

ADDRESSING THE HIGH-RATE DEEP SPACE COMMUNICATIONS SHORTFALL IN NASA'S SPACE TECHNOLOGY MISSION DIRECTORATE'S ENVISIONED FUTURE

Bernard Edwards

NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, Bernard.L.Edwards@nasa.gov

Dimitrios Antsos

NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Dimitrios.Antsos@jpl.nasa.gov

Abhijit Biswas

NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109,

Abhijit.Biswas@jpl.nasa.gov

Richard Reinhart

NASA Glenn Research Center, Cleveland, OH 44135, Richard.C.Reinhart@nasa.gov

Bryan Robinson

MIT Lincoln Laboratory, Lexington, MA 02421, brobinson@ll.mit.edu

Don Boroson

MIT Lincoln Laboratory, Lexington, MA 02421, boroson@ll.mit.edu

Farzana Khatri

MIT Lincoln Laboratory, Lexington, MA 02421, fkhatri@ll.mit.edu

Stephen Lichten

NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109,

Stephen.M.Lichten@jpl.nasa.gov

Abstract

NASA's Space Technology Mission Directorate (STMD) has identified key technologies needed for future crewed and robotic exploration and science missions. STMD is helping to build the civilian technology base by working with other NASA Mission Directorates, other United States government agencies, commercial industry, and academia to identify technology shortfalls and to develop plans to address them. One critical area of shortfalls lies with deep space communications and navigation. While NASA had huge success to date with the Deep Space Network (DSN), recent studies have shown that without enhancements to current systems, the DSN will be unable to support the anticipated increases in the pace of space exploration or the expected higher data rates from deep space needed soon without severely impacting other missions [1]. High-rate communications from the Moon and beyond is needed to enable future exploration and science missions currently being developed or under consideration. For example, a robust communications infrastructure will be needed to support a sustained human presence on the Moon and its eventual industrialization. High data rate trunk lines between the Earth and the Moon are needed to reduce the number of individual links. The human exploration of Mars will also require high-rate communications between Earth and Mars. Return data rates to Earth from Mars for a single link, for example, are anticipated to be greater than 100 Mb/s; forward data rates to Mars, based on experience from the International Space Station, are anticipated to be greater than 20 Mb/s. Future deep space science missions will also require higher data rates than possible with today's technology and the current capabilities of the DSN. To support future exploration and science needs, it will be necessary to upgrade the DSN to enhance its radio frequency (RF) capabilities. In addition, it is envisioned that NASA will gradually introduce optical communications to augment its RF systems [2]. Optical communications will enable new science and exploration missions by providing high data rates and better navigation over long distances [3]. This paper will briefly describe STMD's envisioned future for deep space communications in the 2030+ timeframe and the technology roadmaps being developed for both radio frequency and optical systems.

1. Introduction

NASA's Space Technology Mission Directorate (STMD) worked with other NASA Mission Directorates, especially the Exploration Systems Development Mission Directorate (ESDMD) and the Science Mission Directorate (SMD), other United States government agencies, commercial industry, and academia to identify technology shortfalls for future NASA plans. In the spring of 2024, STMD identified 187 shortfalls [4], of which four were related to communications and navigation:

- In-Situ Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications
- High-Rate Communications Across the Lunar Surface
- Deep Space Autonomous Navigation
- High-Rate Deep Space Communications

While all four are critical to enable future crewed exploration and science missions, this paper will only address the high-rate deep space communications shortfall. Today, NASA's deep space communications are provided by the Deep Space Network (DSN). The DSN is a worldwide network of radio frequency ground stations located in Australia (Canberra), Spain (Madrid), and the United States (Goldstone, California). Its primary function is to support communications and navigation for interplanetary spacecraft; however, it has also been used to support a number of Earth orbiting missions as well as to perform radio astronomy and planetary radar observations from time to time. The facilities are globally located such that a spacecraft in deep space is always in view of at least one ground station. Each of the three DSN sites has at least four antennas with ultra-sensitive receiving systems:

- One 70-meter antenna
- Three or more 34-meter beam waveguide antennas

A recent audit of the DSN [1] found the following limitations and shortfalls:

- The DSN is oversubscribed and will continue to be overburdened by the demands created by an increasing number of deep space missions, including crewed and robotic missions.
- Limitations on the DSN's capacity have already impacted Agency missions' ability to fully meet objectives and achieve full return on investment.
- The DSN Aperture Enhancement Project (DAEP) is behind schedule and over cost.
- Lack of readily available backups and a laborious scheduling process makes it hard to schedule time on the DSN.
- NASA's decision to refurbish the 70m antennas rather than replace them with new 34m antennas limits DSN flexibility in supporting multiple missions simultaneously.

2. High-Rate Deep Space Communications Shortfall

NASA previously recognized the need to upgrade and enhance the existing DSN. Initiated in 2010, DAEP is a program originally conceived to build six new antennas to replace existing antennas, equip each new antenna with a 20 kW transmitter, and add six additional high power 80 kW transmitters. In addition, NASA looked at other options to increase deep space communications capacity, including the development of Lunar Exploration Ground Sites (LEGS), with additional 20m class antenna terminals, also globally located, to support Artemis missions to the Moon. However, as previously mentioned, DAEP is behind schedule and over budget; the new LEGS development has also experienced delays and cost increases. Furthermore, the DSN capacity problem will only get worse with the onset of more sophisticated and longer lasting crewed Artemis missions to the Moon, and, eventually, crewed missions to Mars.

A robust communications infrastructure will be needed to support a sustained human presence on the Moon and its eventual industrialization. That infrastructure will need high data rate trunk lines between the Earth and lunar communications satellites that are capable of aggregating user data in order to reduce the number of individual links to Earth as well as a comprehensive surface wireless communications network. High data rate trunk lines to Earth will also be needed to support the eventual human exploration of Mars. These will be significantly harder to provide due to the immense distances involved. While space communications requirements for a crewed mission to Mars are still in development, high-data rate applications such as 4k video, telemedicine, transfer of science data, remote operations of vehicles, and monitoring the health and

safety of astronauts and their vehicles will be necessary. Whether or not crewed vehicles in the Martian vicinity communicate directly with Earth or via relay satellites at Mars is still to be determined. However, return data rates to Earth for a single link, for example, are anticipated to be greater than 100 Mb/s; forward data rates to Mars, based on experience from the International Space Station, are anticipated to be greater than 20 Mb/s. These data rates will be required when Mars is at maximum distance from Earth, which is the baseline distance used for all Mars planning analyses. To put this in perspective, at maximum Mars range, the highest data rate used to date to a single 34m DSN terminal is 500 Kb/s (when Mars is closest to Earth, data rates of ~ 5 Mb/s can be achieved). Clearly, future deep space science missions will also require higher data rates than possible with today's technology and infrastructure. Key challenges include:

- Low mass, large flight aperture antennas (RF) and telescopes (optical) for use in space
- High efficiency high power RF and optical amplifiers for use in space
- Low recurring cost, large effective area ground apertures

To address this overall deep space communications shortfall, STMD commissioned an activity to identify the underlying technology shortfalls and to create roadmaps of the necessary technology development activities to mitigate and address the shortfalls. Roadmap elements are typically:

- A request for information (RFI) or other data-gathering activity that assists in defining future roadmap activities.
- An investment that has an associated acquisition model and objectives. This includes elements such as studies, ground-based testing, flight testing, and space technology demonstrations.
- A key decision point milestone that bridges investment projects/activities or gates continuation on investment projects/activities.

A group of subject-matter experts from Ames Research Center, Glenn Research Center, Goddard Space Flight Center and the Jet Propulsion Laboratory were convened and charged with identifying specific RF technologies that are needed; likewise, a team from MIT Lincoln Laboratory and the Jet Propulsion Laboratory was convened and charged with looking at optical communications technologies. To guide the development of the roadmaps, the teams used a deep space capability goal of 100 Mb/s on a single link from Mars at maximum distance of 2.7 AU to Earth.

3. Deep Space Radio Frequency Roadmap

RF communications technology has been and will continue to be important for deep space exploration. Today's state-of-the-art RF systems at Mars, however, only deliver a few hundred kb/s when Mars and Earth are maximally separated (~2.7 AU). This is because, even though it is technically possible today to transmit 100 Mb/s from Mars to Earth via RF links, realistic transmission rates are constrained by available spacecraft mass, power, and volume and the resources at Earth. For example, a 100 Mb/s RF return link from Mars at maximum range to an array of four 34-m antenna/receivers in the DSN would require a 500W Ka-band transmitter with a ~5.6m transmit antenna on the spacecraft. Thus, while moderate to high-rate communications via RF links is possible (albeit requiring multiple ground assets) and will continue to be a part of the Mars communication architecture going forward, NASA will need to advance technology to increase data return over RF links and will likely need to use optical communications for very high data rates.

Each of the technologies identified for the RF roadmap entail its development to TRL-6, with the expectation of eventual development of space qualified technology for space flight, with some technologies applicable to ground systems. Many of the technologies identified will support the Mars-to-Moon program objectives for long term exploration or support NASA's near-term objectives of transitioning to commercial relay services in the Near-Earth domain. Examples include:

- **Solid State Power Amplifiers:** Data return from the Mars surface will be limited by the throughput of the trunk links from Mars to Earth. As noted earlier, a 100 Mb/s link from Mars to Earth would require 500 Watts of transmit power with a large 5.6m transmit antenna. To achieve this transmit

power, one approach is high efficiency (>50%), high output power (500 W) Gallium Nitride (GaN) Solid-State Power Amplifiers (SSPAs), both in the 32 GHz and the 27 GHz Ka-Bands. Currently, Traveling Wave Tube Amplifiers (TWTAs) are almost at the point where they can address this need, but they come with attendant penalties in mass and volume, as well as the requirement of special power supplies that produce multiple kilovolts of voltage on the spacecraft. However, space qualified SSPAs current state-of-the-art is power levels well below 100 W. Even though power levels of 500 W can be reached by power combining many tens or even a hundred devices, this approach also comes with a mass and volume penalty. This technology development is needed by the late-2030s to create the necessary high-rate data return trunk links from the Moon and Mars.

- **Traveling Wave Tube Amplifiers:** Along with SSPAs, TWTAs are an alternate technology to achieve the required 500W of transmit power from the Mars surface to Earth. TWTAs operating at Ka-band (both 32 GHz and 27 GHz) with high RF output power (>500 W) and high power-added efficiency (> 55%) will help enable the target data rates from Mars. There currently exist flight qualified Ka-Band TWTAs with 200 W of output power. Two or more of these could be power-combined [10] to produce the required power level of 500 W (to achieve 100 Mb/s from Mars far-range, as described above), but at a significant mass and volume penalty. These will be an alternative power amplifier to the SSPAs described above. The data return from the Mars surface will be limited by the ultimate throughput of the trunk links from Mars to Earth. These will be needed by mid-to-late-2030s.
- **Communication hardware that implements and extends the Proximity-1 (Prox-1) communications' protocol to S- and Ka-band frequencies:** Prox-1 is currently used at Mars at UHF for surface-to-relay orbit communications. The needed technology are radio platforms to support the new Prox-1 (with the added frequency bands) for lunar and eventually Mars operations. Lunar relay communications [5] are planned to employ proximity links with the lunar surface using S- and Ka-band frequency. Some of the proximity links will use the new Prox-1 standard. This lunar use case will similarly extend to Mars, where various landers and relay orbiters will operate in the future. The new and extended Prox-1 standard will cover the frequencies assigned to the lunar communications' regime for proximity links, and in addition it will include ranging as part of the standard, which was not included in the traditional UHF Prox-1 standard. The Consultative Committee for Space Data Standards (CCSDS) will define the extended Prox-1 standard, but there is and there will be a need for hardware platform prototypes to complete, assess, and validate the standard itself and for easier adoption into missions. An ESA/NASA collaborative endeavor is currently pursuing one subset of the standard. Additional development will be needed for proving the full standard, and for early prototyping to better infuse the technology into missions. Due to the use in the Lunar environment, it's recommended that the development of this technology commence as soon as possible, for availability within the next few years.
- **Phase-stable Ka-Band transponder:** Ka-band transponder, sufficiently stable to enable precise Ka-Band ranging. Such a transponder will enable the precise transfer of time between spacecraft, the comparison and transfer of "proper time" between ground and onboard clocks using pseudo-noise ranging and orbit determination with an expected accuracy in the clock comparisons in the order of 1 to 5 ns. The use of Ka-band for uplink and downlink communications provides larger available bandwidths (500 MHz overall in the lunar regime and 500 MHz in the deep-space channel, as compared to 50 MHz at X-band), which will enable higher code chip rates and increased accuracies of range measurements and time transfer. This technology will be required for the coordination of spacecraft constellations at the moon and Mars in the early 2030s.
- **Frequency-agile, RF, wide-band/multi-band radio.** As NASA looks to transition Near-Earth relay services from the Tracking and Data Relay Satellite System (TDRSS) to commercial services from multiple providers, there is need for reconfigurable, Ka-band radio platforms and systems to operate across NASA and commercial frequencies, considering Ka-band, S-band, and L-band. In addition, as lunar activities continue to increase, NASA anticipates increased service providers for direct to Earth, relay and surface communications services at the moon requiring an agile, and potentially wideband radio. These radios will be a key element for increased interoperability among

multiple service providers and across broad frequency ranges. Considering NASA's timeline for transition to commercial services in the late 2020's and early 2030s, this technology is needed in the next few years.

- **Linearized, high-efficiency power amplifiers and transmitters:** To improve the spectral efficiency of space to ground links, the roadmap considers linear high-power amplifiers/ transmitters suitable for use with higher-order modulations (8-Phase Shift Keying, 16-Amplitude and Phase Shift Keying) with minimal distortions for high-bandwidth cislunar and near-Earth communications. These modulations are already employed by Earth Direct Video Broadcasting Satellites (DVB-S) as part of the DVB-S2 and DVB-S2X standards of the European Telecommunications Standards Institute (ETSI) which combine these higher-order modulations with highly efficient Low Density Parity Check (LDPC), Forward Error Correction (FEC) codes that work very close to channel capacity. Unfortunately, the In-Phase and Quadrature (IQ) constellations of higher order modulations are subject to non-linear distortions by gain-saturated power amplifiers, which operate most efficiently near saturation. The objective of this technology development are power amplifiers that are simultaneously power efficient and impart low distortions to the IQ constellations of higher order modulations. Thus far, NASA mostly uses Quaternary Phase Shift Keying (QPSK), to optimize required power with throughput and bandwidth. The only way to fit the future planned high data throughputs within the current narrow RF channel allocations is to use higher order modulations (e.g., 8-PSK, 16-APSK and 32-APSK). These modulations enable the spectrum of higher data rate transmissions to fit in the existing channel bandwidths, at the expense of additional power. Missions with high throughput needs such as LandSat NEXT and other follow-on missions will need these amplifiers by the mid-2030s.
- **Communications' electronics for extreme environments:** Communication electronics needed for extreme environments include radio and amplifiers, receivers, and antennas for environments such as Venus (735 K), the Moon (50-400 K), the frozen oceans of Europa (moon of Jupiter) and others. The planned exploration of the Moon through the lunar night will be limited or not possible without radios, amplifiers and other components that can operate in both high and low temperature, and radiation environments. Without advancement in these critical component electronics, future exploration will be limited to environments within the existing capabilities. For missions to be able to survive the lunar night, these technologies will need to be developed by 2033 timeframe, to support the known exploration plans.
- **Autonomous or cognitive Software-Defined Radio (SDR) platforms:** Future lunar surface communications and Positioning, Navigation and Timing (PNT) capability and functions will require greater autonomy on the lunar surface and cis-lunar space to assist operators on the ground and optimize link efficiency through limited trunk links to Earth. Radio platforms that can autonomously and dynamically schedule, route data and adapt to link conditions to optimize network link capacity and efficiency. Currently, missions operate with pre-arranged, scheduled, ground station communications' passes and relay services, with either fixed modulations and FEC codes or with DVB-S2 type adaptive links., These new capabilities will enable sustained lunar surface operations even when direct connections with Earth are precluded (half the lunar month). Operations on the Moon will entail long-term telerobotic operation of surface assets that will encounter unpredicted environments and operational effects (e.g., rugged, unpredictable terrain, multipath reflections from the lunar regolith). Cognitive radios will autonomously enable connections to Earth through available relay and Gateway links, thus enabling surface communications at all times, independent of the existence of direct links to Earth. Lacking this capability will result in lost opportunities for surface-to-Earth connections, or surface-to-surface communication. Since this technology will enable surface lunar communications among surface elements (e.g., lunar terrain vehicles, habitats, logistics) they will be needed by the mid-2030s.
- **Multi-band and ultra-wideband antennas:** Multi-band and wideband antennas will be needed for near-Earth, cis-lunar and short-range wireless communications, as a companion to the wideband radio systems. NASA's Space Communications and Navigation (SCaN) Communications Services Project (CSP) aims to use commercial relay services for NASA mission data return in the Near-

Earth environment. Other multi-services support (e.g., Gov, Military, commercial, 17.0 to 31.0 GHz) also requires these types of antennas. Cis-lunar spacecraft as well as orbiters and landers could also benefit from multiband and even wideband antennas, if the form factor reduction is a driver for their placement. Transmitting and receiving from a single aperture, with reduced SWaP, interference mitigation, and the potential for reconfigurability will enable interoperability among multiple service providers (NASA, commercial, international partners) in the Lunar environment. The capability could also be used in places such as wideband terminals for use with multiple commercial service providers. Without this technology communications' systems may require multiple antennas, increasing mass, and form factor. These antennas will be needed by the early 2030s.

- **Reversed-band flight radios:** Reversed-band flight radios enable user mission spacecraft to operate both as a user of communication services and as a provider of communication services by changing their proximity/relay operational communications' frequency bands. Typically, spacecraft radios are configured to receive at the NTIA-allocated uplink frequencies and transmit at the downlink frequencies. However, to enable communications during proximity operations, as spacecraft are arriving to the Lunar vicinity or near the planned Lunar Gateway, the traditional transmit/receive bands of the radios would need to be swapped, depending on the phase of the mission or operation (a particular use case of the desired frequency agile radio platforms). If such dual-use communications assets existed, the adoption of standards and uninterrupted, more reliable communications would reduce the mass of carrying multiple radio systems for multiple functions. These reverse-band radios will be required by the early 2030s, as the planned Lunar infrastructure begins deployment.
- **High-sensitivity, ultra-low-noise, wideband receivers.** Existing ultra-low-noise receivers require cryo-cooling, which makes them ineligible for flight, and they are typically limited in their available receive frequencies and bandwidth. The proposed receivers could be used for a variety of purposes, such as for: detecting a wider variety of wavelengths than allowed for by conventional receivers, while reducing SWaP, and in agile spectrum scenarios (i.e., ultra-wideband capability from kHz to THz). The proposed receivers will have increased sensitivity, resistance to interference and broad tunability across multiple spectral bands, operating at ambient temperatures and they will be less sensitive to electromagnetic disruption. These future receivers will be power-efficient and offer further benefits of reduced SWaP, and advantages in form-factor and payload integration. For example, with further development, Rydberg Atoms Quantum Sensors/Receivers have the potential to operate at different wavelengths (i.e., frequency bands) enabling multi-spectral technology for space exploration. In principle, Rydberg Atoms Receivers have the potential to replace legacy technologies such as traditional receiver front ends (i.e., to replace both antenna and receiver components) while enabling multichannel communications. Current technologies do not satisfy all these criteria at once. The ultra-wide band front ends of technologies will enable reception at all frequencies. These receivers will help enable the required forward communication rate of 20 Mb/s to Mars far-range. They will be needed by the late 2030s or early 2040s, in time for human exploration of Mars.

4. Deep Space Optical Communications Roadmap

As previously noted, RF (X-band) communication systems operating at Mars today deliver a few hundred kb/s when Mars and Earth are maximally separated (~2.7AU). While utilization of higher (Ka-band) frequencies and incorporation of state-of-the-art existing RF space transmitter technologies could extend those rates to 5-10 Mb/s, physical spacecraft constraints limit feasible data return rates for RF systems. In addition, even if RF technology advancement were to successfully extend those RF data rates to tens or even hundreds of Mb/s, given that there will be coding overhead and most likely multiple users operating simultaneously, RF spectrum constraints will limit the ability of such RF systems to operate at the higher data rates that will be needed. NASA has long recognized the potential for optical communications to improve the performance of space communications systems and has made significant investments to develop that capability with projects such as Lunar Laser Communications Demonstration [6] and, more

recently, the Deep Space Optical Communications (DSOC) demonstration [7]. These efforts have developed and demonstrated solutions to the critical engineering challenges associated with optical communications links, including ability to point and stabilize the narrow optical beams produced by 10 to 20cm optical telescopes, the ability to efficiently generate and modulate optical signals at average powers of several Watts with peak powers of >100 Watts, and the ability to collect and efficiently couple the received light after propagation through the Earth's atmosphere to highly-sensitive high-count-rate single-photon detectors. The DSOC demonstration, currently operating aboard the Psyche mission, is representative of the current state of the art for deep space optical communications. To date, that system has demonstrated a return data rate of 8.33 Mbps at a range of 2.68 A.U., very close to the maximum Mars-Earth range at which future systems capable of supporting rates >100 Mbps are needed. This link is accomplished with a 22cm transmit aperture and 2 W of average transmit power with 16-ary Pulse-Position Modulation (PPM) format. The primary DSOC ground terminal is the 5-m Hale Telescope aperture which is coupled to a superconducting nanowire photon-counting receiver.

Efficient scaling of this link design to operate at >100 Mbps is not as simple as increasing the transmit power and/or the size of the transmit and receive apertures since the DSOC link at this range operated in the nighttime. The objective Mars-Earth maximum-range link occurs when Mars is close to solar conjunction. Thus, a ground-based receiver will be operating in the daytime and affected by the resulting background from scattered solar photons in the Earth's atmosphere. The effect of solar background on optical receivers can be substantial as meter-class ground-based receive apertures typically must couple many spatial modes of light onto the receiving optical detector, owing to the effects of turbulence in the Earth's atmosphere (which often has a spatial coherence length on the order of several centimeters). Moreover, efficient narrow-band spectral filtering of the solar background can be challenging because of the resulting wide-field of view required to efficiently couple the multi-mode signal to the optical detector. Thus, daytime deep space links may be expected to operate in a background-limited regime, where the number of background photons in the receiver often exceeds the number of signal photons. In this case, there is added benefit to increasing the ratio of signal-to-background photons at the receiver, which improves the receiver efficiency, measured in bits per received signal photon, rather than simply increasing the size of the receive aperture, which keeps the ratio of signal-to-background photons roughly the same [8]. This helps to prioritize the technology advancements needed to facilitate this future link capability.

For spacecraft terminals, increases in transmit power and aperture can improve the effective isotropic radiated power of the transmitter, increasing the data rate through improvements in both the received signal photon flux and the receiver efficiency in the presence of background.

- **High-power optical amplifiers:** Currently demonstrated space-based optical amplifiers in the 1550 nm band provide <10 W with an electrical-to-optical power efficiency of <20%. Future amplifiers will need to operate at 10-100W with efficiencies >20%. Since optical spectrum is plentiful, receiver efficiency can be further improved by increasing the orthogonality of the transmitted signal, either using PPM, as has been demonstrated with systems like LLCD and DSOC, or by using other techniques such as frequency-shift keying (FSK). The use of PPM creates a high peak-to-average optical power at the transmitter. Thus high-average-power optical amplifiers will need to support peak powers of >1 kW. Alternatively, the use of FSK requires amplifiers with multi-wavelength capability.
- **Large, low-mass apertures:** Today's space-based optical transmitters have apertures that are <22 cm in diameter. Future high-rate deep space systems will require apertures that are 50-100 cm in diameter. These apertures will need to provide near-diffraction limited performance at 1550-nm wavelengths with minimal mass. Moreover, they will need to point the optical beam with sub-microradian stability. This pointing system will likely be implemented with a combination of inertial stabilization and/or tracking of an optical source (it is noted that the desired 20 Mbps forward link will likely provide several pW of power that could be used for optical tracking and disturbance rejection).

In contrast to radio communications systems, for which NASA operates the DSN supporting many concurrent operational missions, NASA does not currently have dedicated ground infrastructure to support optical links for science and exploration missions. Optical communications missions to date have developed experimental receivers or utilized existing ground telescopes such as JPL's Optical Communications Telescope Laboratory (OCTL) or the Palomar astronomical observatory used for the DSOC mission. Future missions will require the development of dedicated optical terminals. High-rate links operating at Mars maximum ranges and beyond will require effective receive apertures of ~5-10 meters that can be operated in both night time and day time conditions. To mitigate the effects of clouds on optical link availability, these apertures will need to be deployed at worldwide sites with good cloud statistics. Building out an optical capability akin to the DSN will require a similar sustained investment in deploying and operating a world-wide array of optical ground terminals. This will benefit from several technology developments, including:

- **Low recurring-cost large-aperture ground terminals:** Effective apertures of ~5-10 meters are required to support the envisioned high-rate links to Mars and beyond. The DSOC program's use of the 5-m Palomar astronomical observatory has shown that a single large aperture can be efficiently coupled to a photon counting receiver. A secondary receiver for DSOC has also demonstrated an approach for adding optical reflectors to an existing DSN 34-m radio antenna, the "RF-Optical hybrid" system [9]. However, it may be more cost-effective to build a large effective aperture out of an array of smaller apertures. Both the DSOC and LLCD missions demonstrated an all-digital approach for combining multiple small apertures with photon-counting receivers. Smaller apertures are likely easier to operate in the day time (with solar filters to protect the telescope from direct sunlight). Moreover, an array of small apertures could potentially support multiple missions simultaneously at times when the full aperture is not required for any particular link. The DSOC downlink signal was successfully received in a ground optical array consisting of the Palomar aperture, the RF-optical hybrid system, and the OCTL terminal. Notably, these three optical apertures were arrayed despite physical separations of 100km or more. Clearly a careful trade study is needed to evaluate the cost/benefits of each of these architectures for deep space ground optical terminals.
- **Spatial and spectral filtering:** As noted above, the performance of optical links using ground-based receivers in the daytime is limited by background from scattered solar photons. In this scenario, the receiver efficiency can be improved by reducing the number of spatial modes coupled to the receiver and/or better spectral filtering. Reducing the number of spatial modes may be accomplished with novel adaptive optics approaches to mitigate the effects of atmospheric turbulence across the optical aperture. Low-loss narrow-band optical filters can similarly help to reduce the number of spectral modes entering the receiver, ideally approaching the ~10 – 10,000 MHz (80 – 80,000 pm) spectral width of the modulated optical signal.

The aforementioned technology developments are needed to support high-rate optical return links from deep space. Additional investments will facilitate the envisioned forward links of up to 20 Mbps from Earth to Mars. It is noted that the LLCD mission demonstrated a forward link of 20 Mbps from Earth to the Moon. Extending that link range to Mars requires an additional 60 dB of gain in the link design. With a similar ground-based transmitter approach, this requires additional technology developments beyond the larger receive aperture noted above:

- **High-average-power ground-based optical transmitters:** The minimum beam-width of ground-based uplink transmitters for deep-space links are limited by atmospheric effects near the ground aperture. Thus, delivering sufficient power to support 20-Mbps forward communications to a spacecraft receiver will require very-high average transmit power. Individual transmitter powers of 1-10 kW will be needed. Additionally, the use of PPM data formats to improve receiver efficiency will require peak powers >10 kW.
- **Large aperture space-based transmitter:** An alternative approach would be to utilize an Earth-orbiting space-based transmitter for the forward link. Since this link does not have to first

propagate through the Earth's atmosphere, a larger aperture with near-diffraction-limited performance may be utilized. In this case, a 50-100 cm aperture with 50-100 W transmit power, could be used.

- **High-rate space-compatible photon-counting receivers:** DSOC has demonstrated the use of a photon-counting camera in the space terminal for tracking and low-rate forward communications (1.6 kbps). This camera is based on a 32x32 pixel array of Geiger-mode avalanche photodiodes. Support of future 20-Mbps forward links will require photon-counting detectors that are capable of high-detection-efficiency (>30%), high-resolution (<1-ns) and high-count-rate (~10 – 40 Mcps) time-tagging of received photons. Moreover, these detectors will need to survive operations in the space radiation environment for 2 – 10 years.

5. Conclusion

The Deep Space Network is currently oversubscribed, meaning more antenna time is requested by space missions than can be provided. The demand is driven by the increase in the number of deep space science missions in operations, the increase in the longevity of those missions, and increases in data rates and volumes. Spectrum restrictions and the physics of RF communications links mean that today's X-band systems at Mars and beyond have reached their limits. Future deep space missions will have to move to Ka-band. The communication needs of crewed missions to Mars in the 2040's will almost certainly mandate a further need for optical communications. STMD envisions both Ka-band RF and optical trunk lines between Mars and Earth. Incorporating optical communication links into the architecture greatly reduces the RF Ka-band spectrum pressure and also relieves significant DSN RF antenna loading in those future years. Maintaining a Ka-band capability enables high-rate communications between Mars and Earth to continue in the presence of clouds, when optical is not possible; Ka-band data rates would likely be lower than optical but will still be adequate for those constrained periods. NASA's future deep space missions, and especially future crewed missions to Mars that will involve multiple, independently functioning elements, with human-rated communications and tracking requirements, will require new technologies and capabilities to be fully successful. NASA's Space Technology Mission Directorate is working to ensure those deep space telecommunications technologies are ready for infusion into operational networks.

Acknowledgement

A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). A portion of this work was also performed at MIT Lincoln Laboratory for the National Aeronautics and Space Administration.

References

- [1] "Audit of NASA's Deep Space Network," IG-23-016, Released July 12, 2023.
- [2] Edwards, B.L., Antsos, D. Biswas, A., Braatz, L., Robinson, B.S., An Envisioned Future for Space Optical Systems. In 2023 ICSOS Conference. IEEE.
- [3] Robinson, B.S., Khatri, F., Padula, M., Horowitz S., Bay, M., and King, J., Optical Communications for Human Space Exploration – Status of Space Terminal Development for the Artemis II Crewed Mission to the Moon. In 2022 ICSOS Conference. IEEE.
- [4] "Civil Space Shortfalls", NASA, <https://www.nasa.gov/spacetechpriorities/>, August 2024
- [5] Israel, David J., Gramling, Cheryl J., Lunanet Interoperability Specification Document, Rev 5., NASA/TP–20210021073, September 2023.
- [6] Boroson, D. M., Robinson, B. S., Murphy, D. V., Buriarek, D. A., Khatri, F., Kovalik, J. M., Sodnik, Z., Cornwell, D. M., "Overview and results of the Lunar laser communication demonstration," Proceedings of the SPIE, 8971 (2014).
- [7] Velasco, A. E., et al., "Deep Space Optical Communications (DSOC) from the Psyche Mission", IEEE Summer Topical Meeting Series, Bridgetown, Barbados (2024).
- [8] Boroson, D. M., "On Achieving High Performance Optical Communications from Very Deep Space",

Proceedings of the SPIE, 10524 (2018).

[9] Allmaras, J., Korzh, B., Beyer, A., Wollman, E., Bumble, B., Rogalin, R., Alerstam, E., Mohageg, M., Srinivasan, M., Hoppe, D., Shaw, M., "Large-area SNSPD array for RF/Optical Hybrid 7-segment pathfinder receiver," Proceedings of the SPIE, 12413 (2023).

[10] R. N. Simons, E. G. Wintucky, J. D. Wilson and D. A. Force, "Ultra-High Power and Efficiency Space Traveling-Wave Tube Amplifier Power Combiner with Reduced Size and Mass for NASA Missions," in IEEE Transactions on Microwave Theory and Techniques, vol. 57, no. 3, pp. 582-588, March 2009.