Deep Space Network: The Next 50 Years[1]

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In 2014, NASA's Deep Space Network (DSN) celebrated its 50th year of enabling exploration of the Moon, Solar System planets, and beyond. During those 50 years, the DSN has grown along with the associated spacecraft flight systems, providing some 13 orders of magnitude communications systems improvement. It has also contributed to many of the world's most important scientific discoveries and provided substantial technological spinoffs that have become part of everyday life on Earth. Studies of the next 25 years indicate that deep space missions will need an order of magnitude increased communications performance per decade – and this is likely to continue beyond that time. As exhibited by this meeting, another major change happening right now is the emergence of a standardized international community for tracking deep space missions. The future definitely involves increased international cooperation. This paper explains the near term plans already underway for the DSN. We also consider the plans and possibilities for deep space optical communications. Finally, we will discuss opportunities for international participation in the next 50 years of deep space exploration.

Nomenclature

BWG	=	Beam Waveguide
CCSDS	=	Consultative Committee for Space Data System Standards
DAEP	=	DSN Aperture Enhancement Project
DC	=	Direct Current
DSN	=	Deep Space Network
DSOC	=	Deep Space Optical Communications
DTN	=	Disruption Tolerant Networking
DWDM	=	Dense Wavelength Division Multiplexing
ESA	=	European Space Agency
ISRO	=	Indian Space Research Organization
JAXA	=	Japan Aerospace eXploration Agency
JPL	=	Jet Propulsion Laboratory
LADEE	=	Lunar Atmosphere and Dust Environment Explorer
LLCD	=	Lunar Laser Communications Demonstration
MRO	=	Mars Reconnaissance Orbiter
MRO	=	Mars Reconnaissance Orbiter
QAM	=	Quadrature Amplitude Modulation
QPSK	=	Quadrature Phase Shift Keying

I. Introduction

NASA's Deep Space Network (DSN) was officially founded on December 24, 1963, though some facilities actually existed somewhat before that time. The DSN has been responsible for communications and radiometric tracking in support of NASA's space missions beyond Earth geosynchronous orbit. It also provides these services to

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space missions of other countries through various agreements. Today, the DSN supports approximately 36 missions in any given month, in all phases of their development from design through extended operations. The many missions enabled by the DSN in its first 50 years include Ranger, Voyager, Viking, Galileo, Cassini, New Horizons, and all the Mars rovers.

In addition, the DSN serves as a science instrument in conjunction with space missions. By using the communications link with spacecraft, data from the DSN can be used to observe perturbations, inferring local gravity fields, atmospheric pressure on other planetary bodies, or densities of particles in rings, for example. These are known as radio science observations.

The DSN can also perform science observations on its own. Its large antennas are often used as radio telescopes. In fact, the DSN's 70m antenna in Australia is currently the world's largest radio telescope in the southern hemisphere. Its 70m antenna at Goldstone, California, is equipped with a 500 kW continuous wave transmitter to configure the DSN as radar. In this mode, the DSN captured the first images of the surface of Venus, helped determine the astronomical unit, and today characterizes potentially hazardous asteroids, honing their trajectories while also capturing images and rotational motion.

The DSN currently has antennas in three locations (see Figure 1.) Each has a 70m antenna and multiple 34m antennas that are scheduled to support missions or perform science observations. There is a central control center for the DSN at the Jet Propulsion Laboratory (JPL) in Pasadena, California.

When the DSN began this journey, it was a unique system. Today, several other nations maintain deep space communications facilities. The DSN is now a member of a global community.

The DSN was a state-of-the-art system when it was founded 50 years ago and it remains so today. NASA's continued investment in both the DSN and the corresponding flight systems have resulted in a prolonged robust program of deep space exploration.

Figure 1. Current Configuration of the DSN

We are now at a major juncture in deep space exploration. With the recent New Horizons flyby of Pluto, we have visited all the major objects in the Solar System at least once. We have begun intense exploration of these – concentrating first on Mars. We have sent our first spacecraft into interstellar space. We now know of thousands of new objects of interest orbiting other stars in our galaxy, whetting our curiosity for more knowledge and future interstellar exploration. We are also on the verge of sending humans beyond low Earth orbit for the first time since the Apollo Program.

II. The First 50 Years

When measuring the performance of a deep space communication system, one is always painfully aware of the fact that deep space missions are simply very far from Earth. In fact, the DSN today provides service to missions as close as geosynchronous orbit and as far as the edge of our Solar System. The metrics we use to describe this system performance include "link difficulty," in which the distance between the spacecraft and the DSN is normalized out. For example, in Figure 2 we show the normalized downlink performance of the deep space communication system by dividing each point in the curve by the mean distance to Jupiter squared. In this way, we can see the actual improvement in the communication system as a function of time.

This "downlink difficulty" is, in fact, the metric that best describes the main challenge to the DSN: detect extremely weak signals from extremely far away. The DSN also keeps track of uplink difficulty – though this tends to be much less of a driver for the missions supported thus far. Finally, the link data rate in both directions round out the important communications metrics.

As indicated by Figure 2, downlink difficulty has improved by factor of 10^{13} over the DSN's first 50 years – a rate much higher than even Moore's Law. This was accomplished by improvements on both ends of the link and in systems technologies (such as modulation and coding advances.)

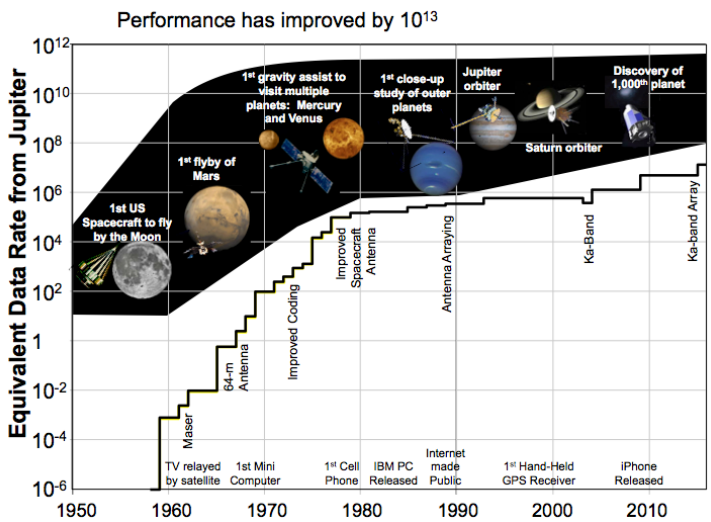

Figure 2. History of Downlink Difficulty

The technology that was developed for the DSN, as well as the other NASA space communication networks, has benefited society in other ways. It laid the foundation for the digitized audio and video – recordings and transmission. It also provided some of the basis for the mobile telephone revolution.

Growth in the downlink difficulty metric has slowed in recent decades. This is partially due to the maturation of radio technology but also can be traced to a more recent thrust to reduce operations and maintenance costs. Much of the recent technological advances have gone into managing the overall cost of the DSN to NASA. In fact, these costs have gone down in the last decade – providing a wedge for investing in newer antennas, software, and signal processing.

Another important metric concerns the ability of missions to navigate a spacecraft to specific locations across the Solar System. Figure 3 shows how the angular accuracy with which a spacecraft can be delivered to a target has increased during the first 50 years of the DSN[1]. The angular accuracy today is so good that it is no longer the limiting error source in landing spacecraft on Mars. Future improvements in pinpoint Mars landings will come from new entry descent and landing (EDL) techniques.

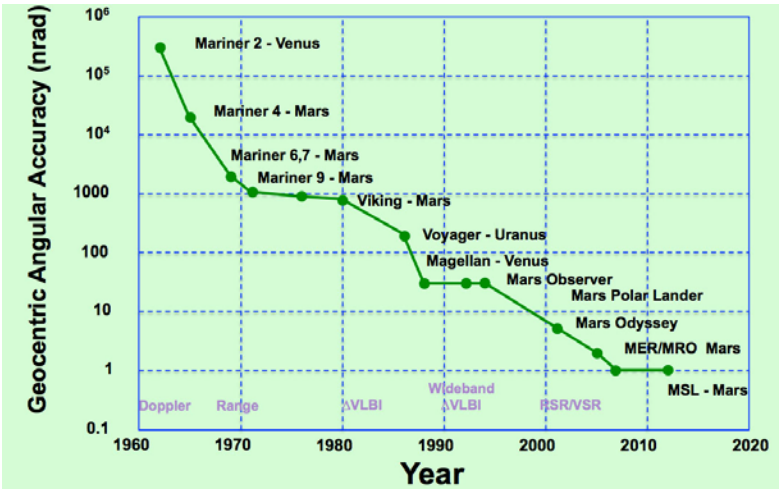

Figure 3. History of Navigational Angular Accuracy

III. The Future of Deep Space Exploration

There has always been a close connection between NASA's aspirations for flight missions and DSN development. This give-and-take is essential because simply improving the capability of the DSN cannot always result in an end-to-end communications or navigation improvement. There has to be a similar set of developments on the space side. To accomplish this, DSN engineers and mathematicians have typically worked on both ends of the link.

In addition, the DSN maintains a future mission modeling capability that looks at least two decades into the future, considering the possible paths NASA mission selections might take, This guides interactions between DSN

staff and mission designers with enough lead time to influence system trades. It also feeds into DSN strategic investments for major long-lead items, including new ground stations.

The next several sections consider results from the most recent of these future mission set analyses.

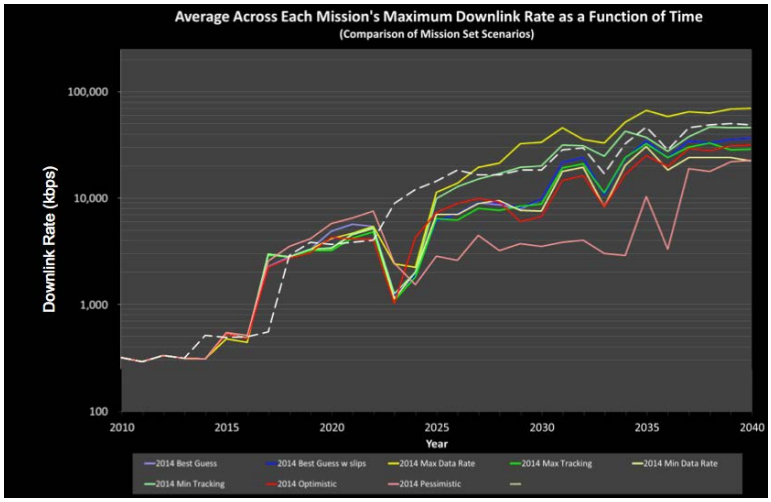

Figure 4. DSN Mission Data Rate Trends

A. Science Directions

With New Horizon's recent encounter with Pluto and its moons, we have visited all the major objects in the Solar System. NASA and the other world space agencies have begun a second wave of exploration with intense study of these objects – beginning with the Moon and Mars. There has been a continuous human robotic presence at Mars now since 2004 with spacecraft from three nations. The Moon is about to enter a second period of exploration, spurred on by a combination of new scientific discoveries (e.g. water near the poles.) Asteroids and comets are now of increasing interest to understand the early Solar System, and protect Earth from possible future catastrophic collisions. In the next decade, humans will venture into deep space for the first time since the end of the Apollo program. In two decades, they could be at Mars.

There is also a trend toward smaller spacecraft in deep space. There will even be CubeSats in deep space in the next few years. Smaller, less costly spacecraft are leading to some interesting new mission concepts that will likely challenge the DSN in new ways. The desire to get reasonable link performance with small spacecraft might lead to the need for increased DSN performance. There will also be a need to track more, smaller spacecraft from the DSN without increasing its operation cost.

B. Future Mission Modeling Results Through 2040

The DSN's most recent analysis of the future mission set indicates the need for a data rate increase of a factor of ten per decade, as shown in Figure 4.

This same analysis shows that these future missions will tend to be closer to Earth than today. The ends of the Voyager, Cassini, and New Horizons missions drive this. There will be fewer outer planets missions taking their place. However, we will need to achieve these two orders of magnitude increase in data rate for various fixed deep space distances – including Mars. This means we will also need a similar increase in the downlink difficulty metric.

The real question for this paper is "what happens after that?"

C. Long Term Communications Trends on Earth

Because we have no reasonable future mission model for the period after 2035, we will need to resort to some extrapolation. We could base the future on the factor-of-10^{13} improvement indicated by the first 50 years of the DSN. However, this is likely too aggressive because that number included the major breakthroughs in early space missions indicative of the start of an exponential technology growth function.

Instead, we will consider terrestrial communications trends going back many years before that.

Figure 5 shows a trend for some long distance terrestrial communication starting with Morse code over the first trans-Atlantic cable. The average exponential increase over this

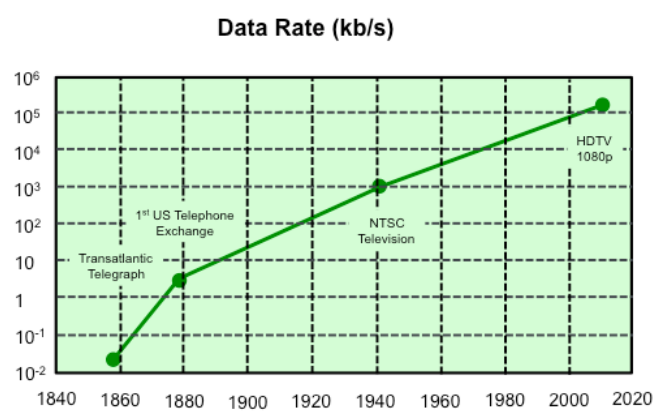

Figure 5. Long Term Communications Trend

~160 year period was 0.34 orders of magnitude per decade – considerably less than the rate predicted for the DSN over then next 20 years.

However, the improvement has been increasing faster since the inception of computer-to-computer communications. Figure 6 shows the growth in modem capabilities in the last six decades[2]. The overall average exponential increase over this period was 1.3 orders of magnitude per decade.

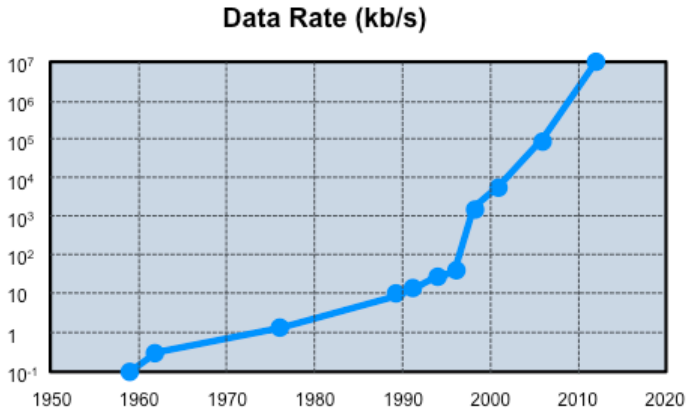

Figure 6. Internet Communications Trend

D. Extrapolation Through 2063

Clearly deep space communications will continue to lag terrestrial capability – but the growth in data sources (spacecraft instruments or public engagement material from space) will likely grow at the same rate. Hence, we will assume a conservative growth rate of an order of magnitude per decade for the entire 50-year future period. This is consistent with the future mission set analysis for the next 20 years

IV. Improving by 10^5

Before embarking on our thought exercise for communications improvements, it is necessary to define a baseline for today's performance. We chose the Mars Reconnaissance Orbiter (MRO) link for this baseline because it represents the state-of-the-art in communications in deep space today. MRO is a Mars orbiter with a 3m X-band high gain antenna and 100 W of transmitter power. It uses rate 1/6 turbo coding for its high data rates, currently the best performing code in the DSN. The routine link for MRO uses a single 34m DSN BWG antenna. With these parameters, the link supports 1.1 Mbps when Mars is farthest from Earth. This is what we will use as the baseline for this paper.

It is also important to note that, based simply on Physics, the same MRO link should be able to support 20 Mbps at Mars closest approach to Earth. However, there are bottlenecks in both the flight hardware and the DSN that artificially restrict the performance to approximately 5 Mbps.

DSN engineers are already working on the first two orders of magnitude communications capability improvements that will be needed in the next two decades. Hence the material in the following two sections is fairly well understood.

A. Decade 1: Antenna Arraying and Ka-Band (10x over today)

The DSN has been using antenna arraying for many years. Arrays of DSN and non-DSN antennas were critical to supporting Voyager's encounters with Uranus in 1986 and Neptune in 1989[3]. When NASA's Galileo spacecraft's high gain antenna failed to open en-route to Jupiter, arraying became the routine mode of operations in 1995[4].

Today, the DSN offers antenna arraying of our 70m and 34m antennas within each complex as a standard service. It is typically used by outer planets missions and for critical events. With today's DSN configuration, it is possible to array up to three 34m antennas, providing essentially a factor of three increase in communications performance over a single 34m antenna. When the DAEP project is complete, it will be possible to array four 34m antennas within each complex, for a factor of four increase.

As mentioned above, there are bottlenecks in the current flight systems and the DSN that artificially restrict data rates to ~5 Mbps. Both of these will be alleviated in the next decade. JPL is currently developing a new flight radio, the Universal Space Transponder, that will allow downlink data rates up to 300 Mbps. Also, the Common Platform[5] signal processing upgrade to the DSN is being designed with the same capability.

Although most missions supported by the DSN use X-band (8.4 GHz) for downlink, Ka-band (32 GHz) is a standard service today. We expect most new deep space missions to be using Ka-band in the next decade. The end-to-end Ka-band system offers about a factor-of-four increase in performance over the X-band system – even with weather effects taken into account.

Hence, between antenna arraying and Ka-band, we should have no problem achieving a factor-of-ten increase in downlink telemetry performance by 2025.

In addition to improving the downlink, the DSN will need to increase uplink performance in the next decade. This is mainly driven by the needs of human spaceflight missions, whereas current DSN uplink is limited to the relatively low-bandwidth requirements of commanding or updated software loads to robotic missions. This will not require any great stretches in technology. The improvements here will include adding error-correcting codes to the uplink.

B. Decade 2: Optical Communications (100x over today)

JPL has been investing in optical communications as a technology development activity since the 1980[6]. In recent years, NASA has made great strides in bringing such a capability within grasp of operational missions.

In 2014, NASA flew the Lunar Laser Communications Demonstration[7] (LLCD) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft. This was the first practical demonstration of optical communication from deep space. It achieved up to 622 Mbps downlink data rate over 400,000 km, operating with three (two NASA and one ESA) receive stations.

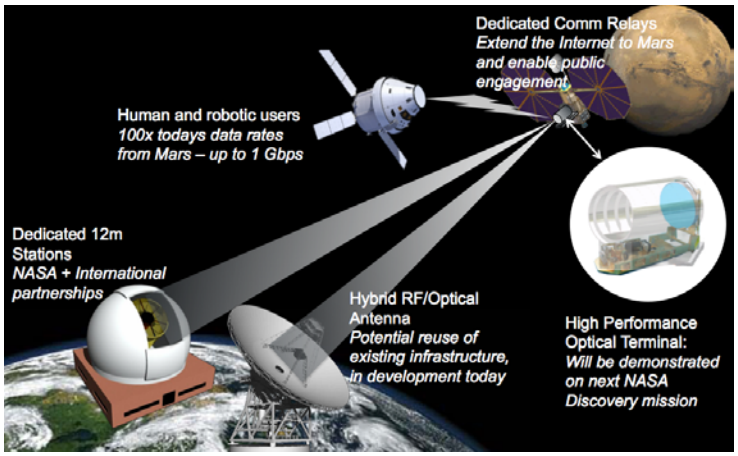

Figure 7. Deep Space Optical Communications Concept

Optical communication systems well beyond the Moon will require additional technological advances. The flight terminals will need much more accurate beam pointing (and associated flight terminal stability.) Additionally both ends of the link will need to "point-ahead" to the predicted locations of the opposite terminal to compensate for the relative motion during the signal propagation.

To this end, JPL is currently developing the Deep Space Optical Communications (DSOC) terminal[8]. It will likely fly as a demonstration on the next NASA Discovery Mission in ~2020. With the last of these technology risks retired, true operational deep space optical communications can begin by 2025. With a 22 cm optical flight aperture and a 12m ground receive telescope, this system will provide ten times the performance of the Ka-band system described in B.

C. Decade 3: Advanced Optical Communications (1000x over today)

The next order of magnitude increase should come naturally from the fact that optical communications will follow a similar exponential technology growth curve to radio and other capabilities. Though it is impossible to forecast exactly what improvements will be the most likely, we can make some educated guesses.

Today, the lasers used for space communications have a DC to light efficiency of ~12%. We predict efficiencies up to 25% in this time frame. Hence, there is a factor of ~2 to be gained.

Optical systems in this timeframe might employ dense wavelength division multiplexing (DWDM) in the downlink transmitter to provide tens or even hundreds of channels, as commonly used in today's commercial fiber telecommunications, to take advantage of the higher power lasers. Space-qualified integrated photonic circuits, as well as ASIC-based error correcting coders, will squeeze the electro-optic components of tens of individual wavelength channels into a chip of less than 1 square centimeter, making this technology viable for spaceflight. This could provide a factor of ten over the Decade 1 optical channel. This technology is available today[9], though not yet space qualified.

The first generation deep space optical systems use direct detection of photons. Future systems will likely also allow for coherent communications, allowing for increased noise rejection in power-constrained applications. This can likely lead to a factor of 3-5 improvement for outer planet mission applications. This will require new technology to allow coherent coupling of many small optical apertures into single-more fibers. Progress is already being made in this area[10].

Natural evolution of optical component technology will also tend to reduce the mass and size of flight terminals, leading to a potential increase of a factor of 2-3 in efficiency.

Between these effects (and others) it is likely that the required factor of 10 will be quite possible in this time frame.

D. Decade 4 and 5: Some Crystal Ball Theory (100,000 over today)

These decades are more problematic as it is much harder to forecast technology this far in advance.

Some improvements will follow natural progressions – even for the then-to-be-mature field of optical communications. Recall that the past history of the DSN has shown that improvements in radio systems are still likely after 50 years of maturation.

Power efficiency of transmitters may improve in these decades, leading to additional increases in performance. Flight components may continue to be miniaturized, resulting in increased efficiency.

It is possible that power generation technology for space may be vastly improved in this time frame – driven by increased human exploration in deep space. This will have a direct impact on communication performance.

The data rate of the individual DWDM optical channels might be increased using high-order, spectrally efficient modulation. For example, dual-polarization QPSK coherent optical modems that can transmit at 100 Gbps data rate (127 Gsps, with including coding overhead included) are commercially available today[11] for fiber communications and could be ruggedized for deep space missions. Eventually, even higher-order modulation types (such as 64-QAM) might become practical, leading to an additional factor-of-ten improvement.

Antenna arraying on a large scale (for both radio and optical) may become economical due to the associated decrease in front end electronics and back end signal processing.

The hardest part of this prediction concerns new technologies that are only at their infancy today. Once of these is quantum entanglement. Entanglement has the potential to completely revolutionize long distance communications both on Earth and in space. Another technology that might come into play is X-ray communications. X-rays are currently being studied as a potential source of navigation information for deep space missions. If the detectors for these applications can be made small enough, perhaps they will also be useful for communications.

In any case, experience with technology indicates that these two orders of magnitude will probably be possible.

E. Relay Communications

Some of the capabilities described in B-D are not likely to be practical on smaller spacecraft. If the small spacecraft are part of mission involving a larger, more capable spacecraft, a relay capability might be emplaced. In this way, the small "daughter craft" need not have nearly as capable a communications system as the larger "mother craft."

NASA has flown several missions involving mother and daughter spacecraft. Examples include the Viking Mars mission, Galileo's Jupiter Probe, and Cassini's Huygens Probe. ESA recently flew a daughter craft on their Rosetta comet mission.

Advanced networking technology, such as Disruption Tolerant Networking[12] (DTN) will likely be used to manage data flow across the various nodes in future configurations. DTN is specifically designed to allow efficient and secure communications in the cases where individual links have long latency (as is the case for deep space) are temporally extant.

F. Planetary Networks as relay infrastructure at other Planets

In locations of more intense exploration, NASA will emplace Planetary Networks to support multiple missions. This is already a very effective Mars Network[13] in place for the past decade. It uses orbiting science spacecraft as communications relays. This has proven to be extremely beneficial for rovers and landers at Mars by freeing them from the need to carry large communications payloads to communicate directly to Earth. As demand for relay service increases, we expect that NASA (perhaps in collaboration with other world space agencies) will deploy dedicated communications and navigation relay orbiters at locations of great interest.

V. Summary of the expected 10^5 gain

Figure 8 shows a summary of the gains explained in Section IV. Predicted performance is shown for various planetary destinations. For Mars, we show performance for closest approach and furthest distance from Earth.

There are three columns representing today's system performance. The first of these represents the "official" baseline described above – MRO's X-band system using a single DSN 34m antenna. Though this is typical for today's system, we can (and do) provide additional performance as needed. This is indicated in the next two "Today" columns. The middle column shows the use of an array of three DSN 34m antennas. The third column shows a single 34m antenna but using Ka-band.

	Distance (AU)	Today (Mbps)			2025 (Mbps)		2035 (Mbps)	2045 (Mbps)	2055 (Mbps)	2065 (Mbps)
DSN Configuration		34m X-band	3 x 34m X-band	34m Ka-band	4 x 34m Ka-band	Optical	Optical	Optical	?	?
Spacecraft Configuration		3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 100 W transmitter 1/6 Turbo code	3m antenna 180 W transmitter 1/2 LDPC code	0.3m optics 10 W transmitter PPM modulation	0.5m optics 50 W transmitter PPM modulation	0.5m optics 200 W transmitter 2nd gen modulation	?	?
Venus (Closest)	0.3	80.0	240	320	2,304	2,800	2.9E+04	2.9E+05	2.9E+06	2.9E+07
Venus (Farthest)	2.4	1.3	3.8	5	36	44	460	4,603	5.E+04	5.E+05
Mars (Closest)	0.6	20	60	80	576	700	7.E+03	7.E+04	7.E+05	7.E+06
Mars (Farthest)	2.6	1.1	3.2	4.26	30.7	37	392	4.E+03	4.E+04	4.E+05
Jupiter	5.4	0.247	0.741	0.99	7.1	8.6	91	909	9,093	9.E+04
Saturn	10.1	0.071	0.212	0.28	2.0	2.5	26	260	2,599	3.E+04
Uranus	19	0.020	0.060	0.08	0.57	0.70	7.3	73.4	734	7,345
Neptune	30.3	0.008	0.024	0.03	0.23	0.27	2.9	28.9	289	2,888

Figure 8. DSN Data Rates: Next 50 Years

There are two columns for 2025. Though optical communication in deep space will become operational in this time frame, most missions will continue to use radio as their main science downlink. Both systems will show considerable improvement.

The columns for 2035 and 2045 show the expected performance of optical communications systems. Radio will still be available and likely will be used by most missions in conjunction with optical. For missions with both radio and optical systems, we expect the radio to be used for engineering data and to aid with navigation and direct science. At time progresses, the optical system will see increased utility for both navigation and science.

The columns for 2055 and 2065 show factors of ten increases as expected – but there is actually little information behind them!

VI. Keeping the Budget Under Control

As mentioned in the introduction, NASA"s budget will not accommodate huge increases in DSN investment. We assume that operations and maintenance costs for the DSN will remain essentially constant in buying power (e.g., will grow only with inflation.) However, some changes in technology will require specific investments in new infrastructure This will likely be the case for optical communications as large ground telescopes will be required in multiple locations. It is possible that some existing DSN radio antennas may be retrofitted to serve as optical receivers – but even this will require an investment.

We believe that deep space exploration will be a global endeavor. By coordinating investments across many nations, we might be able to manage the overall cost of some of these infrastructure enhancements.

VII. The Global Community of DSN

As mentioned several times before, NASA is not alone in its exploration of deep space. Today, even the DSN is not unique. Several other nations, and even some universities have similar capabilities: one or more large radio antennas capable of communications and radiometric track of spacecraft in deep space. By developing communications standards, mostly through the Consultative Committee for Space Data Systems Standards [14] (CCSDS,) most deep space missions can be supported by several of these facilities as needed. Today, the DSN routinely tracks spacecraft from the European Space Agency (ESA), The Japan Aerospace Exploration Agency (JAXA), the Indian Space Research Organization (ISRO), and many others. Likewise, NASA spacecraft are often tracked with ground stations from other agencies.

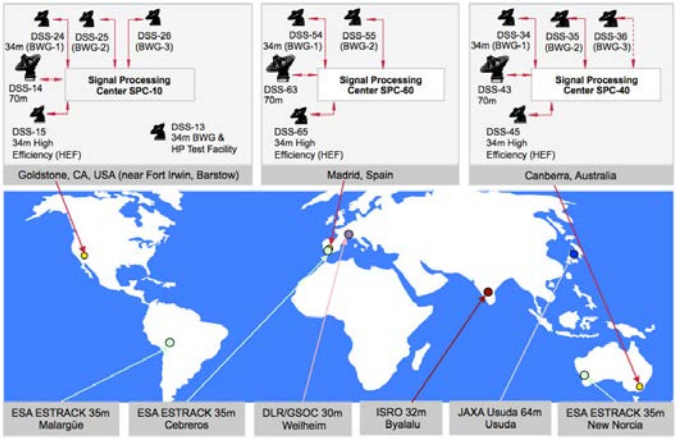

Figure 9. Some Global Deep Space Ground Stations

Figure 9 shows the location of some of these

international facilities today. There has been coordination between agencies as this infrastructure has developed so that the sites compliment one another, providing increased global visibility to deep space and multiple navigational baselines for interferometry.

More recently, universities have begun using large radio telescopes for tracking spacecraft. NASA is currently working with Morehead State University in Kentucky so that their 22m antenna will be capable of tracking deep space missions using CCSDS standards. Such antennas can become part of a future "federated" extension to the DSN.

Within 50 years, we might see commercial activity in deep space. If so, we expect there will be privately owned ground stations capable of supporting deep space missions.

VIII. Conclusion

The DSN has performed well for its first 50 years, enabling most of humankind's exploration of space beyond geosynchronous Earth orbit. Much of what we know about the planets, comets, asteroids, and moons in our Solar System, most of what we know about planets in other star systems, and a great deal of our knowledge of other galaxies has been enabled by the DSN and by similar capabilities developed by other nations.

As we move forward into the next 50 years of exploring and possible exploiting deep space, the DSN and its global brethren will be equally important. They will benefit from a host of new technologies and will likely, in turn, provide technological benefits to other parts of society.

We look forward to presenting another paper in 50 years about the DSN's first century and what we might expect in the next.

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