TRANSFORMING THE DEEP SPACE NETWORK INTO THE INTERPLANETARY NETWORK

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ABSTRACT

Space exploration missions are undergoing a significant transformation as are the expectations of their scientific investigators and the public who participate in these great voyages of exploration. The early reconnaissance missions are giving way to a new data-intensive era of long duration observational outposts, landed vehicles, sample returns, and multi-spacecraft fleets and constellations. Mars exploration has already become a special case of the new operational mode; other destinations will follow. These changes will require orders of magnitude increases in data rates, highly automated and standardized data communications between the remote locations and Earth, more transparent and responsive mission operations procedures, and the ability to engage the public by giving them Internet-based visibility into the missions as they unfold. The new area will demand a new paradigm for the Deep Space Network, with increased emphasis on data networking and the data processing applications that allow users to become more intimately engaged with the conduct of the mission. We call this new paradigm the Interplanetary Network. Its vision is seamless connectivity between scientists and their instruments, new data analysis and visualization tools that will greatly enhance and enable new modes of space exploration, and the involvement of the public via web-based "telepresence."

INTRODUCTION

For forty years the National Aeronautics and Space Administration's (NASA's) Deep Space Network (DSN) has provided telecommunications and navigation services to nearly all U.S. and many international, deep-space missions. This "24-hour by 7-day" network has three complexes around the world that permit continuous coverage of solar system spacecraft and their critical mission events. But, yesterday's missions and DSN, though noteworthy and successful, will give way to future concepts in space exploration. Already, new missions now in design, are targeting the challenging fundamental questions that confront space science. To enable these missions, NASA has demonstrated a commitment to removing the main impediments to deep-space exploration; limited communications capability.[1] Along these lines, future mission requirements will stress the existing DSN, and, in fact, exceed its capacity and capability. The sheer number of missions and mission elements is one factor. Missions involving networks of orbiting and landed elements or vehicles flying in tightly controlled formations, all with increasingly complex and networked mission operations, will soon be common. Demand for bandwidth will grow, as new instruments with ever-increasing spatial, spectral, and temporal resolution are developed and flown. Also, the number of missions has expanded significantly, while the number of deep-space antennas has not kept pace. The resulting contention for tracking time directly limits mission data return. The mission set has also evolved from one characterized mostly by individual spacecraft remote sensing to one having a significant amount of *in situ*, networked operations, particularly at, though not limited to, Mars. Finally, assets of the DSN are aging, and with some of these dating back to the 1960s, reliability issues are being raised. Though the current DSN is in need of upgrade, it nevertheless represents an excellent foundation for the building blocks that will occur.

To energize the necessary new initiative, an updated vision is developing. Formally, this can be stated as, "Enable telescience and telepresence throughout the solar system and beyond," or more colloquially, "Bring the sensors to the scientists and the planets to the public." The goal is to

transform the DSN into an Interplanetary Network (IPN) that:

- provides networked connectivity, wherever needed, across the Solar System—and beyond;
- provides transparent communications, navigation, science, and operations services to customers that enhance, rather than constrain, the accomplishment of their objectives;
- incorporates the latest technologies, as appropriate, to enable improved exploration and discovery;
- provides readily available, secure, and efficient information access to science and public users.

This paper discusses strategies for overcoming obstacles and meeting new requirements.[2] For communications, these will include ongoing work to renovate and "complete" the foundational DSN: development of advanced spacecraft radios, amplifiers, and antennas; prototyping of large arrays of small antennas; demonstration of optical communications; augmentation of the localized Mars Network infrastructure with a dedicated comsat; and development of end-to-end standards and protocols. For mission services, these strategies will include upgraded capabilities and tools for use in deep-space navigation, network and multi-mission operations, mission design, and science and public applications. Effective use of this IPN will be enabled by a layered information architecture and advanced developments in space information systems, reliable mission software, and state-of-the-art access and processing capability.

TRANSFORMATION OF THE CUSTOMER BASE

The DSN's customer base consists of both deep-space missions and those near-Earth missions that must compensate for low effective isotropic radiated power (EIRP) with high-ground receive capability. To ensure that the DSN evolves to meet the growing and ever changing needs of this customer base, DSN long-range planners regularly track and analyze future mission trends.[3]

The tracking and analysis of future mission trends requires the application of two techniques. The first technique, mission demographics analysis, involves collecting key telecommunications-related parameters on each of the current and future missions comprising the customer base out to about a 10-year horizon;[4] then plotting these parameters as a function of time to identify key trends. Concepts for missions more than 10 years out naturally exhibit a design bias towards today's technologies, necessitating a somewhat different approach for anticipating future mission needs in the 10- to 20-year timeframe. This second technique involves identifying Earth-based capabilities that one can reasonably assume scientists will eventually want to apply at other solar system locations (e.g., hyper-spectral remote sensing, autonomous aerial and surface vehicles, etc.). The telecommunications requirements associated with these terrestrial capabilities then provide an indication of what will ultimately be needed to support the application of such capabilities at other planets. Together, these two techniques have yielded four major findings.

Finding #1: The number of DSN-supported spacecraft is continuing to increase. Over the past 15 to 16 years, the number of spacecraft has increased fourfold, while the number of DSN antennas has only increased by 33%. To compensate for this disparity, the network has had to increase its operational efficiency while also sacrificing some of its resiliency and amount of support per mission.

Finding #2: Missions are becoming increasingly more complex to operate. In the solar and astrophysical realms, observatories in low-Earth orbit are being replaced by more capable platforms in Earth-trailing orbits or at the Lagrange points (e.g., Space Infrared Telescope Facility, James Webb Space Telescope). Single, large spacecraft are being replaced by constellations of small, low-cost spacecraft (e.g., Magnetospheric Multiscale, Magnetospheric Constellation). For solar system exploration, missions are evolving away from brief flyby reconnaissance to long-duration, detailed orbital remote sensing (e.g., Mars Reconnaissance Orbiter, Jupiter Icy Moons Orbiter). Finally, in the *in situ* exploration realm, short-lived probes are being replaced by long-lived, surface and aerial mobile elements—with some elements, by the end of the next decade, networked to enable coordinated, cooperative exploration efforts (e.g., Mars Science Laboratory, Mars Long-Lived Lander Network).

Finding #3: Downlink data volume and associated data rates will likely increase 1 to 2 orders of magnitude over the next 8 to 10 years. Such growth is consistent with the trends toward more

capable Lagrange point and Earth-trailing-orbit observatories and the longer duration, more detailed orbital remote sensing missions mentioned above. To the extent that scientists will want to apply current Earth remote sensing and visual media capabilities at other solar system locations (such as Mars), Figure 1 suggests at least 1 to 2 orders of magnitude additional growth in data volumes and data rates by the end of the next decade.

Finding #4: Uplink data volume and associated data rates will also increase, possibly by a factor of 10 to 100 over the 2011–2023 time period. This increase will be associated with a change in the nature of what dominates uplink communications— a change from low-level commanding to uploads of instrument calibration flats, software updates for sophisticated spacecraft operating systems, and large image or terrain files for navigation of mobile *in situ* elements. Consistent with the previously discussed *in situ* exploration trend toward long-lived surface and aerial mobile elements, such uploads will be essential to enabling autonomous negotiation of obstacles in real time rather than awaiting long-light-time commands from Earth. Mobile *in situ* elements will essentially become consumers of data products derived from the long-duration, detailed orbital remote sensing spacecraft. Examination of some of Earth's autonomous mobility elements (cruise missiles, unmanned aerial vehicles, and unmanned ground vehicles) suggests that data rates at least ~100× today's 2-kbps command rate will be needed to support upload of such products.

PERFORMANCE TRANSFORMATION

From Constraint to Enhancement

Factors described in the preceding section, imply a DSN, which though built to be an enabler of critical science missions, has become a constraint on their productivity. Thus a transformation is sought to replace overly constraining links and systems with a network that enhances the kinds of investigations currently underway and enables whole new classes of exploratory activity. In other words, a DSN that users can grow in to, rather than one that they have already outgrown.

Step one in implementing this vision is to renovate and "complete" the foundational DSN. Whatever its current limitations, it provides an excellent base of capability and experience upon which to build the future. A key element of this involves the aging DSN 70m antennas shown in Figure 2. One such antenna exists at each DSN complex: Goldstone (California), Madrid (Spain), and

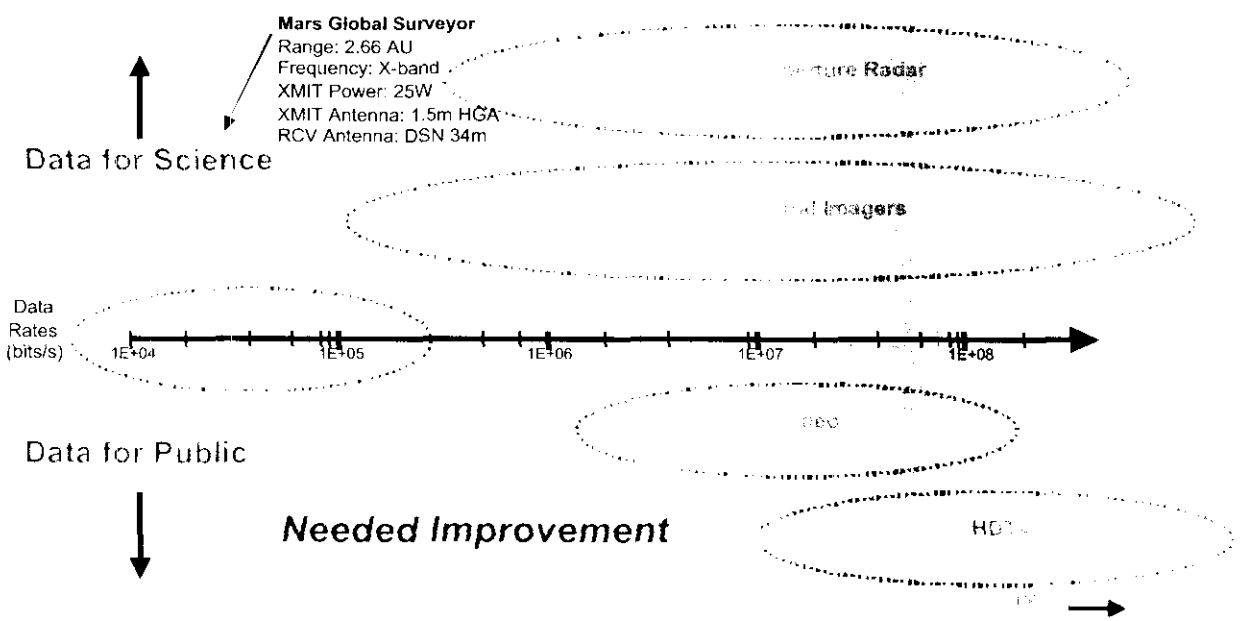

Figure 1: More Data-intensive Instruments and Media Drive Higher Data Rates and Volumes

Canberra (Australia). Though these antennas may eventually be decommissioned and replaced, they are likely to be required for at least another decade—possibly longer. A refurbishment effort will improve the longevity of these critical, top-of-the-line assets.

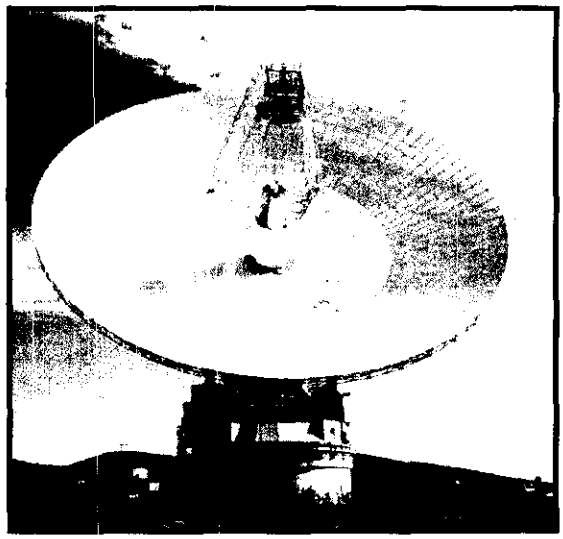

Figure 2: DSN 70m Antenna

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, but only one at Canberra. Though the original intent was to implement four of these antennas per complex, that augmentation fell prey to tight budgets over the last decade. 34m BWGs provide critical uplink capability, and in arrayed mode, downlink backup to the 70m antennas. Decisions about implementing additional 34m antennas or transitioning to other architectural alternatives are pending.

As a first step toward increasing mission data return, the DSN is 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.

Achieving Downlink Greater Than 100×

To make the next leap—from 4x to 100× 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 Figures 3 and 4.

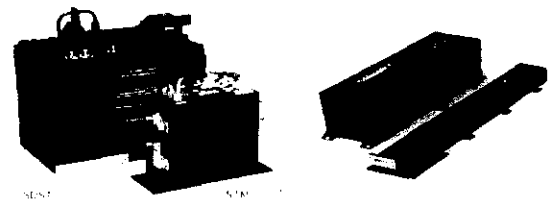

Figure 3: Spacecraft Radios and Power Amplifier

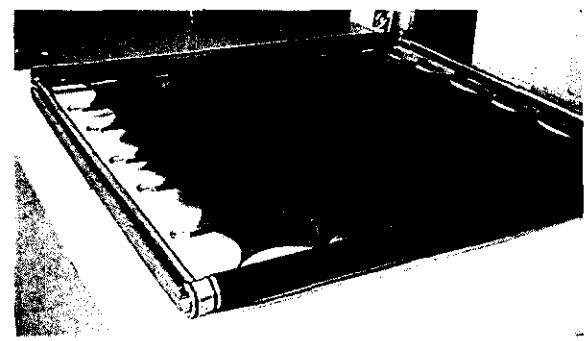

Figure 4: Spacecraft Antenna

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 5 m in diameter. Finally, nuclear-powered missions, such as the Jupiter Icy Moons Orbiter (JIMO) will likely drive the development of kW class power amplifiers.

On the terrestrial side of the link, particularly at radio frequencies, there is a need to greatly expand the available network aperture. Though this could be achieved via construction of additional 70m and/or 34m antennas, costs may be prohibitive. Another potential approach involves implementation of a large array of small antennas (10m class). Such a concept is shown in Figure 5. The premise is that cost per unit of aperture may be significantly less with this approach than with the more traditional alternative of large monolithic

parabolic antennas. Validation of this premise, for both implementation and operations costs, as well as confirmation of array performance will be the main objectives of an array prototype currently in the breadboard design phase.[5]

Figure 5: Large Array of Small Antennas

Another possibility for orders-of-magnitude improvement in link performance involves the use of lasers and optical communications.[6] Optical frequencies, being much higher than radio frequencies (RF), have much more gain, but are also much more susceptible to environmental factors—such as clouds. Strawman designs 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. 10m class telescopes are already in operation for ground-based astronomy, 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 6.

Figure 6: Optical Communications Facility

It is also possible to operate optical links to deep space from above the atmosphere, i.e., in 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 7 m, and encourages a move to coherent detection and diffraction-limited optics. However, given high launch costs, 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.

Finally, other options are also possible. Hybrid approaches—using some space-based and some ground-based assets are being considered. An effort is also underway to examine 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.

Achieving Uplink About 100×

In about 10 years, the emergence of long-lived, autonomous, *in situ* operations will begin to stress the current uplink capabilities of the DSN. The need to transmit large instrument calibration files, image and terrain files for mobile elements and spacecraft software (including operating system) updates will overshadow today's process of loading primitive commands for sequenced execution. This will likely require an increase in the EIRP directed at a remote spacecraft. Even more power will be needed to recover a spacecraft in an emergency state because there is no guarantee that its high gain antenna (HGA) will be pointed toward Earth.

The classic method of providing EIRP on target is to utilize a high power transmitter on a large microwave antenna. Current maximum DSN performance is 20 kW at X-band on a 70m antenna. The classic approach 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 this represents a 6 dB decrease in performance. It also raises issues about whether there exists a sufficient number of these antennas. There are currently nine in the network.

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 can be applied to the existing large antennas of the DSN (34m and 70m) or even to a large array of small antennas.

Navigation and Flight Control

Navigation challenges of future missions can be traced to such requirements as precision landing, aeromaneuvering and multi-spacecraft orbital operations. To meet these requirements, 10× improvements in the precision of tracking observables as well as flight and ground frequency standards will be needed. In the near-term, tracking Ka-band signals will help to meet this need for RF-based navigation. Farther out, the introduction of optimetric observables for spacecraft with optical communications systems will also be needed.

For certain mission events, traditional Earth-based navigation will be augmented with *in situ* navigation techniques. These will require highly precise spacecraft-to-ground and inter-spacecraft time correlation and synchronization. Example scenarios include planetary approach navigation via *in situ* RF links or use of approach imaging. In either situation, autonomy is likely to play a key role. Even farther out, the autonomous ability to monitor and control spacecraft states, execute spacecraft activities and to predict, prevent, and respond to spacecraft anomalies will be highly desirable.

TOPOLOGICAL TRANSFORMATION

Since its inception, at the beginning of the U.S. space program, the DSN has been practically synonymous with its three complexes spaced around, and affixed solidly to, the Earth. At all three sites, the assets have always been owned by a U.S. government agency (NASA). However, at the Spain and Australia sites, staffing has always been provided by local workforce. As the future unfolds, a significant transformation in the deployment and ownership of assets is anticipated.

From U.S./NASA Assets to a Confederated International Network

Although NASA pioneered the deep-space communications, other nations, through their individual or corporate space agencies, have recently entered, or are seeking entry into, this integral part of space exploration. A case in point is the European Space Agency (ESA), which 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.

As other entities enter the arena of deep-space tracking, it makes sense to envision an international confederation of service providers. Seamless interfaces among these variously owned assets will enable efficient data transfer. This kind of architecture should allow end users to be connected to their spacecraft without ever knowing—or even caring—about the routing used to establish the connection.

Impact of Site Diversity

As discussed earlier, an Earth-based optical communications architecture will likely comprise six to nine sites, both for weather diversity as well as good longitudinal coverage. Consequently this would transform the DSN from a three-complex network into perhaps a six- to nine-complex network. Similarly at RF, deployment of the large array of small antennas may also expand to sites other than the current DSN complexes. The rationale for this is to maximize the likelihood of achieving good Ka-band links, which are also somewhat susceptible to weather effects. However, for cost-effectiveness, it may be that most, if not all, of these additional sites will be designed to function autonomously, with minimal infrastructure.

From Earth-Based to Earth-and-Space-Based

Future solar system exploration will include intensive and extended campaigns of *in situ* investigations at particular targets. Right now, the international space community is in the midst of such a campaign at Mars, with five spacecraft

scheduled to arrive at the red planet in the 2003–2004 time frame: two Mars Exploration Rovers, the Mars Express Orbiter and Beagle 2 Lander, and the Nozomi Orbiter. NASA has established a plan for continued science exploration through the end of the current decade, including the 2005 Mars Reconnaissance Orbiter, a 2007 Mars Scout lander mission, and a highly capably 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.[7] Relay communication offers several essential advantages:

- increased data return, due to the high data rates that can be achieved on the short-range link from the Mars surface to a nearby orbiter;
- reduced power and energy requirements, enabling innovative mission concepts for which direct-to-Earth links are not viable;
- link availability for Mars landers at times when Earth is not in view (e.g., Martian night and Mars polar locations, which seasonally are out of Earth view);
- ability to gather high-rate engineering telemetry during critical missions events (such as entry, descent, and landing);
- synergistic collection of radio metric data (Doppler, range) on the relay communication link, providing *in situ* position information in a Mars frame of reference.

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).[8] By adopting a standard link layer protocol,[9] these orbiters offer interoperable telecommunications relay services for future Mars landers.

Beyond this initial infrastructure, NASA's plans call for flight of the first dedicated Mars Telecommunications Orbiter (MTO) in 2009.[10] Science orbiters, for example, are driven by their remote sensing mission needs and typically result in very low-altitude polar orbits with only minutes per sol of contact to a landed asset. In contrast, the MTO mission will be optimized for its relay communications function, with a much higher altitude offering many hours per sol of communications availability, as well as higher-performance orbiter relay link capabilities that use 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 file-based communications protocols,[11] 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. A notional view of a Mars Network is shown in Figure 7.

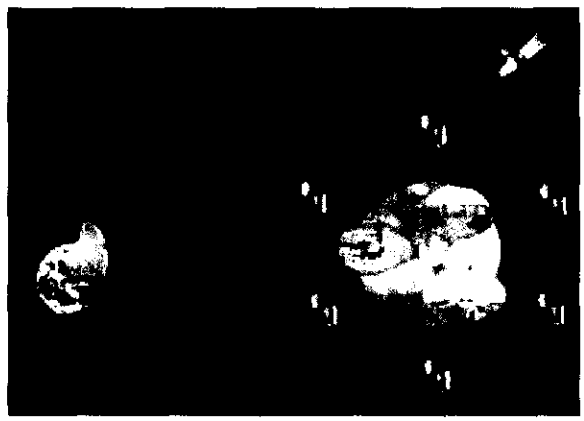

Figure 7: Mars Network

From a Point-to-Point to a Networked Architecture

Throughout the space age, the DSN has evolved to be the "crown jewel" of space communications. Simply put, with its cutting edge link technologies it is the premiere international gateway for communicating to and from deep space. However, just as the Internet has revolutionized terrestrial communications during the past 20 years by allowing diverse regional networks to confederate over a backbone of high capacity point-to-point links, the emergence of concepts such as a Mars Network indicates that we are now poised to see a similar expansion into space as more and more networked space-based assets from different space agencies need to communicate with their ground-based counterparts over long-haul links. The "classic" DSN, therefore, will become the long-haul communications backbone of a future "IPN." In common with the Internet, the key to this expansion will be the accretion of re-usable

communications assets that are tied together by standard data communications protocols.

Internationally Standardized Communications Protocols

When user applications need to exchange information across the Internet, several underlying layers of standard data communications protocol support them. Each layer is programmed with the 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, as technology changes, layers can simply be replaced without bringing down the whole system. This approach, shown in Figure 8, has also been applied to the standardization of space communications.

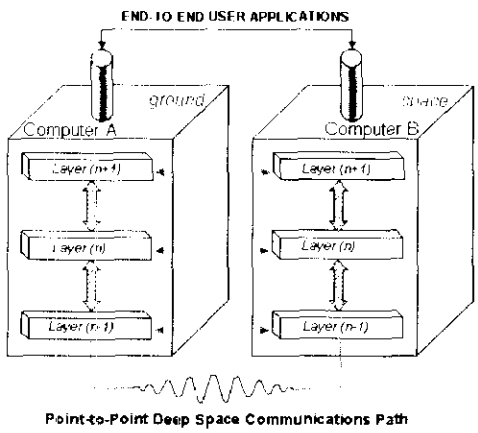

Figure 8: Standard Protocol Layering

Since 1982, the Consultative Committee for Space Data Systems (CCSDS)[12] has been working to achieve international agreements that center around the key point-to-point space link interface. At present, well over 250 spacecraft use these basic space link standards. More recently, CCSDS has been expanding its scope to include new end-to-end "space internetworking" capabilities as shown in Figure 9.

The CCSDS "space" and the Internet "ground" standardization communities are now being brought together within the Internet Research Task Force to develop new technologies that can allow the Internet to reach off-planet. An early product is the "Bundling" protocol suite[13,14] which is the long-haul analog of the Internet's TCP/IP suite and represents a key step towards the IPN.

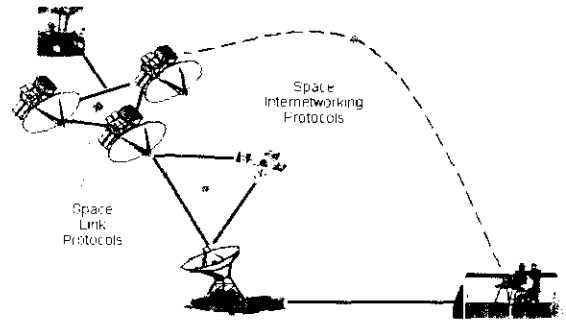

Figure 9: End-to-End Space Communications Standards

SERVICE MODEL TRANSFORMATION

From Complexity to Simplicity

The early days of deep-space exploration were characterized by relatively simple missions, at least as viewed from today's perspective. But they also had fairly complex operational interfaces among mission and DSN elements. A typical mission was a planetary flyby—though there were certainly notable exceptions. Telecommunications capability increased at a dramatic pace, driven by a host of advances in flight systems, ground systems, frequencies, coding, etc. In such a rapidly developing environment, it was very difficult to adhere to a standardized method of operation. Hence each new mission had a tendency to push the state of the art. Custom equipment, custom interfaces, and customer involvement were the norm. Though complex and rapidly changing, the whole effort was feasible because only a few missions at a time had to be accommodated.

In the current era, with its expanded customer base, this type of operation is neither desirable nor efficient. In its place, a new operational concept, dubbed the *Service Paradigm* has been developed. Technological innovations that have proven workable over the past 40 years are being codified into standardized services that can be simply defined and simply accessed. Network users are not expected to have deep involvement with, or even knowledge of, the systems by which their data are moved around the solar system. During the formative stages of a mission, it is now typical to arrange for a "service contract" between the mission and the DSN. As the mission proceeds into operations, the contract is executed, much as one would interface with a telephone company today. Even flight telecommunications equipment is moving toward a standardized product line, e.g.,

the Small Deep Space Transponder. Should a user need to develop custom equipment, it is at least expected to be designed to standardized interfaces so as to provide for "plug & play" insertion into the end-to-end link.

The end goal is to make the acquisition of science data or public outreach media accessible to users in as transparent a manner as possible, somewhat akin to the workings of the World Wide Web on the terrestrial Internet. If successful, users will be freed of the need to manage the communications system and thus be able to concentrate on their actual purposes. Only in this manner can we truly hope to "enable telescience and telepresence throughout the Solar System and beyond," and "bring the sensors to the scientists and the planets to the public."

Achieving the aforementioned simplicity does not imply that technological innovation has come to an end. On the contrary, it will proceed rapidly. In fact, the layered nature of the communications and information systems architecture is specifically designed to accommodate the infusion of new technologies. As these mature, they can be brought into the network in a modular fashion, without creating major ramifications on other elements of the end-to-end network and system.

Network and Service Reliability

In order to make the *Service Paradigm* a reality, it will be necessary to significantly upgrade the reliability of the DSN. Generally 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 will get a user deep into the service provision system faster than failures to deliver. As an example, 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 to operate in the Service Paradigm mode. Thus an effort is beginning to determine the right set of metrics for diagnosing service provision quality and then to identify how the systems must evolve to achieve targeted levels of reliability.

Toward Links Plus Higher Level Services

Extension of today's DSN into tomorrow's IPN will create two marked advantages: 1) establishment of true off-planet infrastructure for the basic mission services of communications and navigation, and 2) great expansion of the bandwidth available to bring information from remote environments back to Earth.

Even a casual study of history indicates that a watershed event in the opening of any frontier is when infrastructure begins to be deployed in the remote environment. Once this step is taken, expeditions or missions need no longer carry all required resources—in self-contained fashion—into the remote environment. Instead, each mission can rely on services and infrastructure already in place, and focus more completely on how to accomplish its given objectives.

In addition to this cost and efficiency advantage for each mission, having local communications and navigation services available in the remote environment opens up another advantage in the long term: mission concepts based on having several heterogeneous assets active concurrently in the same environment—assets that can coordinate their activities via the local infrastructure, without having all such mediation make the round-trip to Earth.

Figure 10 shows one possible scenario at Mars: an orbital platform detecting evidence of recent water at the surface. A general request for further *in situ* investigation goes out to a fleet of mobile surface assets. After considering factors such as proximity and payload, one rover is selected to investigate further.

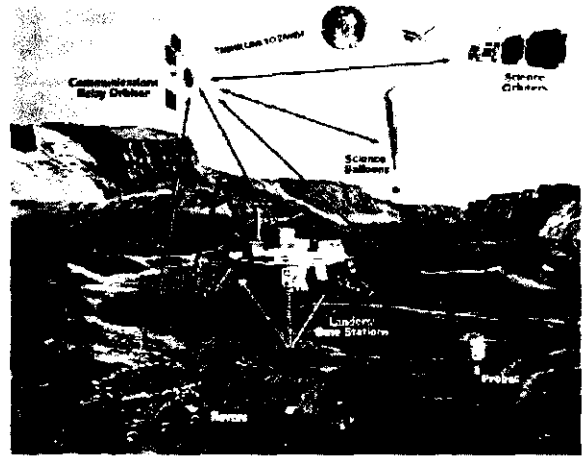

Figure 10: Coordinated Mars Fleets

Long before the IPN enables autonomous deep-space assets to coordinate their activities, it will

pay dividends by providing transparent, higher-level mission services to the science community. With the current DSN, scientists are included, sometimes painfully, in the fine points of commanding and transporting data from spacecraft. Under the truly networked communications of the IPN, standard middleware services such as "store and forward" would hide such details from the scientist, providing for a direct link between investigator and payload—"bringing the sensors to the scientists." The final step of linking the IPN with the terrestrial Internet (with appropriate layers of information technology security) allows the investigator and colleagues to enjoy this intimacy with remote assets from the convenience of the home institution.

When coupled with the other advantage offered by the IPN—greatly enhanced bandwidth—the possibilities for how scientists interact with sensors and instruments expand dramatically, particularly if virtual environment technology comes into play. Increased data volume will have little value unless methods for effectively utilizing this bounty of information for analysis, visualization, and planning of future science observation are realized. In a well-conceived immersive environment, as shown in Figure 11, an investigator could, for example, enter a depiction of a Mars surface environment and—depending on what kinds of data have been collected, returned, and rendered—walk around objects, pick them up, feel their texture, etc. Choices about what observations to make or samples to collect would be much more richly informed under this vision of how to exploit the power of the IPN.

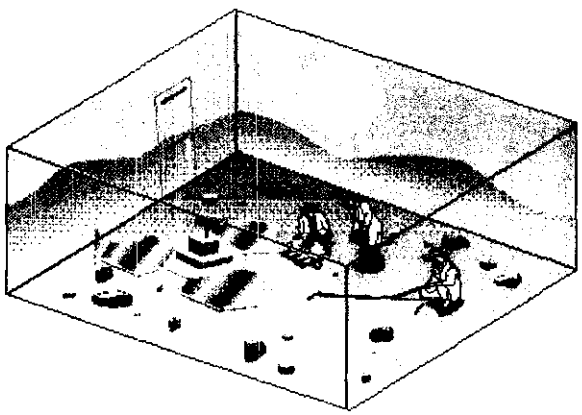

Figure 11: Virtual Sense of Presence

This IPN-based approach to accomplishing science missions could be further enhanced by application-level capabilities for *in situ* science data analysis and automated mission planning built on top of the middleware services. Scientists could create, evolve, and use "proxy" software onboard remote assets. When sought-after or unexpected results appeared, or alternatively, when an investigator gained new insights in the immersive environment, requests could be issued to remote assets, with automated mission planning accommodating those requests. Using the IPN as their virtual laboratory, a science team could access the set of deep-space assets and the remote environments they have been delivered to.

The IPN will offer equally exciting possibilities for the public. High-end immersive environments, as depicted in Figure 12, could be at facilities such as museums, with more modest capabilities on the home desktop. Applications for the public would be conceived to educate and to entertain. The public could explore a remote environment and could "pretend" to be the spacecraft—having its mobility and senses. It could even be possible to experience odors or weather conditions on another planet. Thus the IPN can play a key role in involving and educating the public and inspiring the next generation of explorers.

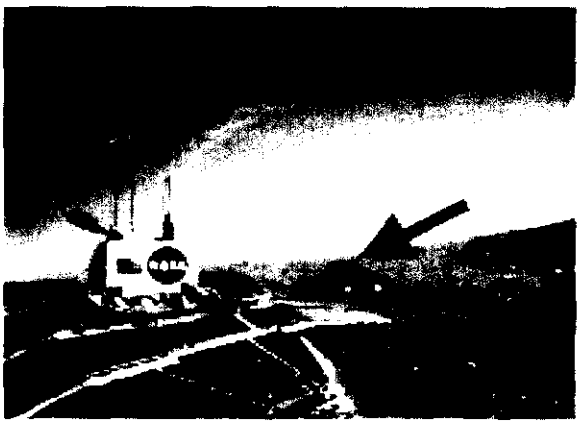

Figure 12: Experiencing the Remote Environment

SUMMARY

Space exploration is changing. The DSN must change to keep pace. This paper has outlined the critical areas in which transformation must occur and shown the directions to be taken to arrive at a desirable future. Bandwidth and reliability must increase. A more topologically diverse network

will come into being, with some assets owned by diverse entities and others located in space. Point-to-point links will evolve towards networked connectivity. Riding atop all this will be new telescience and telepresence services. Collectively these transformations will lead to an "Interplanetary Network" that will bring the sensors to the scientists and the planets to the public.

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