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NASA Deep Space Communications: Future Mission Trends and Their Implications

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In support of NASA's Space Communications and Navigation (SCaN) Program Systems Engineering (PSE) Office, the Jet Propulsion Laboratory (JPL) periodically models and analyzes projected future-mission demand on the Deep Space Network (DSN) out to a thirty-year horizon. These efforts culminate in a set of capacity, spectrum, capability, and network loading trends and associated implications that can then be used to inform decisions regarding the DSN's evolution. This paper describes the findings and recommendations emerging from the latest iteration of these studies. These are always presented to SCaN for strategic planning and programmatic decisions.

On the whole, three key factors appear to be driving how the DSN will need to evolve in the future: (1) unparalleled growth in the number of robotic spacecraft; (2) the emergence of relatively short but tracking-intensive human lunar exploration missions requiring DSN support in the coming decade, followed by an increasing cadence of robotic and then human exploration missions to Mars; and (3) dramatic data rate and associated data volume increases. The growth in robotic spacecraft numbers is projected to substantially raise the level of "base load" demand on the network. On top of this, the intensive tracking associated with each 2-to-4 week human lunar mission is projected to create periodic peak demand levels well in excess of what the DSN has historically supported. To the extent that these missions and certain types of robotic science missions also require much higher data rates, larger-bandwidth uplink and downlink frequencies (e.g., 22/26 GHz) will be needed. And, the data volumes associated with these higher data rates will likely create data handling and management challenges far greater than what NASA has previously had to contend with for deep space missions. In the human Mars exploration era, these higher data rates, in combination with the extreme range distance when Mars is far from Earth, will necessitate arraying up multiple antennas in order to close the communications links – potentially exacerbating any unresolved antenna-hour demand issues in that timeframe.

These findings suggest that, in addition to its planned Lunar Exploration Ground System (LEGS – a subnet of new antennas anticipated to be 18m-class or slightly larger apertures), NASA should: (1) pursue commercial and international/university partner antenna agreements for backfilling antenna-hour supply shortages during peak demand periods; (2) implement ways to use existing antennas more efficiently (e.g., by improving antenna beam-sharing capabilities and equipping more antennas with expanded frequency band capabilities); (3) mitigate increases in "base load" demand by building two additional antennas per Deep Space Communications Complex beyond what is currently planned; and (4) introduce new technologies and systems that will change and optimize the architecture and operations of deep space communications. Example new technologies and systems include: "trunk link" relays at the Moon and Mars that "funnel" all the data from each of these planetary locations down to a single in-view antenna (or antenna array), Delay Tolerant Networking (DTN), optical communications, and greater reliance on autonomous spacecraft and ground systems. SCaN-funded studies are currently in work to further investigate and refine these suggested measures.

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1. Introduction: Factors Shaping the Future Mission Environment

In developing projections of future-mission demand on the DSN out to a thirty-year horizon, we are not trying to predict the future, we are only trying to understand the communications implications of NASA's current set of plans for the future. These plans include returning humans to the Moon, pursuing a sustainable lunar architecture (including a lunar terrain vehicle, commercial crew landing services, a pressurized lunar rover, a lunar space station, fission surface power, an In-Situ Resource Utilization [ISRU] pilot plant, and a surface habitat), a follow-on program to send humans to explore Mars, and a robust robotic science and exploration program that will include: more Earth science missions, more deep space science missions, a Mars Sample Return mission, more capable astrophysics observatories, more heliophysics and space-weather monitoring missions, more near-Earth asteroid detection missions, and a host of science and technology demonstration missions. According to NASA's FY 2023 Budget Request, these plans include "19 crewed, 47 Moon-to-Mars, 55 Science, 19 Climate & Green Aeronautics, 13 ISS Crew Rotation, 27 ISS Resupply, & 20 Technology Missions, Launches, Demonstrations, Instruments or Flights among other operations over the next 6 years."[1] Given NASA's sometimes volatile funding history over the many decades since its inception, and the many fiscal challenges likely to confront the U.S. going forward, it is reasonable to consider whether or not all of these plans will come to fruition on the timescales being envisioned. While we cannot know the answer a priori, there are a number of factors in play that may help foster the continued future pursuit of such plans. These factors include: bipartisan Government support for space exploration; increasing NASA reliance on small spacecraft to enable more frequent, lower-cost missions; increasing commercial launch capacity at lower cost; intensified nation-state competition in space; a resurgence of Government efforts in nuclear power and propulsion that are key to sustained deep space activity; and, a burgeoning commercial space sector. As access to space costs less, including distant destinations such as Mars, market forces will drive up the number of deep space missions.

As evidenced by their budget requests, both prior and current Administrations have steadfastly supported human lunar exploration, deep space robotic exploration, and the goal of ultimately sending humans to Mars in the 2030-2040 timeframe. Over this same time period, both houses of Congress have agreed upon NASA appropriations that have generally increased in each of these areas of endeavor. "Fueled" by this bipartisan support, NASA has been able to design, build, and contract services for many of the elements needed to return humans to the Moon and fund an increasing number of robotic missions beyond geosynchronous orbit in the service of astrophysics, heliophysics, and planetary science. Within the deep space communications and tracking realm, the net result of this is more spacecraft to track, more diverse types of elements needing to communicate (ranging from Gateway and Human Landing Sytem elements to flagship observatories and robotic rotorcraft on Titan), and higher data rates to facilitate increasingly ambitious missions and observations.

Another key factor is NASA's increasing reliance on small spacecraft to enable more frequent, lower-cost missions. While smallsats are not always significantly cheaper to operate than traditional spacecraft, they do tend to be cheaper to build and substantially cheaper to launch.[2] These lower development and launch costs enable a higher mission cadence and better fit to the available budget than would otherwise be the case. To this end, NASA has developed and is working to a Small Spacecraft Strategic Plan that "supports the NASA 2018 Strategic Plan's four strategic goals of Discover, Explore, Develop, and Enable, while promoting a balanced portfolio of science, technology, and exploration missions."[3] Consistent with this, NASA's Science Mission Directorate (SMD) has stated that it is "SMD policy to enable rideshare or launch accommodation opportunities using an ESPA ring as part of the launch service procured for an SMD primary payload."[4] Similarly, NASA's Space Launch System (SLS) for transporting humans to the Moon has been developed with the capability to "carry up to 17 CubeSat slots in a combination of 6U and 12U form factors."[5] All of these factors are translating into more spacecraft launching more frequently.

Beyond the previously discussed secondary payload opportunities available to small spacecraft, there are now more launch vehicle providers for spacecraft of all sizes than there were 10 years ago. One of these relative newcomers, SpaceX, has also played a pivotal role in drastically reducing launch costs through its pioneering efforts in launch vehicle reuseability.[6] Not only has this reuseability allowed SpaceX to offer launch services at lower costs than many of its competitors, but it has also allowed the company to achieve an unparalleled launch rate. Reaffirming reuseability's importance to frequent, low-cost launches, many of SpaceX's potential competitors are now embracing reuseability in their new launch vehicles. Examples include Blue Origin's New Glenn rocket, ULA's Vulcan rocket, and China's Long March 8 and 9 rockets. Meanwhile, SpaceX has been developing an even more capable reuseable rocket, Starship. This rocket is being designed to deliver more than 100 metric tons of cargo to low-Earth orbit, and 21 metric tons to geosynchronous transfer orbit.[7] And, with on-orbit refueling, the Starship will be capable of delivering around 100 metric tons to the lunar surface – using a faring 8m in diameter and 9m in length.[†††] With such launch vehicle capabilities on the horizon, space becomes much more accessible and the range of elements/equipment transportable to deep space destinations much more diverse.

Even with lower-cost spacecraft and more affordable access to space, realizing NASA's ambitious plans for the future will require at least the current funding levels adjusted each year for inflation. Historically, enduring space funding commitments have depended upon international competition and cooperation. In "Historical Dimensions of the Space Age," Roger Launius points out: "At first there was the Moon race in which the two superpowers locked in a Cold War struggle sought to outdo each other. No cost seemed too high, no opportunity to 'best' seemed too slight."[8] He goes on to note that after Apollo, NASA became much more dependent on international partnerships as a way to "tie space exploration to foreign relations objectives…."[9] To many, we now seem to be engaged in another Moon race – one in which China and the US compete for space dominance beyond Earth's orbit.[10] At the same time, both China and the U.S. appear to be trying to build their own international partnerships along theses lines – China primarily with Russia and the U.S. via its *Artemis Accords*.[11] To the extent that these geopolitical developments conform to the same patterns seen during the Apollo era, they may result in a continued national commitment to funding space exploration despite the many fiscal challenges that likely lie ahead.

To really sustain deep space exploration, however, certain technical challenges also need to be surmounted. Two key challenges are power and propulsion. With lunar nights lasting roughly two weeks and the solar insolation on Mars being only about 43% of what it is on Earth, nuclear power looks increasingly necessary for sustained activity at these destinations. Similarly, because of the huge propellant mass and long trip times involved in getting humans to Mars with traditional chemical propulsion, nuclear thermal propulsion and nuclear electric propulsion look increasingly attractive. Meanwhile, climate change is driving increased Department of Energy (DOE) interest in small modular reactors as a safe, reliable alternative to fossil-fuel-generated electricity. And, the increasing energy requirements of military installations, mobile assets, and space assets are driving increased Department of Defense (DOD) interest in mobile microreactors. This convergence of NASA, DOE, and DOD needs within the nuclear energy arena is producing what some are referring to as a "nuclear reactor renaissance."[12] In June 2022, NASA and DOE announced selection of "three design concept proposals for a fission surface power system design that could be ready to launch by the end of the decade for a demonstration on the Moon."[13] And, that announcement comes "on the heals" of an earlier announcement regarding the selection of "three reactor design concept proposals for a nuclear thermal propulsion system."[14] These multi-agency efforts suggest that two of the key technical "roadblocks" to realizing the sustained exploration of the Moon and Mars, insufficient power and propulsion, may be on a path to being overcome.

Perhaps one of the most important factors making NASA's plans for the future potentially sustainable, however, is the burgeoning commercial space sector. During the Apollo era, the taxpayer had to pay for everything. Now, private ventures are materializing that provide services catering to both commercial space endeavors and NASA's taxpayer-funded endeavors. Hence, the underlying cost for such services is no longer borne solely by the taxpayer – it is also supported by commercial revenue. One can already see this occurring in the launch services realm. Rockets that were once used exclusively for government payloads now also routinely launch commercial communications and remote sensing satellites. NASA is endeavoring to extend this launch services model to the delivery of payloads to the Moon through its Commercial Lunar Payload Services (CLPS) program. By building up a cadre of commercial service providers to emplace its payloads at the Moon, NASA intends to demonstrate the utility of these providers to other potential users. To the extent that such users also contract with the CLPS providers, they help to expand the overall revenue base supporting lunar payload services in the future. So far, NASA has awarded 14 "indefinite delivery, indefinite quantity contracts with a combined maximum contract value of $2.6 billion through November 2028."[15]

Another example of the emerging commercial space sector is in the ground station realm. Instead of government payloads being operated solely through government-owned ground stations, we now have a combination of government earth-orbiting spacecraft and commercial spacecraft being operated via commercial ground stations. And,

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[†††] Starship has also been selected by NASA for the Human Landing System to be used on the Artemis-3 mission that will return astronauts to the lunar surface for the first time since Apollo 17.

in April 2022, NASA began extending this model to Earth-orbiting relay satellites, selecting six companies to demonstrate commercial successors to its Tracking and Data Relay Satellite System (TDRSS).[16] Meanwhile, the European Space Agency (ESA) has begun to extend this model even further – to lunar relay satellites. In September 2021, it signed an agreement with Surrey Space Technologies Ltd. (SSTL) to become the anchor tenant for SSTL's commercial lunar relay satellite, Lunar Pathfinder.[17] In so doing, ESA is trying to use the Lunar Pathfinder as a "proof of concept" demonstration for a future commercial lunar communications network – a network for which SSTL and Telespazio were awarded study contracts in May 2021. In June 2022, NASA signed an agreement with ESA to launch Lunar Pathfinder via NASA's CLPS program – with future CLPS payloads at the Moon being amongst its potential customer base.[18] So, even at the Moon, the groundwork is being laid for government-only services to be supplanted by commercial services that are supported by a broader revenue base than just the tax-payer-funded mission set.

Another currently evolving example of the growing commercial space sector pertains to on-orbit refueling. Through on-orbit refueling, missions headed to destinations beyond low-Earth orbit can avoid having to carry all the fuel needed for their entire journey. Instead, they can just carry what they need for getting to the refueling station in low-Earth orbit, then refuel with the amount needed to take them to their destinations. This approach enables launching with smaller, less-costly launch vehicles – or launching with the same vehicles, but with more massive payloads. On its website, SpaceX envisions doing the latter by turning some of its Starships into tankers that can then be used to refuel other Starships headed to the Moon and Mars. The *Starship Users Guide* assumes such refueling when specifying a payload delivery capability to the lunar surface of ~100 metric tons.[19] Clearly, such capabilities would be very helpful to enabling the cost-effective exploration of the Moon and Mars while also spurring the development of on-orbit commercial refueling services for all sorts of other potential customers. Already, Orbit Fab is working to emplace hydrazine and xenon tankers in a "service lane" between gesostationary orbit and the graveyard orbit for non-functioning geostationary spacecraft.[20] In fact, one of the NASA-funded CLPS missions, the Intuitive Machines IM-2 lunar lander, will be carrying the Orbit Fab tanker to geostationary orbit as a secondary payload equipped with a Spaceflight Sherpa-ES orbital transfer vehicle.[21] Once there, satellite servicing vehicles would transfer fuel from the tanker to geostationary satellites running short on propellant – thereby increasing the effective life of such satellites. Astroscale has already signed an agreement with Orbit Fab for up to 1000 kg of xenon that would be used to refuel one of its Life Extension In-Orbit (LEXI) vehicles slated to launch in 2026.[22]

These launch vehicle, ground station/relay satellite, and on-orbit refueling examples are indicative of a growing commercial-space "ecosystem" that promises to spread the costs of space exploration over a broader customer base than just the taxpayer. In the process, this commercial-space "ecosystem" also has the potential to grow the nation's GDP which would further enhance its ability to afford future space exploration. In combination with the nation's bipartisan Government support for space exploration, increasing NASA reliance on small spacecraft to enable more frequent, lower-cost missions, more commercial launch capacity at lower cost, intensified nation-state competition in space, and a resurgence of Government efforts in nuclear power and propulsion that are key to sustained deep space activity, one can see an emerging "climate" conducive to launching more spacecraft more frequently to more destinations and, in some cases, involving much longer-duration operations. From a deep space communications vantage point, all of this translates into more spacecraft needing to be tracked, more diversity in the types of spacecraft/exploration elements needing to communicate, more diversity in the requirements associated with such communications, and generally higher data rates as missions seek to accomplish, and communicate back to the Earth, increasingly ambitious science and exploration activities.

2. Methodology

Modeling and analyzing future mission demand on the DSN out to a 30-year horizon obviously involves significant uncertainties. Chief among those is what missions comprise the future mission set as a function of time. Formulation of our "Best Guess" mission set scenario begins with SCaN's Space Communications Mission Model (SCMM). This model incorporates SCaN's best understanding of the current and projected future mission customers for both its Near Space Network and Deep Space Network. Aside from direct mission customer contacts, key inputs to this model include NASA's internal Agency Mission Planning Manifest (AMPM), NASA's annual budget requests, NASA's decadal surveys, and various NASA strategic plans, implementation plans, and associated roadmaps. The AMPM is particularly useful, since it provides 20-year mission projections from each of NASA's mission directorates based on known and forecast funding "wedges." Together, these inputs to the SCMM provide a fairly representative view of NASA's current mission plans for the future and, hence, establish via the SCMM, a reasonable starting point for our "Best Guess" mission set scenario.

Modeling to a fidelity that allows detailed analysis of trends in key telecommunications parameters and network loading as a function of time, however, requires the development of significantly more information than what the SCMM can provide. For instance, for each mission we need to understand the specific telecommunication and tracking requirements as function of time. Such requirements depend heavily on where the mission is and what it is doing as a function of time – i.e., on its operational segments. Deep space missions generally involve different telecommunications parameters and tracking requirements for each of their operational segments. So, parameters like required uplink Effective Isotropic Radiated Power (EIRP), ground receiving antenna Gain over noise Temperature (G/T), link distance, data rate, frequency band, number of tracking passes, duration of each pass, and visibility to available ground stations will tend to be different for different operational segments. So, each mission within the mission set has to be modeled for such parameters segment by segment as a function of time. This requires extensive research into the mission concept studies that have been performed for missions in the far future (usually in support of NASA's Decadal Studies); and, for nearer-term missions, extensive review of existing mission design, operations interface control, and network ops plan documents. Such modeling also requires an intimate knowledge of each mission's trajectory and associated operations as a function of time.

In many cases, the trajectory that was originally generated for a particular future mission concept no longer applies because the planned launch date has been shifted. And, frequently, the mission concept design team that generated the original trajectory is not available to generate an updated trajectory. So, a significant part of future mission modeling entails generating representative trajectories applicable to the shifted launch dates, then remodeling each mission's operational segments to be consistent with these new trajectories. Since the trajectories are key to deriving both visibilities to each ground station and the link distance as a function of time, such remodeling is essential to understanding each mission's potential demand on the network over time.

Once all of the trajectories have been generated, all the key mission parameters for each operational segment along this trajectory have been modeled, and all the link budgets for each mission across each operational segment have been run, we then begin examining such data as a function of time across all of the missions comprising the mission set scenario. For instance, we look at trends in such things as number of spacecraft, network antenna-hour demand, data rates, frequency band requirements, EIRP requirements, G/T requirements, aggregate mission set range distance, aggregate sky location, etc. as a function of time. We also analyze network antenna-hour demand relative to available, in-view, and band-appropriate supply to get a sense of network loading. And, we run an actual loading simulation that accounts for each mission's band, EIRP, G/T, antenna visibility, antenna contact, and contact duration requirements while building up an aggregate antenna loading schedule over the timeframe of interest. Figure 1 provides an overview of this entire modeling and analysis process – a process we have been evolving over the past two decades.[23,24,25,26,27]

Because of the uncertainty in the future mission set alluded to at the beginning of this Methodology section, we try to bound our analysis results for the "Best Guess" mission set scenario with those of six other mission set scenarios. These include the "Optimistic," "Pessimistic," "Max Data Rate," "Min Data Rate," "Max Tracking," and "Min Tracking" mission set scenarios.

In the "Optimistic" mission set scenario, NASA and its international partners are assumed to have all of the missions in their plans fully funded and occurring at the desired cadence. The secondary payload capacity associated with every applicable mission is maximized, and some commercial-mission supports are also included.

In the "Pessimistic" mission set scenario, by contrast, only the very highest priority missions in NASA's plans are assumed funded, and these typically occur on a cadence that is a few years slower than what is envisioned in the plans. Secondary payload opportunities are few and far between. The same is true for international mission supports. And, commercial-mission supports are excluded.

The "Max Data Rate" mission set scenario is based on the "Best Guess" scenario. But, candidate missions for the competitively-bid mission slots and other placeholder slots in this scenario are selected that maximize downlink data rates. Conversely, the "Min Data Rate" mission set scenario involves the selection of candidate missions for the competitively-bid mission slots and other placeholder slots that minimize downlink data rates.

In the case of the "Max Tracking" scenario, the mission set is based on the "Optimistic" scenario, but with candidate missions for the competitively-bid mission slots and other placeholder slots selected to maximize average annual tracking. Conversely, the "Min Tracking" scenario is based on the "Pessimistic" scenario, but with candidate missions for the competively-bid and placeholder slots selected to minimize average annual tracking.

Together, analysis results from these six additional mission set scenarios reasonably bound the possibility space for how deep space communications capacity, spectrum, and capability needs may evolve in the future. Analysis results from the "Best Guess" mission set scenario generally fall within these bounds. And, as an indication of how results may have changed relative to prior-year analyses, previous "Best Guess" mission set scenario trend lines can be plotted along with the other trend lines for reference. Finally, because smallsats are now emerging as a key driver for a significant portion of the deep space demand, we also include a mission set scenario in which smallsat/cubesat secondary payloads on all future Artemis launches have been excluded from our current "Best Guess" mission set scenario. The analysis results from this "Best Guess without Artemis Cubes" scenario, when compared to those of the "Best Guess" scenario, enable us to assess how much such smallsats contribute to particular trends of interest.

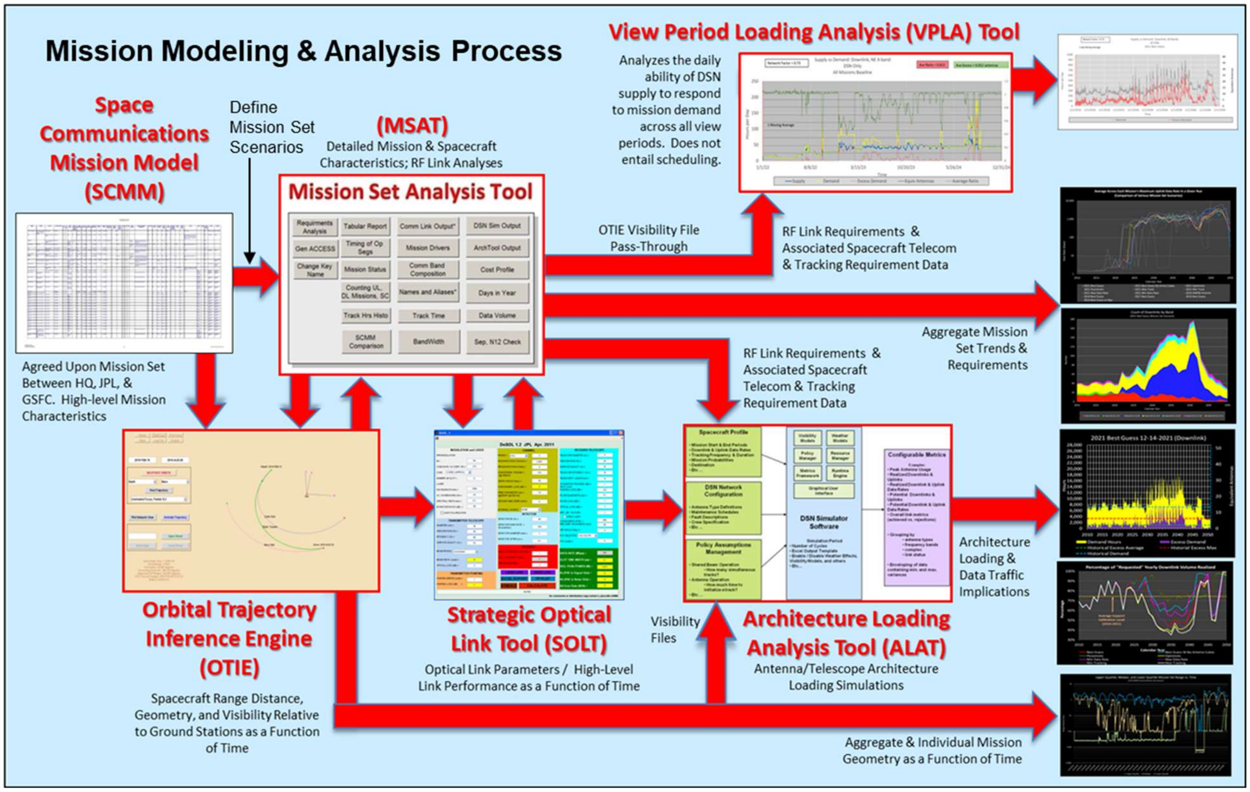


Figure 1. Overview of the Mission Set Scenario Analysis Process

In the sections that follow, the capacity, spectrum, capability, and loading simulation trends that emerge from this modeling and analysis process are summarized and their implications discussed.

3. Mission Trends & Implications

3.1 The Projected Future Mission User Base

Before delving into the specific capacity, spectrum, capability, and loading simulation results emerging from analysis of the various mission set scenarios, we first characterize the general size, composition, and location of the projected future mission set as a function of time. Figure 2 shows the projected spacecraft count as a function of time across all of the different mission set scenarios. Relative to the 2013-2017 projections, the 2018-2021 "Best Guess" projections show a significant increase in the number of spacecraft. For the 2021 "Best Guess" mission set scenario, the spacecraft count almost triples by 2031. Even with no Artemis secondary payloads, the spacecraft count almost doubles. This increase correlates well with the increases in the NASA budget and other factors shaping the future mission environment discussed earlier. Because the missions beyond a 20-year time horizon are exceptionally difficult to forecast, a dramatic decline in the number of spacecraft appears around 2042 that is probably not real, but instead simply reflects a lack of information in hand about missions that far into the future. Given that space exploration is anticipated to continue to increase past 2040, the growth trends evident in the 2030s can be expected to continue (or even accelerate) past 2040.

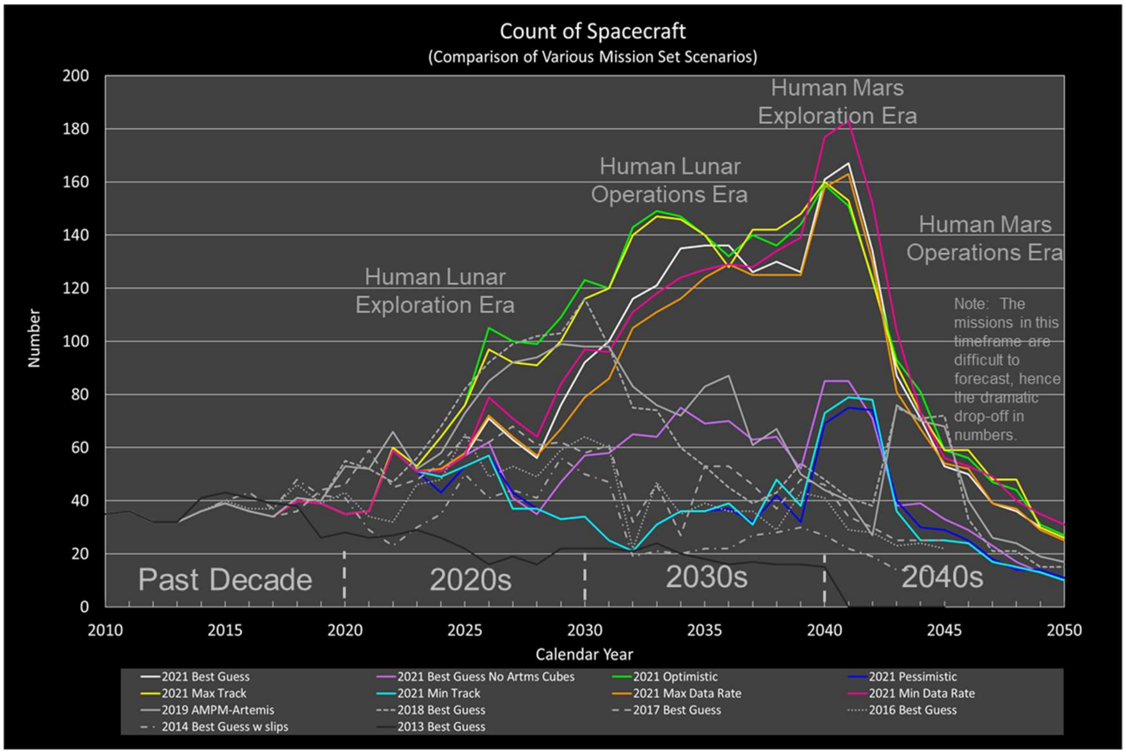


Figure 2. Number of Deep Space Spacecraft Projected Through 2050

The number of downlinks as a function of time tends to be greater than the number of spacecraft since some spacecraft downlink in more than one frequency band. **Figure 3** shows this downlink count for the 2021 Best Guess mission set scenario and breaks the count out by mission sponsor. Consistent with the projected increase in the spacecraft count, the downlink count is projected to more than triple over the next 15 years. NASA's Science Mission Directorate (SMD) tends to be the dominant customer for such deep space downlinks. However, the upcoming human lunar and planned human Mars missions (belonging to the Exploration Systems Development Mission Directorate (ESDMD) and eventually the Space Operations Mission Directorate (SOMD)) constitute an important new and growing customer base with certain communications requirements that have important implications for network utilization going forward. These requirements include 24/7 coverage when humans are present, the need for "hot" backup antennas when executing mission/safety-critical events, the need for real-time communications wherever practical, and data rates that tend to exceed those of most robotic science and exploration missions. As we will see in subsequent sections, such requirements can lead to intermittent periods of significantly elevated antenna-hour demand. As noted previously with respect to spacecraft count, the dramatic decline in the projected number of downlinks around 2042 is more a product of the difficulty in forecasting the mission set that far out in time than it is a reflection of any anticipated downturn in the downlink count.

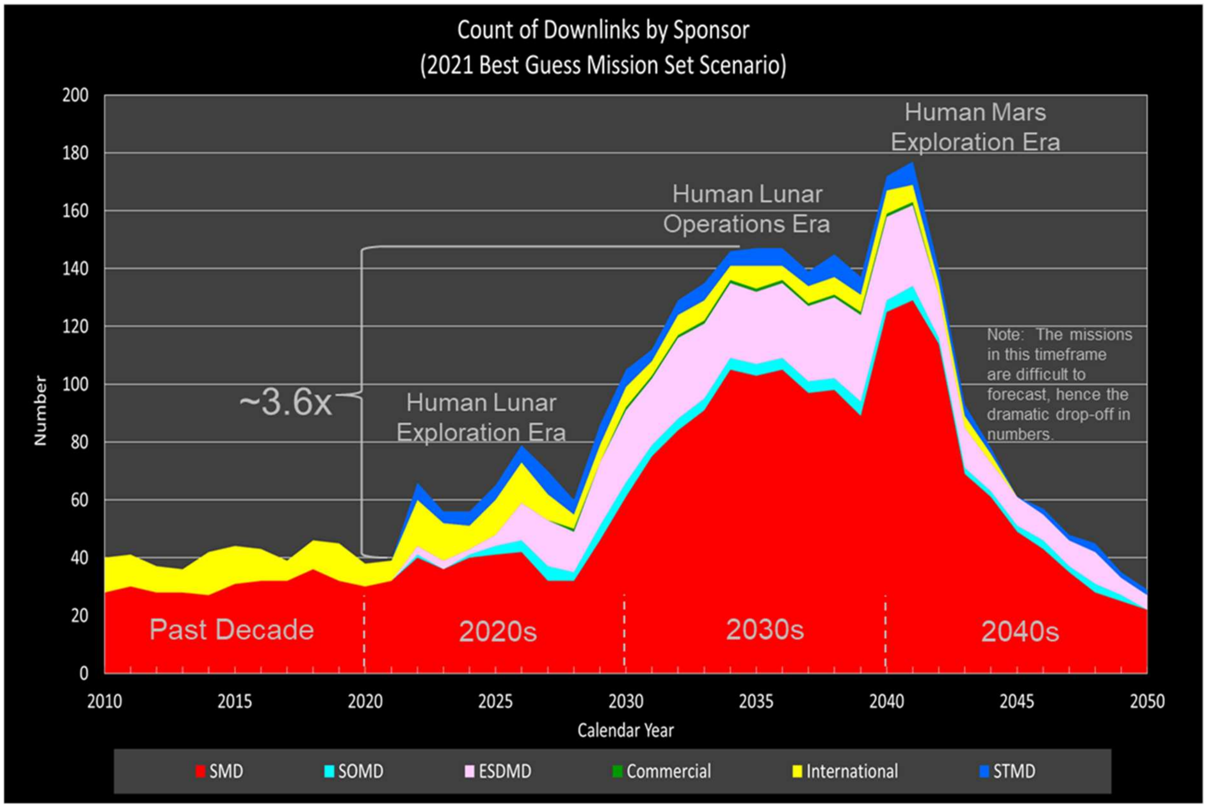
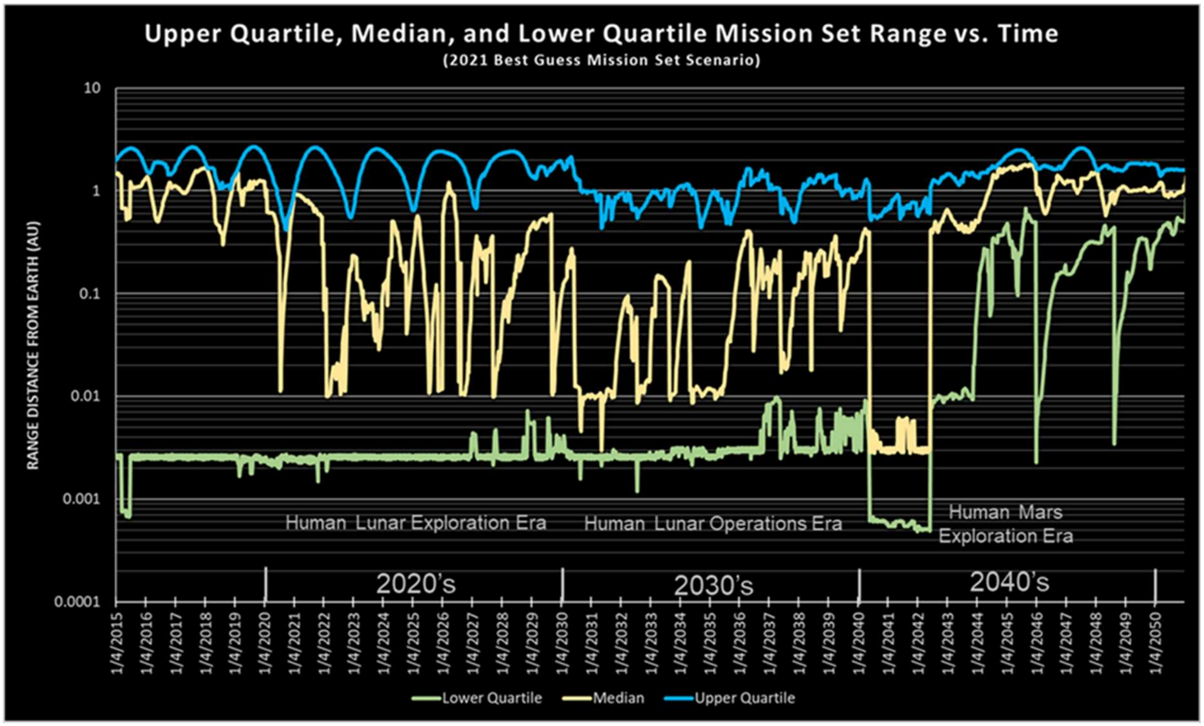


Figure 3. Number of Downlinks by Sponsor Through 2050

Aside from the anticipated size and composition of the projected future mission, another metric relevant to its general characterization is its aggregate range as a function of time. As shown in the quartile plot in **Figure 4**, roughly 25% of the missions occur at lunar distance or less. Another ~25% occur at Mars distance or more. And, ~50% of the missions occur in between the Moon's distance from Earth and Mars's distance from Earth. This appears to be true irrespective of timeframe until one looks at the 2040s where our understanding of the potential future mission set tends to break down. In the 2040s, we have some information regarding potential human Mars exploration plans, but fairly sparse information regarding anything else. Hence, we see the upper quartile, median, and lower quartile all converge around the Mars distance from Earth – with excursions from this distance being driven here and there by other known mission candidates reasonable for the timeframe. While the quartile plot for the "Best Guess" mission set is what is being shown in **Figure 4**, the same general location trend is also visible across the other mission set scenarios.

Mission set range is potentially useful in inferring what general size of ground antenna might be needed to service a particular portion of the mission set – since the supportable data rate on a given link is inversely proportional to the square of the range distance. However, one must be careful to consider what the class of spacecraft is to which the inference is being applied – since the spacecraft transmit power and antenna size will also strongly influence the supportable data rate on a given downlink. A cubesat at lunar distance will not be able to accommodate the large solar panel and battery combination needed for high, sustained transmit powers, nor will it have onboard "real estate" sufficient for mounting a large high-gain antenna. As a result, such a spacecraft will need a much larger ground antenna on the other side of the link than would typically be the case for a spacecraft the size of a a small car. So, the spacecraft-side of the link should always be considered when thinking about the ground-side implications of the range distance.



Reference Distances: Lunar Dist. = 0.00257 AU SEL2 Dist. = 0.01 AU Mars Max. Dist. = 2.67 AU

Figure 4. Quartile Plot of Aggregate Mission Set Range as a Function of Time

3.2 Capacity Trends

One of the key questions operators of ground antennas face is whether or not they have the supply of antenna-hours needed to meet the forecast demand. Antenna-hours in this case encompass more than just track-hours. For instance, it takes time to properly configure the antenna's receivers and transmitters, slew and point the antenna, and perform the necessary equipment calibrations before actually acquiring and locking onto the spacecraft. After the pass is complete, it also takes time to teardown the existing antenna configuration and prepare for setting up the next pass. For deep space tracking, this setup and teardown time typically averages between an hour and an hour and twenty minutes for each and every pass and is currently a significant addition to the missions' required track-hour time. Another factor that can make the required antenna hours larger than the required track hours is a requirement for antenna arraying. For instance, a spacecraft may occasionally need to array two or more 34m antennas to downlink its data within the available pass time at the given range distance. So, if it needs an 8-hour pass but also requires two arrayed 34m antennas in order get all of the data down during that pass, then it requires 16 hours of antenna time before even beginning to account for the setup and teardown time. Similarly, if a human exploration mission during a mission-critical event needs a "hot" backup antenna that can be immediately brought into the link if the prime antenna goes down for some reason, a requirement for an 8-hour track is actually a requirement for 16 hours of antenna time – again, before even factoring in the setup and teardown time.

Without trying to actually schedule across all of the forecast user missions, but simply by looking at their daily antenna-hour demand relative to available supply at the requisite frequency bands and with the allowable view periods, we can begin to asses whether or not a ground antenna network has sufficient capacity to accommodate the forecast user demand. **Figure 5** shows such an assessment for the "2021 Best Guess" mission set scenario in terms of excess downlink demand – i.e., the antenna-hour difference between demand and supply, looking only at downlink antenna-hours. During each planned human exploration mission, we see a spike in excess demand that exceeds the maximum level obtained for missions that occurred in the past. In other words, we see transient excess demand levels larger than anything the DSN has historically experienced. The DSN almost always has a certain level of initial oversubscription that is negotiated down to a supportable level during the scheduling process.[28] However, the transient excess demand spikes we see beginning in late 2025 are larger than any corresponding to the DSN's past oversubscription levels. By the mid-2030s, even the timeframes between the transient excess demand spikes appear to be severely oversubscribed. This is indicative of a growing "base level" of DSN antenna demand that, not even factoring in human exploration support, reaches and exceeds the DSN historical maximum seen for excess demand beyond network capacity.

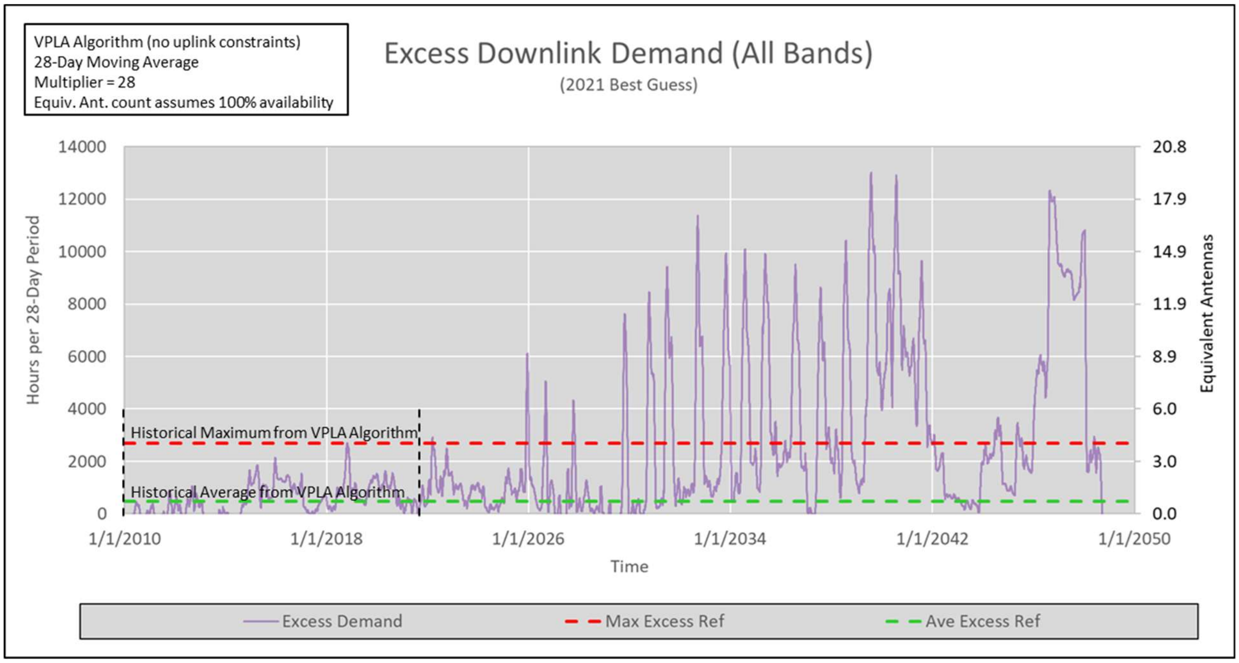


Figure 5. Excess Antenna-Hour Demand on the DSN for the "2021 Best Guess" Mission Set Scenario

Since the results for such demand versus supply comparisons are highly dependent on a host of underlying assumptions, not the least of which is the assumed mission set, we have compared these results with those for the bounding cases of the "2021 Max Tracking" and "2021 Min Tracking" mission set scenarios. **Figures 6** and **7** show the excess downlink demand results for each of those cases, respectively. In the "Max Tracking" case, both the transient excess demand peaks associated with the postulated human exploration missions and the excess demand between such peaks tend to rise well above the levels corresponding to average and maximum levels of oversubscription experienced in the past. In the "Min Tracking" case, however, the excess demand level between the transient excess demand spikes tends to be less than the average historical level of oversubscription. Nonetheless, during the human exploration missions, the transient excess demand spikes still exceed the maximum historical oversubscription level. These results suggest that, regardless of the assumed mission set scenario, human exploration missions tend to cause transient excess demand spikes.

This finding is not particularly surprising since the number of human exploration mission elements (e.g., Gateway, Orion, Human Landing System, Lunar Terrain Vehicle, etc.) requiring simultaneous tracking can exceed the number of antennas available at an in-view DSN Complex. Combined with the need for "hot" backups during mission/safety-critical events, the antenna demand can be almost double the in-view number available. Then, factor in the fact that NASA desires 24/7 coverage for the elements where humans are present and the fact that there are dozens of robotic missions at other locations in the same sky-view that also need coverage, and it is not difficult to see why the excess demand occurs. Because the human exploration missions in the 2020s and 2030s are relatively short compared to most deep space robotic missions (weeks versus years), this excess demand assumes the form of transient spikes. The intermittent, short-duration nature of this excess demand is important to keep in mind when considering possible supply-side mitigation measures.

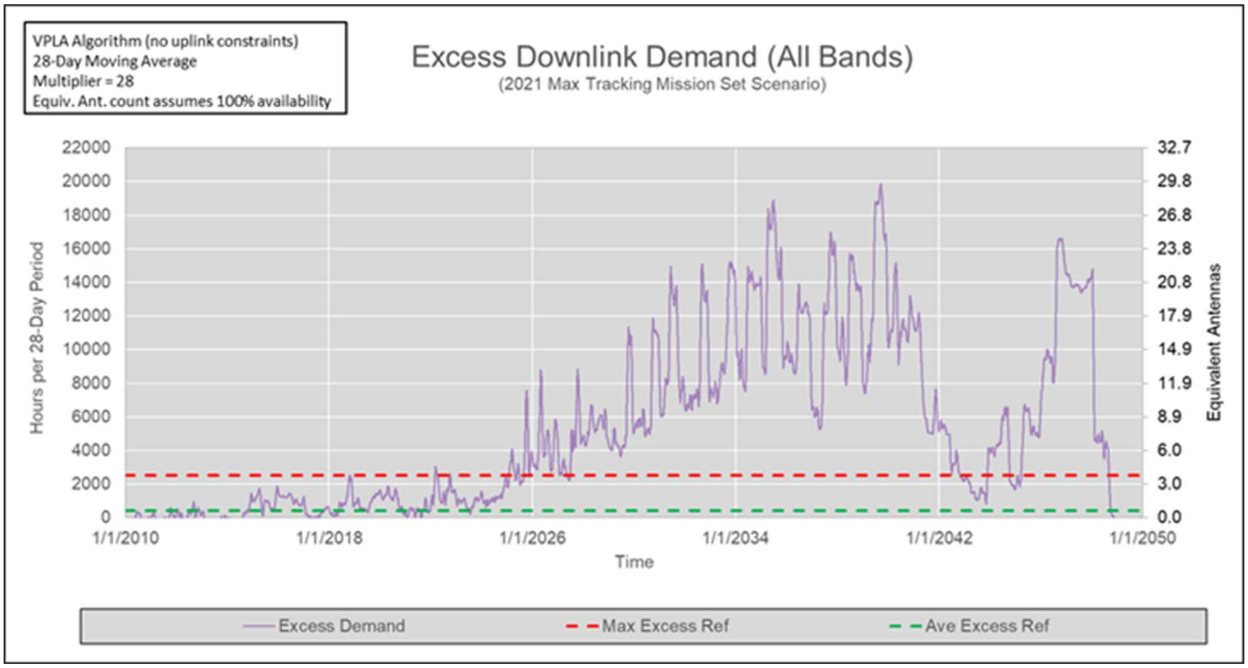


Figure 6. Excess Antenna-Hour Demand on the DSN for the “2021 Max Tracking” Mission Set Scenario

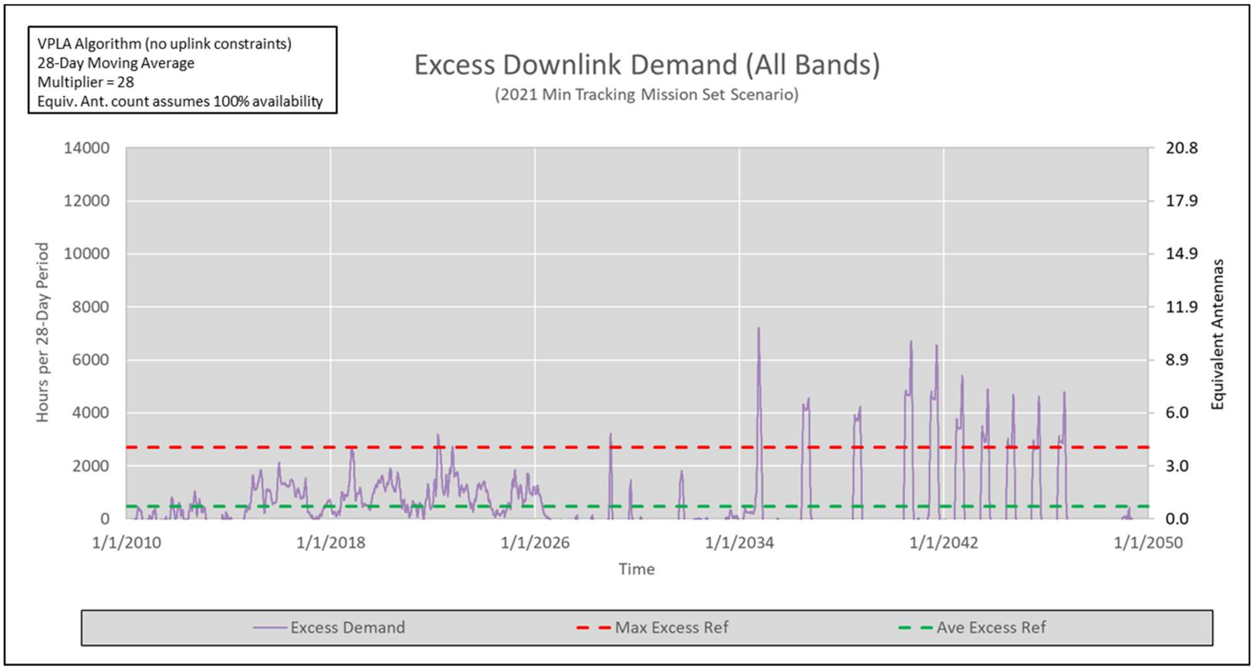


Figure 7. Excess Antenna-Hour Demand on the DSN for the “2021 Min Tracking” Mission Set Scenario

3.3 Spectrum Trends

Looking at the excess demand discussed in the preceding section by frequency band suggests which DSN antenna bands might be in short supply as a function of time. **Figure 8** shows excess downlink demand by frequency band, and **Figure 9** shows excess uplink demand by frequency band. Up to 2025, near Earth S-band up and down, deep space X-band down, and K-26 GHz down appear to be most in demand. This trend is consistent with the near-Earth S-band heliophysics, near-Earth S- and Ka-band astrophysics, and deep space X-band planetary robotic missions dominant in the timeframe. Between 2026 and 2042, K-26 GHz down, K-22 GHz up, near Earth X-band up and down, and near Earth S-band up and down all appear to be in short supply. This excess demand is consistent with a continuation of the prior era's robotic missions in combination with the emergence of multi-element human lunar exploration missions. In the 2039 to 2050 timeframe, the human lunar missions transition to multi-element human Mars exploration missions, leading to elevated demand for Ka-32 GHz down, Ka-34 GHz up, and deep space X-band up and down. To the extent that NASA missions occurring less than 2 million kilometers from Earth must use near-Earth bands and those occurring at greater than 2 million kilometers must use deep space bands, these trends are not particularly surprising. Also, given the fact that higher frequency bands have a space-loss performance advantage over lower frequency bands, it is not surprising to see deep space X-band and Ka-band dominate in the human Mars exploration timeframe.

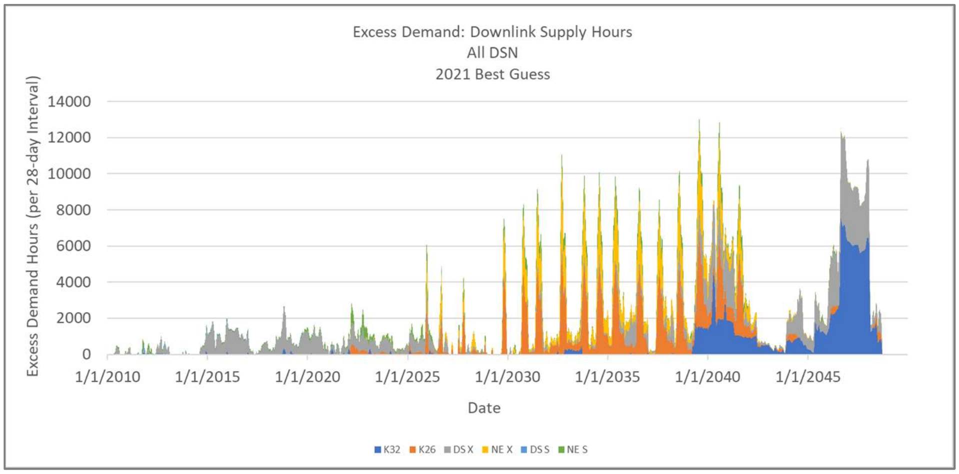


Figure 8. Excess Downlink Demand by Frequency Band

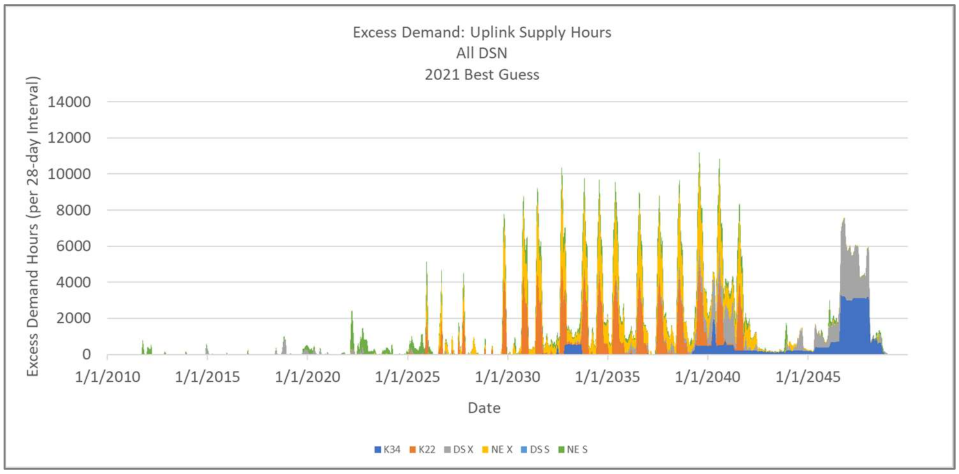


Figure 9. Excess Uplink Demand by Frequency Band

The relative amounts of excess demand for near-Earth S- and X-band are highly dependent on mission set assumptions – particularly assumptions regarding the bands that lunar exploration elements will use. In the January 2022 report of the Interagency Operations Advisory Group's (IOAG's) Lunar Communications Architecture Working Group, the IOAG recommended that both human and robotic Earth-to-Moon and Moon-to-Earth communications be conducted at near Earth X-band for low-rate communications and K-band (22/26 GHz) or optical (1550 nm) for high-rate communications.[29] However, not all CLPS missions, Human Landing System (HLS) concepts, nor lunar-bound smallsat missions appear to be conforming to these interagency recommendations -- instead preferring the widely available, all-weather S-band telecommunications systems. Whether this will continue to be the case as S-band congestion and radio frequency interference issues and X-band space-loss performance advantages, channel bandwidth advantages, and weather tolerance become better understood remains to be seen. Hence, there is some uncertainty in our modeling of the relative amounts of future mission near-Earth S- and X-band demand – modeling that has generally involved assumptions consistent with the IOAG recommendations.

3.4 Capability Trends

As humanity's exploration beyond Earth proceeds, it will likely engage in observations that entail increasing spatial, spectral, and temporal resolution. Whether it be high-fidelity video of human lunar endeavors, hyperspectral and synthetic aperture radar imaging of other bodies around the solar system, or multi-wavelength measurements of astrophysical phenomena as a function of time and/or spatial location, one need only look at what the observational capabilities were 30 years ago versus what they are today to know that most observations tend to trend toward higher fidelity and, hence, drive higher data rate and volume requirements over time. Supporting this assertion, **Figure 10** shows the average across each mission's maximum downlink rates as a function of time for the "2021 Best Guess" mission set scenario, with and without the secondary payload cubesats launching with each of the human lunar and human Mars missions. Without the lower data rate cubesats included (which would drag down the average), this average increases by roughly a factor of 10 over the next 10 years. With such cubesats included, it still increases by about a factor of 6. These rates level out during the 2030s, in part due to available RF spectrum constraints and technology-conservative future mission concepts.[30, 31] If deep space optical communications terminals for both the ground and spacecraft become more available in the 2030s, one would expect to see downlink rates continue to increase. The dips in downlink data rate that we see in the 2040s are largely a product of not being able to fully identify the missions likely to be operating in that timeframe. Instead, we just see the average rate responding to projected human Mars downlink requirements that are on the order of 250 Mbps.[32]

Given the 10x increase in downlink rates anticipated over the next 10 years, one would expect an increase in anticipated downlink volume, as well. **Figure 11** reveals this to be the case. Downlink volume increases by ~37x over the next 10 years, in part due to the 10x increase in downlink rates. They also increase due to the changing nature of the deep space mission set. As noted during the capacity trends discussion, the number of spacecraft almost triples between now and 2031 -- and, even without the cubesats, almost doubles. More spacecraft translate into more downlink volume. On top of that, we now have human exploration missions headed to the Moon. Aside from having downlink rates that tend to be higher than those for many robotic missions, these human missions introduce a requirement for 24/7 tracking. While human missions tends to be shorter than most robotic missions (multiple weeks instead of multiple years), their combination of high data rates and 24/7 coverage leads to very large downlink data volumes. So, with more spacecraft and humand missions with 24/7 coverage requirements, it is not difficult to see why the projected increase in downlink volume is more than three times greater than the projected increase in downlink rates.

Uplink rates and volumes trend very similarly to those of the downlink – though, more extremely and almost exclusively due to human exploration. Most robotic missions still involve uplink rates of ~2 kbps (though, software upload and instrumentation calibration requirements are slowly edging rates up to between 4 and 32 kps). But, with human missions entailing persons at either end of the link, the uplink characteristics have to become a little more symmetric with respect to those of the downlink. Hence, in 10 years, human missions will likely drive uplink rates more than three orders of magnitude higher than they are today. These higher rates, coupled with 24/7 coverage requirements, will drive the associated uplink volumes to be even higher.

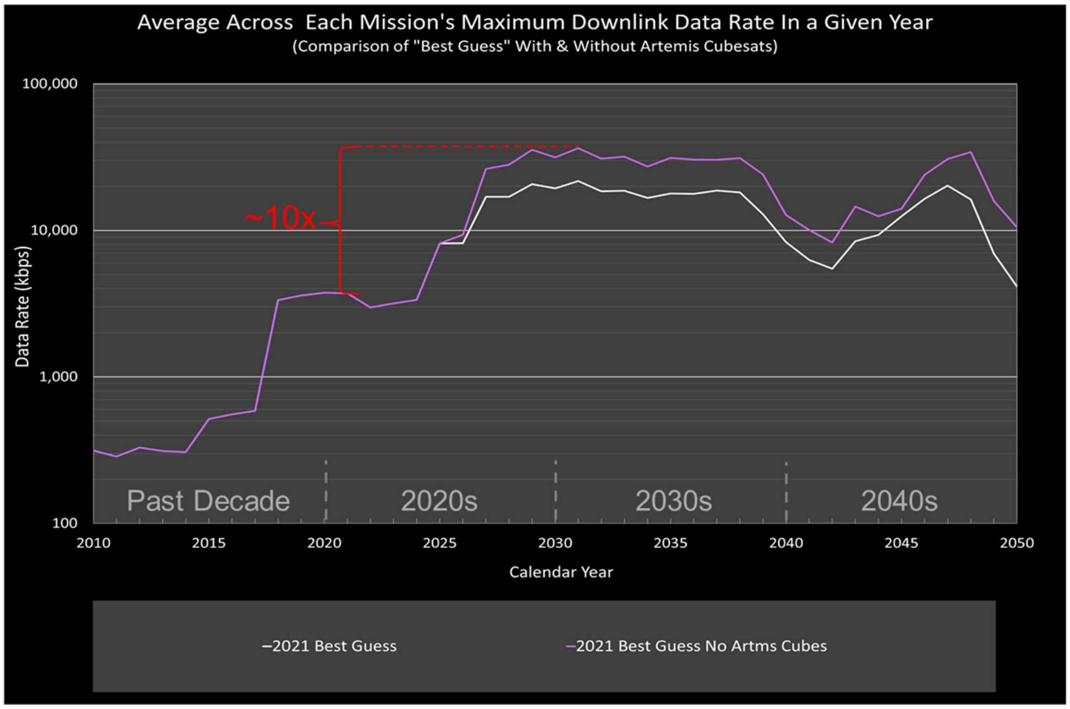


Figure 10. Future Mission Downlink Rate Trends With and Without Artemis Secondary Payload Cubesats

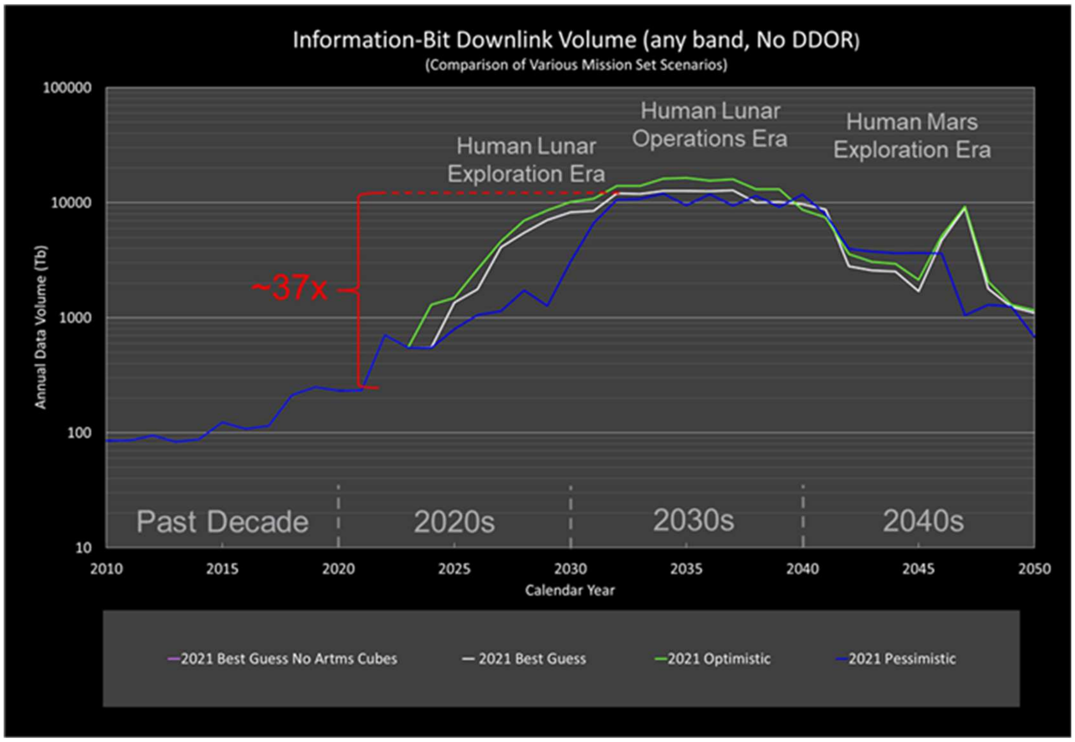


Figure 11. Future Mission Downlink Volume Trends for the “2021 Best Guess,” “2021 Optimistic,” and “2021 Pessimistic” Mission Set Scenarios

Not only do these orders-of-magnitude higher uplink and downlink data volumes create throughput, buffering, and storage challenges for the mission and network ground systems that will need to accommodate them, they also present such challenges to the design of future spacecraft and space-networking architectures. Nodes in a Delay or Disruption Tolerant Network (DTN)[33] will likely need far more data storage and throughput capacity than any of the individual participants might need were they communicating only their own data directly to Earth via a single point-to-point link.

Increasing downlink and uplink data rates also have implications for the size, sensitivity, transmit power, and/or number of antennas needed on the ground to close the communications links with the spacecraft. Downlink requirements for antenna size and sensitivity are generally captured in the G/T requirement, and uplink requirements for antenna size and transmit power are generally captured in the EIRP requirement. **Figure 12** shows the projected maximum individual G/T requirement at X-band as a function of time relative to the DSN's highest G/T antenna, the 70m. One can immediately see that, historically, maximum individual G/T capability at deep space X-band (a.k.a, Category B[‡‡‡] X-band) has been inadequate for some missions. But, such missions have dealt with it by simply dropping their data rates when the link distance necessitates it. This has typically been the case at Mars which at times is around 0.5 AU from Earth and, at other times, is around 2.5 AU from Earth, leading to roughly a factor of 25 change in the supportable data rate. So, here again robotic missions typically operate at their maximum supportable data rates when Mars is close to Earth and reduce their data rates when Mars is far from Earth. However, in the human Mars exploration timeframe, this may not be an option since humans will be on both ends of the communications link, and X-band will likely be used for mission-critical data. In **Figure 13**, a similar story plays out for Ka-band (32 GHz): missions currently drop their data rates when the link distance necessitates it, but in the human Mars exploration timeframe, there may be a need to get high-rate video and science data back to Earth as quickly as possible. So, in both the X- and Ka-band cases during the human Mars exploration era, it may be necessary to achieve the required G/T by arraying up antennas. Or, for high-rate, non-mission-critical Ka-band data, it may make sense to transition to optical communications.[§§§]

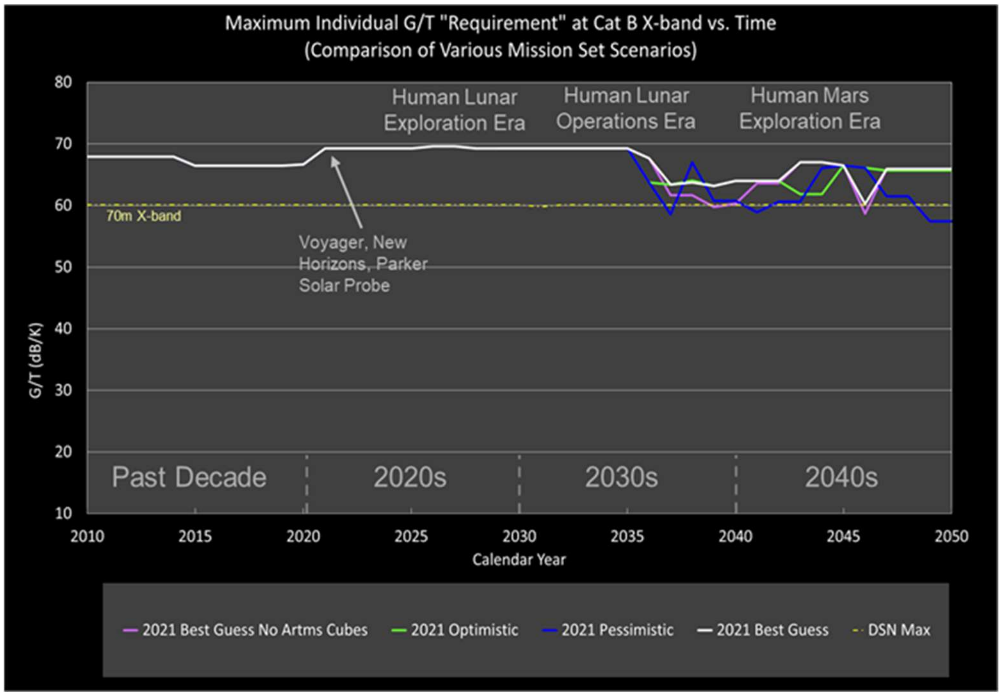


Figure 12. Projected Maximum Individual G/T Requirement at Deep Space X-band as a Function of Time Relative to the DSN's 70m Level of Capability

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[‡‡‡] Where S- and X-band are concerned, missions that are within 2 million km of Earth are assigned Category A or "near-Earth" frequencies. Missions that are at distances from Earth greater than 2 million km are assigned Category B or "deep space" frequencies.

[§§§] Not shown, but also potentially relevant, K-band (26 GHz) has a maximum individual G/T requirement in the 2030s modestly in excess of what a single 34m antenna can support – driven by very high-rate astrophysical observatory missions. Again, arraying or substituting an optical link would likely remedy the shortfall.

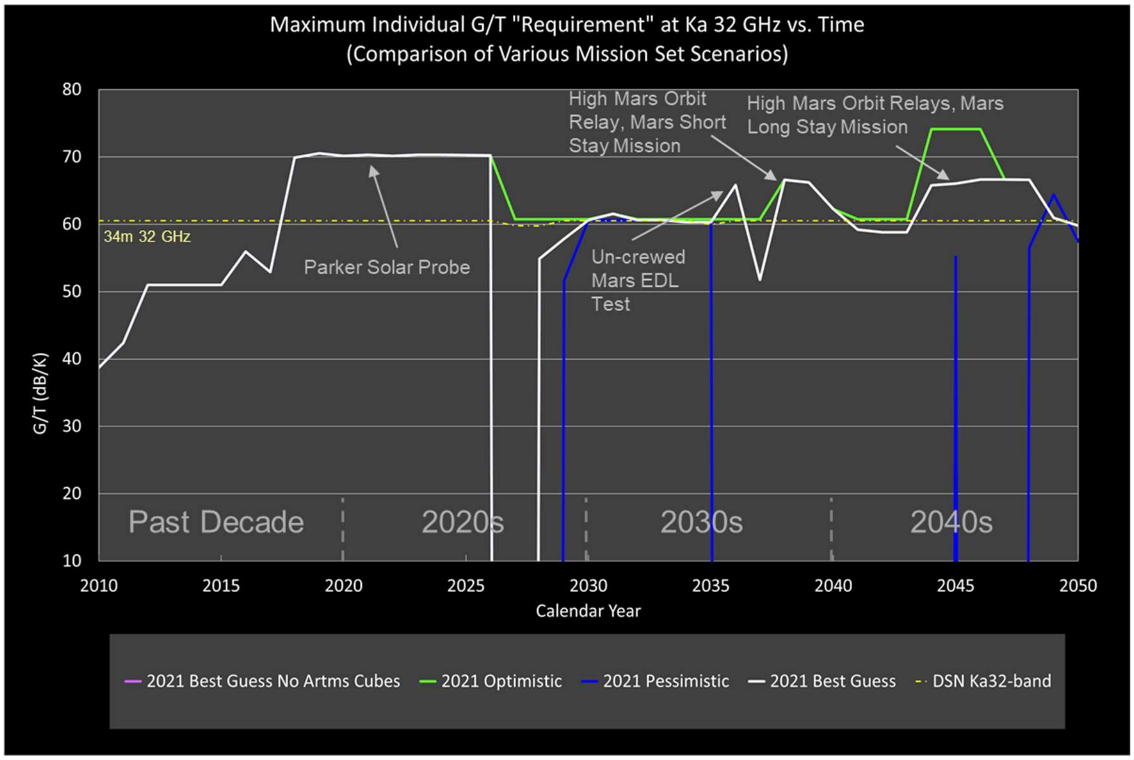

Figure 13. Projected Maximum Individual G/T Requirement at 32 GHz Ka-band as a Function of Time Relative to the DSN's 34m Level of Capability

The potential need to array antennas in the human Mars exploration era raises the question of whether or not the DSN's currently planned complement of antennas in that timeframe will be sufficient to allow such arraying. To this end, we have examined the DSN's aggregate G/T capability at both X-band and Ka-band relative to the projected demand. **Figure 14** shows this comparison for the aggregate, simultaneous X-band G/T. The white line with the square pattern on it, the sampled aggregate simultaneous G/T demand, appears to be significantly above the yellow capability line well into the 2040s. This is probably a product of both the inadequate maximum individual G/T capability at X-band and the excess demand arising from the steep increase in the number of spacecraft discussed in the capacity section. To the extent that the mission set is not well-defined in the 2040s, it is likely that the aggregate, simultaneous G/T capability will actually prove insufficient well into the human-Mars exploration era. This makes problematic having enough antennas per Complex available to array up to achieve the needed data rates in the human Mars exploration era. A similar analysis performed at Ka-band, however, suggests that the aggregate, simultaneous G/T capability in that band will be adequate. On the other hand, such analyses do not take into account the fact that both the X-band and Ka-band reside on the same antennas. So, if the X-band supply is inadequate, there may not be enough 34m antennas to allow adequate arraying at either band – a situation supported by the excess demand results discussed in the spectrum section and more thoroughly investigated later in this paper in the discussion of the loading simulation results.

G/T analyses, of course, only address the downlink-side of the communications capability challenge. EIRP analyses are needed to get a handle on the uplink-side of the challenge. **Figure 15** shows the projected maximum individual G/T requirement at X-band as a function of time relative to the DSN's current and planned future capabilities. During the 2030s, the increased maximum individual EIRP requirement can probably be satisfied with the 70m level of capability. By the 2040s, however, human Mars mission demands will likely necessitate more powerful transmitters and/or uplink arraying.

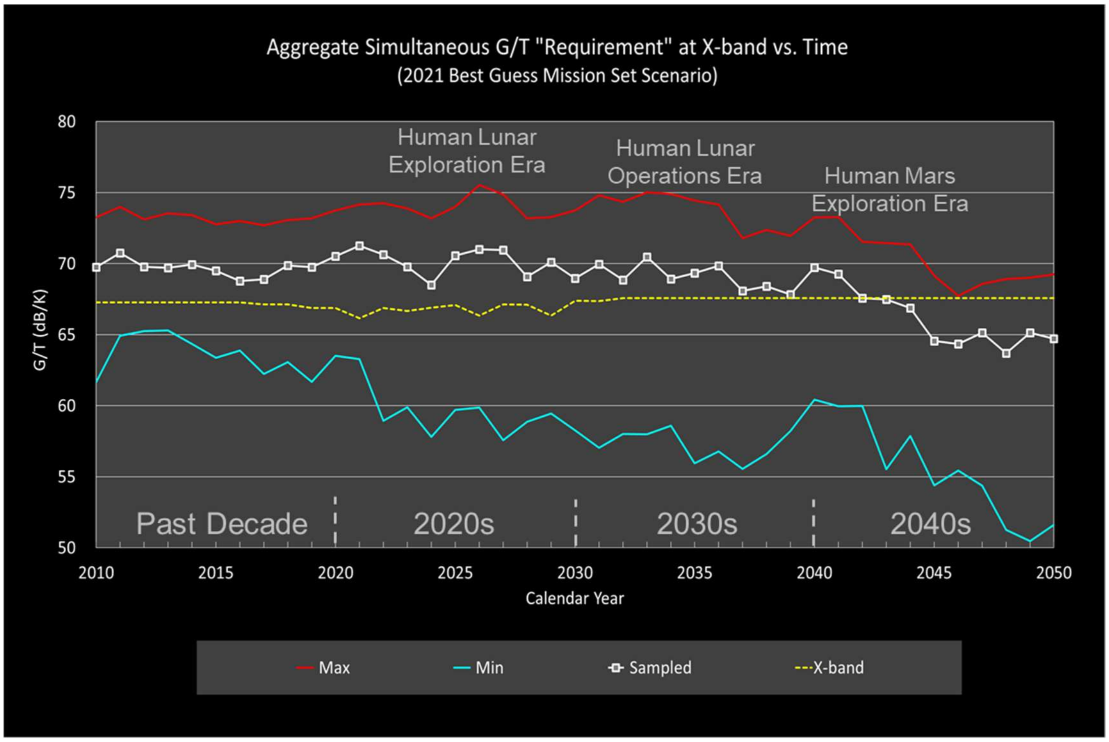

Figure 14. Projected Aggregate Simultaneous G/T Demand at X-band as a Function of Time Relative to the DSN's Aggregate Capability

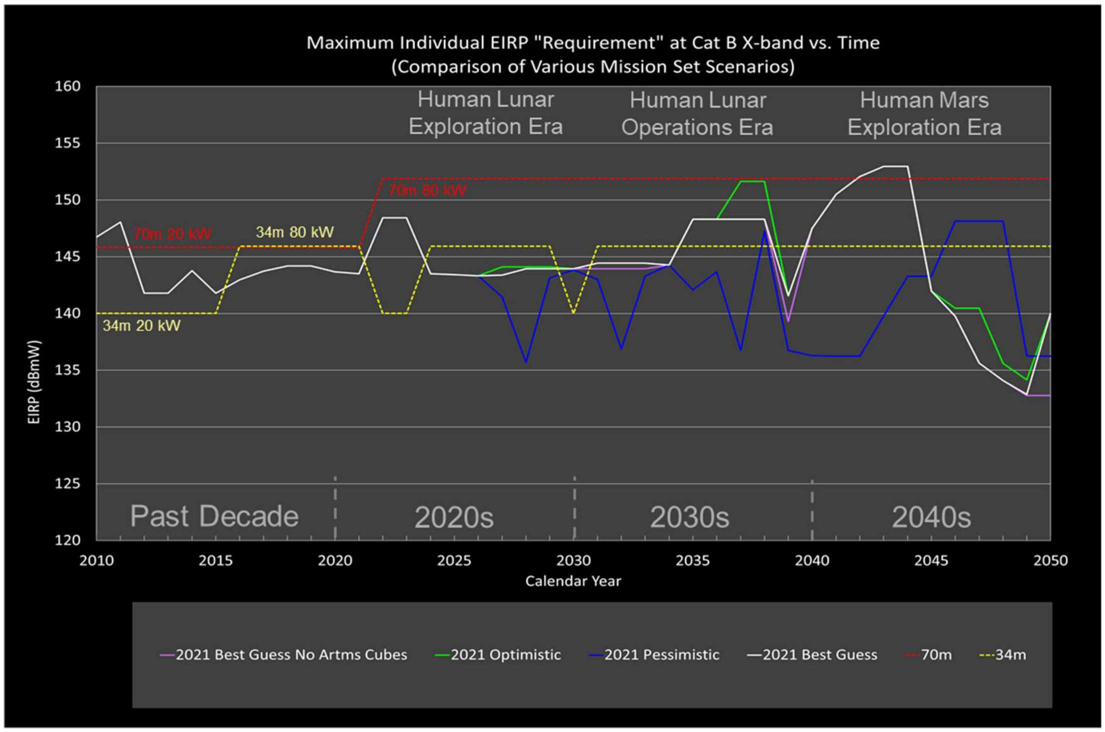

Figure 15. Projected Maximum Individual EIRP at X-band as a Function of Time Relative to the DSN's Current and Planned Future Capabilities

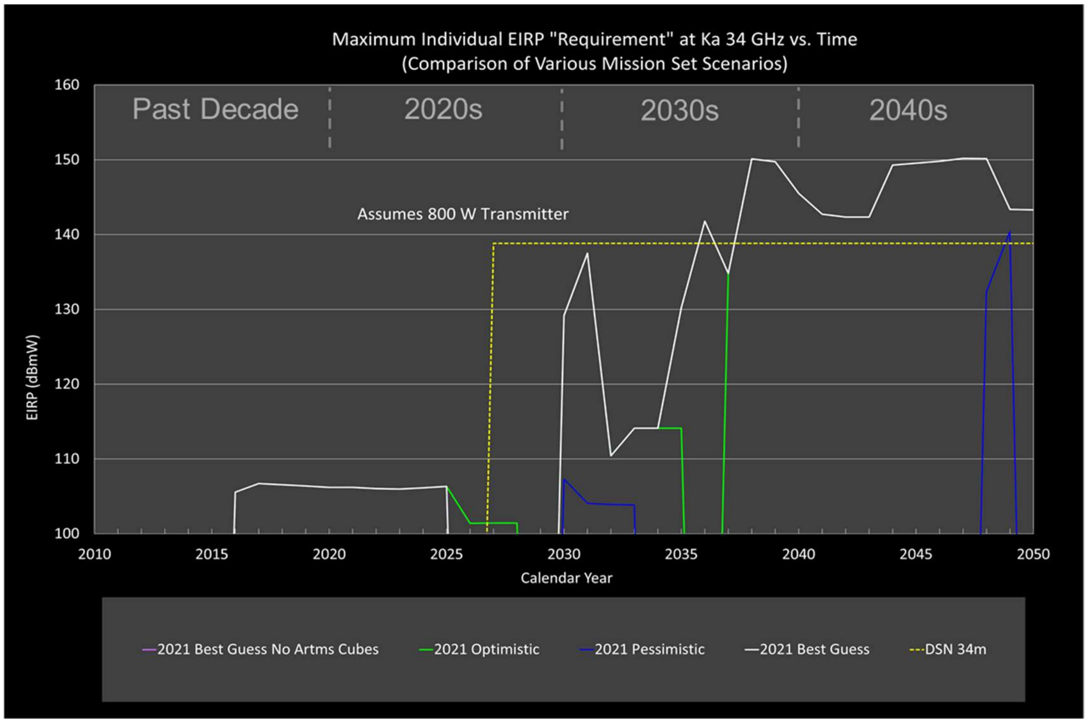

Figure 16. Projected Maximum Individual EIRP at Ka 34 GHz as a Function of Time Relative to the DSN's Current and Planned Future Capabilities[****]

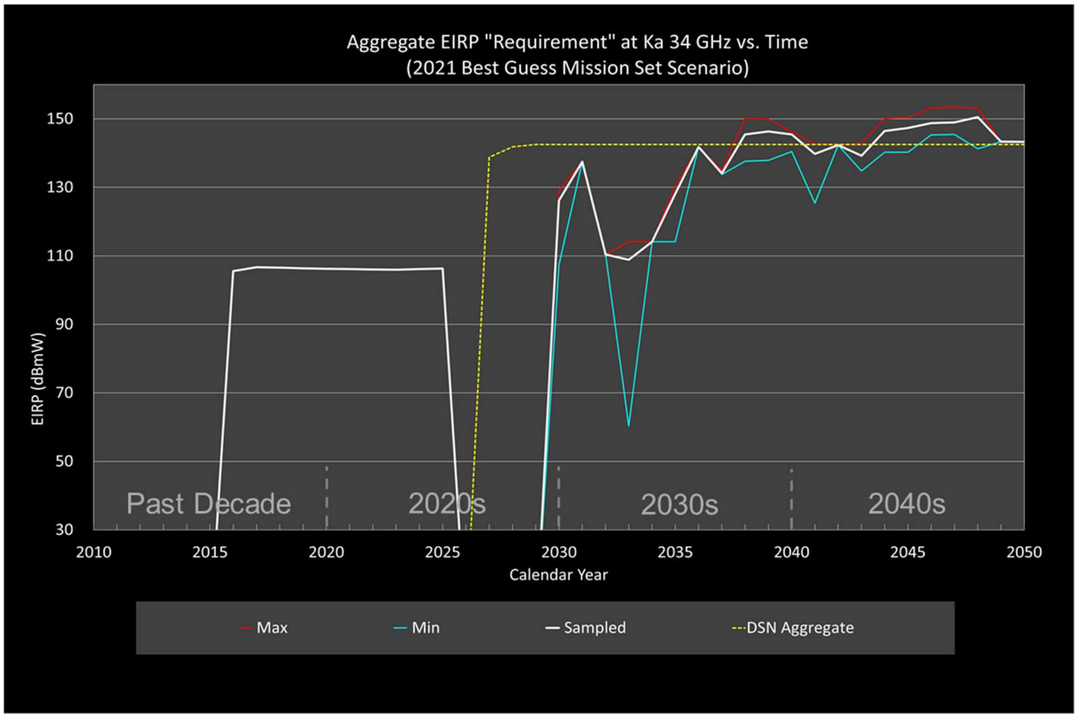

Figure 17. Projected Aggregate Simultaneous EIRP Demand at Ka-band as a Function of Time Relative to the DSN's Aggregate Capability

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[****] Note that the "2021 Best Guess No Artms Cubes" curve is identical to and, hence, sits beneath the "2021 Best Guess" curve.

At Ka-band (34 GHz), the EIRP challenge is even more pronounced. **Figure 16** above shows that, starting in 2036, human Mars exploration missions begin to drive the 34 GHz maximum individual EIRP requirement beyond the 800W transmit capability assumed for that period. Hence, a more powerful transmitter and/or uplink arraying may need to be developed to satisfy the projected uplink capability requirement. So, will there be enough antennas with 34 GHz transmitters available to array up? To try and answer this, we examine, in **Figure 17** (also above), the DSN's currently planned aggregate simultaneous EIRP capability at 34 GHz relative to projected demand. Beginning in the late 2030s, this planned aggregate capability appears to fall short – a shortage that becomes pronounced in the human Mars exploration era. These results suggest that a more optimal combination of 34 GHz transmitter power (e.g., 4 kW) and additional, arrayable antennas equipped with these transmitters may be needed to support human Mars exploration.

3.5 Loading Simulation Drivers and Results

The loading simulation combines all of the prior capacity, spectrum, and capability considerations while attempting to schedule the anticipated mission set on the DSN's antennas as a function of time. Key scheduling considerations as a function of time include each spacecraft's visibility to each of the ground stations, the number of passes within a specified time interval (such as per day or per week), the duration of each pass, the frequency bands required for both downlink and/or uplink during each pass, the required data rates and associated ground antenna G/Ts and/or EIRPs, any radiometric tracking requirements, and whether or not the spacecraft is able to participate in any sort of antenna beam-sharing (e.g., Multiple Spacecraft Per Antenna or MSPA[34]). How exactly these considerations cause each of the spacecraft to load up on the DSN's antennas is strongly influenced by each spacecraft's trajectory, the relative view periods of the more "popular" spacecraft destinations, and the frequency-band capabilities that are available on each antenna.

Trajectories drive antenna view periods, required link performance (i.e., ground station G/T and EIRP), and tracking requirements as a function of time. For each trajectory segment, missions have unique operational objectives and constraints – which, in turn, influence tracking requirements, data rates, and choice of frequency band as a function of time. For instance, the Lucy mission's exploration of Jupiter's Trojan asteroids involves two Earth flybys, a trip through the asteroid belt during which it will fly by and reconnoiter a mainbelt asteroid, a long trip from there to Jupiter's L4 Trojans, individual flyby investigations of four separate asteroids, a long transit back to Earth, a long transit out to Jupiter's L5 Trojans, and individual flyby investigations of two more asteroids.[35] End-to-end, the mission lasts about 12 years. Over that time, there are radical changes in the spacecraft's range distance from Earth, its visbility to ground stations on Earth, its radiometric tracking needs, and level of communications support (i.e., pass frequency, pass durations, data rates, redundant coverage requirements, etc.). The mission's needs during interplanetary cruise tend to be very different from those during one of its many asteroid encounters. And, it spends as much or more time in interplanetary cruise than it does at the Trojan asteroids. Many other deep space missions have similarly complex trajectories, and no two are identical.

Derived from trajectories, antenna view periods determine the allowable track time by a given station as a function of time. Typically, multiple spacecraft are in view of a DSN antenna at any given time, which can result in scheduling challenges that are normally resolved through the DSN's formal scheduling process. Such challenges can prove much more difficult when certain key locations such as the Moon, Mars, Sun-Earth Lagrange points 1 or 2, and other planetary locations, along with all the spacecraft at each location, are all in the same portion of the sky needing to communicate with the same DSN Complex. **Figure 18** illustrates that the Moon and Mars frequently occupy the same portion of the sky. With multiple spacecraft at Mars, multi-element human Missions venturing to the Moon, and only 4-5 antennas available at a given Complex, it is not hard to see how excess demand situations might arise.

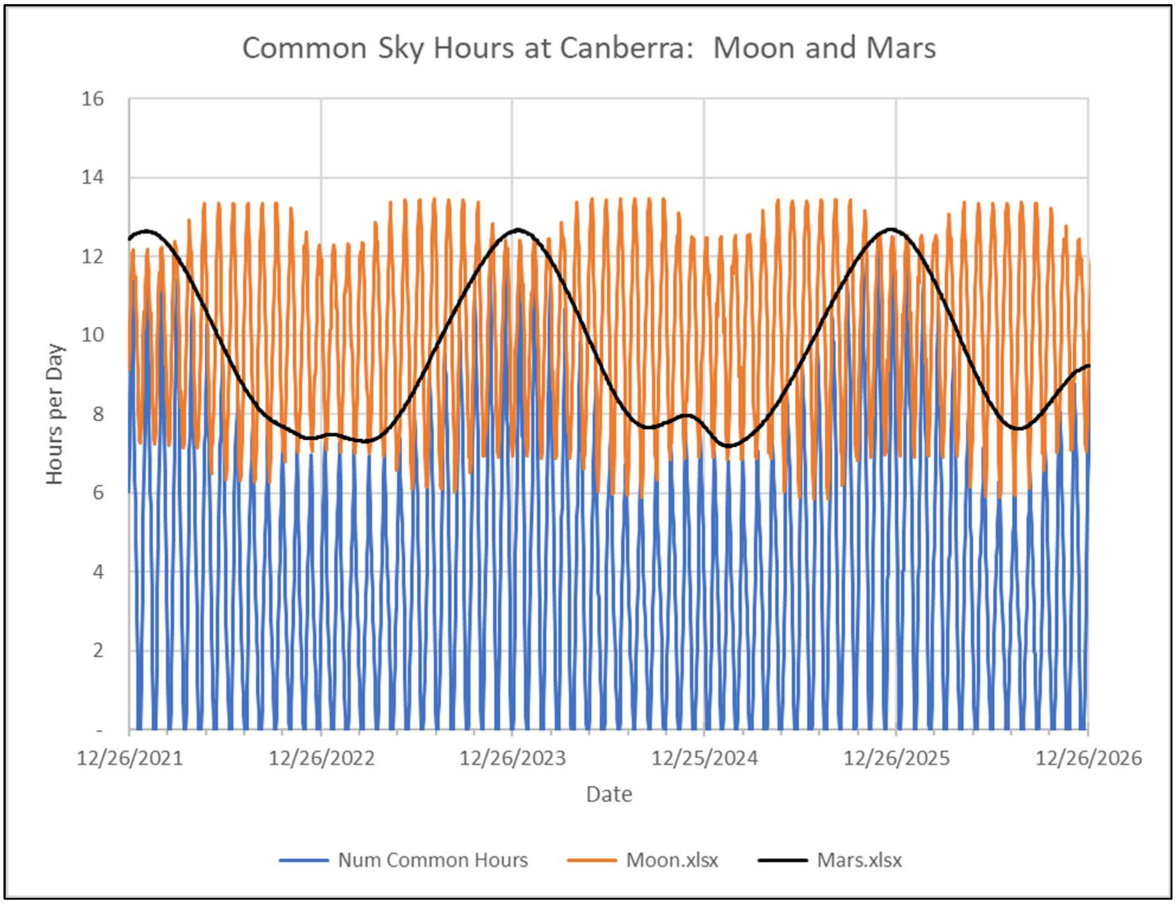

Figure 18. Hours Per Day Over a 5-Year Period that the Moon and Mars Are Both Simultaneously Visible from the Canberra Deep Space Communications Complex

Further complicating any contention over antennas at a particular Complex is the fact that not all antennas are created equal. Each antenna may be equipped with different frequency band capabilities and may have different G/T and EIRP capabilities (e.g., 70m vs. 34m). It is the G/T and EIRP capabilities at each of these bands that determine what spacecraft a particular antenna can support. So, for instance, only two of the four or five antennas per Complex will be capable of supporting 22/26 GHz when the planned K-band upgrades are completed. And, these same two antennas are the only 34m beam waveguide antennas at each Complex capable of supporting near-Earth S-band uplink and downlink. Yet, each human lunar exploration mission will likely involve an Orion crew capsule, the Gateway[††††], a Human Landing System, and some sort of pre-deployed surface element (e.g., a Lunar Terrain Vehicle, a communications tower, or a surface habitat) that will all depend on one or more of these bands. And, when one of these lunar exploration elements is engaged in a mission/safety-critical activity, a "hot" backup antenna with such bands will be required, making antenna-time contention between all of these elements a virtual certainty. At the same time, there are a number of astrophysics and heliophysics observatories dependent on one or more of these bands. So, when the Sun-Earth Lagrange points L1 or L2 are in the same sky as the Moon, these missions will simply exacerbate the contention over the S- and K-band equipped antennas. In a similar fashion, there are presently only three 34m antennas per Complex capable of both near-Earth X-band uplink and downlink. Some of these X-band antennas are the same ones with the S-band and 22/26 GHz K-band. So, if an Artemis mission to the Moon is carrying aloft secondary smallsats that operate at S- or X-band, there may not be enough antennas to simultaneously support all of the smallsats along with the Artemis mission elements. (This has already been a challenge with respect to the 8 Artemis-1 cubesats requiring X-band DSN support at the same time that Artemis-1's Orion capsule required S-band

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[††††] As described on NASA.gov, the Gateway is intended to be "a multi-purpose outpost orbiting the Moon that provides essential support for long-term human return to the lunar surface and serves as a staging point for deep space exploration."

and "hot" backup support.) When Mars is in the same sky as the Moon, the contention just gets worse, since all of the spacecraft at Mars need deep space X-band capable antennas, and two of those per Complex are also the same ones equipped with the near-Earth X-, S-, and K-band. And, all of the resulting contention is before we even begin to consider the larger set of missions across the solar system that are also in view of those antennas and need communications support.

When we run loading simulations that include all of the missions within each mission set scenario, we obtain the plot shown in **Figure 19**. Since we are looking at the percentage of the "requested" downlink hours that were actually realized in the simulation, being above the red-dashed calibration line for the historical worst case is highly desireable and being above the yellow-dashed calibration line for the historical average is even better. Notice that virtually every mission set scenario at one time or another exhibits a percentage realized that falls beneath the historical worst-case calibration line. The most pronounced dips in most of these scenarios tend to be episodic and correspond to when either the human lunar exploration missions or the human Mars missions are occurring.

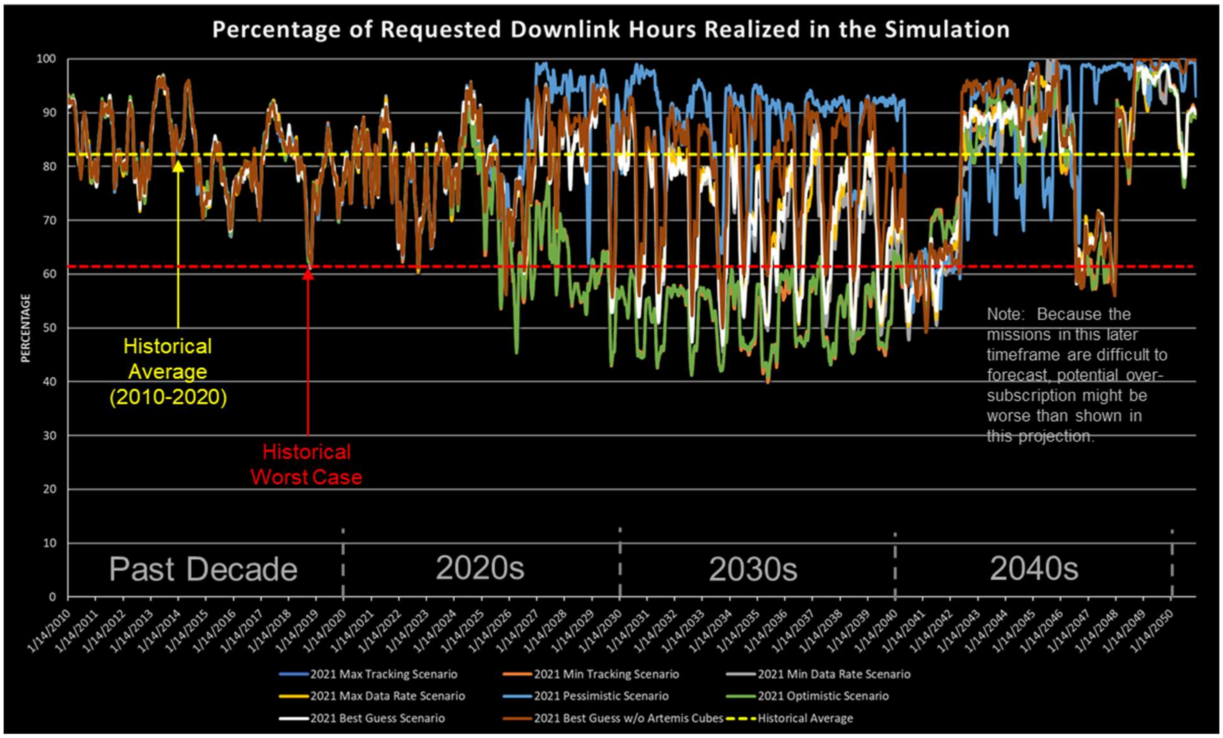

Figure 19. For All 8 Mission Set Scenarios, Percentage of "Requested" Downlink Hours Realized in the Loading Simulation as a Function of Time

Figure 20 focuses on the "2021 Best Guess" mission set scenario and looks specifically at demand and excess demand for downlink antenna hours. The demand for such hours appears as the yellow-colored regions and is quantified in terms of both antenna-hours (left-hand vertical axis) and equivalent antennas, assuming an 80% utilization factor[‡‡‡‡] (right-hand vertical axis). The blue dashed calibration line corresponds to the historical (2010-2021) average demand and can be directly compared to the yellow portion of the graph. The excess demand (demand – supply) appears as the purple-colored regions and is quantified in terms of the same axes as the demand. The orange dashed calibration line corresponds to the historical average excess demand, and the red dashed calibration line corresponds to the historical maximum excess demand. One does not have to peer at the plot too long to realize that antenna-hour demand is increasing and that it is peaking during the human lunar and human Mars exploration missions at levels well above the historical average. One can also quickly see that the corresponding excess demand peaks tend

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[‡‡‡‡] An 80% utilization factor accounts for time required for maintenance, upgrades, repairs, modernization activities and the fact that there are a small number of hours when no planetary missions happen to be in view.

to be at levels well above the historical maximum. So, while the DSN has successfully managed antenna oversubscription in the 2010-2021 timeframe, the projected excess demand spikes are at levels well above what it has seen in the past. Between the peaks, the "base level" of excess demand also increases and appears to reach the maximum historical level sometime in the 2030s.

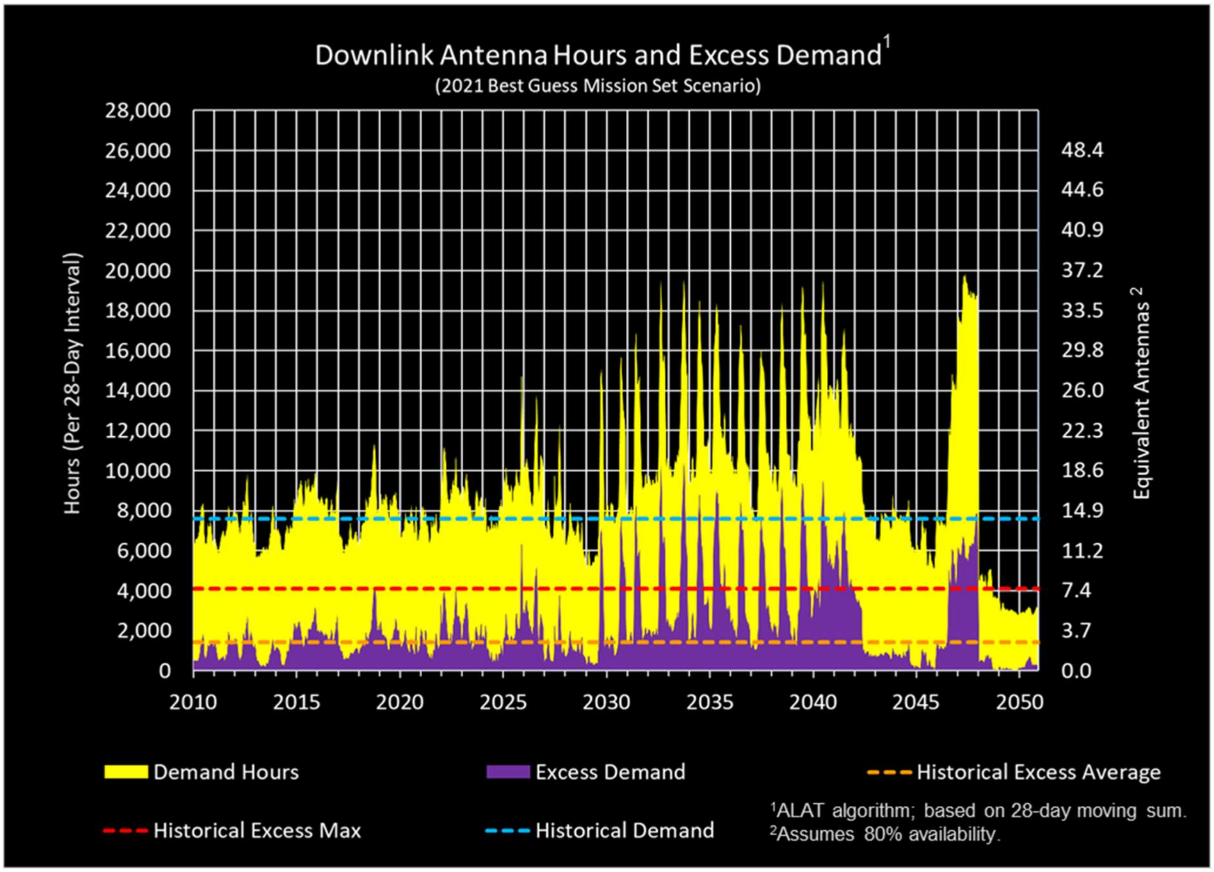


Figure 20. Downlink Antenna-Hour Demand and Excess Demand as a Function of Time for the "2021 Best Guess" Mission Set Scenario

The downlink volume implications of the excess demand for antenna hours is illustrated in **Figure 21**. The first thing to look at is the yellow region which is indicative of the downlink volume demand. Note that, in the historical timeframe, one cannot even see the requested downlink volume on the scale of this plot. This is because the ~37x increase in downlink data volume projected over the next 10 years leads to data volumes that are so much larger than what came before that the plot would need to change to a semilog plot in order to see the historical values. We elected not to change to such a plot, however, because we want to focus the reader's attention on the blue region – the volume shortfall. This shortfall occurs due to the incompleted communications passes that arise from the excess antenna-hour demand shown in **Figure 20.** When mission data rates are low, then the data volume consequences of a missed pass are also low. However, as we saw in the Capability Trends section, data rates are increasing, on average, 6-10x over the next 10 years – with human lunar exploration missions and robotic, high-fidelity-observation missions leading the way. So, when antenna contention leads to unsatisfied communications pass requirements, the lost data volumes associated with those missed passes are quite large.

Of course, one has to be careful about inferring too much from the examination of a single mission set scenario. As noted earlier, we really do not know exactly how the future will unfold, which is why we examined what we believe to be a reasonably representative envelope of different mission set scenarios. In addition to the "2021 Best Guess" scenario, we simulated the loading associated with the "2021 Max Tracking" scenario, the "2021 Best Guess w/o Artemis Cubes" scenario, and the "2021 Min Tracking" scenario. **Table 1** summarizes the antenna-hour excess demand results for each of these scenarios in terms of equivalent antennas for three timeframes: 2021-2030, 2031-2040, and 2041-2050. Peak excess demand results are expressed in terms of equivalent antennas beyond the historical maximum. And, excess demand results between the peaks ("average" excess) are expressed in terms of equivalent antennas beyond the historical average. Results are provided for both downlink and uplink.

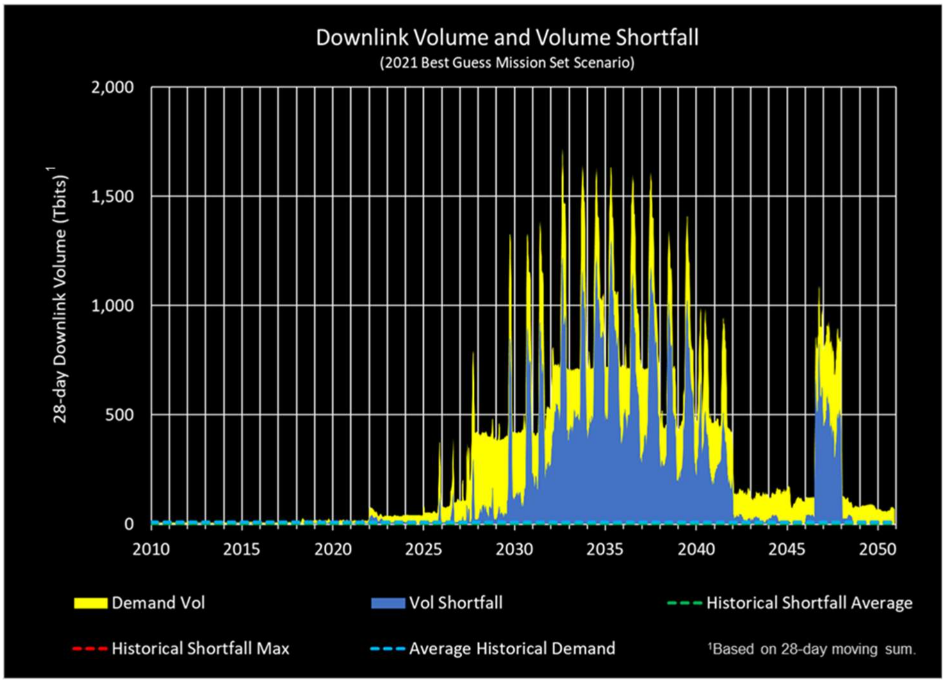
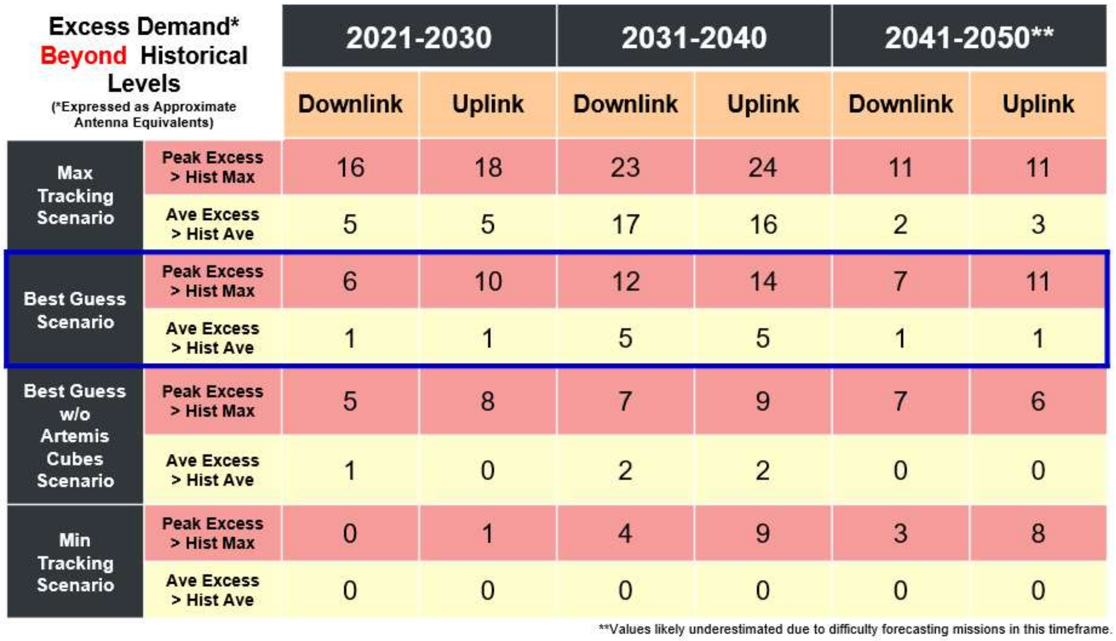


Figure 21. Downlink Volume Demand and Volume Shortfall as a Function of Time for the "2021 Best Guess" Mission Set Scenario

Table 1. Excess Demand Results from Loading Simulations Across Multiple Mission Set Scenarios, Expressed in Terms of Antenna Equivalents (Assuming 80% Availability)



Excess Demand* Beyond Historical Levels (*Expressed as Approximate Antenna Equivalents)		2021-2030		2031-2040		2041-2050**	
		Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Max Tracking Scenario	Peak Excess > Hist Max	16	18	23	24	11	11
	Ave Excess > Hist Ave	5	5	17	16	2	3
Best Guess Scenario	Peak Excess > Hist Max	6	10	12	14	7	11
	Ave Excess > Hist Ave	1	1	5	5	1	1
Best Guess w/o Artemis Cubes Scenario	Peak Excess > Hist Max	5	8	7	9	7	6
	Ave Excess > Hist Ave	1	0	2	2	0	0
Min Tracking Scenario	Peak Excess > Hist Max	0	1	4	9	3	8
	Ave Excess > Hist Ave	0	0	0	0	0	0

**Values likely underestimated due to difficulty forecasting missions in this timeframe.

Examination of **Table 1** reveals a number of important findings. First, in every scenario, the 2031-2040 timeframe entails significantly more excess demand than in the 2021-2030 scenario. And, even with the difficulties associated with forecasting missions in the 2041-2050 timeframe, the excess demand across all of the scenarios remains higher than what is projected in the 2021-2030 timeframe. Second, in all but a couple of cases, excess demand on the uplink is significantly higher than the excess demand for the downlink. In part, this probably has to do with the fact that missions within the same ground-antenna beam (such as at Mars) can be MSPA'd together on the downlink, but not on the uplink. Third, in every scenario, peak excess demand is an issue from the 2021-2030 timeframe on into the future. Fourth, excess demand between peaks is also above average in all of the scenarios except the "Min Tracking" scenario.

4. Discussion

4.1 Recommendations Targeting the 2020's

While one has to be careful about ascribing too much precision to the equivalent antenna estimates for the projected excess demand above the historical maximum, the **Table 1** numbers do suggest that, during each human exploration mission, additional antennas will be needed. NASA's Space Communications and Navigation Office has already begun pursuing the formulation of a Lunar Exploration Ground System (LEGS) to offset some of the human lunar exploration demand and relieve the DSN of a portion of the excess demand and oversubscription detailed above. LEGS will start with one new 18m-class antenna by the mid-2020s, which may ultimately be larger than 18m (e.g. 20m), followed by two more apertures and eventually targeting three additional ones some time in the future for a total of 6. The final schedule for these new antennas is still "to be determined." But, even adding an 18m-class antenna in the mid-2020s followed by two other similar antennas at other locations around the globe in subsequent years, one can see from the loading simulation numbers that additional antennas from commercial and international/university partners will still likely be needed. Even with all six LEGS antennas in place, the deficits in coverage shown in **Table 1** for the 2031-2040 timeframe significantly exceed that number in every mission set scenario – either in terms of the downlink, uplink, or both. Putting in place the mechanisms needed to acquire such support for use during each human lunar exploration mission is probably of paramount importance.

Some additional scheduling flexibility could probably be achieved by adding near-Earth S-band and 22/26 GHz K-band to more of the DSN 34m beam waveguide antennas than what is currently planned (i.e., two per Complex). As we saw earlier, the human lunar exploration missions generally entail at least one-to-two elements operating at S-band and an additional two or more elements operating at K-band. To the extent that just one or two of all these elements are engaged in a mission/safety-critical activity, "hot" backup antennas with those frequencies will also be needed -- leading to more S- and K-band antennas being required than are available at a Complex. And, that is before accounting for the needs of the rest of the spacecraft that are in the same sky as the human lunar exploration elements. So, adding more S- and K-band could at least help with the provision of the required "hot" backups and/or addressing the same-sky robotic mission demand for S- and K-band. These additional bands, however, would not be a panacea for solving all of the projected oversubscription issues. To the extent that all of the available antennas at a Complex are already saturated with demand, the additional bands would only confer more flexibility in how to meet a portion of it – since accommodating more tracks at S- and/or K-band can increase the deficit in DSN support at X- and Ka-band.

The DSN could also improve the excess demand situation by enhancing its antenna beam-sharing capabilities. Currently, the DSN has a 4-MSPA capability, meaning that up to four spacecraft that are within the beam of a single 34m or 70m antenna can schedule to simultaneously downlink through that antenna to separate receivers. On the uplink, however, each of the participating missions can only uplink to their spacecraft one at a time, with a 10-30 minute reconfiguration period between each handover – severely limiting each MSPA participant's available time for commanding and 2-way Doppler and ranging. However, exploratory efforts have been underway for some time to enable Multiple Uplinks Per Antenna (MUPA). In the MUPA concept, Forward Communications Link Transmission Units (FCLTUs) intended for different in-beam spacecraft are time-multiplexed onto a single uplink frequency. The in-beam spacecraft receive these FCLTUs and discern which transfer frames are intended for them on the basis of spacecraft ID. Once implemented, the technique would allow near-simultaneous uplink to multiple in-beam spacecraft using a single antenna, and it would allow all in-beam users to have 2-way Doppler and ranging throughout an entire MSPA pass. Given that all the spacecraft at Mars, Venus, and more distant destinations are typically within the beam of a single 34m antenna all the time at X-band and much of the time at Ka-band, one can readily see the beneficial loading implications of implementing MUPA on all of the DSN's antennas such that any MSPA session can essentially be 2-way. One can also readily see the beneficial loading implications of expanding the number of receivers available to an MSPA session from four to double or triple that number (i.e., instead of 4-MSPA, 8-MSPA or 12-MSPA). The MSPA-MUPA combination could also prove quite useful when trying to deploy multiple secondary payloads (e.g., smallsats) from a launch vehicle's upper stage such as was the case with Artemis-1 and its cubesat secondary payloads. Such payloads are typically all within the beam of a single 34m antenna for many hours, until each smallsat executes the maneuvers needed to take it on its own particular trajectory. With the MSPA-MUPA combination in place, a single antenna could simultaneously provide all of the deploying smallsats with communications and 2-way Doppler and ranging. Similarly, constellations of spacecraft designed to operate within the beam of a single 34m antenna could be very efficiently supported, without any need for a central communications "hub" with which to communicate back to Earth. And, even landed assets on the lunar surface, if concentrated in a particular region such as Shackleton crater, could be simultaneously serviced by a single 34m antenna using the MSPA-MUPA combination. Clearly, these techniques could also be applied using properly equipped non-DSN antennas, with the size of the available beam being inversely proportional to the size of the antenna. In such cases, the available beam size would have to be traded against the antenna size needed to close the communictaions link at the desired data rate.

One variation on MSPA that could also help with the projected excess demand is known as Opportunistic MSPA (OMSPA). In this technique, smallsats that are within the antenna beam of some other spacecraft's already scheduled communications link can transmit open-loop down to the same antenna. Rather than having their their transmissions come down through the antenna to individual receivers, their transmissions are captured on a pre-scheduled open-loop recorder. The recordings for each participating smallsat are then demodulated and decoded in software, and the recovered transfer frames forwarded on to the smallsat's Mission Operations Center (MOC). While it can take up to 24 hours for each participating smallsat's MOC to receive its downlink data, the associated mission can do so at little to no ascribed cost, since it is making opportunitistic use of someone else's already scheduled antenna. In so doing, it also avoids having to compete for antenna-time – the antenna is already scheduled; the OMSPA participants just have to schedule the open-loop recorders associated with the antenna. As long as all of the participants abide by NASA's formal spectrum allocation process, there is no danger of interference between themselves or with the scheduled antenna user. And, in theory under these conditions, there is virtually no limit to the number of in-beam users that can make opportunistic use of the antenna. In practice, there are limitations imposed by the channel bandwidth of each open-loop recorder, the number of channels that the recorder can accommodate, and the speed with which the demodulation and decoding software can recover data from each channel's recording. At the time of this paper's writing, the DSN has just about completed the implementation and acceptance testing of its OMSPA service. While by its very nature it is only a downlink service, it has the potential to off-load a lot of the routine telemetery and science downlink from relatively low data rate spacecraft (e.g., <200 kbps cubesats and smallsats that happen to be located on the sky within a single DSN antenna beam) – with up to 16 in-beam spacecraft able to simultaneously downlink. Hence, the more such missions are encouraged to design for the use of OMSPA in the future, the more it can help reduce the network's projected excess demand levels.

To the extent that excess demand between the demand spikes typically associated with the human lunar missions continues to rise, it makes sense to add one additional 34m beam waveguide antenna to each of the DSN's three Complexes. Such demand is likely more associated with missions at interplanetary distances and, hence, not amenable to being addressed by smaller diameter antennas (such as LEGS) that are planned to improve lunar mission coverage. This recommendation of one additional DSN antenna per Complex assumes timely completion of at least 6 LEGS apertures as well as timely completion of both a Lunar Communications Relay Satellite constellation (and associated Earth ground antennas needed to support it). It also assumes a Mars Communications Relay constellation in time for the anticipated increase in Mars exploration activity, both robotic and human. With the eventual transition from human lunar exploration to human Mars exploration, such additional antennas would then be available to help bolster the number per Complex available for arraying – since such arraying will likely be vital to achieving the data rates necessary for communicating with astronauts at Mars.

4.2 Recommendations Targeting the 2030's

As NASA's human exploration efforts begin to shift to Mars, certain fundamental physical realities begin to weigh heavily on network requirements. One of these is the change in range distance to Earth. The difficulty associated with closing a communications link is inversely proportional to the square of the range distance. So, closing a communications link from Mars is vastly more difficult than closing a communications link from the Moon. When Mars is at its maximum distance from Earth, even a single 70m X-band or 34m Ka-band antenna is insufficient for supporting the tens-to-hundreds of Mbps data rates being discussed for human communications at the Moon. Currently, the only way to support such rates is to array up the available, in-view antennas. But, if an array of three-to-four 34m Ka-band beam waveguide antennas is required to achieve the desired downlink rate when Mars is approaching its maximum distance from the Earth, that only leaves one-to-two antennas at a Complex to handle all the rest of the missions visible in the same sky. This antenna shortage is what drives the excess demand spikes in the human Mars exploration era. Adding one additional Ka-band capable 34m antenna per Complex, in addition to those recommended in the preceding section for the 2020s, would likely help alleviate much of the excess demand during human Mars missions. Such missions and their associated excess demand spikes last much longer than the human lunar missions for the very same reason that the links are more difficult: the distances involved. Human Mars missions are on the order of years, not weeks or even months. Even when the stay on the Martian surface is kept to at most a month, substantial additional time is spent in Mars orbit awaiting the proper alignment of Mars with respect to the Earth in order to facilitate an expeditious transit home. So, the required timeframe for in-view antenna arraying can be quite lengthy, depending upon where Mars is with respect to the Earth.

Another physical reality associated with the shift to Mars pertains to the allowable frequency bands. At distances of more than 2 million km from Earth, near-Earth X-band transitions to deep space X-band and K-band (22/26 GHz) transitions to Ka-band (34/32 GHz). While most of the DSN's antennas are already equipped with, or planned to be equipped with, a 32 GHz downlink capability, only one antenna is currently equipped with a 34 GHz uplink capability – and, as was noted in the earlier EIRP discussion, its transmit power (< 800 W) is insufficient for human Mars uplink rates. This lack of human Mars era uplink capability also contributes to the excess demand situation in that timeframe. Hence, either additional, more powerful 34 GHz transmitters are needed, or many additional 800 W 34 GHz transmitters are needed that can be arrayed up to provide the requisite EIRP. Or, some combination of more powerful 34 GHz transmitters and arraying are needed. Also note that uplink arraying, particularly at 34 GHz, is not an operational capability within the DSN – significant development needs to occur in order to make it so.

For both the Moon and Mars, communications relay satellites in stable orbits around these bodies offer the best hope of significantly reducing the projected excess demand in this timeframe without having to add large numbers of additional antennas back on Earth. To do so, there have to be enough relays to cover all the areas of interest on and above these bodies. And, to keep each relay from needing its own ground station, all of the relays will need to have crosslinks with one another so that the data collected by them can all be funneled to the one relay most in view of the Earth. This relay, in turn, can then serve as the "trunk link" back to a single, in-view ground station – or, in the case of Mars, a single in-view antenna array. At Mars, where two in-view relay satellites might be used in conjunction with a crosslink between them to "load share" the total data being sent back, MSPA could also be used to enable the same in-view ground station, or ground station array, to service both relays simultaneously.[36] In so doing, each relay could contribute toward the total data downlink requirement using only half the data rate that would otherwise be required for a single relay – thereby allowing each relay to be equipped with a smaller onboard telecom system. To make such relay systems a reality in the 2030s, work needs to begin now to: architect them, develop the needed crosslink routing and pointing control technology, and emplace the Delay Tolerant Networking (DTN) capabilities needed for efficient and reliable data flow.

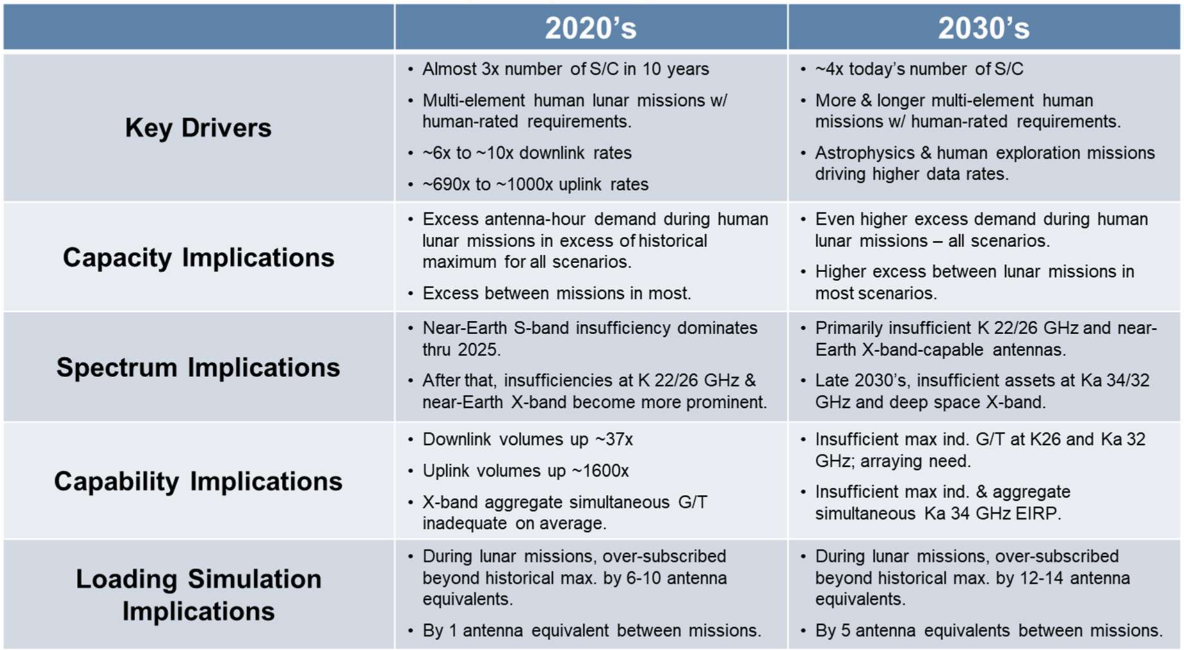
As alluded to in the Capability Trends section, RF bandwidth constraints begin to limit data rate aspirations in the 2030's. For instance, a single 250 Mbps downlink from Mars, supported by QPSK and a rate ½ code, would use up the entire 500 MHz of Ka-band (32 GHz) spectrum allocation. While one could envision transitioning to more bandwidth efficient modulation schemes, those schemes require significantly more power and hence are not well-suited to the long distances typical of deep space missions; optical communications offers a solution virtually free of any spectrum bandwidth constraints. Optical communications also offers an additional potential avenue for excess demand reduction – both in point-to-point communications and in "trunk link" relay operations. Because optical communication systems can generally achieve higher data rates with less required onboard mass and power than their RF counterparts, when not subject to copious quantities of stray light, they offer the promise of greater data return and/or reduced ground station contact times compared to their RF counterparts. These expectations, however, have to be tempered by the fact that RF downlink may also need to occur for mission/safety-critical data due to the potential for weather-related outages. Optical outages around solar conjunctions are also a potential issue, likely necessitating some degree of RF reliance during such periods. And, further complicating the optical picture, the lack of a power-efficient method for optically uplinking at high rates from the Earth's surface to a destination like Mars necessitates a continued reliance on RF uplink. This is because photons downlinking to Earth from Mars do not scatter much in the Earth's atmosphere relative to the distance that they have already traversed; but, photons coming up through the Earth's atmosphere with that same amount of scatter can, in the course of traversing to Mars, end up way off course. Hence, the power needed to optically uplink from the Earth's surface to Mars at tens of Mbps is enormous. So, unless a ground-station-sized optical relay system is emplaced in Earth orbit to bypass the atmospheric scattering issues, or the scattering can in some other way be compensated for, RF uplink to Mars will likely remain a necessity. Clearly, these architectural issues, their associated cost trades, and any remedial developments need to be worked now, so that the tremendous potential of optical communications can be realized in the 2030s and beyond.

Ultimately, keeping antenna-hour supply and demand in sync will likely involve transitioning from pre-scheduled network operations to demand-access operations.[37] In this paradigm shift, spacecraft would be built to operate much more autonomously – with spacecraft "phoning home" only when they determine a need to do so. In "phoning home," they would first signal the desire to do so and the relative urgency with which the request was being made. This signaling might be accomplished via beacon tones that could be detected on the ground with a minimum of RF equipment. Once the ground received this "phone home" request, the network's scheduling system would then schedule, in a timeframe consistent with the urgency of the request, an appropriate ground asset to establish a communications link. At the scheduled time, the ground asset would then point to the spacecraft and command it to downlink whatever data the spacecraft had signaled the need to send. The spacecraft would then send the data in response, completing the scheduled "call." Coupled with on-board navigation, onboard data processing, and on-board decision making, this approach would enable spacecraft to swiftly respond to their circumstances while minimizing the amount of required ground antenna-time. Aside from the spacecraft autonomy challenges associated with this whole paradigm, there is also the challenge of how best to continuously "listen" for "phone home" requests. Even with beacon tones, spacecraft at interplanetary distances will likely need a fairly large diameter antenna that will have to be correctly pointed to pick up the signal. How would one continuously scan the sky with such antennas? How many might be needed? A potential starting point might be to first attempt autonomous spacecraft operations at a location that is always within the beamwidth of a single 34m antenna, such as Mars. OMSPA could then be modified to always be "listening" in the background for "phone home" signals by making opportunistic use of antennas already pointed at Mars for scheduled communications links. Conceivably this could be done at other in-beam locations as well, allowing the gradual demonstration of, and transition to, demand access. As with the other 2030s recommendations, having an operational capability in the desired timeframe means starting now.

5. Conclusion

Table 2 summarizes the key communications-related future mission trends and implications emerging from the analysis of the "2021 Best Guess" mission set scenario. While it is one of eight mission set scenarios analyzed, analysis of the others suggest that it is reasonably representative – i.e., its results tend to fall within the "envelope" of those emerging from the others. And, it is the one that was developed to be most reflective of NASA's current plans for the future. Whether these plans will endure and ultimately be realized over the next couple of decades is something we cannot know for certain. However, there are a number of factors in play that may foster the political support, affordability, and technical/programmatic robustness needed to ensure their continued pursuit. These factors include: bipartisan Government support for space exploration; intensified nation-state competition in space; increasing NASA reliance on small spacecraft to enable more frequent, lower-cost missions; more commercial launch capacity at lower cost; a resurgence of Government efforts in nuclear power and propulsion that are key to sustained deep space activity; and, a burgeoning commercial space sector. Given these factors, today's plans for the future would seem to have a reasonable likelihood of continuing to be pursued in one form or another in the decades to come. Hence, it behooves us to think seriously about how best to address the Table 2 trends and their implications.

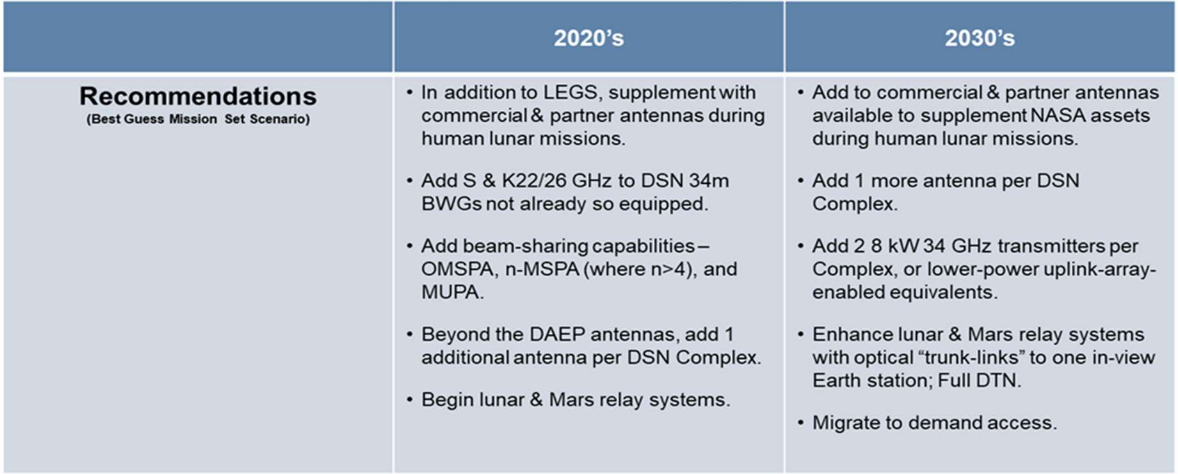
Table 2. Summary of Key Findings for the 2020's and 2030's.



	2020's	2030's
Key Drivers	• Almost 3x number of S/C in 10 years • Multi-element human lunar missions w/ human-rated requirements. • ~6x to ~10x downlink rates • ~690x to ~1000x uplink rates	• ~4x today's number of S/C • More & longer multi-element human missions w/ human-rated requirements. • Astrophysics & human exploration missions driving higher data rates.
Capacity Implications	• Excess antenna-hour demand during human lunar missions in excess of historical maximum for all scenarios. • Excess between missions in most.	• Even higher excess demand during human lunar missions – all scenarios. • Higher excess between lunar missions in most scenarios.
Spectrum Implications	• Near-Earth S-band insufficiency dominates thru 2025. • After that, insufficiencies at K 22/26 GHz & near-Earth X-band become more prominent.	• Primarily insufficient K 22/26 GHz and near-Earth X-band-capable antennas. • Late 2030's, insufficient assets at Ka 34/32 GHz and deep space X-band.
Capability Implications	• Downlink volumes up ~37x • Uplink volumes up ~1600x • X-band aggregate simultaneous G/T inadequate on average.	• Insufficient max ind. G/T at K26 and Ka 32 GHz; arraying need. • Insufficient max ind. & aggregate simultaneous Ka 34 GHz EIRP.
Loading Simulation Implications	• During lunar missions, over-subscribed beyond historical max. by 6-10 antenna equivalents. • By 1 antenna equivalent between missions.	• During lunar missions, over-subscribed beyond historical max. by 12-14 antenna equivalents. • By 5 antenna equivalents between missions.

Table 3 summarizes the key recommendations emerging from the discussion of these future mission trends and their implications. While each recommendation is either targeted for completion in the 2020's or 2030's, work on each, if not already in progress, needs to begin as soon as possible in order to be ready. With this in mind, NASA's Space Communications and Navigation Office is currently funding several on-going studies regarding various aspects of the recommendations and the underlying challenges motivating them. The results of these studies should help advance the deep space communications architecture and underlying systems needed to enable the increasingly ambitious human and robotic science and exploration in the decades to come.

Table 3. Summary of Key Recommendations Targeting the 2020's and 2030's.



	2020's	2030's
Recommendations (Best Guess Mission Set Scenario)	• In addition to LEGS, supplement with commercial & partner antennas during human lunar missions. • Add S & K22/26 GHz to DSN 34m BWGs not already so equipped. • Add beam-sharing capabilities – OMSPA, n-MSPA (where n>4), and MUPA. • Beyond the DAEP antennas, add 1 additional antenna per DSN Complex. • Begin lunar & Mars relay systems.	• Add to commercial & partner antennas available to supplement NASA assets during human lunar missions. • Add 1 more antenna per DSN Complex. • Add 2 8 kW 34 GHz transmitters per Complex, or lower-power uplink-array-enabled equivalents. • Enhance lunar & Mars relay systems with optical "trunk-links" to one in-view Earth station; Full DTN. • Migrate to demand access.

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[1] National Aeronautics and Space Administration, NASA FY 2023 Budget Request Summary, URL: https://www.nasa.gov/sites/default/files/atoms/files/fy23_nasa_budget_request_summary.pdf [cited September 1, 2022].

[2] Abraham, Douglas S., Bruce E. MacNeal, and David P. Heckman, "Enabling Affordable Communications for the Burgeoning Deep Space Cubesat Fleet," SpaceOps 2016 Conference, Session: SSCSO - SmallSat Communications - Standards & Technologies, Daejeon, Korea, May 2016, URL: https://doi.org/10.2514/6.2016-2625 [cited 26 August 2022].

[3] National Aeronautics and Space Administration, *Explore: NASA Small Spacecraft Strategic Plan,* URL: https://www.nasa.gov/sites/default/files/atoms/files/smallsatstrategicplan.pdf [cited 26 August 2022].

[4] Science Mission Directorate, National Aeronautics and Space Administration, "Science Mission Directorate Policy: Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Secondary Payloads Rideshare," SMD Policy Document SPD-32, December 1, 2020, URL: https://www.nasa.gov/sites/default/files/atoms/files/47151_smd_rideshare_policy_spd-2_rev_2_dec_2020_final.pdf [cited 26 August 2022].

[5] Marshall Space Flight Center, National Aeronautics and Space Administration, "CubeSats on NASA's Space Launch System," NP-2020-05-25-MSFC, URL: https://www.nasa.gov/sites/default/files/atoms/files/0364_secondary_payloads_brochure_07282020_508_single_pages_for_web.pdf [cited 26 August 2022].

[6] Reddy, Vidya Sagar, "The SpaceX Effect," *New Space,* June 2018, pp. 125-134.
URL: http://doi.org/10.1089/space.2017.0032 [cited 1 September 2022].

[7] SpaceX, *Starship Users Guide*, Revision 1.0, March 2020,
URL: https://www.spacex.com/media/starship_users_guide_v1.pdf [cited 2 September 2022].

[8] Launius, Roger D., "Historical Dimensions of the Space Age," *Space Politics and Policy: An Evolutionary Perspective*, edited by Eligar Sadeh, Kluwer Academic Publishers, The Netherlands, 2002 [cited 9 September 2022].

[9] *Ibid*.

[10] "Are We Losing the Space Race to China?", Hearing Before the Subcommittee on Space, Committee on Science, Space, and Technology, House of Representatives, One Hundred Fourteenth Congress, Second Session, 27 September 2016, Serial No. 114-95, U.S. Government Publishing Office, Washington D.C., 2017, URL: https://www.govinfo.gov/content/pkg/CHRG-114hhrg22564/html/CHRG-114hhrg22564.htm [cited 9 September 2022].

[11] National Aeronautics and Space Administration, *The Artemis Accords*: *Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes,"*13 October 2020, URL: https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf [cited 9 September 2022].

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[12] Muralidhuran, Rathna K., "The Nuclear Reactor Renaissance: Space Exploration and National Security," *RealClear Energy*, 13 July 2018, URL: https://www.realclearenergy.org/articles/2018/07/13/the_nuclear_reactor_renaissance_space_exploration_and_national_security_110313.html [cited 9 September 2022].

[13] National Aeronautics and Space Administration, "NASA Announces Artemis Concept Awards for Nuclear Power on Moon," Release 22-062, 21 June 2022, URL: https://www.nasa.gov/press-release/nasa-announces-artemis-concept-awards-for-nuclear-power-on-moon [cited 9 September 2022].

[14] National Aeronautics and Space Administration, "NASA Announces Nuclear Thermal Propulsion Reactor Concept Awards," Release 21-091, 13 July 2021, URL: https://www.nasa.gov/press-release/nasa-announces-nuclear-thermal-propulsion-reactor-concept-awards [cited 9 September 2022].

[15] National Aeronautics and Space Administration, "Commercial Lunar Payload Services Overview," URL: https://www.nasa.gov/content/commercial-lunar-payload-services-overview [cited 13 September 2022].

[16] Foust, Jeff, "NASA selects six companies to generate commercial successors to TDRS," *SpaceNews*, 21 April 2022, URL: https://spacenews.com/nasa-selects-six-companies-to-demonstrate-commercial-successors-to-tdrs/ [cited 12 September 2022].

[17] Foust, Jeff, "ESA to be anchor customer on commercial lunar satellite," *Space News*, 16 September 2021, URL: https://spacenews.com/esa-to-be-anchor-customer-on-commercial-lunar-satellite/ [cited 14 September 2022].

[18] Foust, Jeff, "ESA and NASA to cooperate on Earth science and lunar mission," *Space News*, 15 June 2022, URL: https://spacenews.com/esa-and-nasa-to-cooperate-on-earth-science-and-lunar-mission/ [cited 14 September 2022].

[19] SpaceX, *Starship Users Guide*, Revision 1.0, March 2020, URL: https://www.spacex.com/media/starship_users_guide_v1.pdf [cited 15 September 2022].

[20] Foust, Jeff, "Orbit Fab announces in-space hydrazine refueling service," *Space News*, 30 August 2022, URL: https://spacenews.com/orbit-fab-announces-in-space-hydrazine-refueling-service/ [cited 15 September 2022].

[21] Erwin, Sandra, "Orbit Fab to launch propellant tanker to fuel satellites in geostationary orbit," *Space News*, 24 September 2021, URL: https://spacenews.com/orbit-fab-to-launch-propellant-tanker-to-fuel-satellites-in-geostationary-orbit/ [cited 15 September 2022].

[22] Erwin, Sandra, "Orbit Fab secures deal to refuel Astroscale's satellite-servicing robots," *Space News*, 11 January 2022, URL: https://spacenews.com/orbit-fab-secures-deal-to-refuel-astroscales-in-space-servicing-robots/ [cited 23 September 2022].

[23] 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 23 September 2022].

[24] 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 23 September 2022].

[25] 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 23 September 2022].

[26] 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 23 September 2022].

[27] Abraham, Douglas S., Bruce E. MacNeal, David P. Heckman, Yijiang Chen, Janet P. Wu, Kristy Tran, Andrew Kwok, and Carlyn-Ann Lee, "Recommendations Emerging from an Analysis of NASA's Deep Space Communications Capacity," SpaceOps 2018 Conference, CAN – Ground Communications, Marseille, France, 28 May-1 June 2018, URL: https://arc.aiaa.org/doi/10.2514/6.2018-2528 [cited 7 October 2022].

[28] Lichten, Stephen M., Douglas S. Abraham, Belinda Arroyo, Sami W. Asmar, Julia L. Bell, and Charles D. Edwards, "Allocation of Deep Space Network Ground System Tracking and Communications Assets During the 2020-2021 Timeframe of the 'Mars Armada'," SpaceOps 2018 Conference, CAN - Communications, Ground and Space Networking V, Marseille, France, 28 May – 1 June 2018, URL: https://doi.org/10.2514/6.2018-2502 [cited 22 October 2022].

[29] Report of the Interagency Operations Advisory Group, Lunar Communications Architecture Working Group, *The Future Lunar Communications Architecture*, Final Version V1.3, 31 January 2022, pp. 25-26, URL: https://www.ioag.org/Public%20Documents/Lunar%20communications%20architecture%20study%20report%20FINAL%20v1.3.pdf [cited 22 October 2022].

[30] Cesarone, R., D. Abraham, S. Shambayati, and J. Rush, "Deep-Space Optical Communications Visions, Trends, and Prospects," 2011 International Conference on Space Optical Systems and Applications, IEEE, 2011, URL: https://ieeexplore.ieee.org [cited 24 October 2022].

[31] Abraham, Douglas S., Bruce E. MacNeal, David P. Heckman, et al., "Recommendations Emerging from an Analysis of NASA's Deep Space Communications Capacity," [cited previously].

[32] *Ibid.*

[33] Wyatt, Jay, Scott Burleigh, Ross Jones, Leigh Torgerson, and Steve Wissler, "Disruption Tolerant Networking Flight Validation Experiment on NASA's EPOXI Mission," 2009 First International Conference on Advances in Satellite and Space Communications, IEEE, 20-25 July 2009, DOI: 10.1109/SPACOMM.2009.39, URL: https://ieeexplore.ieee.org/document/5194608 [cited 22 December 2022].

[34] Abraham, Douglas S., Bruce E. MacNeal, and David P. Heckman, "Enabling Affordable Communications for the Burgeoning Deep Space Cubesat Fleet," [cited previously].

[35] Davis, Joel, "Exploring Jupiter's Trojan Asteroids," *Astronomy*, from the June 2018 issue, published online 12 September 2018, URL: https://astronomy.com/magazine/news/2018/09/exploring-jupiters-trojan-asteroids [cited 28 October 2022].

[36] Abraham, Douglas S., Bruce E. MacNeal, David P. Heckman, et al, "Recommendations Emerging from an Analysis of NASA's Deep Space Communications Capacity," [cited previously].

[37] Davarian, Faramaz, Douglas Abraham, John Baker, Jay Gao, Norman Lay, Jeffrey Stuart, and Matt Angert, "Improving Small Satellite Communications and Tracking in Deep Space – A Review of the Existing Systems and Technologies With Recommendations for Improvement. Part III: The Deep Space Network," *IEEE Aerospace and Electronic Systems Magazine*, August 2020, ISSN 0885-8985, Volume 35, No. 8, URL: https://www.nxtbook.com/nxtbooks/ieee/aerospace_august2020/index.php?startid=11#/p/4 [cited 7 November 2022].