

## A VIEW OF THE FUTURE OF NASA'S DEEP SPACE NETWORK AND ASSOCIATED SYSTEMS

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### ABSTRACT

The current architecture of the Deep Space Network (DSN) reflects its heritage of supporting past, and ongoing, NASA missions. In the future, the size and character of the Agency's deep space mission fleet will significantly change. Consequently, the DSN must evolve to accommodate anticipated needs. The vision for the future DSN incorporates new applications and a "services-based" paradigm to support highly interactive mission operations, as well as a strong emphasis on operational efficiency. Data volumes will expand by orders of magnitude in both directions. Planetary Area Networks will emerge, to handle the needs of *in-situ* investigations. And finally, the envisioned, high-bandwidth DSN will play a key role in meeting NASA's requirements to broadly disseminate mission results to the public

### INTRODUCTION

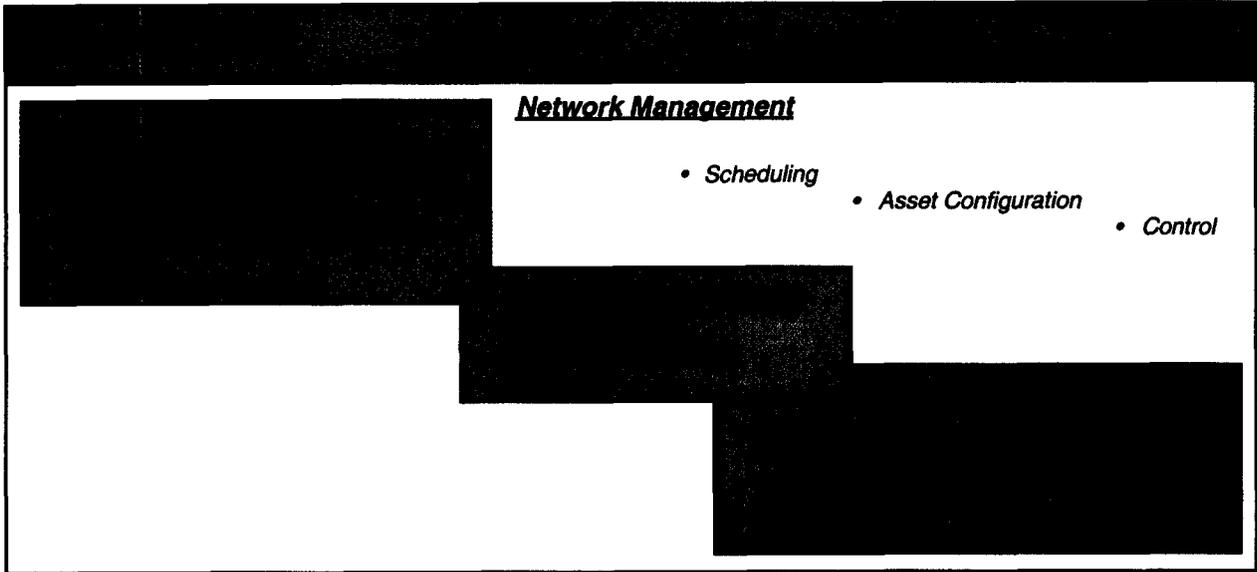
The Deep Space Network (DSN) has a four decade long track record of successfully supporting NASA's space science missions. The current network architecture is a reflection of these past, and ongoing, missions. However, the characteristics of NASA's future deep space missions will differ markedly from those of the past. Hence the DSN must evolve to accommodate the anticipated needs of this future fleet. A fourfold increase in the sheer number of missions, paced by increasing complexity of those missions, creates a need for a new "services-based" paradigm, as well as a strong emphasis on network efficiency. Data volumes carried by the DSN will expand by factors of 10 to 100, or possibly even higher. Planetary Area Networks will emerge, initially at Mars and eventually at other solar system locations. Paralleling state-of-the-art modes of interactive operations, a host of new services will be required by scientists and mission personnel. And finally, Agency requirements to broadly disseminate mission results will create a need to support an expanding array of high-bandwidth services for the public.

This paper will discuss various elements of NASA's envisioned DSN and associated systems, as depicted in the conceptual architecture of Fig. 1. Any successful enterprise must meet two key criteria: 1) provide needed services to customers, and; 2) do so at an acceptable cost. The paper begins with a brief overview of a mission, i.e., customer, demographic analysis. Results of this analysis determine the types, and quantities, of required services, and strongly influence how these must be provided. This motivates a high-level operations concept. Following this, details of the specific services will be described. Next to be treated will be the physical assets by which services are provided. Because these consist of sizeable, and hence expensive facilities, they will be covered in some detail. Finally, to tie it all together, there will be brief discussions of the required standards and protocols and the network management function.

### MISSION DEMOGRAPHICS

This section summarizes an ongoing analysis of mission set (customer base) demographics.<sup>1</sup> A demographic approach is chosen, as opposed to a compendium of hard requirements, because the time frame required to emplace new infrastructure elements is longer than the planning horizon for which definitive requirements are available. The analysis has resulted in four major findings.

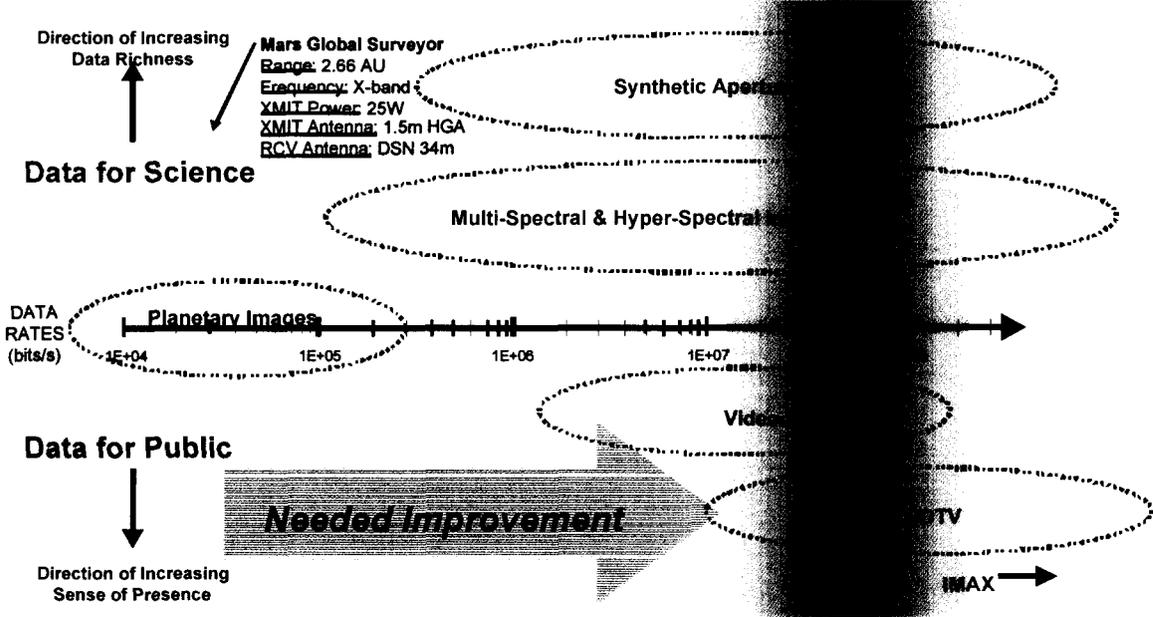
The first finding is that there has been a fourfold increase in the number of missions since 1987. For contrast, during those 15 years, the number of antennas in the DSN has increased by a net of only two, with a third scheduled for completion during 2003.



**Fig. 1: Conceptual View of DSN Architecture**

The second finding is that mission operations scenarios will become much more complex. Observatories in low Earth orbit will be replaced by more distant platforms, typically located at Lagrange points or in Earth-trailing orbits. Single, large spacecraft will be replaced by constellations of small, low-cost spacecraft. Flyby reconnaissance missions will be replaced by detailed orbital remote sensing. And finally, *in situ* exploration via long-lived mobile elements will replace short-lived probes.

The third finding is that downlink data rates and volumes will increase by one to two orders of magnitude, or perhaps even more. This is largely driven by an evolution toward more data-intensive instruments and media, as shown in Figure 2. In addition, the growing use of mobile *in situ* elements and accompanying proximity links will generate a consequent growth of “trunk-line” demand. Complicating this scenario even more is the fact that the Space Science Enterprise mission set shows a tendency to migrate further into deep space, making future missions more reliant on large aperture ground stations



**Fig. 2: More data-intensive instruments and media drive higher data rates and volumes**

The fourth finding is that uplink data rates will also increase, possibly by 10x to 100x, beginning perhaps around 2010. The future will see less reliance on low-level, low data rate commanding. Instead, there will be uploads of instrument calibration frames, large image or terrain files for navigation of mobile *in situ* elements, and software updates for sophisticated spacecraft operating systems.

## OPERATIONS CONCEPT

The operations concept for the future network and systems is driven by the two key criteria described earlier. For the first criteria, the mission demographics define the needed services, both in terms of their character and magnitude. The classic DSN of the late-20<sup>th</sup> century generally evolved to meet the specific needs of one flagship mission at a time – and that mission determined its architecture. A case in point is Voyager, which took the network from S-band to X-band, and drove installation of the 34m High Efficiency (HEF) antennas and upgrade of the large antennas from 64m to 70m. In that era, it was typical to have both Project and DSN personnel working with DSN systems in a hands-on manner to ensure mission success. The new business environment contains few, if any, missions of the flagship variety. Instead, there are significantly smaller missions, but many more of them. In the new reality, no mission, in and of itself, can uniquely determine the network architecture; however, the aggregate sum of the missions does. Additionally, expansion of the mission set clearly precludes the type of hands-on operations that characterized the previous era.

The magnitude of the customer base, along with the operational complexity that will be attempted, creates a need for what has been termed a “service paradigm.” In this new paradigm, mission personnel interact with the DSN in a high-level manner, much as one would make an international call on a cell phone today. There is little, if any, hands-on activity by Project personnel with the DSN and its associated systems. In order to make this paradigm work successfully, two factors are required. First, the interface between Flight Project and DSN must be simple and intuitive, e.g., by specification of requests for telemetry or command services. In contrast, the old paradigm would have witnessed a project specifying a chain of equipment and nursing that equipment, along with DSN personnel, to ensure success. The second factor that determines success of the new paradigm is highly reliable operations of DSN systems. Nothing will get a customer into the innards of a service provider’s processes faster than failures to deliver. Consequently the reliability of all systems that lead to service delivery to the customer must be enhanced. Thus, the hallmarks of the service paradigm are ease of use and high reliability.

The second criteria driving the operations concept is the need for greater network cost efficiency, both in terms of new implementations and continuing operation, maintenance and sustaining activities. The needs of the future missions will demand major new facilities. The need for cost effective implementations is obvious. Somewhat less obvious, but equally important, is the requirement that these be affordable to retain over a long time period. While the mission operations become more complex, the network operations should strive for simplicity to the maximum extent possible. Highly reliable systems will not only benefit customers, but also result in manageable maintenance costs.

## SERVICES & APPLICATIONS

*End-to-End Mission Operations Services* span the space-ground link and can be directed from either end, or perhaps cooperatively by both. Service components must interoperate for the function to be performed. Traditionally, over the last 40 years, space and ground components have been developed separately. However, in the 21<sup>st</sup> century, these will have to be developed in such a way as to provide seamless operability between mission ground systems and spacecraft flight systems.

Most well known among the *End-to-End Mission Operations Services* are Telemetry & Command, which are now grouped under a *Messaging Service*. This service will transfer mission data of any type, in any direction (uplink, downlink or cross-link), and across any network assets using standardized data units defined by the Consultative Committee for Space Data Systems (CCSDS).<sup>2</sup> As mentioned above, data volume requirements are likely to grow by one to two orders of magnitude.

The *Information Management Service* will provide users the capability to access the rapidly expanding volume of mission data (and information) acquired and stored throughout the network. Somewhat akin to the Terrestrial Internet, such access will not require a priori knowledge of the location of the physical data repository.

Missions of the future will require more precise state determination. This motivates three key services. First among these is the *Tracking Service*. Advanced techniques, such as higher frequencies and better ultra-stable oscillators (USOs) will deliver higher accuracy observables. For radio frequencies, these will include Doppler, ranging and Delta-Differenced One Way Range ( $\Delta$ DOR). For optical frequencies, analogs for ranging and plane of sky angles will become available. Many flight projects will wish to obtain not just tracking, but also a *Navigation Service*. This adds data processing to the observables to yield full state determination for a vehicle in flight or positioning for a landed element, e.g., a Mars rover. This service can work with either radio or optical frequency observables. In addition to Earth-based navigation, it will also support planetary approach navigation. This can be done utilizing images from a camera on an approaching spacecraft or a radio link to assets in orbit at the target planet, typically Mars. Further, the service will be able to deliver navigation data autonomously if so desired. Finally, some projects will also wish to obtain the highest-level *Flight Control Service*. This will enable monitor and control of spacecraft states, both navigation (position and velocity) and otherwise (power, thermal, etc.). Through this service, projects will also be able to execute various spacecraft activities and predict, prevent and respond to emergencies.

Time-keeping has always been important but will be even more so in the future when groups or constellations of spacecraft work together to make coordinated observations. A *Timing Service* will provide real-time correlation and synchronization of spacecraft clocks to UTC.

In addition to mission services, the network will support new applications for the public. In 10-20 years, people will expect high-bandwidth in the home and ready access to large volumes of data via the Internet. Mindful of its mandate to broadly disseminate the fruits of its activities, NASA will work internally, and with partners, to enable high-visibility applications that will repay the public investment in space exploration and provide educational value to future generations of students.

## **PHYSICAL ASSETS: BACKBONE**

None of these capabilities can be seriously contemplated without a high-performance and robust physical infrastructure, a major element of which is the telecommunications backbone, also known as the deep space link or long-haul trunk line. This can be broken down into the following initiatives.

### **Upgrade the current Deep Space Network**

Though the 21<sup>st</sup> century DSN will rely on new technological approaches, it will build upon, and fully utilize, capabilities of the pre-existing network. And before these new approaches can come to fruition, certain ongoing developments within the current network must be completed. The first of these is a planned life extension of the large 70m antennas, shown in Figure 3. One such antenna exists at each DSN complex in Goldstone, California, Madrid, Spain and Canberra, Australia. The 70m antennas are on the order of 30 years old, which is 20 years beyond their nominal design life. Further, though designed for a 25% duty cycle, they have operated at 80% duty cycle for most of their lives. And finally, the increase from 64m to 70m has increased the weight carried by key structural elements by 38%.

But even after refurbishment, these antennas will still constitute single points of failure. Facing up to this vulnerability, in 1991 NASA approved a plan to install four new 34m antennas at each of the DSN complexes, or a total of twelve. Combining four of these, with suitable arraying technology, was to provide 70m equivalent aperture and performance. Arrays of modern 34m antennas, called Beam Wave Guides (BWG) from their ray path design and shown in Fig. 4, were to provide the needed 70m backup. However, only five of these antennas have been built: three at Goldstone and one each at Madrid and Canberra. A sixth antenna is currently under construction in Madrid. Although new approaches, such as

large arrays of small antennas, may obviate the need for the full complement of twelve new 34m antennas, engineers and managers at the Jet Propulsion Laboratory are currently recommending at least one additional antenna. This would be in Australia, giving each complex a minimum of two of the new antennas. If for no other reason, these two would provide backup for each other in Ka-band operations. Further, they would have uplink capability, a feature not anticipated for a large array of small antennas.



Fig. 3: 70m Antenna

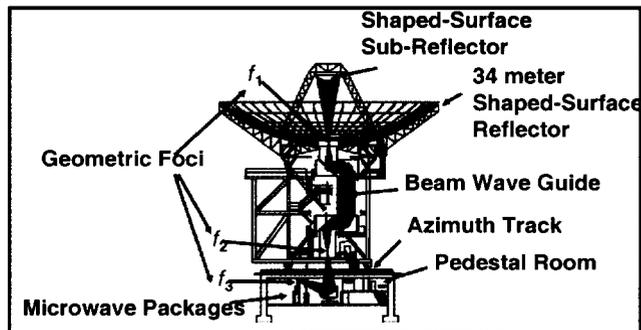


Fig. 4: 34m Beam Wave Guide Antenna

The need for higher data rates is already driving flight projects and the DSN from X-band (8 GHz) up to Ka-band (32 GHz). The higher frequency provides more directivity for enhanced link performance. But perhaps more importantly it also provides ten times the allocated spectrum, i.e., 500 MHz (Ka-band) vs. 50 MHz (X-band). Installation of Ka-band on DSN antennas has already begun and will continue as the network continues to advance.

Another critical capability for the future is high performance uplink mission operations, where uplink data volumes will increase as remote element calibration files, image and terrain files for mobility, and operations for anomalous events (i.e., spacecraft emergencies) it is critical. Oddly enough spacecraft in unusual attitudes has in fact declined by 13 dB over the last fact that current spacecraft carry only X-band command receivers whereas utilized S-band. This, coupled with the fact that the DSN has 400 kW S-antennas but only 20 kW at X-band yields the performance degradation. To recover the performance either by increasing transmit power or by arraying antennas. The latter approach has yet to be demonstrated and is a near-term technology initiative. Upgrades to command modulators will also be needed to enable the higher uplink rates for routine operations.

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Before embarking upon major new antenna implementations, it makes sense to cost-effectively maximize the utility of current facilities. To this end, the DSN supports a communications scenario called "Multiple Spacecraft Per Aperture" or MSPA. As the name implies, one antenna simultaneously supports multiple spacecraft (in downlink mode) provided they are all within the beam width of that antenna. This capability is most useful for support of Mars missions, because there are, and will continue to be, numerous spacecraft targeted for that planet. And once in orbit or on the surface, they easily fall within a DSN 34m antenna X or Ka-band beam width. Today's MSPA supports two spacecraft ( $M = 2$ ) though the operational aspects are somewhat complex and labor-intensive. In the future, the DSN will upgrade to a mostly automated system and be able to support four spacecraft ( $M = 4$ ) simultaneously.

As the number of bits captured by DSN front ends grows, it will be necessary to upgrade the back end systems to handle the higher bit rates. To avoid bottlenecks it will be necessary to replace current telemetry processors, which are limited to 2.2 Mbps, with higher capacity systems. Future missions will be utilizing Turbo Codes for forward error correction. Current Turbo decoders are limited to 1.4 Mbps. These systems will require upgrading to be able to handle the higher downlink rates. The final bottleneck to be removed is the distribution of acquired data from the remote complexes to the appropriate end user, whether via JPL or not. Typically this is referred to as ground communications though there is no actual requirement for the traffic to avoid satellite links. Currently, these data are transferred via leased lines

that are obtained in a few multiples of T1 capacity. Between Goldstone and Pasadena, costs for this capacity are not prohibitive. From the overseas complexes back to JPL, costs are typically about thirty times as high. As data volumes increase by factors of 10 to 100, the costs of ground communications will clearly become prohibitive unless a new paradigm is adopted. This is a current area of investigation. It is likely that a mission critical subset of the acquired data will continue to be transferred over leased lines. However, the great majority of data may eventually move over a public switched network, at affordable costs, as is typical for Internet communications.

The facilities envisioned, the traffic to be handled and the complexity of mission operations attempted all argue for a new automated self-monitor and control system. Without such a system, there is little hope that the ease of use and affordability goals, as stated in the operations concept, will be realized.

Finally, an emerging trend is for NASA's DSN to work cooperatively with assets of other international space agencies. In the future, other nations will expect to play a bigger role in deep space telecommunications and tracking. Most notably, the European Space Agency's (ESA) 35m station at New Norcia, Australia is nearing its initial operating capability. Somewhat further out, Agenzia Spaziale Italiana (ASI) is planning to construct a 64m antenna on the island of Sardinia to support radio astronomy and space operations. Centre National d'Etudes Spatiales (CNES) is developing plans to construct its own deep space station, possibly to be located in South Africa or South America. These, and other international facilities that come on line, are considered welcome additions to the set of assets available to track the far-flung mission fleet. In order to enable the DSN and other facilities to actually interoperate, it will be necessary to utilize standards that apply across all layers of the link. Many of these standards are already in place whereas others are currently being devised. Through the auspices of the CCSDS (Ref. 2), space faring nations are all working together to ensure that the interoperability that all desire will actually come to pass.

### Flight Segment

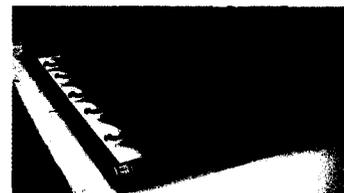
Because communications requires capability at both ends of a link, there will be improvements to equipment on board elements in space or on planetary surfaces. Three devices are key in establishing the deep space link, the first of which is spacecraft radios. The current state of the art is embodied in a device known as the Small Deep Space Transponder (SDST). In the future, advanced radios will be developed. They will be smaller in terms of mass, volume and power requirements, as well as in parts count. Yet they will have dual frequency (X and Ka-band) and a higher level of functional integration. Example radios are shown in Fig. 5.



**Fig. 5: SDST & Advanced Radio**



**Fig. 6: 35W-100W Ka-band TWTA**



**Fig. 7: 3.5m X/K-band Reflect-Array**

A second key flight device is the final radio frequency (RF) amplifier. The Mars Reconnaissance Orbiter, to be launched in 2005, will fly a dual system with 100W X-Band and 35W Ka-Band traveling wave tube amplifiers (TWTA). Sample amplifiers are shown in Fig. 6. Plans exist to develop a 100W Ka-band TWTA by later in the decade. In the further future, very high power amplifiers may become available to take advantage of the wattage afforded by NASA's new nuclear power in space initiative.

The third key device is the spacecraft antenna. Most current deep space antennas are solid parabolas, either hard mounted to the spacecraft body or on a deployable boom. But in either case, their size is constrained by the limitations of launch vehicle fairings. Many future missions will require high-gain antennas whose size exceeds these fairing constraints. Hence the need for devices in which the

antenna surface itself is deployable, most likely by means of inflatable technology. Fig. 7 shows a concept for a deployable 3.5m diameter reflect-array, expected to be available later in this decade. This approach uses an array of cross dipoles and/or patches to effectively synthesize a parabola. A larger size, in the 5m to 7m class may be available early next decade. Other types are also being investigated, including inflatable lens antennas, which may be available around 2010.

### **Large Array of Small Antennas**

When advantages of higher frequency (Ka-band) operation and advanced spacecraft radios, amplifiers and antennas are considered, link performance is still unlikely to be able to support future data rate and volume requirements. Closing this performance gap will require additional aperture within the DSN. Though RF is not the only solution, it is expected to be a mainstay for many years to come. The classic approach would be to construct additional large aperture antennas of the 34m and 70m size class. However, a significantly lower cost option, using large arrays of small antennas (10m class), may be a viable alternative. This is depicted in Fig. 8. Work in recent years, by the radio astronomy community and Direct Broadcast Satellite (DBS) systems providers, seems to be lowering the cost per unit aperture of high-performance RF antennas. Advances in low cost, low noise amplifiers and reliable cryogenics are also occurring. Coupling these with advances in signal processing capability yields an architectural approach that must be considered. More detail on this topic can be found in a companion paper.<sup>3</sup>



**Fig. 8: Large Array of Small Antennas**

An example concept could ultimately have on the order of 3600 12m antennas at each of the three DSN longitudes. However, to improve Ka-band weather statistics, these would likely be split into four groupings of about 900 antennas. Each such group would be located sufficiently far away so as to be in an uncorrelated or even anti-correlated weather cell. Large apertures would be synthesized from these groups of small antennas, autonomously and on an as needed basis, to support the mission fleet with high-performance links. Antennas could be swapped in or out as link margins change during a pass. The physical distance separating antennas could be used to provide interferometric baselines with which to derive plane of sky navigation information. Other capabilities, such as interferometric nulling of unwanted radio frequency interference (RFI), are also possible. However, one limitation of the concept, as currently envisioned, is that it would support downlink only. Hence the large array of small antennas would have to work cooperatively with DSN 34m and 70m antennas to provide needed uplinks.

Because this approach has a very large scope, it will be necessary to construct a prototype array. Its purpose will be to validate technological readiness, system performance, operations and maintenance, and cost estimates before proceeding with full-scale development. This prototype is expected to be constructed at Goldstone and be available for testing late in this decade. It will nominally be sized to equal the aperture of two 70m antennas. If the prototype meets expectations, it could eventually be transferred to operations as the first installment of a large array of small antennas within the DSN.

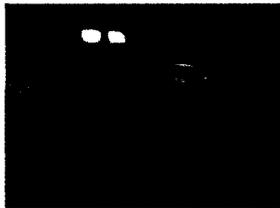
### **Deep Space Optical Communications**

Another approach that holds the promise of orders of magnitude performance improvement is optical communications. In this scenario, messages would be beamed via lasers and telescopes rather than RF amplifiers and antennas. Hence an optical architecture requires a fundamental change in spacecraft telecommunications equipment that is not required for users of a large array of small antennas. On the other hand, the optical architecture promises even more performance gain and the possibility of

lower mass spacecraft communications subsystems. There are two fundamental approaches to optical communications, ground basing or space basing the assets at the Earth end of the link.

The ground-based alternative is currently the preferred approach. In this scenario, a number of 10m telescopes would be used for signal reception from deep space. Though 10m is the size of the Keck telescope atop Mauna Kea in Hawaii, a similarly sized telescope for optical communications could be obtained for much lower cost. The savings trace to the fact that optical communications does not require imaging-quality optics. Instead, using a direct detection approach with pulse code modulation, all that is needed is the ability to ascertain the arrival time of photons. A telescope to support this approach, called a "photon bucket," is significantly less expensive than a diffraction-limited imaging system. Two deployment options are being considered for ground basing. Considerations involve full longitude coverage, support of multiple spacecraft and weather diversity. The first option, called the Linearly Dispersed Optical Subnet (LDOS) would emplace six to seven photon buckets around the Earth spaced in roughly equal increments of longitude. This approach would require NASA to obtain facilities and development infrastructure in geographic regions where it does not currently have a presence. The second approach, called Clustered Deployment Optical Subnet (CDOS) would emplace three 10m photon buckets in each longitude region, or a total of nine worldwide. Site diversity would help to offset weather effects, much as in the case of the deployment plan for the large array of small antennas.

A final option is space basing of a sizeable optical terminal, perhaps on the order of 7m, in mid or high Earth orbit. Space basing avoids 3 dB of atmospheric signal attenuation, hence the smaller size. Also, with atmospheric turbulence effects removed, there is rationale to move to a diffraction-limited coherent detection scheme. However a single terminal in Earth orbit is likely to cost as much as the total of either ground-based scheme yet be able to support only one spacecraft at any given time.



**Fig. 9: 1m OCTL Facility  
(Under construction)**



**Fig. 10: 10 cm Optical Comm  
Demonstrator**



**Fig. 11: 30 cm Optical  
Comm Terminal**

In the next few years, these architectural options, and possibly others, will be further analyzed. Also technology demonstrations, some of which have already begun, will continue and expand with the goal of validating the feasibility of an operational optical communications capability. Near-term demonstrations will utilize a 1m telescope currently under construction at JPL's Table Mountain Facility in the San Gabriel Mountains. This facility, called the Optical Communications Technology Laboratory (OCTL), shown in Fig. 9, will be on-line during 2003. On the flight side, a 10 cm Optical Communications Demonstrator, shown in Fig. 10, has already been developed and a 30 cm Optical Communications Terminal, shown in Fig. 11, is under development. Planned demonstrations, of an uplink beacon and downlink telemetry, will characterize performance of optical links first between Earth orbit and the ground, and eventually from deep space to the ground. The deep space optical technology effort has strong collaborative ties to related activities within NASA's Earth Science Enterprise and also with the Department of Defense

## **PHYSICAL ASSETS: PLANETARY AREA NETWORKS**

In addition to the potentially new physical assets that will be deployed on, or near the Earth, there is an emerging need for telecommunications infrastructure emplaced at other locations within the Solar System. These will provide breakthrough increases in communications and navigation capabilities in support of sustained exploration at those locations. The first, and most obvious location for such deployment is in the vicinity of Mars, to support NASA's long-term commitment to explore that planet.

There are a number of drivers for Planetary Area Networks, traceable to the mission set demographics and NASA strategic planning. Chief among these is the Agency's intention to achieve virtual presence in the solar system.<sup>4</sup> This objective will require significantly increased data return, which in turn will enable new science and increased public outreach. Another key driver is the anticipated complexity of *in-situ* operations, which will require much improved communications connectivity. This will result in lower latency science planning cycles, increased science return from life-limited elements and an ability to explore sites not necessarily in direct view of Earth, such as a long-term Mars polar outpost. A third driver has to do with the robustness of exploration programs, especially during high-risk, critical mission events. For these types of events, localized communications assets can successfully provide critical telemetry when links with Earth may not even be possible. Another capability enabled by a highly sensitive localized relay is that of low-mass, low-power *in situ* exploration concepts. Major reductions in communications systems requirements are possible if they do not have to close links to Earth. Finally, for a number of future missions, that require greatly improved navigation for precision approach and landing, only a localized infrastructure can suffice.



**Fig. 12: Mars Network**

Mars Network, the first Planetary Area Network, will initially comprise a constellation of remote sensing science orbiters. These will incorporate hardware and software for store and forward relay communications, and will be able to support landed elements having only micro-communications systems. As Mars Network grows, it is likely to incorporate dedicated comsats, most likely in medium Mars orbits. Eventually, one or more areostationary relay satellites are envisioned, to provide continuous video-class bandwidth for robotic outposts and human presence. Finally, a “human-rated,” high-reliability Mars Network will support integrated human-robotic activities. A graphic depiction of Mars Network is shown in Fig. 12. As other targets become the focus of ongoing exploration, e.g., Europa and Titan, they may also become sites for deployment of local communications infrastructure.

## **STANDARDS & PROTOCOLS**

The DSN and associated systems envisioned for the future span many types of applications and physical assets, in many locations and at times working cooperatively with non-NASA assets. In this environment, it is absolutely essential to rely upon rigorously applied standards and protocols. These serve as the “glue” enabling the numerous physical assets and services to work together as a unified architecture. Fortunately, the CCSDS has laid the groundwork for standards and protocols that are subscribed to by all cooperating space agencies. These apply in different layers of networks and systems.

Top layer standards and protocols support the applications, which can be thought of as the interface point between the network and its users. Low layer standards and protocols support the actual space link, which thus enable connectivity and communication between physical assets. Finally, there are End-to-End Networking standards and protocols that span all layers, including any type of physical routing. These provide for seamless interoperability between ground and flight systems. More detail on this topic can be found in a companion paper.<sup>5</sup>

## **NETWORK MANAGEMENT**

The standards and protocols couple the applications to the physical assets so they can work together. Behind all this is the network management function, which ties all these layers together so as to

achieve the objectives of the network operations concept. Because of the diversity of network elements, in terms of both character and distance, a new management concept is required.

Backbone elements of the network will require scheduling, asset configuration and control. Scheduling is expected to move in the direction of increased automation. Advanced asset configuration and control at DSN complexes will result in higher efficiency. Human intervention will still be available but is expected to occur on an operation-by-exception basis. Finally, the capability to respond to spacecraft requests will likely occur, transitioning the operation into more of a demand access mode.

As Mars Network, and other Planetary Area Networks, come on line, they will also require scheduling, asset configuration and control. Approaches similar to those characterizing the backbone network are anticipated. However, for these *in-situ* networks, automation is likely to be even more important because of the great distance and consequent communications delay.

Finally, end-to-end network management must span all elements of the Planetary Area Networks and the backbone network. Automation of end-to-end network management functions is again the key to efficiency. For the benefit of the end users, whether scientists, mission personnel or public, operations will be fully integrated with the Terrestrial Internet. These users will perceive seamless, unified operations across all the diverse elements of the envisioned network and systems.

## SUMMARY

Future missions are expected to drive major advances in the services provided by the DSN and its associated systems. These will require significant upgrades of the physical assets. In the near term, these will include upgrades of the current DSN and improvements in flight telecommunications equipment. Further out, investments in large arrays of small antennas and optical communications will bring these technologies into operational readiness. Paralleling these developments will be the first deployment of a Planetary Area Network, at Mars. Ongoing work in standards and protocols will ensure that these diverse elements work together. A network management concept will evolve to schedule, configure and control all the diverse elements. Finally, with diligence and support, the concept of easy to use, highly reliable and efficient operations will be achieved both for the networks and its customers.

## ACKNOWLEDGEMENTS

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