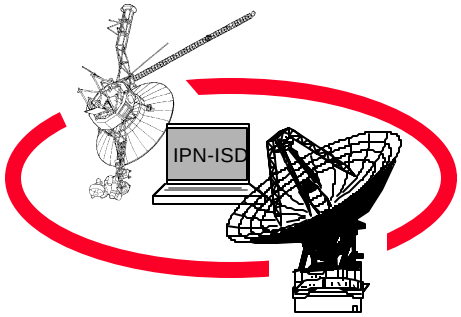
Technologies for the InterPlanetary Network



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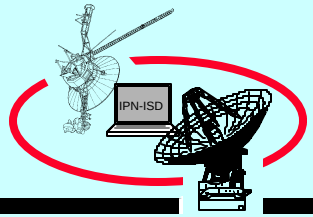
California Institute of Technology

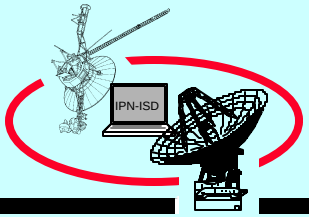
Core Technologies for Space Conference

November 28, 2001

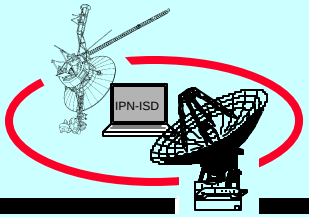
Outline



- Current Deep Space Network (DSN) capabilities
- Future mission needs and constraints
- The InterPlanetary Network (IPN) vision
- Elements required for the vision
  - High capacity interplanetary trunk lines
  - Planetary Local Area Network technologies
  - Supporting information technologies
- Summary



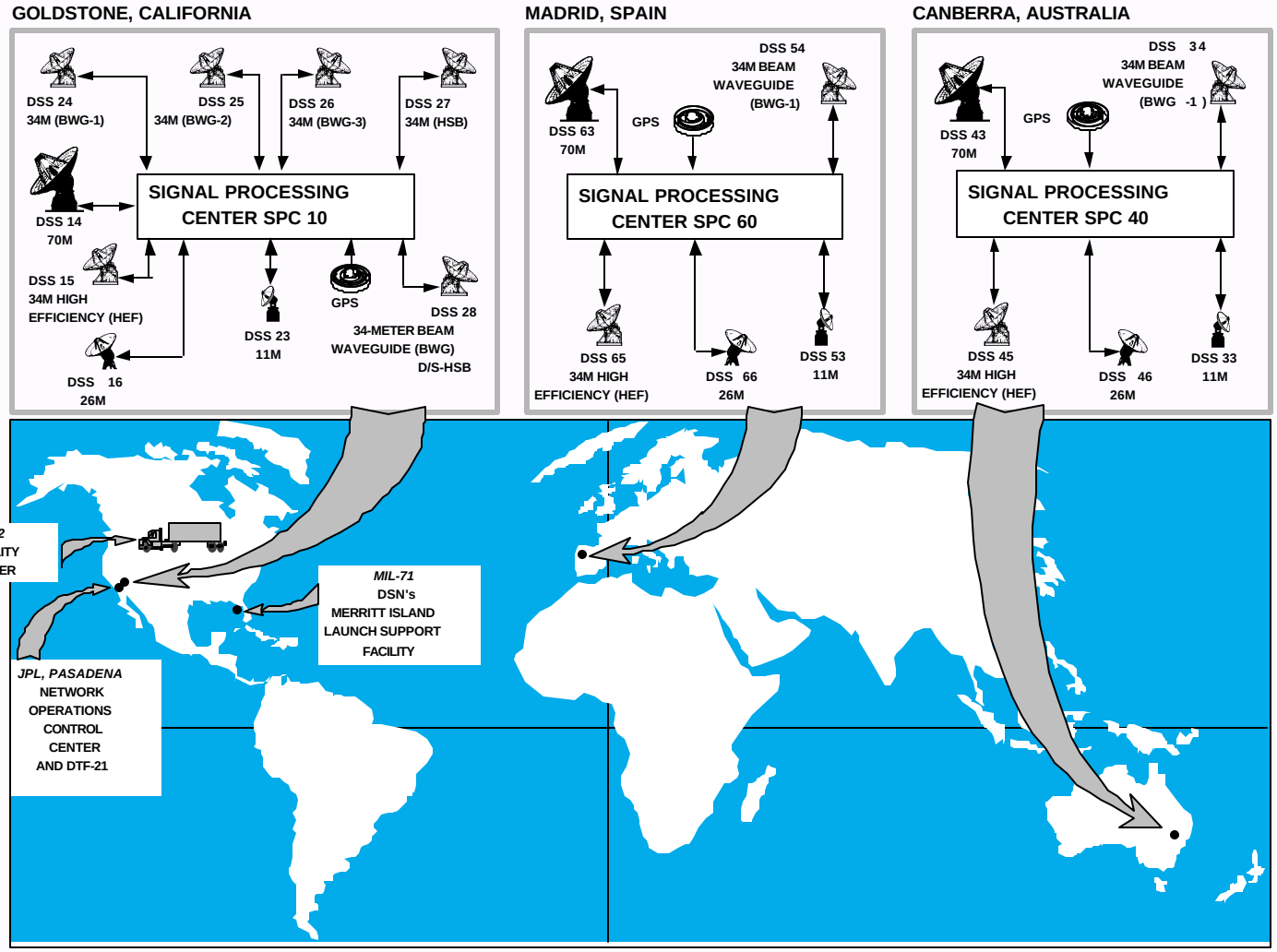
Current Deep Space Network Capabilities



Current Deep Space Communications

- Large antenna assets on Earth
- Precious rationing of resources on scientific spacecraft
  - Mass, power and size are at a premium
- Primarily single link established between S/C and ground
  - Sometimes via intermediate relay (e.g. planetary surface to planetary orbiter to Earth)
- Intermittent link connections with changing topologies
  - Planetary rotations (including Earth)
  - Orbits of S/C around target planets
  - Orbits of planets around the sun
- Most of the intelligence resides on Earth
  - Link connection scheduling done on ground
  - Ground system keeps track of data flow
  - Autonomy on S/C only if required for specific mission functions
- Data rates are modest
  - 10's-100's of kbps from Mars
  - 1-10kbps from outer planets
- Essentially a circuit-scheduled, low-rate, remote-control networks

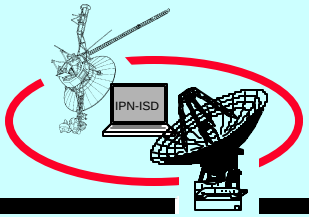
Current Ground Infrastructure



- 70-m antenna

- 34-m antennas

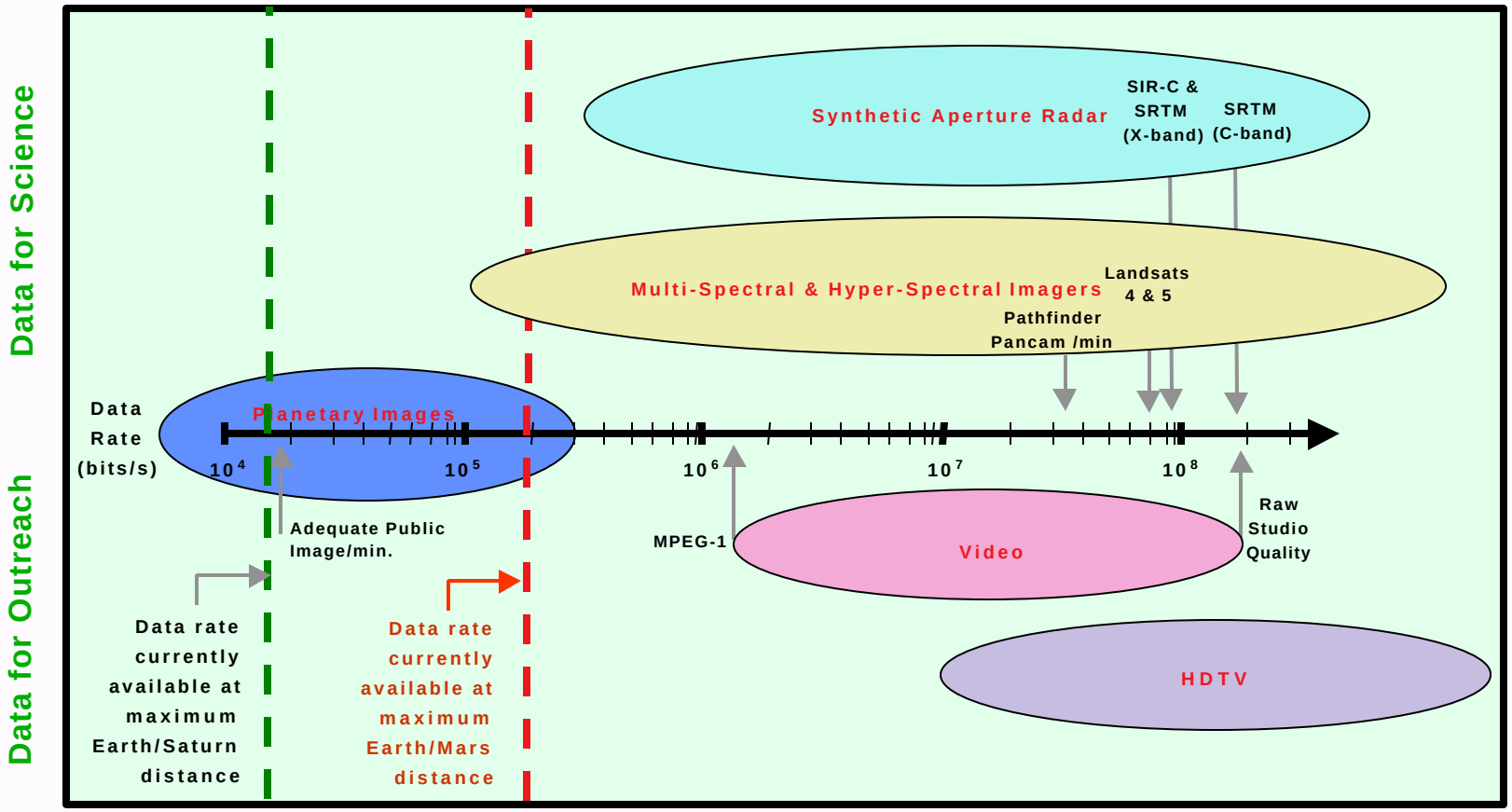
- One 70-m antenna and several 34-m antennas at each geographical location



Future Mission Needs and Constraints

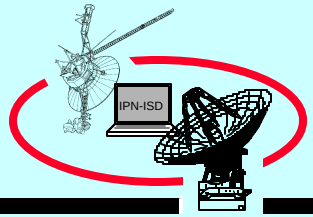
Code S Mission Needs

Future Scientific and Outreach Needs



- Data rate requirements for science and public outreach are factors of 10 to 100 higher than can be provided by current communications technology

Physics and Other Constraints



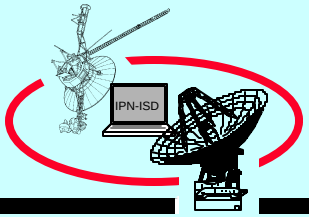
- **Communications Over Extreme Distances**
  - **Communications performance scales as $1/R^2$**
  - **Communicating with an Outer Planet mission like Neptune or Pluto is *~10 billion* times more difficult than communicating from a commercial GEO satellite to Ground**
    - **1000 times more difficult than a Mars-Earth link at nominal Mars-Earth range**
- **Wide Range of Environments**
  - **Challenging thermal, radiation, shock requirements**
    - **E.g. MRad radiation levels at Jupiter**
  - **Outer planet solar intensity very weak ---> Electrical power difficult to generate**
    - **Often requires use of nuclear power sources for far outer planet missions**
- **Additional Navigation Constraints**
  - **Comm signal also used for navigational tracking**
- **High Launch/Delivery Cost per Unit Payload Mass**
  - **Drives need for low mass, low power and low-cost flight systems**

Code S Mission Needs (Cont.)

Current communications subsystems require significant spacecraft resources

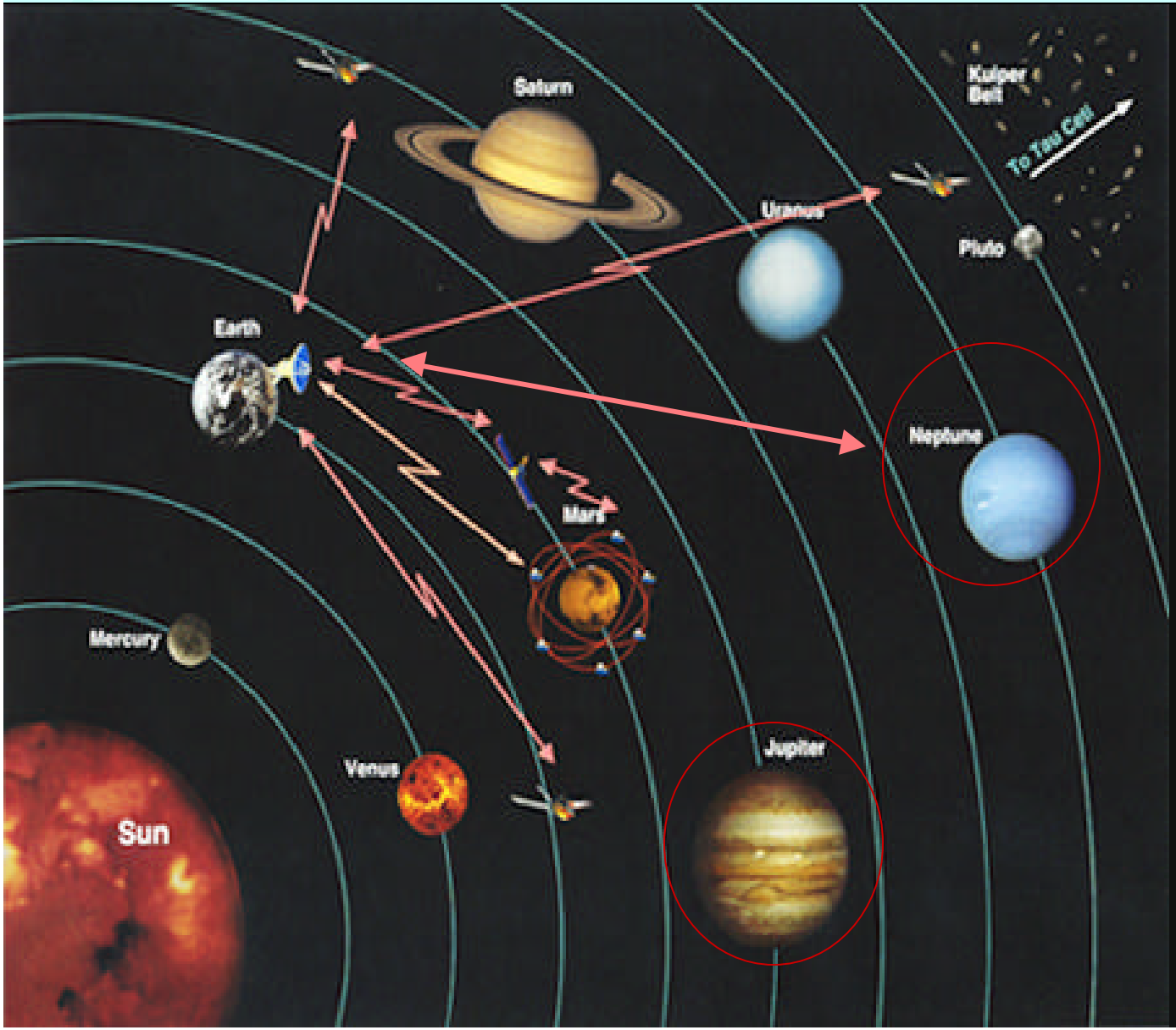
Mission	Study Date	Peak Power (W)			Dry Mass (kg)		
		Comm.	total	fraction	Comm.	total	fraction
Venus Sample Return	Feb-99	41	79	52%	11	454	2%
Comet Nucleus Sample Return	Mar-98	281	396	71%	23	766	3%
Europa Lander	Oct-98	27	68	40%	10	190	5%
Jupiter Deep Multiprobes	Oct-01	70	172	41%	27	272	10%
Titan Explorer	Jun-01	112	234	48%	37	345	11%
Saturn Ring Observer	Apr-99	72	125	58%	11	111	10%
Neptune Orbiter	Apr-99	122	184	66%	13	116	11%

- **Approximately 40-70% of the spacecraft prime power is allocated to the communications subsystem during peak communications periods**
- **The percentage of the communications subsystem dry mass increases from 2% for Venus mission to >10% for outer planet missions**



The Vision

The InterPlanetary Network Vision

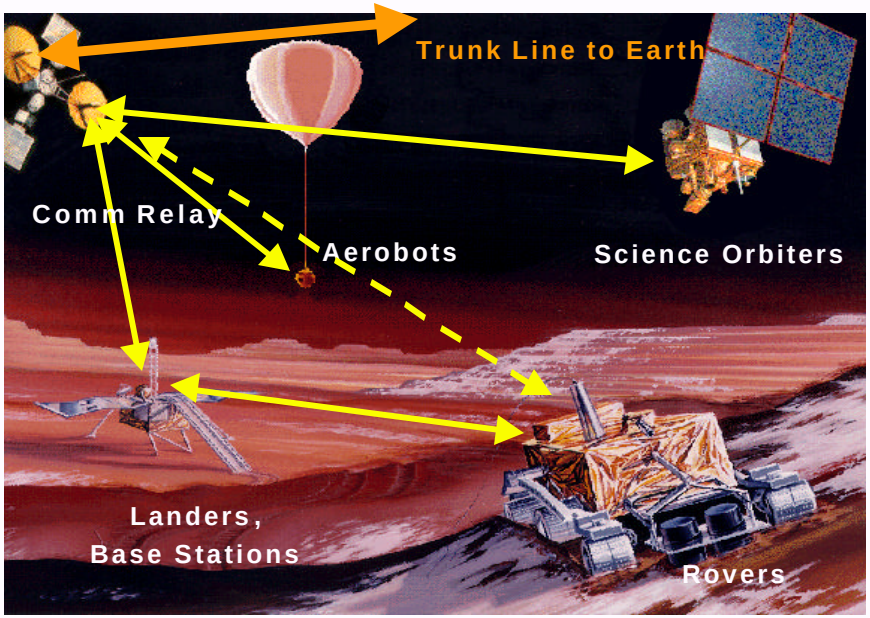


A network of networks, connecting nodes across the Solar System

Robust, high bandwidth links that are easy to establish, evolvable, transparent to the user, & secure.

End-to-end information delivery System

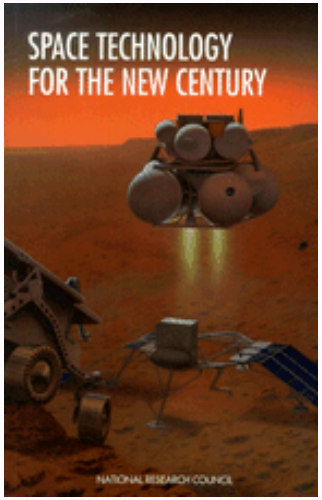
Supports NASA's Vision



NASA's Strategic Plan 2000

- Code S - "allow the public to participate 'virtually' in the adventure of exploring new worlds"

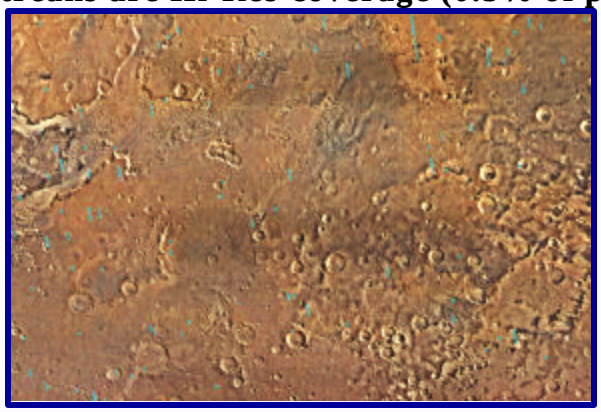
The National Research Council identified Wideband, High Data-Rate Communications over Planetary Distances as one of the six space technology needs of NASA for the next century.

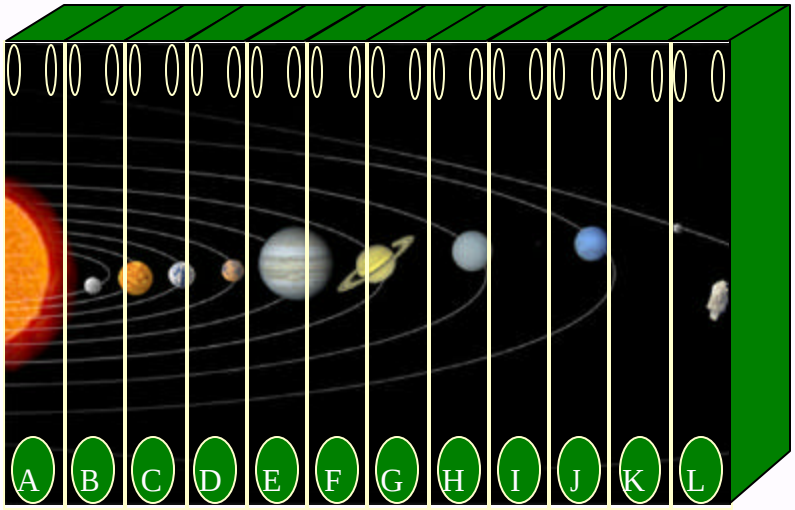


A Living Solar System Encyclopedia

- Mars 05 will map only 1% of the Mars surface at high (20 cm) resolution
  - We may miss many important discoveries
- If, instead, we had high BW communications wherever we explored, we could assemble a comprehensive data repository
  - A living encyclopedia with all the fusion and cross indexing expected in such a compendium
  - Automatically updated through the IPN
  - Including data that has not been fully analyzed by NASA scientists!
- High school and college students could explore truly-unknown territory and make real first-time discoveries or test theories
- As further missions occur, we would fill in details
  - Students could use "NASA as Educator" assets to fill in data themselves!
- Future mission planners could more effectively plan the next series of missions
- Allows science to continue decades after the physical mission has ended

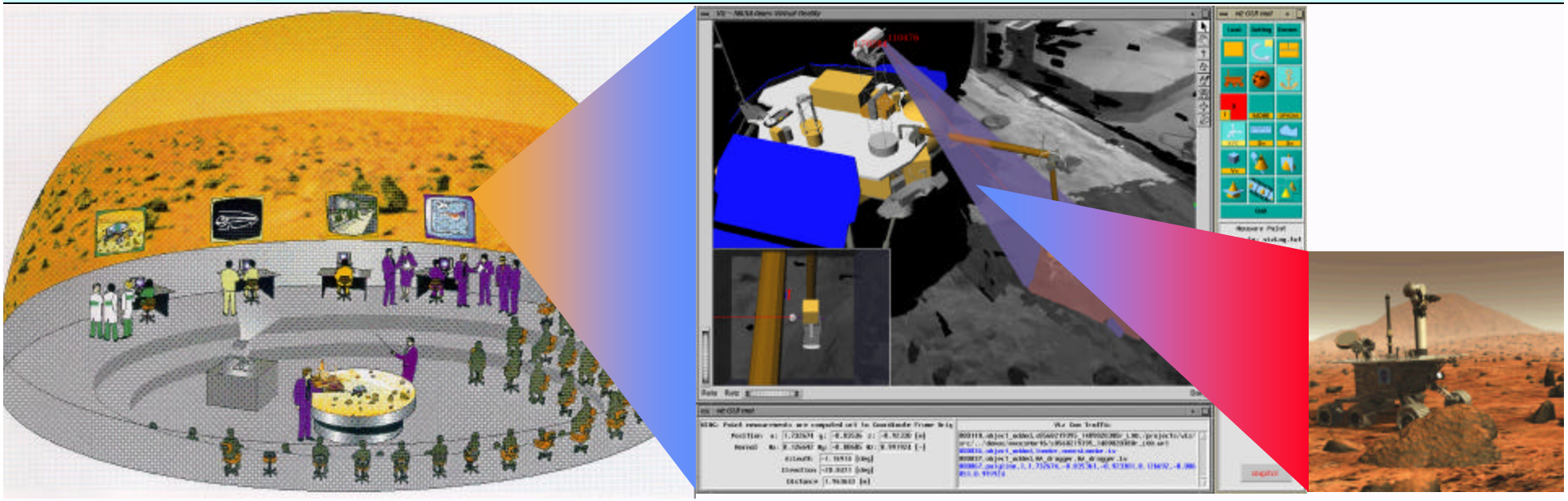
Mars Global Surveyor Mission
Blue streaks are Hi-Res coverage (0.3% of planet)



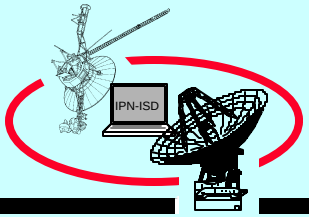


Living Solar System Encyclopedia

Virtual Exploration



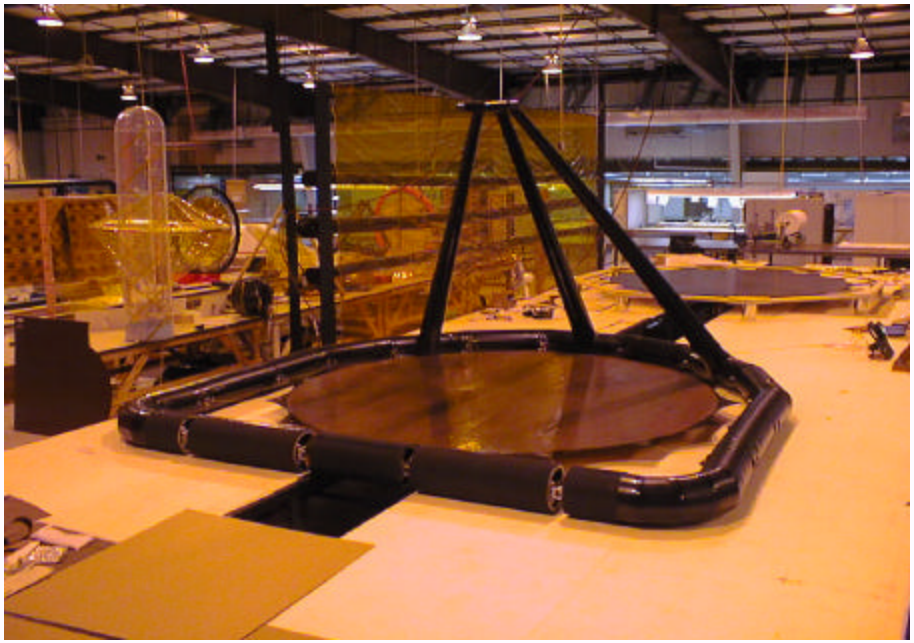
- Future deep space exploration will involve much more complex exploration
  - In situ science analysis, Sample handling and return, Cooperating sciencecraft
- Humans will have to interact with these missions as the primary explorers
- The IPN will allow explorers to interact with their “ships” without actually traveling along
- Visualization and control applications, enabled by communication, shared computing, and shared sensors, will allow scientists to share in the immediacy and excitement of initial discoveries, resulting in more human-like strategies for reacting to the unknown
- The IPN would allow humans to travel to Mars orbit and participate in real-time telerobotics on the Martian surface



Elements Required for the Vision

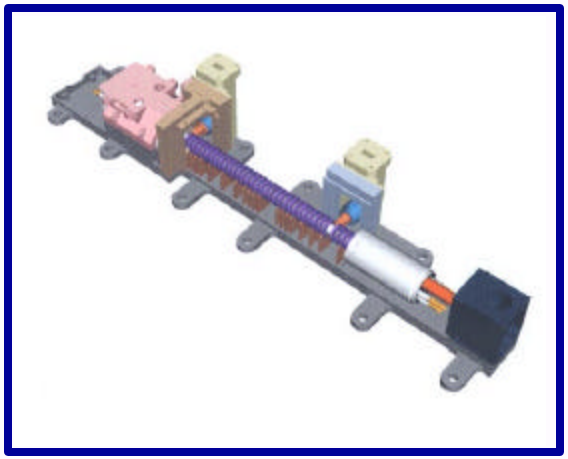
Ka-band (32GHz) Communications

Spacecraft Technology

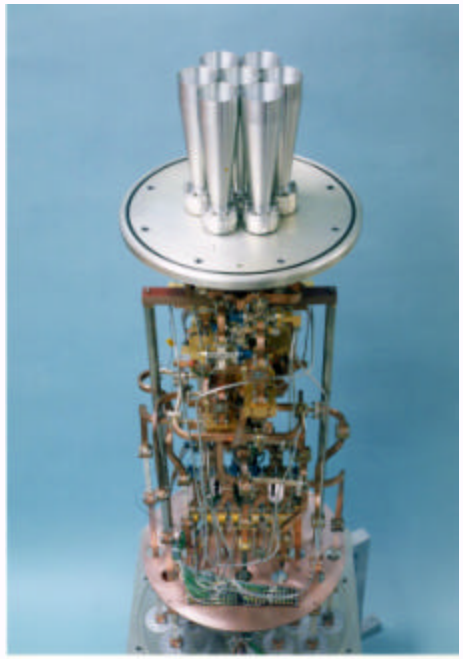


3m Diameter Ka-band Inflatable Reflectarray Antenna

35W Ka-band Traveling Wave Tube Amplifier (TWTA)



Ka-band on 70 m Antennas

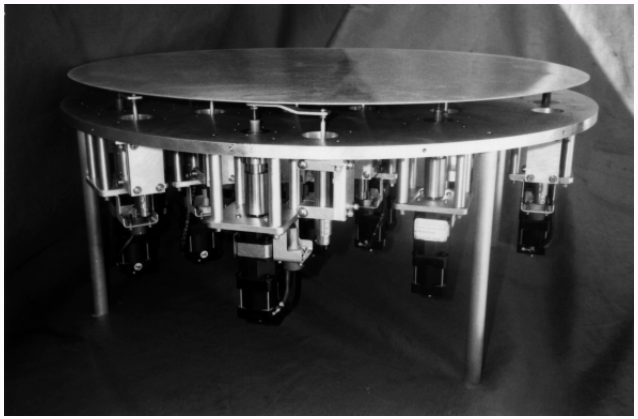


Seven Element Array Feed with 4.45-cm Diameter Dual-Mode Horns

- **Study and Test Two Candidate Technologies:**

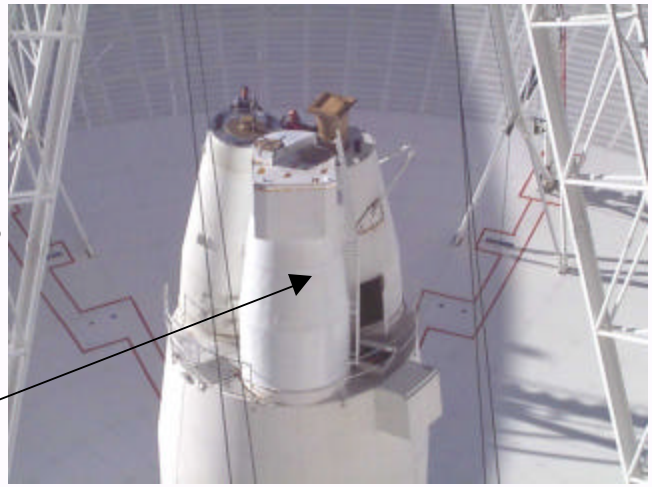
A: 7 element Array Feed Compensation System (AFCS) is a close loop system for surface distortions, optics misalignments and tracking

B: 16 actuator Deformable Flat Plate (DFP) is an open loop system for gravity distortion compensation, with a Monopulse tracking feed added for close loop tracking



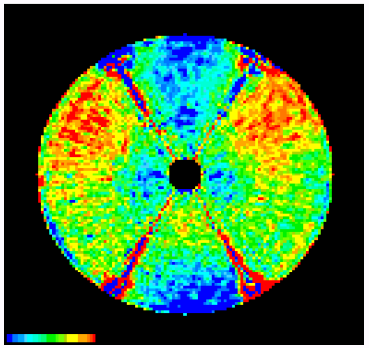
DFP side view. Mirror surface is adjusted either up or down by 16 motors

Preliminary test results show 2.8 dB combining gain / compensation at 8.5 deg. El when both the AFCS and DFP operating jointly



Holography cone installed on DSS-14 with integrated DFP, AFCS, MP, TPR, and Holography

•Gravity Roll-Off of DSS-14 :
6.5-dB at 80-deg El
3.6-dB at 12-deg El



Increased Effective Ground Aperture

- **Techniques are being investigated to increase the effective ground collection area**
  - **Larger antennas**
  - **Arrays of smaller antennas**

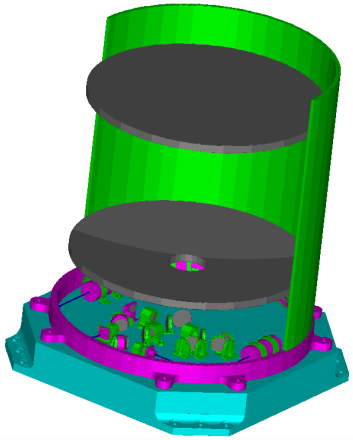
Optical Communications Developments

- **Important initial technology steps have been taken**
  - **Optical Communications Demonstrator**
  - **GOPEX (Galileo) and GOLD (ETS-VI) demonstrations**
  - **Designs for multi-function optics**
    - **Optical comm/imaging/laser altimeter**
- **Installing a 1-m Optical Comm. Telescope Laboratory (OCTL) at Table Mtn**
  - **Will support optical comm technology validations and near-Earth system demonstrations**

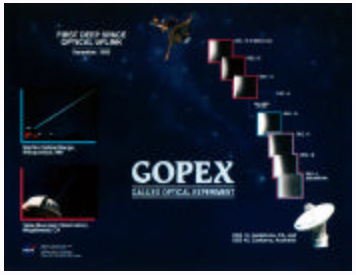
Optical Comm Demonstrator
- 10 cm telescope
- Fiber-coupled laser

GOLD/ETS-VI Demo
Table Mtn Facility

1-m OCTL Facility (under construction)

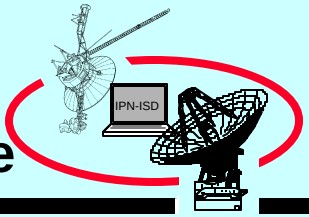


30-cm Optical Comm Terminal with Hi-Res. Imaging and Laser Alt. Reception



GOPEX Deep-Space Demo with
Table Mtn Facility and Starfire Optical Range

Communications Improvements Possible



- X-band (8 GHz) - Current baseline capability
- Ka-band (32GHz) communications (ready for infusion)
  - 11.6dB theoretical gain over X-band
  - 4-6 dB enhancement available immediately; more later with improvements
- Optical Communications
  - 65dB theoretical gain relative to X-band
  - 10+ dB enhancement relative to X-band in the near term
  - Large (10's of dB's) additional growth potential over time as technology matures
- These performance gains can be used to:
  - Increase science data return, or
  - Reduce the impact (mass/power) on S/C (for a given data rate), or
  - Reduce required contact time with (and costs of) ground reception station support, or
  - A combination of the above

Example

A 10dB gain can enable:

- 10x data return, **or**
- 90% power reduction*, **or**
- 90% reduction in GND tracking time, **or**
- Combined impact of:
  - 2.5x data return, **and**
  - 50% reduction in power*, **and**
  - 50 % reduction in ground time

- Ka-band is being developed and is ready for initial deployment.
- Optical communication needs to be developed and validated

Mars Network (First Stop on IPN)

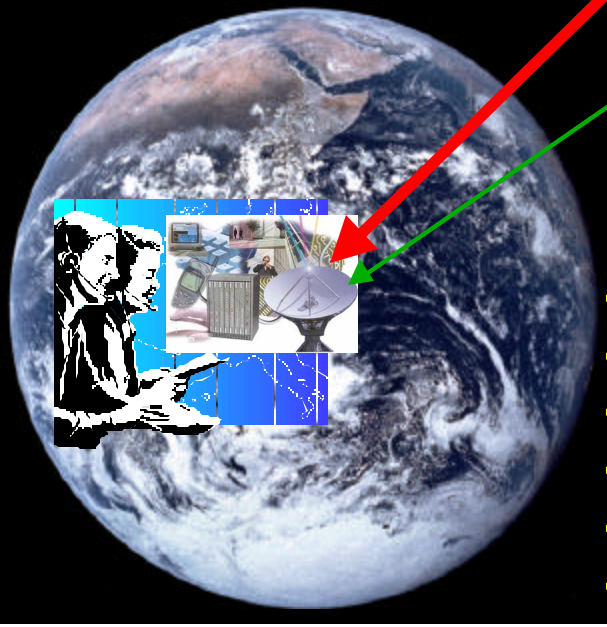
Flight Elements:

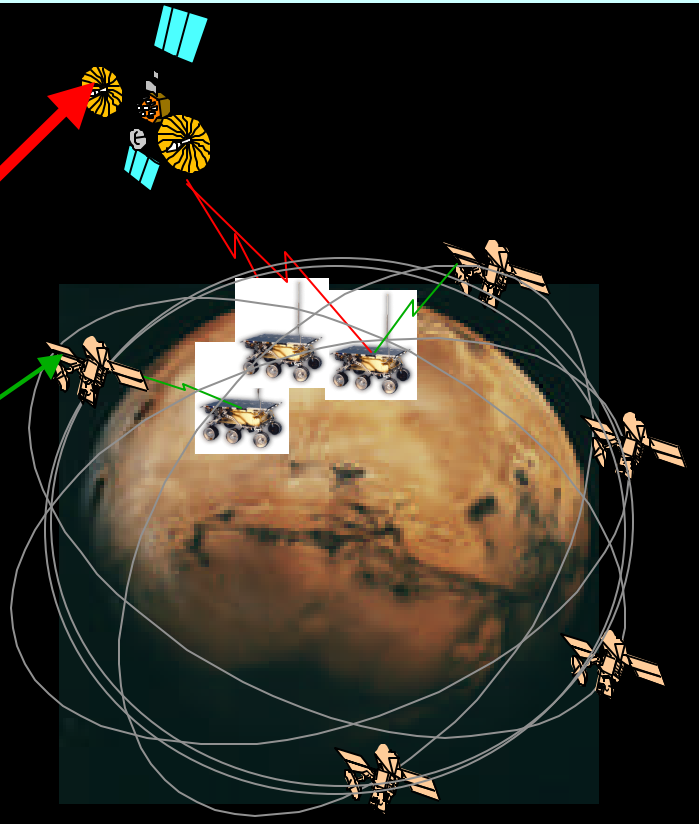
Low-Altitude Constellation

- *>1Gb/sol low-lat data return*
- *10-100m position determination*

Areostationary MARSAT

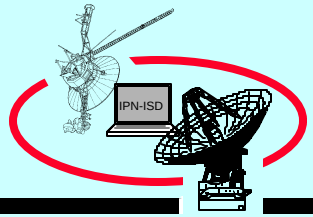
- *1Mb/s near-continuous contact, streaming video*
- *100 Gb/sol data return*





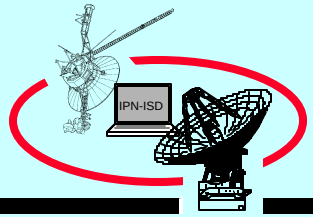
- *Breakthrough communications bandwidth increases on interplanetary links*
- *Seamless end-to-end information flow across the solar system*
- *Layered architecture for evolvability and interoperability*
- *IP-like comm protocols tailored to operate over long round trip light times*
- *Efficient, miniature short-range communications systems*
- *Integrated communications and navigation services*

Other Technologies Required



- Ubiquitous in-situ local navigation at primary targets of interest (e.g. Mars)
- Network architectures that minimize additional asset investments while maintaining robust connectivity
- Efficient end-end protocols that guarantee data delivery (even over multiple-hop dynamically-routed links) while respecting the need for overall communications power efficiency
- Distributed intelligence that allows new modes of space exploration operation
- User-friendly exploration data bases
- Information fusion techniques
- Virtual reality immersion systems

Conclusions



- Current capabilities for interplanetary communications are very limited
- Future missions will require significantly more capability and infrastructure service
- The InterPlanetary Network Vision encompasses those needs
- Key technologies are being developed
  - High capacity, long-haul trunk lines
    - Ka-band initially
    - Optical communications
    - Larger effective ground apertures
  - Network technologies
    - Architectures
    - Protocols
    - In-situ navigation
    - Distributed intelligence
  - Information systems
    - Information fusion
    - Visualization systems
    - User-friendly data bases