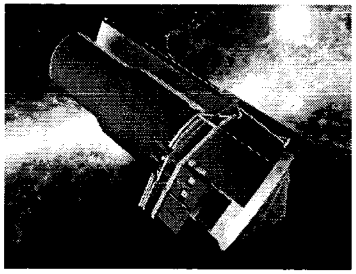
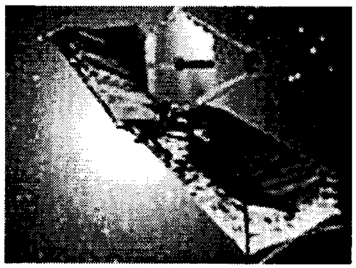
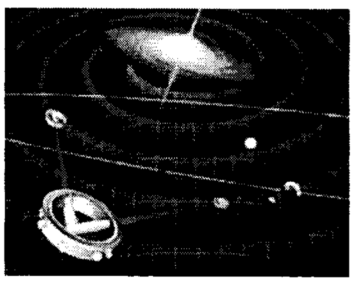
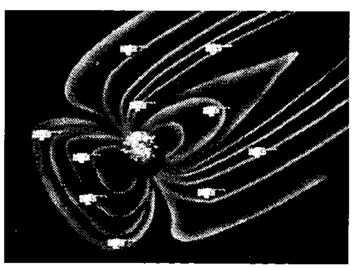
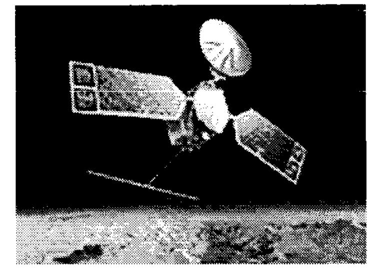
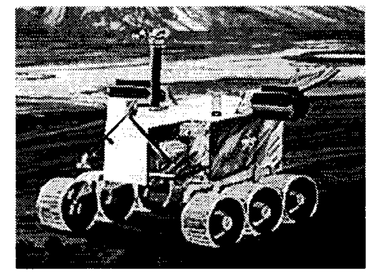
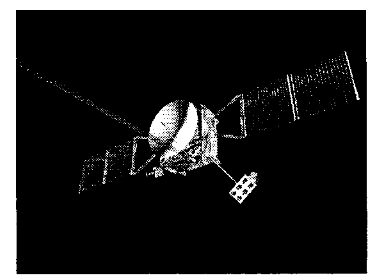
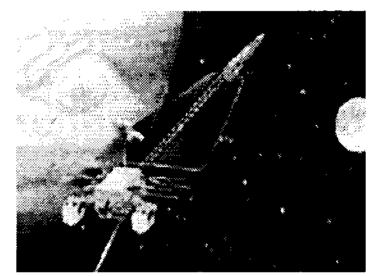





# Long-Range Planning for the Deep Space Network

**Robert Cesarone**
**Doug Abraham**

**Jet Propulsion Laboratory**
**California Institute of Technology**

AIAA Space 2003 Conference
Long Beach, California
September 25, 2003

# Topics

- NASA Strategic Planning
- The Changing Mission Paradigm
- Responding to the Changing Mission Paradigm
- Summary

# NASA Strategic Planning

## The NASA Mission

***To understand and protect our home planet***

***To explore the Universe and search for life***

***To inspire the next generation of explorers***

***.... as only NASA can***

## JPL's Mission Flows from the NASA Mission & Strategic Plan

*A key item of the JPL Mission is:*

***To enable a virtual presence throughout the solar system by creating the Interplanetary Network***

## The NASA Strategic Plan

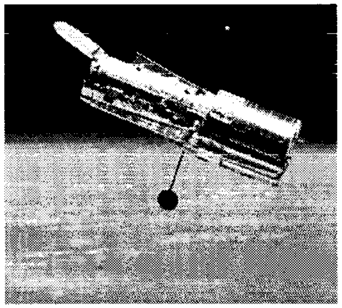
**Objective 10.3**

***Develop breakthrough information and communication systems to increase our understanding of scientific data and phenomena.***

***Communications technology will provide a broad, continuous presence and coverage for high-rate data delivery to scientists and engineers.***

# The Changing Mission Paradigm

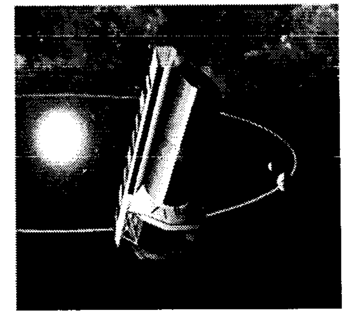
Jet Propulsion Laboratory
California Institute of Technology

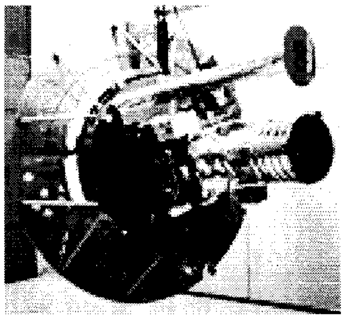


Low-Earth-orbit solar and astrophysical observatories.

→

Observatories located farther from Earth.
(e.g., SIRTF, JWST)

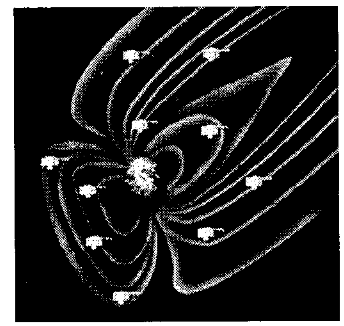


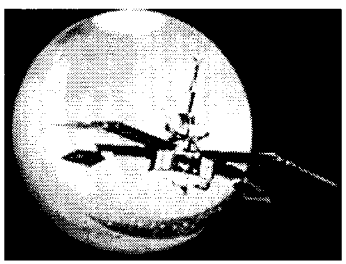


Single, large spacecraft for solar and astrophysical observations.

→

Constellations of small, low-cost spacecraft.
(e.g., MMS, MagCon)

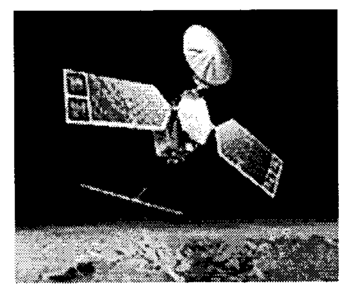


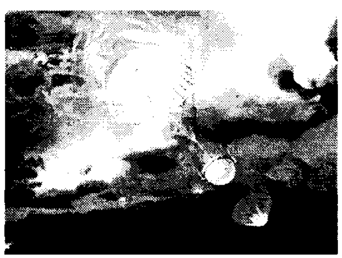


Preliminary solar system reconnaissance via brief flybys.

→

Detailed Orbital Remote Sensing.
(e.g., MRO, JIMO)

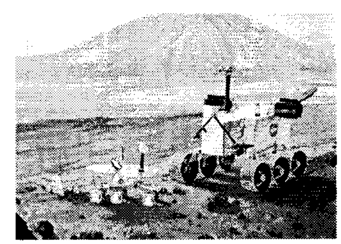




*In situ* exploration via short-lived probes.

→

*In situ* exploration via long-lived mobile elements.
(e.g., MER, MSL)

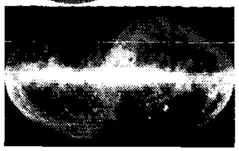


# Trend #1: More Spacecraft Supports

- In 1987
  - DSN fielded 9 deep space antennas
  - These antennas routinely tracked ~ 6 spacecraft
- Today
  - DSN fields 12 deep space antennas
  - These antennas routinely track ~ 26 spacecraft
- Over the last 15 years, the deep space mission set has expanded fourfold whereas the tracking assets have only grown by 33%.
- The DSN must also support those near-Earth spacecraft that need to compensate for low on-board EIRP with high ground receive capability.
  - Typically constellation spacecraft (spinners with omni antennas)

# Future U.S.-Led Science Missions from the Code S Roadmaps**

**Jet Propulsion Laboratory**
California Institute of Technology



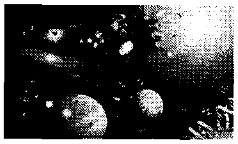
SEU

- GLAST
- GRAVITY PROBE B
- SWIFT
- SPIDR
- EUSO
- WISE

- LISA
- DARK ENERGY PROBE
- EXPLORER MISSIONS

- CONSTELLATION-X
- INFLATION PROBE
- BLACK HOLE FINDER PROBE
- EXPLORER MISSIONS

- BIG BANG OBSERVER
- BLACK HOLE IMAGER
- EXPLORER MISSIONS



ASO

- KEPLER

- SPACE INTERFEROMETRY MISSION
- JAMES WEBB SPACE TELESCOPE
- EXPLORER MISSION
- DISCOVERY MISSION

- TERRESTRIAL PLANET FINDER
- SINGLE APERTURE FAR-INFRARED OBSERVATORY
- EXPLORER MISSION
- DISCOVERY MISSION

- SPACE ULTRAVIOLET / OPTICAL TELESCOPE
- LIFE FINDER
- PLANET IMAGER
- EXPLORER MISSION
- DISCOVERY MISSION

SSE**

- DEEP IMPACT
- MESSENGER
- DAWN
- PHOENIX
- NEW HORIZONS
- MARS RECONNAISSANCE ORBITER

- DISCOVERY MISSIONS
- SOUTH POLE AITKEN BASIN SAMPLE RETURN
- JUPITER ICY MOONS ORBITER*
- MARS SCOUTS
- MARS SCIENCE LABORATORY
- MARS SAMPLE RETURN

- DISCOVERY MISSIONS
- JUPITER POLAR ORBITER/PROBES*
- VENUS IN-SITU EXPLORER
- COMET SURFACE SAMPLE RETURN
- MARS SCOUTS
- MARS LONG-LIVED LANDER NETWORK

- DISCOVERY MISSIONS
- MARS SCOUTS
- MARS UPPER ATMOSPHERE ORBITER*
- EUROPA LANDER
- TITAN EXPLORER
- NEPTUNE ORBITER WITH PROBES*

SEC***

- SOLAR-TERRESTRIAL RELATIONS OBSERVATORY
- THEMIS
- GEOSPACE ELECTRODYNAMIC CONNECTIONS
- MAGNETOSPHERIC MULTISCALE
- SOLAR DYNAMICS OBSERVATORY
- RADIATION BELT STORM PROBES
- IONOSPHERE THERMOSPHERE STORM PROBES
- CINDI
- TWINS
- AIM

- MAGCON
- SOLAR PROBE
- TELEMACHUS
- IONOSPHERE THERMOSPHERE MESOSPHERE WAVES COUPLER
- HELIOSPHERIC IMAGER AND GALACTIC OBSERVER
- RECONNECTION AND MICROSCALE
- INNER HELIOSPHERE SENTINELS
- INNER MAGNETOSPHERIC CONSTELLATION
- TROPICAL ITM COUPLER
- JUPITER POLAR ORBITER*

- AURORAL MULTISCALE
- GEOSPACE SYSTEM RESPONSE IMAGER
- INTERSTELLAR PROBE
- SOLAR CONNECTIONS OBSERVATORY FOR PLANETARY ENVIRONS
- SOLAR POLAR IMAGER
- DAYSIDE BOUNDARY LAYER CONSTELLATION
- MAGNETOSPHERE-IONOSPHERE OBSERVATORY
- PARTICLE ACCELERATION SOLAR ORBITER
- L1-DIAMOND
- MAGNETIC TRANSITION REGION PROBE
- SOLAR IMAGING RADIO ARRAY
- STELLAR IMAGER
- SUN EARTH ENERGY CONNECTOR
- SUN-HELIOSPHERE-EARTH CONSTELLATION
- NEPTUNE ORBITER*
- IO ELECTRODYNAMICS
- MARS AERONOMY*
- VENUS AERONOMY

**Key**

- **DSN Support Likely**
- **DSN Support Possible**
- **DSN Support Unlikely**

2008 2013 2018 2023

**Very Approximate Launch Epoch**

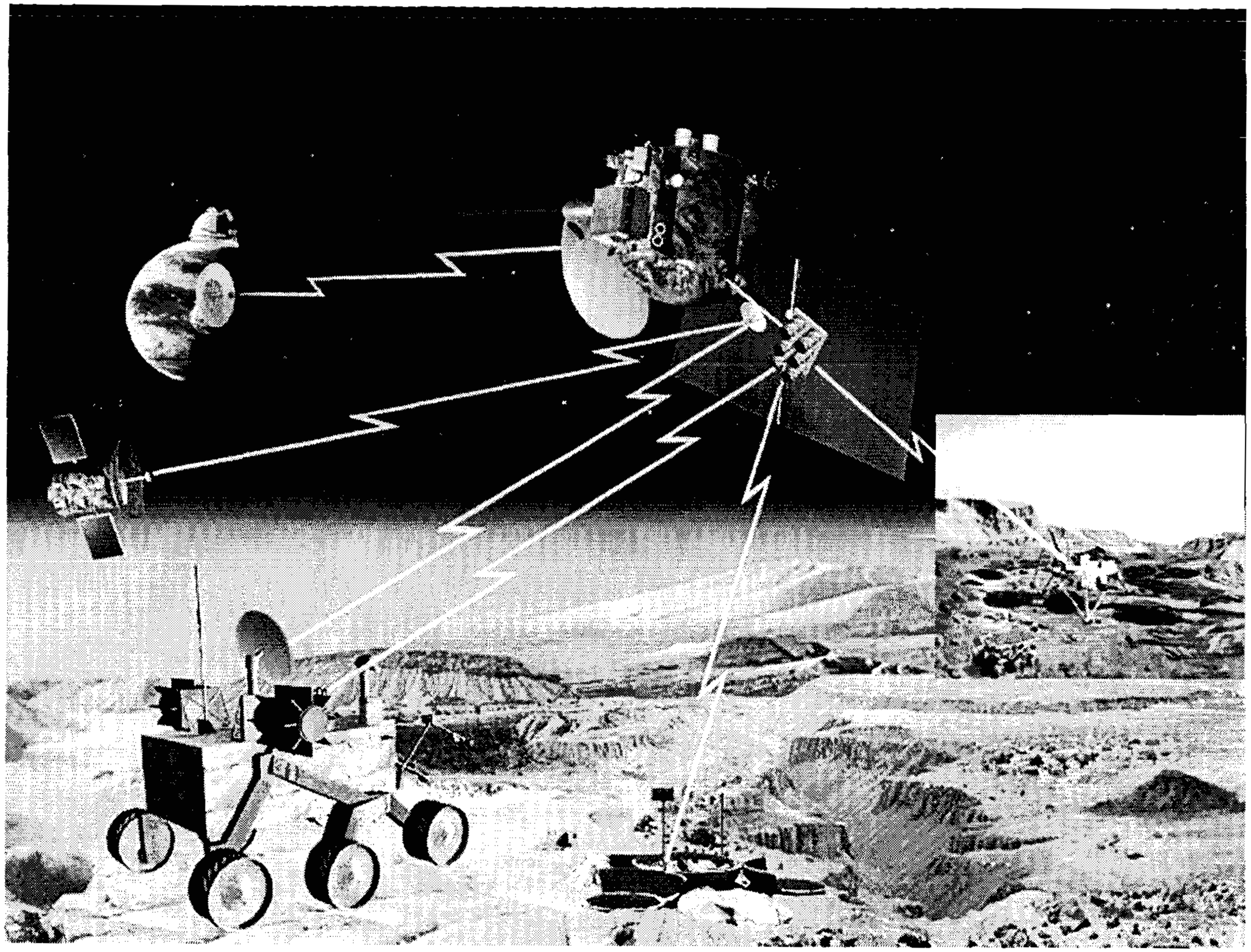
*Indicates possible overlap between SSE and SEC.
**SSE also based on Planetary Decadal Survey; some missions may be New Frontiers missions; some SEU & SEC missions derived from latest Explorer awards.
***Some missions may be Explorer or Discovery.

# Trend #2: Greater Mission Operations Complexity

- Increased coordination between separate spacecraft elements within a mission and among missions
- Challenges for the next decade:
  - •6 or more constellation missions
  - •7 or more missions involving proximity (relay) links (Several at Mars)
  - •Up to 7 LaGrange Point missions (incl. the 4 spacecraft Constellation-X)
  - •Up to 5 passive formation flight missions
  - •At least 1 3-spacecraft active formation flight mission (LISA)
  - •7 or more missions with entry-descent-landing at an extraterrestrial body
  - •At least 3 missions using aerobraking
  - •At least 3 missions using low-thrust propulsion
- Challenges for the following decade:
  - •Autonomous coordination among *in-situ* exploration elements
  - •Autonomous coordination among constellation elements

# Growth in Mission Operations Complexity





Notional View of Possible Future Proximity Link Missions at Mars

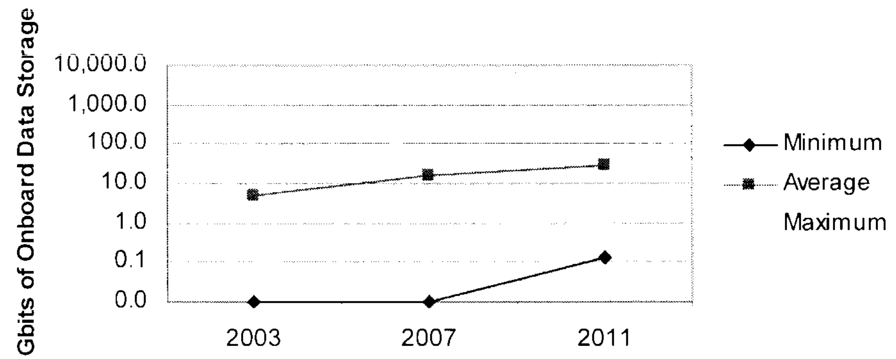
# Trend #3: Order-of-Magnitude (or more) Increases in Downlink Data Volumes

- Drivers
  - Increasingly capable science instruments generate large volumes of data to be transmitted to Earth via high data rates links
  - Long- duration orbital remote sensing missions
  - Long- lived mobile elements for *in-situ* exploration
- This Decade:
  - 10 x to 100x increase in downlink data rates likely
  - Applies to both deep space and near-Earth missions
- Following Decade:
  - An additional 10x to 100x increase is likely

# 8-Year View: Downlink Trends

Jet Propulsion Laboratory
California Institute of Technology

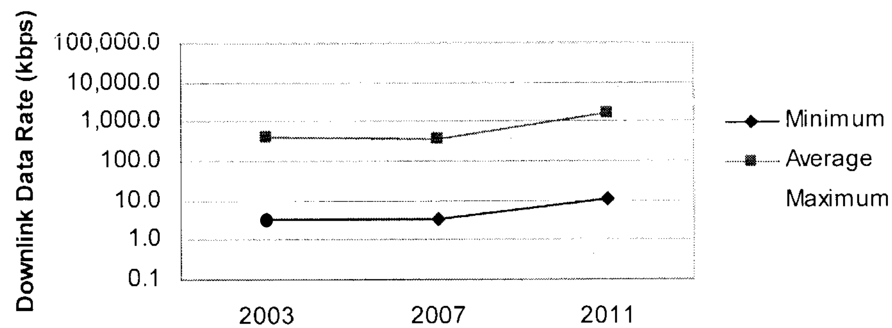
### Spacecraft Data Storage Capacity as a Function of Time*




*RadioAstron, MTO, and JIMO not included.

Spacecraft data storage trends suggest collected data volumes will increase by 1-to-2 orders of magnitude.

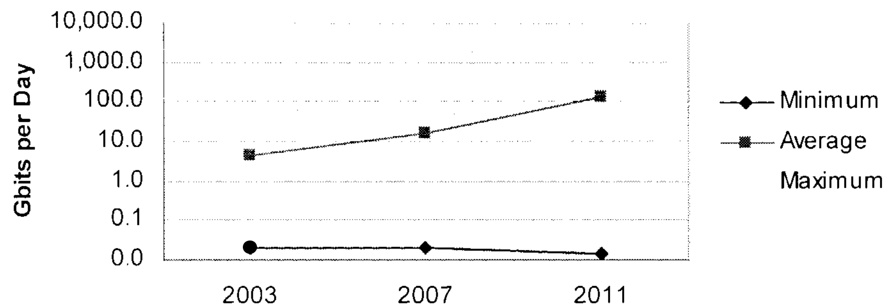
### Near-Earth Downlink Data Rates as a Function of Time*




*Excludes RadioAstron.

Near-Earth downlink rates also appear to be increasing 1-to-2 orders of magnitude.

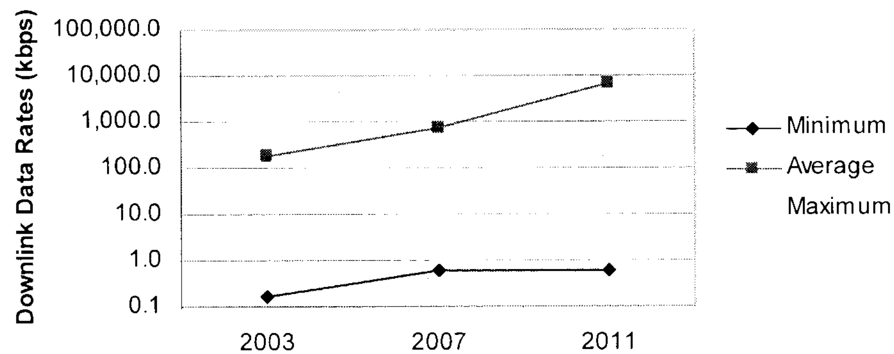
### Project-Estimated Daily Data Volume as a Function of Time*




*RadioAstron, MTO, and JIMO not included.

Project-estimated daily data volumes also exhibit an increase of 1-to-2 orders of magnitude.

### Deep Space Downlink Rates as a Function of Time




Deep space downlink rates are increasing by 1-to-2 orders of magnitude as well.

# Looking Toward the 20-Year Horizon: Downlink Trends

- Problem: Mission concepts more than 10 years out exhibit a heavy bias towards today's technologies.
- What We Know: Scientists want to be able to carry out science investigations at other planets with same ease, precision, and resolution as they can on Earth.
- Solution: Use current Earth-based capabilities as an indication of what will be needed for future deep-space capabilities.
- Case in point: Remote Sensing from Space

**Earth Remote Sensing:**

1958 → 2002+

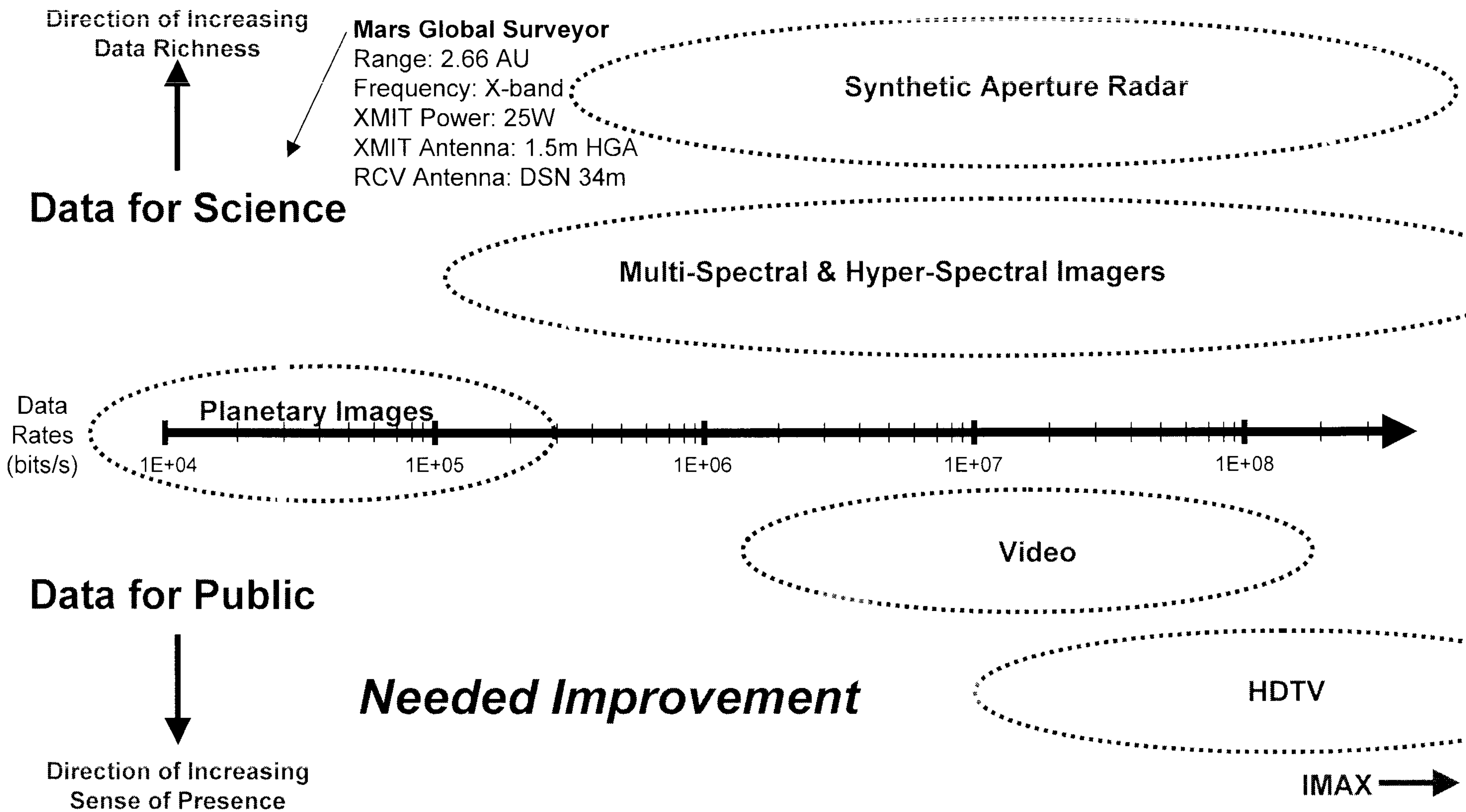
B&W Photos, Color Photos, Multi-Spectral, Synthetic Aperture Radar, Hyper-Spectral, Ultra-Spectral

**Remote Sensing at Other Planets:**

1958 → 2002+

B&W Photos, Color Photos, Multi-Spectral, Synthetic Aperture Radar, Hyper-Spectral

# Growth in Downlink Data Rates

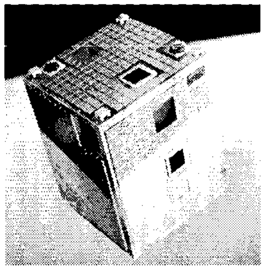


# Trend #4: Order of Magnitude (or more) Increases in Uplink Data Volumes

- Drivers
  - Increasingly capable on-board - and reprogrammable - processors, with increasingly sophisticated software, will require large volumes of data to be transmitted from Earth via high data rates links
  - JWST will require a 16 kbps uplink rate for instrument calibration flats
  - Uplinking will transition from low-level commanding to uploads of large image files and software updates
  - Autonomy may simplify the uplink process BUT increase uplink data volumes
- This Decade:
  - Emergence of a deep space mission (JWST) with uplink rate > 2 kbps
- Following Decade:
  - 10x to 100x increase in uplink data rates likely

# Near-Term, Near-Earth Missions with Software-Driven Uplinks

## PROBA



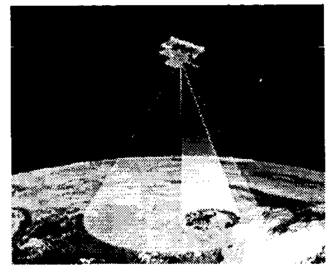
### ESA's Project for On-Board Autonomy

- Onboard autonomous agent provides for routine housekeeping and resource mgmt.
- Instrument planning, scheduling, and pointing also handled autonomously
- Requires upload of target request file

### Telecom Impacts:

- Reduction of downlink data associated with engineering telemetry
- 4 kbps uplink (2x > than current rate)

## Space Technology 6



### Autonomous "Sciencecraft" Demonstration

- Onboard autonomous agent selects interesting features for observation
- Data return decisions based on change criteria
- Some onboard analysis of data

### Telecom Impacts:

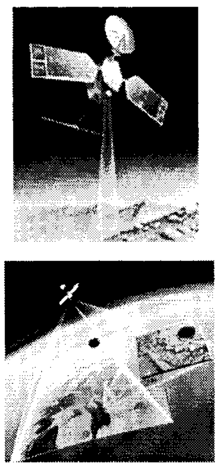
- Significant reduction of downlink data associated with science
- 50 kbps uplink (25x > than current rate)

# Looking Toward the 20-Year Horizon: Uplink Trends

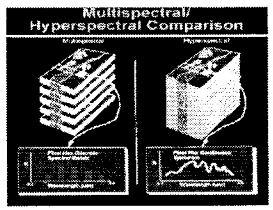


## The Changing Operations Paradigm:

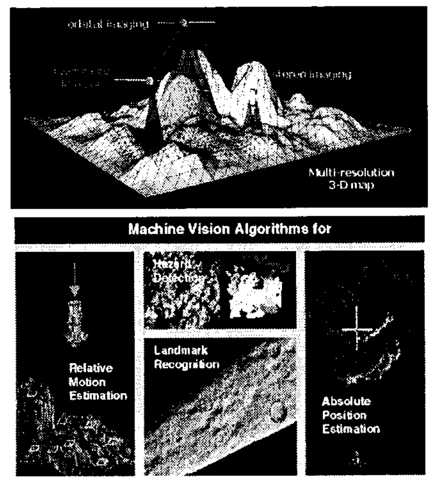
(1) More onboard autonomy, less low-level commanding.
(2) In situ exploration elements as consumers of orbital remote sensing data.



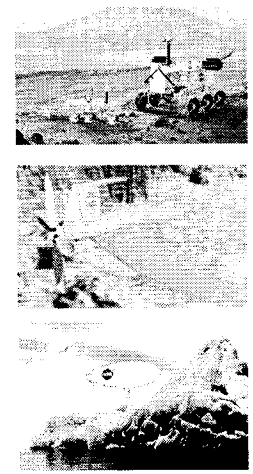
**Orbital Remote Sensing**




**Large Downlink Data Volumes**




**Production of GN&C and Science Targeting Data Products**



**Large Software Uploads on Uplink**

(3) Significant increase in uplink rate to accommodate software uploads.

- In-flight-retargetable cruise missile, UAV, and UGV analogies suggest an uplink rate of 200 kbps.
- 100x increase over today's uplink rate.

## Formal Vision Statement:

***"Enable telescience and telepresence throughout the Solar System - and beyond."***

## Colloquial Vision Statement:

***"Bring the sensors to the scientists and the planets to the public."***

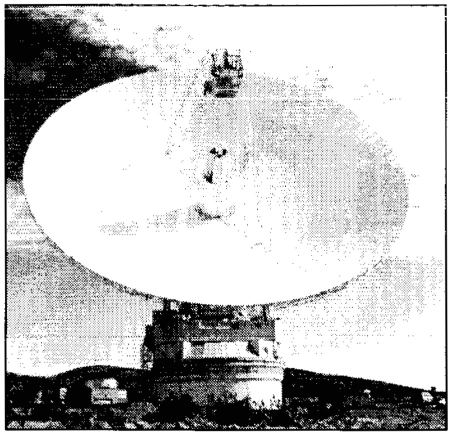
- The Goal is to transform the DSN into an Interplanetary Network that provides:
  - A sufficient number of links that are highly reliable and available on demand;
  - Transparent networked communications along with navigation, science, and operations services that facilitate accomplishment of customer objectives;
  - Orders-of-magnitude increases in downlink capability;
  - Order-of-magnitude increase in uplink capability.

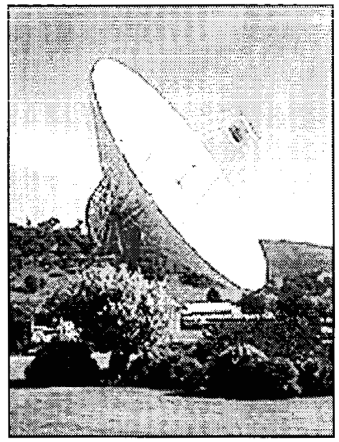
## Response #1: Increase DSN Link Capacity, Availability & Reliability

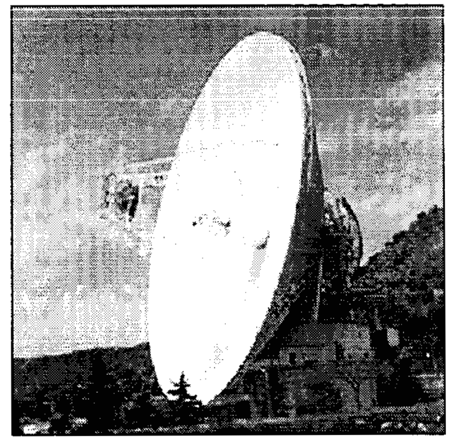
- Renovate and complete the "foundational" DSN
  - Refurbish the existing 70m antennas
    - Continue to provide maximum communications performance (Uplink & Downlink) for critical and/or anomalous events
  - Assess the utilization of 34m antennas
    - A case may exist for 1, or possibly 3, more
    - Provide adequate uplink capacity
- Increase availability and reliability
  - Today's DSN runs at ~ 98% availability (acceptable for a custom-equipped "R&D" type of facility)
  - Expanded customer base, with increasingly complex mission operations, will likely require significantly improved availability and reliability
    - Quantitative improvement goals remain to be specified and implemented
    - Will entail upgrade or replacement of obsolete systems, components and software

# DSN Antennas

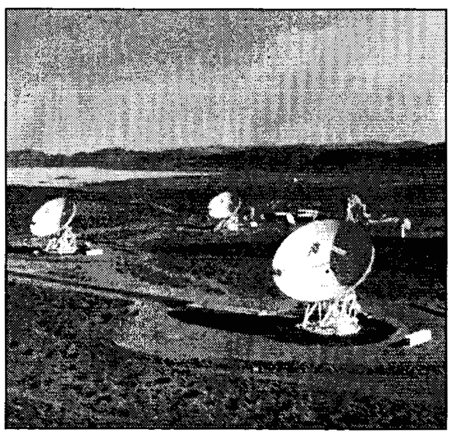
## 70m Antennas

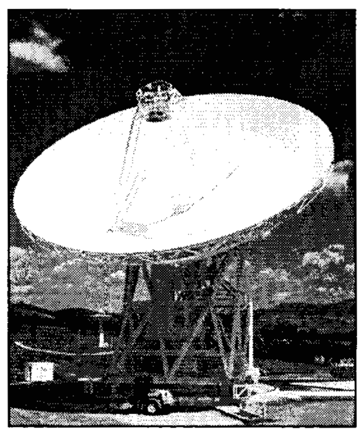

Goldstone: DSS 14

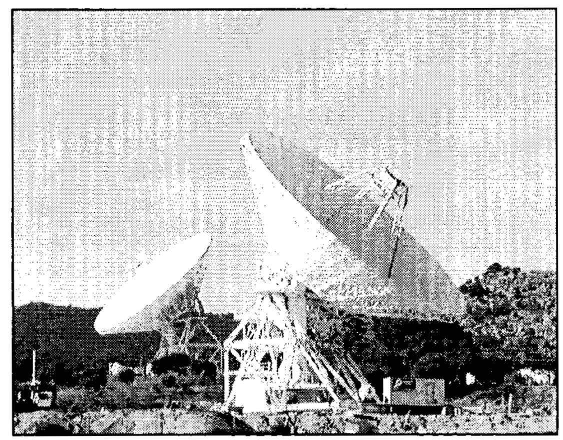

Canberra: DSS 43


Madrid: DSS 63

## 34m (Beam Wave Guide) Antennas


Goldstone: DSS 24, 25 & 26

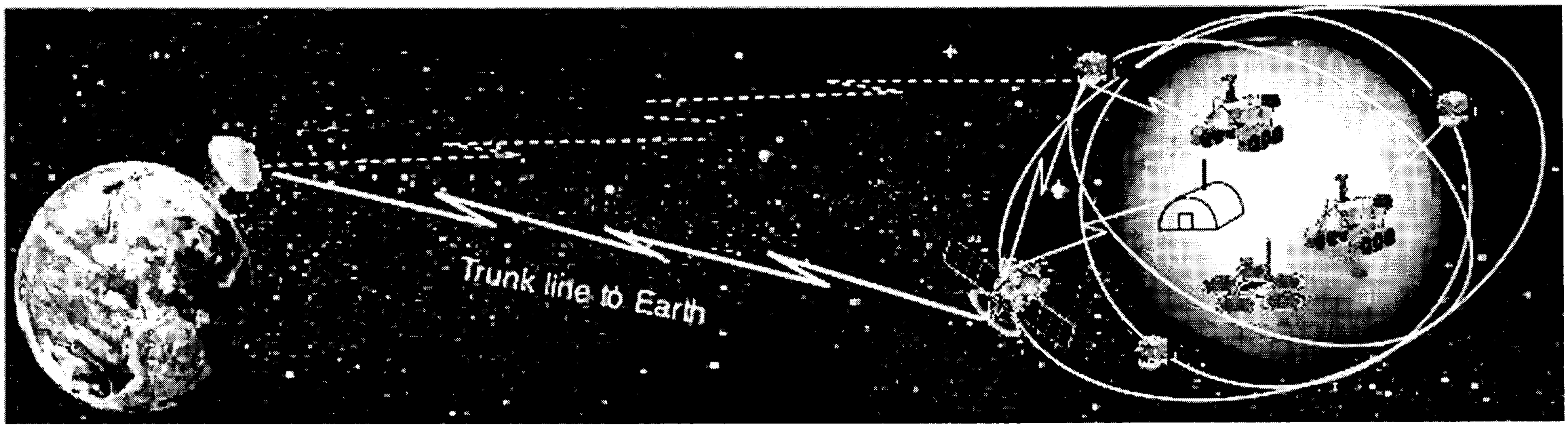

Canberra: DSS 34


Madrid: DSS 54 & 55

## Response #2: Develop a Standards-Based Service Paradigm

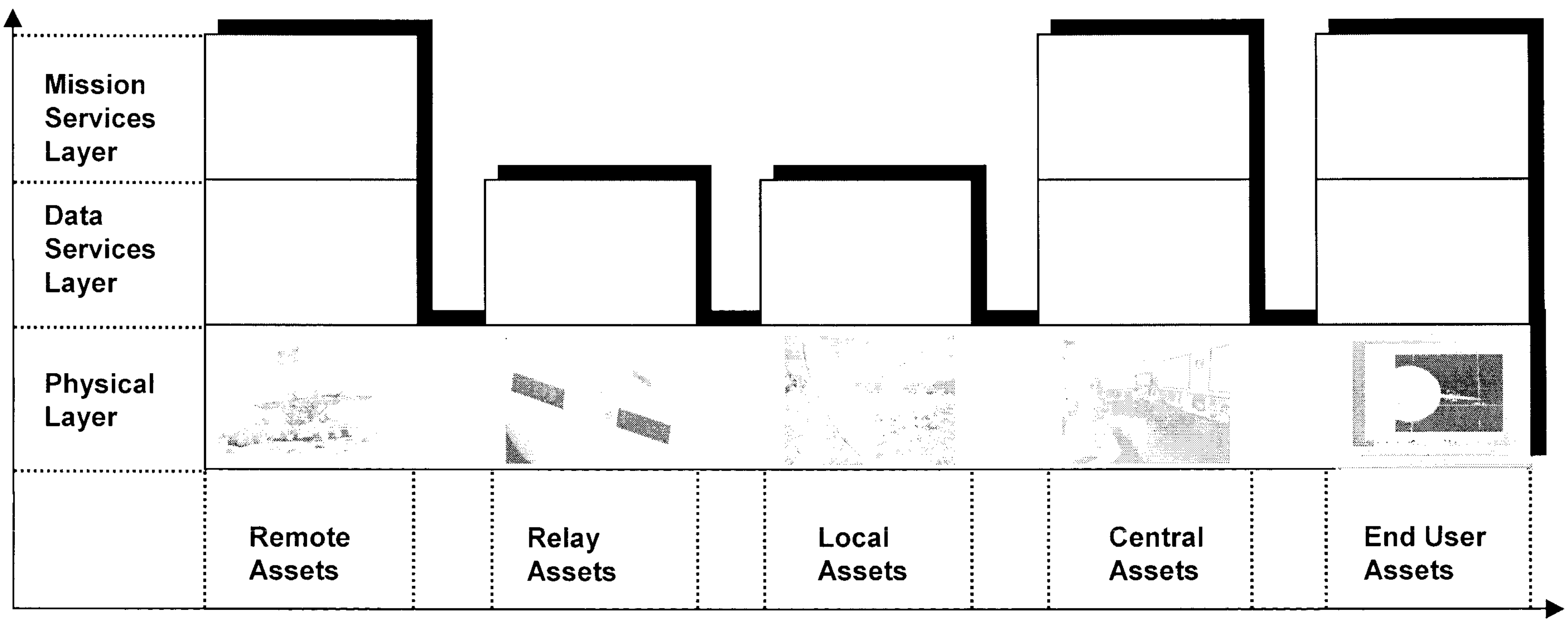
- Previously, mission interfaces with the DSN were *ad hoc* and customized
  - This worked well with 5 - 6 missions operating simultaneously
- Serving today's fleet of 25 - 30 spacecraft demands the benefits provided by standardization of services and systems
  - Efficient support for the many missions in operations
  - Cross support with spacecraft and tracking assets of other Agencies
  - Cost-effective implementations of new capabilities and services
  - Layered architecture for end-to-end data delivery
- Mars Network - the first "Planetary Area Network"
  - Relay infrastructure in Mars orbit enables expanded link availability, high rate communications and in-situ navigation
    - Comprises radio relay systems on existing science orbiters and, by 2010, a dedicated Mars Comsat
  - Key characteristics:
    - Standardized proximity link capability
    - Delay-tolerant, file-based communications protocols for seamless data transfer from Mars surface to scientists and public on Earth

# Mars Network



# "U-Chart"

- **Remote Asset** = Endpoint of a communication line in deep space or on a planetary surface
- **Relay Asset** = Waypoint of a communication line in deep space (e.g., MarsNet)
- **Local Asset** = Waypoint of a communication line on Earth or in near-Earth space (e.g., 70m, 34m or Arrayed Antennas; Photon-Buckets; Earth-Orbiting Optical Relay Terminal; non-NASA assets)
- **Central Asset** = Control point & distribution point for DSMS (i.e., JPL)
- **End User Asset** = Endpoint of a communication line at the user's location

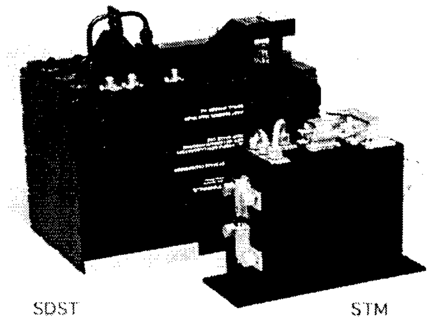


# Response #3: Increase Downlink Capability

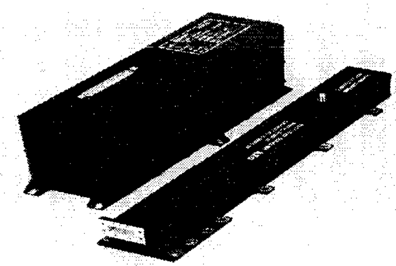
- Transition from X-band (8 GHz) to Ka-band (32 GHz) provides:
  - 4x gain (6 dB) - after accounting for losses
  - 10 x bandwidth availability (500 MHz vs. 50 MHz)
  - Though significant, this falls short of the eventual need
- The leap from 4x to 100x improvement in downlink requires:
  - Development of advanced flight telecommunications equipment
    - Radios (transponders, transceivers)
    - Power amplifiers - incl. kW class for nuclear powered missions (JIMO)
    - Deployable antennas
  - Addition of greatly expanded ground aperture at RF
    - Option 1: Implement additional large (34m-70m) monolithic antennas
    - Option 2: Implement a large array of small (12m) antennas
      - May achieve 10x-100x (or more) gain at lower "cost per unit aperture"
      - Validation of this assertion is the objective of an array prototype task
  - Optical communications can also provide "Orders-of-Magnitude" gain
    - Network of 6 - 9 10m ground-based "Photon Buckets" located so as to provide longitude coverage and weather diversity
    - 1 or 2 7m telescopes in high Earth orbit
    - Other options: Ground-Space hybrid; Large Array of Small Telescopes

# New Flight & Ground Developments

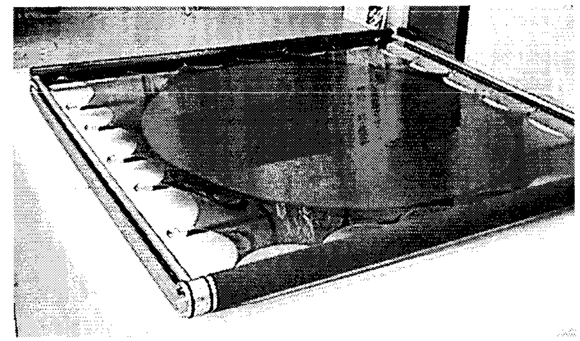
## Flight Telecommunications Equipment




Radios
- Transponders
- Transceivers



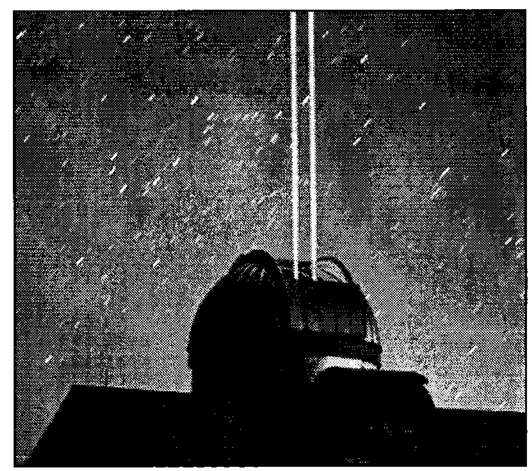
Power Amplifiers
- Solid State
- Traveling Wave Tube



Antennas
- Deployable
- Inflatable

## Large Array of Small Antennas

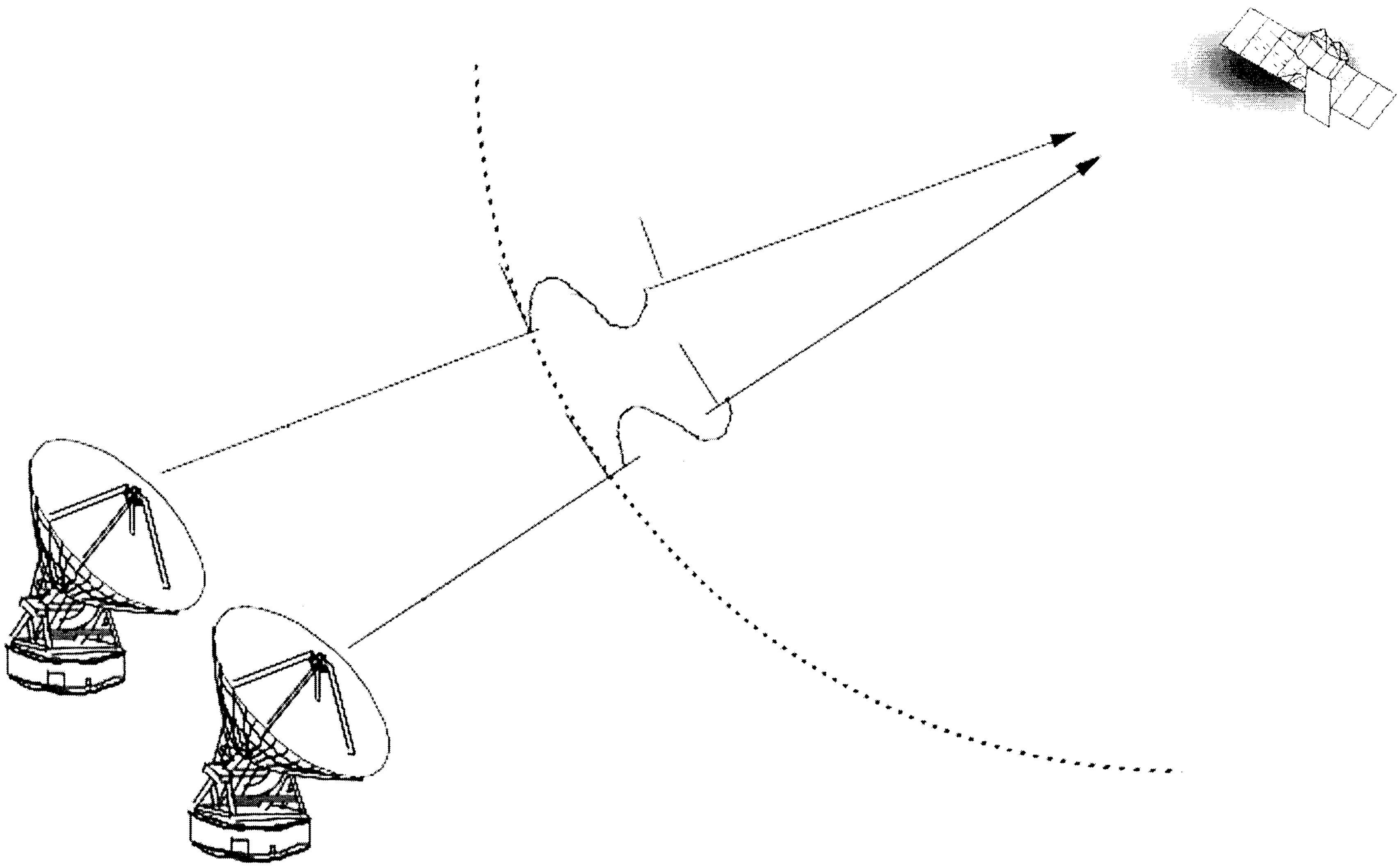
## Deep Space Optical Communications



# Response #4: Increase Uplink Capability

- Classically, Effective Isotropic Radiated Power (EIRP) is provided on target by means of a high power transmitter on a large microwave antenna
  - Needed for routine high-rate uplink or emergency communications
- Today's maximum DSN X-band performance is 20 kW on a 70m antenna
  - Raises issues about 70m longevity (currently 30-40 years old)
- The DSN also currently employs 20 kW at X-band on 34m antennas
  - Smaller aperture results in 6 dB performance decrease
  - Raises issues about whether there are a sufficient number of 34m antennas
- Alternative approach involves the use of arrayed uplink
  - Somewhat analogous to arraying antennas for downlink
  - But it is difficult to have knowledge and control of the phase front
    - Closed loop control with deep space vehicles is not possible
  - Nevertheless offers great potential to put extremely high EIRP on target
  - Technology effort will strive to demonstrate feasibility and retire technical risk
  - Applicable to existing large antennas or to a large array of small antennas

# Uplink Arraying



# Summary