Enabling Richer Data Sets for Future Astrophysics Missions

Infrastructure Activity white paper submitted to the National Academy of Sciences Astro2020 Decadal Survey on Astronomy & Astrophysics

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This document contains pre-decisional information — for planning and discussion purposes only.

A consequence of our improved understanding of the Universe and our place in it is that future Astrophysics missions must envision richer data sets. NASA has enabled an infrastructure that permits future Astrophysics missions to deliver richer and more complex data sets. Importantly, this infrastructure has been and is being implemented without requiring funding from NASA's Astrophysics Division, but it is available to future Astrophysics missions and future Astrophysics missions would benefit from making use of it. This Activity white paper outlines both the current status of that NASA infrastructure and development plans into the next decade.

Key Science Goals and Objectives

Often, the science return from a mission is dictated ultimately by how much science data can be returned. As only one example, in order to meet its prime science objectives, the *Kepler* mission selected only portions of the focal plane to transmit to the ground, rather than transmitting all of the data recorded—while *Kepler* data have been used to address questions beyond the initial science mission, the experience from the archives of both space missions and ground-based telescopes amply demonstrates that having access to the original data opens the possibility of being able to achieve scientific results beyond those initially planned from a telescope. Had the full *Kepler* data volume been able to be transmitted to the ground, even more discoveries would continue to be possible. We stress that *Kepler* is only one such example, similar experience has been observed for the *Planck* mission and others.

Looking toward the future, the TESS mission is already paving the way for much higher data rates for Astrophysics missions, and the *James Webb Space Telescope* will show how significant data rates can be obtained from the Earth-Sun L2 point. Multiple Probe-class concepts also envision large sky surveys or time-domain observations that would yield much greater science returns if the full data volume generated on-board the spacecraft could be returned to Earth, even for spacecraft at the Earth-Sun L2 point or in Earth-trailing orbits (such as that of *Spitzer*).

Technical Overview

NASA's Deep Space Network (DSN) is a series of large, sensitive antennas distributed around the world (Figure 1). While known primarily for enabling Planetary Science missions, the DSN has been or will be integral to a number of Astrophysics missions including *Chandra*, XMM-Newton, TESS, and the *JWST*. With an increasing number of Astrophysics missions likely to be in orbits around the Earth-Sun L2 point or in cis-lunar space, the DSN can play a critical role in ensuring the maximum possible data return.[1]

The value of the DSN for Astrophysics missions is its highly sensitive antennas. At each DSN Complex, there is a 70 m antenna and multiple 34 m antennas, all equipped with cyrogenic microwave receivers. Just as for science observations, a crucial parameter for downlinking data from a spacecraft to the ground is the signal-to-noise ratio of the spacecraft signal as received at the ground antenna. Large, sensitive antennas enable either fulfilling the data rates required by a mission with a robust margin for the signal-to-noise or exceeding the notional mission data rates from a mission at standard margins.

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[1] DSN Now, https://eyes.nasa.gov/dsn/dsn.html, presents a real-time view of the set of missions being enabled by the DSN.

Figure 1. By the middle of the 2020s, NASA's Deep Space Network will have five antennas at each of its three Complexes, one 70 m-diameter antenna and four 34 m-diameter antennas, providing the capability to obtain high data rates (> 300 Mbps) and large data volumes for Astrophysics missions.

Table 1. Illustration of Deep Space Network 34 m antenna capabilities, for an Astrophysics mission at the Earth-Sun L2 point, based on an analysis for the WFIRST mission.

	Data Rate		**Signal-to-Noise Ratio**
Current	270 Mbps	120 GB/hr	18.6
Future Potential	733 Mbps	330 GB/hr	3.0

Table 1 provides a specific example of the current data return capabilities of a 34 m-diameter DSN antenna for a mission at the Earth-Sun L2 point and the maximum potential future capabilities allowed by standard signal-to-noise ratios and with signal processing hardware upgrades, based on an analysis conducted for the WFIRST mission. As is apparent, the DSN capabilities provide for significant data return. Over a typical 6 hr down-link pass, a data volume of nearly 2 TB could be delivered, even from the Earth-Sun L2 point. Further, the DSN has the capability to array multiple 34 m antennas together, to increase the signal-to-noise ratio or data rate, for particularly high value data. Finally, missions in cis-lunar space could anticipate much higher data rates by virtue of the smaller distances—about 400,000 km to the Moon versus about 1.5 million km to the Earth-Sun L2 point, equivalent to a factor of nearly 15 in signal-to-noise ratio.

In addition to the value provided by the highly sensitive antennas, the DSN has been taking steps during the current decade to enhance its capabilities. Figure 1 shows the state of the DSN in the middle of the 2020s decade, at the conclusion of the DSN Aperture Enhancement Project (DAEP).

The DAEP has the objective of increasing the number of 34 m-diameter antennas at each Complex to a total of four, with two currently under construction at the Madrid Complex.

A complementarily effort has been to equip at least one antenna at each Complex with receivers operating in the K band (approximately 26 GHz). The standard deep space telecommunications frequency has been X band (approximately 8.5 GHz), which has two increasingly problematic aspects.

1. The international spectral allocations for spacecraft telecommunications provide for narrower bandwidths, implying lower data rates, at X band as compared to K band. For comparison, only 50 MHz of bandwidth is allocated at X band as compared to 1500 MHz at K band.
2. The number of missions using X band has grown over time to the point at which spectral congestion can be an issue, i.e., interference between the transmissions from multiple spacecraft. This issue is particularly acute at Mars, where there are multiple spacecraft, from multiple agencies. While Mars is not a target for Astrophysics missions, it can be close on the sky to either the Earth-Sun L2 point or to the Moon, where current and future Astrophysics missions likely will be.

The value of telecommunications at K band for improved data delivery is recognized by missions such as TESS and *JWST*, which are using or plan to use the DSN's K-band capabilities.

On a longer term, the DSN has been investing in laser, often termed optical,[2] communications. The value of laser communications for delivering higher data rates and larger data volumes is a combination of higher efficiency by virtue of the intrinsically narrower beams as compared to radio frequencies and naturally larger bandwidths.

Much of the deep space laser communication development has been focused on high data rate communications from Mars, both for Planetary Science and future human spaceflight missions. A first demonstration of deep space laser communications, the Deep Space Optical Communications (DSOC), is scheduled on the Planetary Science Psyche mission, with the laser communications aspects having been funded by a combination of NASA's Space Technology Mission Directorate (STMD) and the Space Communications and Navigation (SCaN) Program and spacecraft accommodation funded by the Planetary Science Division. The DSOC technical demonstration consists of a 22 cm telescope and 4 W laser on-board the Psyche spacecraft paired with the 5 m Hale telescope at the Palomar observatory.

Looking beyond the DSOC technical demonstration, the DSN is planning to modify the design of subsequent 34 m-diameter antennas to include a joint radio frequency-laser communications capability, in what is termed an RF-Optical Hybrid Antenna. For a standard DSN 34 m-diameter antenna, the reflecting surface is a series of metal panels; for an RF-Optical Hybrid Antenna, the inner panels are replaced by mirrors. The collecting area for the "optical" portion of the antenna is equivalent to an 8 m-diameter mirror, and the design minimizes any effects on the radio performance of the antenna.

By comparison with typical Planetary Science missions, an Astrophysics mission at the Earth-Sun L2 point is closer and could obtain much higher data rates. Table 2 illustrates a recent analysis conducted for a potential future Astrophysics mission at the Earth-Sun L2 point, comparing the

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[2] Actual wavelengths used are 1.064 μm (uplink) and 1.55 μm (downlink), placing the transmissions in the near-infrared portion of the spectrum.

notional data rate required by the mission and that that could be delivered by a DSOC-like capability. Clearly apparent is the orders of magnitude increase that is feasible.

Table 2. Illustration of laser communications capabilities for an Astrophysics mission at the Earth-Sun L2 point, based on an analysis for the Lynx mission concept.

	Notional Radio Frequency Capability	**Illustrative Laser Communications Capabilities**	
Data rate	22 Mbps 9.9 GB/hr	Up to 10,000 Mbps Up to 4.5 TB/hr	Up to 170,000 Mbps Up to 76.5 TB/hr
Spacecraft antenna	0.19 m × 0.25 m patch	0.22 m telescope	0.22 m telescope
Transmitter power	20 W	4 W	4 W
Ground station	34 m DSN antenna	2 m telescope	DSN RF-Optical Hybrid Antenna (8 m equivalent)

Moreover, Astrophysics missions at the Earth-Sun L2 point have a substantial advantage over potential Planetary Science missions that might use laser communications. As seen from the Earth, an Astrophysics mission at the Earth-Sun L2 point is always in the night sky, and the sky background level is low (and the signal-to-noise ratio is high) relative to a Planetary Science mission that would likely have to plan for operations during the day. Further, the ground terminal (a.k.a. telescope) need not take any precautions against stray sunlight illumination. Finally, even modest apertures on the ground, such as 4 m in diameter, can yield substantial data rates. In principle, partnerships with existing astronomical facilities could yield significant increases in capability for Astrophysics missions.

NASA's Advanced Multi-Mission Operating System (AMMOS) is a suite of software tools and services designed to facilitate the rapid construction of low-cost and reliable mission operations

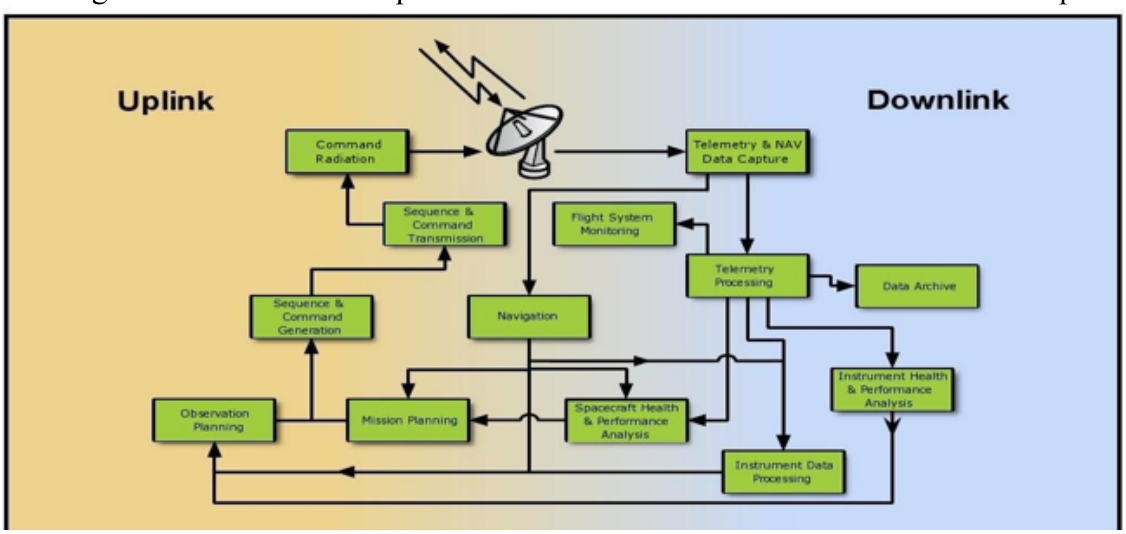

Figure 2. Conceptual overview of the major functional elements for a typical mission. The objective of the Advanced Multi-Mission Operations System (AMMOS) is to provide a standard suite for all NASA missions enabling re-use and reliability.

and data processing capabilities for robotic missions.[3] The underlying concept and motivation for the AMMOS is that there are a set of standard functional elements for many robotic missions (Figure 2). Rather than developing these anew for each new mission, more robust and reliable mission operations can be enabled by reuse of relevant functions.

AMMOS was developed originally in a Planetary Science context, however, it is found to be of value for various NASA and international Astrophysics missions, which have adopted certain components of the AMMOS. Most notably, the *Hubble Space Telescope*, Chandra, *Spitzer Space Telescope*, TESS, and INTEGRAL missions have all used the Mission Design & Navigation capabilities of AMMOS. Because the AMMOS components have been adopted by multiple missions, there has been significant testing of the software suite and components can be adopted "out of the box" or with only minor revisions. Doing so both facilitates more rapid mission design and provides efficiencies during operations, as fewer individuals are needed to handle the spacecraft. Looking ahead to future Astrophysics missions, particularly those that would be around the Earth-Sun L2 point or in cis-lunar space, these Mission Design & Navigation capabilities would be straightforward to adopt.

Table 3 provides metrics by which the heritage and wide-spread deployment of AMMOS is evident. Notably the suite of missions making use of AMMOS components includes missions across the full suite of NASA's science (Astrophysics, Planetary Sciences, Heliophysics and Earth Sciences Divisions) and both NASA and international space agency missions. Astrophysics missions historically have adopted the Mission Design & Navigation components, which are among the components of AMMOS that have benefited most from years of experience with previous missions and refinement of the software.

Table 3. Illustration of the wide-spread deployment and heritage of the AMMOS.

Number of missions using AMMOS components	53
Code base	Over 12 million software lines of code
Annual Operations, Development, and Maintenance	Approximately 100 full-time equivalents
Operations and Development	15 years

Looking into the first part of the next decade, the AMMOS has been taking steps to ensure even more rapid adoption and robust operations. Two areas of focus have included a "cloud" implementation and enhanced data visualization. A **cloud implementation** would allow mission operations or science teams to process data only when needed. Rather than maintaining computer clusters, missions could produce an instantiation of a mission control center only when data are downloaded from the spacecraft. **Enhanced data visualization** enables mission operators and scientists to conduct rapid assessment of spacecraft health and the initial capabilities to examine science data before higher level data products are produced.

Technology Drivers

In many cases, technologies are in hand to continue DSN and AMMOS improvements throughout the next decade, though continued innovation and technology development would provide

[3] The full AMMOS catalog is available at https://ammos.nasa.gov/.

performance increases or efficiencies in the entire infrastructure, from the initial reception of a spacecraft signal to the processing of the data and delivery to the science community. Deutsch et al. (2016) describe a number of potential future improvements, some of which we summarize here.

Future radio antennas and antenna arraying: There are missions for which radio frequency telecommunications will remain critical, even though laser communications can provide substantial increases in data rates and volumes. Astrophysical missions could also take advantage of these improvements in data rates from radio telecommunications. While the DSN employs antenna arraying in a limited fashion today, larger scale radio antenna arrays akin to radio astronomical arrays could be employed in the future, which could achieve substantial increases in data rates. This approach may also allow for synergies between future radio astronomical systems and radio telecommunications systems.

Next-generation laser communications systems: Among the avenues that exist to increase capability in laser communications systems, increases in the flight terminal aperture size (from 20 cm to 50 cm), improvements in the optical power amplifier average output level (from 5 W to 50 W), and efficiency (from 15% to 30%) are all feasible. In some cases, proof-of-concept technologies already exist, for example, the HIRISE camera on the Mars Reconnaissance Orbiter (MRO) has a 50 cm aperture.

Organization, Partnerships, and Current Status

Both the DSN and AMMOS are elements of NASA's infrastructure for science and exploration. The DSN is funded by the Space Communications & Navigation Program, under the Human Exploration Mission Directorate, and the AMMOS has been developed under the Planetary Sciences Division technology program. This end-to-end data and information infrastructure is operated for NASA by the California Institute of Technology's Jet Propulsion Laboratory.

The DSN routinely partners with a variety of other organizations in order to ensure constant communications and commanding capabilities to spacecraft. Near the Earth, the DSN can partner with NASA's Near Earth Network during critical intervals after launch and as spacecraft transition from a low-Earth orbit to a trajectory to its final destination (e.g., Earth-Sun L2 for an Astrophysics mission). NASA has established a formal cross-support agreement with the European Space Agency (ESA), for use of its complementary, though smaller network of deep space antennas. Other strategic partnership agreements allow collaboration for the use of other stations such as those at the Japanese Aerospace Exploration Agency (JAXA) and other agencies. Further, on an as-needed basis, agreements to use other antennas are negotiated, for instance, with the Sardinia Deep Space Antenna of the Italian Space Agency, the Morehead State University's antenna, and antennas associated with various radio astronomical institutes.

The AMMOS code base has been developed in collaboration with software developers at NASA's Ames Research Center and Goddard Space Flight Center, the Johns Hopkins University Applied Physics Laboratory, and a number of universities.

Schedule

Table 4 summarizes key milestones discussed earlier.

Table 4. Key milestones for improved Astrophysics data delivery

2023	Deep Space Optical Communications (DSOC) technical demonstration on Psyche Discovery mission	Psyche Discovery mission funded by NASA Planetary Sciences Division DSOC funded by NASA Space Technology Mission Directorate and NASA Human Exploration and Operations Mission Directorate/Space Communications & Navigation Program
2024	DSS-23 34 m-diameter antenna RF configuration operational (Goldstone Complex)	Funded by NASA Human Exploration and Operations Mission Directorate/Space Communications & Navigation Program
2025	DSS-23 34 m-diameter antenna RF-Optical Hybrid configuration operational (Goldstone Complex)	
2026	DSS-33 34 m-diameter antenna RF-Optical Hybrid configuration operational (Canberra Complex)	

References

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