SpaceOps Conferences
28 May - 1 June 2018, Marseille, France
2018 SpaceOps Conference

10.2514/6.2018-2528

Check for updates

Recommendations Emerging from an Analysis of NASA's Deep Space Communications Capacity*

Douglas S. Abraham†, Bruce E. MacNeal‡, David P. Heckman§, Yijiang Chen**, Janet P. Wu††, Kristy Tran‡‡, Andrew Kwok§§, Carlyn-Ann Lee***
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

During 2016-2017, NASA's Space Communications and Navigation (SCaN) Office chartered a study of Deep Space Network (DSN) communications capacity relative to projected future-mission demand over the next 30 years. In this paper, we briefly describe the methodology used to analyze capacity vs. demand over such a broad timeframe, summarize key findings emerging from the analysis, and discuss the associated recommendations.

Performing the analysis entailed: identifying key factors shaping the anticipated future mission set, identifying several alternative future mission set scenarios consistent with these factors, and then analyzing each mission set scenario in terms of required antenna capacity, downlink and uplink capabilities, and spectrum as a function of time. On the basis of these aggregate requirements, DSN loading simulations were then conducted that examined how well each of the postulated mission sets could load up onto the the DSN's "in-plan" architecture. To the extent that capacity shortfalls emerged during these baseline simulations, architectural solutions to the shortfalls were then postulated and tested via additional simulations.

In general, the trend analyses and baseline loading simulations indicated a significant progression in challenges over the next three decades. In the current decade, the DSN appeared to be operating very close to capacity. The first human exploration mission and its secondary payload launch opportunities for cubesats traveling beyond GEO contributed to this loading. As a consequence, the main challenge appeared to be managing peak asset-contention periods. In the next decade, the DSN continued to operate close to capacity but also began transitioning to more frequent human mission support. Upgrading for, and operating, a human-rated system while continuing to meet robotic mission customer requirements emerged as the key challenge. In the 2030's and beyond, simulations suggested a need for fundamentally new capability and capacity. The high data rates and long link distances characteristic of human Mars exploration drove requirements far beyond what is currently "in plan." The key challenge then became determining the most cost-effective combination of RF and optical assets for communicating with the postulated human Mars assets while still providing for the needs of all the other missions across the solar system.

Various link budget, visibility, and loading analyses ultimately suggested that the human Mars exploration demands of the 2030's could best be addressed with two cross-linked RF-optical areostationary relays (or an areostationary relay and deep space habitat) providing a dual "trunk link" to an array of 2-to-3 additional 34m beam waveguide antennas and an ~8.5m optical antenna at each DSN Complex. The dual "trunk link" would enable the same amount of total data return to Earth as a single trunk link at twice the data rate, but with only half the required array size on the ground, assuming use of Multiple Spacecraft Per Antenna (MSPA) techniques. MSPA techniques, including a Multiple Uplink Per Antenna (MUPA) technique currently under investigation, also showed promise for reducing asset contention in the decades prior to human Mars exploration.

---

* Copyright 2018 California Institute of Technology. U.S. Government sponsorship acknowledged.
† Strategic and Systems Forecasting Lead, Interplanetary Network Directorate, AIAA Senior Member.
‡ Senior Systems Engineer, Communications Architectures & Research Section.
§ Systems Engineer, Communications Architectures & Research Section.
** Optical Engineer, Flight Communications Systems Section.
†† Optical Engineer, Flight Communications Systems Section.
‡‡ Telecommunications Engineer, Communications Architectures & Research Section.
§§ Senior Systems Engineer, DSN Systems Engineering Section.
*** Engineering Applications Software Engineer, Communications Architectures & Research Section.

Copyright © 2018 by California Institute of Technology. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

I. Introduction

In 2016, NASA's Space Communications and Navigation (SCaN) Office initiated a "Deep Space Capacity Study" under Wallace Tai's leadership within the Interplanetary Network Directorate at the Jet Propulsion Laboratory (JPL). The purpose of the study was to "conduct the cost/performance trades needed to support the recommendation of a top-level investment strategy for deep space communications and navigation evolution." In pursuit of this, the study was charged with "taking into account future mission needs, including those for human Mars exploration during the 2030s - 2040s."[1] This latter charge on future mission needs involved two significant endeavors: (1) looking at the "needs of all deep space missions to be supported by the SCaN communications assets" from now into the 2040s and (2) modeling specific human Mars exploration activities and their associated communications traffic. This paper focuses on the overall deep space future mission needs: how they were derived, what the trends and implications are, how well different architectural approaches to Deep Space Network capacity appear to satisfy the projected aggregate mission set demand, and what recommendations emerge from these considerations.

II. Derivation of Future Deep Space Mission Needs

Projecting future-mission demand for deep space communications capacity over the next 30 years is an undertaking fraught with uncertainty. No one knows exactly how the future will unfold. A practical approach to dealing with this uncertainty is to postulate an "enveloping" set of scenarios for how things might unfold and develop projections based on an analysis of each of the scenarios. For projections of future-mission demand on the DSN, then, the first step was formulating an "enveloping" set of future mission set scenarios. We developed seven different future deep space mission set scenarios that we felt, in total, spanned the reasonable possibility space for how NASA's current plans for the future might evolve in terms of its telecommunications requirements. These scenarios included: a 2016 "Best Guess" mission set, an "Optimistic" mission set, a "Pessimistic" mission set, a "Max Data Rate" mission set, a "Min Data Rate" mission set, a "Max Tracking" mission set, and a "Min Tracking" mission set. Each mission set scenario included approximately 177-330 individual missions (depending upon scenario) operating between 2010 and 2045.

The 2016 "Best Guess" mission set used SCaN's latest Space Communications Mission Model (SCMM) as a starting point. This model provides SCaN's best estimate of the current, planned, and projected future missions for each of the networks that it oversees. These networks include the Deep Space Network (DSN), the Near Earth Network (NEN), and the Space Network (SN). Missions beyond geosynchronous orbit that would likely make use of the DSN were extracted from this mission set and incorporated into the 2016 "Best Guess." In cases where these future missions were poorly defined (for lack of information) or were used as placeholders for competitively-bid missions (Explorer, Discovery, New Frontiers, etc.) the latest National Research Council decadal surveys and NASA roadmaps were used to derive candidate missions. The choice of candidate missions was also modulated by NASA and Congressional Budget Office projections of the near-term and long-term budget environments, respectively. The final result was a "best guess" enumeration of DSN-supported missions as a function of time.

The "Optimistic" mission set scenario was then derived from the "Best Guess" by assuming a more robust funding profile that allowed more mission concepts, and more ambitious mission concepts, to be added to the "Best Guess" mission set. Similarly, the "Pessimistic" mission set scenario was derived by assuming a significantly reduced funding profile. This profile allowed inclusion of only NASA's highest priority missions within each mission directorate or, in some of the human Mars exploration cases, assumed a much slower, more drawn out pace of exploration.

In the case of the "Max Data Rate" and "Max Tracking" scenarios, candidate missions for competitively-bid mission slots and other placeholder slots were selected that maximized downlink data rates and annual tracking hour requirements, respectively. Similarly, in the case of the "Min Data Rate" and "Min Tracking" scenarios, candidate missions were selected that minimized downlink rates and tracking hour requirements, respectively.

To get a feel for how these mission set scenarios compared with those used in other earlier studies, an eighth 2014 "Best Guess" mission set scenario was also included, with updates for mission launch slips and other changes that had occurred in late 2014 and early 2015.

With the mission set scenarios defined, the real work associated with modeling each mission and performing the aggregate mission set analyses for each scenario began. Figure 1 shows the overall process and tools used to perform these analyses – a process that has steadily evolved over the past 15 years.[2,3,4,5] The first step in this process involved modeling, within the Mission Set Analysis Tool (MSAT), each mission's specific telecommunications, tracking, and mission design information as a function of time. For nearer-term missions, DSN Service Agreements, Operations Interface Control Documents, and Network Ops Plans provided the necessary modeling details. For missions further in the future, mission concept studies associated with the latest National Research Council decadal surveys, NASA roadmaps, and internal mission development endeavors were used to infer the necessary detail.

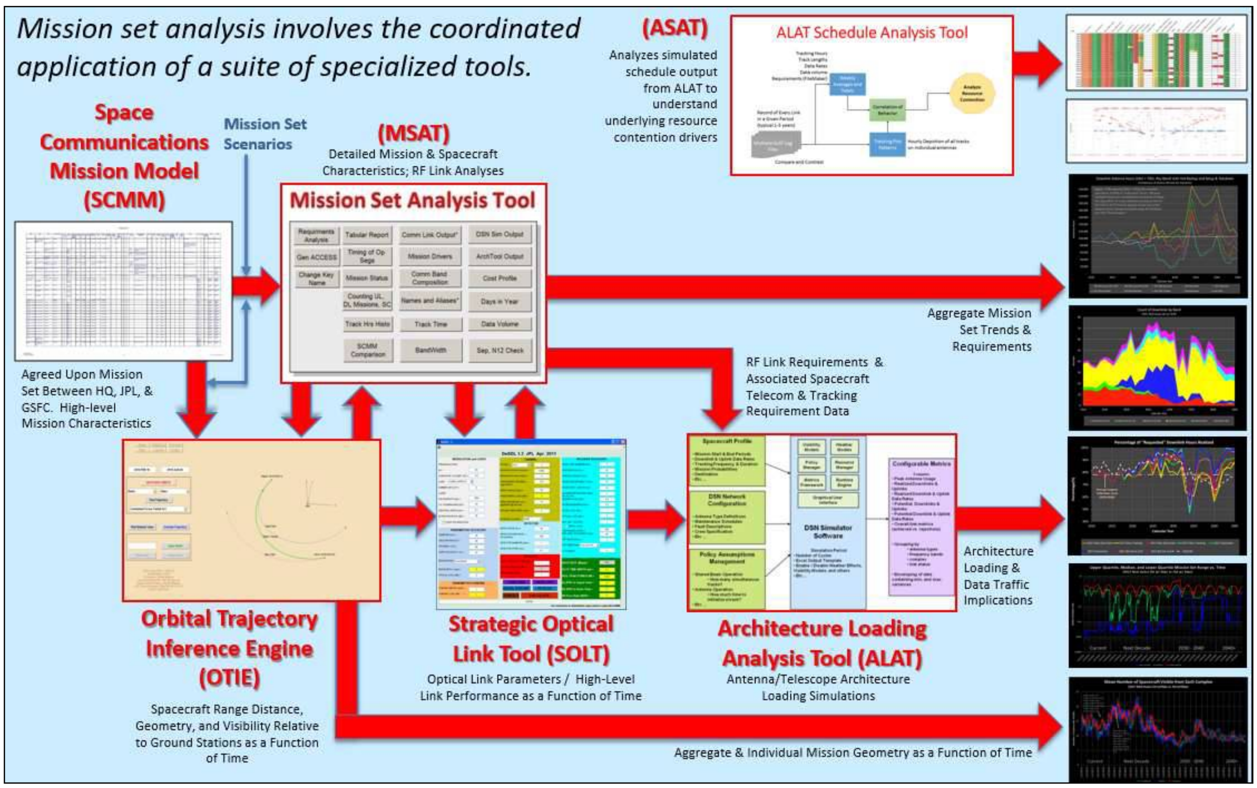

Figure 1. Mission Set Scenario Analysis Process.

In many cases, the trajectories of the original mission concept designs no longer corresponded to the potential launch dates in the roadmaps. To provide updated trajectories, the Orbital Trajectory Inference Engine (OTIE) was employed. This tool also provided MSAT with each mission's range distance as a function of time – which MSAT then used to compute each spacecraft's RF link performance as a function of time. For concepts involving specialized low-energy and/or low-thrust trajectories, mission-specific trajectory development support was obtained from JPL's Navigation and Mission Design section. With the required trajectories in hand, OTIE then computed the visibility of each spacecraft from each DSN ground station as a function of time.

MSAT then used much of the above data to generate a variety of aggregate mission set trends as a function of time (e.g., average and maximum data rates, G/T and EIRP requirements, antenna-hour requirements, frequency band usage, etc.). It also generated an output file to use as input for subsequent loading simulations. Key fields in this output file included mission name, science exploration theme area, spacecraft ID, operational segment name, operational segment start date, operational segment end date, distance from Earth at segment start, distance at segment end, the segment-applicable visibility file(s) to load for each mission, the required subnet name, days between tracks, track length, the tracking network, link direction, link type, band, frequency, required antenna gain vs. noise temperature (G/T), required Effective Isotropic Radiated Power (EIRP), and data rate. The definition of operational segments for each mission was key to accurately modeling many of the above fields because deep space missions

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

generally have different requirements depending upon whether they are in the launch and early orbit phase, cruise, performing a critical event like an orbit insertion or planetary gravity assist, conducting their prime science mission, conducting an extended science mission, or serving as a relay. Special circumstances such as solar conjunctions can also have an impact on how the mission operates over a given time period and were modeled accordingly.

The Architecture Loading Analysis Tool (ALAT) then used this output from MSAT, in conjunction with the corresponding RF visibility files from OTIE, to simulate how well all of the missions in each scenario load up on the DSN's antennas as a function of time. Figure 2 summarizes ALAT's key inputs and outputs. For each required track, ALAT used the requested track frequency (i.e., recurrence rate) to establish a window of opportunity in which to schedule the track. So, for instance, for a spacecraft requiring one track per week during a particular operational segment, the window of opportunity was between the earliest possible start time for that week and the earliest possible start time for the next track in the following week. Within that window of opportunity, an antenna with the required characteristics had to be both visible to the spacecraft and available in order to be scheduled. If antennas with the requisite characteristics were available and/or visible for only a portion of the requested track time, ALAT assigned the spacecraft to the antenna providing the longest possible track. If no antennas with the requisite characteristics were available, ALAT rejected that particular track. This process was repeated for every track in every operational segment for every mission across the entire timeframe of interest – more than 800,000 individually scheduled antenna tracks over 35 years. Simulation results were typically plotted in terms of the percentage of requested hours actually realized in the simulation as a function of time.

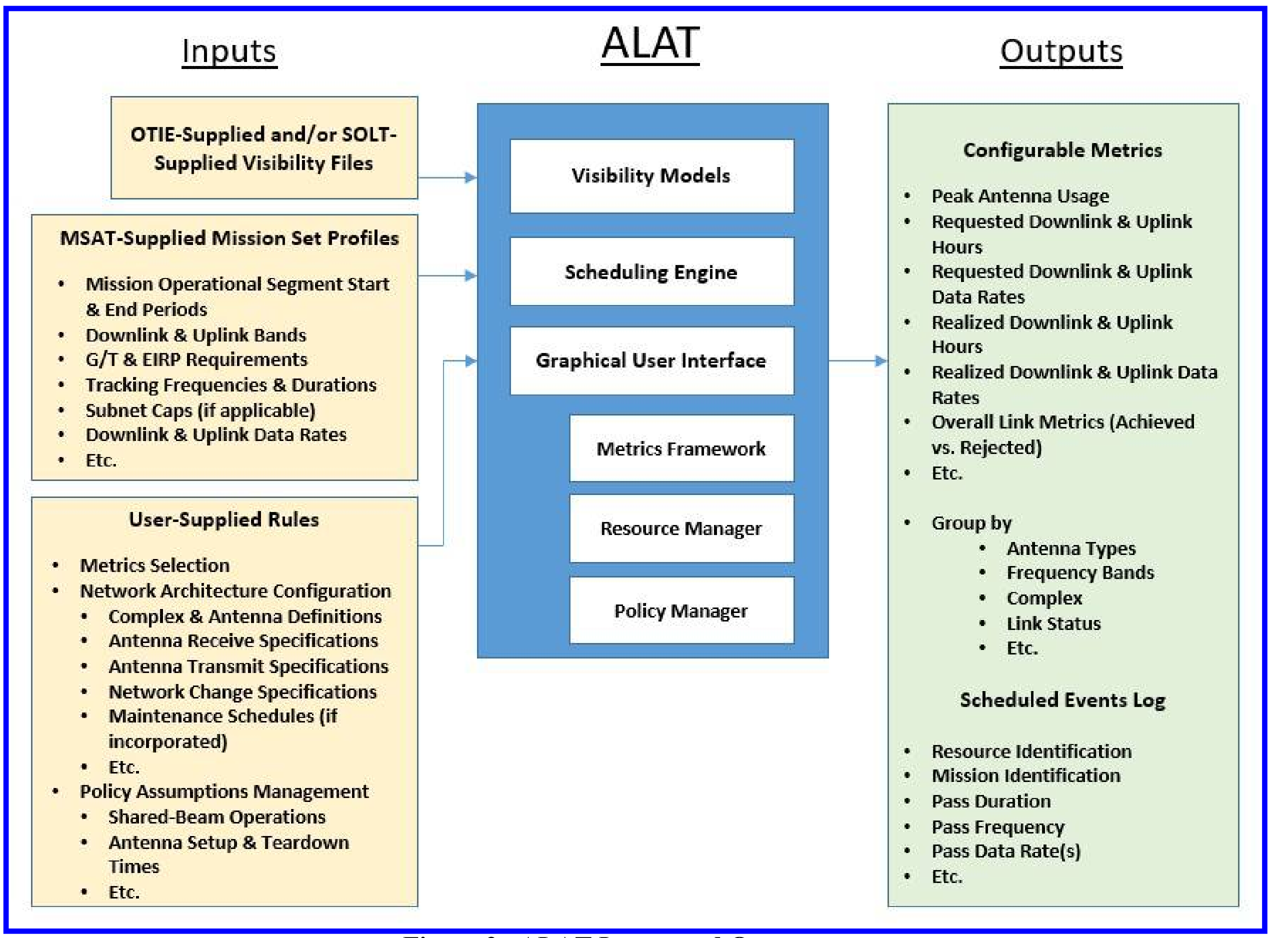

Figure 2. ALAT Inputs and Outputs.

While ALAT can be used to simulate loading on the current DSN, it can also be used to simulate loading on alternative concepts for evolving the DSN in the future. In the RF realm, this is just a matter of changing the number, locations, and characteristics of the antennas modeled in ALAT (with corresponding changes to the link performance calculations and visibility computations from MSAT and OTIE, respectively). In the optical communications realm,

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

however, the modeling becomes a bit more complex. The Pulse Position Modulation (PPM) used in deep space, as well as factors such as photon scattering and various other forms of background atmospheric noise, fundamentally change the manner in which link performance can be calculated. RF concepts like G/T and EIRP no longer constitute criteria applicable to "antenna" selection and scheduling under such circumstances. As a result, required vs. supportable data rate becomes one of the key criteria for deciding whether or not an antenna with optical capability can support an optical mission.

Deriving the supportable data rates for each optical aperture required the use of another tool in Fig. 1 – the Strategic Optical Link Tool (SOLT). Using visibility, Sun-Earth-Probe angle, Sun-Probe-Earth angle, and range data from OTIE, SOLT was used to calculate the supportable data rate as a function of time across every available visibility window within every optical ops segment, assuming a particular ground aperture size. In the MSAT output to ALAT, these SOLT files were then tagged for use rather than the typical RF visibility files.

For both the RF and optical ALAT runs, loading simulation results were typically expressed in terms of the percentage of realized versus requested downlink hours. The underlying hour data were also combined with data rate information to understand the percentage of realized versus requested data volume. Because the results apply to the aggregate mission set, understanding the individual mission drivers behind particular features in the result plots was not always easy. To facilitate greater insight into the specific drivers, an ALAT Schedule Analysis Tool (ASAT) was created to relate ALAT's scheduled-events-log output to the input from MSAT.

III. Mission Trend Analysis & Loading Simulation Results

This section focuses on the results that were derived from applying the Fig. 1 tool suite to the various mission set scenarios discussed in the last section. Because the number and type of trend analyses and simulations that were conducted are more numerous than we can hope to cover in this paper, we only discuss those trends and simulations key to understanding some of the primary recommendations that emerged from the Deep Space Capacity Study. These include the number of spacecraft and downlinks vs. time, downlink rates vs. time, antenna-hour demand vs. supply, and baseline-DSN loading simulations. The results from each of these areas culminated in particular questions or issues for which alternatives to the current DSN were then formulated and tested using similar analysis techniques.

A. Number of Spacecraft and Downlinks vs. Time

The number of spacecraft and downlinks projected for the future provides an indication of how much telecommunications capacity may be needed in the coming decades. While it is common to think in terms of mission numbers, one must remember that many missions consist of multiple spacecraft, with each spacecraft frequently requiring its own deep space downlink and uplink support. Figure 3 shows the number of spacecraft anticipated as a function of time for each of the eight scenarios considered in the study. Notice that spacecraft numbers increase substantially over the next 10 years.[†††] Underlying drivers for this include human exploration, smallsats, and the interplay between the two. As human exploration missions beyond geosynchronous orbit begin to occur over the next 10 years or so, they create more secondary-payload launch opportunities. Exploration Mission One (EM-1), for instance, is slated to carry 13 cubesats as secondary payloads – equivalent to almost a third of the total number of spacecraft the DSN supports today. And, because human exploration may consume a larger portion of NASA's overall budget in the future, the more economical nature of smallsats may make them increasingly popular with other parts of NASA as they strive to maintain their desired mission cadences. The human exploration missions themselves also drive up support numbers, since such missions generally involve multiple types of spacecraft, with each spacecraft involving multiple downlinks and uplinks. Figure 4 shows the number of downlinks anticipated as a function of time for each of the 8 scenarios discussed earlier. Comparison of Figures 3 and 4 clearly illustrates how the number of downlinks is significantly larger than the number of spacecraft. It is the number of downlinks (and uplinks) that truly drive the demand on the antennas.[‡‡‡] Substantially increasing the number of downlinks over the next 10 years, without a corresponding increase in antenna numbers, would seem likely to impact antenna-hour demand and associated

[†††] More recent mission trend analyses conducted during 2017 indicate that spacecraft and downlink numbers in 2027 may be almost double what they were in 2017.

[‡‡‡] The number of required uplinks per spacecraft usually tends to be equal to or less than the number of required downlinks per spacecraft. Hence, the number of downlinks is taken to be the primary indicator of demand.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

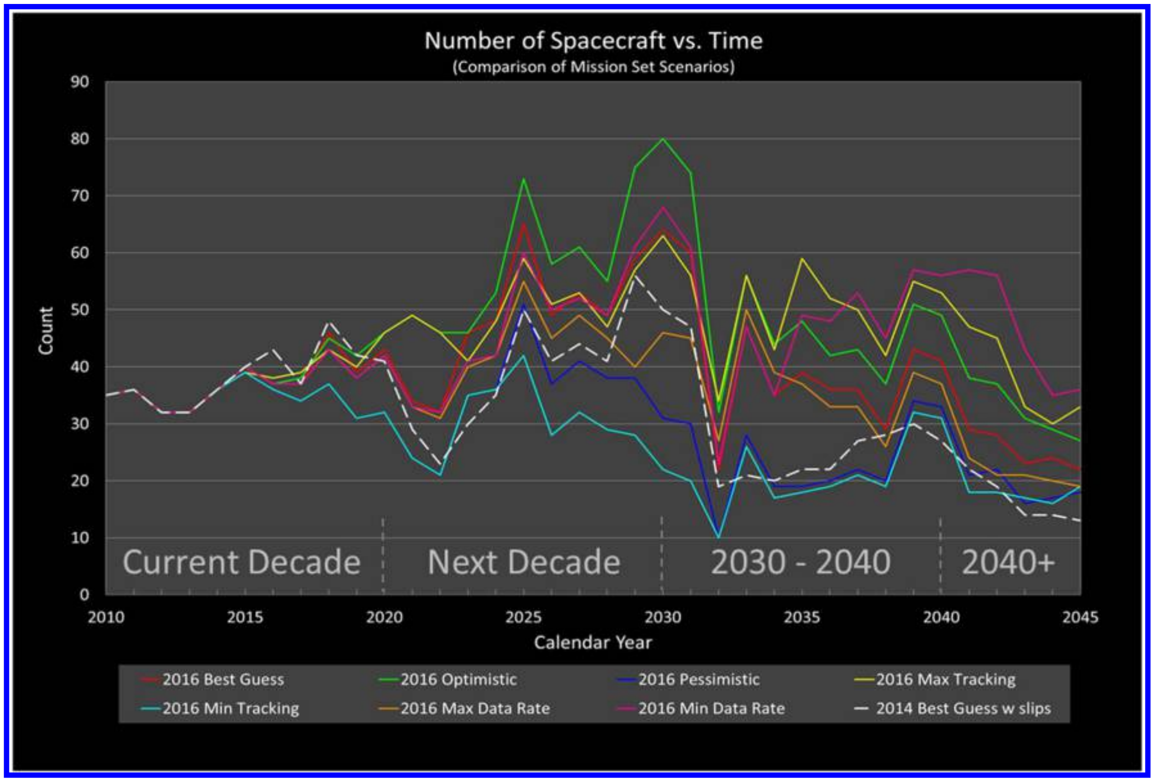

Figure 3. Number of Spacecraft Projected Through 2045

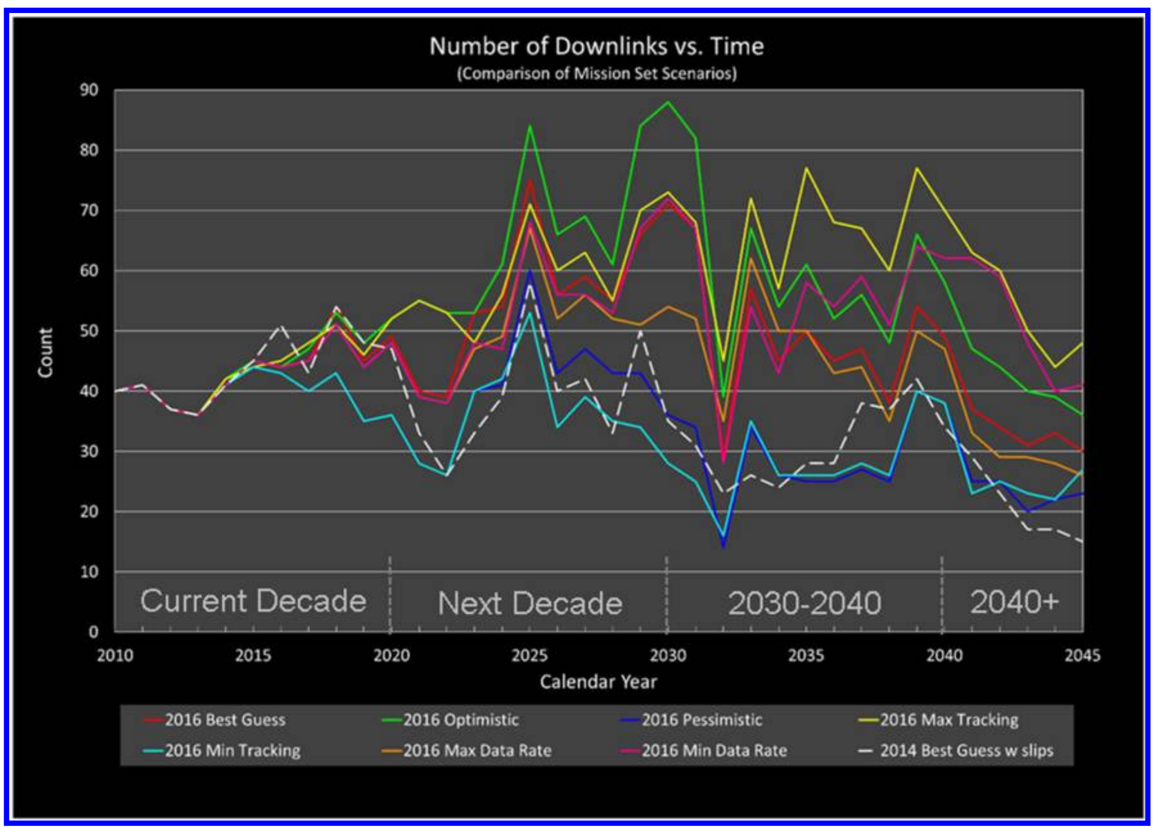

Figure 4. Number of Downlinks Projected Through 2045

loading – an impact that will be discussed further when we discuss antenna-demand vs. supply and the baseline-DSN loading simulations.

B. Downlink Rates vs. Time

In addition to the number of spacecraft and downlinks, downlink data rates can also drive capacity – even though one might typically think of them as more of a capability driver. Figures 5 plots the average across each mission's annual maximum downlink data rate. Note that downlink data rates are projected to increase by roughly two orders of magnitude over the next two decades.[§§§] Much of this increase in the first decade is driven by high-rate astrophysical observatories. Further out in time, however, projected human Mars exploration missions and related relay infrastructure, when operating at or near maximum Mars distance, are the key drivers. To the extent that achievable data rates are inversely proportional to the square of the link distance, having such high data rates out at Mars distance suggests associated links that are immensely difficult to close – perhaps as much as two orders of magnitude more difficult than the links we close today (Fig. 6). Since the achievable data rates are also proportional to the area of the receiving antenna, one way to close these more difficult links in the future would be to build larger antennas.

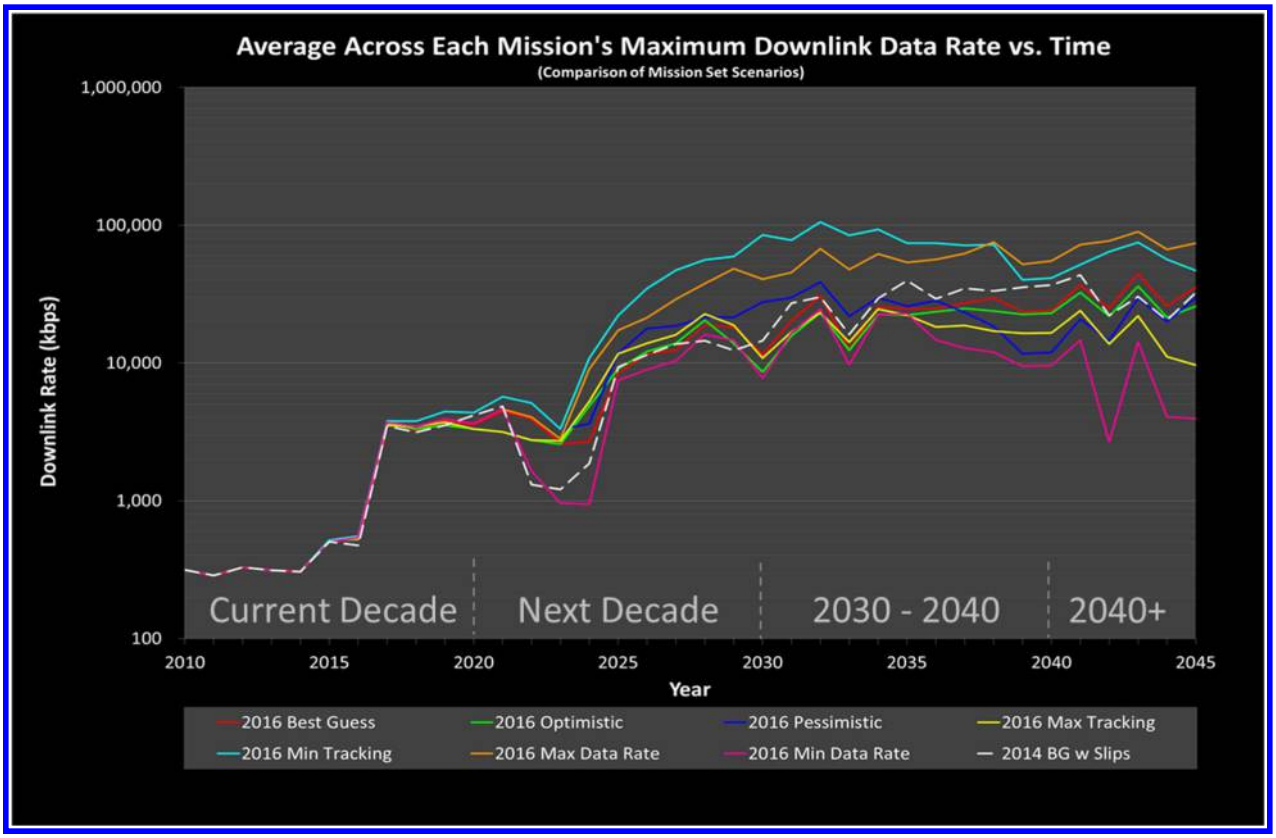

Figure 5. Average Downlink Rates Through 2045

However, designing and building antennas larger than those the DSN uses today would be a very expensive proposition. Another approach would be to array up existing antennas in order to synthesize a very large receiving aperture. This, however, has significant capacity implications, since antennas arrayed up to support one mission are then not available to simultaneously support other missions in other sky locations. Hence, using antenna arraying to increase link capability diminishes overall network load capacity -- an impact that will be discussed further when we discuss antenna-demand vs. supply and the baseline-DSN loading simulations.

[§§§] More recent mission trend analyses conducted during 2017 continue to project this trend, with a 16x increase in data rates occurring within the next 10 years.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

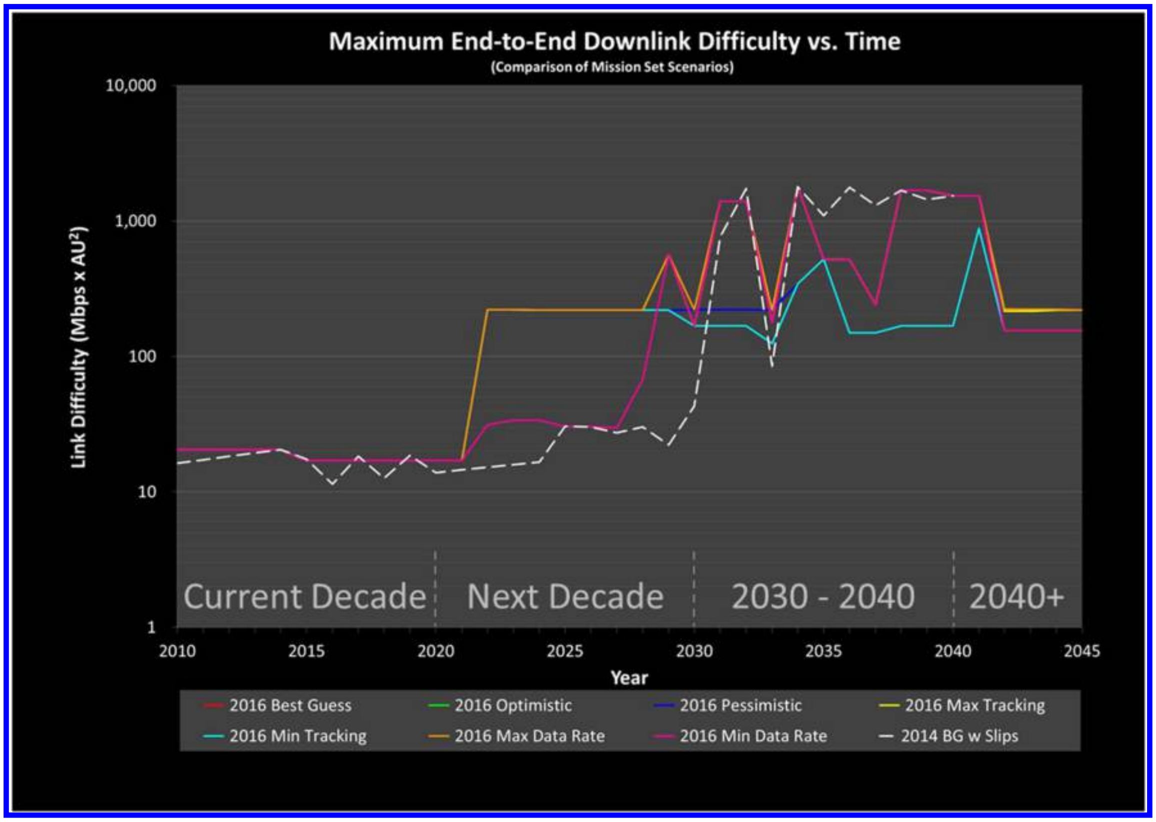

Figure 6. Maximum End-to-End Downlink Difficulty as a Function of Time

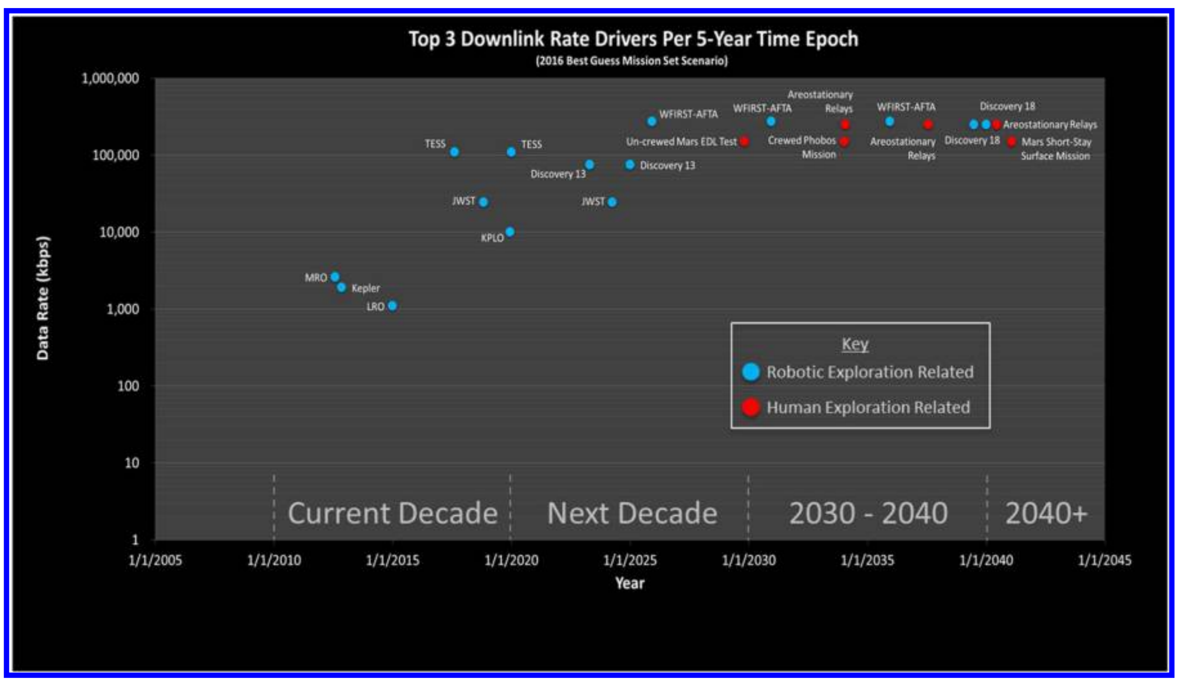

Figure 7. Top 3 Downlink Rate Drivers Per 5-Year Time Epoch

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Another important feature in the Fig. 5 plot is the fact that the steep increase in data rates occurring over the next decade appears to level off in the 2030's and beyond. Figure 7, for the 2016 "Best Guess" scenario, provides an indication of what the specific driver missions and their associated maximum data rate requirements might be. As discussed earlier, many of these drivers tend to be human Mars exploration missions – along with some observatory-class missions. The maximum data rates for all of these tend to hover around 250 Mbps and do not exceed 300 Mbps. Possible reasons for this include: (1) the previously discussed difficulty associated with closing Mars-distance links at these rates (not a problem for the near-Earth observatory-class missions) and (2) the fact that the bandwidth requirement associated with such rates would use up most of the allocated Ka-band spectrum. While spatial reuse of spectrum is possible when high-bandwidth missions are located in very different parts of the sky, it is not generally an option when they are all clustered in the same region – such as at Mars. Hence, RF spectrum bandwidth considerations, along with the sheer difficulty of the links, may be causing mission concept designers to constrain spacecraft data rates to the 100 - 300 Mbps range – leading to the flattening of the curves visible in the 2030s and beyond. While more bandwidth-efficient modulation schemes might help ameliorate such constraints, they tend to require more spacecraft power, and spacecraft power at such solar distances is not readily available. To the extent that optical communication is not subject to the same allocated spectrum constraints and tends to require less mass and power than RF communications, it may constitute the means by which progressively higher data rates can be achieved in future decades.

C. Antenna-Hour Demand vs. Supply

One of the most direct indications of required future capacity is that of required downlink antenna hours relative to supply. The term "antenna hours" is used rather than "tracking hours" because it actually encompasses more than just the hours associated with a mission's antenna passes. It encompasses the time required for antenna setup and teardown on each pass, and it accounts for the extra antenna time tied up in arrayed-antenna passes. So, for instance, a mission might request an 8-hour tracking pass, but need an array of two 34m antennas to close the link on that pass. The total antenna-hour time associated with the 8-hour request, then, is actually the sum of the 8-hour track and the 1-to-1.5 hours for the setup and teardown, all multiplied by two (since two antennas are required to close the link). This measure underscores an important point: deep space capacity requirements are not only a function of how many spacecraft users there are and how much antenna time each of them seeks but, also, the data rates they require when multiple antennas are needed to close the link.

Human missions may also levy a "hot backup" antenna requirement – meaning that a second ground antenna must be ready to immediately bring online if a malfunction occurs in the primary antenna. In the case of a single antenna user, this requirement essentially doubles the antenna-hour requirement. In this study, where arrays of antennas are needed to close the link, only one "hot-backup" antenna was assumed, since the probability of all the antennas in an array simultaneously malfunctioning is pretty small.

Figure 8 compares the projected 34m antenna-hour demand for the eight mission set scenarios considered in the study relative to the estimated antenna-hour supply (based on SCaN's antenna plans for the DSN at the time of the study). The estimated antenna-hour supply assumes that each antenna in the DSN will only be available around 80% of the time due to planned maintenance, malfunctions, or simply not having any spacecraft visible in the requisite portion of the sky. Note that, for the majority of the scenarios, antenna-hour supply only marginally keeps up with projected demand over the next decade.[****] Beyond 2030, projected demand markedly exceeds supply. This post-2030 demand is largely driven by the postulated human Mars exploration missions whose high data rate requirements necessitate arraying up to six 34m antennas. As mentioned earlier in the "Downlink Rates vs. Time" discussion, this need for arraying consumes antenna capacity that would otherwise go toward satisfying the tracking requirements of the rest of the projected spacecraft users -- hence, the large out-year discrepancies between demand and supply shown in the figure.

[****] More recent studies completed at the end of 2017 suggest somewhat greater antenna-hour contention over this same time period.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

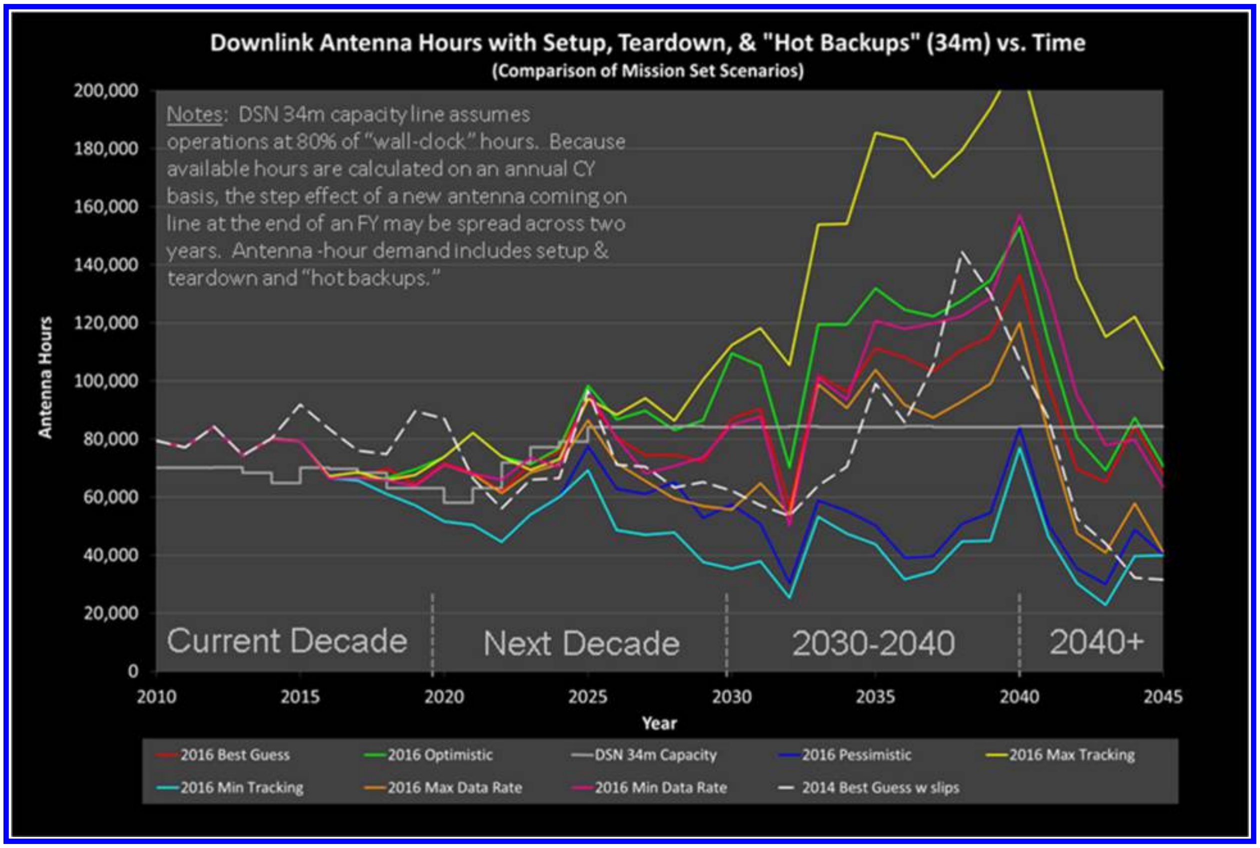

Figure 8. Projected DSN 34m Downlink Antenna-Hour Demand vs. Supply

D. Baseline-DSN Loading Simulations

Antenna-hour demand vs. supply curves, however, do not really tell the full story. Not all of the DSN's antennas are identical. Some are 34m, some are 70m. Some have S-band, X-band, and Ka 26 GHz capability, and some have X-band and Ka 32 GHz capability. Depending upon the particular antenna and supported band, transmit powers can range from 250 W to 100 kW. So, antenna asset contention can occur even when the total antenna-hour supply appears to exceed demand. For instance, when four spacecraft need a particular band that is only on one antenna per Complex, scheduling contention is likely to occur. Because of this, loading simulations that account for the data rates, frequency bands, track durations, and track numbers needed by each and every mission as a function of time can provide a higher fidelity indication of required telecommunications capacity than a simple look at antenna-hour requirements.

Figure 9 shows the results for just such a full-up loading simulation. In particular, it shows the percentage of "requested" downlink hours actually realized in the simulation across all 8 study scenarios as a function of time. Because ALAT cannot negotiate away potential schedule conflicts and load up the antennas in the simulation as efficiently as the DSN's collaborative Resource Allocation Process (RAP) does in reality, a calibration line has been drawn on the plot. This calibration line indicates the percentage-level in the simulation that historically, on average, has corresponded to the DSN meeting all of its post-RAP mission customer tracking requirements. Anything in the future above this line is generally deemed supportable. Anything in the future significantly below the line is deemed problematic. Inspection of the Fig. 9 curves reveals periods of potential scheduling contention late in this decade and early in the next, depending upon the scenario.[††††] The real significant mismatches between antenna supply and demand, however, are projected to occur in the 2030s and beyond, during the postulated human Mars exploration era. During this timeframe, six of the eight scenarios dip well below the calibration line. This is due to the large number

[††††] 2017 analyses that update for launch slips, mission design changes, and new missions suggest periods of peak asset contention on repeated occasions throughout the next 10 years.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

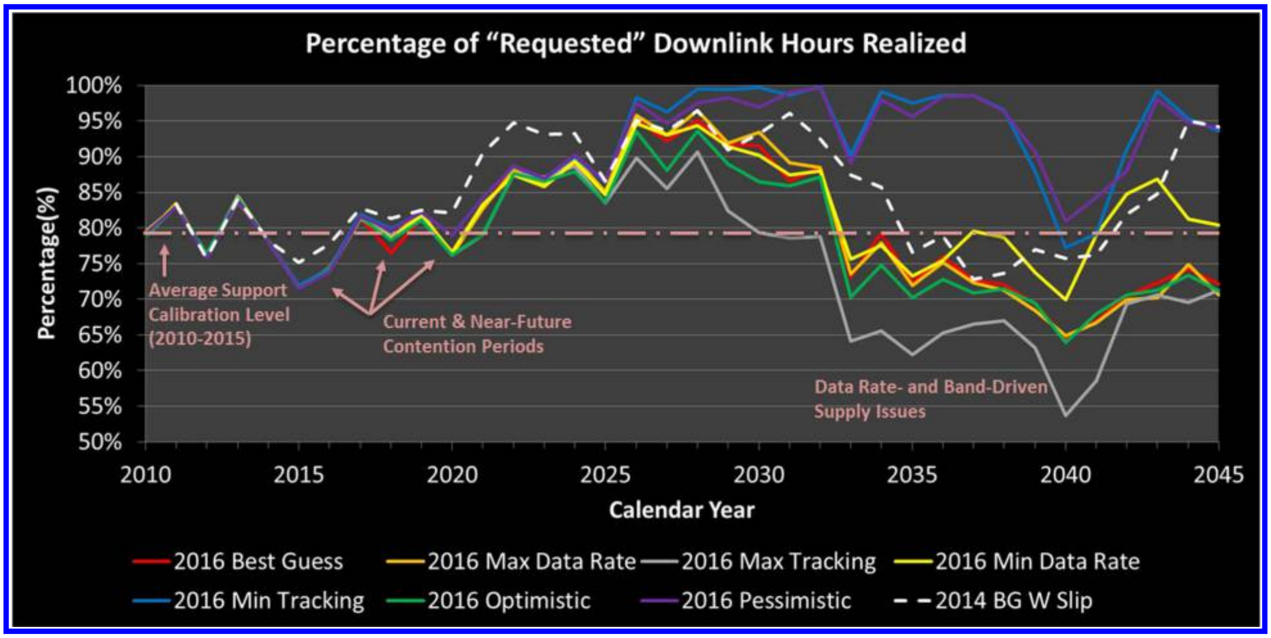

Figure 9. Combined 34m + 70m Loading Simulation, Accounting for Each Antenna's Band, G/T, and EIRP Capabilities

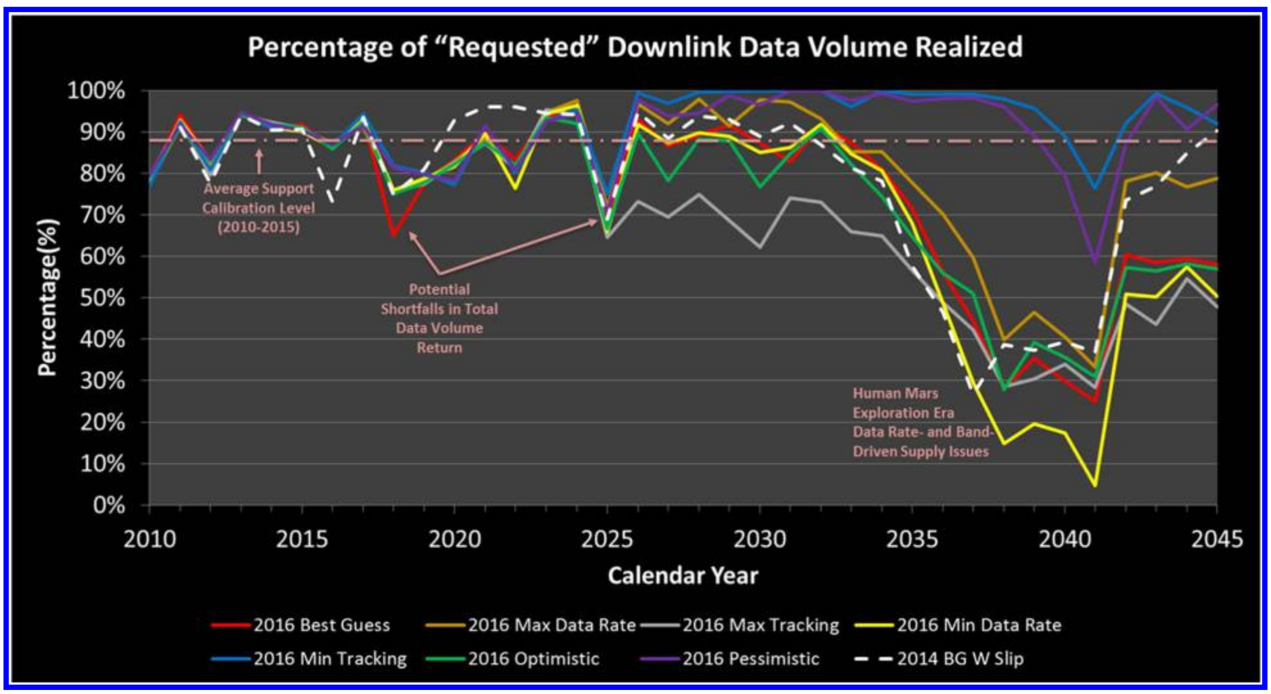

Figure 10. Combined 34m + 70m Loading Simulation, Looking at Downlink Data Volume Rather than Downlink Hours

of antennas that have to be arrayed up to close the high-data-rate links at Mars distance and due to some of those links being postulated to occur at 37-37.5 GHz – which was not supported in the baseline DSN configuration.[‡‡‡‡]

Figure 10 shows the same loading simulation results from the perspective of realized downlink data volume rather than realized downlink hours. From this perspective, more pronounced shortfalls occur during the next decade. Some of these shortfalls are the result of postulated human lunar exploration mission requirements for 26 GHz downlink and 22 GHz uplink -- which are sparse and non-existent, respectively, in the current DSN. Because the postulated missions are relatively short, the downlink hour impact is minimal. But, because their data rates are high, the data volume impacts associated with lost passes are much more apparent. Similarly, some of the shortfalls are the result of observatory-class missions missing only a few passes, but losing large data volumes due to their very high data rates. In interpreting these results, one has to remember that the simulator does not distinguish between mission tracking requirements on the basis of mission importance or the criticality of a particular track. For instance, in the simulation, a routine tracking pass for a cubesat might immediately precede a critical-event pass for a flagship mission in view of the same available antenna. The cubesat would then get the pass, preventing the flagship from downlinking to the antenna. In reality, such scheduling conflicts would be actively managed. The more serious shortfalls occur in the postulated human Mars exploration era and roughly correlate to the Fig. 9 shortfalls in the percentage of "requested" downlink hours realized.

E. Summary Implications

Taken together, the downlink number and data rate trends, antenna-hour demand vs. supply plot, and baseline loading simulations suggest a progression in the nature and magnitude of the challenges confronting the DSN over the next thirty years.

During the next 10 years, the DSN will likely be operating at capacity -- relying heavily on the active "down-sizing" of customer requirements during the RAP negotiations to enable the mission set's aggregate antenna-hour requirements to fit within available capacity. Human exploration missions will contribute a growing number of smallsat secondary payload launch opportunities that will likely further strain this capacity. And, these human missions will levy their own new safety-focused requirements on how the DSN's antennas are allocated and operated. So, a key challenge will be to upgrade for, and operate, a human-rated system while managing periods of peak asset contention in a way that allows continued success in meeting the robotic mission customer requirements.

Successful management of peak asset contention periods will be particularly important due to the fact that most of the projected two-order-of magnitude increase in data rates also appears likely to occur over the next 10 years. That means that, even when the percentage of "requested" downlink hours realized is quite high, a single missed pass can result in a large loss of data volume.

The projected capacity shortfalls in the 2030s and beyond signal the need for fundamentally new capability and capacity. Downlink rates from Mars are projected to be at least 2 orders of magnitude higher than today's and drive end-to-end link difficulties at least 100 times greater than today's. The number of 34m antennas that would have to be arrayed together to satisfy these link requirements exceed the number available at a DSN Complex, even with the few additional antennas planned for implementation between now and 2025.[§§§§] So, a key challenge for this timeframe will likely be to implement and operate a cost-effective approach to meeting the human Mars exploration requirements while ensuring cost-effective applicability to communicating with assets across the rest of the solar system. Because it may take many years to design and build the required capability and capacity, figuring out the most cost-effective approach needs to be occurring right now. To this end, the Deep Space Capacity study looked at a variety of RF and optical approaches. The sections that follow describe some of these, as well as the loading simulation results achieved with them.

[‡‡‡‡] During the Human Exploration & Development of Space (HEDS) initiative in the late 1990s, NASA proposed using 37-37.5 GHz for human-related downlinks at Mars and 37.5-38 GHz for human-related downlinks from the Moon.

[§§§§] The DSN Aperture Enhancement Project (DAEP) is focused on building enough additional 34m beam waveguide antennas to have four 34m antennas per Complex. This number would allow them to be temporarily arrayed together to provide X-band performance equivalent to a 70m antenna, thereby providing emergency backup for the aging 70m antennas during mission-critical events.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

IV. Pass-1: Eliminating the Capacity Shortfalls

Initial efforts focused on finding a combination of RF assets that would definitively eliminate the capacity shortfalls while providing the required capability. We then attempted to "ratchet down" this option to ones that would utilize existing assets more efficiently and entail lower cost while still meeting requirements. We then introduced an alternative mix of both RF and optical assets to see if an even more cost-effective approach could be achieved. The subsections that follow describe each of these steps.

A. Developing the "RF-Only" Study Option

Detailed analysis of the postulated human-Mars-exploration-era link-difficulty drivers revealed that one of the largest was the Mars Areostationary Relay. Historically, most NASA-internal human Mars exploration studies have assumed two such relays – one for each Mars hemisphere such that there is global coverage. RF designs have assumed a maximum downlink rate of 250 Mbps at 37 GHz, a maximum uplink rate of 50 Mbps at 40 GHz, a 6m deployable high gain antenna, a 500W transmitter, QPSK modulation, and an LDPC rate ½ forward error correction code. Table 1 shows the number of arrayed 34m antennas needed to close the downlink from an areostationary relay given the above assumptions.

Table 1. Number of 34m Antennas Needed to Close Link with a Mars Areostationary Relay Satellite Transmitting at 250 Mbps

	Range from Earth (AU)	Number of 34m Antennas
Mars Average (Time-based)	1.71	2.89 -> 3; plus 1 "hot" backup
Max Mars (50 yrs)	2.66	6; plus 1 "hot" backup
Min Mars (50 yrs)	0.38	0.14 -> 1; plus 1 "hot" backup

With the Mars Areostationary Relay requirements in mind, an initial "RF-Only" option was developed that assumed the construction of 7 new 34m antennas per Complex with X/X, 34/32 GHz, and 40/37 GHz capability. To be ready for Mars exploration in the 2030s, these antennas were assumed built in sets of three at the rate of one set per year, starting in 2024. To address a perceived lack of S/S and 22/26 GHz capability during the human lunar exploration era, the 2024 set of 3 antennas was assumed to have these band capabilities added to it, as well.

Because all of these postulated antennas, in conjunction with the existing and planned DAEP antennas, appeared capable of providing sufficient capacity to both replace the 70m antennas with operational arrays and service the rest of the mission set, the architectural option was then evolved to assume decommissioning of the 70m antennas by end of 2025. Were this decommissioning to be done any sooner, the number of new 34m antennas built out would be insufficient for both arraying up operationally for 70m-equivalent capability during critical events and supporting the rest of the mission set load. Even immediately after the decommissioning, simulation results suggested that peak asset contention would likely remain an issue until another set of 34m antennas was built out.

With this peak asset contention in mind and the peak asset contention predicted between now and 2025, we began looking for other techniques that would help us to utilize our existing antennas more efficiently. One technique of particular interest is known as "Multiple Spacecraft Per Antenna" or MSPA.[*****] In this technique, multiple spacecraft within the same beam of a ground antenna can schedule to have their downlinks all come down through the same antenna to separate receivers – each tuned to a particular spacecraft's downlink frequency. The technique is

[*****] MSPA is also sometimes referred to as "Multiple Spacecraft Per Aperture."

particularly useful for spacecraft around Venus, Mars, and more distant planets because they will always tend to be within the same beam of a single 34m antenna. Currently, simultaneous downlink from 4 spacecraft, a.k.a. 4-MSPA, is the supportable limit. While it is not currently possible to simultaneously uplink at four separate frequencies to the four spacecraft sharing the MSPA pass, serial-uplink-swapping allows each spacecraft to share a portion of the pass for its uplink – enabling each to get in some 2-way Doppler and ranging, as well as commanding.

To really help with the peak asset contention, however, we contemplated moving beyond 4-MSPA to n-MSPA, where "n" was some number greater than 4. Other than the cost of the hardware receivers, the primary limitation to moving beyond 4-MSPA has to do with the fact that the current DSN architecture only allows for four analog copies of the IF stream coming from the antenna to the Complex's signal processing center. However, the DSN is in the process of moving to an architecture that enables digitization of the IF at the antenna – allowing any number of digital copies of the IF to be sent to the Complex's signal processing center. To the extent that the current hardware receivers could be replaced with much less expensive software receivers, the digitization at the antenna, in combination with software receivers, would then make it possible to have operational n-MSPA.

But, n-MSPA would only help the downlink. On the uplink, the serial uplink swapping would become infeasible since the same pass duration would have to be divided up into ever tinier chunks as the number of spacecraft sharing the antenna during the n-MSPA increased. So, with this in mind, we also began looking into Multiple Uplinks Per Antenna (MUPA) techniques. One of the more promising of these involves time-multiplexing command sequences from all of the different spacecraft Mission Operations Centers (MOCs) onto a single uplink frequency and then simultaneously broadcasting this to all of the n-MSPA spacecraft. Each spacecraft would differentiate its commands from those of the others via spacecraft ID. And, each spacecraft would be able to make use of 2-way Doppler and Ranging by having its radio make use of variable turnaround ratios. Work is currently underway to develop techniques for enabling spacecraft to acquire and maintain lock on this single frequency broadcast in high relative Doppler environments.[6] In formulating our architectural option, however, we assumed that these techniques would be successfully developed, enabling n-MSPA with MUPA.

We also assumed widespread use of Opportunistic MSPA (OMSPA). In this concept, like n-MSPA, all of the participating spacecraft must reside in the same antenna beam. However, unlike n-MSPA, the individual spacecraft transmissions would not come down through the antenna to separate receivers. Instead, they would come down to a wideband IF recorder that would essentially see everything the antenna "sees" in the frequency band of interest. So, multiple missions that know they will have spacecraft within the ground antenna beam of some other spacecraft with a scheduled, traditional downlink could arrange to transmit open-loop while in this beam. They could then retrieve the time- and frequency-relevant portion of the recording for subsequent demodulation and decoding or subscribe to a service that does it for them. The advantages over n-MSPA include the fact that use of the service would not involve scheduling the antenna. It would involve making opportunistic use of someone else's scheduled beam. Assuming the user spacecraft have gone through the official frequency allocation process, they should not interfere with the scheduled user and would essentially be "invisible" to it. Hence, a virtually unlimited number of users could make use of this technique without contributing to the scheduled load on the DSN's antennas or causing any associated schedule contention.[†††††] The disadvantages relative to n-MSPA include the fact that data recovery would likely entail somewhat higher latency and risk. And, because of its opportunistic nature and latency, it would tend to only work for routine downlink -- since any uplink, including MUPA, would tend to be scheduled. That said, proof-of-concept demonstrations performed to date suggest that the concept could be successfully implemented.[7,8] And, as shown in Figure 11, simulation suggests that during certain periods over the next 30 years, OMSPA could free up to 10,000 hours on the network, or the annual downlink equivalent of a little more than one 34m antenna.

With n-MSPA, MUPA, and OMSPA postulated for helping mitigate peak asset contention, we then reduced our initial "RF-Only" option by one antenna at Goldstone. Loading simulations were then conducted relative to the baseline architecture, assuming the "Best Guess" mission set scenario. As shown in Figure 12, the revised "RF-Only" option (baseline -1 antenna + n-MSPA/OSMPA & MUPA -70m antennas + 7 new 34m antennas per Complex) proved more than adequate to meet projected downlink-hour demand – with or without S/S and 22/26 GHz being added to

[†††††] In reality, the total number of users in a given antenna beam would probably be limited by the bandwidth of the recorder and the availability of assignable RF frequency slots.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

the first set of new antennas in 2024.[‡‡‡‡‡] Even from a downlink volume perspective, as shown in Figure 13, the "RF-Only" option proved adequate to meet demand, with only a few exceptions – and, in those cases, the dips below the average support calibration level were within the level of historical dips that proved manageable.

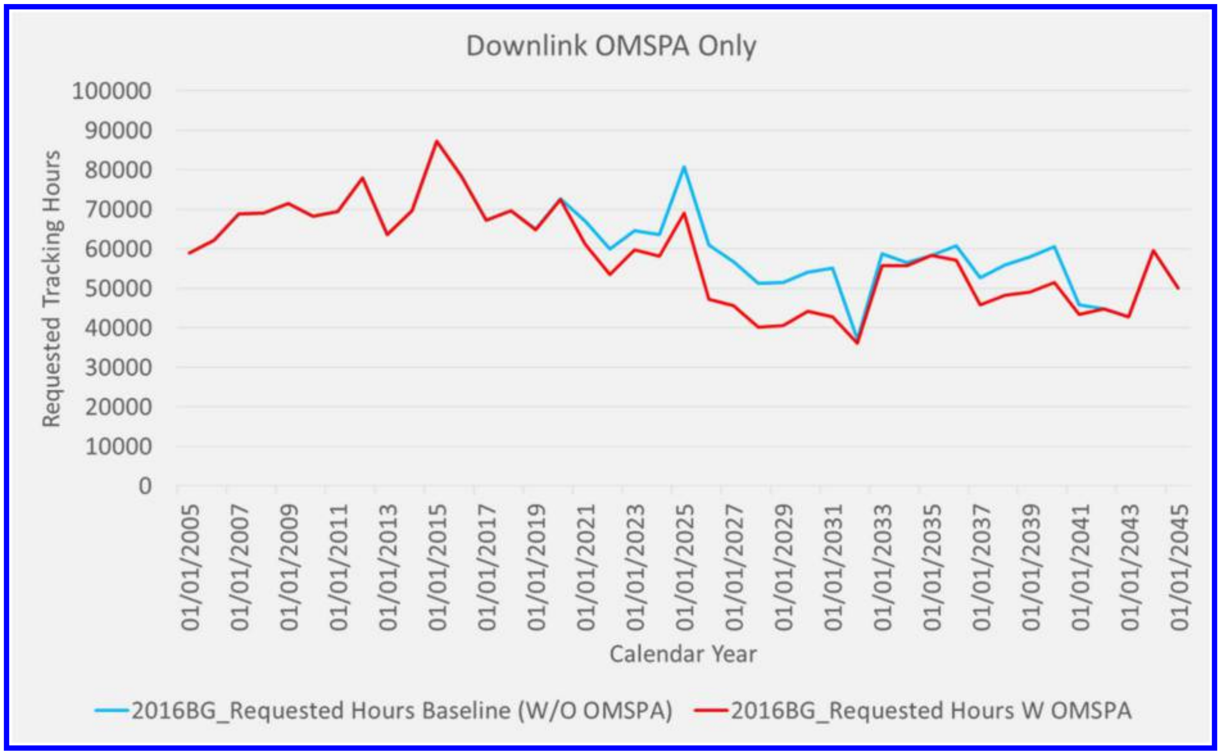

Figure 11. Potential Savings in Antenna Time with OMSPA (Based on 2016 Best Guess Mission Set Scenario)

B. Developing the "Combined RF-Optical" Study Option

Figures 12 and 13 also reveal a "Combined RF-Optical" option. Development of this option required assuming that all of the high-rate Ka-band downlinks in 2025 and beyond could be replaced with optical downlinks. On the ground-side of these links, we postulated three 12m optical ground stations with locations similar to those of the DSN to ensure global coverage. These locations included Goldstone, California; Alice Springs, Australia; and Tenerife, Spain. On the spacecraft-side, we assumed three types of flight terminals, corresponding to the relative link difficulty associated with each mission's location and desired data rate (Table 2). The Strategic Optical Link Tool, discussed earlier, was used to batch compute optical links for each mission's relevant operational segments. The optical wavelength in all cases was assumed to be 1550 nm. The output for each mission was used to calculate an "average" optical data rate by summing the potential data volume over all three ground sites and dividing by the total sum of visibility time (corresponding to each mission phase).[§§§§§] The mission phase average optical data rate was then used to scale the duration of the originally requested Ka-band downlink tracks such that the same data volume could be achieved. Figure 14 provides an idea of how big this postulated optical communications mission set was as a function of time. At its height, the projected optical mission set constituted ~1/4 of the total deep space mission set.

[‡‡‡‡‡]Since the conduct of this study, the advent of the Deep Space Gateway and its high data rate requirement for 22/26 GHz suggests that the need to add 22/26 GHz capability on the first set of antennas might not be so easily dismissed.
[§§§§§] Site "visibility" was defined as spacecraft >= 20° elevation, Sun-Earth-Probe angle >12°, and Sun-Probe-Earth angle >3°.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

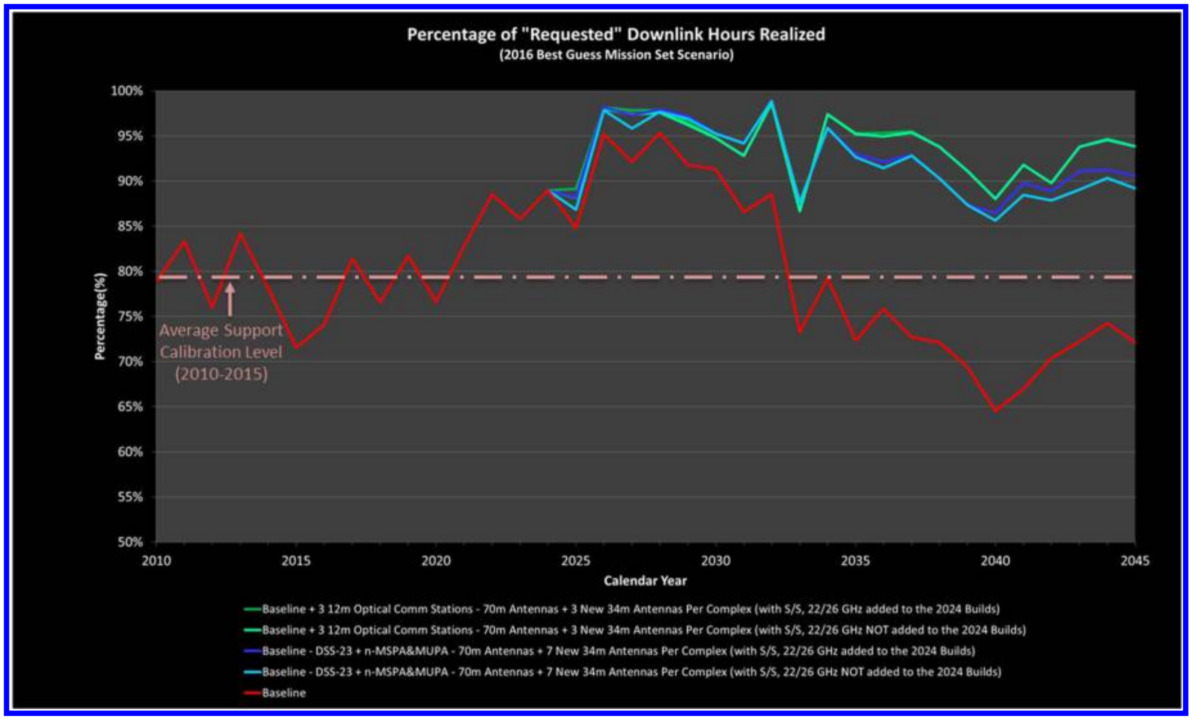

Figure 12. Comparison of Baseline, "RF-Only," and "Combined RF-Optical" Options from a Downlink Hours Perspective

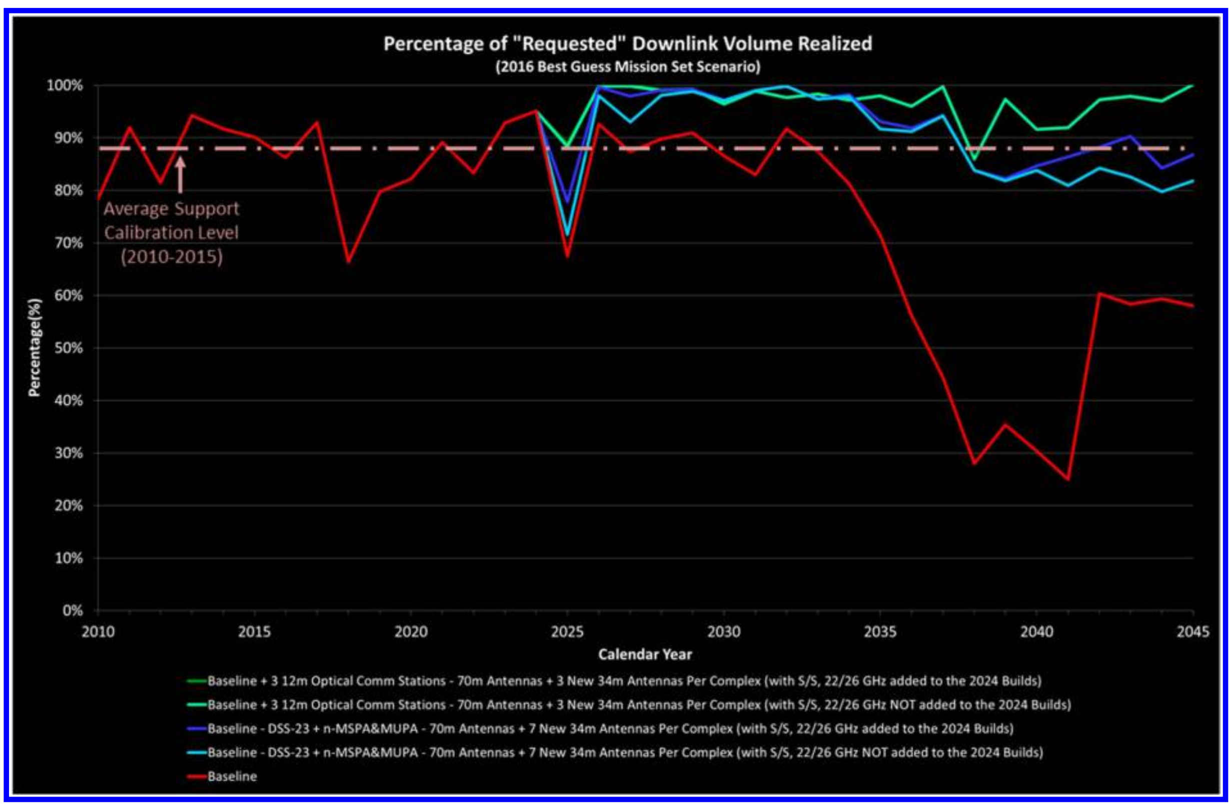

Figure 13. Comparison of Baseline, "RF-Only," and "Combined RF-Optical" Options from a Downlink Volume Perspective

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Table 2. Optical Flight Terminal Assumptions by Location

General Locale	Aperture Size	Optical Power	Slot Width	PPM Range	Code Rate
SEL 2	0.22 m	4.0 W	0.2 nsec	16-128	0.66
Moon & ELL 2	0.11 m	0.5 W	0.2 nsec	16-128	0.66
Planetary (Mars)	0.50 m	50.0 W	0.12 nsec	16-256	0.66

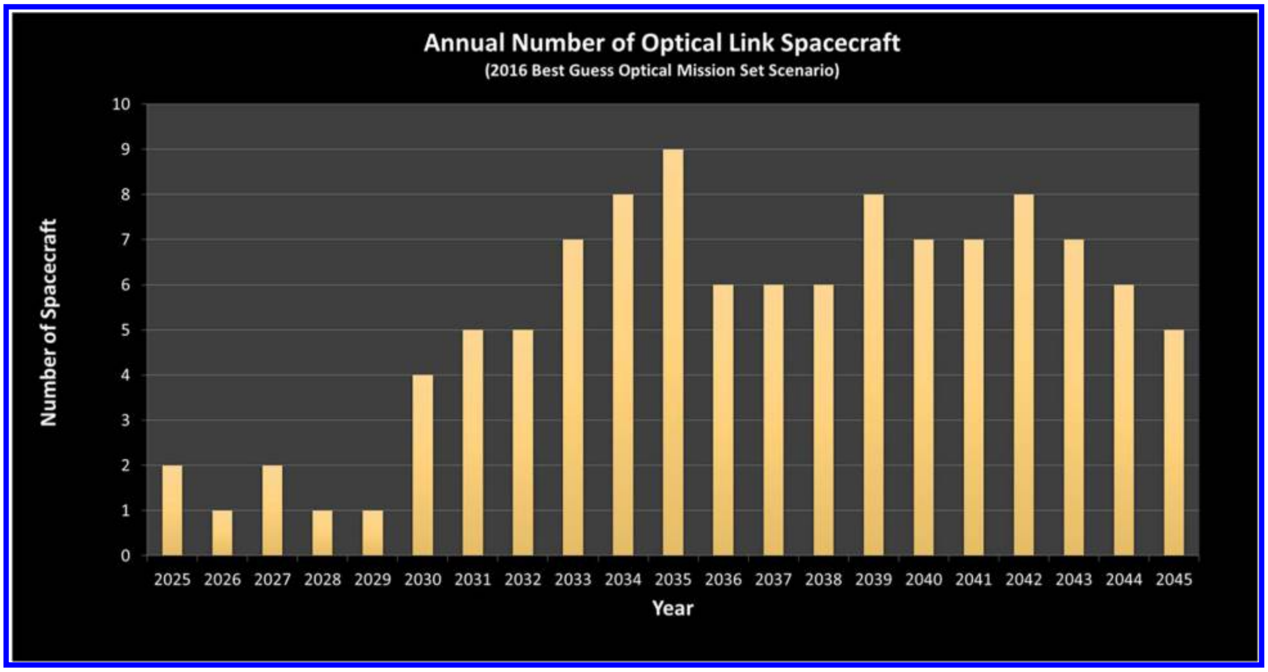

Figure 14. Number of Spacecraft Assumed Capable of Optical Downlink as a Function of Time

While optical communications was substituted for high-rate Ka-band links on these missions, their X-band engineering telemetry downlinks were left as originally modeled, since such mission-critical data was deemed too important to leave to the mercy of the weather and other potential sources of optical link interference. And, a reduced backup Ka-band downlink capability was assumed for times when the Sun-Earth-Probe angle and/or the Sun-Probe-Earth angle were not large enough to enable a reliable link.

Similarly, no optical communications uplinks were assumed – either for mission-critical commanding or high-rate uplink. Aside from weather vulnerability, the close proximity of the atmosphere at the beginning of an optical link leads to photon scattering that, when propagated out over interplanetary distances, leaves far too few photons reaching their intended target. With current technology, the optical uplink powers needed to compensate for this effect are neither feasible nor safe (particularly from the vantage point of anything flying overhead in the intervening space). Hence, the initial "Combined RF-Optical" study option assumed an array of 2-to-3 34m, X/X and 34/32 GHz antennas per Complex to provide high-rate uplink (~50 Mbps) to human Mars exploration assets at maximum Mars distance (as well as a backup Ka-band downlink capability for small SEP and SPE angles).

Even with this antenna addition for uplink, the "Combined RF-Optical" option assumed 11 less 34m antennas than the "RF-Only" option. And, without the same sort of high-rate RF bandwidth drivers (given their conversion into optical missions), the remaining Ka-band links could all be accomplished at 34/32 GHz rather than having to upgrade the antennas to also operate at 40/37 GHz. The "Combined RF-Optical" option, however, did retain the 70m antennas due to the smaller number of 34m antennas available for X-band arraying during critical events and spacecraft emergencies.

Figures 12 and 13 (shown previously) indicate that the "Combined RF-Optical" option outperforms the "RF-Only" option in loading simulations from both a downlink-hour and a downlink-volume perspective – generally remaining above the average support calibration line in both cases. Because of the difference in achievable data rates, the required optical track hours to achieve the same data volume returns are an order of magnitude less than the Ka-band track hours required in the "RF-Only" option. And, a look at optical antenna-hour demand vs. supply in Figure 15 suggests that the three optical ground stations assumed for global coverage could easily meet the antenna-hour demand associated with the postulated optical communications mission set. Figure 16, however, does remind us that optical communications can be subject to significant outages when the angle between the probe and the Sun gets small relative to an observer on Earth and when the angle between the Earth and the Sun gets small relative to the probe that is looking for a laser beacon from Earth to guide the pointing of its optical downlink. Mission designers will need to be sure to design around such events.

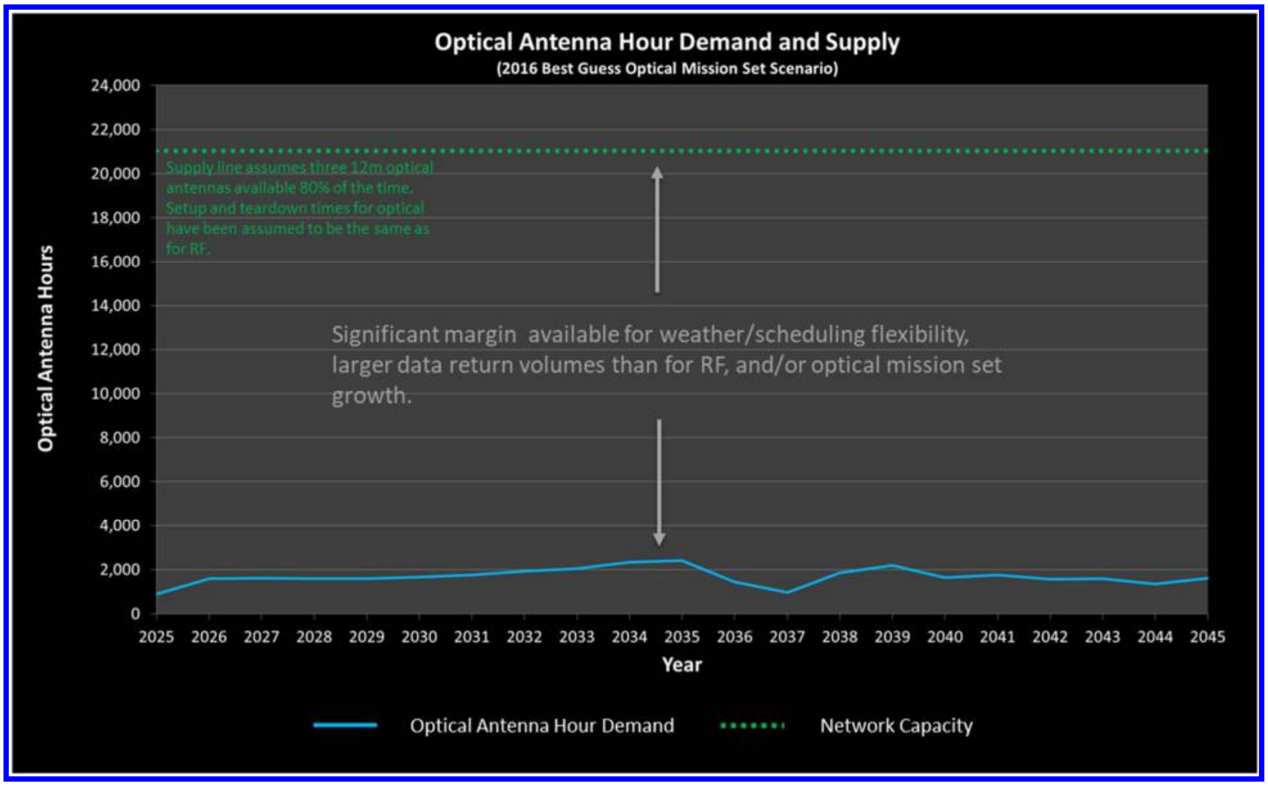

Figure 15. Demand vs. Supply, Assuming 3 12m Optical Ground Stations

V. Pass-2: Updating the Mission Set Scenarios and Refining the Options

A. Updating the Mission Set Scenarios

Because roughly a year transpired between definition and modeling of the 2016 mission set scenarios and presentation of the final Pass-1 findings, each of the scenarios was updated in Pass-2 to reflect the addition of new missions, down-selections for competitively-bid program lines, mission slips, mission cancellations, and changes in mission requirements. In addition, SCaN management requested pursuit of a "what if" scenario that assumed half the maximum uplink and downlink rates as those assumed in the original "Best Guess" for the human Mars exploration missions. So, two 2017 "Best Guess" scenarios appear in subsequent figures: "2017 Best Guess – OA" with the original assumptions and "2017 Best Guess – JSA" with the half-max-rate assumptions. Also, in the "2017 Best Guess – JSA," we assumed that the high-rate human Mars exploration downlinks would use 32 GHz (rather than 37 GHz) and that the corresponding uplinks would use 34 GHz (rather than 40 GHz). Figures 17 and 18 compare how well each of these scenarios loads onto the baseline DSN relative to the "2016 Best Guess." Clearly, halving the maximum human Mars exploration data rates and moving to "in plan" frequencies helps alleviate much of the downlink-hour- and downlink-volume-shortfalls, respectively.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

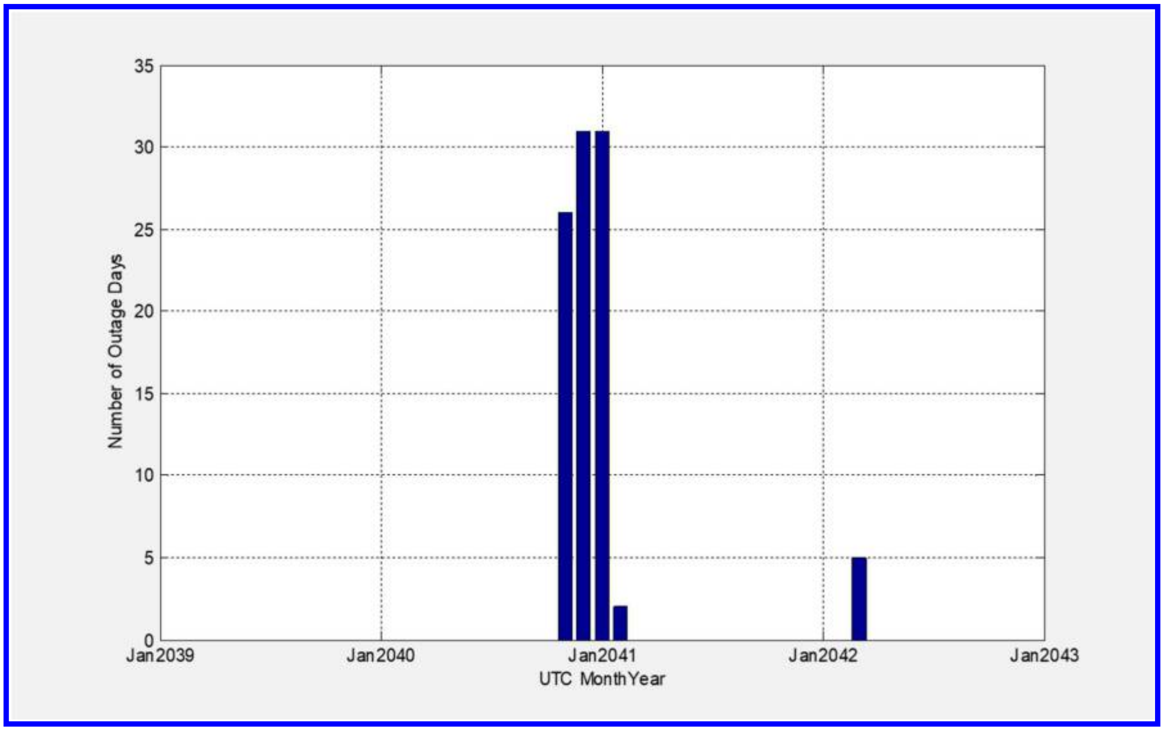

Figure 16. Example Occasions When SEP Angles < 12° and SPE Angles <3° Might Cause Optical Link Outages for Human and/or Robotic Explorers at Mars

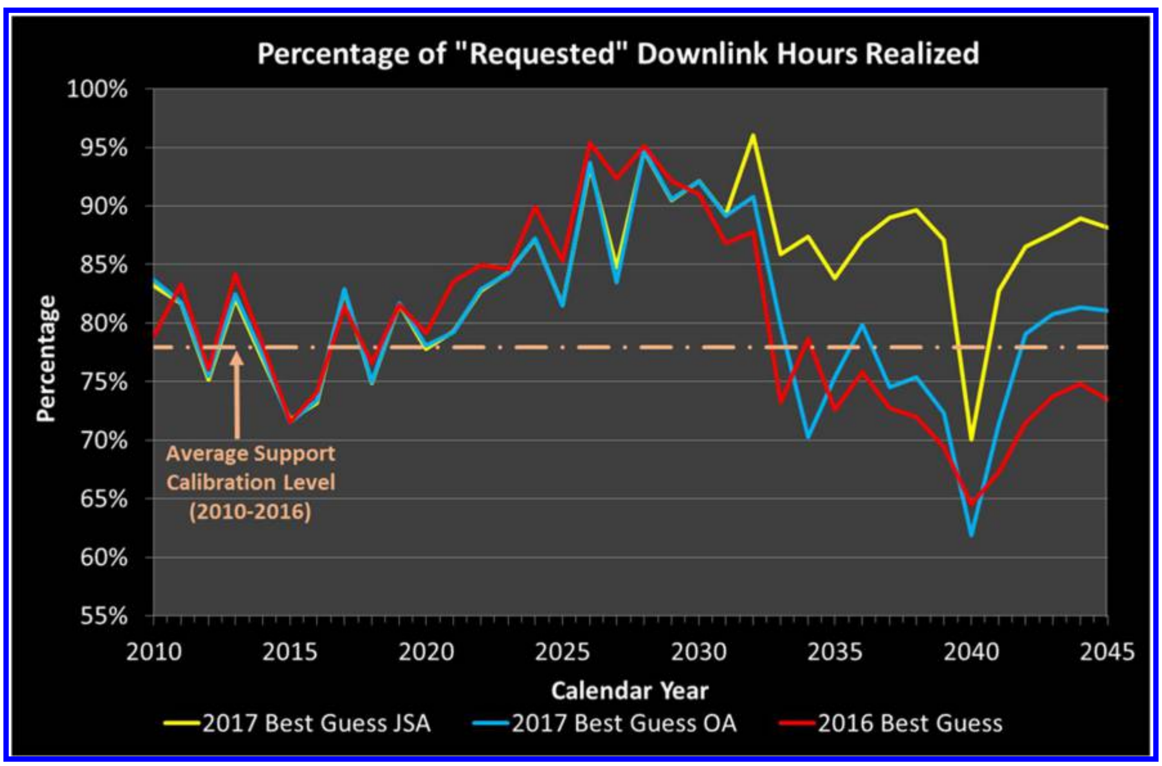

Figure 17. Comparative Loading, from a Downlink-Hours Perspective, Between the Updated Mission Set Scenarios and the 2016 Best Guess.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

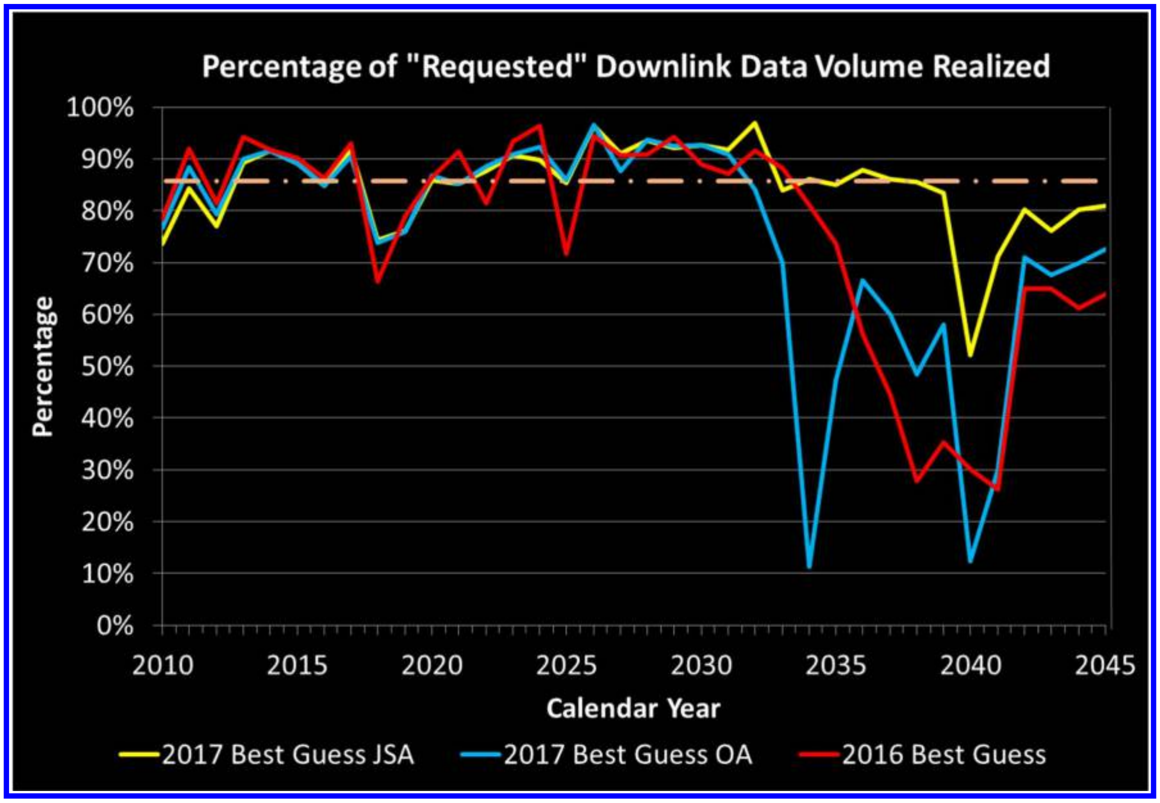

Figure 18. Comparative Loading, from a Downlink-Volume Perspective, Between the Updated Mission Set Scenarios and the 2016 Best Guess.

B. Refining the Options

To the extent that the "2017 Best Guess – JSA" mission set scenario looked significantly more supportable with the half-max-data-rate assumption for the human Mars exploration downlink-rate drivers, we began looking for ways we could support the same downlink volume at half the data rate. Increasing the tracking time was not an option since that would simply exacerbate the loading shortfalls. However, establishing a communications cross-link between the two driving areostationary relay spacecraft looked like a potential way to split the total data load between each of them, such that they could each downlink half their data at half their original data rate. And, since at Mars both spacecraft would be within the same beam of the arrayed ground antennas, they could conceivably downlink simultaneously to these antennas via MSPA. However, we wondered if both spacecraft would be simultaneously in view of the Earth often enough to make this scheme practical. Subsequent analysis showed that the maximum Mars coverage by two areostationary relays, while preserving mutual visibility to Earth, could be achieved by positioning them close to, but no more than, 160.9 degrees apart. Figure 19 shows that this separation would ensure that both relays will be simultaneously in view of the Earth for ~22 hours out of every 24.6 hours.[******] And, in the remaining 2.6 hours, at least one relay would always be in view. So, this arrangement, in conjunction with MSPA on Earth, would enable return of the total data volume at roughly half the required data rate and associated G/T, thereby roughly halving the number of additional antennas that would need to be built relative to our earlier revised "RF-Only" option. Similarly, transmitters on the ground could send the required uplink data at roughly half the rate and associated EIRP. This arrangement could minimize the extent to which uplink arraying at Ka-band might be needed – though, this extent would depend heavily on the maximum transmit power available on a single antenna.

With this arrangement in mind, we changed the revised "RF-Only" option from Pass-1 to one that only involves adding three X/X and 34/32 GHz antennas per Complex beyond plan. As before, 22/26 GHz was also added to two antennas per Complex. However, based on the Pass-1 results and the need for 70m-equivalent critical event

[******] Over the course of an Earth-Mars synodic year, the Earth will at times be well above or well below the Mars equatorial plane, occasionally improving this simultaneous visibility estimate.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

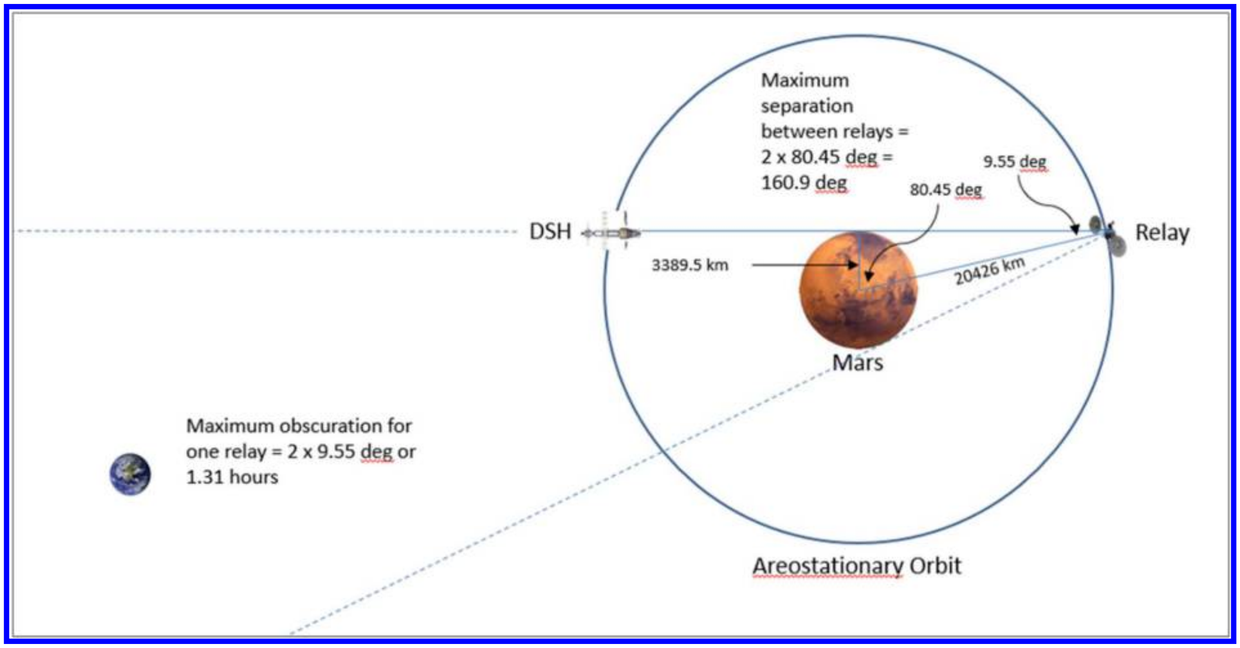

Figure 19. Optimal Geometry for Earth Visibility of Cross-linked Mars Areostationary Relays

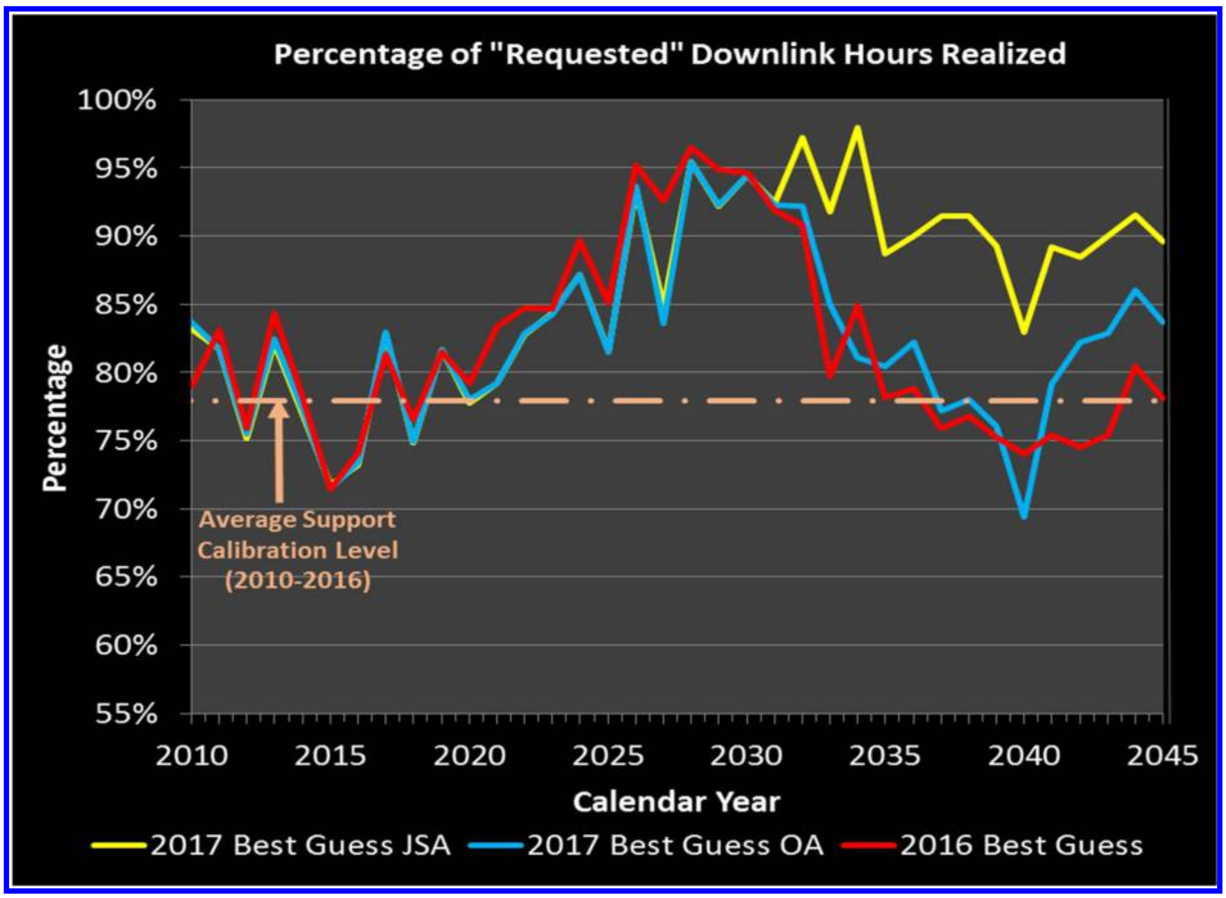

Figure 20. Downlink-Hour Performance of "Dual-Trunk Link, RF-Only" Option

coverage, 70m decommissioning was deferred until the third set of X/X and 34/32 GHz antennas was postulated to be implemented in October, 2031. Figures 20 and 21 show how well each of the three mission set scenarios loaded up, assuming this "Dual Trunk Link, RF-Only" option. From a downlink-hours perspective, the "2017 Best Guess – JSA" mission set scenario appears to be readily supportable, residing entirely above the average support calibration line. Not surprisingly, the other two scenarios not embodying the half-max-rate assumptions and still containing 40/37 GHz components, while displaying improved supportability, still dip down beneath the average support calibration line. From a downlink-volume perspective, the "2017 Best Guess – JSA" mission set scenario remains above the average support calibration line and, hence, is readily supportable until the 2040's. Even then, the amount it dips beneath the average support calibration line is small relative to historical dips, suggesting supportability. For the mission set scenarios with the original data rate and band assumptions, however, significant potential downlink volume shortfalls are indicated.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

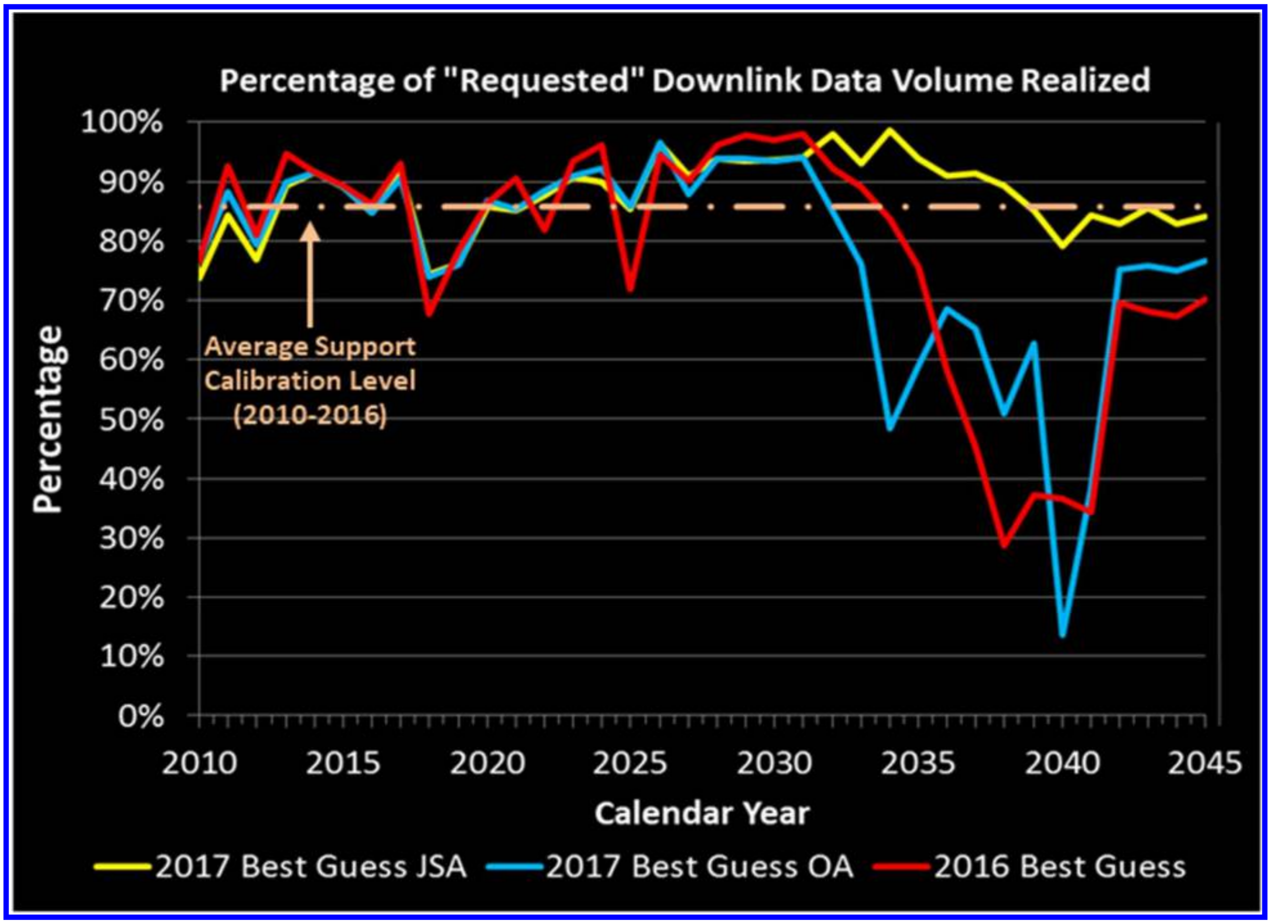

Figure 21. Downlink-Volume Performance of "Dual-Trunk Link RF-Only" Option

Another significant development with respect to the uplink requirement emerged from detailed modeling of human exploration activity and associated communications requirements during the postulated Mars Short Stay Mission and Crewed Mission to Phobos. This modeling effort suggested, among other things, that the total average data rate from Earth to Mars during these postulated missions amounts to approximately 30 Mbps – significantly less than the 50 Mbps postulated during Pass-1. So, instead of arraying up three 34m antennas for uplink as in Pass-1, only two antennas were needed. And, by taking the same dual-trunk link approach for uplink as for downlink, the two antennas would not even have to be arrayed. Link analyses showed that each antenna would be individually capable of closing the link at 15 Mbps (assuming a 1 kW 34 GHz uplink capability on each antenna), for a combined rate of 30 Mbps. Hence, of the three antennas needed for arrayed downlink, two could also be used for uplink. And, this uplink could be done without the cost and complexity of trying to operationally array them. Figure 22 shows the overall architecture for the "Dual-Trunk Link, RF-Only" option that emerged from these considerations. The three 34m antennas are arrayed and MSPA'd for downlink such that the data from both trunk links comes down through the same antennas to two separately assigned array processing receivers. Two of the antennas also individually uplink data to the relays, which can then share the data via the cross-link to acquire the total uplink data volume.

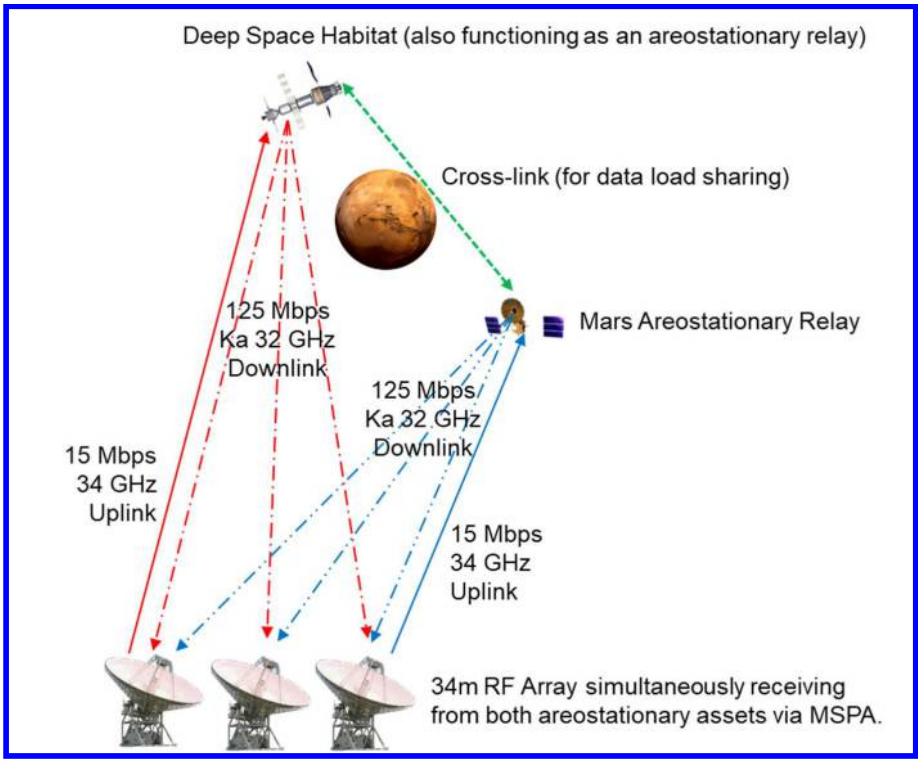

Figure 22. Mars Relay Dual-Trunk Link with Earth: RF-Only Option

With the use of cross-links at Mars and MSPA at Earth enabling a much more viable RF-only option, we then turned our attention to how these same techniques might be applied to a combined RF-optical option. In our Pass-1 "Combined RF-Optical" option, the optical terminals were sized to support a downlink rate of ~250 Mbps, and our Ka-band uplink array was sized to support an uplink rate of ~50 Mbps. With the Pass-2 30 Mbps revision to the uplink requirement and application of the dual-trunk link approach, the downlink rate for a single trunk link changed to 125 Mbps and the uplink to 15 Mbps. Using SOLT, we calculated that the ground aperture size needed to support the 125 Mbps downlink rate was ~8.5m, rather than the 12m previously assumed during Pass-1.[††††††][9] However, to get the 250 Mbps data-volume-equivalent down from both relays in a purely optical mode, without adding additional ground aperture, one would have to MSPA at optical frequencies. Figure 23 shows an architecture that might be associated with such an option. The optical aperture is actually part of a hybrid RF-optical antenna. The RF portion of the hybrid antenna, working in tandem with the RF-only antenna, would provide the necessary dual-trunk uplink capability. (The RF-only antenna and the RF portion of the hybrid antenna could also be arrayed together on the downlink to provide a reduced-rate Ka-band backup to the optical downlink capability.) Whether the narrow beam-width associated with optical communications and the necessary frequency difference in the two trunk links could be dealt with in a cost-effective manner remains an open question.

[††††††] Since then, a Tungsten silicide superconducting nanowire single photon detector (WSi SNSPD) array with a 93% quantum efficiency has come to light that might enable reliance on a single 8m ground aperture, while assuming a much less stringent 0.2 nsec slot width, to achieve a data rate close to 250 Mbps.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

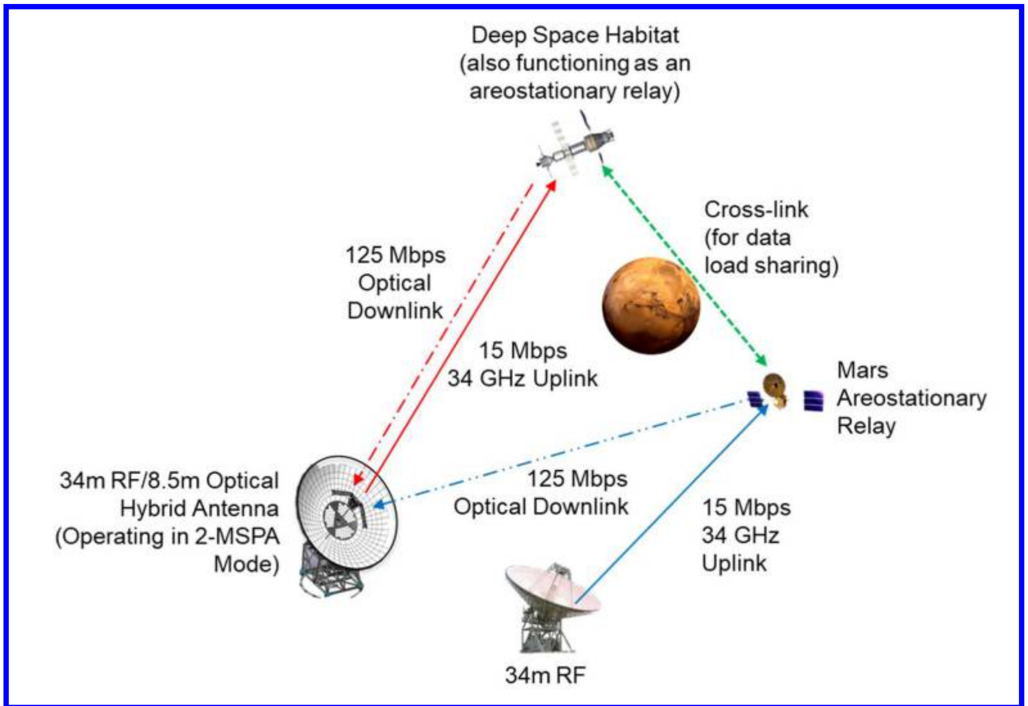

Figure 23. Mars Relay Dual-Trunk Link with Earth: Optical Option

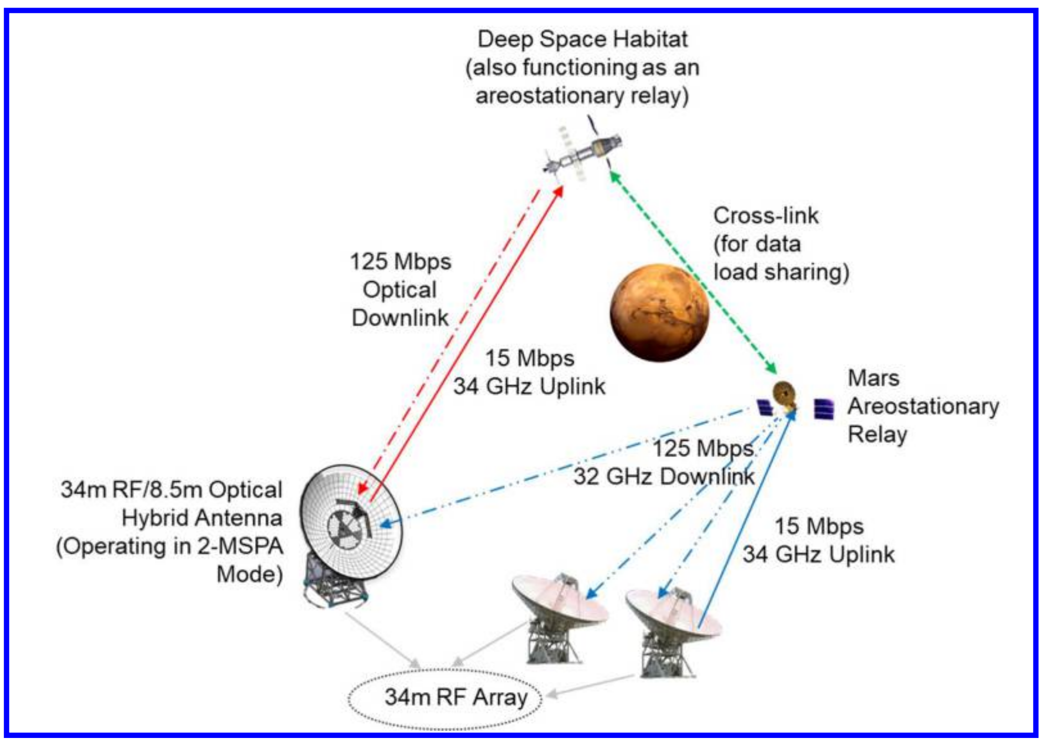

Figure 24. Mars Relay Dual-Trunk Link with Earth: Unsymmetrical Combined RF-Optical Option

In reviewing the "Dual-Trunk Link RF-Only" and "Dual-Trunk Link Optical" options, the Study Lead, Wallace Tai, hit upon a third "Unsymmetrical Combined RF-Optical" option (Fig. 24). In this dual-trunk link variation, two RF-only 34m antennas are combined with a single 8.5m RF-optical hybrid antenna.[‡‡‡‡‡‡] The RF-optical hybrid antenna would support an optical 125 Mbps downlink from one of the Mars areostationary relays. The two RF-only antennas and the RF portion of the RF-optical hybrid antenna would all be arrayed together to support a 32 GHz, 125 Mbps downlink from the other relay. Together, the two RF-only antennas and the RF-Optical hybrid would provide the required 250 Mbps total downlink capacity. At times when the SEP angles are less than 12 degrees (e.g., superior conjunction), both Mars relays could transmit at 32 GHz to an array consisting of the RF portion of the RF-optical hybrid antenna and the two RF-only antennas – all operating in a 2-MSPA mode. By operating in this configuration, it would be possible to maintain a total downlink capacity that is still very near the required 250 Mbps capacity. For uplink, any two of the three antennas could transmit at 15 Mbps, each to one of the two areostationary relays, providing a combined uplink rate of 30 Mbps.

Since all three Pass-2 options require significantly fewer assets than those identified in Pass-1, they would seem to represent far more cost-effective approaches to meeting the high-data-rate requirements postulated for the human Mars exploration era. While the addition of a cross-link is an added expense that enables the Pass-2 options, that expense pales in comparison to the cost savings associated with requiring fewer RF antennas and/or smaller optical aperture. Table 3 provides a summary comparison of the three Pass-2 options. A "sister" paper at the SpaceOps 2018 conference, "Mars Planetary Network for Human Exploration Era – Potential Challenges and Solutions," provides a more in-depth treatment of these options.[10]

Table 3. Comparison of Pass-2 Architecture Options

Considerations	Pass-2 Options		
	Dual-Trunk Link RF-Only	**Dual-Trunk Link Optical**	**Dual-Trunk Link Unsymmetrical Combined RF-Optical**
Cost	Lowest Cost	Intermediate Cost	Highest Cost
Nominal Performance	Comparable	Comparable	Comparable
Performance Growth Potential	Bandwidth Limited by Allocated Spectrum	Extensible to Higher Rates	Extensible to Higher Rates
Performance at Mars Superior Conjunction	Design Rate	Significantly Reduced Rate	Design Rate
Loading Reduction Potential	Lowest	Capable of Off-loading High-Rate RF Demand	Capable of Off-loading High-Rate RF Demand
Technical Maturity	Highest	Lowest (e.g., Optical MSPA)	Intermediate
Fault Resilience	Graceful Degradation	Little Resilience to Ground Station Failure	Multiple Graceful Degradation Options

VI. Summary, Conclusions, and Recommendations

For the vast majority of the postulated future deep space mission set scenarios, analysis of trends in spacecraft numbers, downlink numbers, antenna-hour requirements, and loading simulations suggest a steep increase in demand for antenna-network capacity over the next 10 years. Careful assessment of this demand relative to planned antenna capacity suggests that it should be manageable, though recurring periods of significant asset scheduling contention are likely to occur. This contention may be mitigated somewhat by more aggressively pursuing shared-beam operations in locales and situations where multiple spacecraft are likely to reside within the half-power beam-

‡‡‡‡‡‡ Subsequent refinements of the optical link budget (prior to learning about the Tungsten silicide superconducting nanowire single photon detector) suggested that the link could be closed with an 8m RF-optical hybrid antenna.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

width of a single DSN antenna (e.g., Mars, Venus, constellations, etc.).[§§§§§§] Downlink beam-sharing is already used at Mars for up to 4 spacecraft at a time (4-MSPA), and preliminary efforts to expand this capability to n>4 (n-MSPA) are currently underway – as are open-loop recording techniques for allowing downlink via unscheduled, opportunistic use of other already scheduled antenna beams (i.e., OMSPA). Efforts are also underway to allow more flexible serial uplink swapping between downlink-MSPA'd spacecraft. And, techniques for enabling simultaneous multiple uplinks per antenna (MUPA) are currently under investigation.

The next 10 years also appears to be characterized by a steep increase in maximum downlink rates. After that, such rates begin to level off at around 250 Mbps. Most of the steep increase appears to be driven by high-rate observatory-class missions. However, by the end of the next decade, postulated human exploration missions and associated relay infrastructure become the dominant data rate drivers. And, because these high-rate missions at least partially occur at maximum Mars distance, their projected end-to-end link difficulties (data rate x square of distance) exceed current levels by almost two orders of magnitude. The sheer difficulty associated with closing such links may be inhibiting mission concept designers from designing to any higher data rates, causing the plots of average and maximum data rates to level off in the 2030s and beyond. But, available allocated RF spectrum may also be dissuading mission concept designers from postulating data rates much higher than 250 Mbps, since such rates would use up most, if not all, of the entire deep space Ka-band allocation.

Beyond the RF spectrum issue, these increasing data rates and associated link difficulties also pose a potential capacity issue. As we showed in Pass-1 of the Deep Space Capacity Study, a "brute force" approach to closing such links at Ka-band requires arraying roughly 6-to-7 34m antennas (depending upon whether including a "hot backup" antenna for human missions). When these antennas are tied up with such arraying, there are then fewer antennas available to service all the rest of the spacecraft in other sky locations. And, in the current baseline plan for the future, the DSN only has four 34m antennas per Complex. Hence, when we look at antenna-hour plots and loading simulation results for the 2030's and beyond, we see significant capacity shortfalls (sometimes exacerbated by the unavailability of certain frequency-band capabilities such as 37-37.5 GHz).

To the extent that the primary drivers for the most difficult links are the Mars Areostationary Relays needed for the postulated human Mars exploration era, we showed in Pass-2 that a cross-link between the relays could allow each one to send down (to Earth) half the data that one with the requisite Mars surface and/or Phobos view would otherwise be sending down. Hence, each relay could send that data down at half the original data rate, making the link about half as difficult to close. By applying some of the same MSPA techniques needed to minimize peak asset contention during the 2020s, it would then be possible to simultaneously recover the data from both relays. Thus, with only 2-3 additional antennas beyond what is currently planned per Complex, the same total downlink volume could be recovered as with the 6-to-7 additional antennas per Complex considered in Pass-1.

While treated somewhat implicitly in this paper to keep the length manageable, the application of the cross-link to redistributing data uplinked to one or the other of the two relays would also eliminate the need to array two or more antennas at Ka-band to achieve the required 30 Mbps uplink. With the cross-link, two of the three antennas needed for downlink could each transmit half the uplink data at half the data rate. The data arriving at each of the relays could then be routed as needed via the crosslink.

Loading simulations suggest that adoption of the preceding dual-trunk downlink and uplink architecture for human Mars exploration, in addition to the four 34m antennas and one 70m antenna per Complex already in the baseline plan, would enable satisfaction of the aggregate mission set's capacity requirements. However, this architecture ignores the allocated spectrum bandwidth issue alluded to above in the downlink rate trend discussion. At either 32 GHz or 37 GHz, there are only 500 MHz available or suggested, respectively. One could pursue use of both frequencies, but that would add significant cost and still create a 1000 MHz bandwidth limit. By instead using optical communications in a dual-trunk link architecture, one could avoid the RF spectrum bandwidth issue. And, by making use of one RF-optical hybrid antenna and one additional RF antenna per Complex, one could satisfy the uplink requirement while having a reduced-rate Ka-band backup for when the Sun-Earth-Probe and Sun-Probe-Earth

[§§§§§§] In addition to beam sharing, SCaN/DSN is working to mitigate contention periods by developing additional large-antenna cross-support arrangements with other space agencies and universities. It is also working to foster reliance on less-DSN intensive navigation techniques, particularly with respect to the cubesat users.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

angles get too small. One open issue with this dual-trunk optical option involves determining whether or not two, simultaneous pulse-position-modulated optical downlinks can be successfully MSPA'd.

To sidestep this open issue, we also examined an unsymmetrical, dual-trunk link combined RF-optical option. In this option two additional RF antennas accompany the RF-optical hybrid antenna. One Mars relay trunk link comes down at Ka-band to an array of the two RF antennas and the RF component of the RF-optical hybrid antenna. The other comes down to the optical component of the RF-optical antenna. With this design, there are more than enough RF-capable antennas to provide the dual-trunk uplink, and there is the possibility of defaulting to an MSPA'd RF dual-trunk arrayed downlink in the event of an optical communications failure or when the Sun-Earth-Probe and Sun-Probe-Earth angles get too small. Hence, the unsymmetrical option would potentially provide very high resilience to failures. And, if run in the RF MSPA'd mode along with the optical, this option could provide even higher data return than required in the study.

While it is probably too soon to settle on any particular path, a couple of things are clear. First, load-sharing cross-links between relays can significantly reduce required antenna/aperture numbers at Earth, provided that the Earth ground station or arrayed stations make use of MSPA – something that is needed anyway to reduce asset scheduling contention over the next ten years. Cross-link technology, in terms of both the physical link and the management of data across the link, merit further investment.

Second, advances in technology can significantly change which path may look most promising. For instance, we routinely assume throughout this study that it is possible to array up antennas at Ka-band to achieve the required downlink, but demonstrations of such capability are few and far between. Similarly, in Pass-1, we assumed it possible to array up Ka-band antennas to achieve the required uplink, but that, too, is a work in progress. In the optical realm, we assumed that spacecraft laser powers as high as 50 watts could be achieved – but, again, getting spacecraft laser powers to those levels will take a lot more time and effort. We also pointed out the open issue regarding the viability of optical MSPA, upon which the feasibility of the dual-trunk optical option hinges. Meanwhile, recent developments regarding new high efficiency nanowire superconducting photon detectors might render the dual-trunk approach to optical unnecessary. Similarly, investment in the development of new, higher power 34 GHz transmitters could render the dual-trunk approach to uplink unnecessary. If both of these latter cases were to prove true, then a single RF-optical hybrid antenna per Complex, in addition to what is already in the baseline plan, might be all that would be needed for routine human-Mars exploration support. So, a modest investment in all of the above technologies might be a necessary prerequisite for finding the right path. However, with the early 2030s in mind for operational capability, time is short. Historically, it takes several years to design the type of spacecraft that might operate as relays, and just building a single 34m antenna takes a couple of years. We do not have much time to invest in and evolve technologies before choosing a path. So, we ought to start now.

Acknowledgments

The authors would like to thank Wallace Tai for his sponsorship of this paper and Lincoln Wood for his derivation of the optimal areostationary relay spacing for cross-links. The research described in the paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The research was supported by NASA's Space Communications and Navigation (SCaN) program.

References

[1] Tai, Wallace, Douglas Abraham, and Kar-Ming Cheung, "Mars Planetary Network for Human Exploration Era – Potential Challenges and Solutions," SpaceOps 2018 Conference, CAN-03, Marseille, France, 29 May 2018 [cited pre-publication].

[2] Abraham, Douglas S., "Identifying Future Mission Drivers on the Deep Space Network," SpaceOps 2002 Conference, T3-64, Houston, Texas, October 2002, URL: https://arc.aiaa.org/doi/10.2514/6.2002-T3-64 [cited 5 January 2018].

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

[3] MacNeal, Bruce E., Douglas S. Abraham, Rolf C. Hastrup, Janet P. Wu, Richard J. Machuzak, David P. Heckman, Robert J. Cesarone, Raffi P. Tikidjian, and Kristy Tran, "Mission Set Analysis Tool for Assessing Future Demands on NASA's Deep Space Network," IEEE Aerospace Conference 2009, April 2009, URL: http://ieeexplore.ieee.org/document/4839377/ [cited 5 January 2018].

[4] Cheung, K.-M. and D. S. Abraham, "End-to-End Traffic Flow Modeling of the Integrated SCaN Network," *Interplanetary Network Progress Report*, 42-189 (Jet Propulsion Laboratory, California Institute of Technology, May 15, 2012), URL: https://ipnpr.jpl.nasa.gov/progress_report/42-189/title.htm [cited 5 January 2018].

[5] Yijiang Chen, Douglas S. Abraham, David P. Heckman, Andrew Kwok, Bruce E. MacNeal, Kristy Tran, and Janet P. Wu, "Architectural and operational considerations emerging from hybrid RF-optical network loading simulations," Proc. SPIE 9739, Free-Space Laser Communication and Atmospheric Propagation XXVIII, 97390P (15 March 2016), URL: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9739/1/Architectural-and-operational-considerations-emerging-from-hybrid-RF-optical-network/10.1117/12.2213594.full [cited 10 January 2018].

[6] Morabito, David and Douglas Abraham, "Multiple Uplinks Per Antenna (MUPA) Signal Acquisition Schemes," SpaceOps 2018 Conference, CAN-09, Marseille, France, 31 May 2018 [cited pre-publication].

[7] Abraham, Douglas S., Susan G. Finley, David P. Heckman, Norman E. Lay, Cindy M. Lush, and Bruce E. MacNeal, "Opportunistic MSPA Demonstration #1: Final Report," *Iinterplanetary Network Progress Report*, 42-200 (Jet Propulsion Laboratory, California Institute of Technology, February 15, 2015), URL: https://ipnpr.jpl.nasa.gov/progress_report/42-200/title.htm [cited 19 February 2018].

[8] Towfic, Zaid, David Heckman, David Morabito, Ryan Rogalin, Clayton Okino, and Douglas Abraham, "Simulation and Analysis of Opportunistic MSPA for Multiple Cubesat Deployments," SpaceOps 2018 Conference, CAN-01, Marseille, France, 28 May 2018 [cited pre-publication].

[9] Biswas, Abhijit, Joseph M. Kovalik, Meera Srinivasan, Matthew Shaw, Sabino Piazolla, Malcom W. Wright, and William H. Farr, "Deep space laser communication," Proc. SPIE 9739, Free-Space Laser Communication and Atmospheric Propagation XXVIII, 97390P (15 March 2016), URL: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9739/97390Q/Deep-space-laser-communications/10.1117/12.2217428.full [cited 2 March 2018].

[10] Tai, *ibid*.

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528

This article has been cited by:

1. Douglas S. Abraham, Yijiang Chen, David P. Heckman, Leslie Heid, Andrew Kwok, Bruce E. MacNeal, Kristy Tran, Hua Xie. Future Deep Space Mission Communications Trends and Their Implications for NASA's Deep Space Network 373-419. [Crossref]

Downloaded by 2600:6c50:487f:9d7c:9a2b:5138:6038:8df1 on December 13, 2024 | http://arc.aiaa.org | DOI: 10.2514/6.2018-2528