IDENTIFYING FUTURE MISSION DRIVERS ON THE DEEP SPACE NETWORK

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ABSTRACT

This paper discusses the methodology used to identify mission drivers on the future architecture for the Deep Space Network (DSN). Two approximate time epochs were treated: the 2010 epoch and the post-2010 epoch. Downlink drivers were treated first, then uplink.

Treatment of the 2010 epoch relied largely on the analysis of DSN mission set demographics and, from that, identification of the most robust, enduring trends. Four distinct trends emerged that indicated the need for increased future downlink capability. Inherent mission model uncertainties were addressed by applying a quasi-Monte Carlo technique to the analysis of the data.

Because mission and spacecraft designers do not have a reliable means for knowing the capabilities that may exist in, say, 2020 or 2030, mission concepts for such time frames are generally biased toward today's capabilities. To avoid this bias, treatment of the post-2010 epoch involved less reliance on mission demographics and more on using Earth-based science capability trends as predictors of deep space science capability needs. In particular, the downlink analysis benchmarked current DSN capabilities against the future deep-space data rate requirements implied by current Earth remote sensing capabilities. This analysis revealed the need for potential orders-of-magnitude growth in current DSN downlink capabilities.

In the examination of 2010-epoch uplink trends, mission set demographics analysis revealed little change in the standard 2 kbps command rate until around the end of the decade, when the first significantly larger uplink data rate requirement appears. For the post-2010 epoch, an effort has been initiated to derive drivers from examination of the uplink data rates required for operating current autonomous, Earth-robotic vehicles -- vehicles that have navigation and targeting needs similar to those for the autonomous, *in situ* exploration elements planned for other solar system locations. Together, the 2010 epoch and post-2010 epoch examinations suggest a change in the nature of how the uplink will be used – with less need for low-level commanding and greater need for responding to *in situ* requests for science instrument calibration data, navigation-related information, and occasional re-configurable system software uploads. Key capacity-related questions still outstanding are: (1) What is the anticipated size of the uploads as a function of time? (2) What is the anticipated frequency of these uploads?

1.0 INTRODUCTION

While the DSN has always needed to keep abreast of future mission characteristics that might drive changes to its architecture, two factors have emerged over the past decade that particularly underscore its need to do so: its aging assets and the changing robotic space exploration paradigm.

1.1 Motivation #1: The Deep Space Network's Aging Assets

Nearly 60% of the DSN's operating antennas are more than 15 years old.[1] Its largest antennas, the 70m antennas, were originally constructed as 64m antennas some 30-to-40 years ago and were designed for a 10-year service life based on a 25% utilization factor. About 16 years ago, they were extended to 70 meters and, throughout, have been operated at an estimated 80% utilization factor. These sobering statistics suggest that the need to refurbish and/or replace many of the DSN's current assets is looming large on the horizon. Under such circumstances, questions arise regarding what future mission needs the DSN must be in a position to support. This knowledge, in turn, helps address such questions as "which current assets will still be needed in the future?" "What new assets will be needed?" And, "what will be the appropriate asset mix?"

1.2 Motivation #2: The Changing Robotic Space Exploration Paradigm

The nature of robotic space exploration has also undergone some dramatic changes over the past ten years. In the solar and astrophysical realms, many missions are now preferring to observe from Earth-trailing heliocentric orbits and the Sun-Earth Lagrange-points rather than from the more thermally and optically challenging environment of low-Earth orbit. These more distant observation points translate into longer communications link distances, suggesting increased reliance on larger antennas and more powerful transmitters. In addition, observations from single, large spacecraft are gradually being supplanted by coordinated observations from constellations of small, lower-cost spacecraft. This change suggests greater future reliance on proximity links between spacecraft and use of a single spacecraft for relay of the collective data back to Earth. In the planetary exploration realm, missions have moved beyond preliminary flyby reconnaissance of the solar system to more detailed, longer-duration remote sensing – suggesting growth in returned data volumes and a consequent need for higher data rates. And, as we have undertaken more detailed exploration of our solar system, *in situ* exploration has evolved from short-lived probes to longer-lived, more autonomous mobile elements. This evolution suggests growth in returned data volumes, a consequent need for higher data rates, greater reliance on proximity links between elements and on relays to "beam" their collective data back to Earth, and significant changes in how all of these elements are commanded and operated. All of these changes, together, suggest emerging demands on the DSN that are much different from those of a decade or more ago.

2.0 METHODOLOGY

While changes over the past decade may suggest future directions for the DSN, reliable identification, quantification, and extrapolation of trends more than a couple of years into the future requires careful examination and analysis of future mission plans. In the study described below, this examination and analysis of future mission plans has taken roughly two years and involved three general steps: data gathering, mission demographics analysis, and extrapolation from Earth-based capability analogies.

2.1 Data Gathering

The study began with a thorough review of the most up-to-date, applicable NASA strategic plans, roadmaps, and related National Academy of Science documents. In parallel with this review, interviews were conducted with scientists and mission designers believed to be representative of the potential future DSN user community. The information gathered through these parallel efforts was then used to construct a potential future mission set through about 2020. The nearer-term missions (through ~2012) were validated against NASA Space Science Enterprise and Space Operations Management Office mission lists in existence at the time. After arriving at an agreed upon future mission set, the study then focused on identifying the parameters important to characterizing mission drivers on the DSN. These parameters included such characteristics as mission uplink and downlink data rates, uplink and downlink frequency bands, onboard data storage volumes, mission destinations, associated link distances, planned antenna usage, and dozens of other characteristics that might have a bearing on future DSN support. Once these parameters were identified, the author began the process of finding and entering the corresponding data for each mission into a very large EXCEL workbook. For near-term missions, the data were derived from the support agreements that DSN representatives had already worked out with the missions. For longer-term missions, data were derived from mission design review packages and/or mission concept studies, depending upon the concept's level of maturity. After nearly a year of effort, the resulting mission model was ready for analysis.

2.2 Mission Demographics Analysis

The mission demographics analysis began by extracting mission data for specific time intervals. Initially, the study looked at the 2000, 2005, 2010, and 2015 time periods.[2] Later, the study used updated mission data to look at the 2002, 2007, and 2012 time periods. Data for these time periods, for a specific parameter or set of parameters, were then organized into EXCEL spreadsheets conducive for analyzing and plotting trends across the given time intervals. Within the time intervals, mission data were also broken down by Space Science Enterprise theme area (i.e., Exploration of the Solar System, Sun-Earth Connection, Structure & Evolution of the Universe, and Astronomical Search for Origins) to see if one or more particular theme areas manifested trends with a bearing on the DSN different from any of the other theme areas. The results of the analysis are discussed in the "Findings" section of this paper.

The second stage of the demographics analysis involved conducting a sensitivity analysis to ascertain how resilient each trend was to changes in the mission model. As anyone who has tried to keep track of future mission plans can attest, the mission set is, at best, a "moving target." Some mission concepts never make it into design and development. Some missions do, but later get cancelled for budgetary, technical, or other reasons. Some missions get deferred for similar reasons, and some missions that do make it into operations then fail. Throughout, mission plans and parameters change. Hence, for any of the identified trends to serve as credible indicators of future mission needs, their resilience to such upsets had to be demonstrated. To do this, the author introduced a "quasi-Monte Carlo" approach. In this approach, 50% of the mission set, for each time interval, was randomly selected for elimination. The same trend analyses were then run on the remaining mission set and the results plotted. Then, returning to the original mission set, another 50% was randomly selected for elimination. The same trend analyses were again run on the remaining mission set and the results plotted. This procedure was repeated several times until all of the missions had been randomly selected at one time or another for elimination. (A true Monte Carlo analysis would have utilized thousands of runs, but this was unnecessary due to the very limited size of the mission set within each time interval.) The results of each run were compared to each other and to the original run with the full mission set. While many of the runs showed trends lower in magnitude than in the original run (due to having had 50% of the mission set eliminated), the trends themselves persisted.

2.3 Extrapolation from Earth-based Science Capability Analogies

While mission demographic trends appear to provide a reasonable indication of emerging demands on the DSN over the next 10 years, concepts for missions beyond this time frame begin to manifest a strong bias toward known capabilities. This tendency can prove problematic when trying to determine what the requirements should be for very long-lived assets. As mentioned near the beginning of the paper, some of the DSN's antennas have been in use for 30-to-40 years. Hence, looking out only 10 years for mission drivers does not suffice.

To solve this dilemma, the author began to look for Earth-based capability analogies from which to extrapolate. In general, we know that scientists want to be able to carry out science investigations at other planets with the same ease, precision, and resolution as they can on Earth. Ergo, the data rate demands associated with current Earth-based science capabilities provide an indication of what will ultimately be needed for future deep-space science capabilities. A case-in-point is remote sensing from space. The instrumentation and associated media used in Earth remote sensing have always outpaced the fidelity of that used in remote sensing at other planets. For instance, by the time missions began taking high-resolution color photographs at other planets, Earth remote sensing spacecraft were already taking multi-spectral and synthetic aperture radar images of Earth. This time lag is largely due to the extreme mass, power, volume, and life-limiting constraints associated with deep space missions. To overcome these constraints, significant technological advances in areas such as instrument miniaturization and radiation hardening have to occur – advances that take time. Hence, today's remote sensing capabilities at Earth suggest tomorrow's capabilities at other solar system destinations.

In the study, the downlink data rate requirements for the DSN beyond the 2010 era were derived largely from such a remote sensing analogy. As shown later in the "Findings" section (Figure 7), Earth orbiting science instrument data rates for everything from single, monochromatic images to hyper-spectral images were plotted along and above a data rate axis. Similarly the data rates for various types of public outreach media were plotted along and below the data rate axis. Some of the past and present deep space science instrument rates were also plotted for comparison. (These generally exhibited much lower data rate requirements than their Earth-orbiting counterparts due to the collected data having to be stored in memory and then trickled back to the Earth at the maximum data rate allowed by the communications link.) Analysis consisted of benchmarking, relative to the instrument data rates, the data rate performance of a reference spacecraft downlinking to DSN 34m and 70m antennas from a particular solar system location. Each specific benchmark corresponded to a destination- and associated science investigation-scenario delineated in NASA's strategic plans. The difference between the benchmarked data rate and the desired science instrument data rate was then used to derive the amount of improvement in link performance needed to support the scenario. The results of these benchmarking analyses are summarized in the "Findings" section of this paper.

In the case of uplink, post-2010 era data rate requirements on the DSN are in the process of being derived from a different type of Earth-based capability analogy – the upload requirements associated with autonomous vehicles (e.g., cruise missiles, unmanned aerial vehicles, and unmanned ground vehicles). Because the choice of analogy was, in part, driven by findings from the mission demographics analysis, discussion of this particular analogy and how it is being used will be deferred until after discussion of the findings from the prior analyses.

3.0 FINDINGS

3.1 Downlink Circa ~2010

As noted above, treatment of the ~2010 epoch relied largely on the analysis of DSN mission set demographics and, from that, identification of the most robust, enduring trends. Four distinct trends emerged that indicated the need for increased future downlink capability. These trends included:

- Migration of the DSN-supported Space Science Enterprise mission set into deep space.
- Future mission plan reliance on large aperture ground stations.
- Evolution toward more data-intensive instruments and media.
- Growing use of proximity links and consequent growth of "trunk-line" demand.

With respect to the first trend, migration of the DSN-supported Space Science Enterprise mission set into deep space, Figure 1 clearly shows the proportion of low-Earth orbit (LEO) and high-Earth orbit (HEO) spacecraft to be decreasing significantly over the next 10 years. By contrast, the relative proportion of spacecraft located in deep space (i.e. at distances > ~2 million km) and at the Lagrange points increases over the same time period. This increase, particularly in the deep space component, will translate into a greater number of longer-distance links, driving an increasing need for larger effective aperture.

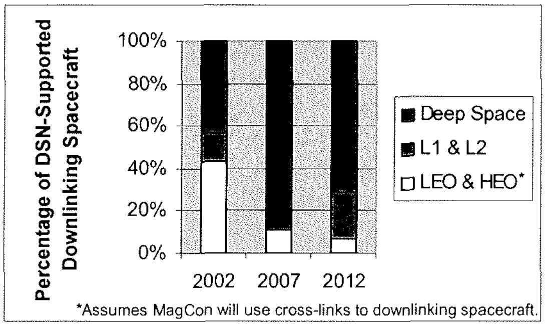

Figure 1. Spacecraft Locational Distribution as a Function of Time

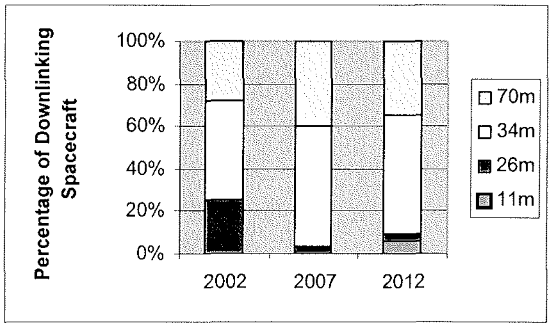

Figure 2. Relative Proportion of Downlinking Spacececraft Utilizing Each Antenna Type as a Function of Time

This need for larger effective aperture can, in part, be seen in Figure 2. Over the next 10 years, the proportion of spacecraft planning to rely on 34m and 70m antennas increases, while the proportion planning to rely on the 26m antennas decreases. While largely attributable to the migration of the mission set into deep space, some of this shift may also be due to the fact that the 26m antennas only support S-band downlink. Many missions are moving to higher downlink frequencies (i.e., X- and Ka-band) that are capable of supporting larger allocated bandwidths and higher data rates. Beyond these trends, Figure 2 also suggests some 11m demand in 2012. The resurgence of Lagrange point missions in this time frame (Figure 1) at least partially drives this demand. However, some of the latest design efforts for such Lagrange point missions suggest that 11m aperture may not be adequate for the anticipated data volumes.[3]

In fact, consistent with a trend toward more data-intensive instruments and media, data volumes in general appear to be on the increase. In Figure 3, the plot of onboard spacecraft data storage capacity as a function of time suggests that missions will collect 1-to-2 orders of magnitude more data over the next 10 years than they are currently. Figure 4 indicates a corresponding increase in mission data rates of approximately 10x in 10 years. Examination of this increase by Space Science Enterprise theme area reveals that some of the peak downlink data rates are driven by missions belonging to the Exploration of the Solar System (ESS) theme area – largely by those at Mars. As illustrated in Figure 5 (next page), Mars orbiter data rates increase by almost 2 orders of magnitude in 10 years due to the large data volumes associated with high-resolution spatial, spectral, and radar imaging.

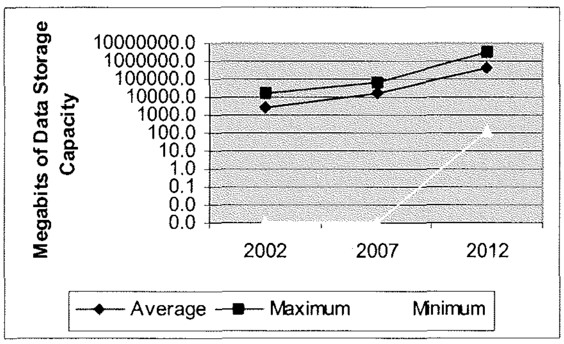

Figure 3. Spacecraft Data Storage Trends

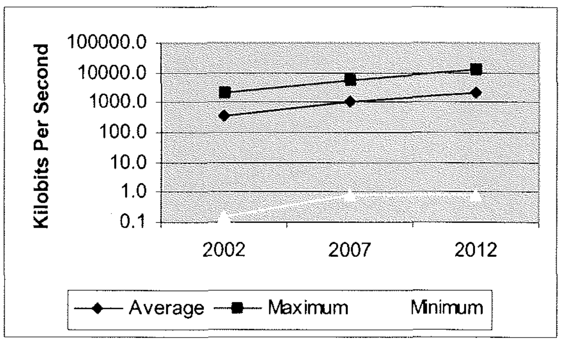

Figure 4. Telemetry Rate Trends Across All Space Science Theme Areas

Figure 6 illustrates the fourth and final trend – growing use of proximity links and consequent growth of "trunk-line" demand. In this trend, a growing proportion of the mission set is also serving a relay function for a growing number of locally "networked" exploration elements within each mission. These exploration elements are generally either members of constellations or are *in situ* landers, rovers, and probes. As the ratio of these "communication nodes" to relay links grows over time so does the bandwidth demand on the "trunk-lines" between the relays and Earth.

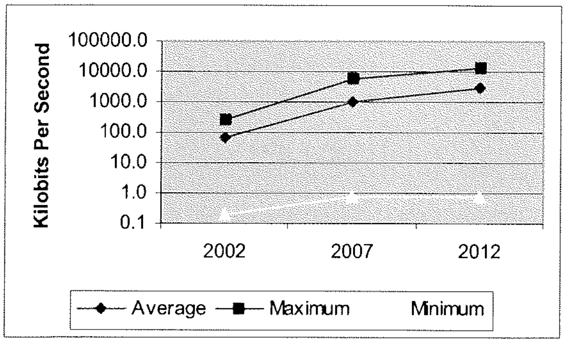

Figure 5. ESS Telemetry Rate Trends

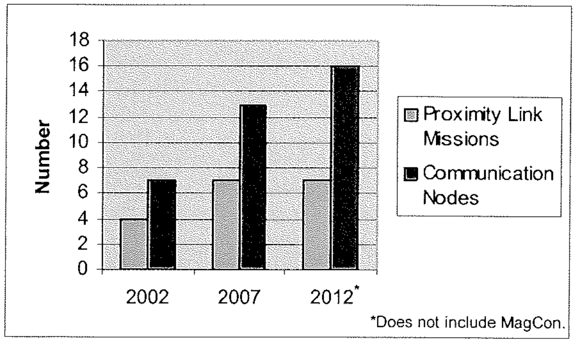

Figure 6. Proximity Link Trends

3.2 Downlink: Looking Beyond 2010

As described in the methodology discussion, looking beyond 2010 involved benchmarking DSN-supportable downlink rates for various future mission scenarios relative to Earth-based remote sensing data rate requirements. Two of these benchmarking scenarios are provided below for purposes of illustration. Figure 7 shows, relative to a Mars Global Surveyor (MGS) benchmark[4], a future Mars orbiter/relay scenario in which the spacecraft is using a powerful 100-watt Ka-band transmitter and a huge, deployable 5m high-gain antenna to downlink its data to DSN 34m and 70m assets. Note that such spacecraft telecom equipment does not currently exist, nor does 70m, Ka-band capability. Despite the huge increase in data rates these assumptions support relative to MGS, the 70m performance still falls roughly an order-of-magnitude short of the data rates we would like to be able to support at Mars – data rates needed to provide synthetic aperture radar (SAR) and hyper-spectral imagery investigations of the same fidelity as that already being conducted at Earth.

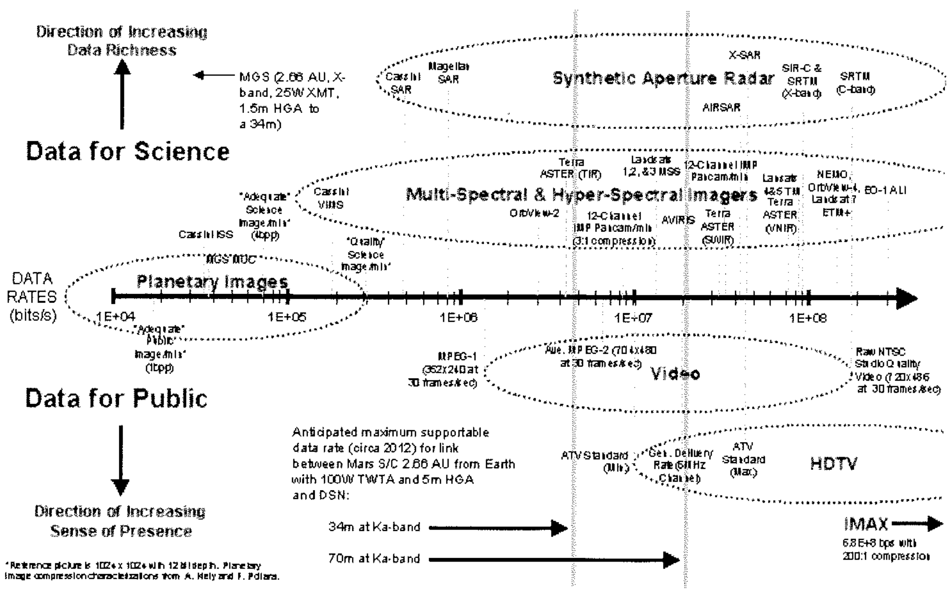

Figure 7. MGS[4] Relative to Mars Orbiter Relay Scenario Circa 2012 (Maximum Supportable Rates at 2.66 AU with RF Flight Hardware Improvements and Ka Ground Improvements)

Figure 8 shows how this data rate shortfall becomes more pronounced at more distant targets, in this case at Titan – a likely post-Cassini mission candidate due to the vast quantities of organic molecules present on its surface and in its atmosphere. Again, the scenario assumes a powerful 100-watt Ka-band transmitter and a huge, deployable 5m high-gain antenna – Ka-band capabilities and telecom equipment that do not currently exist. Note that the 70m performance now falls roughly two orders-of-magnitude short of the data rates needed to support detailed interferometric SAR measurements and *in situ* hyper-spectral imagery.

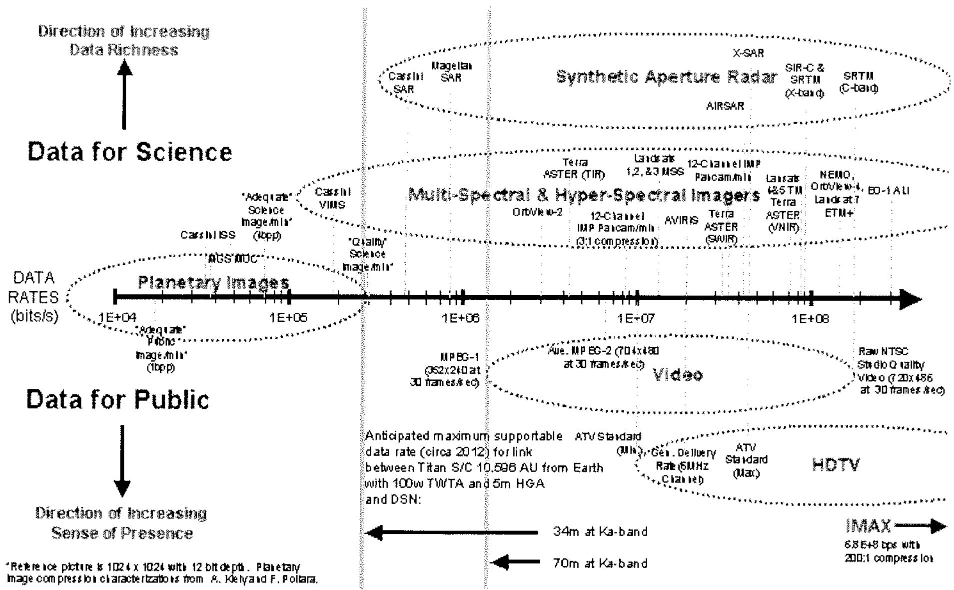

Figure 8. Titan Orbiter Relay Scenario Circa 2012 (Maximum Supportable Rates at 10.6 AU with RF Flight Hardware Improvements and Ka Ground Improvements)

Given the anticipated factor-of-10 increase in data rates by 2010, the order-of-magnitude data rate shortfall for a Mars mission post-2010 (Figure 7), and the two-order-of-magnitude shortfall for a later Titan mission (Figure 8), it would not be unreasonable for the DSN to set a downlink data rate improvement goal of 10x per decade. Because the benchmarking scenarios portrayed in Figures 7 and 8 already assume substantial telecom improvements onboard the spacecraft, as well as Ka-band capability on the 70m antennas, this 10x-per-decade goal would likely have to be realized through the addition of substantial new receiving aperture on the ground.

3.3 Uplink Circa ~2010

In the examination of 2010-epoch uplink trends, mission set demographics analysis revealed little change from the standard 2 kbps uplink rate until around 2012. As shown in Figure 9 (next page), a peak uplink data rate occurs at this time that is almost 10x the norm. Corresponding to the Next Generation Space Telescope (NGST) mission, this data rate is driven not by the need to command, but rather, by the need to upload calibration flats for one of the science instruments.[3] This upload requirement may signal the beginning of a change in the dominant communications function of the uplink. To date this function has been spacecraft commanding. However, as onboard spacecraft autonomy increases, spacecraft commanding may become less frequent and higher level, while periodic software uploads to support the autonomy may begin to dominate the uplink. Figure 10 provides us with an indication of what the difference in uplink duration may be between routine commanding and software uploads.[5] Figure 11 suggests that such software uploads may be growing in complexity and required uplink duration with each subsequent mission and that, even within the same mission, upload times for subsequent versions of the same software do not necessarily decrease.[6,7]

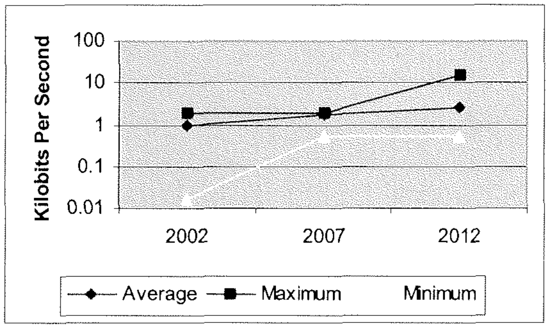

Figure 9. Uplink Rate Trends Across All Space Science Theme Areas

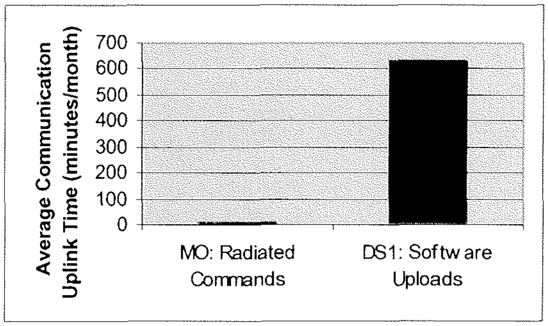

Figure 10. Comparison of Average Monthly Communication Uplink Time[5]

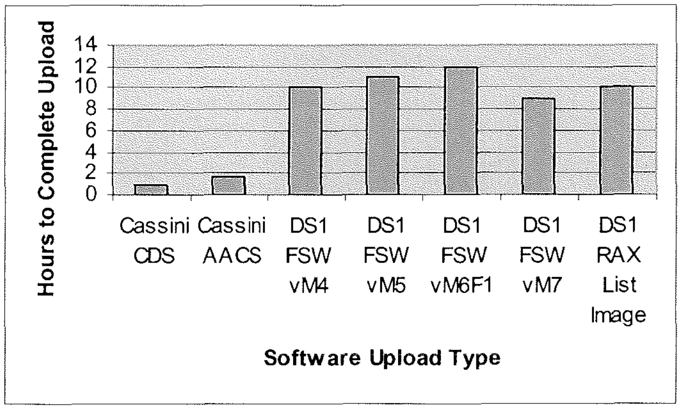

Figure 11. Comparison of Software Upload Times Normalized to a 2 kbps Uplink Rate[6,7]

3.4 Uplink: Looking Beyond 2010

While the post-2010 downlink drivers were derived from an examination of Earth remote sensing capabilities, the author focused on a different post-2010 analogy for the uplink -- the upload requirements associated with Earth's current, autonomous vehicles (e.g., cruise missiles, unmanned aerial vehicles and unmanned ground vehicles). The anticipated increase in *in situ* exploration over the next couple of decades makes this focus on current, Earth-based autonomous vehicles particularly relevant. This is because *in situ* exploration will directly entail, or depend heavily upon, robotic mobility elements (e.g., rovers, aerobots, airplanes, hydrobots, etc.). Intelligent use of such mobility elements, however, will require the ability to navigate them, not only to the target destination, but also around any intervening obstacles or hazards. Unfortunately, at most solar system destinations, the time available to negotiate such obstacles or hazards is far less than the two-way light time needed to command from Earth – hence, the need for onboard autonomous navigation and targeting capability.

Cruise missiles, unmanned aerial vehicles (UAVs), and unmanned ground vehicles (UGVs) are Earth-based analogs that depend on onboard autonomy, in conjunction with remote sensing data product uploads, for navigation and targeting. Figure 12 shows these three analogs and the *in situ* exploration scenarios to which similar navigation and targeting techniques might apply. Note that in each case, guidance and/or targeting depends on comparisons with an onboard data product that was derived from some sort of SAR, hyper-spectral, or multi-spectral remote sensing data.[8,9,10] In the downlink discussion, it was shown that these types of remote sensing data involve very large data volumes. Hence, it is reasonable to assume that uploads of guidance and/or targeting products based on these data types would also be somewhat large and require correspondingly high uplink data rates. While a preliminary review of the literature reveals a multitude of potential uplink data rates for the Earth-based analogs ranging from kilobits per second to tens of megabits per second, ~200 kbps appears to be about the norm – an uplink capability about two orders of magnitude greater than current deep space uplink rates.[11] In the future, this study will seek to validate and/or refine this potential uplink data rate driver, identifying the situations in which it is likely to apply, the frequency with which such situations are likely to arise, and how such characteristics are likely to change as a function of time.

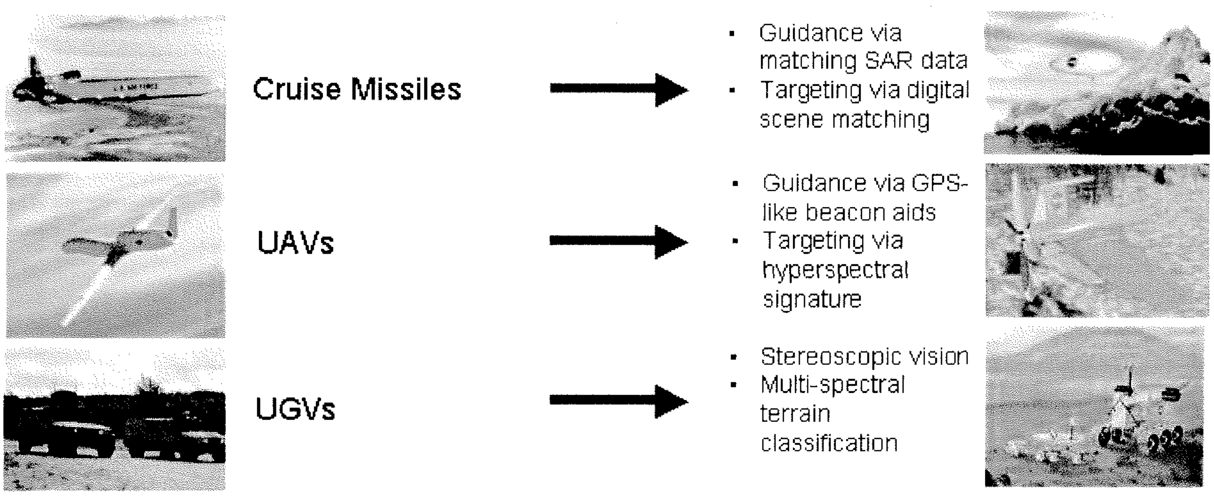

Figure 12. Earth-based Autonomous Vehicle Navigation and Targeting Data Types as Indicators of Upload Requirements for In Situ Exploration Elements[8,9,10]

4.0 SUMMARY

DSN-supported Space Science Enterprise missions of the future will, as a whole, occur further from Earth, rely on larger aperture, acquire more data, and involve a greater number of relay-dependent proximity links than ever before. Mission demographic analyses and Earth remote sensing analogies indicate that the data rate demand associated with these missions will increase by a factor of 10 over the next 10 years and at least two orders of magnitude more over the following two decades – suggesting that the DSN should seek to increase its downlink capability by at least 10x per decade.

While uplink data rates appear relatively stable over the next 10 years, the dominant function of the uplink appears likely to begin shifting from low-level commanding to science- and software uploads – with a consequent 10x jump in peak data rates by the end of that time period. In subsequent years, the proliferation of *in situ* exploration throughout the solar system will drive greater use of autonomous navigation and targeting techniques. Earth-based analogies (cruise missiles, UAVs, and UGVs) indicate that this autonomous navigation and targeting will involve onboard comparisons with data products derived from orbital SAR, multi-spectral, and hyper-spectral images – in essence, *in situ* exploration elements will become consumers of orbital remote sensing data products. These data products, like the downlink images from which they are derived, will likely involve large data volumes and, consequently, will likely require high data rate uplinks. Preliminary efforts to derive an uplink rate requirement from the Earth-based analogies suggest something on the order of 200 kbps – or 100x the current 2 kbps uplink rate. However, much work still needs to be done to validate and/or refine this estimate relative to the broad spectrum of uplink situations likely to be encountered, ascertain the frequency with which such situations are likely to arise, and project how these characteristics are likely to change over time.

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