LONG-RANGE PLANNING FOR THE DEEP SPACE NETWORK

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ABSTRACT

Conduct of space exploration is undergoing a significant transformation. Initial reconnaissance missions are giving way to long duration observations with data-intensive instruments, *in situ* investigations and complex operations. To keep pace, a transformation in the Deep Space Network is in order. Downlink performance must increase by 1 to 2 orders of magnitude over the next decade and by a similar amount in uplink over the next 20 years. Comparable improvements in navigation precision will be required. Network topology will encompass a diversity of sites, including some owned by non-NASA agencies, others in Earth orbit, and still others deployed as local planetary infrastructure, particularly at Mars. Point-to-point links between nodes will evolve toward networked connectivity among nodes. Provision of services will move toward greater simplicity for the user backed by highly reliable systems. Finally, new types of high-level information services, enabled by high-capacity connectivity, will be developed so as to enable and enhance the next wave of space exploration.

INTRODUCTION

Since its inception in 1963, the National Aeronautics and Space Administration's (NASA's) Deep Space Network (DSN) has been developing, implementing, and operating state-of-the-art communication and navigation services for use by a variety of U.S. and international-cooperative space science missions. To ensure that these services evolve to meet future mission needs, the DSN's long-range planners regularly monitor NASA strategic directions, track and analyze future mission trends, study options for addressing such directions and trends, and with guidance from NASA Headquarters, develop long-range plans for realizing the preferred options.

NASA recently published in its *2003 Strategic Plan* a new vision and mission focused on the pursuit of the "compelling questions that drive exploration." Namely, "How did we get here?" "Where are we going?" And, "Are we alone?" NASA also identified and resolved to surmount four technological barriers to pursuing these questions. One of the barriers was communications—more specifically, "providing efficient data transfer across the solar system."[1]

Consistent with this new strategic emphasis on communications, mission trend analyses by the DSN's long-range planners have revealed significant capacity and capability challenges looming in the network's future.[2] Changes to the fundamental mission paradigm are occurring that are leading to: more spacecraft supports; greater mission operations complexity characterized by more coordination between separate spacecraft elements within a mission or between missions; order-of-magnitude or more increases in downlink data volumes and associated data rates over the next 10 years; and, similar magnitude increases in required uplink data volumes and associated data rates over the next 20 years.

To accommodate these trends and address the communications barrier identified in NASA's *2003 Strategic Plan*, the DSN's long-range planners have identified a number of strategic focus areas for further study, development, and/or possible implementation.[3] Examples of such areas include increasing the reliability and availability of the current DSN, improving radio frequency (RF) flight components, exploring the use of large arrays of small antennas, developing and demonstrating optical communications, developing techniques for networking *in situ* exploration elements, advancing navigation tools and techniques to make maximum use of these other capabilities, and developing the standards and protocols, tools, and techniques needed to make all of these areas reliably play together in the end-to-end provision of cost-effective multi-mission services.

To guide and unify the efforts in these strategic focus areas, DSN personnel are working with NASA Headquarters to develop a shared vision, architecture, and associated long-range plan for the DSN of the future—a plan for a truly Interplanetary Network.

UNDERSTANDING THE CHANGING MISSION PARADIGM

Over the past decade or so, the paradigm for conducting robotic space exploration has been changing. As shown in Figure 1, solar and astrophysical observatories are being located less in low-Earth orbit and more in orbits further from Earth, such as in Earth-trailing orbits or Lagrange point halo orbits. These observatories are also increasingly assuming the form of constellations of

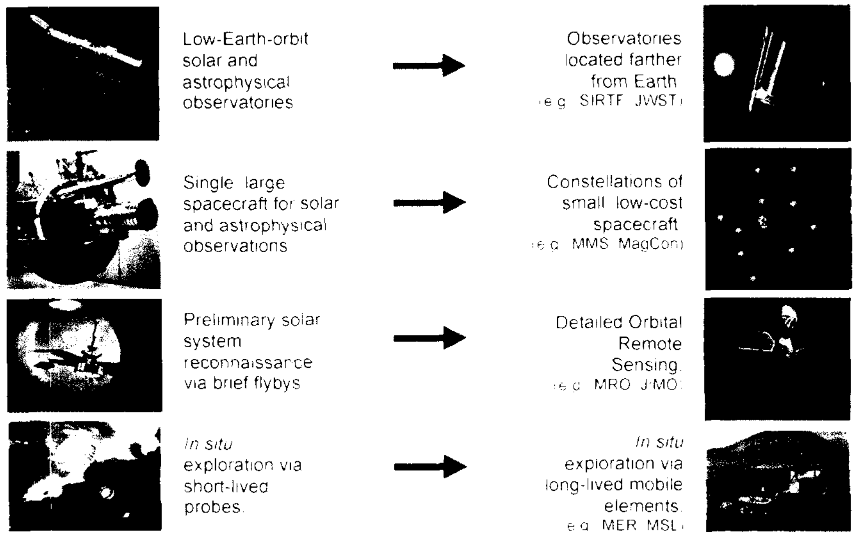

Figure 1: The Changing Mission Paradigm

small, low-cost spacecraft as opposed to single, large spacecraft. And, in the solar system exploration realm, reconnaissance missions involving brief flybys are giving way to detailed, long-duration, orbital remote sensing missions. Complementing these orbital remote sensing missions are the latest generation of *in situ* exploration missions; missions that have evolved from short-lived probes to long-lived, mobile elements. All of these changes suggest a transformation of the customer base that may have significant implications for the Deep Space Network.

To better understand this ongoing transformation, the DSN's long-range planners have been tracking and analyzing future mission trends on an annual basis. They have used two approaches: one for looking toward the 10-year horizon and one for looking toward the 20-year horizon. The 10-year, mission-demographics-analysis approach has involved collecting data on key telecommunications-related parameters for each mission likely requiring DSN support over the next decade. These data have then been analyzed in aggregate using descriptive statistics and plotted as a function of time to identify key trends.

Because mission concepts more than 10 years out tend to exhibit a heavy design bias towards today's technologies, the DSN's long-range planners have had to take a different approach to developing the 20-year outlook. This latter approach has involved identifying terrestrial capabilities (like hyperspectral remote sensing and autonomous aerial and surface vehicles) that scientists will likely want to employ in the future at other solar system locations. By examining the telecommunications requirements associated with these terrestrial capabilities, DSN planners have been able to derive an indication of what will eventually be needed to support the application of such capabilities at other planets.

Together, these two approaches have enabled identification of four major trends regarding the future number of spacecraft supports, complexity and coordination of multi-element mission operations, downlink data volumes and associated data rates, and uplink data volumes and associated data rates.

<u>Trend #1: More Spacecraft Supports</u>

In 1987, the DSN routinely tracked approximately six spacecraft with deep space antennas. Today that number has grown by more than a factor of 4. Meanwhile, the net number of deep space antennas supporting these spacecraft has grown by only a factor of 1.33—implying that these antennas are now heavily loaded (if not overloaded).

Mission demographics analyses suggest that this load will not likely diminish over the next eight to ten years; in fact, slight additional growth in the deep space mission set is anticipated. The DSN must also support those near-Earth missions that need to compensate for low effective isotropic radiated power (EIRP) with high ground-receive capability. As can be seen in Figure 2, even though the number of such missions may decrease in the future, the number of near-Earth spacecraft associated with those missions will increase significantly. This phenomenon is due to the fact that more of the future solar and astrophysical missions will depend upon constellations of small, low-cost spacecraft that must be individually tracked. While not all the spacecraft in these constellations will be located far enough from Earth during their planned downlinks to require DSN tracking, link analyses indicate a significant number will—further exacerbating the antenna loading situation.

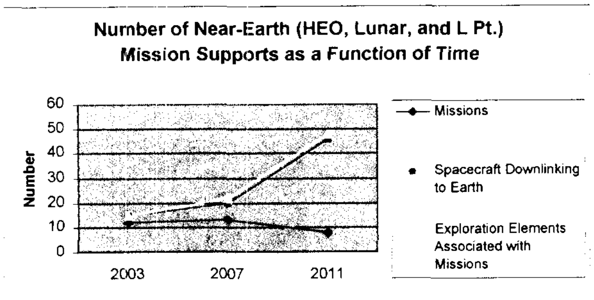

Figure 2: Constellation Missions Drive Low-EIRP, Near-Earth Spacecraft Supports

Trend #2: Greater Mission Operations Complexity—Characterized by More Coordination between Separate Spacecraft Elements within a Mission or Between Missions

As alluded to earlier in the discussion of the changing mission paradigm, missions are increasingly operating with multiple spacecraft in more challenging environments. Over the next 10 years, the DSN will likely be supporting six or more constellation missions, each with spacecraft that must be individually operated and tracked. Over the same period, the DSN will be supporting seven or more missions that will involve multiple exploration elements that communicate with one another via proximity links and communicate back to the Earth through a relay spacecraft. As shown in Figure 3, several of these missions will occur at Mars. Such constellation and proximity link missions present significant operational challenges in terms of link resource allocation, scheduling, and ensuring seamless end-to-end information flow.

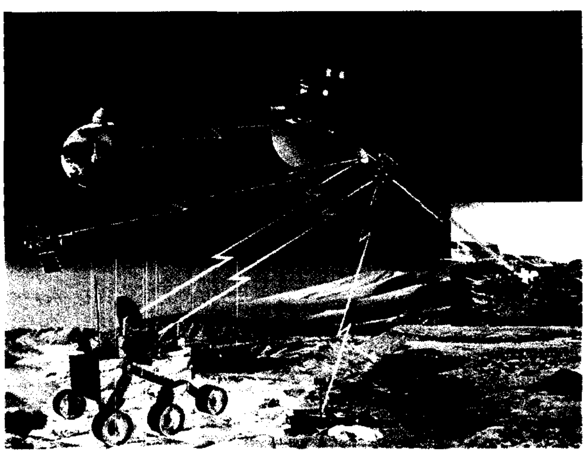

Figure 3: Notional View of Possible Future Proximity Link Missions at Mars

Many of these same missions will also be presenting significant navigational challenges. Over the next 10 years, as many as seven solar and astrophysical missions will be navigating the unique three-body gravitational fields associated with the Lagrange points—and one of them (Constellation-X) will be a four-spacecraft constellation. Up to five missions will involve passive formation flight, and at least one three-spacecraft mission (LISA) will employ active formation flight. In the *in situ* exploration realm, seven or more missions will involve some sort of controlled descent to, or impact on, an extraterrestrial body. And in the long-duration, orbital-remote-sensing realm, at least three missions will use aero-braking, while another three will employ low-thrust propulsion. To successfully operate all of these missions, appropriate navigation tools and techniques will be needed in concert with communications capabilities.

Mission concepts in the 10- to 20-year time frame entail even greater levels of operational complexity. In the case of constellations, for instance, mission concepts call for autonomous coordination between constellation elements, both in terms of navigation and the shared processing of science instrument data. The situation is somewhat analogous in the *in situ* exploration realm where plans call for a sustained robotic presence at Mars (and perhaps the Moon). In this vision, multiple surface, aerial, and orbital robotic elements work together in a largely autonomous fashion, relying heavily on routine *in situ* communication and navigation to coordinate operations. Realizing such constellation and *in situ* exploration visions will clearly demand significant changes from the DSN's current service paradigm, with more service components migrating to the flight elements and much more emphasis being placed on location-independent end-to-end service provision.

Trend #3: Order-of-Magnitude or More Increases in Downlink Data Volumes and Associated Data Rates Over the Next 10 Years and Again in the Following Decade

With more missions consisting of multiple exploration elements undertaking detailed long-duration orbital remote sensing and/or conducting *in situ* exploration via long-lived mobile elements, the prediction that more data will be downlinked to Earth in the future may not be too surprising. Both the analysis of onboard spacecraft data storage trends and project-estimated daily data volumes indicate that downlink data volumes will likely increase by 1 to 2 orders of magnitude over the next eight to ten years. Consistent with these higher data volumes, analysis of planned data rates indicate that both near-Earth and deep space data rates will also increase by 1 to 2 orders of magnitude over the next eight to ten years.

For the 10- to 20-year time frame, we have to rely more on analogies to Earth-based capabilities such as the data rates associated with today's Earth remote-sensing and visual-imaging capabilities. Assuming that scientists will want to apply these capabilities at other solar system locations (such as Mars), Figure 4 suggests that at least another 1 to 2 orders-of-magnitude growth in data volumes and associated data rates will need to occur by the end of the next decade. To effectively support and work with such volumes and rates, not only will capability at both ends of the link need to be improved, but also the capability and tools associated with data delivery and data mining.

<u>Trend #4: Order-of-Magnitude or More Increases in Required Uplink Data Volumes and Associated Data Rates Over the Next 20 Years</u>

While mission demographic analyses indicate that most missions will stick with a 2 kbps uplink rate over the next 10 years, instrument and spacecraft trends toward increasingly complex flight software suggest that higher uplink rates and/or longer-duration uplinks may become the norm shortly thereafter. For instance, the James Webb Space Telescope (JWST) is currently planning on a 16 kbps uplink rate to support the upload of instrument calibration flats.[4] In the non-DSN supported mission realm, the European Space Agency's (ESA's) Project for On-Board Autonomy (PROBA) has been testing the use of an onboard autonomous agent for routine housekeeping and instrument management.[5] While this autonomy has helped reduce the downlink of engineering telemetry, it has also culminated in a factor-of-two increase in the required uplink rate. Similarly, the autonomous "sciencecraft" demonstration planned for Space Technology 6 (ST6) is being designed to reduce science data downlink through application of an onboard autonomous agent for feature selection, partial onboard data analysis, and data return decisions. But to do this, ST6 designers have been contemplating an uplink rate of 50 kbps, 25 times the current rate. [6] In short, we may be starting to see a transition in what dominates the uplink—a transition from low-level commanding to the software and information uploads needed to program and reprogram software-driven subsystems.

In the 10- to 20-year time frame, terrestrial analogies suggest that these software and information uploads will dominate the uplink. This dominance will be driven by the expanding role of long-lived, mobile elements in the *in situ* exploration realm. For such elements to engage in real-time exploration, they will have to negotiate obstacles faster than the long-light-time commands from Earth will allow. The in-flight-retargetable cruise missile, unmanned aerial vehicle (UAV), and unmanned ground vehicle (UGV) analogies shown in Figure 5 suggest potential solutions to this problem that depend on uploads of remote-sensing data products to enable autonomous navigation and targeting. In practice, such solutions would involve downlinking the large data volumes being collected by

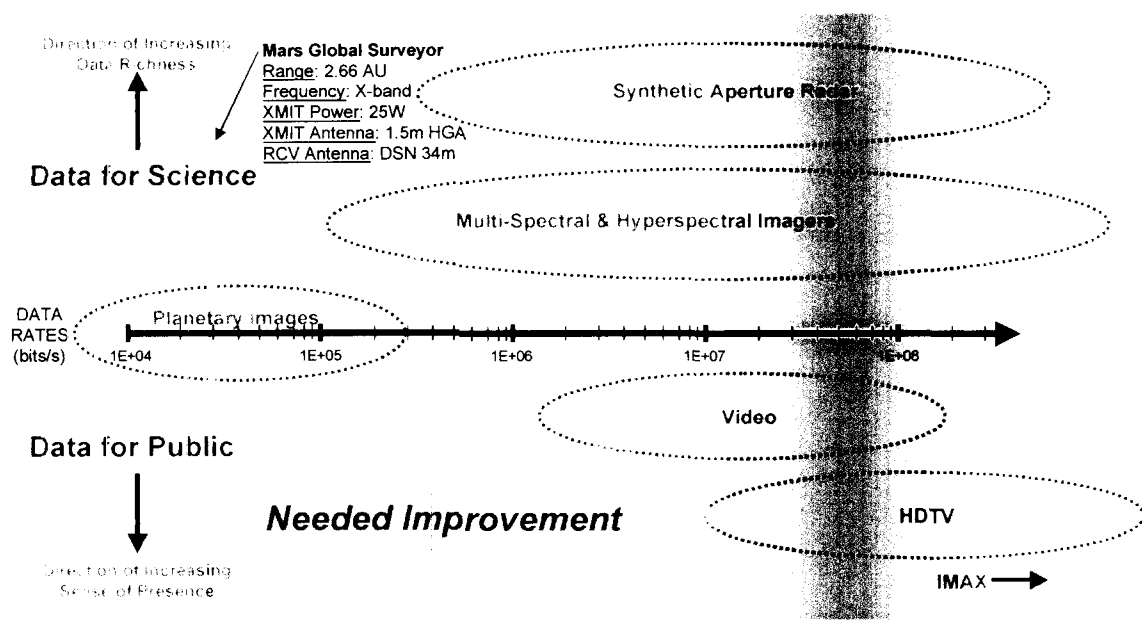

Figure 4: More Data-intensive Instruments and Media Drive Higher Data Rates and Volumes

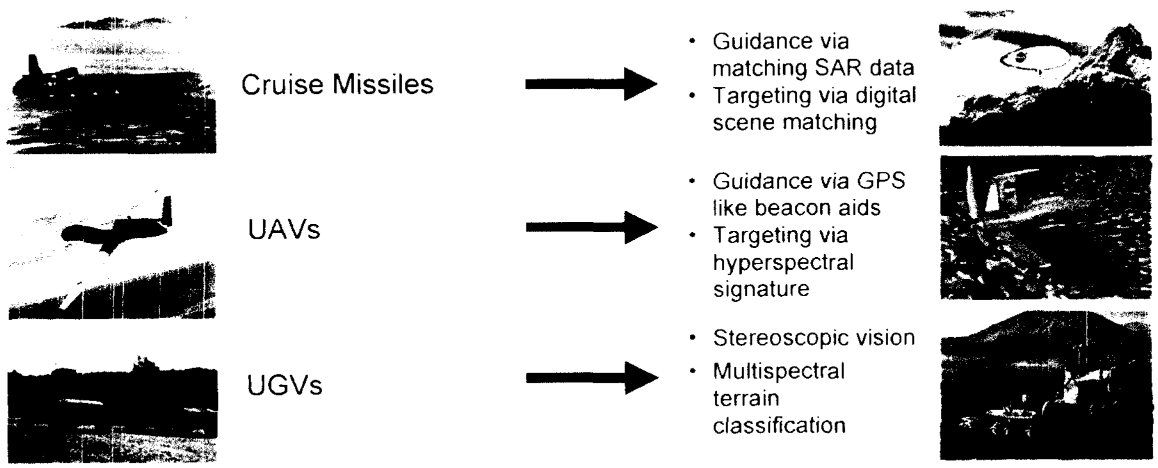

Figure 5: Terrestrial Analogies Suggesting that *In Situ* Mobility Elements Will Become Consumers of Data Products Derived from Orbital Remote Sensing Assets

orbital remote-sensing assets, transforming these data volumes into guidance, navigation, and control (GN&C) and/or science-targeting data products, and then uploading the GN&C/science-targeting products for autonomous use by the mobile *in situ* exploration elements. To the extent that our terrestrial analogies employ a similar process utilizing communications equipment designed to the Tactical Common Data Link (TCDL) standard, we can infer that uploads to mobility elements at other planets will need an uplink rate of at least 200 kbps—a 100 times today's uplink rate.[7]

RESPONDING TO THE CHANGING MISSION PARADIGM

Meeting the challenges posed by the preceding four future mission trends will require a significant initiative to upgrade and transform today's DSN. To energize this new initiative, an updated vision is developing. Formally, this can be stated as:

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

A more colloquial form of the vision would be:

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

The goal is to transform today's 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;
- orders-of-magnitude increases in uplink capability.

Increasing DSN Link Capacity, Availability, and Reliability

In the discussion of the first mission trend, it was noted that over the past 16 years there has been a fourfold increase in the number of spacecraft supported by the DSN's deep space antennas. Over this same period, the net number of such antennas has increased by only 33%, from nine antennas to twelve. Although it has proven possible to support the mission set, this is being done with more contention for tracking resources and less resiliency in the face of anomalous events. As we move toward the newly articulated vision for the DSN, these factors will need to be addressed. Ideally there will be sufficient links to enable availability on demand, and these will be provided with very high reliability, much as one would expect today from service by a terrestrial telephone company.

Because of the need to provide ongoing support to missions and to reap a return on past investments, it is not possible to just start from scratch. Instead the first step in implementing the new vision is to renovate and "complete" the foundational DSN. Despite its current limitations, it provides an excellent base of capability and experience upon which to build for the future. A key element of this involves the aging DSN 70m antennas, shown in Figure 6. One such antenna exists at each DSN complex: Goldstone (California), Madrid (Spain), and Canberra (Australia). Though these may eventually be decommissioned and replaced, they are likely to be required for at least another decade—and possibly longer. A refurbishment effort will improve the longevity of these critical, top-of-the-line assets.

Figure 6: The Goldstone, Canberra, and Madrid 70m Antennas, Respectively

Another part of the foundational DSN involves the complement of 34m Beam Wave Guide (BWG) antennas. Currently the network comprises three of these at Goldstone, two at Madrid, and only one at Canberra. These are shown in Figure 7. Though the original intent was to implement four of these antennas per complex, that augmentation fell prey to tight budgets during the last decade. 34m BWGs provide critical uplink capability, and in arrayed mode provide downlink backup to the 70m antennas. Decisions about implementing additional 34m antennas or transitioning to other architectural alternatives are pending.

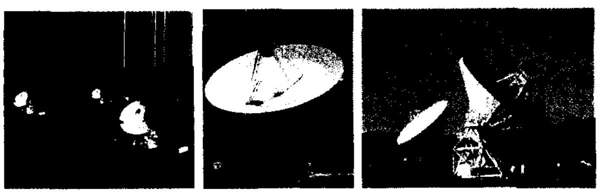

Figure 7: The Goldstone, Canberra, and Madrid 34m BWG Antennas, Respectively

Because of the expansion of the customer base for the DSN, it will be necessary to significantly upgrade the reliability of the network. Providing services to this customer base in a transparent manner requires sufficient link availability and reliability. By experience it is quite clear that when services are delivered with very low failure rates, users have little reason to delve into the details of how these are provided. By contrast, nothing gets users scrutinizing the service provision system faster than failures to deliver. Today, DSN telemetry service reliability is typically better than 98%—quite good for a custom-equipped research and development facility. Yet, two failures in 100 attempts is almost certainly not good enough for the envisioned future network. To draw a parallel, terrestrial telephone users would not likely accept this level of reliability. Thus, an effort is being initiated to determine the right set of metrics for diagnosing service provision quality and to then identify how the systems must evolve to achieve targeted levels of reliability.

<u>Developing a Standards-Based Service Paradigm</u>

Another ramification of the expanding and changing customer base is the need to deliver services to users in a much more streamlined fashion than has been done in the past. Historically, missions interacted with the DSN in an *ad hoc* and customized fashion. The capability of these missions evolved rapidly during the last 40 years, and the DSN worked hard to keep pace. But in this kind of rapid research and development environment, there was very little opportunity for standardization. Nevertheless, the exploration enterprise worked because there were not that many missions operating simultaneously. At any given time, only five or six missions might be demanding support, with typically one of these having the financial resources and political clout to drive the DSN's architecture. Consequently, mission and DSN personnel could accommodate the complexities associated with the use of customized equipment, processes, and procedures.

In contrast, today's DSN must serve a fleet of about 25 to 30 spacecraft at any given time, and with the emergence of constellation missions, possibly many more in the future. In this kind of environment, it is not possible to operate in a mission-by-mission *ad hoc* fashion. Rather, the environment demands standardization. To this end, the Consultative Committee for Space Data Systems[8] has been developing standards and protocols for use by space communications service providers. Standardization has numerous advantages, among which are:

1) efficient support for a host of different missions simultaneously in operations;
2) the ability of the DSN to provide cross-support to missions of other space agencies and, conversely, the ability for space communications assets owned and operated by other space agencies to provide cross-support to NASA missions;
3) cost-effective implementation of new capabilities and services; and
4) a layered architecture for the end-to-end data system.

The first advantage has been discussed in the previous section. For the second item, other agencies besides NASA are becoming increasingly active in the creation and operation of deep-space missions and are also establishing infrastructure to provide telecommunications and tracking services. As an example, the ESA has recently commissioned a 35m antenna at New Norcia, near Perth, Australia. Additional ESA-owned antennas may follow. Agenzia Spaziale Italiana (ASI) and Centre National d'Etudes Spatiales (CNES) have also expressed interest in implementing and operating deep-space tracking stations.

Fundamentally, the third advantage maximizes the leverage of invested non-recurring resources by developing capabilities and services in a way that is multi-mission and, hence, can be utilized by succeeding missions.

The advantages of a layered data system are well known to the computer networking community, and this approach is also applicable for networking the solar system. Figure 8 shows a graphic depiction of a layered data system. Shown on the horizontal axis are the various types of assets that will be nodes on the communications network. These range from rovers deployed on a distant planetary surface to Principal Investigators doing data analysis at their home institutions. The vertical axis shows how the Mission Services and Data Services Layers are "stacked upon" the underlying physical layer. Clean interfaces between layers enable designers to update hardware and software elements of the data system at any given point in the stack without disturbing the adjoining layers.

Although it might appear that the evolution of standardized services spells an end to technical innovation, the opposite is in fact true. To see this more clearly, we may consider all the technical innovations that have occurred over the past 40 years. Those that did not prove to have long-term value are no longer relevant. Those that did are becoming standardized. Standardization may reduce certain kinds of innovation, but this would only be in areas where it is no longer necessary to "reinvent the wheel." This frees up the designers to devote their scarce resources to pushing the technological frontier in communications and mission services.

While Figure 8 underscores the importance of maintaining clean interfaces between the physical, data services, and mission services layers, it also highlights the challenge of trying to smoothly develop each of these layers across a variety of disparate assets, all in widely varying locations. This challenge is particularly apparent within the data services layer, where seamless end-to-end information flow is the goal. Such seamless information flow is difficult to achieve when it depends on a variety of communications assets that are almost continuously changing their positions relative to one another and are frequently not in view of one another. To surmount such difficulties, an effort is underway to develop a "delay tolerant networking (DTN) architecture" and associated protocols.[9] In particular, these networking efforts are evolving protocols that render the transmission robust in the face of intermittent connectivity, high transmission latency, high error rates, variable congestion, variable transmission rates, non-symmetrical data rates, variable name/addressing syntax, and variability in the transmission order of the data. In short, work is underway to provide Internet-like capability within, and subject to the realities of, the interplanetary exploration environment.

Another key to the services paradigm is navigation. Not only will future spacecraft and *in situ* exploration

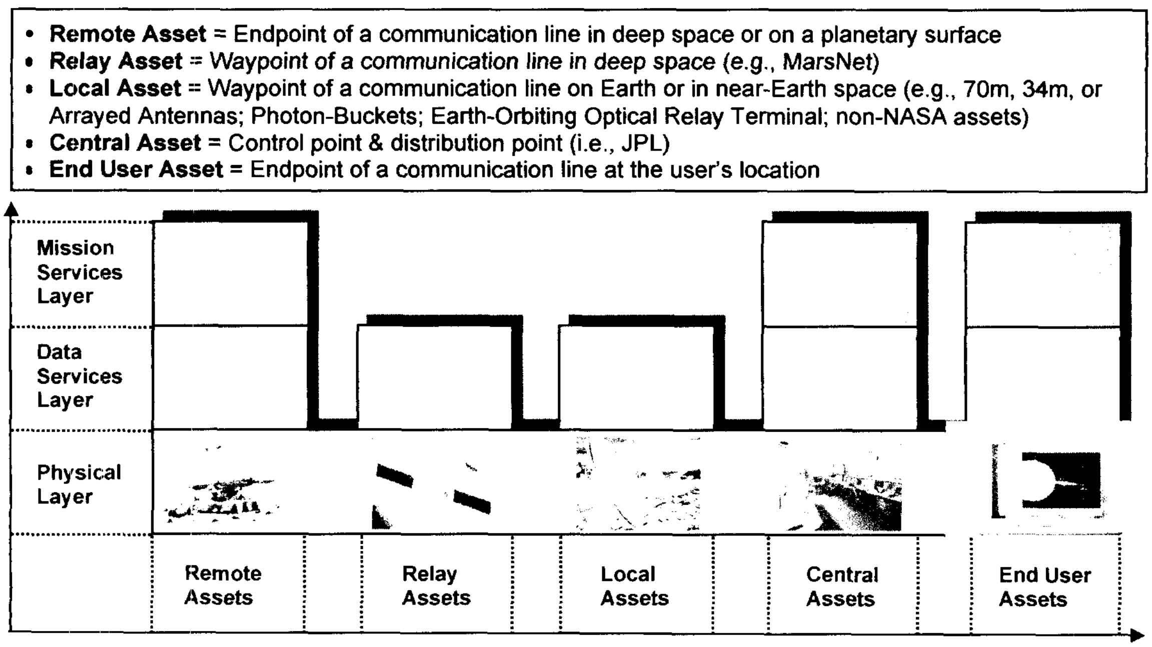

Figure 8: Layered Data System Architecture for the Future DSN

elements need to navigate with far greater precision to accomplish their missions, the deployed communications assets on which they may depend will need very carefully determined positions and relative timing in order to provide proper support. Efforts are underway to advance such areas as higher frequency radiometrics, optimetrics, autonomous optical navigation, trajectory dynamics and optimization, and aeromaneuvering navigation and mission analysis, not too mention the development of precision onboard clocks or ultra-stable oscillators.

The delay tolerant networking architecture and future navigation and timing capabilities will probably see their first prominent use in Mars exploration. Currently Mars is playing host to two NASA orbiters, Mars Global Surveyor and Mars Odyssey, and is awaiting the near-term arrival of five additional spacecraft: two Mars Exploration Rovers, the Mars Express Orbiter and Beagle 2 Lander, and the Nozomi Orbiter. Looking further out, NASA has established a plan for continued science exploration through the end of the current decade, including the 2005 Mars Reconnaissance Orbiter (MRO), the 2007 Phoenix lander mission, and a highly capable, mobile 2009 Mars Science Laboratory (MSL).

As part of this strategy of Mars exploration, an orbital infrastructure is being developed, allowing Mars *in situ* spacecraft (e.g., landers, rovers, aerobots) to relay data back to Earth through one or more orbiters, as an alternative to conventional direct-to-Earth communications.[10] Relay communication offers several advantages:

- increased data return due to the high data rates possible on the short-range *in situ* link;
- reduced power and energy requirements for assets on the Martian surface;
- link availability for Mars landers at times when Earth is not in view;
- ability to gather high-rate engineering telemetry during critical mission events;
- synergistic collection of radio metric data (Doppler, range) on the relay link.

This initial Mars telecommunications infrastructure is being established by including a standardized proximity link relay payload on each science orbiter (1996 Mars Global Surveyor, 2001 Mars Odyssey, 2003 Mars Express, and 2005 Mars Reconnaissance Orbiter).[11] By adopting a standard link layer protocol,[12] these orbiters offer interoperable telecommunications relay services for future Mars landers.

Beyond this initial infrastructure, NASA plans to deliver a dedicated Mars Telecommunications Orbiter (MTO) in 2009.[13] In contrast to science orbiters, MTO's design will be optimized for relay communications. This will entail a high altitude orbit offering many hours per sol of communications availability, as well as higher-performance relay link capabilities, utilizing directional UHF and X-band proximity-link antennas. MTO will offer several orders-of-magnitude data return increase for the 2009 MSL mission, relative to direct-to-Earth links or relay through existing science orbiters. With implementation of delay-tolerant, file-based communications protocols, MTO will enable reliable, seamless transfer of data products from the surface of Mars to scientists and the public not only for the 2009 MSL mission, but also throughout the subsequent decade of exploration.[14] A notional view of a Mars Network is shown in Figure 9.

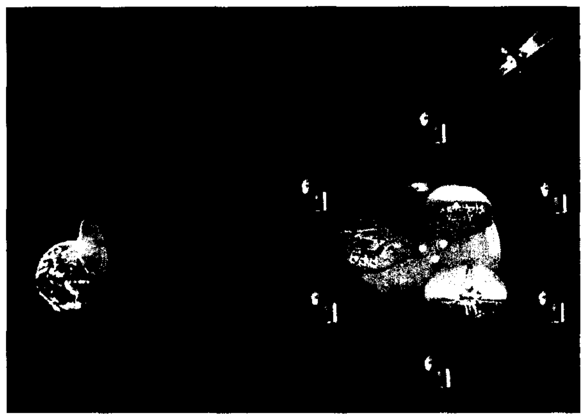

Figure 9: Notional Mars Network

Increasing Downlink Capability

An additional element of the foundational DSN involves transitioning from X-band (8 GHz) to Ka-band (32 GHz) for downlink operations. The directivity of the higher frequency provides a fourfold gain (6 dB) (after accounting for various losses), and the allocated spectrum provides 10 times the bandwidth available at X-band. Ka-band receive systems are currently being installed on all DSN 34m BWG antennas. Though a fourfold improvement in downlink data rates falls short of the eventual need, the Ka-band implementation represents an essential step toward the future network.

To make the next leap—from 4x to 100x improvement in downlink—requires significant development and implementation in numerous areas, both on the spacecraft and on the ground. For the flight telecom systems, advanced spacecraft radios, amplifiers, and antennas are envisioned. Examples of these are depicted in Figure 10. Developments include radios (transponders) that are smaller, lower in power, more integrated and reprogrammable; higher power amplifiers for both X- and Ka-bands (100W class); and deployable antennas as large as 5m in diameter. Finally, nuclear-powered missions, such as the Jupiter Icy Moons Orbiter (JIMO) will likely drive the development of kW class power amplifier systems.

Figure 10: Spacecraft Radios, Power Amplifiers, and Antennas

On the terrestrial side of the link, particularly at radio frequencies, there is a need to greatly expand the available network aperture. This could be achieved via construction of additional 70m and/or 34m antennas. However, costs for this approach may prove to be prohibitive. Another potential approach involves implementation of a large array of small antennas. Currently designers are focusing on 12m class antennas. Such a concept is shown in Figure 11. Cost per unit of aperture may be significantly less with this approach than with the more traditional alternative of large monolithic parabolic antennas. However, array performance, implementation, and operations costs, require validation. This will be the main objective of an array prototype currently in the breadboard design phase.[15]

Figure 11: Large Array of Small Antennas

Another possibility for orders-of-magnitude improvement in link performance involves the use of lasers and optical communications.[16] Optical frequencies are much higher than radio frequencies. Consequently, they have much more gain, but are also much more susceptible to environmental factors - such as clouds. Existing architectural concepts for ground-based optical networks typically involve six to nine 10m class telescopes geographically located so as to provide good longitude coverage and/or simultaneous tracking from uncorrelated or even anti-correlated weather cells. Precedent exists for ground-based 10m astronomical telescopes, e.g., the twin Keck Telescopes on Mauna Kea, Hawaii. However, ground-based 10m telescopes for optical communications need not have the extremely expensive diffraction-limited optics required for astronomical imaging. Lower precision mirrors, called photon buckets, with the use of direct detection and pulse position modulation (PPM), provide the performance required to carry out the communications function. An example of such a ground-based facility is shown in Figure 12.

Figure 12: Optical Communications Facility

Optical links to deep space can also be operated from Earth orbit. Space-basing eliminates the deleterious effects of the Earth's atmosphere, namely reduced weather availability from clouds and a 3 dB attenuation even under "clear skies." This enables use of a smaller mirror, perhaps 7m, and encourages a move to coherent detection and diffraction-limited optics. However, with the high launch costs anticipated for the foreseeable future, space-basing of one optical terminal may cost as much as a whole network of ground stations. And it does not provide for simultaneous links to numerous spacecraft.

Hybrid approaches—using some space-based and some ground-based assets—are also possible. A ground-based approach that synthesizes a large optical aperture by means of many small, and presumably inexpensive, telescopes (much as the large array of small antennas does at RF) is also being considered.

Increasing Uplink Capability

In about 10 years, long-lived missions with autonomous, *in situ* operations will become commonplace. These will stress the current uplink capabilities of the DSN. Requirements to transmit large instrument calibration files, image and terrain files for mobile elements, and spacecraft software (including operating system) updates will become the norm. This is in contrast to today's process of loading primitive commands for sequenced execution. Thus there will likely be a need to increase the EIRP directed at remote spacecraft. Even more power will be needed to recover spacecraft in emergency states because there is no guarantee that their high-gain antennas (HGA) will be pointed toward Earth.

Classically, EIRP is provided on target by means of a high power transmitter on a large microwave antenna. Today's maximum DSN X-band performance is 20 kW on a 70m antenna. The capability is likely to continue although it raises issues about the expected longevity of the 70m antennas, which are currently 30–40 years old. The DSN also currently employs 20 kW at X-band on 34m antennas, though the smaller aperture results in a 6 dB decrease in performance. It also raises issues about whether there exist a sufficient number of these antennas. The DSN currently fields nine 34m antennas—the six 34m BWGs mentioned earlier, plus three additional 34m high efficiency (HEF) antennas.

Another approach involves the use of arrayed uplink. It is somewhat analogous to the idea of arraying antennas for downlink. However, a key difference lies in the fact that it is difficult to have knowledge and control of the phase front from an array of transmitting antennas. The round trip light times (RTLT) to deep-space vehicles are typically too long to allow for closed loop control. Nevertheless, the approach has great potential to put extremely high levels of EIRP on target, either for routine high-bandwidth uplink or for emergency communications. A technology effort in this area is underway with a goal to demonstrate feasibility and retire technical risk. Assuming it is successful, the approach may be applicable to the existing large antennas of the DSN (34m and 70m) or even to a large array of small antennas.

SUMMARY

Space exploration is undergoing a significant transformation. Analysis of this transformation by the DSN's long-range planners has revealed four key trends: (1) more spacecraft for the DSN to support, (2) more complex operations with more coordination between exploration elements, (3) order-of-magnitude or more increases in downlink data volumes and data rates each decade, (4) order-of-magnitude or more increases in uplink data volumes and data rates over the next 20 years. To address these trends, DSN planners have identified several strategic focus areas for further study and/or development. These areas are oriented toward increasing DSN link capacity, availability, and reliability, developing a standards-based service paradigm, increasing downlink capability, and increasing uplink capability. To better guide and unify the efforts in each of these areas, DSN personnel are currently working with NASA Headquarters to develop a shared vision, architecture, and associated long-range plan for the DSN of the future—a plan for a truly Interplanetary Network.

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