A REVIEW OF 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 from planetary surface-to-surface, surface-to-orbit 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, proximity (i.e., short distance) 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. In contrast, trunk-line communications to a centralized habitat on the surface and back to Earth (e.g., relays, satellites, and landers) will necessitate high gain, low mass antennas such as novel inflatable/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 last few years, NASA Glenn Research Center has been heavily involved in the development and evaluation of candidate antenna technologies with the potential for meeting the aforementioned requirements. These technologies range from electrically small antennas to phased arrays and large inflatable antenna structures. A summary of these efforts will be discussed in this paper. NASA planned activities under the Exploration Vision as they pertain to the communications architecture for the Lunar and Martian scenarios will be discussed, with 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.

A Review of Antenna Technologies for Future NASA Exploration Missions

Félix A. Miranda*, James A. Nessel, Robert R. Romanofsky and Roberto J. Acosta
NASA Glenn Research Center, Cleveland, OH 44135, USA

*E-mail: Felix.A.Miranda@nasa.gov
Tel: 216-433-6589

12th Ka and Broadband Communications Conference
Naples, Italy
September 27-29, 2006

Outline of Presentation

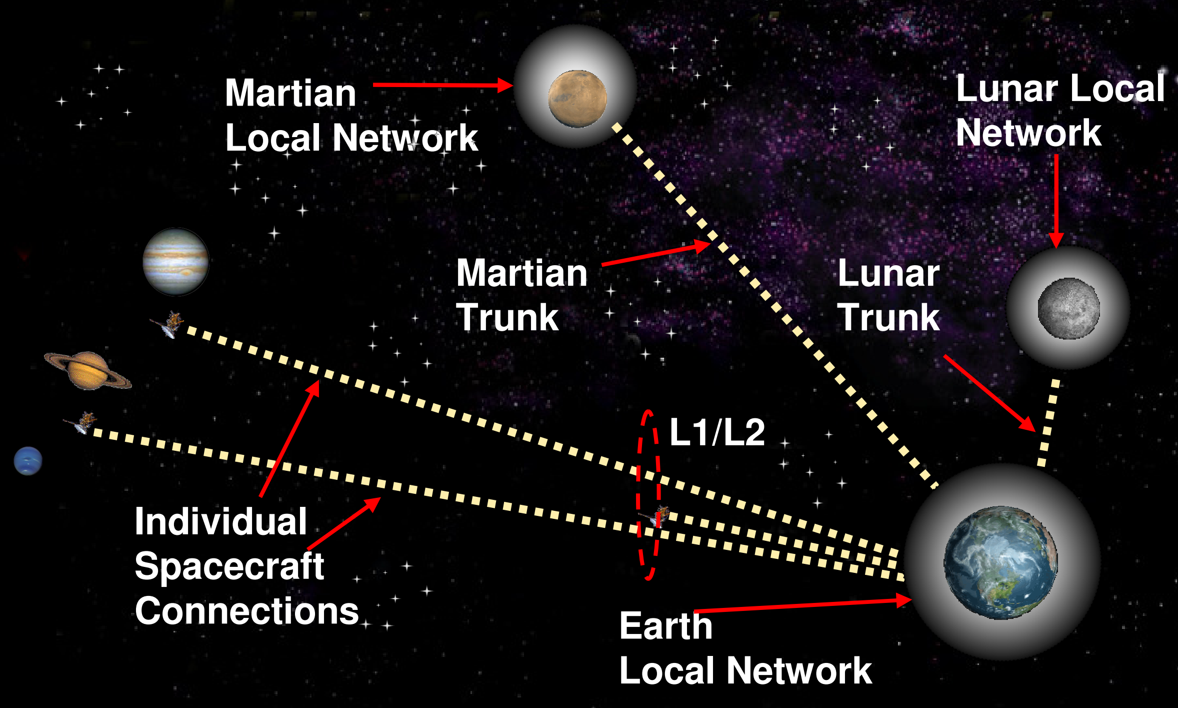
- The Vision for Space Exploration
- Communications Architecture for Exploration
- Asset-Specific Communications Requirements
- Summary of Relevant Antenna Technologies
- Conclusions

A Bold Vision for Space Exploration

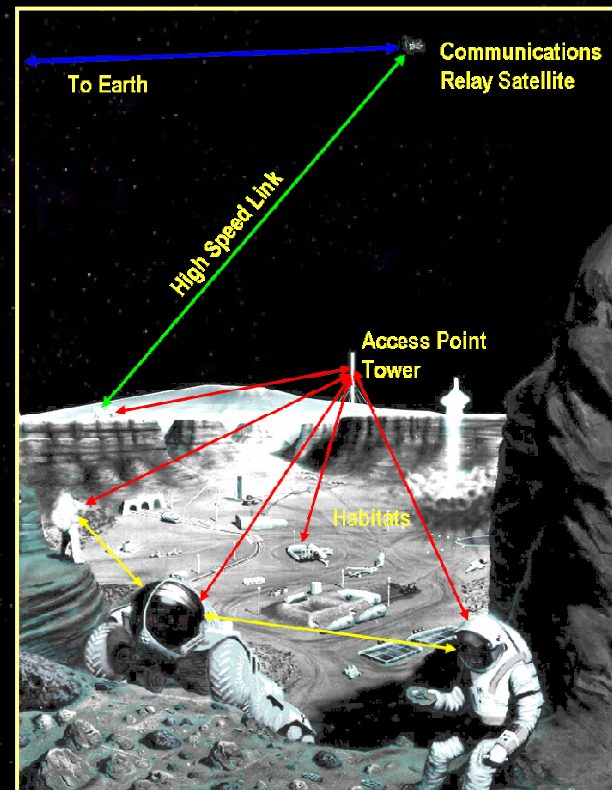
- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014 (goal of 2012)
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable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

Communications Architecture

Communications Network Architecture



Top Level Conceptual Communication Architecture ~2030: A "network of networks"



Communications architecture on the Lunar Surface

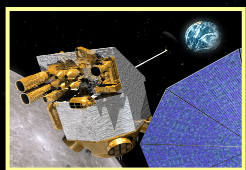
Ref 1: James S. Schier, John J. Rush, W. Dan Williams, and Pete Vrotsos, "Space Communication Architecture Supporting Exploration and Science: Plans and Studies for 2010-2030," AIAA 1st Space Exploration Conference, Jan. 2005.

Ref 2: Final Report Space Communications Architecture Working Group (SCAWG): NASA Space Communications and Navigation Architecture Recommendations for 2005-2030, 15 May 2006.

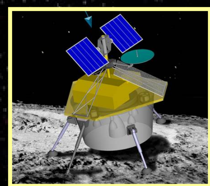
Ref: CRAI/APIO Roadmap Team, "Communication and Networking for Space Missions," Joint Workshop, Sec. 2.1, Sept. 2004.

Lunar and Mars Communications Assets

Lunar Network

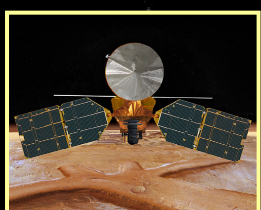


Lunar Reconnaissance Orbiter (LRO)



Robotic Lunar Lander

Martian Network



Mars Reconnaissance Orbiter (MRO)

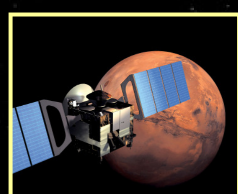
Arrival Date: March 10, 2006

Mars Odyssey

Arrived October 24, 2001

Mars Global Surveyor (MGS)

Arrived September 12, 1997



Mars Express (ESA)

Arrived December 25, 2003

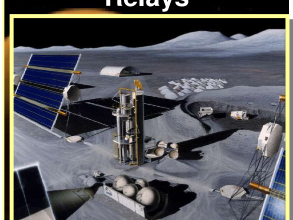
Characteristics of Communication Assets for the Lunar and Martian Networks

Communications Asset	Frequencies	Data Rates	Purpose
The Moon			
Lunar Reconnaissance Orbiter	S-band	125 to 256 bps	TT&C/Rx from Earth
	UHF/S-band	125 to 256 bps	Tx/Rx to Moon
	Ka-band	> 100 Mbps	Tx to Earth
Robotic Lunar Exploration Landers	S-band/Ka-band	TBD	Tx/Rx to Earth
	UHF	TBD	Surface Comm.
Mars			
Mars Reconnaissance Orbiter	X-band	300 kbps	Tx/Rx to Earth
	UHF	0.1 to 1 Mbps	Tx/Rx to Mars
	Ka-band	5 Mbps	Tx to Earth
Mars Global Surveyor	X-band	20 kbps	Tx/Rx to Earth
	UHF	128 kbps	Tx/Rx to Mars
	Ka-band	85 kbps (max)	Tx to Earth
Mars Express (ESA)	X-band	230 kbps	Tx to Earth
	S-band	< 2 kbps	Rx from Earth
	UHF	128 kbps	Tx/Rx to Mars
Mars Odyssey	X-band	128 kbps	Tx/Rx to Earth
	UHF	128 kbps	Tx/Rx to Mars

Asset-Specific Communications Nominal Specifications

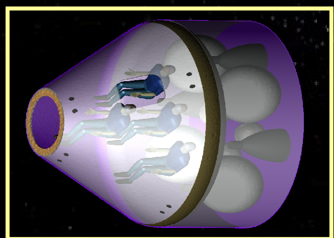
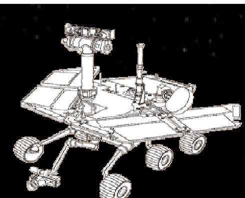
Antenna Technology Summary

Surface Communications Assets

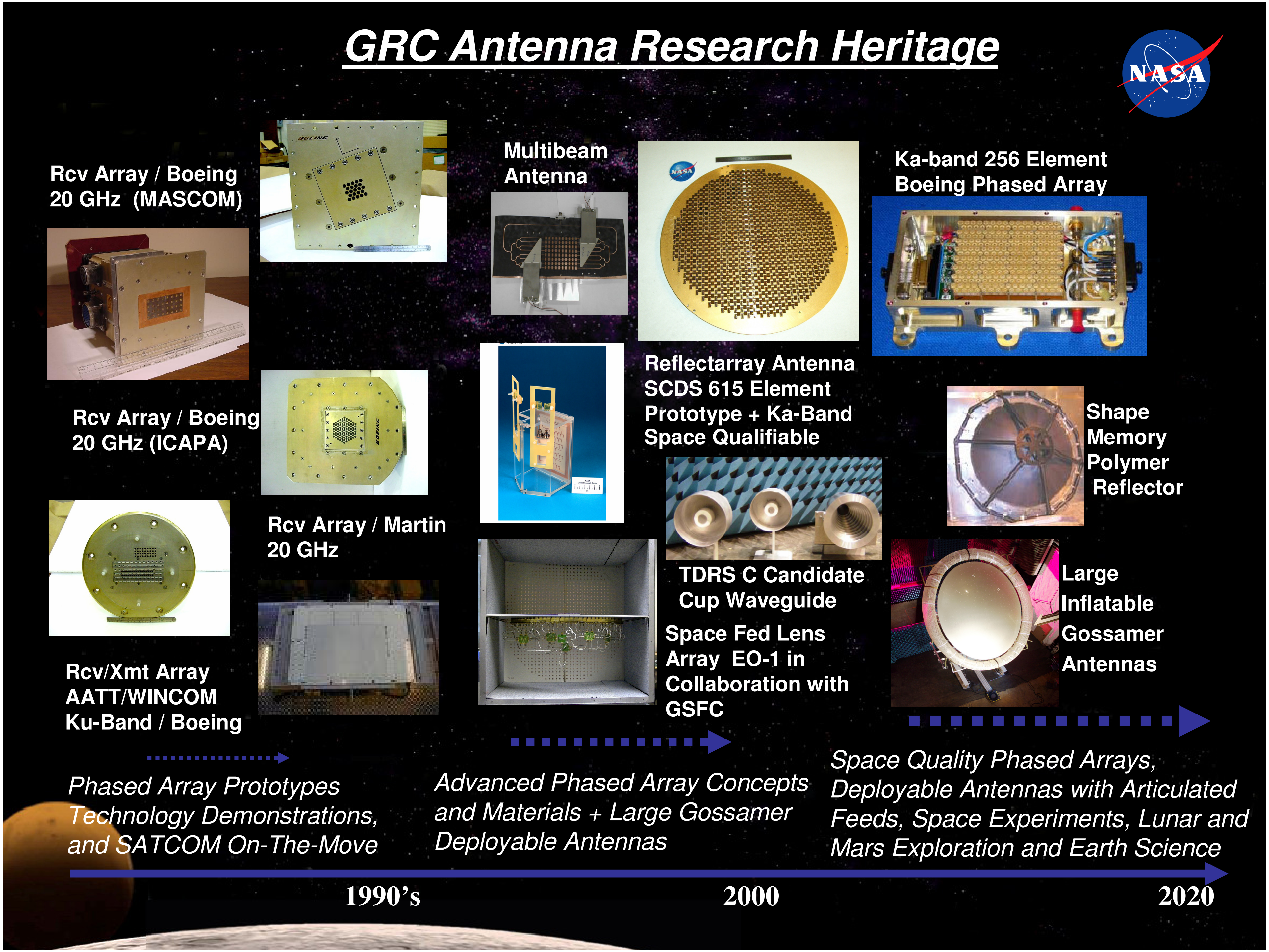
Surface/ Surface Communications	Potential Frequencies	Comments/Specs	Desirable Antenna Technologies
Astronaut EVA Suit 	**UHF/VHF** **S-band**	**<u>Data Services</u>** **Audio** — **8-64 kbps/channel (at least 4 channels)** **TT&C*** — **<100 Kbps** **SDTV Video** — **6 Mbps** **HDTV Video** — **19 Mbps** **Biomedical Control*** — **70 kbps** **Biomedical Monitoring*** — **122 kbps** **Limited power/space availability ; UHF/S-Band surface comm. frequencies** ***Must be reliable links** ➢ 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 Radio (SDR) to reduce size, weight and power (SWaP)***	• Miniature Antennas • Multi-directional (to support mobility) • Wearable Antennas • Dipole/Monopole (omni-directional coverage)
	**UHF/VHF** **S-band**	➢ 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).***	• Miniature Antennas • Omni antennas • Phased Arrays (pitch/roll compensation)
	**UHF/VHF** **S-band**	➢ 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.***	• Miniature Antennas • Dielectric Resonator Antennas • Wideband Antennas • Solar Cell Integrated Antennas ▪Retro-directive Antenna
Habitat/Surface Relays 	**HF (OTH Propagation)** **S-band** **X-band**	➢ 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)***	• Deployable Antennas • Multi-directional coverage (to support mobility) • Smart/reconfigurables • Multi-beam antennas (to support connectivity to different nodes) • Electrically & physically small antennas

Antenna Technology Summary

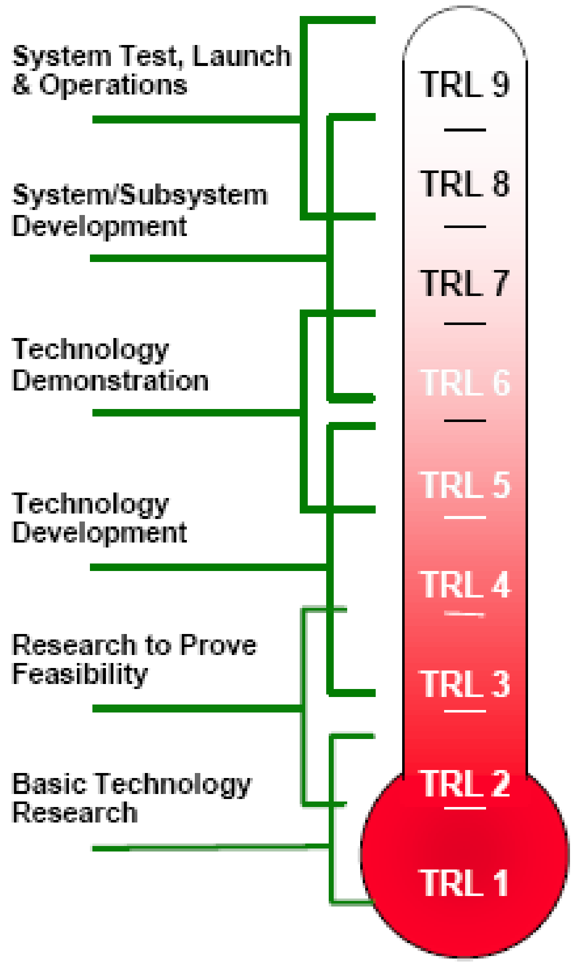
Space Communication Assets

Surface/Orbit Communications	Potential Frequencies	Comments/Specs	Desirable Antenna Technologies
CEV 	S-band X-band Ku/Ka-band	➢ Robotic Lunar Exploration Program (RLEP-1,2) ➢ Lunar Reconnaissance Orbiter (LRO) (RLEP-1) ➢ Crew Launch Vehicle (CLV) ➢ Crew Exploration Vehicle (CEV) ➢ *Antenna Requirements: Conformal, Reconfigurable or Multiband antennas, phased arrays (most likely S-band for Initial CEV, with omni or patch antennas).*	➢ Phased Arrays ➢ Wideband/multiband and conformal antennas ➢ Frequency selective surface (FSS) antennas
Satellites Systems 	UHF S-band X-band Ku/Ka-band	➢ Relay satellites (around the moon (e.g., LRO after its initial prospecting mission, it 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*	➢ Gimbaled Dish ➢ Phased Arrays ➢ Deployable Antennas ➢ Multi-Beam antennas ➢ High Gain Antennas
Rovers 	UHF S-band	➢ 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.	➢ Miniaturized antennas ➢ Phased Arrays
	UHF	➢ 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.*	➢ Miniature Antennas ➢ Solar Cell Integrated ➢ Antennas ➢ Patch antennas ➢ Retro-directive antennas

Relevant Antenna Technologies


GRC Antenna Research Heritage
NASA
Rcv Array / Boeing
20 GHz (MASCOM)
Rcv Array / Boeing
20 GHz (ICAPA)
Rcv/Xmt Array
AATT/WINCOM
Ku-Band / Boeing
Rcv Array / Martin
20 GHz
Multibeam
Antenna
Reflectarray Antenna
SCDS 615 Element
Prototype + Ka-Band
Space Qualifiable
TDRS C Candidate
Cup Waveguide
Space Fed Lens
Array EO-1 in
Collaboration with
GSFC
Ka-band 256 Element
Boeing Phased Array
Shape
Memory
Polymer
Reflector
Large
Inflatable
Gossamer
Antennas
Phased Array Prototypes
Technology Demonstrations,
and SATCOM On-The-Move
Advanced Phased Array Concepts
and Materials + Large Gossamer
Deployable Antennas
Space Quality Phased Arrays,
Deployable Antennas with Articulated
Feeds, Space Experiments, Lunar and
Mars Exploration and Earth Science
1990's
2000
2020

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)

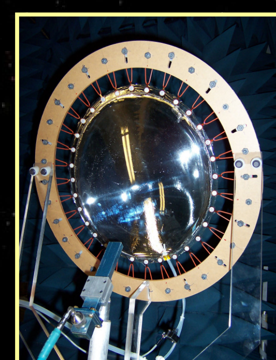
Benefits
- Reduced mass (~1 kg/m^2)
- Low fabrication costs
- High packaging efficiencies (as high as 50:1)
- Proven performance at S-Band & L-Band frequencies

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

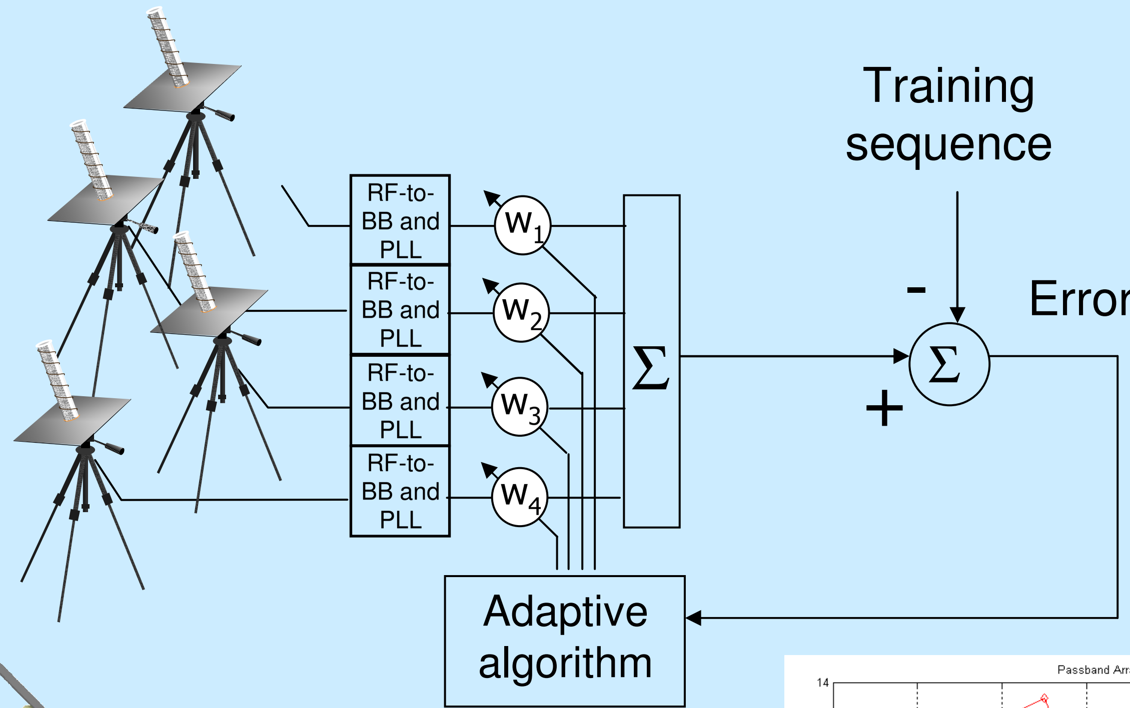
2.5 m “Beach Ball” Antenna

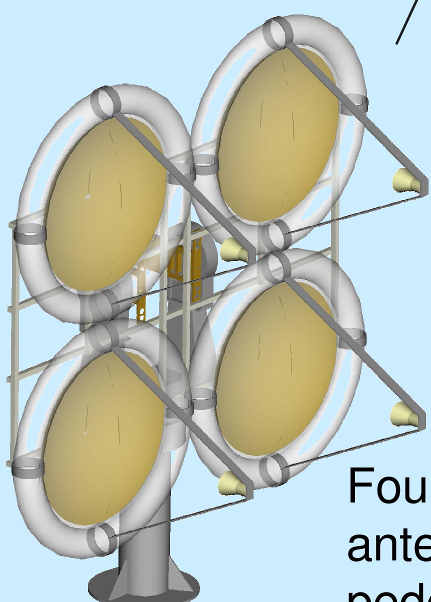
4 x 6 m offset parabolic



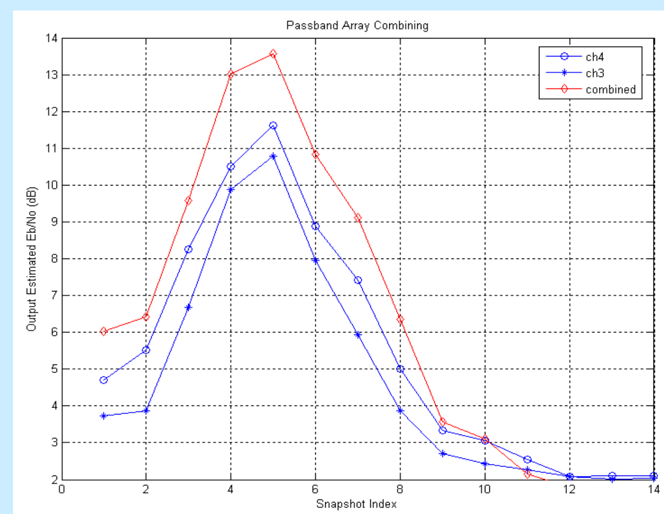
0.3 m Parabolic Antenna

“Terrestrial” Deployable Antennas





Four 1-meter inflatable membrane antennas under assembly and pedestal array concept



4 Element Inflatable Antenna Array

August 2005

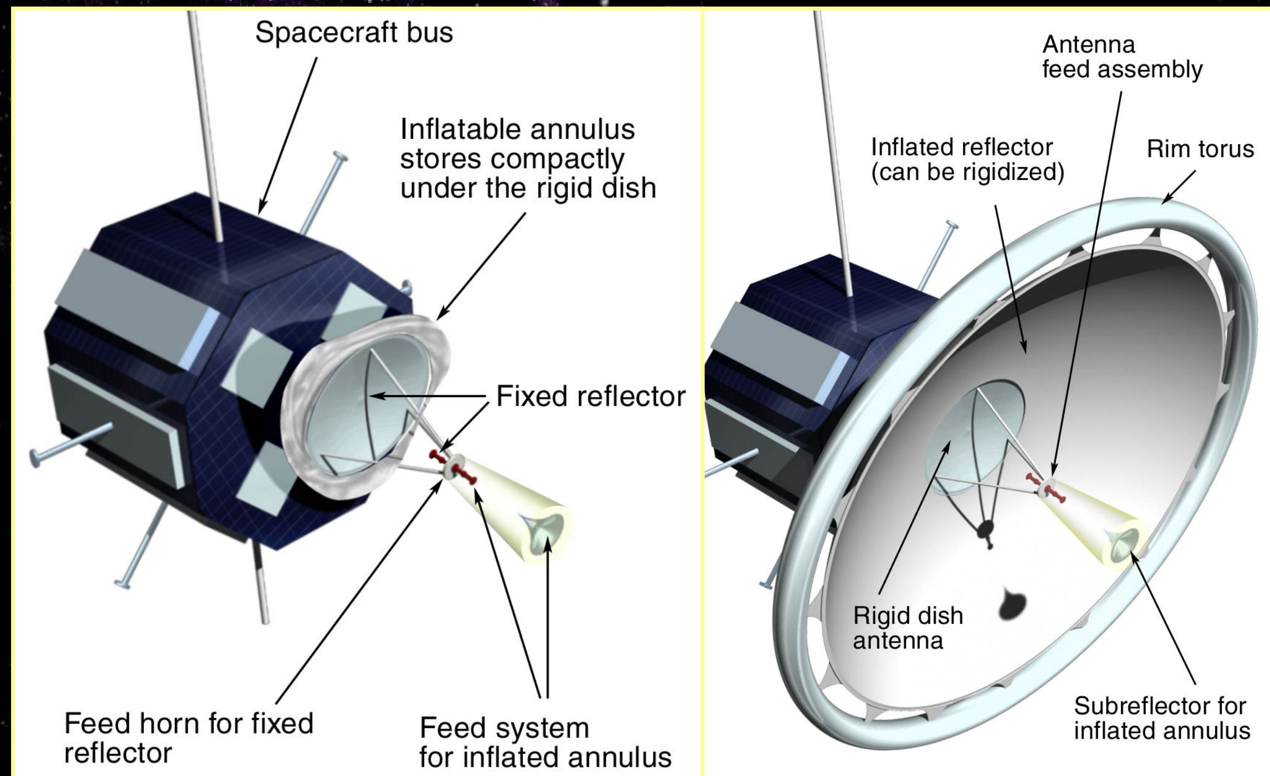
- Georgia Tech "GCATT" building adaptive array algorithm verification Experiment with the SAC-C satellite August 22-25, 2005

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**

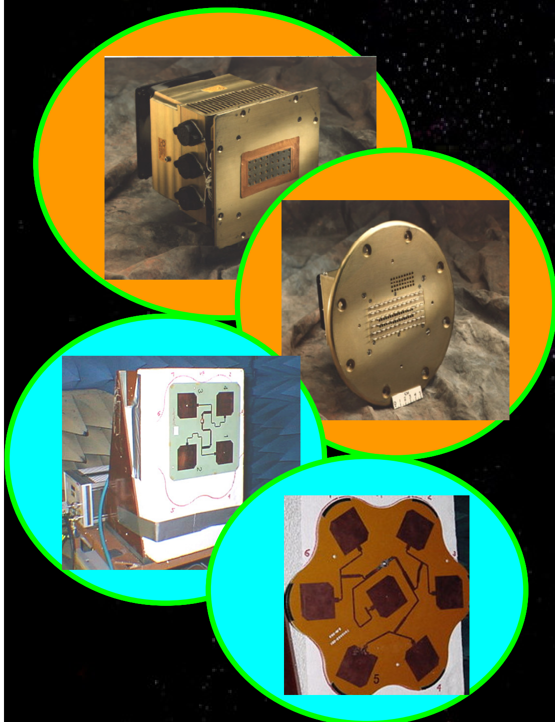


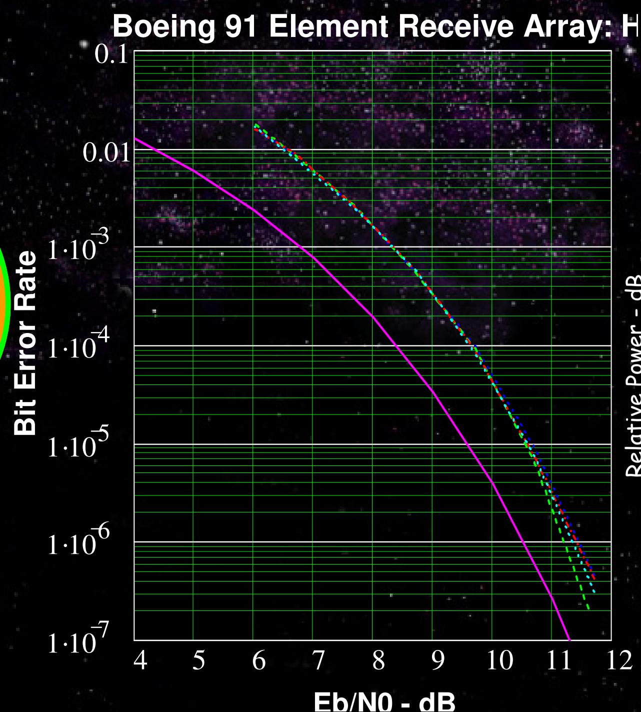
JHU/APL under NASA Grant

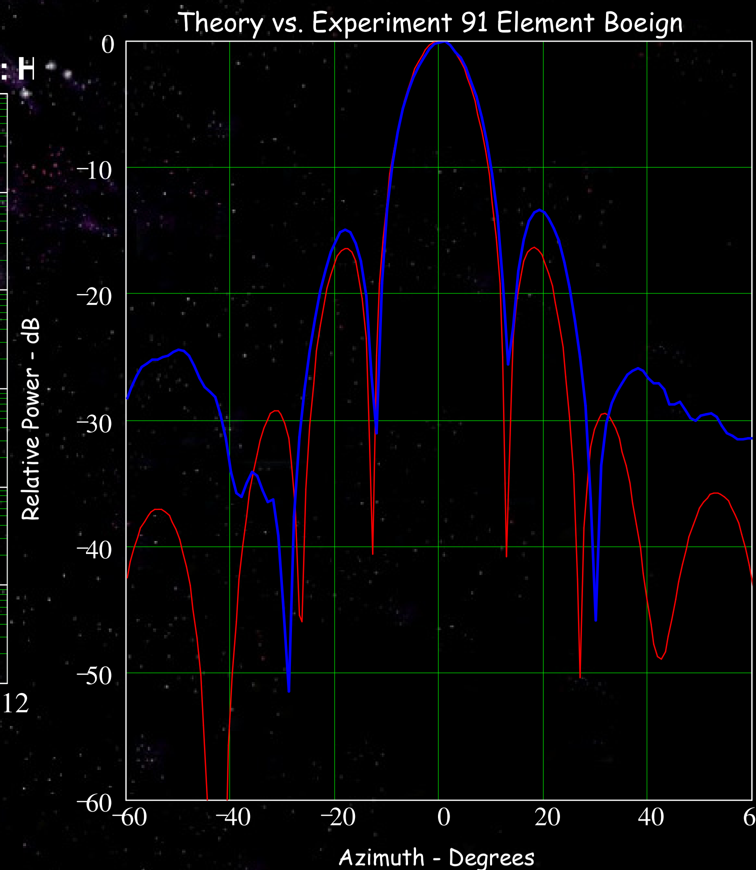
(1) Low cost fabrication and inflation of an annulus antenna
(2) Overall surface accuracy 1 mm
(3) Negligible gravity effects
(4) Elimination of large curve distortions across the reflector surface (i.e. Hencky curve)

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

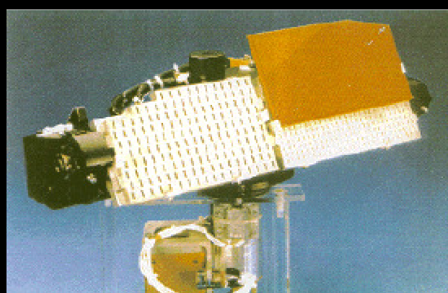
Issues
- Low MMIC efficiency (thermal management problems)
- Cost per module
- FOV (limited to +/- 60°)

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

GRC Low Cost Electrically Steerable Array Antenna Road Map

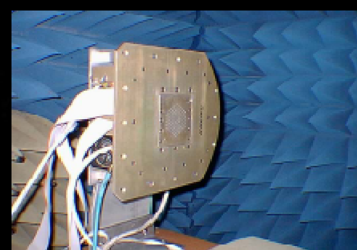
1990 - 1998

Past Significant GRC Ka-band phased array developments



Mechanically steered Array proof-of-concept

32 element breadboard proof-of-concept



91 element breadboard proof-of-concept

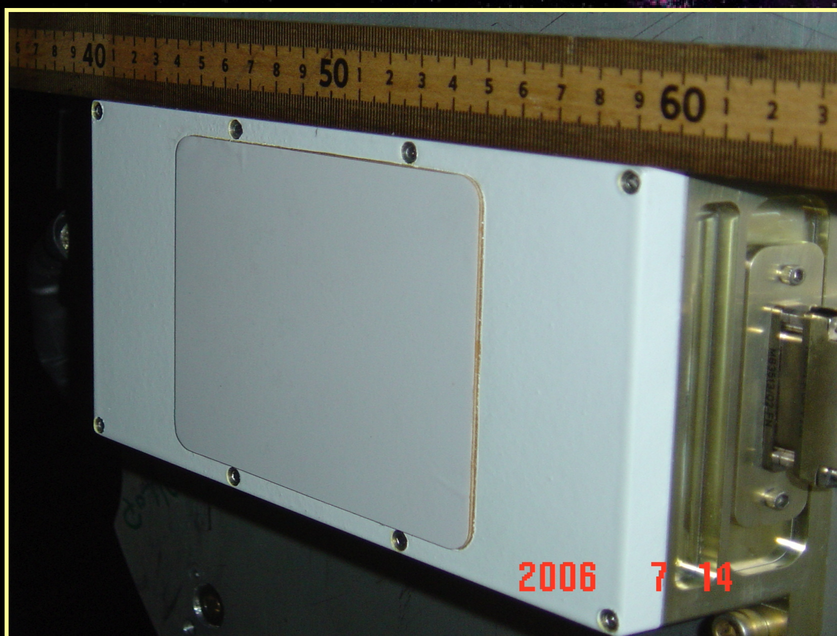
Parameter	Forward Link	Return Link
Ka-band Frequency Plan	30	20
Channel Bandwidth	9.6Kbps (NB) 1.5Mbps (WB)	9.6 – 128 Kbps (NB) 1.5Mbps (WB)

2000 - 2006

Parameter	Forward Link	Return Link
Ka-band Frequency Plan	22.555 – 23.545	25.545 – 27.195
Channel Bandwidth	50 MHz	650 MHz

- 1990-1998 : Funding Source ACTS
- 2000-2003 : Funding Source SCDS

256-Element Ka-Band Phased Array Antenna (PAA)



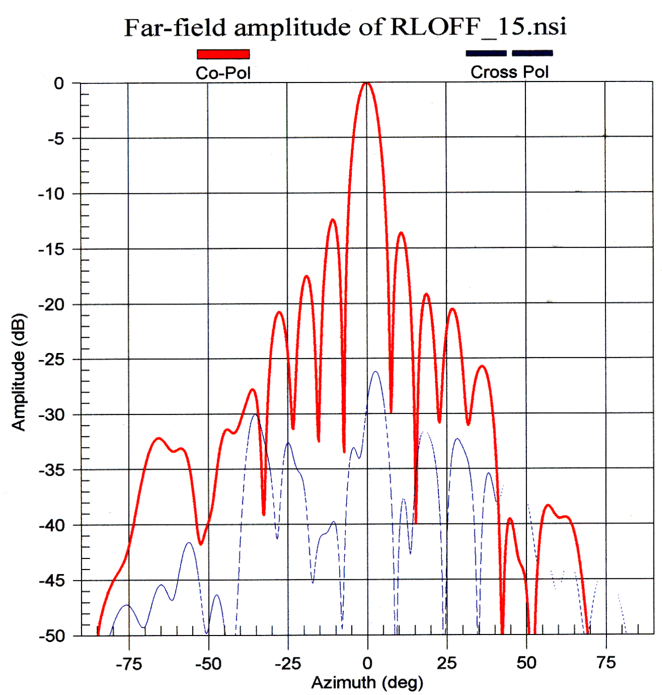
256 Elements Array (Boeing)

Summary Array Specification (Boeing)

Array Number of Elements	256 Elements
Frequencies	25.5-27.5 GHz
Bandwidth	> 1 GHz
Gain (CP)	28 dBi
Antenna EIRP	Peak 36.5 dBW @ 60 Degrees 33 dBW
Antenna 3 dB - Beam width	Nominal 5 Degrees
RF Input Drive Level	130 mW (1 beam)
Array Total DC Power	90 Watts (1 beam)
DC Power Supply	+28 V (± 7V)

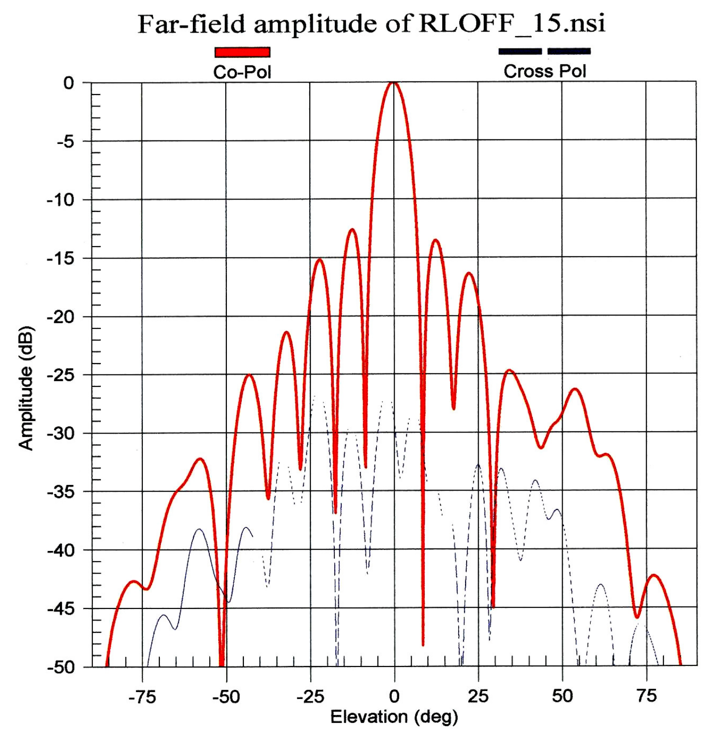
Two Principal Planes Cuts Antenna
(Beam 1)

LHCP w/RHCP off, phi = 0
(Measured by Boeing)



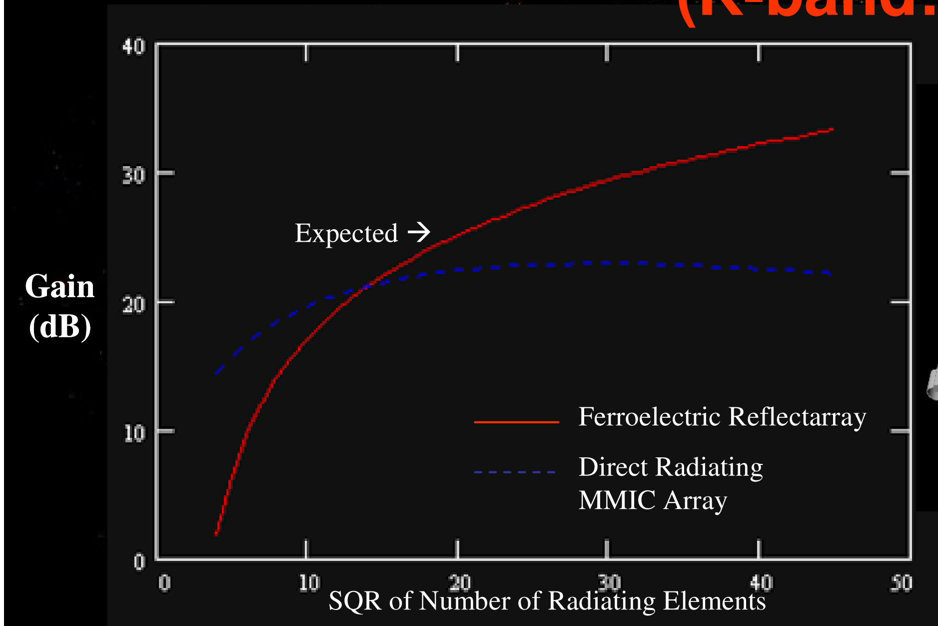
- AR < 1.1
- Directivity (estimated from pattern measurements) : 27.6 dBi
- Directivity (predicted no M-coupling) : 28.2 dBi
- Beamwidth: 6.7 deg

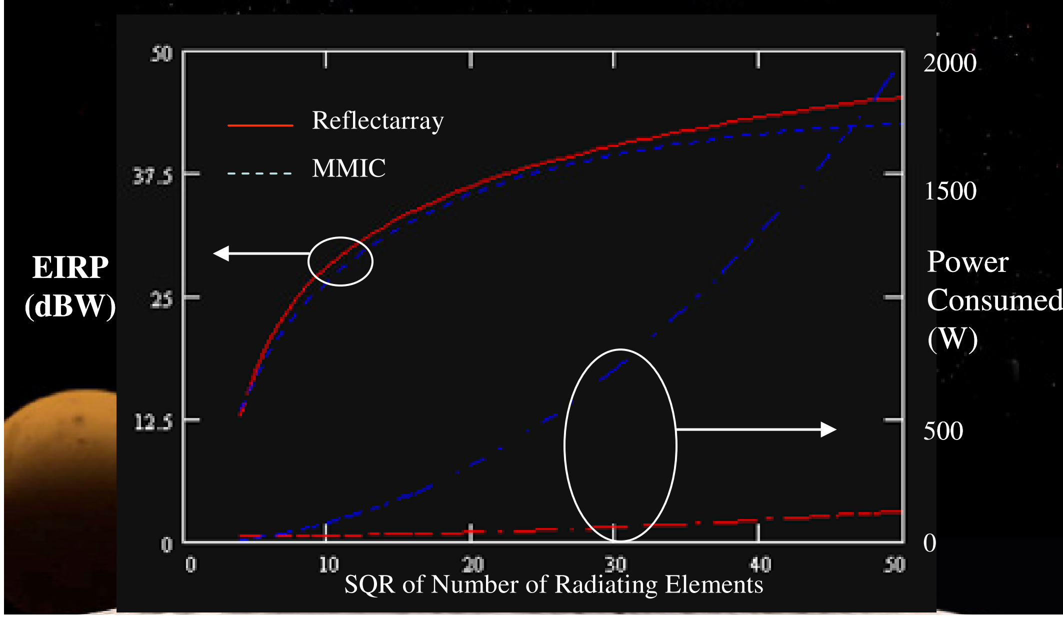
LHCP w/RHCP off, phi = 90
(Measured by Boeing)

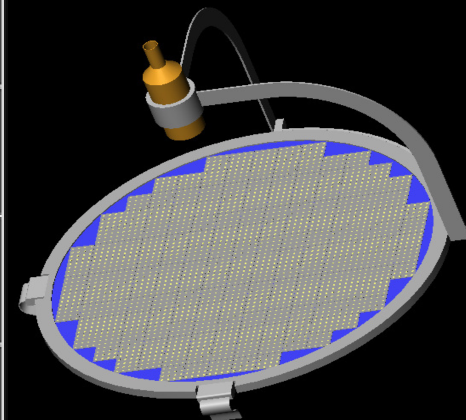


- AR < 1.1
- Directivity (estimated from pattern measurements) : 27.6 dBi
- Directivity (predicted no M-coupling) : 28.2 dBi
- Beamwidth: 7.7 deg

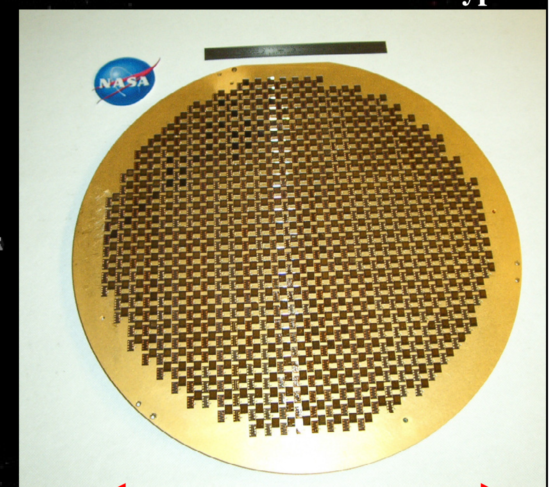
Ferroelectric Reflectarray Development
(K-band: TRL 3)



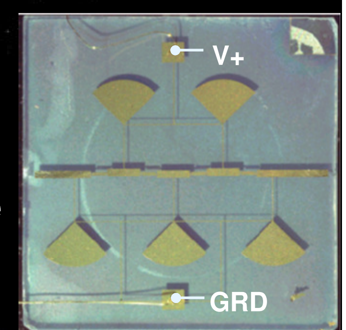




19 GHz 615 Element Prototype



≈ 28 cm Active Diameter

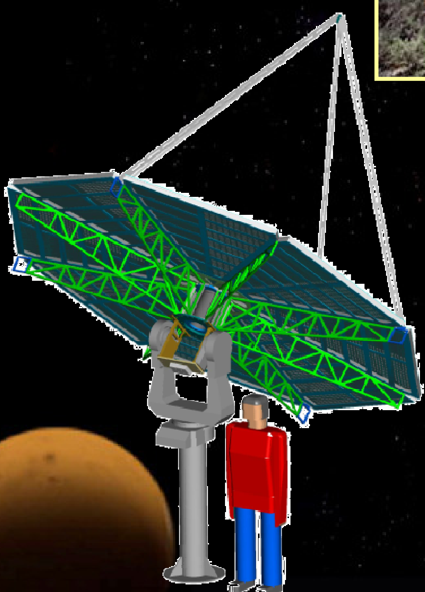


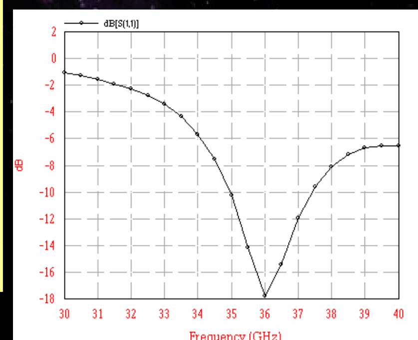
Benefits
- High efficiency
- Zero manifold loss
- Electronically steerable
- Lightweight, planar reflector

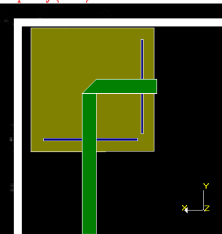
Potential Applications
- Satellite Antenna Systems
- Ground-based Deep Space Network Array

Next Generation Deep Space Network Concept

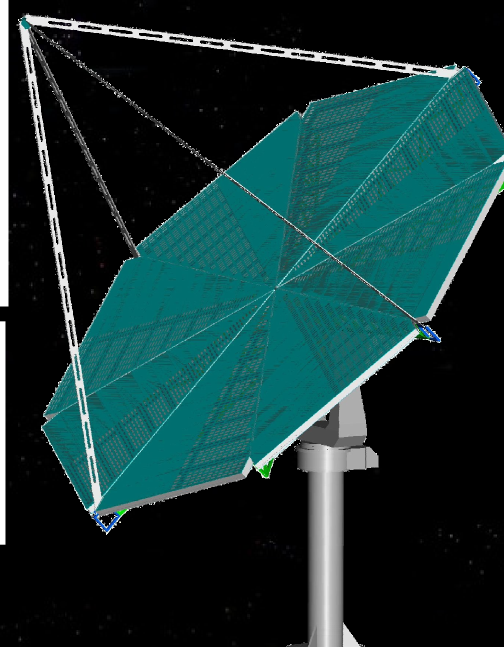
- Achieving required Ka-band surface tolerance difficult for very large apertures
- Large antenna cost proportional to (diameter)$^{>2}$
- Advances in Digital Signal Processing make arraying a large number of “small” antennas feasible







GRC Antenna Farm Concept
Based on Reflectarray Technology

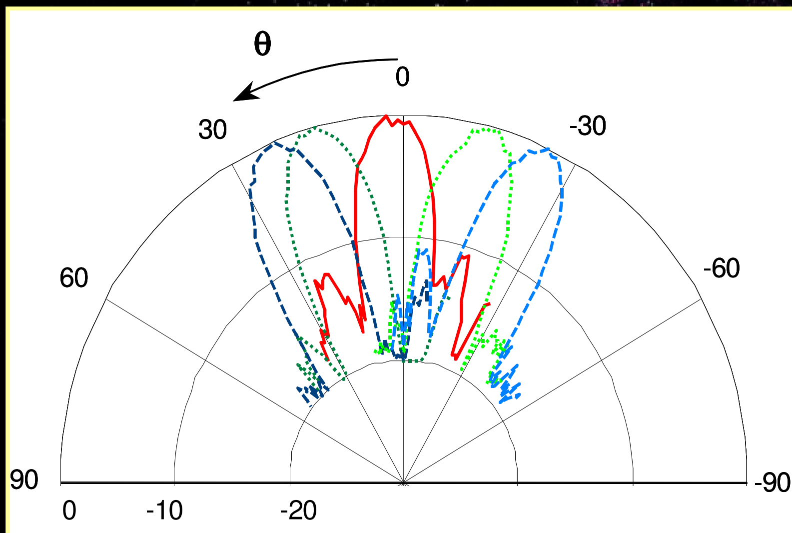


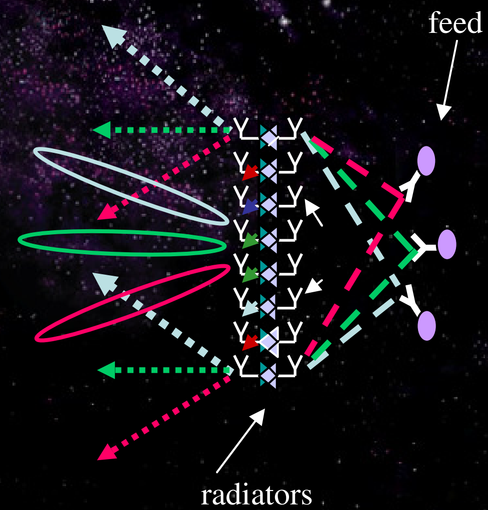
Flat panels containing printed microstrip patch radiator arrays assembled into circular aperture to save weight and manufacturing cost. Benefits cascade because of simplified gimbal drive systems and reduced maintenance

4 m prototype

Multi-Beam Antennas

(S-, Ka-band: TRL 4)



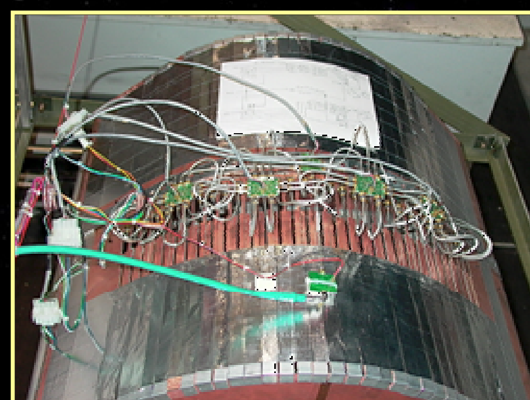


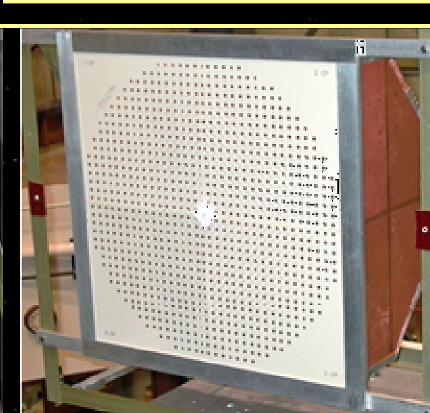
Benefits

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

Potential Applications

- Smart Antenna Systems
- Ground-based Communications (*i.e.*, Habitat, Relays)
- Satellite Constellations





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

SMALL ANTENNAS
(TRL 1-3)

Antenna Technologies for Future NASA Exploration Missions

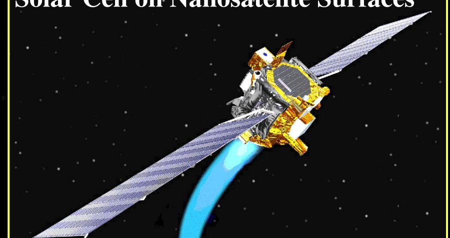
Description and Objectives:

- Develop new design concepts and candidate miniature antenna structures capable of supporting the communication needs of future Lunar and Martian surface exploration activities.
- Develop compact, self-powering, self-oscillating communications package utilizing miniature antenna development effort.
- Perform trade-off studies among in-house miniature antenna designs and state-of-the-art commercial off-the-shelf (COTS) antennas for Exploration Missions.
- Develop processing algorithm for a randomly distributed network of Lunar surface sensors to enable a surface-to-orbit communication without the need of a Lunar surface base station.

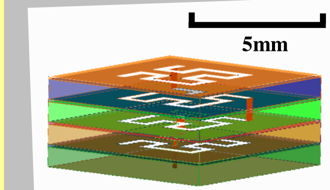
Application: Lunar Surface Exploration Missions

- **Robots and Rovers**
- **Surface Sensors/Probes**
- **Astronaut EVA**
- **Nanosatellites**

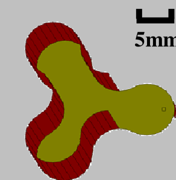
Solar Cell on Nanosatellte Surfaces



Technology Products:

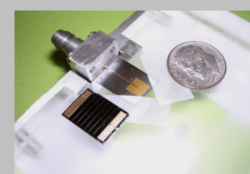


Folded Hilbert Curve Fractal Antenna

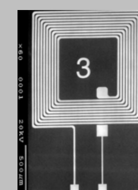


Compact Microstrip Monopole Antenna

TRL $_{in}$ = 2
TRL $_{out}$ = 3

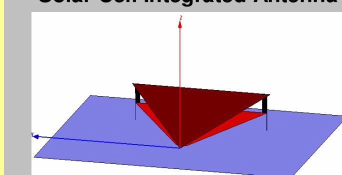


Solar Cell Integrated Antenna

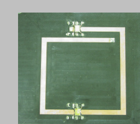


Miniaturized antenna for Bio-MEMS Sensors

TRL $_{in}$ = 2
TRL $_{out}$ = 3

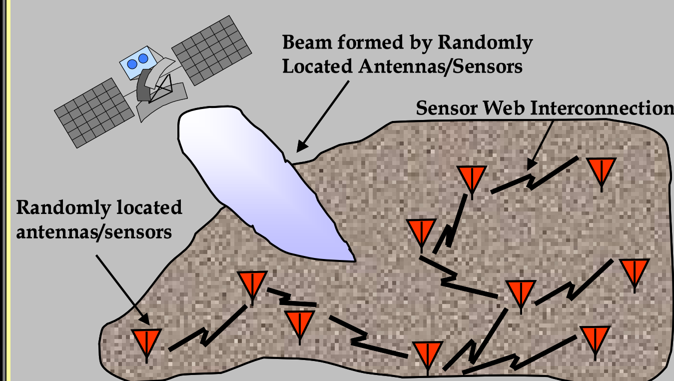


Two-layer Sector Miniature Antenna



MEMS Integrated Reconfigurable Antenna

TRL $_{in}$ = 2
TRL $_{out}$ = 3



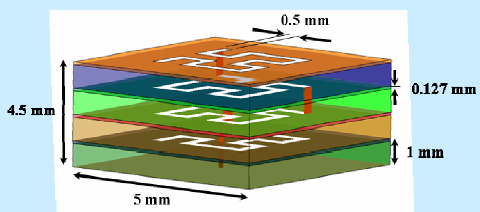
Random Sensor Network Array

TRL $_{in}$ = 2
TRL $_{out}$ = 3

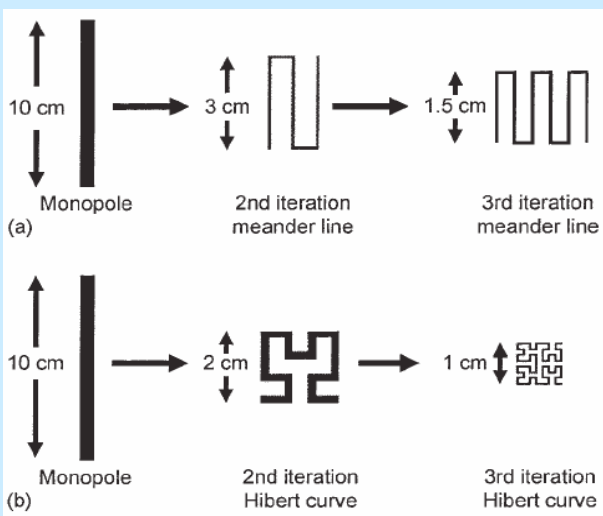
folded Hilbert Curve Fractal Antenna (fHCFA)

Design Concept:

- Fractal antenna geometry allows for unique wideband/multi-band operation due to pattern-repetitive nature of fractal shapes. Geometry also allows for antenna miniaturization, similar to meander lines, but with more efficient space utilization.
- Develop an antenna based on a 3rd order Hilbert curve geometry folded upon itself (multilayer) to further decrease antenna footprint.



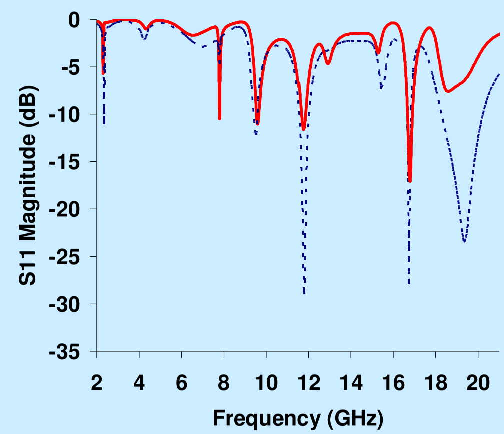
< λ/30 !

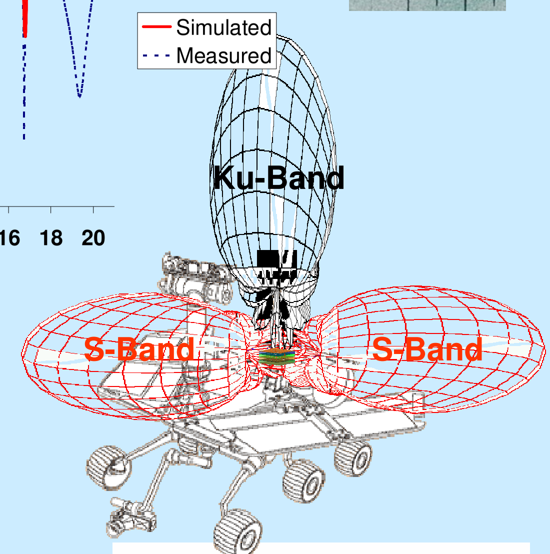


[1] James A. Nessel, Afroz J. Zaman, Félix A. Miranda, "A Miniaturized Antenna for Surface-to-Surface and Surface-to-Orbiter Applications," Microwave and Optical Technology Letters, Vol. 48, No. 5, May 2006, pg. 859-862

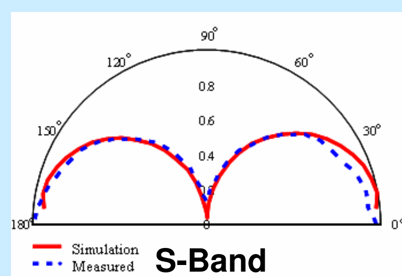
Results:

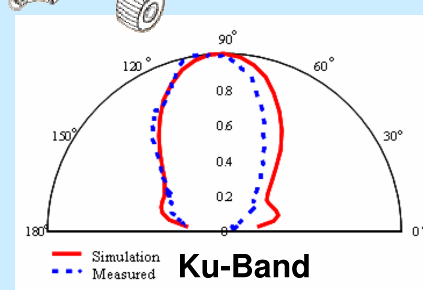
- fHCFA exhibits multi-resonant behavior.
- Two modes of operation with optimized radiation pattern diversity for surface-to-surface and surface-to-orbit communications at relevant frequencies without switching.





TRL $_{in}$ = 2
TRL $_{out}$ = 3



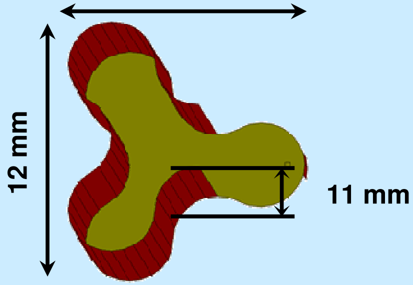


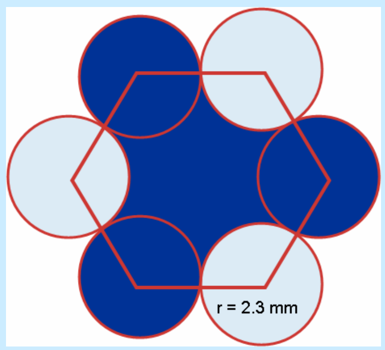
Compact Microstrip Monopole Antenna (CMMA)

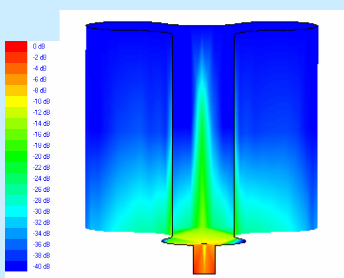
Design Concept:

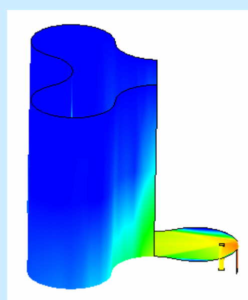
- Reduce operating frequency of patch antenna through use of grounding wall and increased perimeter with a compact footprint.
- Adjust for inherent decrease in directivity with vertical wall.
- Combine a microstrip patch with a 3-dimensional structure to attain a highly directive, broadband, compact antenna which radiates like a miniature monopole antenna.

$< \lambda/12$!





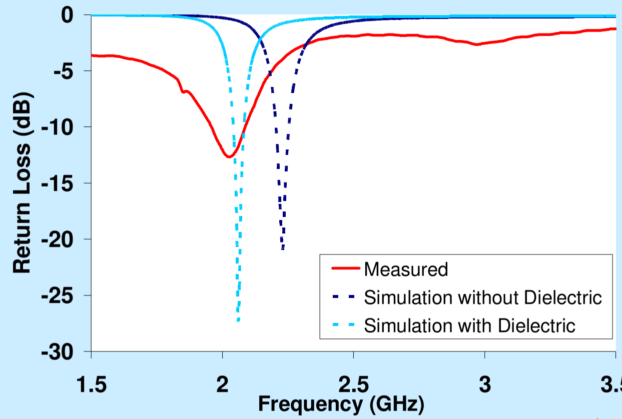


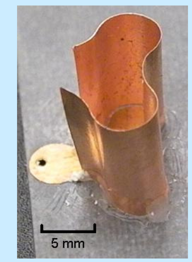


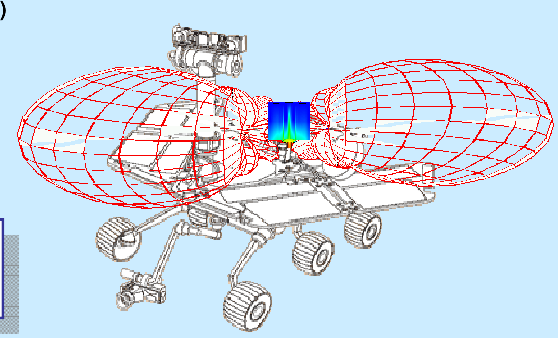
[2] Philip Barr, Afroz Zaman, Félix Miranda, "A Compact, Broadband Antenna for Planetary Surface-to-Surface Wireless Communications," Microwave and Optical Technology Letters, Vol. 48, Iss. 3, March 2006, pg. 521-524

Results:

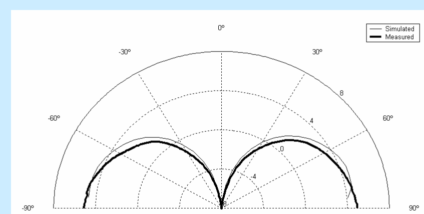
- End-fire radiation pattern allows for lunar surface-to-surface communications with an antenna structure 1/6th the size of a monopole antenna.



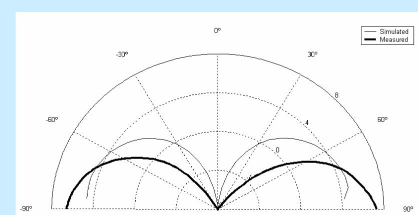




$TRL_{in} = 2$
$TRL_{out} = 3$



E-Plane

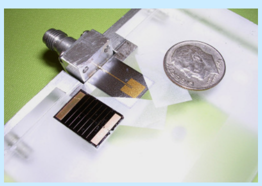


H-Plane

Solar Cell Integrated Antennas

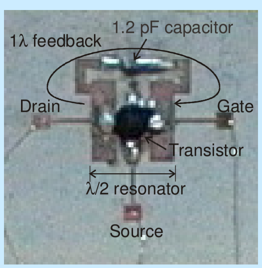
Design Concept:

- Integrate solar cell, local oscillator and miniature antenna for complete, compact, self-powering communications system.
- Integrated antenna radiating element/oscillator generates it's own RF power.
- Demonstrate prototype active oscillator solar cell array antenna modules capable of beam steering based on multi-junction GaAs solar cell and oscillator antenna technologies.
- Foundation for larger aperture, beam-steerable antennas using coupled oscillator approach.
- The proposed system will enable the development of low-cost, lightweight satellites with high directivity communication links for Flexible Access Networks.



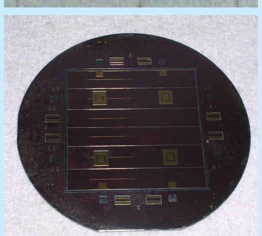
Miniature Antenna

Provides compact structure to transmit RF signal



Local Oscillator

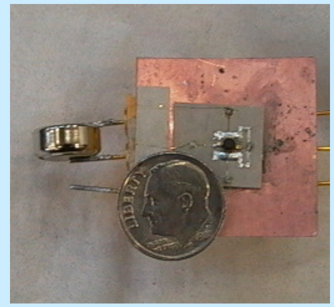
Provides modulation of frequency carrier for relevant data transmission



Solar Cell

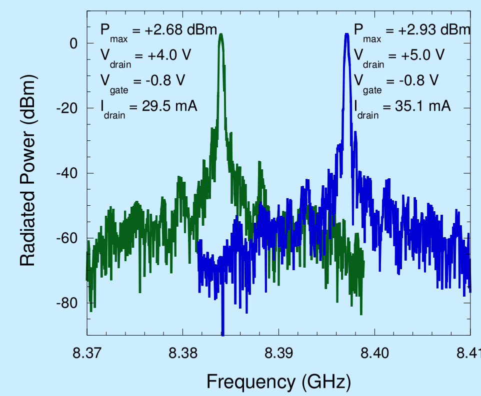
Provides power for communications system. Can be integrated on antenna layer, or on oscillator layer.

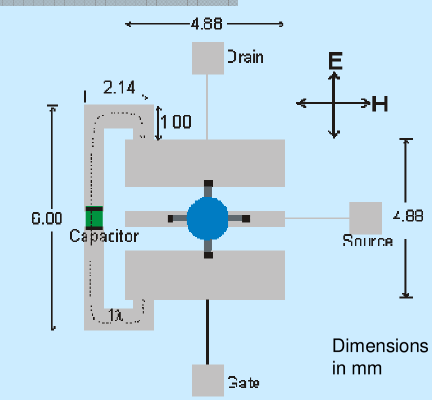
Results:

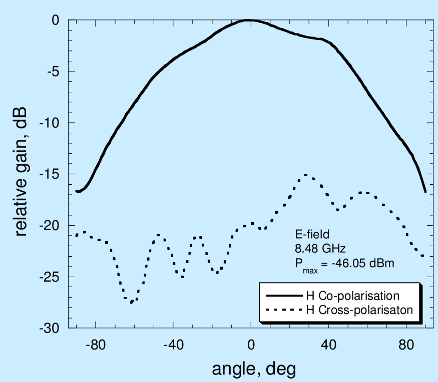


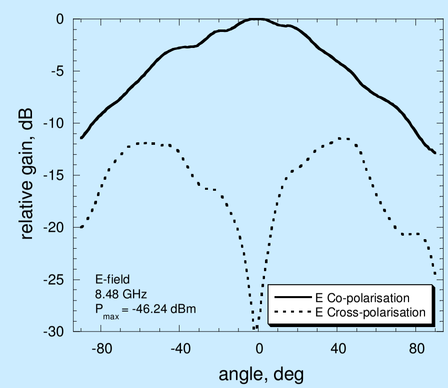
Fabricated integrated antenna/oscillator using Duroid RT 6010 microwave laminate (dielectric constant = 10.2), with pseudomorphic high electron mobility gallium arsenide transistors

TRL_{in} = 2
TRL_{out} = 3







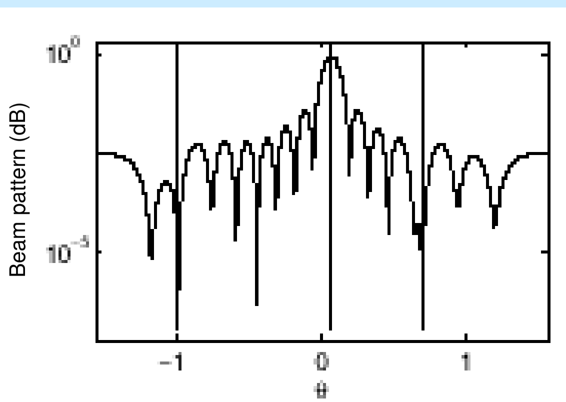


Miniaturized Antennas in Random Sensor Arrays for Planetary Surface Exploration

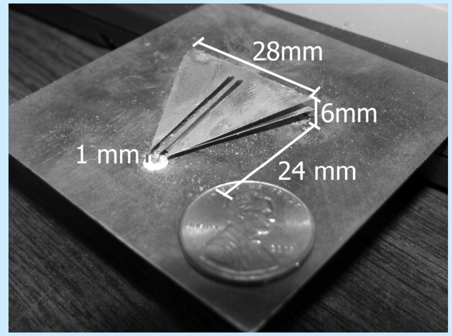
PI : Dr. Jennifer Bernhard/Univ. of Illinois

Concept:

- Develop electrically small antennas and self-healing, adaptive decision algorithms for coherent signal detection and transmission from an array of randomly distributed planetary sensors. The sensor array will configure itself to form a beam in a general direction that can be intercepted by a passing orbiter or directed to a particular satellite or planetary surface-based receiver.
- Develop miniaturized antennas and beam forming algorithm for random sensor arrays that enable the sensor to work together to communicate their data to remote collection sites without the need for a base station
- Develop 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.
- Development of distributed Bayesian Algorithm based fault tolerant, self organizing random sensor detection



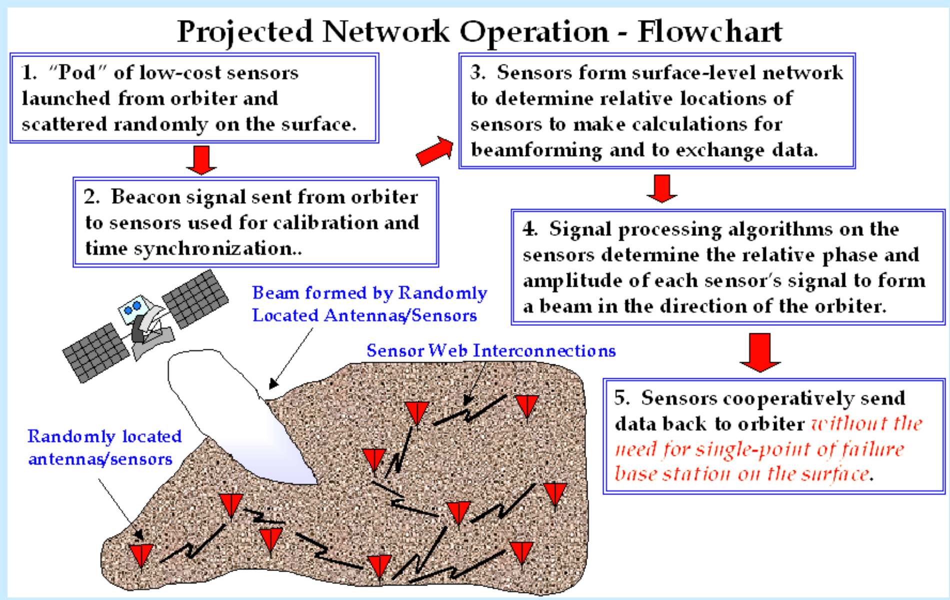
Simulated Beam forming Achieved Using Bayesian Estimation Method For a Random Sensor Array



Prototype Miniaturized Antenna

TRL $_{in}$ = 2
TRL $_{out}$ = 3

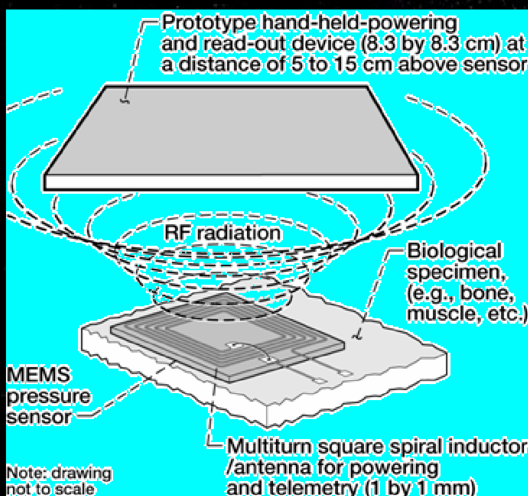
Approach allows randomly distributed Lunar surface sensors to work together as an array and thus enhances communication capabilities by decreasing the probability of single point communication failure.



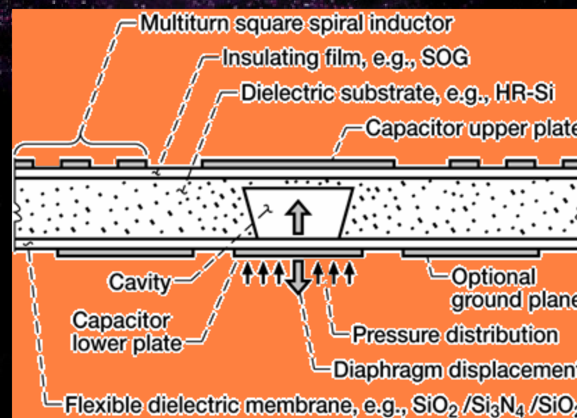
RF Telemetry System for Implantable Bio-MEMS Sensors

(TRL 3-4)

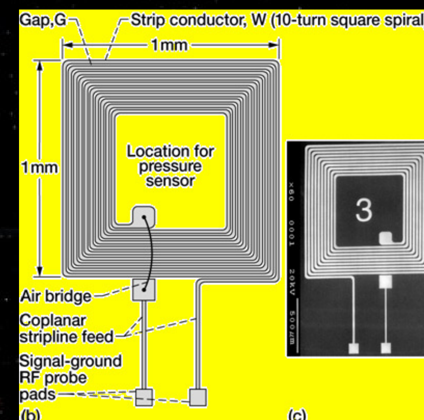
- **NASA seeks to develop telemetry based implantable sensing systems to monitor the physiological parameters of humans during space flights**
- **A novel miniature inductor and pick-up antenna for contact-less powering and RF telemetry from implantable Bio-MEMS sensors has been developed.**



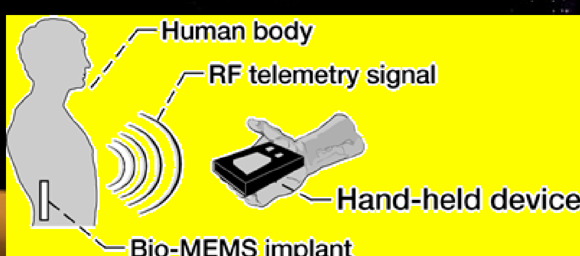
Contact-less powering and telemetry concept



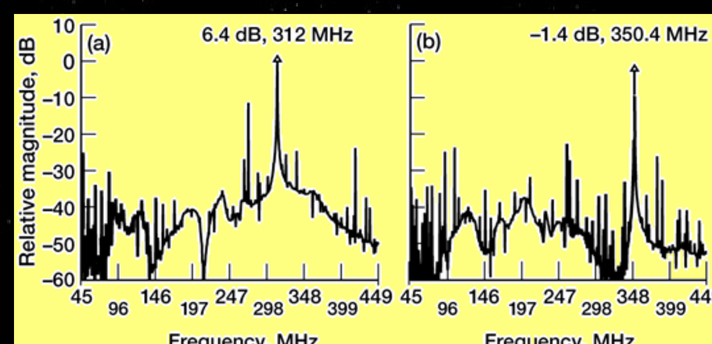
Schematic of a capacitive pressure sensor.



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.

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

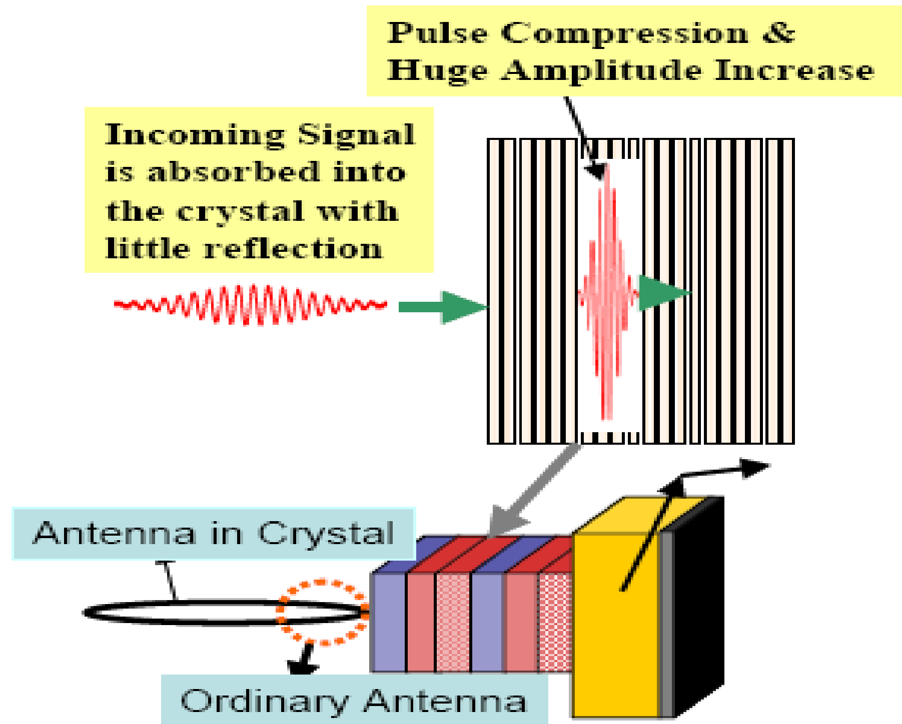


Fig. 1. MPC stack design and related benefits, including unidirectionality.

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

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)