Advanced Optical Technologies in NASA's Space Communication Program: Status, Challenges, and Future Plans

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A goal of the NASA Space Communications Project is to enable broad coverage for high-data-rate delivery to the users by means of ground, air, and space-based assets. The NASA Enterprise needs will be reviewed. A number of optical space communications technologies being developed by NASA will be described, and the prospective applications will be discussed.

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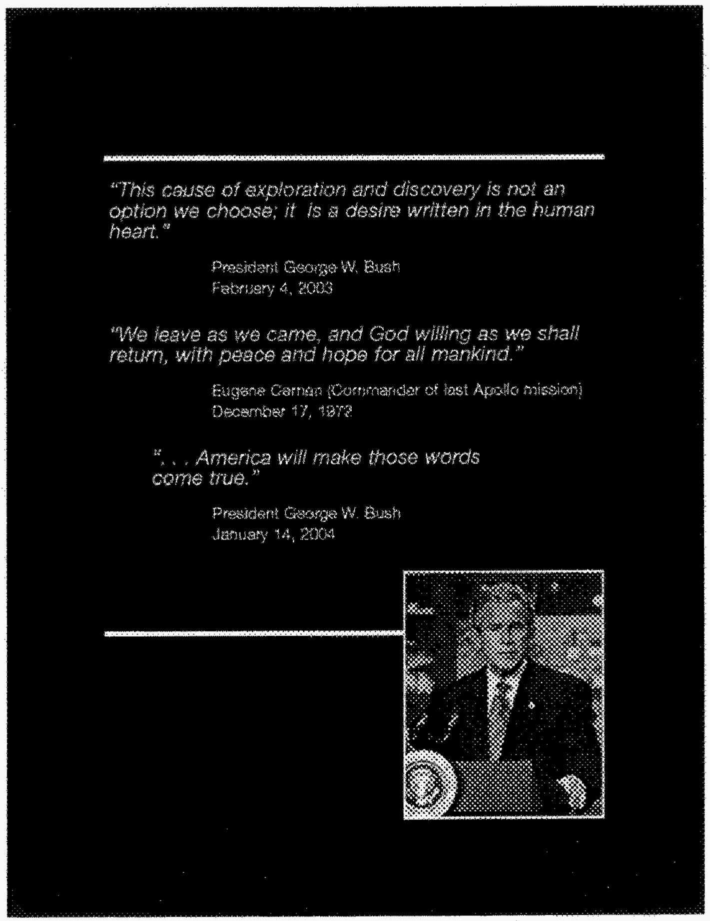
presentation to the

Great Lakes Photonics Symposium

June 2004

Dr. John Pouch
NASA Glenn Research Center

A New Future for U.S. Civil Space Programs

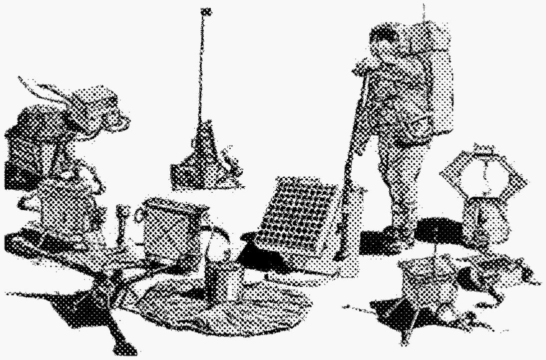


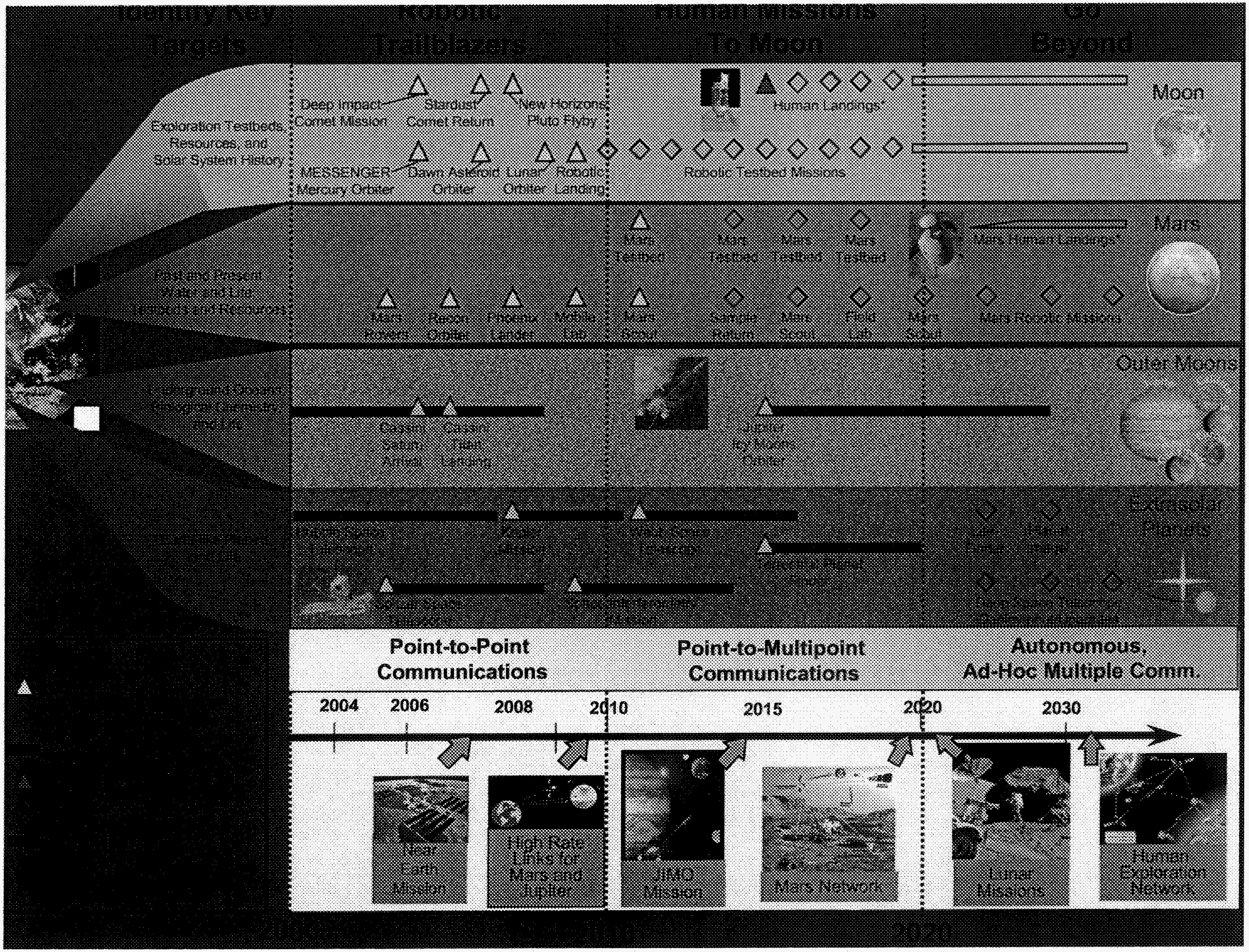
- On January 14, 2004, President Bush articulated a new Vision for Space Exploration in the 21st Century
- This Vision encompasses a broad range of human and robotic missions, including the Moon, Mars and destinations beyond
- It establishes clear goals and objectives, but sets equally clear budgetary 'boundaries' by stating firm priorities and tough choices
- It also establishes as policy the goals of pursuing commercial and international collaboration in realizing the new vision

Key Elements of the Nation's Vision

- Objectives
  - Implement a sustained and affordable human and robotic program
  - Extend human presence across the solar system and beyond
  - Develop supporting innovative technologies, knowledge, and infrastructures
  - Promote international and commercial participation in exploration

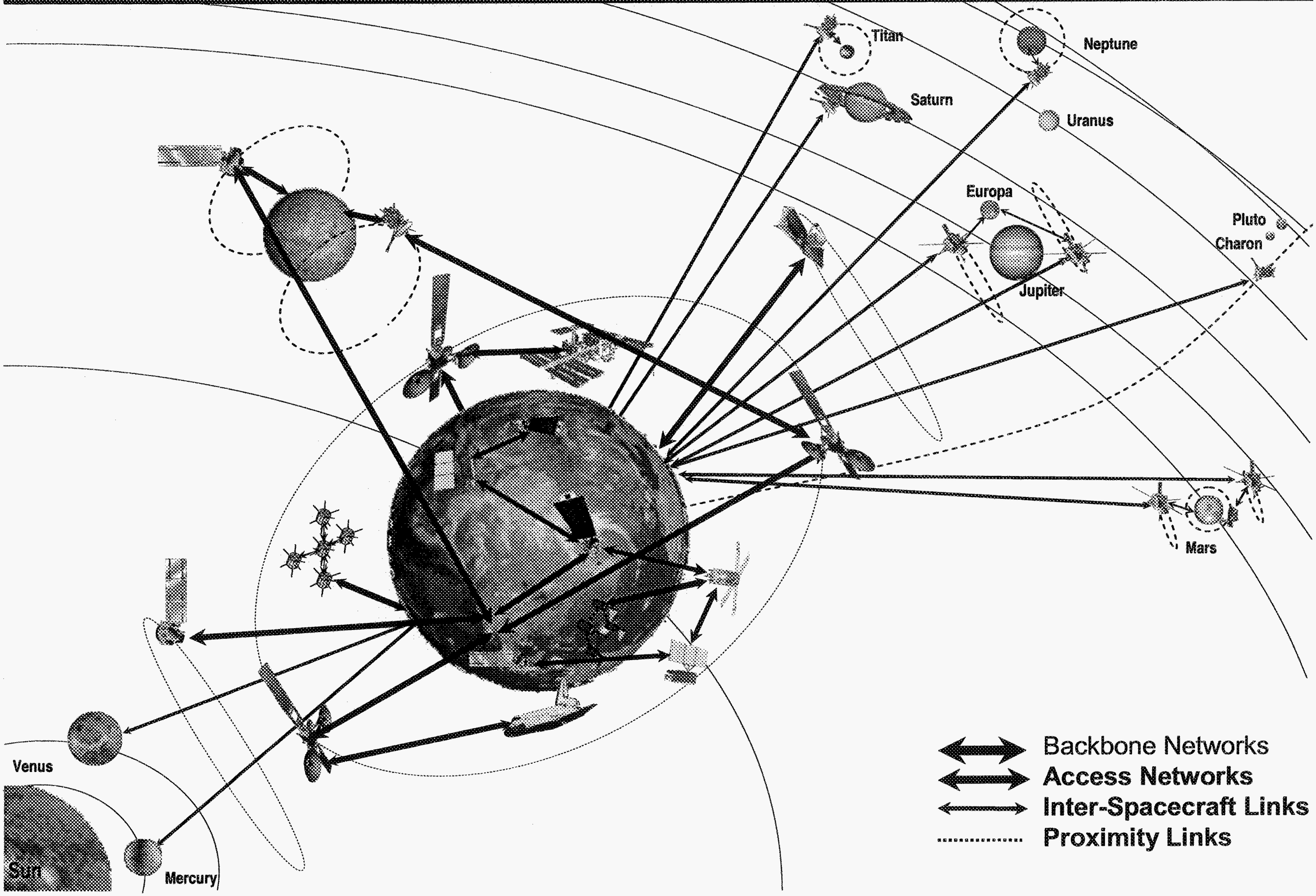
- Major Milestones
  - 2008: Initial flight test of CEV
  - 2008: Launch first lunar robotic orbiter
  - 2011: First Unmanned CEV flight
  - 2014: First crewed CEV flight
  - 2015: Jupiter Icy Moons Orbiter (JIMO)/Prometheus
  - 2015-2020: First human mission to the Moon





Targets
Trailblazers
To Moon
Beyond
Moon
Deep Impact Comet Mission
Stardust Comet Return
New Horizons Pluto Flyby
Human Landings*
Exploration Testbeds, Resources, and Solar System History
MESSENGER Mercury Orbiter
Dawn Asteroid Orbiter
Lunar Orbiter
Robotic Landing
Robotic Testbed Missions
Mars
Mars Testbed
Mars Testbed
Mars Testbed
Mars Testbed
Mars Human Landings*
Mars Rovers
Recon Orbiter
Phoenix Lander
Mobile Lab
Mars Scout
Sample Return
Mars Scout
Field Lab
Mars Scout
Mars Robotic Missions
Outer Moons
Cassini Saturn Arrival
Cassini Titan Landing
Jupiter Icy Moons Orbiter
Extrasolar Planets
Point-to-Point Communications
Point-to-Multipoint Communications
Autonomous, Ad-Hoc Multiple Comm.
2004
2006
2008
2010
2015
2020
2030
Near Earth Mission
High Rate Links for Mars and Jupiter
JIMO Mission
Mars Network
Lunar Missions
Human Exploration Network
2020

NASA's Integrated Space Communication Architectures



Space Communications Project Overview

Goal

Enable broad, continuous presence and coverage for high rate data delivery from ground, air, and space-based assets directly to the users.

Approach

- Enterprise requirements obtained and analyzed
- Technology challenges identified / roadmaps developed
- Technology investment made to competitive selection

Partners

- NASA Centers (JPL, GSFC, JSC, ARC)
- Industry (Lockheed Martin, IBM, Boeing, Northrup Grumman, ITT, BBN, Spectrum Astro, CISCO)
- Academia (MIT, Stanford, Univ. of Illinois, CWRU, Kent State Univ. New Mexico Univ, USC, Rice)
- DoD, NRO

NASA Mission Customers:

- **Jupiter Icy Moons Orbiter**
- **Mars '05/07/09 missions**
- **Magnetospheric Multi-Scale**
- **MAXIM and Constellation X**
- **Terrestrial Planet Finder**

NRC 2003 Review Comments

"World-Class Space Communication hardware"

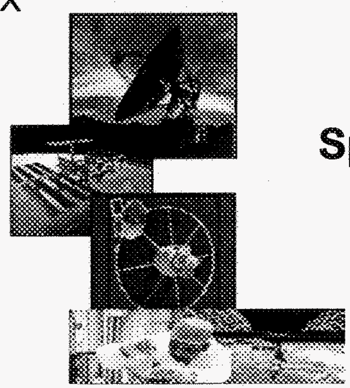
"The SC project was exemplary in that it generally had clear objectives, measurable outcomes, and milestones."

"SC Project has a more coherent vision, better plans, and better project management"

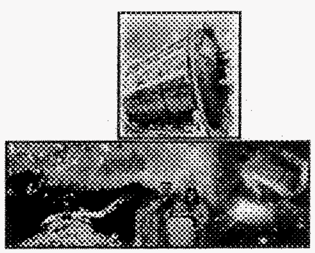
Enterprises Needs and Missions

Earth Science Missions:
- GPM Mission
- Leonardo Mission
- **NPOESS Mission**
- **Earth Science Technology Office**

Space Science Missions:
- **Jupiter Icy Moons Orbiter**
- Europa Orbiter
- Europa Lander
- Saturn Ring Observer
- Titan Organic Explorer
- **Mars '05/07/09 missions**
- **Magnetospheric Multi-Scale**
- MAXIM and Constellation X
- Inter-Magnetosphere Constellation
- **Terrestrial Planet Finder**
- Next Generation Space Telescope



Space Flight Missions:
- **Shuttle mission**
  - Wireless Sensor Network for Health Monitoring
- ISS Mission
- **Space Communication and Data Services**
- Human Exploration



Earth Science Needs:
- Increase data rates 10-100 Gbps rates for some observations by 2025.
- Increase data rate for Multi-spacecraft applications to 45 Mbps by 2010 and 155 Mbps by 2025 from the current SOA of 4 Mbps.
- Provide communication technology for far-out vantage points (e.g., Geostationary, Moon, and Lagrangian points)

Space Science Needs:
- Increase Data rates for Mars mission to 1 Mbps by 2010 and 10 Mbps by 2020 and 10 times for planetary missions
- Inter-satellite communications for distributed spacecraft mission for coordinated observations.
- High-rate Communications from Lagrange points L1 and L2

Space Flight Needs:
- Develop space communications technologies for 500- to 1,000-day class human missions
- Increase data rates from low Earth orbit (the current SOA 50 Mbps)
- Develop efficient wireless sensor networks for health monitoring

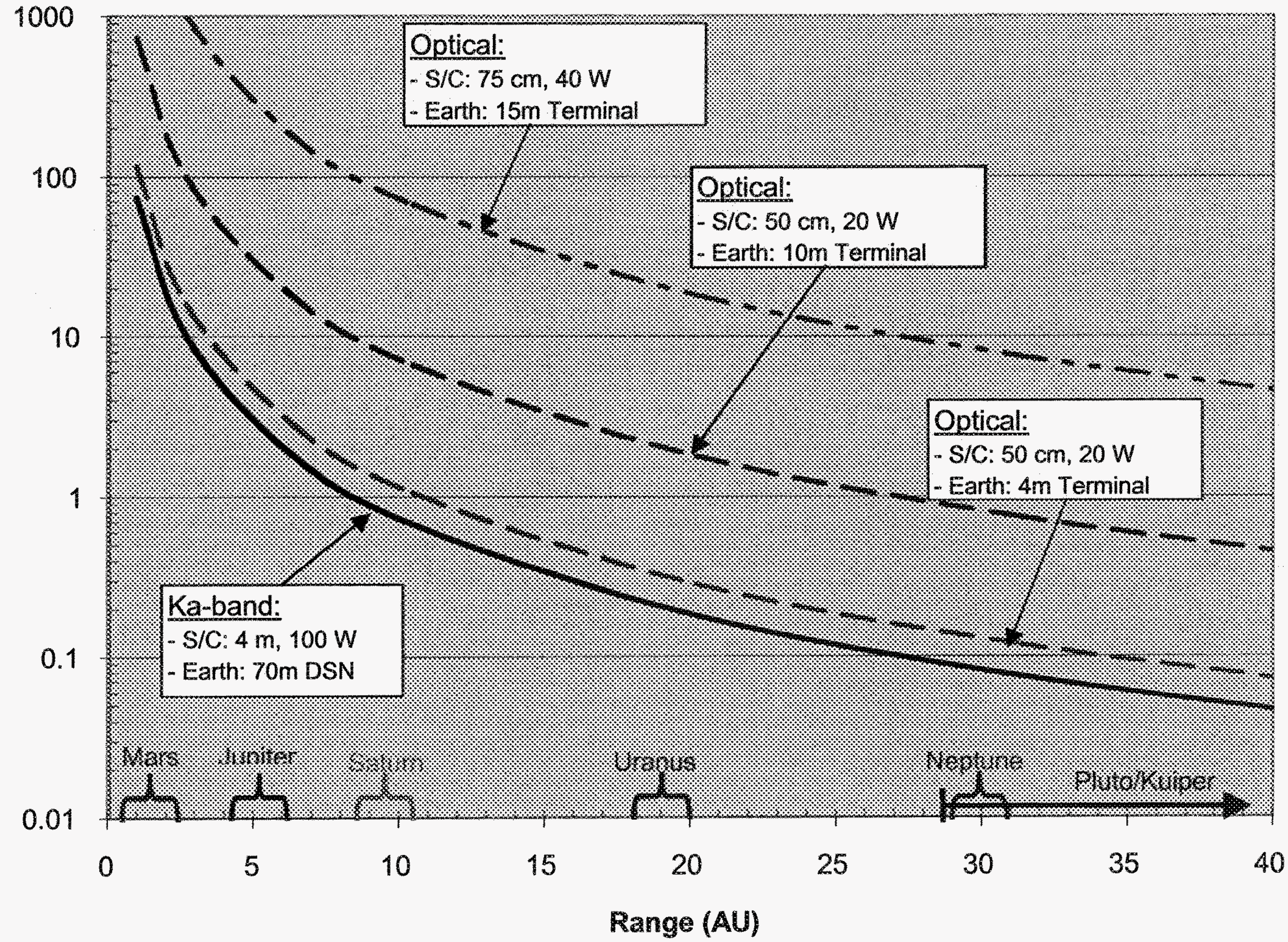
Biological and Physical Science Needs:
- Advanced communications for remote diagnostics and surgery
- Wireless Instrumentation and Communication
- Establish a distributed sensor networks

Optical Communications: Characteristics

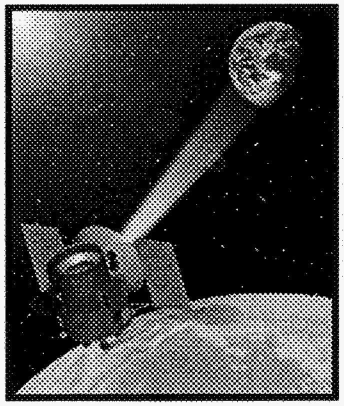
- Higher gains and higher data rates
- Potential for low mass (low-weight payloads), small size (receivers/ transmitters), and low power consumption
- High bandwidth
- Narrow beam transmission (communication security)

The Potential of Laser Communications

- Using Ka-band with a 70 m DSN antenna is roughly the same as an optical link with a 4 m receiver.
- Using a 10–15 m optical receiver, however, means 10 – 100 times more science data can be returned.



Enabling High Data Rates in Space

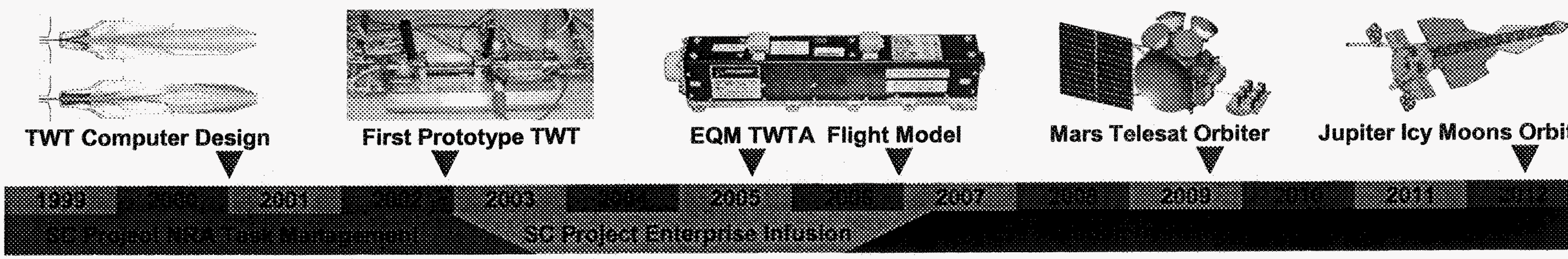


100 Watt Traveling Wave Tube for 2009 Mars Telesat Mission

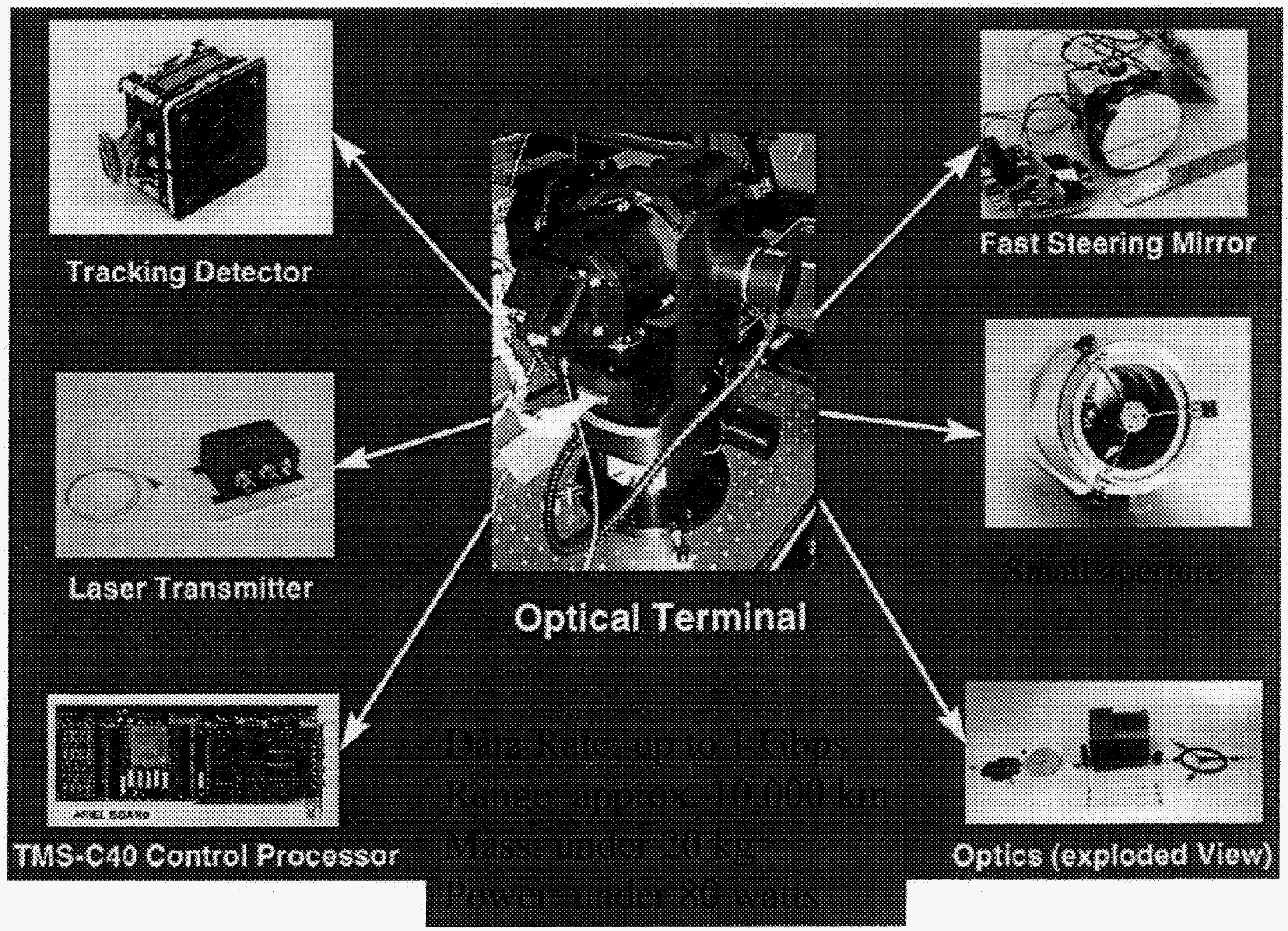
- Will increase the data return to 4.6Mbps from Mars. Factor of 3 increase over current state of the art
- Full transmitter being jointly developed by Code S, Code M Code R/Code T.

Ultra High Power Transmitter for 2012 JIMO Mission

- Will deliver 10Mbps data return from Jupiter.
  Factor of 20 increase over current sate of the art.
- 180W Traveling Wave Tube and Hybrid Power Combiner technology development in progress.



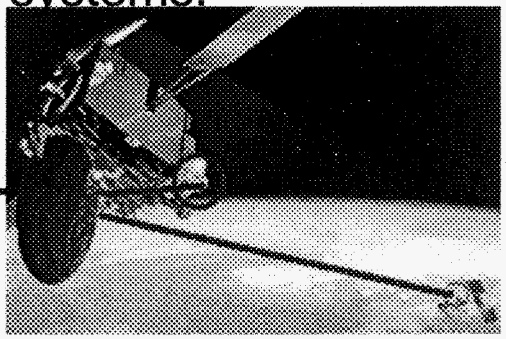
Components of an Optical Communications Transmitter



Courtesy of JPL

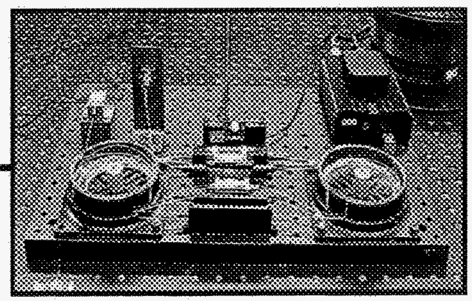
Current Optical Communication Technologies

Goal: Provide laser communication technologies for Inter-Spacecraft links and long-haul communications to enable deep space lasercom rates up to 1 Mbps and low cost, light weight systems up to 155 Mbps for multi-spacecraft systems.



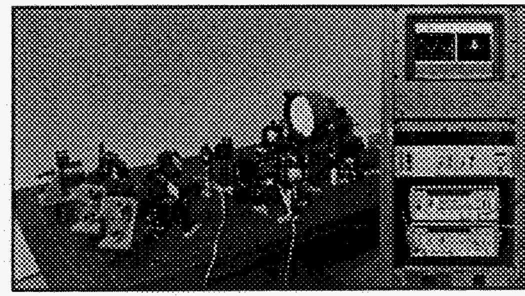
Liquid Crystal Optical Beam Steering

- Demonstrated a liquid crystal (LC) four-stage digital beam deflector with a laser scanning range of ±56 milliradian in 8 milliradian steps.
- Demonstrated feasibility of sub-microradian beam pointing.
- Validated wave-front distortion correction ability of low cost LC-on-silicon (LCOS) devices for use in large (8-inch and greater) optical systems



Efficient 20 W Deep-Space Laser

- 20W average output power
- At least a >2X data rate return over microwave
- Will enable a reduction in antenna aperture from ~5m (RF) to ~30cm (lasercom)



Precision In-Space Optical Pointing

- Demonstrated combining of low rate Reference Sources (e.g. star tracker) with High Bandwidth Inertial Sensors (e.g. accelerometers) to produce high bandwidth vibration compensation

RF Microphotonics

Goals:

Develop advanced communication receiver components with a 5x-10x reduction in volume and power consumption compared to current SOA while maintaining high rate data capability.

Objectives:

Demonstrate experimentally and theoretically a mm-wave receiver using microphotonic components. Show potential for increased scientific returns & low cost missions. Identify and analyze mm-wave, microphotonic receiver application (completed,TRL 2 [initial analysis]). Challenges: Design and integrate RF resonator with microphotonic components, demonstrate nW sensitivity, and incorporate stabilization feedback control.

Accomplishments:

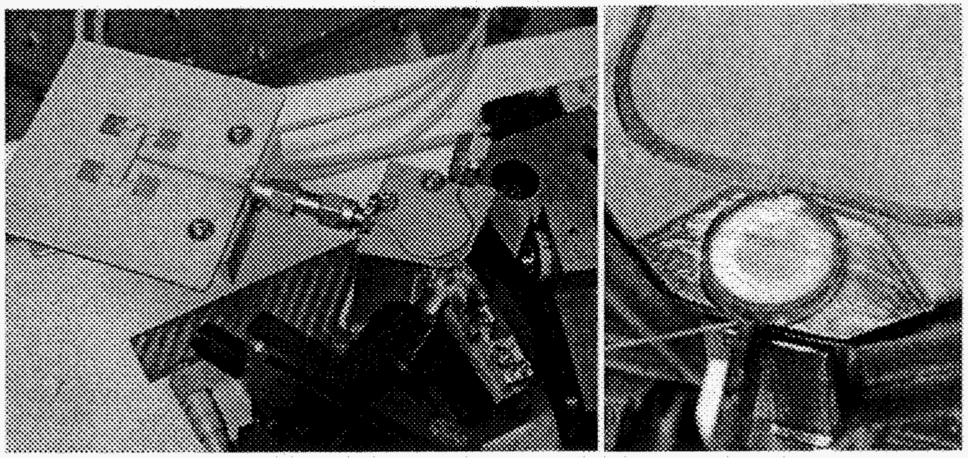
- Completed design and fabrication of electro-optic microdisk modulator with optical Q in excess of 10^6
- Completed laboratory demonstration of data and video transmission over RF wireless link at X/Ku band.
- Completed demonstration of single frequency operation at 26.1 GHz and 29.6 GHz and demonstration of tunable RF and optical response.

NASA Enterprise Impact:

Space Science, Earth Science: ESE (remote sensing mission), SSE (Mars rover)

Exploration System: Lunar Mission, Robotics/Human Mission. Enable extremely low power, reduced mass and volume modular microwave receivers (from X through Ka Band) for use in lunar and planetary surface environments.

Participants: NASA GRC, University of Southern California



RF microphotonic set-up showing micro-disk.

•Product Milestones	•04	•05	•06
Proof-of-concept laboratory tests	☑		
•TRL (achieved at year end)	•3		

Efficient Deep Space Laser Communications

Goals:
Provide laser communication technologies for inter-spacecraft links and long-haul communications to enable deep space lasercom rates up to 10 Mbps and low cost, light weight systems up to 155 Mbps for multi-spacecraft systems.

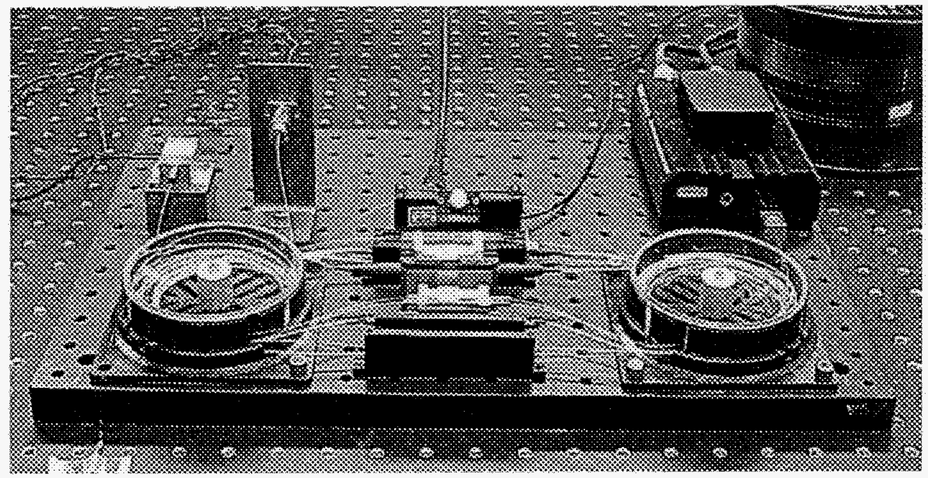
Objectives:
Optimize the design for high power with the highest possible efficiency. Obtain 20 W average output power. Design with space packaging and reliability in mind, even though product to be delivered is a breadboard at TRL 3.

Accomplishments:
- Reduced amplified spontaneous emission (ASE) in preamplifier stage allowing for increased power for signal amplification, with reduced optical loss
- Achieved average power level gain of 25 dB in a candidate material for preamplifier stage.
- Designed custom optical fiber for preserving phase conjugation

NASA Enterprise Impact:
Space Science, Earth Science: Mars Telesat, JIMO

Exploration System: Lunar Mission and Robotics/Human Mission. Development of a high quality laser source is a key system component to enable high rate optical communications between the Earth and the Moon, Mars, Jupiter, and the outer planets.

Participants: NASA GRC; Monica Minden and D. Cris Jones, HRL Laboratories



Close up photograph of breadboard fiber amplifier.

•Product Milestones	•04	•05	•06
•TRL 3 breadboard master- oscillator power-amplifier (MOPA) laser source delivery to JPL	☑		
•TRL (achieved at year end)	•3-4 •		

Liquid Crystal Based Beam Steering

Goals:
Provide low-cost, low-weight, low-power laser communication technologies for inter-spacecraft links

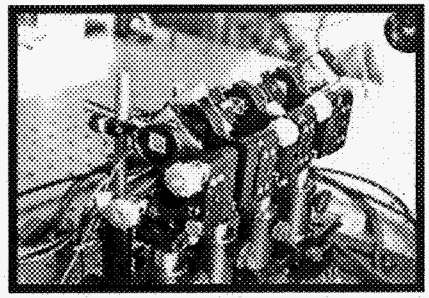
Objectives:
Provide advanced understanding of optical phased array devices through modeling with purpose of designing devices that demonstrate sub-microradian pointing accuracy; design devices that will enable the optical beams to steer to angles greater than 1 milli-radian. Show potential for increased scientific returns and low-cost missions. Conduct research in liquid crystal materials and develop theoretical models (TRL 2). Demonstrate beam steering with first test device (TRL 3).

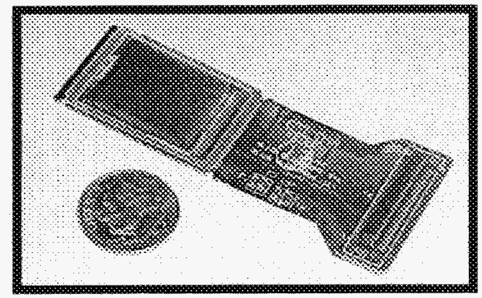
Accomplishments:
Demonstrated improvement in Strehl ratio of a distorted wave front by a factor of 100. Demonstrated fine steering (microradian) device.

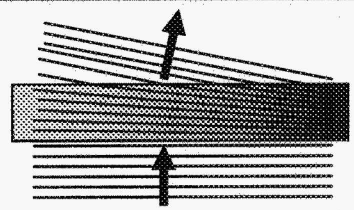
NASA Enterprise Impact:
Space Science, Earth Science: Enable demand access links for satellite-to-satellite beam pointing/tracking.

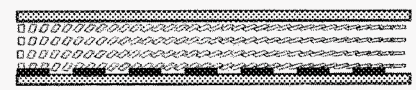
Exploration System: Lunar Mission, Robotics/Human Mission. Will enable very low cost, low power non-mechanical beam steering systems for optical communications for long-range point-to-point links and shorter-range multi-point to multi-point applications (single- and multi-beam communication links). Technology will be demonstrated at TRL 3.

Participants: NASA GRC, Liquid Crystal Institute (LCI) at Kent State University (KSU)









Gradient in the index of refraction is achieved with a liquid crystal device.

•Product Milestones	04	05	06
Build and Demo 1mrad steering device	☑		
Pathway to wave-front corrector	☑		
•TRL (achieved at year end)	•3		

Self-Powered Modulating Retroreflectors for InterSpacecraft Optical Communication and Relative Navigation

Goals:

Develop an ultra low power two-way optical link using a single conventional laser transmitter and tracker rather than using two laser transmitters with associated gimbaled telescopes and pointing/tracking systems.

Objectives:

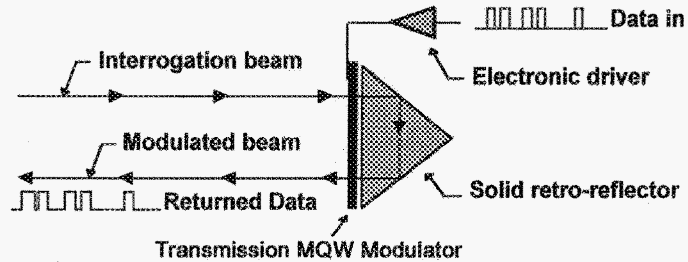
Develop a Modulating Retro Reflector (MRR) to reflect incoming laser communication signals directly back to source and modulate the returned signal with an elector-optic shutter using a semiconductor-based optical switch based on GaAs multiple quantum wells (MQW). A photovoltaic (PV) receiver will be integrated to utilize the incident sunlight and the incident laser light for self power generation. The MRR will have a very low mass (≈ 10g) and negligible power consumption (0-100mW) and a data rate of 10Mbps.

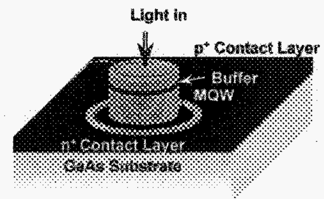
Accomplishments:

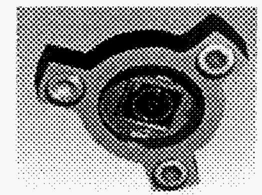
MRR devices with 6.3 mm diameter aperture developed and successfully operating at 1550 nm at -5V with data rates as high as 10 Mbs. Design of the power circuitry based on capacitive storage with a super-capacitor was completed.

~~NASA Enterprise Impact:~~

Space Science, Earth Science: Low-power, miniature, all-optical network for formation flying satellite communications, targeting, and acquisition.
Exploration System: Light weight, self-powered, optical data link can be used with a small payload for remote sensing in extreme environments. Mars Exploration Program is leveraging this technology into a remote sensing application for the Mars surface communications network.
Participants: Dr. Robert Walters, NRL







Modulating Retro Reflector (MRR)

Product Milestones	04	05	06
Study optical comm./rel. nav.	☑		
Flight Prototype		☑	
TRL (achieved at year end)			
Total ($K)	654	615	293

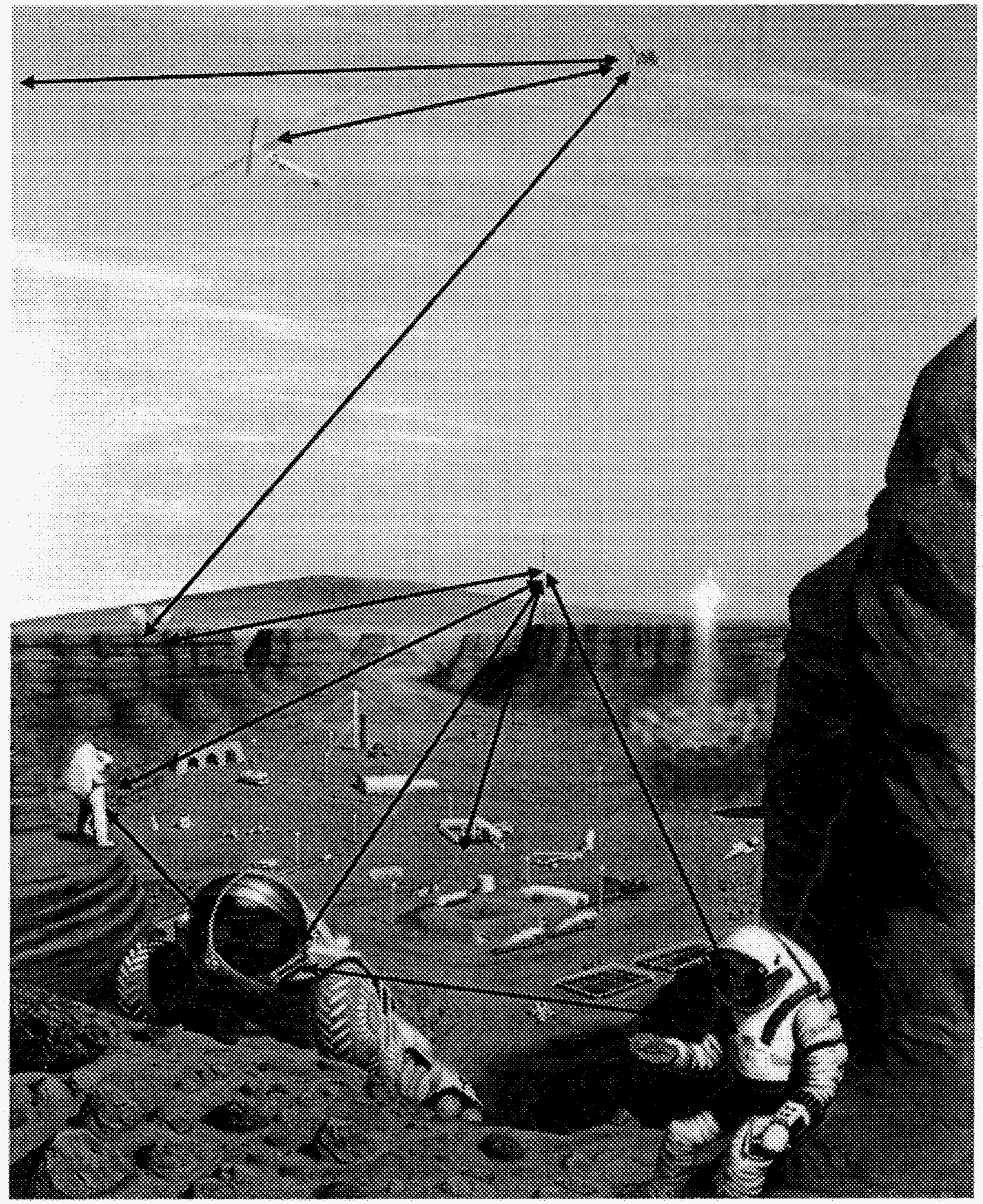
Enabling Human and Robotic Missions through Communication Networks and Systems

Long haul backbone to Earth

Access connections to Mars orbit relays

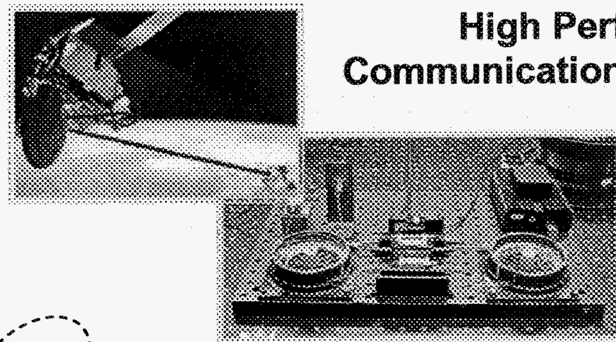
Wireless local area network (WLAN)

Interpersonal communications

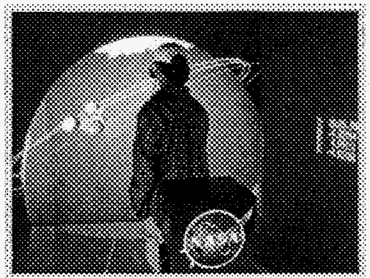


Backup

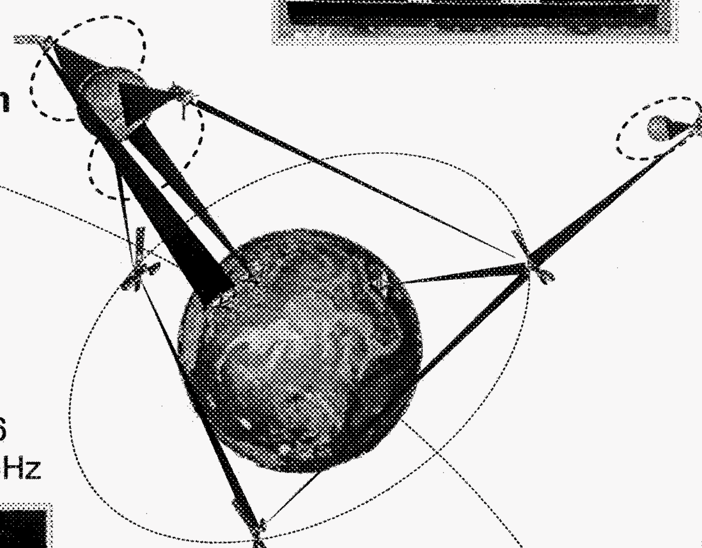
Enabling Planetary Communications Infrastructure



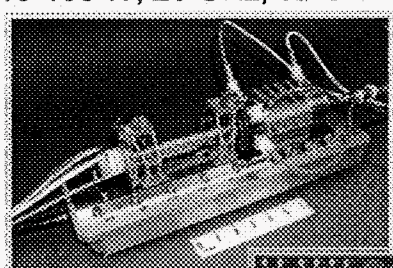
High Performance Optical Communication Technologies for Mars



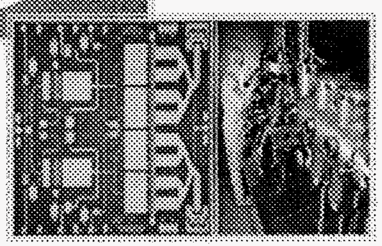
End-to-End Space Communication Emulation



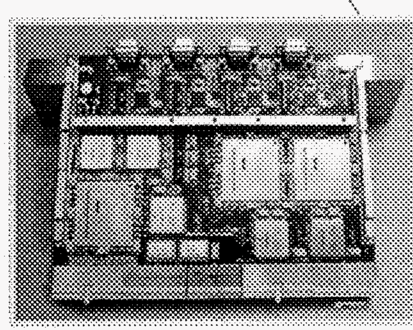
10-100 W, 26 GHz, 32 GHz



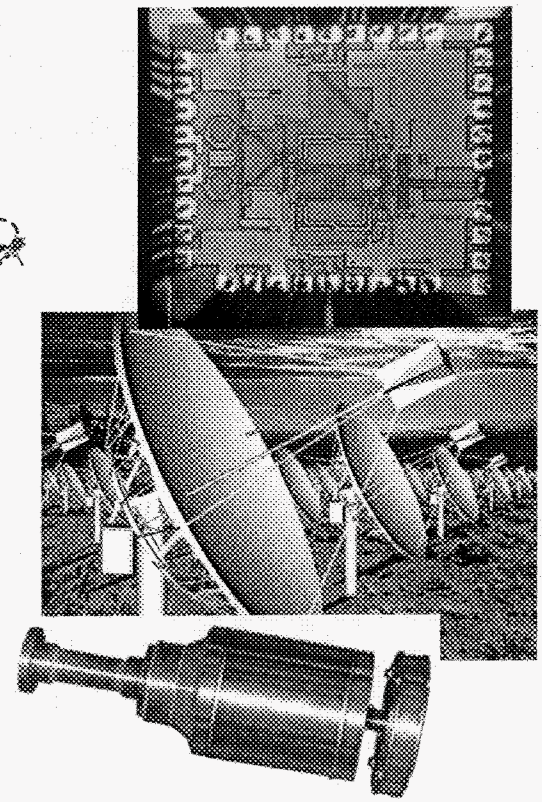
5-10 W, 26 GHz, 32 GHz



High Efficiency Traveling Wave Tubes and Power Module for Lunar and Mars Links

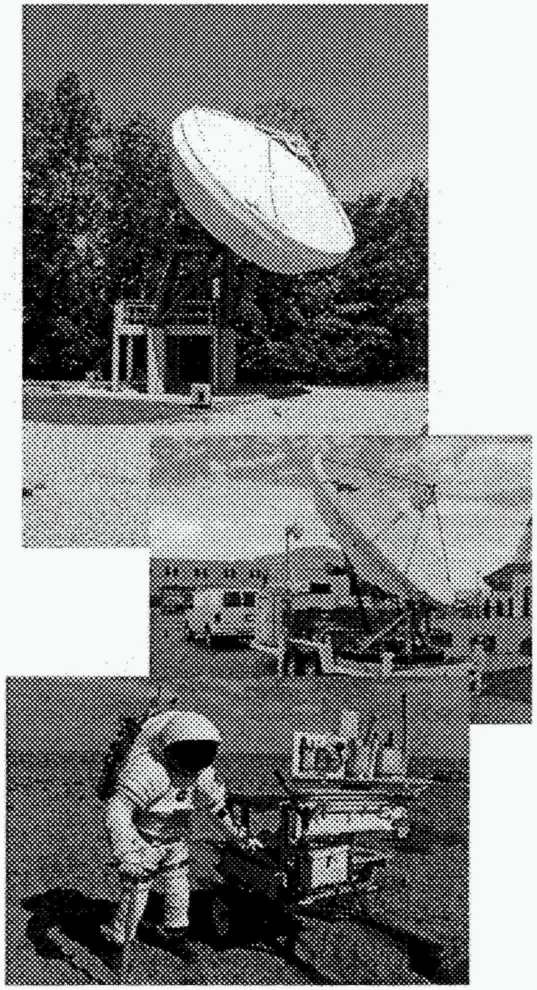


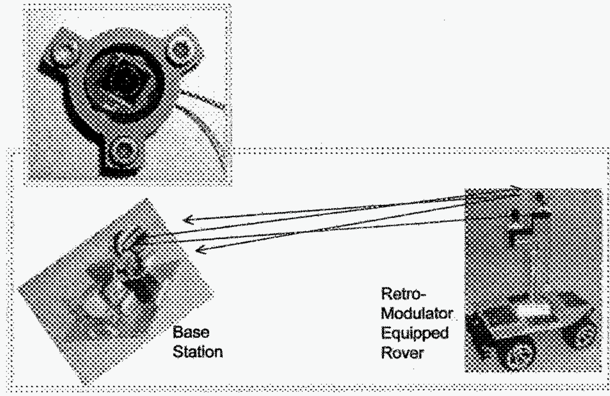
Networking Bus Modules for Internet Protocol Enabled Spacecraft



Miniaturized Cryocooled SiGe receivers for large arrays

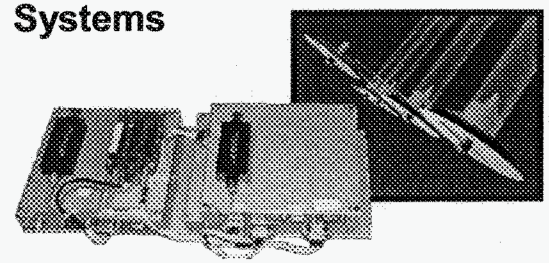
Enabling Lunar and Mars Surface Networks



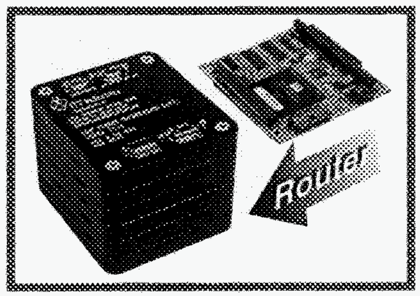


Optical Wireless Networks

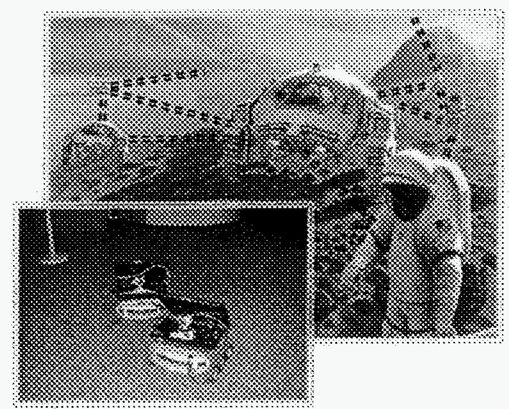
Micro Sensor Communications Systems



Inter Spacecraft Communications Technologies



Miniaturized Transceivers with Routing Capabilities



End to end emulation capabilities to establish reliability, security, performance, and to understand operating with over 40 min delays

Mobile Wireless Wide Area Networks (WWAN)

Space Communications Project Technology Roadmap

Technology Development:

- High Power, High Efficiency Transmitters
- Low Mass Power Efficient Phased Array Antennas
- Optical Communication Technologies
- Space Network Technologies and Efficient Internet Compliant Protocols
- Miniature Comm/Sensor Modules
- Ka-Band Amplifiers and Receivers
- 1st Generation Crosslink Technologies
- High Speed Digital Modems

- 10 Gbit-Rate Comm. Systems
- On-Board Processing
- Low Cost, Miniature, Low Power Integrated Components
- Ad-Hoc Networks for Multiple Spacecrafts
- Reconfigurable Antennas
- Multicasting Networks
- Ultra Low Loss MEMS Components for Receivers

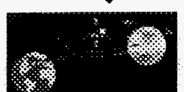
- Seamless High Data Rate Information Delivery
- Intelligent, Ad-Hoc User-Centric Communication Networks
- Communication Technologies for Multiple Spacecraft Networks Connected to Deep Space Backbone
- Integrated Communications / Navigation Systems for Distributed Cluster / Formation Flying Constellations

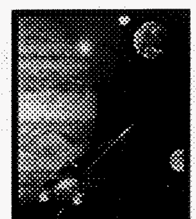
Capabilities: Point-to-Point Communications | Point-to-Multipoint Communications | Autonomous, Ad-Hoc Multiple Comm.

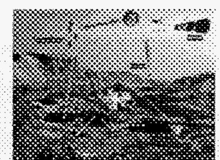
2004 2006 2008 2010 2020 2030

Applications / Missions:


Near Earth Mission


High Rate Links for Mars and Jupiter


JIMO Mission


Mars Network


Lunar Missions

Human Exploration Network