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On the Quantification of the Scientific Productivity of NASA's Deep Space Network

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ABSTRACT. — The Deep Space Network (DSN) is the primary means of commanding, tracking, and receiving data from all of NASA's deep space missions as well as a number of deep space missions operated by other international space agencies. Standard DSN operations involves developing a schedule for when each mission will be contacted. For a variety of reasons, a scheduled track for a mission may be missed. A long-standing question has been what the consequences are of such missed tracks.

This document develops two metrics for assessing the consequence of a missed track, one scientific and one financial. The scientific metric is motivated by the fact that the DSN was developed to enable robotic science missions. The scientific metric uses the number of peer-reviewed scientific papers produced by a mission and the number of hours that the DSN tracks the mission. In effect, the science metric is an effort to measure the advance of knowledge about the Sun, Solar System, and the Universe and relate that to the amount of DSN time used. While the science metric varies, depending upon the science focus of the mission, typical values range between approximately one scientific paper produced per hour of DSN tracking time and one scientific paper produced per 10 hr of DSN time.

The financial metric recognizes that there are costs associated with operating both the DSN and the missions. The financial metric uses estimates of the (future) cost of operating NASA's robotic science missions to assess the financial implications of operating a mission while unable to communicate with its spacecraft. As above, the financial metric varies depending upon the scientific focus, but, averaged across NASA, a missed DSN track incurs approximately an extra $100,000 per hour in mission operations costs.

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I. Background and Motivation

The Deep Space Network (DSN) is the primary means of commanding, tracking, and receiving data from (henceforth simply "tracking") all of NASA's deep space missions as well as a number of deep space missions operated by other international space agencies. Standard DSN operation involves developing a schedule for when each mission will be contacted. Due to the long light travel times, potentially hours to days, the intent is that the schedule be developed well in advance.

For a variety of reasons, a scheduled track for a mission may be missed. Though such missed DSN tracks are generally infrequent, that the DSN will miss a spacecraft track is not new. The question this document addresses is how to quantify the consequence of a missed track on the DSN.

The specific motivation for this work stemmed from the requirement that the DSN enable the Artemis I mission and the 10 CubeSats that were released as part of that mission. By the end of the Artemis I mission, slightly less than 1600 hours (≈ 9.5 weeks) of DSN time originally scheduled for missions managed by NASA's Science Mission Directorate (SMD) had been rescheduled to enable the Artemis I mission or the associated CubeSats. In addition, slightly more than 500 hours of scheduled DSN maintenance had been deferred. Harmon et al. [1] provide additional discussion and perspective on the planning for and interactions between the DSN and the Artemis mission.

The reduction in scheduled DSN tracks (or time) was not distributed uniformly across SMD missions. Some missions experienced a reduction of only a few hours of DSN time from that scheduled, while other missions experienced reductions in excess of 100 hours.[1] Regardless of the amount of DSN time that was rescheduled from SMD missions, no mission failed. Can it therefore be concluded that the loss of DSN time from an SMD mission has no consequence?

The structure of this manuscript is as follows. Section II describes different reasons that the DSN might miss a track, Section III focusses on quantifying the lost science in terms of a productivity metric that is used commonly in NASA Senior Reviews for SMD missions, and Section IV focusses on quantifying the consequence using a financial metric. The conclusions of this work are presented in Section VI. Appendices present supporting information or additional details, with an aim of describing the process used in sufficient detail to enable the results to be reproduced.

II. Scenarios Resulting in Missed DSN Tracks

This section identifies and summarizes four specific scenarios that result in a mission missing one or more DSN tracks. These distinctions are crucial because two of them

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[1] The missions with the largest reductions in DSN time are also those with the largest SMD investments, namely the James Webb Space Telescope (JWST) and the suite of Mars missions.

(both types of Flight Segment Disruptions) are outside of the control of the DSN. Moreover, all missions accept an implicit risk that some of their science data will not be able to be collected in order to recover a spacecraft from another mission; concomitantly, every mission makes an implicit assumption that, in the event of a Flight Segment Disruption, it will be able to obtain time on the DSN for recovery efforts. By contrast, Ground Segment Disruptions can be minimized or their effects mitigated quickly by proper and regular maintenance and having the appropriate number of spare components.

Flight Segment Disruption This scenario occurs when one of the missions in the DSN's mission suite experiences a disruption that affects other missions. The most common such example is when a spacecraft enters "safe mode" or a mission declares a spacecraft emergency, necessitating that time scheduled for other missions be diverted to address the disruption. Whether a spacecraft will enter "safe mode" often cannot be predicted. Thus, addressing its disruption typically involves other missions not being able to obtain their scheduled DSN tracks and potential or probable data loss. Included in this scenario are delays in launch, if they are short enough that rescheduling DSN tracks for other missions cannot be achieved.

Artemis Flight Segment Disruption This scenario is identical to the previous Flight Segment Disruption. It is distinguished because the DSN was designed to enable robotic science missions, particularly those with long latencies due to their distances. By contrast, Artemis missions are crewed, meaning that they are treated as higher priority. Further, experience with the Artemis I mission, including its launch, suggests that future Artemis missions have the potential to be much more dynamic than the typical robotic science missions.

Ground Segment Disruption This scenario refers to an unplanned disruption within the DSN itself, distinct from planned maintenance or other scheduled activities when a DSN antenna is not available. The disruption can occur at the antenna intended to receive the science data from a spacecraft, or it could be broader and affect multiple antennas at a DSN Complex.[2] This scenario also can result in the loss of data if the spacecraft has insufficient on-board data storage to retransmit the science data to another DSN antenna. In the most extreme case, if the light travel time to a spacecraft is in excess of an hour, it is possible that the antenna (or DSN Complex) was operational when the science data transmission began but not when the signals reached the antenna. Once again, this scenario can result in the potential or probable loss of data but would affect only a single spacecraft. The combination of planned maintenance and Ground Segment Disruptions define the DSN's availability, or the fraction of the time that antennas are operational relative to all antennas operating all of the time.

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[2] A specific example is the failure of the private cloud appliance (PCA) at the Goldstone Deep Space Communications Complex during the Artemis I mission, which resulted in the entire Goldstone Complex being inoperative for 33 hours.

Lost Opportunity In this scenario, a spacecraft, or its instruments, is designed such that some data that are collected are never transmitted to Earth, thereby precluding future scientific discoveries or advances. Specific examples of such limited data acquisition include the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO), which has covered "just a few percent of" Mars even after 16 years of operation [2], and the Kepler mission, for which, due "to data storage and transmission limitations, only about 6% of the 96 million pixels [acquired were] stored for eventual transmission to the ground" [3]. There are two consequences of these lost data. First, considerable NASA resources have been invested in constructing the instruments and spacecraft, verifying their performances, and developing the science data systems, only to "throw away" a significant fraction of the data collected. Second, NASA maintains a series of data archives precisely because, *if archived*, scientific data can be re-analyzed, in some cases for reasons never envisioned when they were collected. The value of NASA's data archives is addressed in multiple reports from the National Academies, with *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* [4, Figure 4.7] illustrating how more scientific publications now result from the data in the Hubble Space Telescope archive than from new observations. Most recently, the development of the "pure-parallel" observing mode for the JWST mission [e.g., 5, 6] enables scientifically valuable observations to be acquired simultaneously with a secondary detector while a primary observation with another detector is occurring. Clearly, if the scientific data are never collected, or never transmitted to the ground, opportunities such as those above are never possible.

III. Approach: Scientific Considerations

This section develops a metric for assessing the value of a missed DSN track using factors of common use within the scientific community and the DSN. The science quantification metric SQM is defined as

$$\mathrm{SQM} = \frac{N_{\mathrm{paper}}}{N_{\mathrm{hr}}}, \tag{1}$$

where N_{paper} is the number of archival journal papers produced from a mission during some interval and N_{hr} is the number of hours that the DSN tracked that mission during that same interval. The intent of the SQM is to capture the consequence of a missed DSN track or number of hours lost in terms of scientific advances that did not happen.[3]

While no metric likely is perfect or captures all possible nuances, the SQM has several favorable elements. First, the number of DSN tracking hours N_{hr} is recorded and available from the DSN Project. This number also is used commonly in considerations regarding both DSN performance and the scenarios described above (e.g., "a DSN

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[3] Expressed colloquially, "Because of a missed DSN track of duration of N_{hr} hours, the body of knowledge resulting from this mission will be delayed or lost by N_{paper} scientific papers."

antenna became inoperative and N hours of Mission M were not obtained as a consequence"). Second, while imperfect, the number of archival journal papers is a common metric for assessing the performance of both individuals and missions, particularly the latter in the context of NASA Senior Reviews.

The SQM is assessed for missions, grouping them by the primary sponsoring SMD Division[4] (Astrophysics, Heliophysics, or Planetary Science) within NASA's SMD. While a mission may be sponsored primarily by one Division, the instruments on the spacecraft may be capable of conducting cross-disciplinary scientific investigations. Examples of such cross-disciplinary investigations include a study of the surface of Venus (traditionally a topic for Planetary Science) by an instrument on the Parker Solar Probe of the Heliophysics Division [7] or observations of the cosmic optical background (traditionally a topic for Astrophysics) by an instrument on the New Horizons spacecraft of the Planetary Science Division [8]. The method of assessing the number of papers produced by a mission should be robust to such cross-disciplinary investigations, and Appendix A describes how the number of papers was determined for each mission, with the aim that these results be reproducible. Omitted from these assessments is DSN time scheduled originally as project-related test and training, which typically is a small amount of time (~ 10 hours over a decade).

Comparisons of the SQMs between missions sponsored by different SMD Divisions is not fruitful. The amount of data required to obtain a scientific result varies between the various disciplines; indeed, it may vary even between subfields within a specific discipline.

Table 1. Science Quantification Metric (SQM) for Astrophysics Missions

		Number		
Mission	**Interval**[a]	**Papers**	**Hours**	**SQM**
Chandra X-ray Observatory	2008–2023	31,239	37,639	0.83
Transiting Exoplanet Survey Satellite (TESS)	2018–2023	4,806	3,568	1.35

[a] Years are fiscal years.

Table 1 summarizes the SQM for Astrophysics missions. The international Astrophysics missions with which the DSN assists, typically those from the European Space Agency (ESA), were not considered. The DSN provides only a fraction of the antenna time required for those missions, and separating the DSN's contribution from that of the ESA's ground assets would be difficult and uncertain. At the time of acquiring the set of DSN tracking hours, the JWST had been conducting science observations for only

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[4] In addition to the three Divisions considered here, SMD also contains the Earth Science and Biological & Physical Sciences Divisions. The Biological & Physical Sciences Division is relatively new and has sponsored no missions enabled by the DSN. With the exception of the Deep Space Climate Observatory (DSCOVR), Earth Science missions are enabled by other NASA communication networks and therefore are not considered here.

slightly more than one year, so it was not included in this analysis.

Table 2 summarizes the SQM for Heliophysics missions. Where possible, tabulations of papers compiled by the mission teams have been used. Multiple Heliophysics missions involve multiple spacecraft (Solar TErrestrial RElations Observatory [STEREO] A and B, Voyager 1 and 2, etc.). The DSN time reported for such missions is the combination of all hours for all spacecraft.

Table 2. Science Quantification Metric (SQM) for Heliophysics Missions

		Number		
Mission	**Interval**[a]	**Papers**	**Hours**	**SQM**
Advanced Composition Explorer (ACE)	2008–2016	2,832	15,672	0.18
	2017–2023	8,083	13,055	0.62
Magnetospheric Multiscale (MMS)	2015–2023	1,307	34,854	0.04
Parker Solar Probe	2018–2023	3,005	16,930	0.18
Solar TErrestrial RElations Observatory (STEREO)	2008–2023	5,008	66,349	0.08
Voyager Interstellar Mission[b]	2008–2022	9,248	118,177	0.08
Wind	2008–2022	4,701	23,305	0.20

[a] Years are fiscal years.

[b] While it started as a Planetary Science Mission, during the interval analyzed, Voyager was sponsored by the Heliophysics Division.

Table 3 summarizes the SQM for Planetary Science missions. No effort has been made to distinguish between the various Mars missions because the standard operational mode is for Mars surface missions (Mars Exploration Rovers [Spirit and Opportunity], Mars Science Laboratory [Curiosity], Mars 2020 [Perseverance]) to relay data through one or more Mars orbiters (Mars Odyssey, MRO, Mars Atmosphere and Volatile Evolution Mission [MAVEN], and most recently ESA's Trace Gas Orbiter [TGO]). Moreover, often, scientific data from multiple Mars orbiters is received simultaneously by using the DSN's multiple spacecraft per aperture (MSPA) capability. It was not judged worthwhile to attempt to separate out the various missions for the purposes of assessing DSN time.

As noted above, the SQMs vary from mission to mission and Division to Division, ranging from $0.03\,\mathrm{hr}^{-1}$ to $1.35\,\mathrm{hr}^{-1}$. Averaging across all SMD missions, $\mathrm{SQM} = 0.34 \pm 0.03\,\mathrm{hr}^{-1}$, if Mars missions are not included, and $\mathrm{SQM} = 0.30 \pm 0.03\,\mathrm{hr}^{-1}$, if Mars missions are included. Consequently, on average, for every three hours of DSN time that a mission does not obtain, the loss to knowledge is one scientific paper.

IV. Approach: Financial Considerations

This section describes an approach to developing a quantifiable metric in the context of operational costs for NASA. This financially based metric is developed by considering

Table 3. Science Quantification Metric (SQM) for Planetary Science Missions

		Number		
Mission	**Interval**[a]	**Papers**	**Hours**	**SQM**
Juno	2011–2023	3,088	43,103	0.07
Lunar Reconnaissance Orbiter (LRO)	2009–2023	3,475	10,673	0.33
New Horizons	2008–2023	4,940	37,054	0.13
Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx)	2016–2023	2,758	29,166	0.09
Mars missions[b]	2008–2023	12,217	399,316	0.03

[a] Years are fiscal years.

[b] Mars missions are considered to be Mars Odyssey, Mars Exploration Rovers (Spirit and Opportunity), MRO, Mars Science Laboratory (Curiosity), MAVEN, and Mars 2020 (Perseverance). See text for additional discussion of Mars missions.

the cost of operating a mission, in a unit such as dollars per hour ($\$\ \mathrm{hr}^{-1}$). If a mission does not obtain a scheduled DSN track, NASA continues to fund the mission's operations (considered broadly as both the mission operations and the science teams). Thus, the "cost" of a lost DSN track is the product of duration of the track and the mission operations cost

$$C = N_{\mathrm{hr}} \times R_{\mathrm{mission}}, \tag{2}$$

where, as above, N_{hr} is the duration of the DSN track in hours and R_{mission} is the mission operations cost in a unit such as dollars per hour.

Table 4 presents the projected mission operating costs for those missions using or planning to use the DSN across the Astrophysics, Heliophysics, and Planetary Sciences Divisions, with Appendix B providing operations costs for each deep space mission within each Division. These values are obtained from NASA's FY 2025 Budget Request [9], specifically from the "FY 2025 Full Budget Request (Congressional Justification)" portion of the budget request.

During the course of the preparation of this manuscript, the budget request for FY 2026 was released. That budget request presents a substantial change to the number of SMD missions, but the FY 2026 budget remains under development. As such, the budgetary figures presented here should be considered indicative, but actual appropriations may, and likely will, differ from the values presented here. Moreover, while actual appropriations likely will differ, the approach presented here, and quantified in eqn. (2), remains robust. Once again, because of differences in the nature of the missions sponsored by the different SMD Divisions, comparisons between Divisions is not fruitful.

Table 4. Projected Mission Operating Costs for Missions Reliant upon the DSN

Mission	**FY25 ($M)**	**FY26 ($M)**	**FY27 ($M)**	**FY28 ($M)**	**FY29 ($M)**	**Total ($M)**
Astrophysics	185.6	153.6	153.6	153.6	132.2	**778.6**
Heliophysics	140.0	112.8	97.1	84.1	146.1	**580.1**
Planetary Science	455.2	389.9	382.1	395.9	436.2	**2068.3**
Total	**780.8**	**656.3**	**632.8**	**633.6**	**714.5**	**3427.0**

Values are obtained from NASA's FY 2025 Budget Estimates.

Over a five-year interval, NASA's SMD had been planning to spend approximately $3400M in operating its deep space missions throughout and beyond the Solar System. A standard "work year" amounts to 2,080 hours, implying that the average mission operations cost for SMD is approximately $329,000 per hour. However, NASA missions operate continuously, or 8,766 hours per year, implying an average mission operations cost of approximately $78,000 per hour.

Likely, a more reasonable estimate for SMD's average mission operation cost is between these two extremes. For the purposes of this document, a reasonable estimate is that the financial consequence of a missed DSN track is $100,000 per hour.

V. Case Study: Missions to Mars

In this section, the specific consequences resulting from a missed DSN track for missions to Mars are described. This section is motivated by two considerations. First, NASA (and its international partners) operate many missions to Mars. Because of the way that they are operated, the loss of a DSN track can affect multiple Mars missions simultaneously. Second, the Mars missions were among those most affected by the tracks shifted from SMD missions to the Artemis I mission.

This section begins with consequences that can and do result from a missed DSN track, regardless of the cause (disruption resulting from another mission, Ground Segment Disruption from the DSN itself, etc.), then considers specific consequences resulting from Artemis Flight Segment Disruptions experienced during the Artemis I mission. Much of this section is based on experience obtained during the course of the MRO mission, but the effects are more general to other Mars orbiters, and they could be factors for future Mars or lunar missions.

A. Navigation

The sequence of science activities requires knowledge of where the orbiter will be in its orbit. For example, a science objective might involve obtaining images of a particular surface feature or set of features, which can occur only when the orbiter is above the surface feature or features. Prediction of an orbiter's orbit relies on engineering telemetry obtained from previous orbits. If those telemetry data are of insufficient quantity or missing entirely, the time of both the navigation and science teams is not used productively because sequences of science activities are developed that cannot be executed. In the worst case scenario, the science team simply "stands down," as they cannot plan any activities until sufficient engineering telemetry is obtained for the navigation team to update the orbit.

B. Mars Relay Network

Particularly at Mars, much of the data from surface assets, namely the Curiosity and Perseverance rovers, is relayed through one or more orbiters. Planning subsequent rover activities requires the data relayed through an orbiter. If relay data are not obtained due to a missed DSN track, the rover team likely would have to "stand down" for at least one day. As for the orbiters, the loss of a day's worth of activities from a rover results in the typical loss of one scientific paper. Rover operations are somewhat more expensive than those of orbiters, thus the cost of the non-productive effort by the rover team is larger than that for an orbiter.

C. Artemis Flight Segment Disruption

This experience is based on the disruptions due to the delays in the launch of the Artemis I mission, which both necessitated the development of new science activity plans and resulted in the full loss of some science data. The science team estimates that the development of new science activity plans effectively resulted in double the workload——not only was an initial or desired activity plan developed but at least one contingency or revised activity plan had to be developed. Due to delays in notifications, often the development of these revised activity plans occurred at inopportune times (e.g., late evenings, weekends). Not developing those contingency or revised activity plans would have resulted in multiple days of non-productive effort as science and navigation teams reconstructed the state of the spacecraft and developed new plans.

Particularly vexing disruptions were those in which the DSN was required to reschedule one or more tracks for the orbiters with insufficient time to coordinate with the orbiter mission team. The consequence was that the orbiter simply was conducting no science activities either because it had not been provided with an activity plan or, worse, no data could be downloaded from the orbiter because it was occulted by Mars (i.e., on the other side of Mars as seen from Earth). In this second state, effectively one or more DSN antenna was pointing at Mars, but the orbiter was not transmitting, making the time twice as non-productive, both from the perspective of the science mission and from the perspective of the DSN.

VI. Conclusions

This manuscript has described four different scenarios by which a NASA mission would not obtain "tracking time" on the Deep Space Network (DSN), thereby failing to achieve science data that had been collected or an inability to send commands or both. While most of these scenarios are not new, recent changes in the set of missions being enabled by the DSN warrant assessing the cost of such missed tracks.

Two different metrics have been developed. One is a science quantification metric (SQM), designed to capture the consequences in a "currency" used commonly within the scientific community, namely scientific papers. The second metric is a financial metric, stated in terms of the operations cost to NASA for its missions. While the values of both metrics vary from mission to mission and, more generally, depending upon which Division within the Science Mission Directorate is sponsoring the mission, the average SQM is about $0.3\,\mathrm{hr}^{-1}$, meaning that for every three hours of a missed DSN track, the loss to knowledge is one scientific paper. From a financial consideration, a reasonable estimate is that the financial consequence of a missed DSN track is $100,000 per hour.

The manuscript closes with a discussion of a "case study" focussing on missions to Mars. Because of the way that Mars missions are operated, the loss of a DSN track can affect multiple Mars missions simultaneously. Moreover, the Mars missions were among those most affected by the tracks shifted from SMD missions to the Artemis I mission.

Beyond the metrics described above, the loss of a Mars track can have repercussions for days, as science and operations teams use the results from one track to plan operations for future days. Moreover, while the loss of a DSN track might suggest that the science and operations teams have less work, because less data have been retrieved, a lost track can double the amount of work required. Having developed one plan, the science and operations teams must develop a new plan to compensate for the lost track.

While missed DSN tracks are unavoidable, the various metrics and analyses presented here make it clear that efforts to minimize the number of missed tracks is warranted and profitable.

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Appendices

I. Scientific Considerations: Mission Assessment

This appendix provides details about how the number of archival journal papers was determined in the computation of the SQM for each mission, with the aim that these results be reproducible.

A. Astrophysics Missions

NASA's Astrophysics Data Service (ADS), specifically its "Modern Form,"[5] was used to assess the number of archival journal papers produced for Astrophysics missions. I specify the text entered using a `monospaced font`, and, for legibility, long lines are split.

In all cases, `property:refereed` was specified to restrict the search to those papers that had undergone some level of scientific merit review, and `pubdate:[YYYY-MM TO YYYY-MM]` was specified to restrict the search to the appropriate interval. The field `body` was used to specify the mission name. Because authors are inconsistent in their usage of the field, the `facility` field was not used for searching.

Chandra X-ray Observatory The search was performed specifying

```
pubdate:[2007-10 TO 2023-09] property:refereed
                            body:(Chandra OR "Chandra X-ray"~1)
```

The number of papers found is likely an overestimate because "Chandra" can be the name of a person. Consequently, the SQM in Table 1 likely is an *overestimate.*

Transiting Exoplanet Survey Satellite (TESS) The search was performed specifying

```
pubdate:[2018-10 TO 2023-09] property:refereed
 body:(TESS OR ("Transiting Exoplanet"~1 AND "Survey Satellite"~1))
```

B. Heliophysics Missions

Where possible, tabulations of papers compiled by the mission teams have been used. For those missions for which the mission team had not tabulated the number of papers, NASA's ADS was used in a similar manner as for Astrophysics missions.

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[5] `https://ui.adsabs.harvard.edu/`

Advanced Composition Explorer (ACE) Prior to 2016, the ACE mission team compiled a summary of papers.[6] For the interval 2017 to 2023, the ADS search was performed specifying
`pubdate:[2017-10 TO 2023-09] property:refereed`
`body:(ACE OR ("Advanced Composition"~1 AND "Composition Explorer"~1))`

Magnetospheric Multiscale (MMS) The MMS team has established an identifier `J-5393-2013` at the Web of Science. Results obtained from the Web of Science are used.

Parker Solar Probe The ADS search was performed specifying
`pubdate:[2018-10 TO 2023-09] property:refereed`
`body:(PSP OR ("Parker Solar"~1 AND "Solar Probe"~1))`
The number of papers found is likely an overestimate because “PSP” can be used in other contexts. Consequently, the SQM in Table 1 likely is an *overestimate.*

Solar TErrestrial RElations Observatory (STEREO) The ADS search was performed specifying
`pubdate:[2008-10 TO 2023-09] property:refereed`
`body:(STEREO OR ("Solar Terrestrial"~1 AND "Relations Observatory"~1))`

Voyager Interstellar Mission The ADS search was performed specifying
`pubdate:[2008-10 TO 2023-09] property:refereed body:(Voyager)`

Wind The Wind Project Scientist maintains a listing of publications.[7]

C. Planetary Science Missions

NASA’s ADS was used in a similar manner as for Astrophysics missions.

Juno The ADS search was performed specifying
`pubdate:[2011-10 TO 2023-09] property:refereed body:(Juno)`

Lunar Reconnaissance Orbiter (LRO) The ADS search was performed specifying
`pubdate:[2009-10 TO 2023-09] property:refereed`
`body:(LRO OR ("Lunar Reconnaissance"~1 AND "Reconnaissance Orbiter"~1))`

New Horizons The ADS search was performed specifying
`pubdate:[2008-10 TO 2023-09] property:refereed`
`body:("New Horizons"~1)`
In seven returned papers, the phrase “new horizons” appeared but clearly did not refer to the NASA mission. The total was adjusted accordingly.

OSIRIS-REx The ADS search was performed specifying
`pubdate:[2016-10 TO 2023-09] property:refereed body:(OSIRIS-REx)`

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[6] `https://izw1.caltech.edu/ACE/ASC/publications.html`

[7] `https://wind.nasa.gov/bibliographies.php`

Mars Missions The ADS search was performed specifying the following queries, the results of which were summed.

```
pubdate:[2008-10 TO 2023-09] property:refereed
                      body:("Mars Odyssey"~1)

pubdate:[2008-10 TO 2023-09] property:refereed
body:(MRO OR ("Mars Reconnaissance"~1 AND "Reconnaissance Orbiter"~1))


pubdate:[2008-10 TO 2016-09] property:refereed
body:(("Mars Exploration"~1 AND "Exploration Rover"~1) OR ("Spirit" AND
"Rover") OR ("Opportunity" AND "Rover"))

pubdate:[2012-10 TO 2023-09] property:refereed
body:(("Mars Science"~1 AND "Science Laboratory"~1) OR ("Curiosity" AND
"Rover")))

pubdate:[2014-10 TO 2023-09] property:refereed
body:(("Mars Atmosphere"~1 AND "Volatile Exploration"~1) OR ("MAVEN"))


pubdate:[2012-10 TO 2023-09] property:refereed
body:(("Mars Science"~1 AND "Science Laboratory"~1) OR ("Curiosity" AND
"Rover")))

pubdate:[2020-10 TO 2023-09] property:refereed
       body:(("Mars 2020"~1) OR ("Perseverance" AND "Rover"))
```

II. Financial Considerations: Assessment of Mission Operations

This appendix provides details about which mission or program within each Science Mission Directorate (SMD) Division was assessed as being reliant upon the Deep Space Network (Tables 5, 6, and 7). In all cases, the NASA Budget Estimate provides an amount for FY 2023 per the Operations Plan ("Op Plan"). For consistency and reference, those values are tabulated as well, but they are not included in the totals provided.

Because the notional operating plan is that missions conducted under the Commercial Lunar Payload Services (CLPS) program would not use the DSN, none of the costs for CLPS missions are tabulated.

Table 5. Projected Funding for Operations of Astrophysics Missions

Mission	Op Plan FY23 ($M)	FY25 ($M)	FY26 ($M)	FY27 ($M)	FY28 ($M)	FY29 ($M)	Total ($M)
Chandra	68.4	41.1	26.6	26.6	26.6	5.2	**126.1**
JWST	124.0	127.0	127.0	127.0	127.0	127.0	**635.0**
TESS	18.7	13.5	-	-	-	-	**13.5**
XMM-Newton	4.0	4.0	-	-	-	-	**4.0**
Total	**215.1**	**185.6**	**153.6**	**153.6**	**153.6**	**132.2**	**778.6**

Notes on specific missions.

JWST: Only the requested amount for Mission Elements is tabulated; Webb Science is not included.

TESS: Requested amount reflects commitments from the 2022 Senior Review; any funding beyond FY25 will be determined as part of the 2025 Senior Review.

X-ray Multi-Mirror Mission-Newton (XMM-Newton): Requested amount reflects commitments from the 2022 Senior Review; any funding beyond FY25 will be determined as part of the 2025 Senior Review.

Table 6. Projected Funding for Operations of Heliophysics Missions

Mission	**Op Plan FY23 ($M)**	**FY25 ($M)**	**FY26 ($M)**	**FY27 ($M)**	**FY28 ($M)**	**FY29 ($M)**	**Total ($M)**
Voyager Interstellar Mission	6.5	7.0	7.2	7.8	7.6	7.6	**37.2**
SOHO	2.4	2.2	0.1	-	-	-	**2.3**
Wind	2.3	2.3	2.3	2.3	2.3	2.3	**11.5**
Geotail	0.1	-	-	-	-	-	**-**
Solar Orbiter	6.6	11.2	9.8	8.4	4.2	-	**33.6**
Parker Solar Probe	13.1	26.6	21.7	25.0	25.0	24.0	**122.3**
IMAP	-	63.9	39.5	23.9	15.3	-	**142.6**
Carruthers Geocorona Obs.	-	-	2.9	2.2	2.7	-	**7.8**
MMS	21.9	20.2	20.1	18.9	18.4	18.4	**96.0**
STEREO	5.6	6.6	6.4	6.0	6.0	6.0	**31.0**
SunRISE	-	-	2.8	2.6	2.6	1.8	**9.8**
HelioSwarm	-	-	-	-	-	86.0	**86.0**
THEMIS	-	-	-	-	-	-	**-**
Subtotal	**58.5**	**140.0**	**112.8**	**97.1**	**84.1**	**146.1**	**580.1**

Notes on specific missions:

Solar and Heliospheric Observatory (SOHO): Requested amounts reflect commitments from the 2023 Senior Review; any funding beyond FY25 will be determined as part of the 2026 Senior Review.

Geotail: The mission is in Phase F and will be ceasing operations.

Interstellar Mapping and Acceleration Probe (IMAP): Only mission operations are tabulated.

Time History of Events and Macroscale Interactions during Substorms (THEMIS): Two of the five THEMIS spacecraft are at the Moon, are are now called Artemis, and are reliant upon the DSN. The operations costs of the three inner THEMIS spacecraft versus those of the two Artemis spacecraft are not distinguished, thus costs for THEMIS are not tabulated.

Sun Radio Interferometer Space Experiment (SunRISE): A launch in FY26 is assumed.

HelioSwarm: A launch in FY29 is assumed.

Table 7. Projected Funding for Operations of Planetary Science Missions

Mission	Op Plan FY23 ($M)	FY25 ($M)	FY26 ($M)	FY27 ($M)	FY28 ($M)	FY29 ($M)	Total ($M)
VIPER	-	-	-	-	-	-	**-**
Lunar Trailblazer	-	3.3	0.8	-	-	-	**4.1**
Lunar International Mission Contributions	0.2	0.5	0.5	0.5	0.5	0.5	**2.5**
Lunar Reconnaissance Orbiter (LRO)	22.1	22.1	22.1	22.1	22.2	22.0	**110.5**
Psyche	109.3	32.6	30.8	32.6	33.6	38.1	**167.7**
Lucy	18.9	25.9	23.8	34.8	34.0	25.7	**144.2**
BepiColombo/Strofio	0.9	1.8	1.2	2.3	2.4	1.0	**8.7**
International Mission Contributions	4.8	11.9	13.8	12.1	11.6	8.0	**57.4**
OSIRIS-Apophis Explorer	5.0	16.0	19.9	22.1	31.0	36.5	**125.5**
Origins Spectral Interpretation Resource	30.7	5.4	-	-	-	-	**5.4**
New Horizons	10.4	10.0	3.0	7.8	6.5	6.5	**33.8**
Juno	30.5	26.2	8.1	-	-	-	**34.3**
Mars 2020/Perseverance	91.1	85.5	82.0	82.5	83.0	83.0	**416.0**
Trace Gas Orbiter – ExoMars	2.0	2.0	2.0	2.0	2.0	2.0	**10.0**
Mars Mission Operations	5.1	5.5	5.6	5.4	5.4	5.7	**27.6**
Mars Science Laboratory/Curiosity	42.1	53.0	40.0	40.0	40.0	40.0	**213.0**
Mars Reconnaissance Orbiter (MRO)	25.5	25.4	26.6	26.3	26.0	26.0	**130.3**
Mars Odyssey	11.2	11.0	11.0	11.0	11.0	11.0	**55.0**
Mars Express	0.3	0.3	0.3	0.3	0.3	0.3	**1.5**
MAVEN	22.5	24.0	24.0	-	-	-	**48.0**
Europa Clipper	-	89.3	80.6	77.7	84.0	127.0	**458.6**
JUpiter ICy moons Explorer (Juice)	4.5	3.5	2.8	2.6	2.4	2.9	**14.1**
Subtotal	**437.1**	**455.2**	**398.9**	**382.1**	**395.9**	**436.2**	**2068.3**

Totals may differ slightly due to rounding.

Notes on specific missions:

Volatiles Investigating Polar Exploration Rover (VIPER): Following the announcement that the project will be terminated, no amounts are tabulated.

Juno: The current expectation is that the mission will cease operations in FY26.

MAVEN: The current budget estimate assumes that mission operations will cease in FY26.

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