High Data Rates from the Outer Solar System

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Abstract— **Outer planet missions play an important role in JPL and NASA's space exploration objectives in the coming decades. This paper assesses the technical options available for ensuring that the Deep Space Network (DSN) can enable future missions to the outer Solar System and recommend investment options for flight and ground communication systems and technologies that would meet the future data return requirements. The major takeaways are summarized as follow: a) Given the current and near-term state of technology development there are major challenges in operating optical links at outer planet distances (e.g., Sun-Earth angle effects, spacecraft power available for the laser, optical ground network development plans, etc.). b) Due to the spacecraft limitations at outer planet distances, e.g., antenna pointing and solar/Radioisotope Thermoelectric Generator (RTG) power, the 'biggest bang for the buck' on enhancing data return is by improving the capabilities of the DSN at Ka-band. c) Concurrently with enhancing DSN capabilities at Ka-band, NASA should encourage the use of Ka-band in missions by actively incentivizing the use of Ka-band on high-rate science downlinks using technologies already available today, while retaining X-band capability for low-rate telemetry, commanding, and emergency support.**

To improve DSN capabilities at Ka-band, we consider two alternative approaches: 1) operation use of 34-m Beam Waveguide (BWG) arrays, and 2) upgrading the 70-m antennas. For each option, we quantify the expected performance and compare it against known upcoming users. We describe past DSN development and flight demonstrations, summarize the technological advances conducted to-date, and identify additional engineering work required to operationalize the system. We recommend the following: a) For arraying of 34-m BWG at Ka-band, additional demonstration activities are needed to better characterize the system performance under different conditions, including operations in adverse weather conditions or close to a hot body source. b) For upgrading the 70-m antennas, new holography measurements (and panel setting) should be conducted, and operational versions of previously prototyped gravity compensation systems like array feeds and deformable flat plates should be developed and installed.

Using these approaches, we expect the DSN downlink performance at Ka-band to improve by 4-6 dB compared to X-band, providing an increase in downlink data rate of 2.5x to 4x.

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1. INTRODUCTION

The 2022 "Origin, Worlds, and Life" Decadal Survey Report outlines a prioritized strategy for space science missions related to the overview of planetary science, astrobiology, and planetary defense. Of the recommended destinations, 75% are in the outer Solar system (at Jupiter or beyond). There have been several missions to the outer planets, primarily conducted by NASA and European Space Agency (ESA). For examples, Voyager 1 and 2 launched in 1977 [1], Galileo in 1995 [2], Cassini-Huygens in 1997 [3], New Horizon in 2006 [4], JUNO in 2011 [5], and the more recent JUICE in April 2023 [6].

Further, in the near-term, there are planned missions to explore the outer planets. Examples are:

1. Europa Clipper [7] – this mission aims to study Jupiter's moon Europa, which is thought to have a subsurface ocean beneath its icy crust. The Europa Clipper spacecraft will conduct multiple flybys of Europa, investigating its potential habitability and searching for signs of life.

2. Titan Dragonfly [8] – Dragonfly is a planned mission to Saturn's largest moon, Titan. It will carry a rotorcraft lander that will explore various locations on Titan's surface, studying its chemistry and potential for habitability.

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In preparation for the Origins, Worlds, and Life Decadal Survey [9], the Ice Giants Pre-Decadal Survey [10] and the Neptune Odyssey Study [11] were conducted. And for the on-going Solar & Space Physics Decadal Survey, the Interstellar Probe Study [12][13] was carried out. These mission concept studies introduced several high-value flagship-class mission concepts to Uranus, Neptune, and beyond were introduced. These concepts are within reasonable budget constraints and without significant technology challenges. Representative examples are:

1. Uranus flyby or Orbiter, with Probe Option [10] – the Ice Giants Pre-Decadal Survey Report introduces several mission concepts to visit Uranus. The primary scientific objectives include atmospheric composition and dynamics, internal structure and magnetic fields, moons, and rings, magnetospheric environment, and comparative planetology. Later when the Origins, Worlds, and Life Decadal Survey was published in 2022 [10], it recommended the flagship mission to Uranus with an atmospheric probe as the highest priority, and the Enceladus Orbitlander mission as the second highest priority.
2. Neptune Odyssey [11] – the mission concept includes an orbiter and atmospheric probe to the Neptune-Triton system to study Neptune, its rings, small satellites, space environment, and its unique planet-sized moon, Triton.
3. Interstellar Probe [12] [13] – this proposed mission aims to send a spacecraft into deep space that aims to explore and travel beyond the solar system into the interstellar space. The primary objectives are to study the space environment, interstellar medium, and potentially encounter other star systems.
4. Enceladus Orbilander [14] – the Origins, Worlds, and Life Decadal Survey [10] recommends Euceladus Orbilander to be the second highest priority new flagship missions for the decade 2023 – 2032. Enceladus is a Saturn moon believed to house an ocean world beneath its thick icy crust that can harbor life. A mission to Enceladus can answer the fundamental question on whether there is life beyond Earth or not.

Outer planet missions play an important role in JPL and NASA's space exploration objectives in the coming decades. This paper assesses the technical options available for ensuring that the DSN can enable future missions to the outer Solar System and recommend investment options for flight and ground communication systems and technologies that would meet the future data return requirements.

In this paper, we assess the prior, planned, and proposed mission concepts in [1-14] and assume a reference flight communications system design for operations in the outer planets over the next 50 years. We identify a number of major technical challenges and uncertainties that constrain the improvement on the flight side of the communication links. We then discuss a couple of "low-hanging-fruit" in Deep Space Network (DSN) and ground improvements that would meet the data return requirements of the upcoming planned and proposed outer planet missions. This includes:

1. Arraying of 34m Beam Waveguide (BWG) Antennas in Ka-band.
2. Adding Ka-band on 70m Antenna.

The rest of the paper is organized as follows: Section 2 summarizes the mission challenges and technology challenges on communications with spacecraft from outer planets. Section 3 surveys the mission data return requirements and current flight/ground capabilities. Section 4 describes the link geometry to outer planets (and Pluto). Section 5 discusses the proposed DSN upgrades to meet outer planet mission needs. Section 6 provides the concluding remarks.

2. Mission and Technical Challenges

Outer planets of our solar system include Jupiter, Saturn, Uranus, and Neptune. In this paper, we also consider Pluto, Kuiper Belt, and beyond. Missions to outer planets and beyond present a unique set of challenges that include:

1. Long mission duration – outer planets such as Jupiter, Saturn, Uranus, and Neptune are located much farther from Earth compared to inner planets like Mars, Mercury, and Venus. The long travel times plus science operations can range from several years to a few decades, depending on the mission and the alignment of the planets. Spacecraft components and subsystems have to survive during the long travel time in the harsh space environment. High reliability components and cross-strapped redundancy are employed in the spacecraft system and subsystem designs.
2. Communication delays – due to the vast distances, the time it takes for signals to travel between Earth and the outer planets are substantial. Communication delays can range from tens of minutes to hours, which complicates real-time control, feedback, and decision-making during missions, especially during spacecraft dynamic and off-nominal situations. Spacecraft designers and mission planners must account for these delays and develop autonomous system to handle unexpected situations.
3. Harsh environment – outer planet missions encounter intense radiation belts around giant planets, particularly Jupiter and Saturn. The radiation can damage spacecraft electronics, affect data transmission, and pose risks to onboard instruments and systems. Shielding and radiation-hardened designs are needed to protect sensitive equipment. Also, outer planets and their moons experience extreme cold temperature. Spacecraft and instruments must be designed to withstand and operate in the harsh temperature environment.

4. Resource limitations – solar power becomes less effective as spacecraft venture farther from the Sun. Outer planet missions often rely on alternative power sources such as radioisotope thermoelectric generators. Spacecraft have to carry enough non-replenishable resources such as fuels to last the long-duration missions. Spacecraft must also carry enough memory to store onboard engineering and science data to facilitate communications with Earth, and to ensure reliable communication as data can be corrupted during transmission through the deep space and might require re-transmissions.

5. Navigation and trajectory planning – precision navigation is crucial for outer planet missions to ensure accurate arrival at the target destination and successful encounters with moons or planetary rings. Complex gravitational interactions, planetary flybys, and trajectory adjustments are required to optimize mission trajectories and conserve fuels.

These mission challenges in turn pose technology and operation uncertainties and affect the flight and ground communication system designs. This results in a number of design-trade implications, particular on the trade-off between RF and optical links: A few noteworthy implications are:

1. Additional Size, Weight, and Power (SwaP) for a flight optical communication system – in the foreseeable future, a deep space spacecraft carrying an optical communication system would also carry an RF system for navigation and low-rate and off-nominal scenarios. The additional SwaP of an optical system might not justify the additional data return, if any.

2. Pointing challenges of optical links – compared to RF, deep space optical communications in principle could dramatically increase the data return from an outer planet mission. Link analysis [10] shows that a flight laser transceiver with a 50 cm telescope and 20 W average power laser, and a ground-based Earth receiver with a 11.8 m diameter are reasonable choices for the next decade. The highly directional optical flight terminal has a beamwidth of a few μrad. The pointing control will have to be a lot tighter for the Ice Giant links. Current deep space optical links requires a beacon reference signal from Earth to assist the spacecraft telescope to acquire and to maintain pointing to the Earth's ground telescope. The Earth's atmosphere limits transmission of diffraction limited lasers through the turbulence induced refractive index fluctuations [10]. This problem becomes more challenging as more power has to be pumped through the atmosphere to provide sufficient reference signal at the distance of the ice planets. Another challenge is that at outer planet distances, from the vantage point of the spacecraft optical telescope, Earth and its beacon reference signal will be angularly close to the Sun. It would be challenging to acquire the beacon signal when Sun is in telescope's field-of-view. For example, at Uranus range of 20 AU, the Sun-Probe-Earth angle is always less than 2.86°, see Figure 1. Pointing techniques that do not require an Earth's beacon are being investigated.

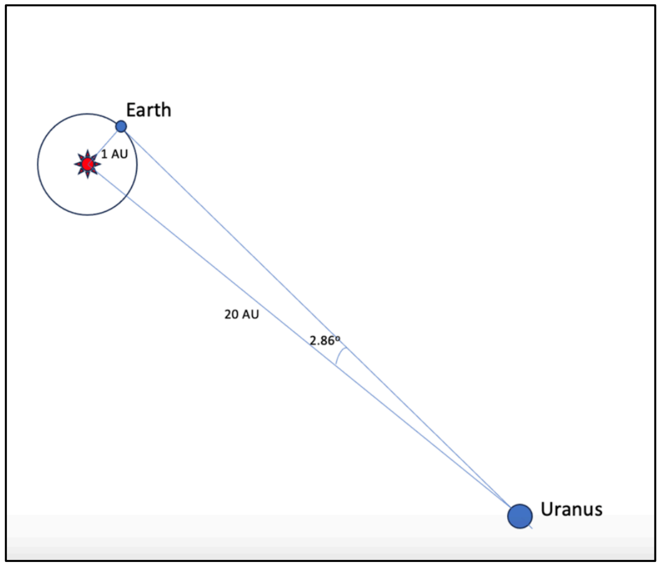

Figure 1: Earth-Sun-Uranus Geometry

3. The $\frac{1}{r^2}$ versus $\frac{1}{r^4}$ challenge of High-Photon-Efficiency (HPE) optical communications at outer planet ranges – the HPE waveform like Pulse Position Modulation (PPM) is in theory more efficient for deep space applications in terms of the amount of information that a photon can carry – number of bits per photon. The channel capacity of PPM is a function of signal flux rate (photons/slot), noise flux rate (photons/slot), laser pulse slot width T_s (ns), and PPM order M [15]. There are practical technology limitations on laser power output, T_s, M, and high background radiance in deep space. For a given PPM system design and with photon-counting detection, there is a critical range R_c which when smaller than R_c the channel capacity decreases as a function of $\frac{1}{r^2}$, and when larger than R_c channel capacity decreases as a function of $\frac{1}{r^4}$. This can be seen from the approximate expression for capacity, C, in equation (5) of reference [15], which is of the form: $C \propto P_r^2 / (\alpha P_r + \beta)$. Here P_r represents the received signal power, and α, β are constants. The first term in the denominator, αP_r, represents signal-dependent shot-noise, and the second term represents independent additive noise from any other source including background and system thermal noise that does not depend on the signal. If signal-dependent shot-noise dominates, such that $\alpha P_r >> \beta$, then capacity can be approximated as $C \propto P_r^2 / \alpha P_r \propto P_r$, which is proportional to $\frac{1}{r^2}$. However, if independent

additive noise dominates, $\beta >> \alpha P_r$, then $C \propto P_r^2 / \beta \propto P_r^2$, which is proportional to $\frac{1}{r^4}$.

For the current and near-term technologies, the critical range is much smaller than the outer planet ranges and thus the channel capacity falls off as a function of $\frac{1}{r^4}$ for most of the primary mission phase. It was stated in [15] that for a deep space operating point with noise spectral density α_b= 1 pW/m^2 (conservative), the state-of-the-art flight and ground optical systems[1] results in the critical range R_c = 0.89 AU. For a more optimistic operation point with α_b= 0.1 pW/m^2 (clear night sky), R_c can be as high as 2.67 AU. This is still a lot lower than the outer planet ranges. Different technical approaches to mitigate this $\frac{1}{r^2}$ versus $\frac{1}{r^4}$ challenge are being investigated. It was stated in [16] that a future high-power large-aperture optical flight terminal and a large-aperture ground telescope[2] could deliver 1 Gbps from Jupiter, and 3 Mbps from the Heliopause.

4. Concern on using Ka-band for long-life missions – proposed ice giant mission concepts [10,11] include both X-band and Ka-band communication links. In the Interstellar Probe mission [12,13], the baseline design employs only X-band. Due to the vast ranges of the icy planet and interstellar missions, spacecraft need to carry large high-gain antenna with sizes ranging from 3 m to 5 m. This imposes stringent pointing requirements for Ka-band. The spacecraft need to have precise attitude knowledge and have good pointing control within a small fraction of a degree. This kind of pointing accuracy can only be provided by reaction wheels and not thrusters. Currently there is no reaction wheel product that can meet a design life requirement of a few decades for the long-life missions to the outer planets and beyond.

5. Spacecraft power constraints at outer planet distances – For spacecraft visiting Uranus, Neptune, and beyond, they are so far away from the Sun that solar panels are not effective in generating power, and Radioisotope Thermoelectric Generators (RTGs) are used for power and heating. RTGs are ideal for remote and harsh environment and can provide power for an extended period of time. But the power generated is limited to a few hundred Watts or less. This limits the spacecraft power allocated for communications.

3. Mission Data Return Requirements and Current Flight/Ground Capabilities

We delve into the design and costing of several distinct mission options recommended by the Ice Giants: Pre-Decadal Survey Missions Study Report [10], and the Neptune Odyssey Study Report [11]. Later the Origin, Worlds, and Life Decadal Survey [9] recommend the next two flagship-class mission should be the Uranus Orbiter & Probe and the Enceladus Orbilander [14]. Furthermore, an Interstellar Probe mission [12, 13] presents the challenge of launching a spacecraft for interstellar exploration by 2030. The data return requirements can be summarized in Table 1.

Table 1. Data Rate Requirements for Outer Planet Missions

Mission Concept	Destination	Range [AU]	Required Data Rate [kbps]	Comments
Cassini	Saturn	10	14	Provided for reference
Uranus Orbiter & Probe	Uranus	20	15	Based on pre-Decadal Survey concept study report
Neptune Odyssey	Neptune	30	29	Based on Planetary Mission Concept Study
Interstellar Probe	Beyond the heliosphere	375	2.592	Based on pre-Decadal Survey mission concept study report

[1] This includes Psyche's Deep Space Optical Communication Experiment 22-cm diameter flight terminal and 4W power, and a 11.8-m ground telescope.

[2] This assumes a 1-m diffraction-optical telescope with 40-W power, and a 15-m equivalent ground telescope.

Table 2. EIRP of Past (Top 5) and Future (Bottom 4) Outer Planet Missions

Mission	Planetary Body	Frequency Band	Transmit Power [W]	Antenna Diameter [m]	Impl. Losses[3] [dB]	EIRP [dBm]	Ref.
Galileo	Jupiter	X-band	20	4.8[4]	-0.15 dB	92.37	[2]
Juno	Jupiter	X-band	25	2.5	-0.15 dB	87.67	[5]
Europa Clipper	Europa	X-band	20	3.0	-0.15 dB	88.28	[7]
Cassini	Saturn	X-band	20	4.0	-0.15 dB	90.78	[3]
New Horizons	Pluto	X-band	12	2.1	-0.15 dB	82.97	[4]
NASA Enceladus Orbilander	Enceladus	X-band	65	2.2[5]	-0.15 dB	90.71	[14]
		Ka-band	60	2.2	-0.5 dB	101.63	
NASA Ice Giants Study	Uranus, Neptune	X-band	25	3.0	-0.15 dB	89.25	[10]
		Ka-band	35	3.0	-0.5 dB	101.98	
ESA Ice Giants Study	Uranus, Neptune	X-band	65	3.0	-0.15 dB	93.40	[26]
		Ka-band	100[6]	3.0	-0.5 dB	106.54	
APL Interstellar Probe	Up to 1000 AU	X-band	52	5.0	-0.15 dB	96.87	[12]

We summarize the frequency band, transmit power and antenna diameter used by past JPL deep space missions, as well as from proposed NASA, ESA, and APL missions. For the newly proposed missions, we provide the expected spacecraft capabilities both at X- and Ka-band. The results are shown in Table 2.

The outer planet missions require the large apertures of the DSN for tracking and communications. The DSN is a global network of ground-based antennas managed by NASA's Jet Propulsion Laboratory (JPL). Its primary purpose is to provide communication and tracking support for interplanetary missions, enabling scientists and engineers to exchange data with spacecraft exploring the depths of our solar system and beyond. The strategic placement of DSN ground stations in the longitudinally separated sites of Goldstone, Madrid, and Canberra ensures comprehensive coverage visibility for spacecraft telecommunications.

The DSN's distributed geometry with stations in Goldstone, Madrid, and Canberra further enhances simultaneous downlink capabilities, as spacecraft can be tracked by multiple complexes simultaneously. Simultaneous downlink operations enable multiple spacecraft to transmit data to Earth. This capability is vital for missions that require continuous data acquisition or those with multiple spacecraft operating in proximity. By supporting multiple spacecraft downlinks concurrently, the network ensures that valuable scientific data is efficiently collected, minimizing downtime, and optimizing the utilization of resources.

Each DSN complex comprises multiple antennas, including the 34-meter and 70-meter subnet. These antennas can be assigned to different spacecraft, allowing for concurrent downlink operations. Both types of antennas have a two-axis mount allowing movement in both azimuth (horizontal) and elevation (vertical) directions. The azimuth range extends from 0° to 360°, while the elevation range spans from 0° to 90°. This

[3] The telecom subsystem of each spacecraft has different implementation losses. We assume here 0.15 dB at X-band based on personal communications with Mike Kobayashi and Charles Wang, from the Flight Communications Systems Section of JPL. At Ka-band, we assume worse performance to account for additional losses in the RF front-end of the spacecraft radio.

[4] The value provided is for the 4.8-m high gain antenna that failed to deploy. Therefore, the number is representative of expected system performance during planning rather than operational performance.

[5] The mission concept assumes downlinks using X-band only for communications via the LGAs and MGAs. However, the HGA is X-band compatible for uplink purposes.

[6] The ESA report indicates that 100W of RF power is optimistic (TRL 2). However, high-TRL Ka-band TWTAs for near-Earth applications are already listed by commercial manufacturers such as Thales, which offers a 70W TWTA (see https://www.thalesgroup.com/en/markets/market-specific-solutions/microwave-imaging-sub-systems/radio-frequency-microwave-sources-4#twt).

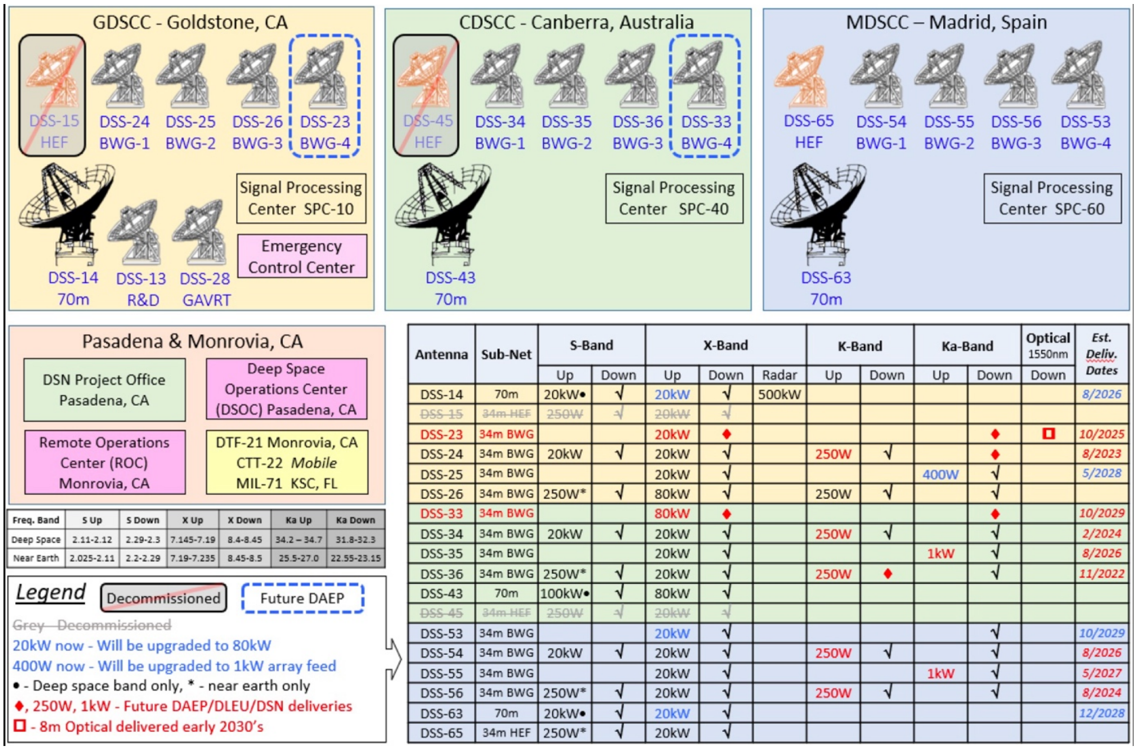

Figure 2. DSN Capabilities as listed in [17]

enables the antennas to track spacecraft across the sky, compensating for the Earth's rotation and providing continuous communication during missions.

The DSN operates in S-band, X-band, K-band, and Ka-band. These frequency bands offer different advantages and are selected based on mission requirements, distance to the spacecraft, data transfer rates, and signal quality considerations. Figure 2 [17] summarizes the operating modes and characteristics at each station. DSN can also support Multiple Spacecraft Per Antenna (MSPA) and arraying multiple downlinks simultaneously from spacecraft within its beamwidth. Arraying phases up and combines the signal received by multiple ground antennas to boost the received signal-to-noise ratio. A more detailed specification of the key characteristics of the DSN antennas can be found in the DSN Telecommunications Link Design Handbook [810-005, 29], which describes the available DSN stations in terms of antenna size and type, location, operating bands, EIRP, and signal gain.

4. LINK GEOMETRY TO OUTER PLANET (AND PLUTO)

We explore the geometry between Earth, Sun, and outer planets, and its impacts on the communication links. Figure 3 depicts the planets of our Solar System, and Table 3 summarizes the orbital parameters of the planets[7].

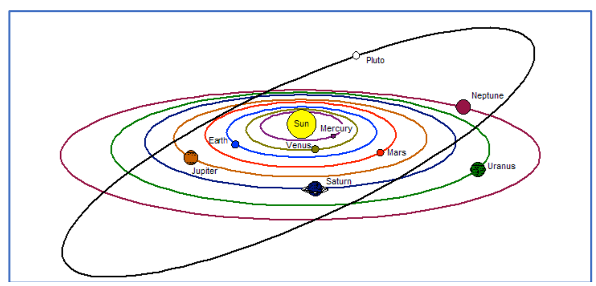

Figure 3. The Solar System [16]

The three main geometric properties that affect communication link design, system development, and mission operations are range between Earth and the outer planet, the Sun-Earth-Planet (SEP) angle, and the Sun-Planet-Earth (SPE) angle.

For a spacecraft in the vicinity of an outer planet, its range with Earth exhibits an approximate range profile of the outer planet radius around the Sun and oscillates between +1 AU and -1 AU. Figure 4 shows the 50-year range profile of the outer planets and illustrates the oscillating patterns. For Uranus and Neptune, the ranges are relatively constant at 20 AU and 30 AU respectively.

[7] In August 2006, the International Astronomical Union (IAU) downgraded the status of Pluto to that of "dwarf planet."

Table 3. Key Orbital Parameters of the Planets [16]

Planet	Orbital Max Radius (10^6 km)	Orbital Min Radius (10^6 km)	Orbital Revolution	Planet Rotation	Orbital Speed (km/s)	Axis/Orbit (*)	Mass (**)	Surface Escape Velocity (km/s)
Mercury	69.7	45.9	88 d	59 d	47.9	28º/7º	0.055	4.4
Venus	109	107.4	224.7 d	(-)243 d	35	3.0º/3.4º	0.815	10.4
Earth (moon)	152.1	147.1	365.26 d	23h,56m,4s	29.8	23º 27'/0º	1	11.2 (2.4)
Mars	249.1	206.7	687 d	24h,37m,23s	24.1	23º 59'/1.9º	0.108	5.0
Jupiter	815.7	740.9	11.86 y	9h,50m,30s	13.1	3º 5'/1.3º	317.9	59.5
Saturn	1507	1347	29.46 y	10h,14m	9.6	26º 44'/2.5º	95.2	35.5
Uranus	3004	2735	84.01 y	(-)11 h	6.8	82º 5'/0.8º	14.6	21.3
Neptune	4537	4456	164.8 y	16 h	5.4	28º 48'/1.8º	17.2	23.5
Pluto	7375	4425	247.7 y	6d,9h	4.7	---º/17.2º	0.1	1.3

* : inclination to ecliptic (Earth's orbital plane)
** : Mass relative to earth
(-) : retrograde motion

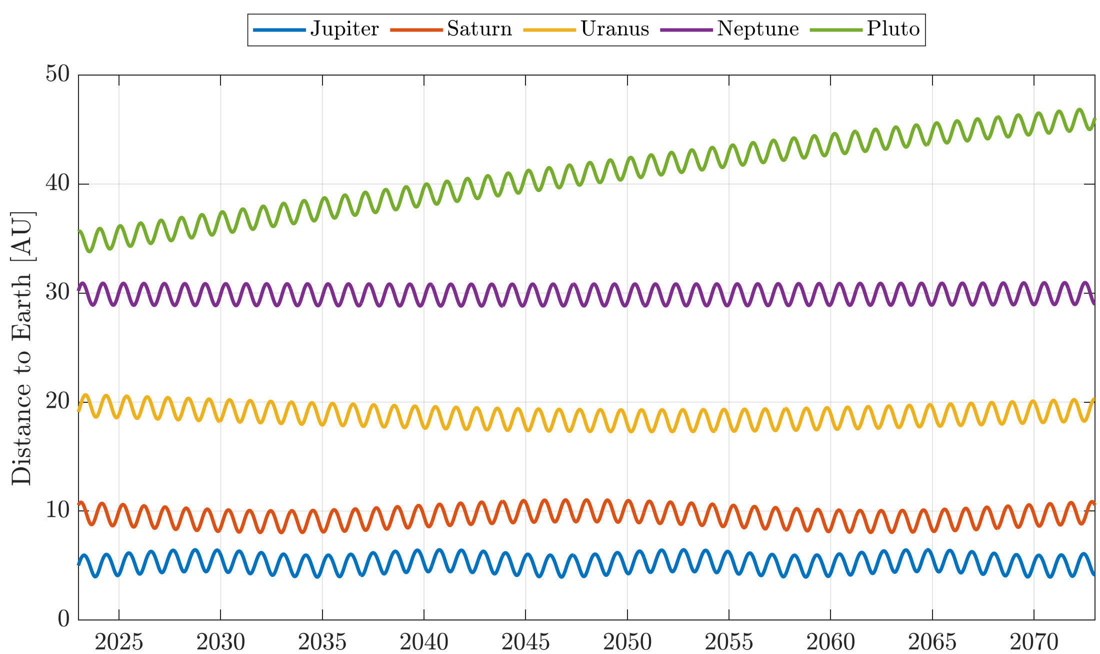

Figure 4. 50-Year Range Profile of Outer Planets and Pluto

The SEP angle of the outer planets ranges from 0º to 180º in a regular pattern as shown in Figure 5. Every year during superior solar conjunction when the SEP angle is small, scintillation effects introduce outages to both RF uplink and downlink communications with the spacecraft. The durations of outages depend on the frequency band. Small SEP angle also would have detrimental effects on optical downlink as the Sun is angularly close to the weak signals from the spacecraft at outer planet range.

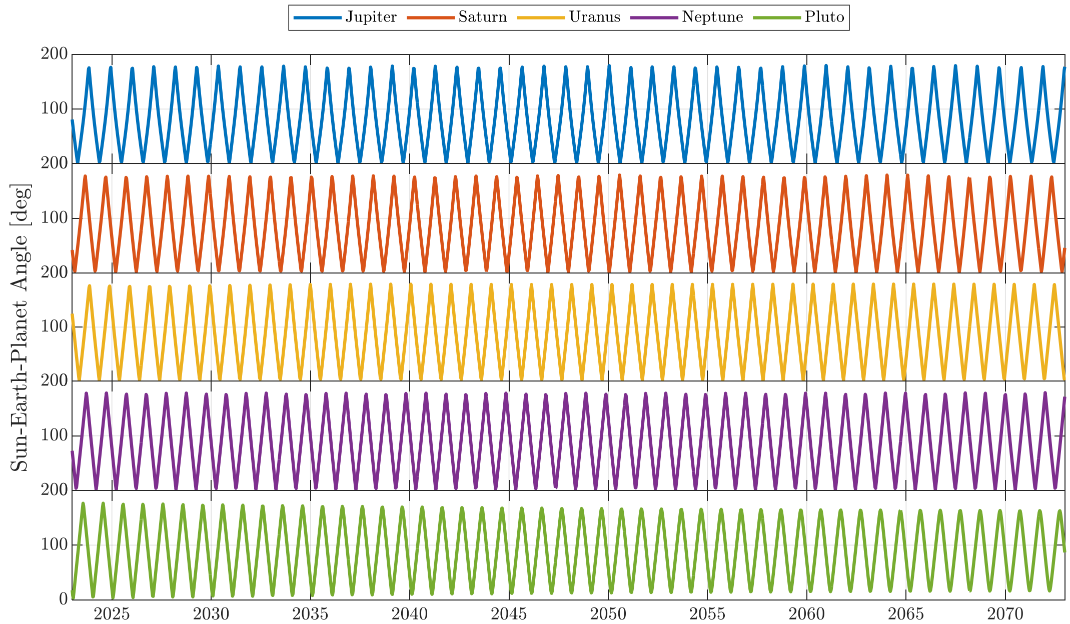

Figure 5. Sun-Earth-Probe Angle Profile for Outer Planets and Pluto

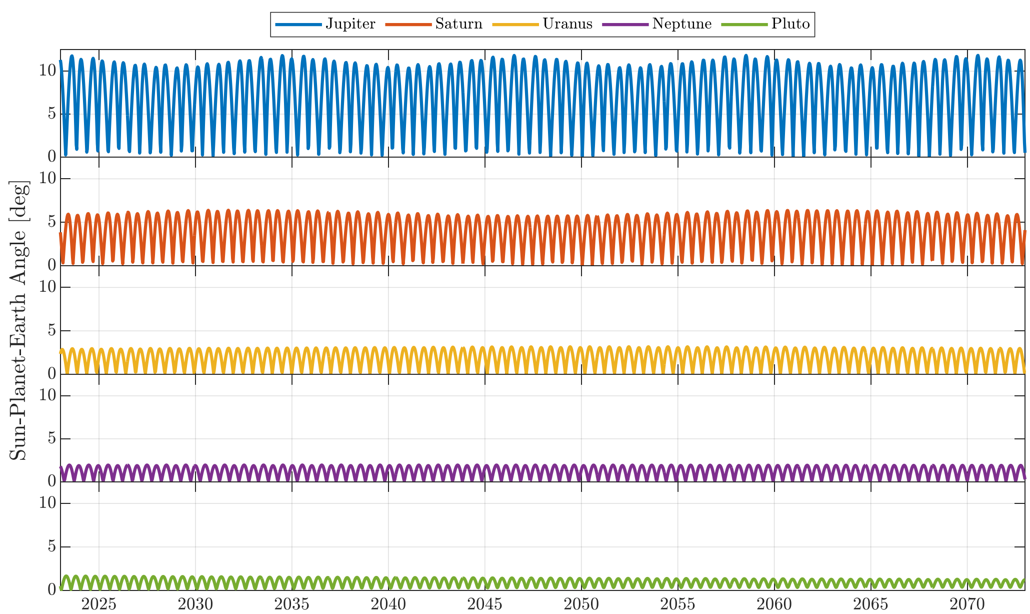

Figure 6. Sun-Planet-Earth Angle Profile for Outer Planets and Pluto

The SPE angles are small for the outer planets, and the further the outer planets are the smaller are the SEP angle as shown in Figure 6. As discussed in Section 2, small SPE angle would affect optical uplink as the Sun is angularly close to Earth from the vantage point of a spacecraft at outer planet distance, and this can be challenging to the optical communication system that would require a beacon from Earth to assist its pointing.

5. PROPOSED DSN UPGRADE TO MEET OUTER PLANET MISSION NEEDS

In Section II we identify several major technical challenges and technology and cost uncertainties of spacecraft flight communications system. Improvements of the ground system seem to be more amenable in terms of technical risk and cost. We propose the following "low-hanging-fruit" on DSN improvements in operation capabilities in Ka-band links that would meet the data return requirements of the upcoming planned and proposed outer planet missions. This includes:

1. Arraying of 34m BWG Antennas in Ka-band.
2. Adding Ka-band on 70m Antenna.

Arraying of 34m BWG Antenna at Ka-Band

DSN has demonstrated arraying in Ka-band in prior missions, and this capability is transitioning into operational. To the best of our knowledge, five experimental arraying activities at Ka-band have been conducted by DSN and JPL personnel to date:

1. A first Ka-band arraying experiment was conducted in 2007 by JPL personnel using up to six 22-m antennas in the Australia Telescope Compact Array (ATCA) [18] fitted with DSN receivers to track the 32 GHz carrier from Cassini. Expected arraying gains were demonstrated in the received signal-to-noise ratio within ~1 dB of its theoretical value.
2. A second experiment conducted in 2012 is documented in [19] and used two 34m BWG antennas and the same 32 GHz carrier from Cassini. Combining of signals received via each antenna was conducted in post-processing using samples collected with open loop recorders. Analysis of the combined signal clearly demonstrated the ability of the post-processing system to compensate for relative phases between the signals at both antennas, thus yielding arraying gains within a few tens of dB from the theoretical value.
3. A third experiment was conducted on December 27, 2015 using pairs of DSN 34m BWG antennas both at Goldstone and Madrid using Kepler as a signal of opportunity.
4. A fourth experiment was conducted on May 29, 2017 using Kepler as a signal of opportunity. The DSCC Downlink Array (DDA) combined signals from DSS-25 and DSS-26 and the resulting signal was feed into DSS-26's downlink channel. Using this configuration, an average gain of 2.5 dB in symbol SNR was measured and both the mission and the DSN confirm receipt of downlink data. This was the first validation exercise for DSN arraying at Ka-band that included data recovery.
5. A fifth experiment was conducted recently using the Parker Solar Probe. Details of this activity have not been yet published.

Downlink arraying at Ka-band is theoretically equivalent to arraying at S- and X-band because all processing is performed in the baseband domain, after down-conversion. However, there are subtle differences driven by the behavior of Earth's atmosphere at Ka-band, which causes phase differences between antennas to be larger and vary slightly faster over time. Another operational difference is higher data rates at Ka-band, which requires arraying to be performed over larger bandwidth signals.

Although Ka-band experimental activities have been conducted to date, we now list several additional experimental and test activities that would help further operationalize downlink arraying at Ka-band for support of high-rate data transfer from outer planets:

- Phase measurements and/or Site Test Interferometry-derived measurements at Ka-band over a wide range of atmospheric conditions to obtain cumulative distributions (CDs) for arraying loss at Ka-band at each DSN site. This information would be included in the DSN Link Design Handbook to aid in mission formulation in a manner analogous to atmospheric noise and attenuation (see [27]).
- Determination of the atmospheric conditions (fog, clouds, rain, wind) that render downlink arraying impractical or infeasible (if any) due to the inability to reliably phase align the signals received from each antenna. This information could be used by the DSN operations team to predict the likelihood of abnormal operations during a given pass using short or medium-term atmospheric predictions.
- Measurements of the arraying loss as a function of the DSN the pointing mode (monopulse vs. CONSCAN) and received signal SNR. This information would help refine the limiting conditions under which a power-limited downlinks could be closed by arraying two or multiple antennas because the monopulse tracking loop has insufficient SNR.
- Measurements of the increase in the system noise temperature of an array when tracking a spacecraft close to a planetary body. This information could also be provided in the DSN Link Design Handbook to aid in mission planning.
- Quantification of the SNR improvement when tracking a spacecraft close to a planetary body using the "countermeasures" already available in the DDA to reduce the effect of an interfering planet [20].
- In-flight validation of telemetry recovery during a Ka-band downlink arraying tracking (rather than measurements of a single carrier) using the new DDA equipment developed and deployed during the FY24-FY26 DSN arraying enhancement project. This is

particularly timely because it would serve as the first in-flight validation of the new operational equipment.

- Simultaneous arraying at X- and Ka-band for the purpose of characterizing differences in phase fluctuations and overall system performance. This exercise should ideally be repeated several times under different weather conditions to understand how differences in phase fluctuations vary with the state of the atmosphere.

The outcome of these activities would enhance the maturity of DSN operations at Ka-band in several ways: First, it would demonstrate arraying using the new DDA equipment, thus validating the new system implementation. Second, it would provide empirical information to help validate and improve JPL's DDA Combining Algorithm Simulator. And third, it would provide additional information to deliver better and more credible predictions of the array performance at different weather conditions, which would aid in mission formulation and analysis.

Implementation Path for Ka-Band on DSN 70m Antennas

The aperture of the 70m antenna at DSS-14 is greater by a factor of 4.2 (or 6.3 dB) than the apertures of the DSN's Apollo Station 34m BWG antennas DSS-24/25/26. However, several factors conspire to limit the practical realization of the full advantage of the 70m antenna at Ka-band (32 GHz) and higher frequencies, including:

- Flexibility of the primary reflector backup structure.
- Flexure of the quadripod supporting the subreflector.
- Misalignment of primary reflector panels and subreflector position.

Based on previous experiments carried out at Goldstone [21], these limiting factors can be mitigated using advanced techniques and equipment including holographic re-alignment of the primary reflector panels and subreflector positioning, and the implementation of an active compensation system consisting of a deformable flat plate and a real-time 7-channel array feed compensation system. The theoretical basis of array feed compensation is discussed in reference [22].

The present aperture-efficiency performance of the DSS-14 antenna at Ka-band is marginal as a result of two independent effects: loss at the rigging angle due to the rms surface error of the main reflector and losses due to gravity-induced deformation. The marginal rigging-angle aperture efficiency of 31 percent is mostly due to the main reflector rms error of 0.73 mm. It is expected that this rms error can be reduced to between 0.35 and 0.45 mm, thus increasing the overall antenna aperture efficiency to between 55 and 60 percent at the rigging angle using a combination of three techniques: Arraying Feed Compensation System (AFCS), Deformable Flat Plate (DFP), and Panel Realignment (PNL). The curve labeled "AFCS + DFP Current" in Figure 1 shows the gravity performance of the antenna with joint AFCS–DFP compensation, while the curve "AFCS + DFP + PNL Set" shows the expected efficiency performance when compensation is applied to the antenna after panel setting. Thus, with appropriate panel setting and gravity compensation benefits from both systems, the DSS-14 antenna can achieve excellent performance at Ka-band, thereby enabling the predicted 6-dB communications improvement relative to X-band.

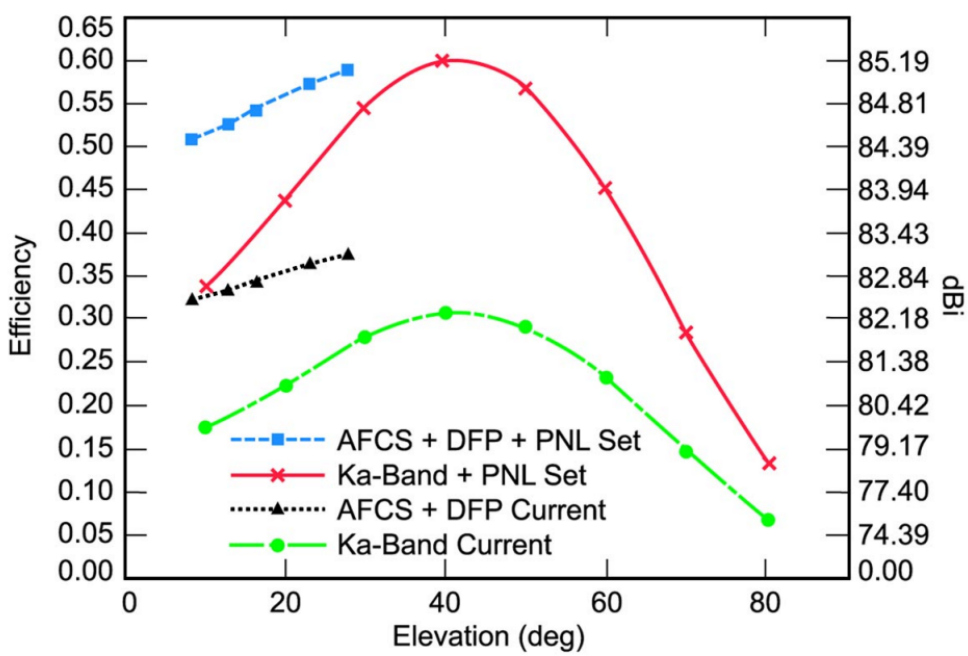

Figure 1. Measured and predicted performance of the 70m antenna (32 GHz). PNL set refers to adjusting the panels of the 70m antenna using holographic measurements.

Previous efforts to improve the Ka-band efficiency of the 70m antenna at DSS-14 has shown that a real-time 7-element array feed system (AFCS) designed to collect and combine signal energy diverted away from the 22 dBi central design horn by antenna distortions, together with a modeled (static) deformable flat plate (DFP), can recover most of the energy currently lost at high and low elevations due to gravity deformations, thermal effects and wind. Since the panels and the subreflector positions on the DSN's 70m antennas at Goldstone, Canberra and Madrid were last reset via holography some 35 years ago, then resulting in substantial gains at Ka-band. It is likely that these antennas have aged and hence another holographic readjustment might provide additional gains. Therefore, the following roadmap is recommended to prepare these aging 70m antennas for future Ka-band operation:

- Determine the current state of the 70m antenna at DSS-14, via holography.
    - Adjust panels and update the subreflector position tables as needed.
- Develop an operational version of the DFP, install on DSS-14, test/finalize.
- Develop an operational version of the AFCS, install on DSS-14, test/finalize
- Implement operational AFCS-DFP system on DSS-14/43/63

A roadmap such as this should provide the DSN with 70-m Ka-band capability to increase data-rates and extend the operational range of future NASA missions exploring the solar system and beyond.

Signals of Opportunity at Ka-band

Ka-band signals from an operational spacecraft are needed to test and to validate the proposed ground improvements. While Cassini is no longer an option, three spacecraft have been identified as potential candidates for conducting the proposed experiments: Juno's Gravity Science instrument, Solar Parker Probe's Ka-band subsystem, and Europa Clipper's Ka-band subsystem.

Juno's Gravity Science instrument is currently used to obtain high-precision measurements of the Jupiter's gravity field [9]. It typically operates in two-way mode at both X- and Ka-band simultaneously, i.e., it receives and transmits an X-band and Ka-band signal. Alternatively, it can also operate in two-way mode by coherently transmitting an X- and Ka-band downlink carrier from a single X-band uplink. Juno's Gravity Science instrument is well suited for validating arraying at Ka-band for several reasons. First, two-way operation ensures that the downlink carrier is ultra-stable, thus isolating the atmosphere as the main contributor for unpredictable shifts in the phase of the received signal. Second, simultaneous operation at X- and Ka-band allows the DSN to perform simultaneous arraying activities at both frequencies and compare, as a function of time, the difference in phase fluctuations at both bands. And third, Juno's orbit provides several flyby opportunities that can be used to measure the effect of hot body noise on the DSN array performance.

The Parker Solar Probe spacecraft carries a 34 W Ka-band TWTA connected to a 0.6m high gain antenna for radiometrics and science data return [23]. DSN support of the spacecraft at Ka-band has been extensive and has yielded valuable operational experience and system performance measurements. Performing arraying experiments with Parker Solar Probe would complement Juno's Gravity Science experiment because it would allow the DSN to test actual data return (including synchronization, demodulation, decoding, etc.) as opposed to operation with a single carrier.

Finally, the upcoming Europa Clipper mission offers a third signal of opportunity for conducting the testing activities. The mission's telecom subsystem includes a Ka-band downlink used for science data return as well as for gravity science [24]. Like Parker Solar Probe, the telecom subsystem can operate in two-way coherent mode for high-precision gravity measurements, which is advantageous for atmosphere and hot body noise characterization. It can also be used to demonstrate successful data recovery using a future Ka-band array.

Supportable Data Rate with Proposed DSN Upgrades

For the proposed outer planet missions, assuming the flight system link parameters in Table 2 and the data rate requirements in Table 1, we found that the aforementioned DSN upgrades (dashed lines) can meet the data rate requirements of all missions except the Interstellar Probe. This is illustrated in Figure 7. The link analyzes are mostly accurate at Uranus and beyond. At Jupiter and Saturn there can be additional link degradation for the orbiting spacecraft due to the planet's hot body noise. For current Jupiter and Saturn missions there is plenty of link margin for the required data rate especially with the DSN upgrades, and this should mitigate the hot body noise effect in most cases.

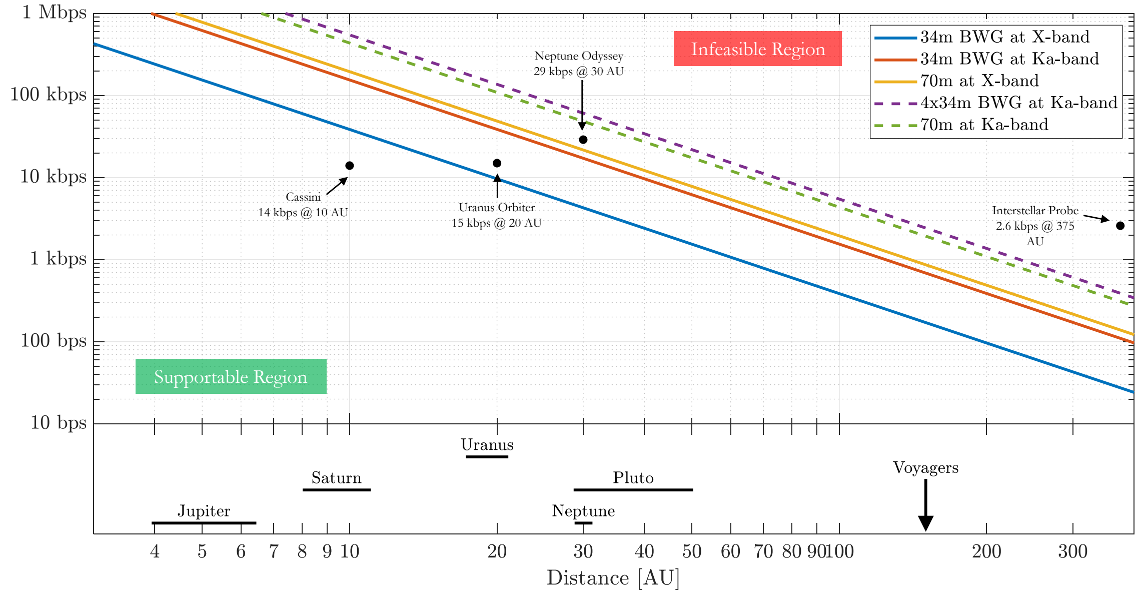

Figure 7. Supportable Data Rate as a Function of Outer Planet Range

6. CONCLUSION

Outer planet missions play an important role in JPL and NASA's space exploration objectives in the coming decades. This paper assesses the technical options available for ensuring that the Deep Space Network (DSN) can enable future missions to the outer Solar System and recommend investment options for flight and ground communication systems and technologies that would meet the future data return requirements.

The major takeaways are summarized as follow:

- Given the current and near-term state of technology development there are major challenges in operating optical links at outer planet distances (e.g., Sun-Earth angle effects, spacecraft power available for the laser, optical ground network development plans, etc).
- Due to the spacecraft limitations at outer planet distances, e.g., antenna pointing and solar/RTG power, the 'biggest bang for the buck' on enhancing data return is by improving the capabilities of the DSN at Ka-band.
- Concurrently with enhancing DSN capabilities at Ka-band, NASA should encourage the use of Ka-band in missions by actively incentivizing the use of Ka-band on high-rate science downlinks using technologies already available today, while retaining X-band capability for low-rate telemetry, commanding, and emergency support.

To improve DSN capabilities at Ka-band, we consider two alternative approaches: 1) operation use of 34-m BWG arrays, and 2) upgrading the 70-m antennas. For each option, we quantify the expected performance and compare it against known upcoming users. We describe past DSN development and flight demonstrations, summarize the technological advances conducted to-date, and identify additional engineering work required to operationalize the system. We recommend the following:

- For arraying of 34-m BWG at Ka-band, additional demonstration activities are needed to better characterize the system performance under different conditions, including operations in adverse weather conditions or close to a hot body source.
- For upgrading the 70-m antennas, new holography measurements (and panel setting) should be conducted, and operational versions of previously prototyped gravity compensation systems like array feeds and deformable flat plates should be developed and installed.

Using these approaches, we expect the DSN downlink performance at Ka-band to improve by 4-6 dB [28], providing an increase in downlink data rate of 2.5x to 4x.

The following are a few topics that deserves further investigations:

1. In addition to DSN, the proposed next-generation Very Large Array (ngVLA) can be a ground system development have the potential to greatly improve data return from outer planets. The ngVLA is envisioned to consist of 244 18-m antennas with an effective area of 53106 m^2. This provides a 20+ dB improvement over a 34-m BWG antenna. The Interstellar Probe mission concept [12] relies on ngVLA to close the X-band downlink at a distance of 1000 AU.

2. As many of these mission concepts involve a spacecraft orbiting around the outer planet, there are times when the planet falls within the antenna beam(s). The planet emits hot body noise that degrades the link performance. In the case of arraying, the hot body noises received by individual antennas are correlated. As the planet's angular footprint is larger for the closer outer planets, the hot body noise contribution is higher for outer planets like Jupiter and Saturn. The effects of hot body noise generated by the planet itself need to be considered in the deep space links between the spacecraft and Earth.
3. The lack of high-reliability reaction wheel forces long-life mission concepts like Interstellar Probe to use X-band instead of Ka-band, thus reduces data return. Development of reliable long-life reaction wheels with a design life requirement of decades would enable higher data return for missions going to the outer planets and beyond.
4. In the US, the only RTG currently available is the 120 W MMRTG, and this limits the spacecraft transmitting power. A Next Generation RTG (NGRTG) is under development, with an estimated 242 W at the beginning of life [25]. The NGRTG is designed to operate in the vacuum of space with an overall design life of 18 years, with end of design life power of 177 W.

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