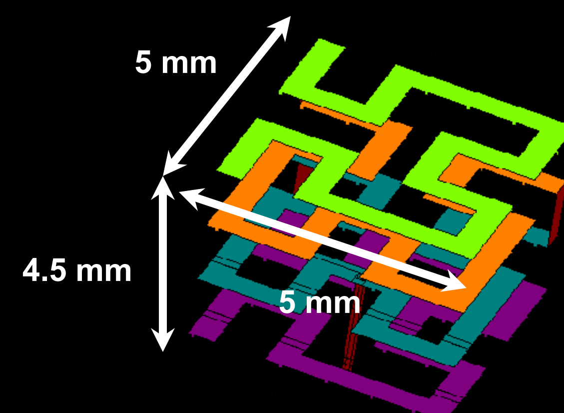
Surface-to-Orbit

<u>Benefits</u>

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

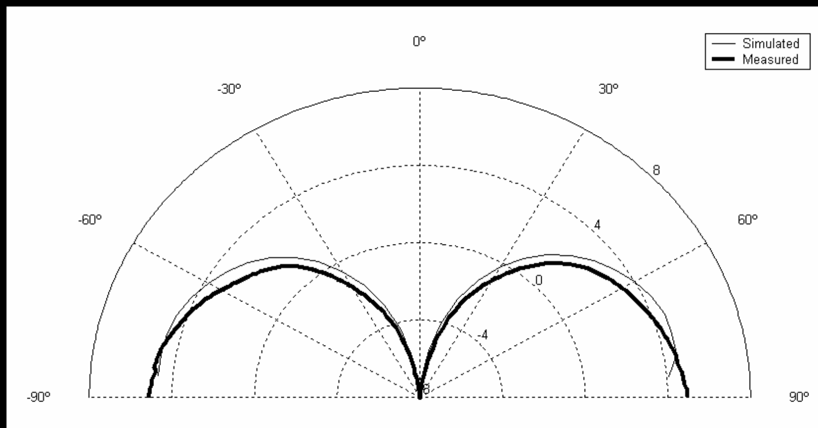
<u>Potential Applications</u>

- Sensors/probes
- Robotic rovers
- Astronaut EVA

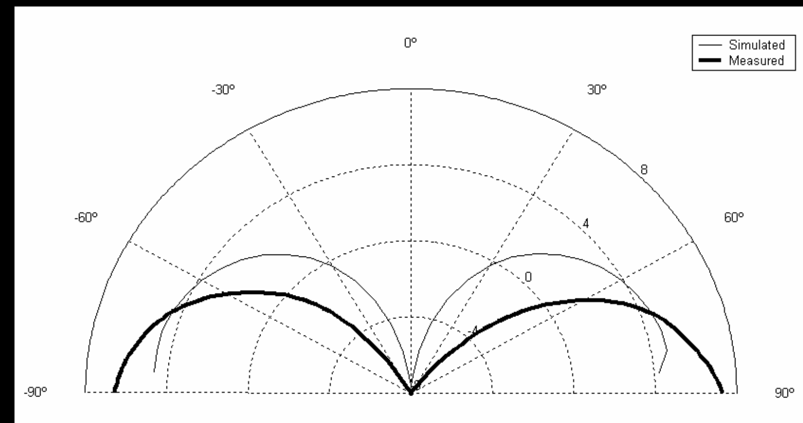


Folded Hilbert Curve Fractal Antenna

Miniature Antennas
(S-band: TRL 3)



E-plane Pattern



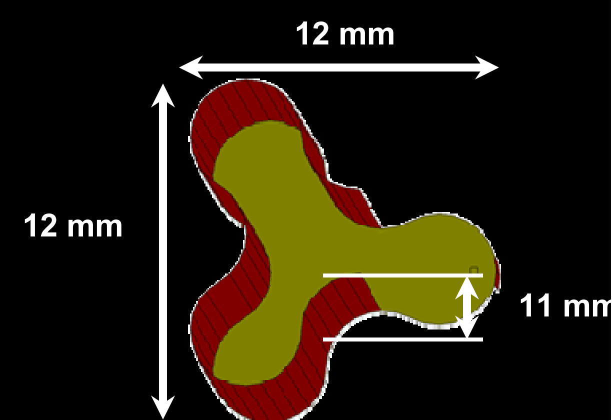
H-plane Pattern

<u>Benefits</u>

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

<u>Potential Applications</u>

- Sensors/probes
- Robotic rovers
- Astronaut EVA

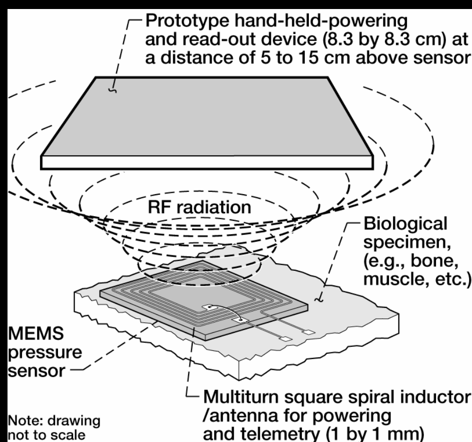


Compact Microstrip Monopole Antenna

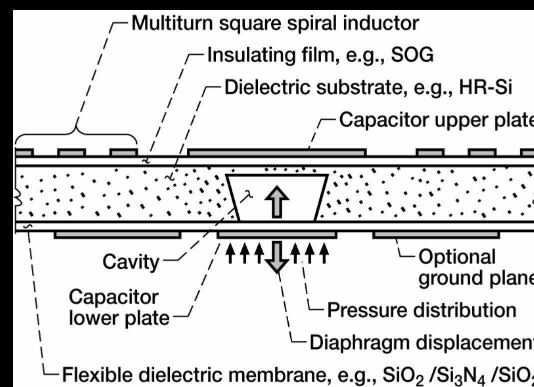
RF Telemetry System for an Implantable Bio-MEMS Sensor
(TRL 3-4)

- NASA seeks to develop telemetry based implantable sensing systems to monitor the physiological parameters of humans during space flights

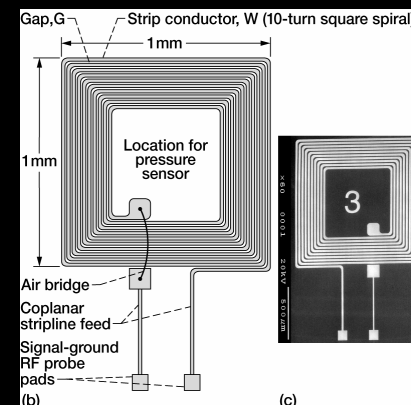
- A novel miniature inductor and pick-up antenna for contact-less powering and RF telemetry from implantable Bio-MEMS sensors has been developed.



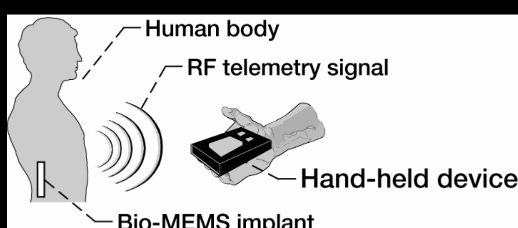
Contact-less powering and telemetry concept



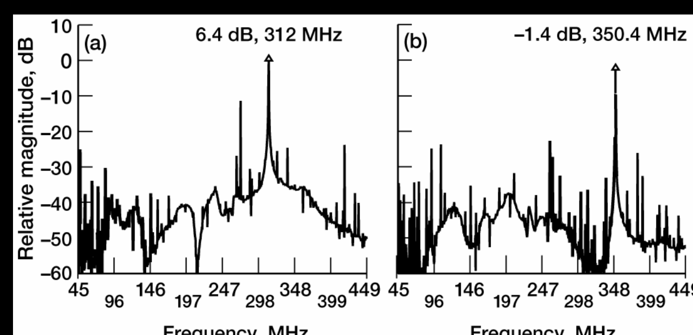
Schematic of a capacitive pressure sensor.



Schematic of miniature spiral inductor on SOG/HR-Si wafer and Photomicrograph of inductor/antenna.



Contact-less powering and telemetry application in biosensors



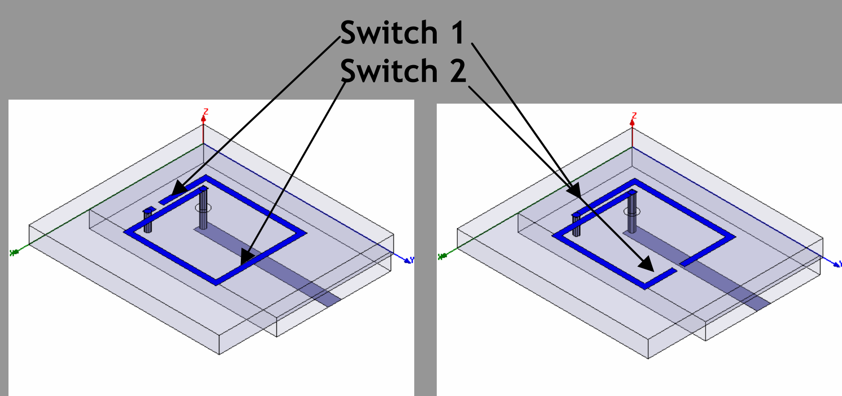
Measured received relative signal strength as a function of frequency. (a) Pick-up antenna at a height of 5 cm. (b) Pick-up antenna at a height of 10 cm.

Reconfigurable Antennas
For High Data Rate Multi-beam Communication

PI: Prof. Jennifer Berhard, U. Illinois, Grant # NAG3 2555

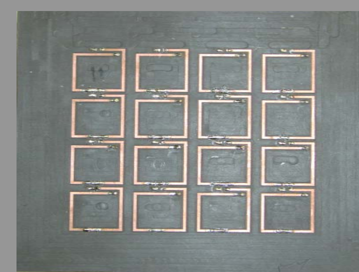
Target Technology:
Reconfigurable antenna elements capable of producing multiple beams, multiple frequencies, and array scan angles from broadside to horizon. Intended for inter-satellite, satellite-mobile and satellite-ground communication with a single array.

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

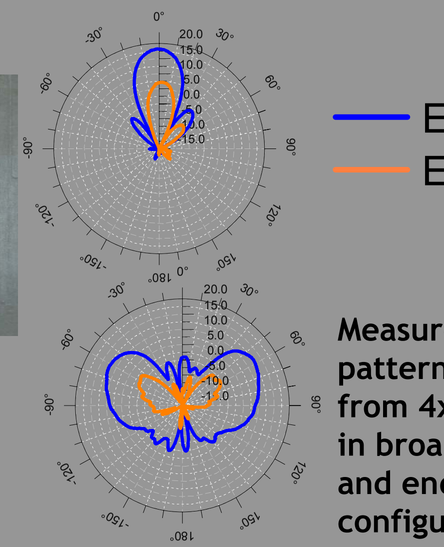


Feed through ground plane opening with via from Reverse side 50Ω microstrip line

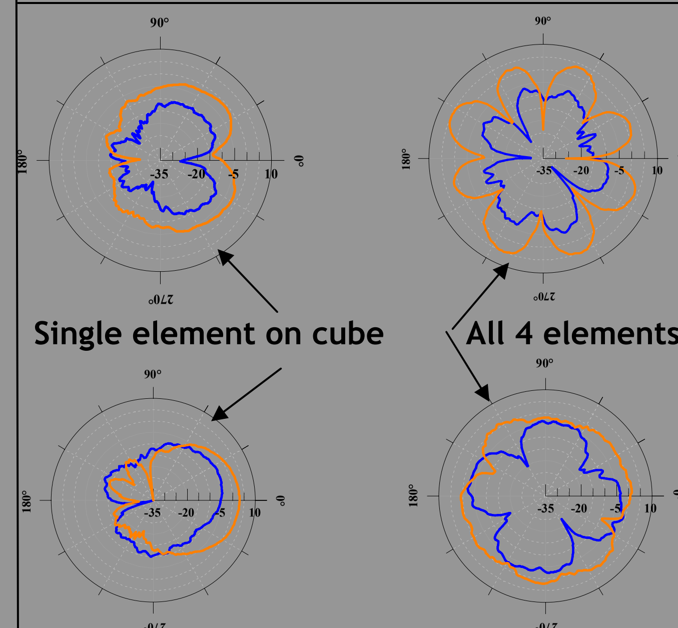
IC Compatible Prototype Square Element For monolithic MEMS integrated fabrication

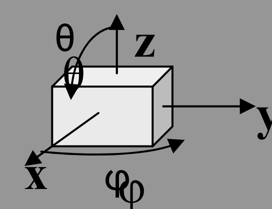


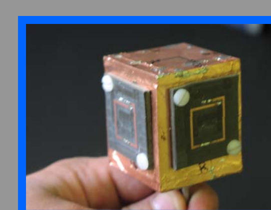
Reconfigurable antenna array (with 16 shorting wire switches)



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







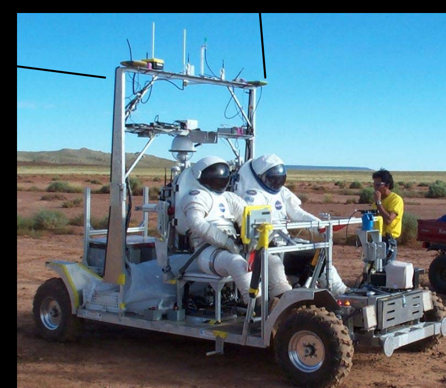
Human/Rover Application

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.

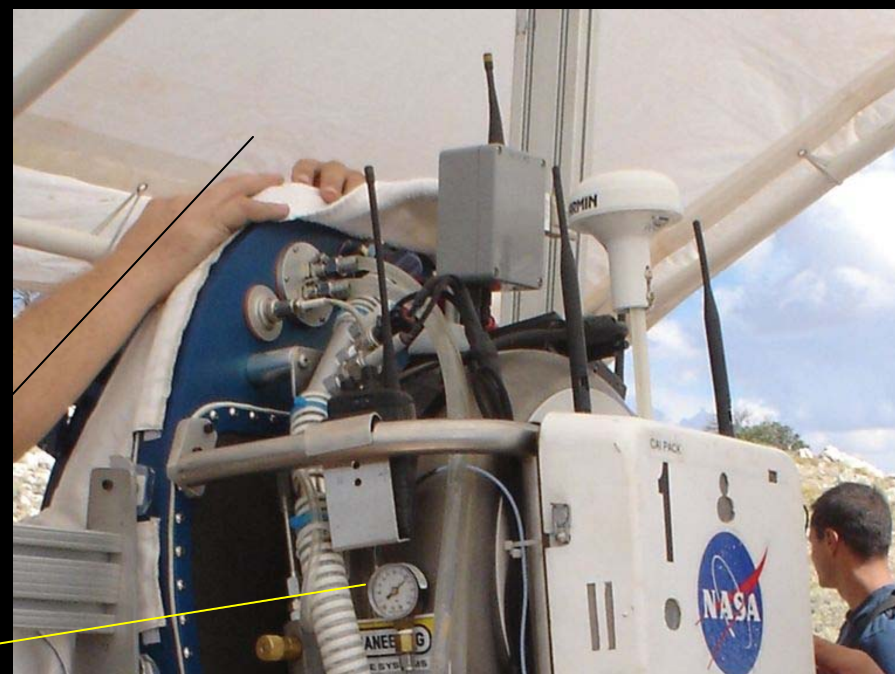
D-RATS Antenna Survey

SCOUT Rover Antenna Platform



D-RATS Antenna Survey

Voice Repeater System
VHF Omni Antenna (1)
UHF Omni Antennas (3)



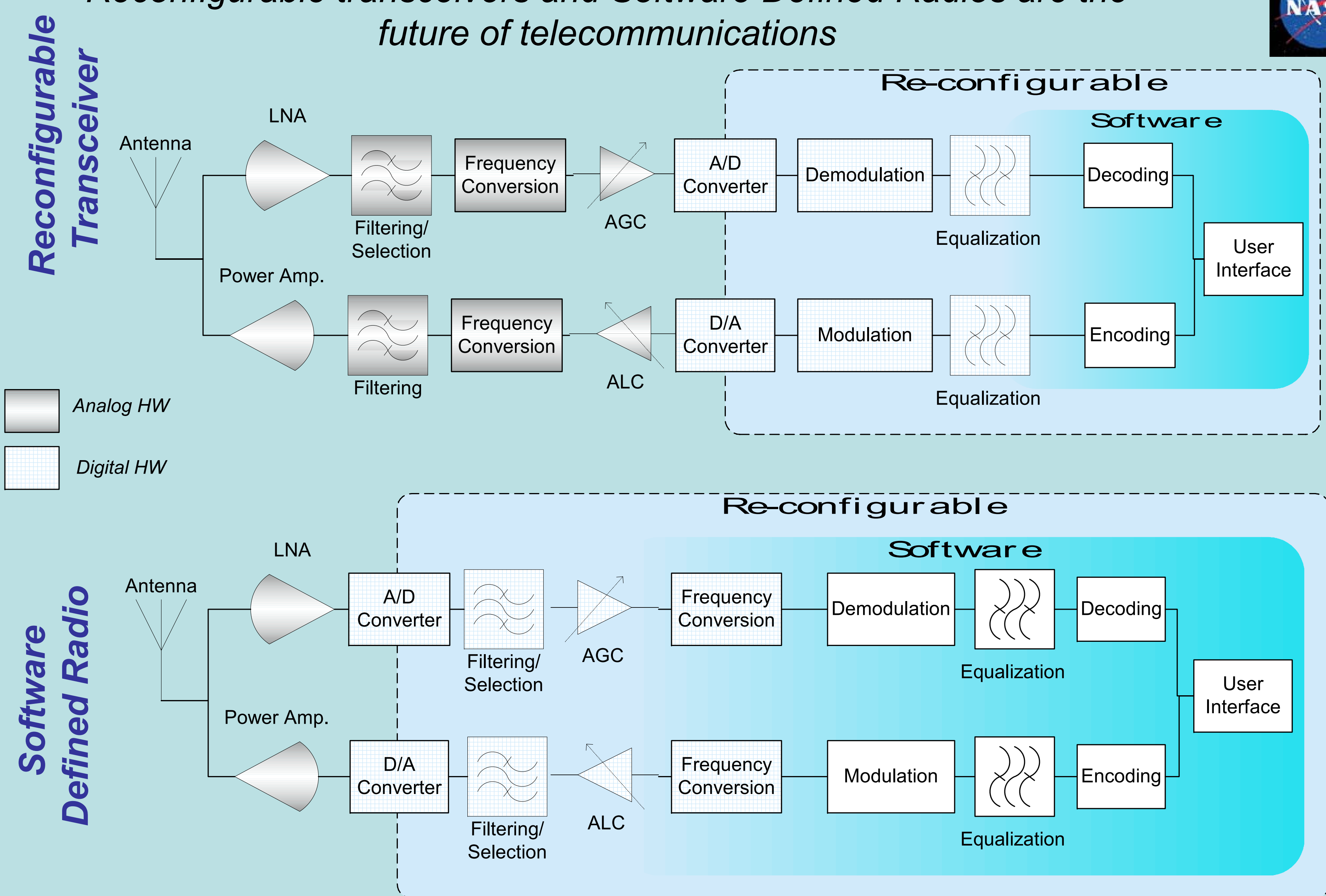
Spacesuit Antennas

D-RATS Antenna Survey

Suit Subject working at Science Trailer

D-RATS Antenna Survey

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)