Transforming the Deep Space Network into The Interplanetary Network

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54th International Astronautical Congress
Bremen, Germany
September 29 - October 3, 2003
Topics

- Strategic Motivation
- Transformation of the Mission Paradigm
- Performance Transformation
- Topological Transformation
- Service Model Transformation
- Summary
The NASA Strategic Plan

Objective 10.3

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

A Key Item of JPL's Mission Statement is:

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

Interplanetary Network Vision

Formal: “Enable telescience and telepresence throughout the Solar System - and beyond.”

Colloquial: “Bring the sensors to the scientists and the planets to the public.”
Transformation of the Mission Paradigm
Transformation of the Mission Paradigm

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**

- GLAST
- GRAVITY PROBE B
- SWIFT
- SPIDR
- EUSO
- WISE
- LISA
- DARK ENERGY PROBE
- EXPLORER MISSIONS
- CONSTITUTION-X
- INFLATION PROBE
- BLACK HOLE FINDER
- PROBE
- EXPLORER MISSIONS
- BEBIG BANG OBSERVER
- BLACK HOLE IMAGER
- EXPLORER MISSIONS

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**Key**

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

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*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.

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**Very Approximate Launch Epoch**

- **2008**
- **2013**
- **2018**
- **2023**
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
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
Spacecraft data storage trends suggest collected data volumes will increase by 1-to-2 orders of magnitude.

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

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

Deep space downlink rates are increasing by 1-to-2 orders of magnitude as well.
• **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**
  - B&W Photos
  - Color Photos

- **2002+**
  - Multi-Spectral
  - Synthetic Aperture Radar
  - Hyper-Spectral
  - Ultra-Spectral

**Remote Sensing at Other Planets:**

- **1958**
  - B&W Photos
  - Color Photos

- **2002+**
  - Multi-Spectral
  - Synthetic Aperture Radar
  - Hyper-Spectral
Growth in Downlink Data Rates

Data for Science

Direction of Increasing Data Richness

- Mars Global Surveyor
  - Range: 2.66 AU
  - Frequency: X-band
  - XMIT Power: 25W
  - XMIT Antenna: 1.5m HGA
  - RCV Antenna: DSN 34m

- Synthetic Aperture Radar

- Multi-Spectral & Hyper-Spectral Imagers

Data for Public

Direction of Increasing Sense of Presence

- Needed Improvement

- Video

- HDTV

- IMAX

Direction of Increasing Data Richness

Range of Data Rates (bits/s): 1E+04 to 1E+08
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 rate 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:
  - 10 x to 100x increase in uplink data rates likely.
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)
The Changing Operations Paradigm:

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

From Science Constraint to Science Enhancement

First Step: 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
- Transition from X-band (8 GHz) to Ka-band (32 GHz) provides:
  - 4x gain (6 dB) - after accounting for losses
  - 10x bandwidth availability (500 MHz vs. 50 MHz)
  - Though significant, this falls short of the eventual need
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
The leap from 4x to 100x improvement in downlink requires:

- Development of advanced flight telecommunications equipment
  - R adios (transponders, transceivers)
  - P ower amplifiers - incl. kW class for nuclear powered missions (JIMO)
  - D eployable antennas

- Addition of greatly expanded ground aperture at RF
  - O ption 1: Implement additional large (34m-70m) monolithic antennas
  - O ption 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
  - N etwork 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
  - O ther 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
Towards Uplink > 100x

- 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
Performance Transformation

Navigation & Flight Control

Example Challenges

- Precision Landing
- Aeromaneuvering
- Multi-Spacecraft Ops

Example Solutions

- Higher Frequency RF Tracking
- Navigation Via In Situ RF Links
- Optimetrics
- Autonomous Navigation
Topological Transformation
From US/NASA to a Virtual International Network

- Deep space communications has traditionally been done by the US Deep Space Network, operated for NASA by JPL

- Other entities are now seeking a role in this aspect of space exploration
  - The European Space Agency (ESA) has recently commissioned a 35m antenna at New Norcia, near Perth, Australia
  - Additional ESA 35m antennas may follow (e.g., at Cebreros, Spain)
  - Agenzia Spaziale Italiana (ASI) has expressed interest in a deep space tracking role for the Sardinia Radio Telescope
  - Centre National d'Etudes Spatiales (CNES) has also expressed interest in implementing and operating deep space tracking stations

- A “Virtual International Network” may naturally come into being
  - Seamless interfaces among variously-owned assets will enable efficient data transfer
  - End users will be connected to their spacecraft without ever knowing -- or caring -- about the routing used to establish the connection
Site Diversity

- An Earth-based optical communications network will likely comprise 6 to 9 sites
  - Good longitude coverage
  - Weather diversity
- A Large Array of Small (RF) Antennas may eventually expand to sites other than the existing DSN complexes
  - Maximizes the likelihood of achieving good Ka-band links, which are also susceptible to weather effects
- Thus the DSN may transform from a 3-Complex Network into a 6- to 9-Complex Network - perhaps even more
  - For cost-effectiveness, most, if not all, additional sites will be designed to function autonomously, with minimal infrastructure.
Topological Transformation

From Earth-Based to Earth + Space-Based

- Mars Network -- the first “Planetary Area Network”
  - Relay infrastructure in Mars orbit enables expanded link availability, high rate communications and *in-situ* navigation
    - Currently comprises radio relay systems on existing science orbiters
      *Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter (in development)*
    - By 2010 will include a dedicated Mars Comsat
      *Mars Telecommunications Orbiter*
  - 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
  - “Planetary Area Networks” will eventually appear at other locations around the solar system
    - These will be linked together by “big pipe” trunk lines
Mars Network

*Trunk line to Earth*
From Point-to-Point to Networked Architecture

- Classically, deep space communications involved a point-to-point link between an asset in deep space and a large DSN antenna on Earth.

- The future is likely to witness an expansion in the number of:
  - Exploration assets in deep space
  - Relay communications assets (e.g., Mars Network)
  - Communications assets at the Earth (Antennas, Telescopes)

  *Note: These can all be thought of as nodes in a communications network*

- An expansion in the number of computers (nodes) was a key element in the development of the terrestrial Internet.

  - By analogy, a networked architecture will evolve to support deep space communications.
  - This is coming to be known as the Interplanetary Network.

- This networked architecture **WILL NOT** emplace a router on every planetesimal in the solar system.

- But it will provide routing options for end-to-end links all the way from a remote asset in deep space to an investigator's desktop or a school classroom.
Internationally Standardized Communications Protocols

• In a modern network, several underlying layers of standard data communications protocols support exchange of information among user applications

  • Each layer has rules by which the sending and receiving ends can perform a modular part of the total dialog

  • A layered architecture is highly amenable to evolution since layers can be replaced, as technology changes, without bringing down the whole system

• CCSDS* has worked to define and reach international agreement on space link communications standards and protocols

  • Recently the CCSDS has been expanding its scope to include new end-to-end "space internetworking" capabilities

  • An example is the "Bundling" protocol suite that provides a long-haul analog of the Internet's TCP/IP suite

* CCSDS = Consultative Committee on Space Data Systems
Layered Network Architecture

- **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
Service Model Transformation
From Complexity to Simplicity

In the early days of space exploration
- Missions were relatively simple - at least as viewed from today!
  * Typical mission was a planetary flyby - with some notable exceptions!
- But they had complex interfaces among mission & DSN elements
- Telecommunications capability increased at a dramatic pace
  * Flight Systems; Ground Systems; Frequencies; Coding
- Custom equipment / interfaces and customer involvement were the norm
- This worked well with 5 - 6 missions operating simultaneously

The current era requires a new approach, called the Service Paradigm
- Driven by the number of missions, and their complexity
- Innovations that have proven workable become standardized services
- Users need not have intimate knowledge of the information systems
- Service Contracts are written during design and executed during operations
- End Goal is transparent acquisition of science or outreach data so that users are free to focus on their discipline objectives

Standardization and the Service Paradigm encourage technological progress
- Scarce resources are not expended on “reinventing the wheel”
- Layered architecture easily accommodates technological innovation
Network & Service Reliability

- To make the Service Paradigm a reality, it will be necessary to significantly upgrade the reliability and availability of the DSN
  - When services are delivered with very low failure rates, users have little reason to delve into how they are provided
  - By contrast, nothing will get a user scrutinizing the service provision system faster than failures to deliver
- Today’s DSN runs at ~ 98% availability
  - Acceptable for a custom-equipped “R&D” type of facility
  - Probably not acceptable for supporting the expanded customer base, with increasingly complex mission operations
    - Quantitative improvement goals remain to be specified and implemented
    - Will entail upgrade or replacement of obsolete systems, components and software
Toward Links + Higher Level Services

- Communications and navigation infrastructure in the remote environment will enable locally coordinated operations in lieu of links to Earth
  - Automated mission planning S/W will act as a “proxy” for science investigators to take advantage of serendipitous exploratory opportunities

- Transparent, high-level, end-to-end services will connect scientists and the public to the remote assets
  - Accessible from research institutions, museums or home desktops

- High bandwidth links will enable the interaction between sensors and users to evolve toward operation in a virtual and immersive environment
  - Explore a remote environment by “being” the spacecraft