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Design Reference Missions for Deep-Space Optical Communication

Julian Breidenthal* and Douglas Abraham†

ABSTRACT. — We examined the potential, but uncertain, NASA mission portfolio out to a time horizon of 20 years, to identify mission concepts that potentially could benefit from optical communication, considering their communications needs, the environments in which they would operate, and their notional size, weight, and power constraints. A set of 12 design reference missions was selected to represent the full range of potential missions. These design reference missions span the space of potential customer requirements, and encompass the wide range of applications that an optical ground segment might eventually be called upon to serve. The design reference missions encompass a range of orbit types, terminal sizes, and positions in the solar system that reveal the chief system performance variables of an optical ground segment, and may be used to enable assessments of the ability of alternative systems to meet various types of customer needs.

I. Introduction

The impending viability of deep-space optical communications for operational use by NASA raises various questions of what ground segment characteristics are needed to support a future mission set that is somewhat uncertain within the 5- to 10-year horizon of NASA's mission selection processes. Over the full lifespan of the infrastructure facilities that might eventually be acquired by NASA's Space Communications and Navigation (SCaN) Program Office and the Deep Space Network (DSN), the uncertainties are greater still. Nonetheless, it is valuable to consider the range of missions that might eventually need deep-space optical communications services in order to enable effective planning for a robust optical ground segment.

This article examines what is known about specific potential missions, and general types of mission concepts, that could become customers of a deep-space optical communications ground segment. We considered the NASA mission portfolios under evaluation by the NASA Chief Technologist and by the NASA Chief Financial Officer. We also considered trends in deep-space, lunar, and near-Earth mission characteristics to identify other types of missions that could potentially become customers of an optical ground segment. At sponsor request,

* Communications Architectures and Research Section.
† Interplanetary Network Directorate Architecture, Strategic Planning, and System Engineering Office.

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we included some “what-if” mission types for very small CubeSat-class, optically communicating spacecraft, although we recognize that the technological approach to such missions is still in development.

To assist in characterizing the potential population of missions, we identified a set of 12 design reference missions (DRMs) selected to reveal the envelope of potential system requirements for the ground segment. The DRMs encompass a range of orbit types, terminal sizes, and positions in the solar system that reveal the chief system performance variables of an optical ground segment, and may be used to enable assessments of the ability of alternative systems to meet various types of customer needs. The DRMs do not represent a forecast of a particular set of missions that is likely to be selected by NASA for actual execution; because the selection decisions are competitive and are yet in the future, no particular set can be identified in advance. Rather, the DRMs represent stressing cases that assist to understand the envelope of services that an optical ground segment could reasonably be expected to support over its lifetime.

This article supports another contemporaneous summary report regarding optical communications performance provided in the *The Interplanetary Network Progress Reports* [1].

II. Defining the Mission Set

A. Candidate Optical Communications Missions

At the request of our sponsors, we examined what was known about the potential missions under consideration by NASA, and compiled[1] an exhaustive list of the known missions from NASA sources, including the NASA Office of the Chief Technologist (OCT) and the Office of the Chief Financial Officer (CFO). The mission concepts identified from these sources were evaluated as to their suitability for optical communications and for early optical communications demonstrations. The article also considers likely emerging needs for optical communication from nontraditional sources such as CubeSats, and provides a set of recommendations as to effective strategies for dealing with the high level of uncertainty as to which missions will be funded.

The existence of multiple mission models in the sponsors’ portfolios makes it clear that many decisions remain to be made before the final mission set is determined, and makes it inherent in the ground segment design problem that most of the mission selections will be made in the far future. Therefore, the mission sets described here can only be taken as describing the range of potential mission sets that need to be considered in selecting the optical ground segment architecture.

We discuss further the specifics of the OCT and CFO mission sets below.

OCT Roadmap Missions

The OCT roadmap compiled potential missions from the NASA Human Exploration, Astrophysics, Heliophysics, and Planetary Science mission directorates in their report *2014 05 16*

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[1] D. Abraham, “Candidate Deep Space Optical Communications Missions: 2015–2030+,” presentation to Optical Ground System Study Group, Jet Propulsion Laboratory, Pasadena, California, June 26, 2014.

DRM Source and Mission Class and Needs. The OCT only calls out optical communications as an “enabling technology” for two mission opportunities: Discovery 13 and New Frontiers 5. Both are competed opportunities and could go virtually anywhere in the solar system. Also, the OCT identified crewed missions to the lunar surface as having an optical emphasis.

Representative Mission Candidates Likely to Benefit from Optical Communications

We independently evaluated the potential applicability of optical communication to the OCT mission set, as detailed in Table 1. Of the missions postulated, ~40 percent of the Discovery candidates and ~30 percent of the New Frontiers candidates entail environments and data rates and/or mass-power-volume constraints suggestive of potential benefit from optical communications.

It is important to recognize that the NASA mission concept lists, of which OCT’s is one example, are very uncertain as to which missions could be selected. In general, NASA is still in the process of downselecting from among many possible candidates. At the present time, the following partial downselects have been made for near-term missions:

On September 30, 2015, NASA selected five mission concepts for further study for Discovery-13:

- Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI)
- Venus Emissivity, radio Science, InSAR, Topography, and Spectroscopy (VERITAS)
- Psyche Orbiter
- Near-Earth Object Camera (NEOCam)
- Lucy (Trojan asteroid reconnaissance)

On August 20, 2012, NASA HQ downselected Interior Exploration using Seismic Investigations, Geodesy, and Heat Transport (InSight) from three Discovery-12 candidates:

- A Mars geophysical station (InSight)
- A Titan lake lander (Titan Mare Explorer, or TiME)
- A comet multiple lander mission (Comet Hopper)

In May 2011, NASA also announced funding for three mission concepts to mature their designs for possible selection in the future. These were Primitive Material Explorer (PriME), Whipple, and Near-Earth Object Camera (NEOCam).

On May 25, 2011, NASA HQ downselected Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) from three New Frontiers 3 candidates: Surface and Atmosphere Geochemical Explorer (SAGE), OSIRIS-REx, and MoonRise.

The *Planetary Decadal Survey, Vision and Voyages for Planetary Science in the Decade 2013–2022* recommends that New Frontiers 4 be one of the following: Comet Surface Sample Return, Lunar South Pole–Aitken Basin Sample Return, Saturn Probe, Trojan Tour and Rendezvous, or Venus In Situ Explorer. It also recommends that New Frontiers 5 be one of the mission concepts not selected for New Frontiers 4 or be an Io Observer or a Lunar Geophysical Network.

Table 1. Rough data rates for representative candidate missions.

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
Discovery	TIME	~0.44 kbps from surface of cloud-enshrouded Titan	No; environment not conducive
Discovery	Comet Hopper	~18 kbps while touch-and-go with potentially ice- and dust-enshrouded comet up to 4 times in 2 years	No; environment not conducive
Discovery	PriME	~50 kbps while rendezvousing with a potentially ice- and dust-enshrouded comet	No; environment not conducive
Discovery	Whipple	~2.5 Mbps from an ETO at about 0.4 AU from Earth	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.
Discovery	NEOCam	~30 Mbps (possibly up to 260 Mbps) from a SEL1	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.
New Frontiers	SAGE	~250 kbps for 21 days post-flyby; carrier acts as relay while flying by Venus	Possible; however, comm is not a strong driver
New Frontiers	MoonRise	See Lunar South Pole–Aitken Basin Sample Return	—
New Frontiers	Comet Surface Sample Return	~18 kbps while sampling a potentially ice- and dust-enshrouded comet	No; environment not conducive
New Frontiers	Lunar South Pole–Aitken Basin Sample Return	~198 kbps from a lunar relay orbiter	Possible; however, comm is not a strong driver
New Frontiers	Saturn Probe	~1.6 kbps from Saturn; carrier acts as relay	Possible; however, comm is not a strong driver for the probe, but extended mission for the carrier could be a driver
New Frontiers	Trojan Tour and Rendezvous	~30 kbps from Jupiter vicinity (possible mass, power, volume–driven candidate)	Yes; possible data-rate-driven optical comm candidate. Ka-band is a viable alternative, but optical may provide mass/volume/cost benefits.

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Table 1 continues on next page

Table 1. Rough data rates for representative candidate missions. (Contd.)

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
New Frontiers	Venus In Situ Explorer	Concepts with relay data rates that range from ~25 kbs to ~14.5 Mbps	Yes; possible data-rate-driven optical comm candidate
New Frontiers	Io Observer	~50 kbps from intense Jupiter radiation environment (mass, power, volume [MPV] constrained)	Mixed; MPV constraint makes optical attractive, but high radiation environment may be impractical for optical comm terminal
New Frontiers	Lunar Geophysical Network	~125 kbps from each of four landers	Possible; however, comm is not a strong driver
HEOMD	Asteroid Redirect Robotic Mission (2013–2021)	~100 kbps baseline; but, stereo HDTV from CubeSats desired	Yes; possible data-rate-driven optical comm candidate
HEOMD	Asteroid Redirect Crewed Mission (2021–2027)	~24.2 Mbps from lunar DRO; HDTV coverage desired; ~5.8 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to NEA (2027–2033)	~25 Mbps from ~0.6 AU; HDTV coverage desired; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to Lunar Surface (2027–2033)	~25 Mbps from lunar surface; early desire for ~150 Mbps; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mission to Mars' Moons (2027–2033)	~25 Mbps from Mars orbit; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Orbital Mission (2033+)	~25 Mbps from Mars orbit; ~6 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Surface Mission (2033+)	~150 Mbps from Mars surface habitat at 2.5 AU; ~25 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
HEOMD	Crewed Mars Surface Mission — Minimal (2033+)	~150 Mbps from Mars surface habitat at 2.5 AU; ~25 Mbps uplink	Yes; possible data-rate-driven optical comm candidate
SMD	Wide-Field Infrared Survey Telescope (WFIRST) (2025)	~150 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Table 1 continues on next page

Table 1. Rough data rates for representative candidate missions. (Contd.)

Program	Mission	Rough Data Rate*	Suitability for Optical Comm
SMD	Gravitational-Wave Surveyor Mission (2045)	~90 kbps from each of 3 S/C in ETO; laser-links to maintain formation	Possible; however, comm is not a strong driver
SMD	CMB Polarization Surveyor Mission (2040)	~100 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Far-Infrared Surveyor Mission (2040)	~100 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Large UV/Visible/IR Surveyor Mission (2035)	~24.5 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	X-ray Surveyor Mission (2035)	~8 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Exo-Planet Direct Imaging Mission (2030)	~>24.5 Mbps from SEL2	Yes; possible data-rate-driven optical comm candidate
SMD	Interstellar Mapping and Acceleration Probe (IMAP) (NET~2022)	~76.4 kbps from SEL1	Possible; however, comm is not a strong driver
SMD	Dynamical Neutral Atmosphere–Ionosphere Coupling (DYNAMIC) (NET~2026)	~1.4 Mbps from each of two S/C in Molniya orbits	Possible; however, comm is not a strong driver
SMD	Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI) (NET~2030)	~1.4 Mbps from each of two S/C in 8 Earth-radii circular orbit	Possible; however, comm is not a strong driver
SMD	Explorer Missions (2018, 2024, 2030)	Significant concept variability from kbps to Mbps	Possible
SMD	Mars 2020 (2020)	~10 kbps direct-to-Earth at 2.6 AU; ~128 kbps to 2 Mbps to relay orbiter	Optical has not been selected
SMD	Europa (2022–2024)	~134 kbps at 6.4 AU within Jupiter's intense radiation belts	Mixed; data rate makes optical attractive, but high radiation environment may be impractical for optical comm terminal
SMD-	Mars Sample Return (>2026)	~10 kbps direct-to-Earth at 2.6 AU for ERV and rover; relay is ~>5.2 Mbps	Yes; possible data-rate-driven optical comm candidate

* All rates are rough estimates for prime science. In some cases, exact rates are proposal proprietary.

Again, the conditional nature of these decisions indicates that the actual mission set is likely to change in the future.

The NASA CFO's 2015 Agency Mission Planning Model

The NASA CFO maintains a new Agency Mission Planning Model (AMPM), which introduces a number of changes relative to the OCT mission model. These include:

- Mission deletions — e.g., no Asteroid Redirect Robotic Mission (ARRM), no Europa Mission, one less New Frontiers.
- Mission additions — e.g., European Space Agency's Jupiter Icy Moons Explorer (JUICE), numerous Astro and Helio small explorers (SMEXs).
- Mission slips — e.g., Astro Flagships, Solar Orbiter, Solar Terrestrial Probe (STP)–6+, Living with a Star (LWS)–7+, New Frontiers 4+, Exploration Mission (EM)–2.
- Mission accelerations — e.g., Discovery 14+, Astro & Helio SMEXs.

A summary of potential deep-space optical missions appears in Figure 1, with indications where they are affected by differences between the OCT and CFO mission candidate sets.

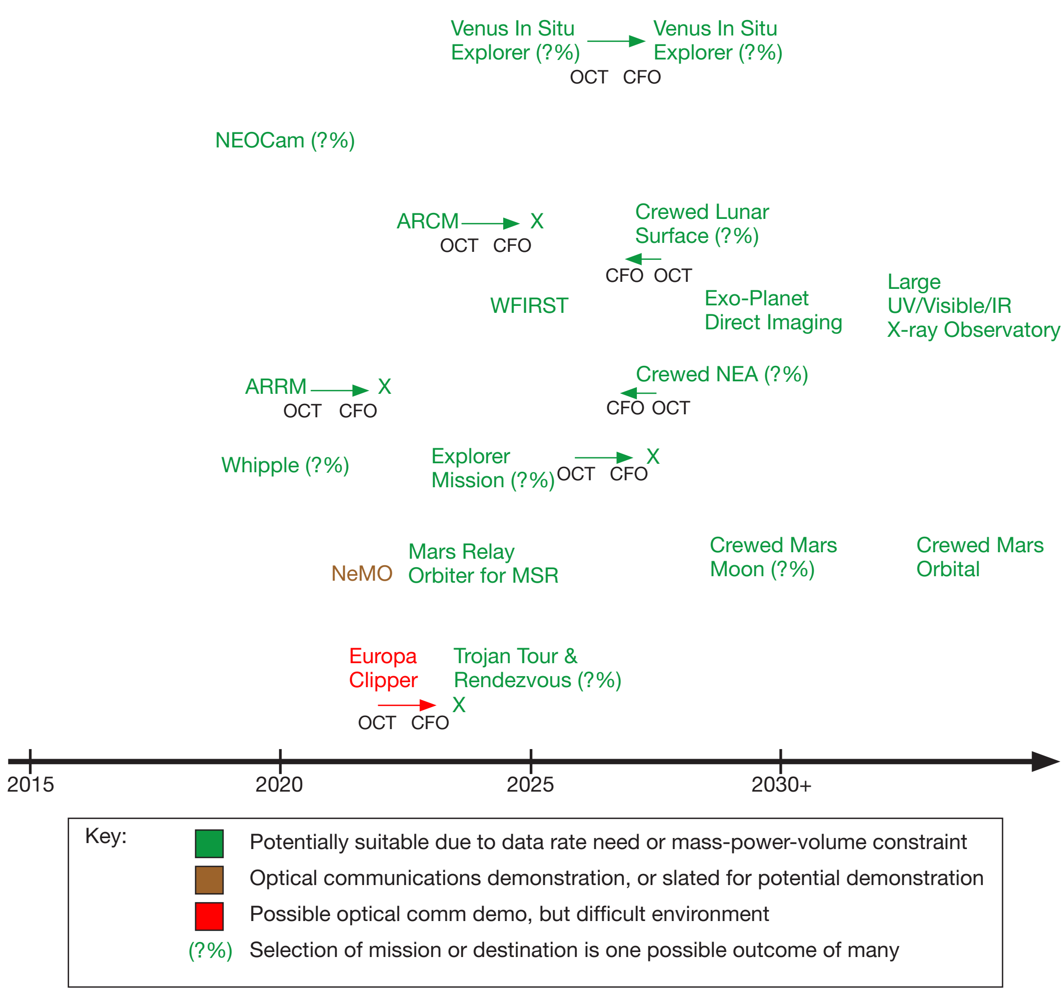

Figure 1. Potential deep-space candidate missions using NASA OCT and CFO data.

Looking Beyond the Classical Missions — Deep Space

While NASA has been deferring and eliminating flagship and New Frontiers–class missions in recent AMPMs, the agency is now adding smaller, less-expensive Discovery, Explorer, and SMEX missions. Overall, the agency's mission set appears to be trending toward smaller, less-expensive missions.

These missions are not necessarily high data rate, but they may be constrained by mass, power, and volume.

While higher data rates have often been used in the past to justify optical communications (particularly when those rates push on allocated spectrum bandwidth constraints), the primary motivation for the next 15 years may be spacecraft mass, power, and volume constraints. While not fully reflected in the AMPM, NASA has also been aggressively funding the launch and development of CubeSat missions for both low-Earth orbiting (LEO) and deep-space applications. This could further increase the anticipated "pool" of mass, power, volume (M-P-V) constrained missions.

JPL has asserted in the past that, for deep-space spacecraft with equivalent allocated mass, power, and volume, optical communications provides roughly a 10× performance improvement over a Ka-band system. Hence, for the same performance, the optical communications system should enable a significant reduction in spacecraft mass, power, and volume. The M-P-V reduction will probably not be fully commensurate with the forgone performance improvement, unless the RF system can be completely eliminated. Nonetheless, it should be possible to significantly decrease the RF system M-P-V "footprint."

Looking Beyond the Classical Missions — Lunar and Near-Earth

The Interagency Operations Advisory Group commissioned a multilateral study of the business case for cross-support of optical communications. In their report of 2012, the study group concluded that the constraint of optical communication to avoid clouds dictated the use of optical ground stations that are geographically diverse to support LEO, lunar, and Sun–Earth Lagrange point missions. They considered the possibility of Earth-orbiting relay stations, both for intersatellite links and ground feeder links, and recommended the use of 1550-nm wavelength for uplink to ease usage constraints associated with eye safety for aviators who may cross the uplink beam. They found that space terminals are rapidly maturing, that space terminal intersatellite link and feeder link capabilities have been demonstrated, and relay terminals were under development. They also found that corresponding ground terminals to support space optical assets are technically and economically feasible, and that there is demand for the high data rates possible with optical communication.

As a result of these findings, they considered it likely that LEO satellites (160- to 2000-km altitude), lunar, and Sun–Earth Lagrange point missions would use Earth-based optical services. The space terminals for such missions would likely be smaller (8- to 14-cm aperture) and lower-power (0.5 to 5 W) compared to those used for deep space.

III. Reference Missions for Architecture Evaluation

Considering the current situation, in which the expected lifetime of an optical ground segment goes well beyond NASA's current planning horizon, and the wide range of mission options still under consideration within that planning horizon, it is not possible to identify at this time any specific set of missions that the ground segment will actually serve. Recognizing the substantial uncertainty concerning the precise mission set to be handled, it is helpful to define a set of reference missions that bound the space of potential customer requirements, so that the ability of alternative systems to meet various types of customer needs can be evaluated. We identified 12 DRMs for this purpose, which encompass the wide range of applications that an optical ground segment might eventually be called upon to serve. These mission concepts encompass a range of orbit types, terminal sizes, and positions in the solar system that reveal the chief performance variables of an optical ground segment. The set of DRMs is summarized in Table 2 and described in greater detail in subsequent sections.

Some remarks are in order regarding the DRMs for small optical terminals (5-cm aperture, 1 watt of transmitter power). At the outset of this study, small optical terminals were not included, but several stakeholders requested that they be added in the context of missions both near and far from Earth. We attempted to do this in an exploratory way, taking into account mission needs from the preceding section. However, definition of suitable requirements or DRMs involving small terminals needs further study.

The potential carriers for small optical terminals are many, including CubeSats, small (but larger than CubeSat) spacecraft, landers, larger relay spacecraft, circumplanet networks, intersatellite cross-links, etc. In all of these potential applications, the notion of a "small" optical terminal inherently assumes a tight combination of mass, power, volume, and complexity constraints. Simple reapplication of the approaches used for larger optical terminals may not be capable of meeting such tight constraints. This situation is recognized by the research community, and work is actively underway to find solutions.

Nonetheless, we explored small terminals in the spirit of a "what if" study. The available tools limited us to being able to explore only the case of smaller aperture, lower power, and pulse-position modulation (PPM). For pointing, we assumed diffraction-limited, and for peak/average power ratio of the lasers we assumed greater than 128. These two characteristics are not currently achievable within mass, power, and volume constraints consistent with a 5-cm aperture, but are included as placeholders.

The DRMs involving small terminals, therefore, should be regarded as very approximate descriptions from a "what if" study and should only be used for broad considerations that would be applicable when a rescaling occurs to reflect the true architecture of small terminals. Our results for the small-terminal reference missions probably should not be used for quantitative comparisons between large and small terminals. Despite the limitation, some general features of the problem space can be illuminated by our approach. The comparative value of larger ground apertures, for instance, in improved cumulative data returned from a given spacecraft terminal should still be valid, as would be comparative increases due to ground aperture in achievable range for a given data rate. Also the role of larger apertures in

Table 2. Summary of optical ground segment study design reference missions.

Article Page No./ DRM	Location	Orbit Type	Example Mission Type	Example Mission Name	Start, CY	Finish, CY	Wave-length, nm	Min Range, AU	Max Range, AU	Max SEP, deg	Min SEP, deg	Terminal Class	Transmit Power, W	Aperture Diameter, m	Downlink Data Rate Requirement	Uplink Data Rate Requirement
11. Small Optical Terminal at Mars	Mars	Heliocentric/Mars	Lander Demo Optical Terminal or CubeSat at Mars	Mars 2020	2022	2023	1550	0.42	2.6	180	3	Small	1	0.05	~10 kbps DTE at 2.7 AU; ~128 kbps to 2 Mbps to relay orbiter	[1 kbps*]
11. Medium Optical Terminal at Mars	Mars	Heliocentric/Mars	Mars Orbiter	NeMO	2022	2023	1550	0.42	2.6	180	3	Medium	4	0.22	~>5 Mbps	[100 kbps*]
12. Large Optical Terminal at Mars	Mars	Heliocentric/Mars	Crewed Mars Surface	Crewed Mars Surface	2036	2038	1550	0.42	2.5	180	3	Large	20	0.5	~150 Mbps to 600 Mbps	~25 Mbps
12. Deep Space Observatory–Nighttime	SEL2	Sun–Earth Lagrange Point 2	Observatory	WFIRST at L2	2024	2025	1550	0.009	0.011	175	~160	Medium	4	0.22	~150 Mbps to 262.5 Mbps	[100 Mbps*]
13. Deep Space Observatory–Dawn or Dusk	ETO	Solar Earth Trailing Orbit	Observatory	Whipple	2020	2022	1550	0.4	0.4	80	75	Small	1	0.05	~2.5 Mbps	[1 Mbps*]
13. Deep Space Observatory–Daytime	SEL1	Sun–Earth Lagrange Point 1	Observatory	NEOCam	2020	2020	1550	0.009	0.011	~20	3	Small	1	0.05	~30 Mbps (possibly up to 260 Mbps)	[100 Mbps*]
14. Medium Optical Terminal at Jupiter Distance	JSL3	Heliocentric/Jupiter Trojan	Outer Planets	Trojan Tour and Rendezvous	2030	2031	1550	4.2	6.2	180	3	Medium	4	0.22	~12.5 to 30 kbps	[1 kbps*]
14. Large Optical Terminal at Saturn	Saturn	Heliocentric/Saturn	Outer Planets	Saturn Atmospheric Entry Probe or Enceladus Life Finder	2039	2040	1550	8.5	10.5	180	3	Large	20	0.5	~1.6 kbps relay [1 Mbps*]	[10 kbps*]
15. Large Optical Terminal at Jupiter	Jupiter	Heliocentric/Jupiter	Outer Planets	Europa Clipper	2024	2025	1550	4.2	6.4	180	3	Large	20	0.5	~134 kbps	[10 kbps*]
15. Inner Planets	Venus	Heliocentric/Venus	Inner Planets	Venus In Situ Explorer	2024	2026	1550	0.28	1.72	50	3	Medium	4	0.22	~25 kbps to ~14.5 Mbps relay	[100 kbps*]
16. Very Small Terminal at Lunar Distance	Moon	Geocentric/Moon	Crewed Lunar (Surface)	Crewed Lunar (Surface)	2027	2029	1550	0.003	0.003	180	3	Very Small	0.002	0.02	~25 Mbps; early desire for ~150 Mbps	~6 Mbps
16. Mars Trunk Line	Mars	Heliocentric/Mars	Mars Relay Crewed Mars Orbital	Aerostationary Orbiter Crewed Mars Orbital	2030	2031	1550	0.42	2.6	180	3	Large	10	0.3	~250 Mbps	[100 kbps*]

*Provisional value in absence of customer statement.

improving the return on investment in spacecraft capability should be supportable with our approach.

Small Optical Terminal at Mars

The prototypes of mission concepts for small optical terminals at Mars are either CubeSats at Mars, or a terminal on the outside of a Mars lander such as was considered at one time for accommodation on Mars 2020. The goal is to provide a much higher data volume by relay to another optical communication asset orbiting Mars, or direct to Earth (DTE) at a lower data rate but still high compared to RF. The required data rate is about 10 kbps DTE at 2.6 AU, and about 270 kbps at 0.5 AU, and about 128 kbps to 2 Mbps to a relay orbiter. In the CubeSat scenario, a CubeSat would be sent to orbit Mars, perhaps piggybacked with another spacecraft, to perform observing or relay functions. In both these cases, a 5-cm aperture and a 1-W laser transmitter would be used.

The approval status of this type of mission is that the Mars Program has approved the Mars 2020 rover mission, based on the Mars Science Laboratory architecture. The 2013 science definition team conditionally recommended the inclusion of either a large or a small optical terminal to improve data return and promote the future use of optical as a primary data channel. The decision to include a demonstration optical terminal on the mission has not been made, but an accommodation study was made during early 2015 for a small terminal. However substantial time has elapsed suggesting that the optical terminal is unlikely to be approved for the 2020 time frame[2,3,4] [2–6]. However, this type of mission would be a system driver for a ground segment, and it is possible that this type could be flown during the lifetime of the system.

Medium Optical Terminal at Mars

The prototype of mission concepts for a medium-sized optical terminal at Mars is an optical demonstration on a Mars orbiter sent for a scientific purpose. In this scenario, a Mars orbiter carries a Deep Space Optical Communications (DSOC) terminal for a DTE link. Relay data rate requirement is unknown; the value 5 Mbps is approximate based on analogy with a relay orbiter for Mars Sample Return, but higher data rate requirements for remote sensing needs are conceivable. The aperture would be 22 cm and the power 4 W.

The approval status of this type of mission is that the Mars Exploration Program is studying a possible Next Mars Orbiter (NeMO) mission that could fly as early as 2022, and which could be a possible first user of optical at Mars.

This is an important reference case because it is a high-priority target in NASA plans, and may be the first user of a ground optical system. However, there may be Discovery missions that may carry similar optical terminals and would occur about the same time or slightly later[5] [6].

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[2] D. Abraham, June 26, 2014, op cit.

[3] A. Biswas, “Deep Space Optical Communications,” presentation for DSOC for Discovery Technology Day, April 9, 2014.

[4] H. Xie, J. Wu, B. Moison, and S. Piazzolla, *Strategic Optical Link Tool Annual Report* (internal document), Jet Propulsion Laboratory, Pasadena, California, October 10, 2012.

[5] D. Abraham, June 26, 2014, op cit.

Large Optical Terminal at Mars

The prototype of mission concepts for a large optical terminal at Mars are potential crewed missions, either orbiting or landing on Mars, the latter being the more demanding case for an optical ground segment due to the number of assets involved and the associated high data rates. In this scenario, a crewed mission would be sent to land on Mars and return to Earth, preceded by a substantial robotic campaign to place assets on Mars to support human presence. One estimate for the required data rate believed to stem from legacy studies from the Constellation program circa 2007, is 150 Mbps downlink and 25 Mbps uplink. The purpose of the high data rates would be to carry high-definition television (HDTV), software uploads, and crew training materials. Another estimate based on International Space Station (ISS) experience (the system size is expected to be comparable to ISS) is 250 Mbps (ISS current) to 600 Mbps (ISS future).

The Crewed Mars Surface mission is under evaluation by the Human Exploration and Operations Mission Directorate. NASA HEOMD is pursuing evaluations of both Mars orbital and asteroid retrieval missions.

This is an important reference case because the data rates are high, but constraints on the spacecraft terminal are less severe due to the large size and power of the spacecraft for human occupation[6] [7,8]. We assumed a 50-cm aperture and 20-W transmitter for this case.

Deep Space Observatory — Nighttime

The prototype of missions for deep-space observatories in the nighttime direction from Earth is the Wide-Field Infrared Survey Telescope (WFIRST). This mission repurposes a telescope with a 2.4-m aperture built under contract to another agency and then made available to NASA. Two instruments are planned: a wide-field instrument that provides wide-field imaging and slitless spectroscopic capabilities required to perform the dark energy, exoplanet microlensing, and near-infrared surveys; and a coronagraph instrument to support high-contrast exoplanet imaging and spectroscopic science. The required data rate was 150 Mbps at one time, but a recent request was received to investigate up to 262.5 Mbps.

WFIRST is planned by the Science Mission Directorate (SMD) for launch in 2025, and is in pre-Phase A. The project website has an Earth geostationary orbit as its design reference trajectory, although this may be out of date. However, another version of the mission would involve a trajectory to Earth–Sun Lagrange point 2 (SEL2) launching in 2023, and the NASA Interplanetary Network office has been asked to evaluate this version by the project. The spacecraft might first begin in geosynchronous orbit, get checked out, and then transfer to SEL2.

A significant issue for L2 missions is that Earth appears against the Sun from that location, interfering with the uplink beacon. We assumed that an L2 mission could be placed in a halo orbit providing at least 5 deg of Sun–Earth–probe angular offset.

This mission is an important design reference case because it realizes the full capability of optical under ideal nighttime conditions. The potential for a large observatory to be placed

[6] H. Xie et al., October 10, 2012, op cit.

at Sun-Earth L2 is frequently discussed, suggesting that the possibility should be considered in evaluating optical facility options[7] [9].

Deep Space Observatory — Dawn or Dusk

The prototype of missions for deep-space observatories in the dawn or dusk direction from Earth is the Whipple mission concept. The Whipple mission would place an observatory spacecraft in an Earth-trailing orbit at about 0.4 AU, possibly beginning as early as 2020–2024, to "develop and validate a technique called blind occultation that could lead to the discovery of various celestial objects in the outer solar system and revolutionize our understanding of the area's structure." The required science data rate would be about 2.5 Mbps.

Whipple is one of three candidate Discovery mission concepts (PriME, Whipple, NEOCam) that were funded in 2011 to mature their designs for possible selection in the future. Selection of the Whipple mission is yet to be determined; it is only one possible outcome among many.

Whipple is an important reference case because its orbit would carry it between daytime and nighttime conditions near sunrise/sunset. This accounts for a substantial and rapid data rate variation during individual passes, as the range from Earth causes less variation in raw data rate. The spacecraft terminal is undefined, but the required data rate could be met with a terminal significantly smaller than the DSOC terminal (4 W, 22 cm) generally offered to Discovery missions. For the DRM, the hypothetical terminal was sized small (1 W, 5 cm) comparable to the Mars 2020 small terminal candidate to convey to the customer the potential benefit of optical in smallness, to reveal the Sun elevation angle effects, and to reveal sensitivity to smaller Earth stations. There are other small terminals planned; e.g., 10 W intermittent, 2 mm diameter, 1064 nm wavelength, by Welle et al. 2015[8,9] [5,10,11].

Deep Space Observatory — Daytime

The prototype of missions for deep-space observatories in the daytime direction from Earth is the NEOCam mission. This mission has a spacecraft that would be placed in an orbit at Sun–Earth Lagrange point 1, about 1 (to 1.5) million km from Earth in the direction of the Sun, making it a daytime object as observed from Earth. NEOCam would carry a telescope to assess the present-day risk of near-Earth object (NEO) impact, to study the origin and ultimate fate of our solar system's asteroids, and to find the most suitable NEO targets for future exploration by robots and humans. The required data rate would be about 30 Mbps (possibly up to 260 Mbps).

NEOCam is one of three candidate Discovery mission concepts (PriME, Whipple, NEOCam) that were funded in 2011 to mature their designs for possible selection in the future. The team proposed NEOCam to NASA's 2015 call for Discovery proposals, with a selection announcement currently scheduled for November 2015.

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[7] D. Abraham, June 26, 2014, op cit.

[8] Ibid.

[9] A. Biswas, April 9, 2014, op cit.

NEOCam is an important reference case because its orbit, when on station, would have a small Sun–Earth–probe angle. This causes a general, sustained impact of background scattering and higher than average atmospheric turbulence. The spacecraft optical terminal is unknown publicly as the mission is still in competition (the public mission description baselines radio communication), but the required data rate could be met with a terminal significantly smaller than the DSOC terminal (4 W, 22 cm) generally offered to Discovery missions. For the design reference mission, the hypothetical terminal was sized small (2 W, 5 cm) to convey to the customer the potential benefit of optical in smallness, to reveal the Sun–Earth–probe angle effects, and to reveal sensitivity to smaller Earth stations[10,11] [5,10,12].

Medium Optical Terminal at Jupiter Distance

The prototype of missions for a medium-sized optical terminal at JupiterDRM distance is the Trojan Tour and Rendezvous. In this mission concept, a spacecraft would travel to the vicinity of the Trojan cloud of asteroids, fly by multiple asteroids, rendezvous with one, and possibly land on it. The purpose is to characterize the bulk chemical composition of a Trojan asteroid surface, to observe the current geologic state of the surface and infer past evolution and the relative importance of surface processes, to characterize the bulk physical properties and interior structure of a Trojan asteroid, and to search for or constrain outgassing from subsurface volatiles. An average data rate of 12.5 kbps would be required.

The approval status of this type of mission is that the decadal study by the National Academies recommended a Trojan Tour and Rendezvous as a New Frontiers candidate mission. The mission is included in plans for the competition for the next mission, scheduled to being in FY2016. The mission, if selected, would launch around 2021. This mission is included as an SMD mission in the OCT Roadmap.

This would be a low-data-rate, mass-power-volume driven mission that superficially appears to be able to benefit from a small optical terminal based on the low data rate needs. Including a Trojan Tour and Rendezvous as a DRM, however, forces an examination of uplink constraints, where the size of the terminal may be driven more by the difficulty of detecting an uplink beacon than by downlink data rate. It may require a larger spacecraft aperture, or drive the ground segment to a more powerful uplink beacon[12] [13,14].

Large Optical Terminal at Saturn

The prototype of missions for a large optical terminal at Saturn is the Saturn Atmospheric Probe. This mission concept would deploy a probe into Saturn's atmosphere to characterize its layers as well as noble gas abundances and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen. A carrier/relay craft with the probe would arrive at Saturn approximately 7 years after launch. The probe would separate from the carrier, enter the atmosphere and begin measurements, with the nominal mission ending after 55 min of data collection. The probe would be designed to survive to 10 bar atmospheric pressure, and the carrier/relay would continue to listen for as long as the entry site remains visible.

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[10] D. Abraham, June 26, 2014, op cit.

[11] A. Biswas, April 9, 2014, op cit.

[12] D. Abraham, June 26, 2014, op cit.

The Saturn Atmospheric Probe mission is included in plans for the competition for the next New Frontiers mission, scheduled to begin in FY2016. The mission, if selected, would launch around 2021. This mission concept is also included as an SMD mission in the OCT Roadmap; under this concept, launch is proposed for August 30, 2027, for a June 22, 2034, arrival.

Including a Saturn mission as a DRM forces an examination of uplink constraints, where the size of the terminal may be driven more by the difficulty of detecting an uplink beacon than by downlink data rate. Acquiring an uplink beacon may require a larger spacecraft aperture and/or a more powerful uplink (e.g., 50-cm aperture and 10- to 20-kW beacon), or possibly a different pointing strategy. If only a demonstration were to be required of optical, smaller Earth and space terminals could suffice during an early mission phase. Either the Saturn Atmospheric Entry probe or the Enceladus Life Finder mission concept are possible candidates. If the mission is the atmospheric probe, then low data rates by X-band may be acceptable and would tend to show a case where RF may be preferable. However, the Enceladus Life Finder might carry a similar optical payload, and being a data-rich mission may justify using an optical communication system; although the proposal process is still open, one press report mentions that an optical communication payload is included[13] [14–19].

Large Optical Terminal at Jupiter

The prototype of missions for large optical terminals at Jupiter is the Europa Mission. This planned mission would conduct detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life. The mission would place a highly capable, radiation-tolerant spacecraft in a long, looping orbit around Jupiter to perform repeated close flybys of Europa. The Europa Mission entered formulation phase effective June 2015.

Including Europa Mission as a DRM forces an examination of uplink constraints, where the size of the terminal may be driven more by the difficulty of detecting an uplink beacon than by downlink data rate, though the uplink challenge would not be as severe as for Saturn. The mission may require a larger spacecraft aperture and/or a more powerful uplink beacon (e.g., 50-cm aperture and 10-kW beacon). The mission would be of long duration and includes high-resolution cameras, for which the high data volume afforded by optical is beneficial[14] [15,20,21].

Inner Planets

The prototype of missions for the inner planets is the Venus In Situ Explorer. This mission concept would characterize the chemical composition and dynamics of the atmosphere of Venus, and/or measure surface composition and rock textures. The mission design may include both a lander and a balloon aerobot.

This mission was originally proposed in the 2003 planetary science decadal survey, and it is now included in the New Frontiers 4 call for proposals, and would roll over to the New Frontiers 5 call if not selected at first.

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[13] D. Abraham, June 26, 2014, op cit.

[14] Ibid.

The mission would be at approximately zero to 45 deg SEP angles, and potentially have a high data rate that may benefit from optical communication[15] [22,23].

Very Small Terminal at Lunar Distance

The prototype of missions for very small terminals at lunar distance is a CubeSat or a small landed instrument or relay that provides services in the context of a surrounding crewed mission. This type of mission concept also gives an idea of what might be possible with optical communication from geostationary or LEO payloads, with appropriate scaling for distance.

A crewed mission would be sent to land on the Moon and return to Earth. The best estimate for the required data rate for all the crewed deep-space missions, based on legacy studies from the Constellation program circa 2007, is a 25- to 150-Mbps downlink and a 6- to 25-Mbps uplink. The purpose of the high data rates is to carry HDTV, software uploads, and crew training materials.

There is continuing international and industrial interest in lunar missions as evidenced by the Global Exploration Roadmap. NASA/HEOMD is pursuing evaluations of both Mars orbital and asteroid retrieval missions, which may eventually include circumlunar communication sites.

Lunar missions are not a driver on the ground segment. However, a ground segment sized for interplanetary communication is so powerful that it opens up the possibility of new operations concepts using very small, ubiquitous laser communication terminals. Even if constrained for eye safety, tiny terminals with mW-level power and small apertures (mm to cm) may enable multi-Mbps data rates. The character of communication would be very similar to deep space for lunar down to high-Earth-orbiting spacecraft; for low-Earth orbiters, faster-tracking ground telescopes would be needed, as well as a data system capable of reliably acquiring many short bursts of high-rate data [7,8,24].

Mars Trunk Line

The prototype of missions for a Mars trunk line is the Mars Aerostationary Relay. In this scenario, one or two satellites in orbit about Mars in aerostationary orbit would provide both communications and navigation capability for a number of potential user missions: science missions to the martian moons, relays for landers or sample return, and relays for crewed orbital or surface missions.

Aerostationary relays were recommended by the Space Communication Architecture Working Group in 2006 and the Deep Space Mission System roadmap of 2005. Interest continues for including optical telecom in the next Mars orbiter for the early 2020s time frame.

This is an important reference case because it may be the first high-rate optical communication system at Mars distance[16] [25,26].

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[15] D. Abraham, June 26, 2014, op cit.

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IV. Summary

We studied the wide range of mission concepts under consideration by NASA over the next 20 years, and classified them as to whether they are likely to benefit from optical communication. Given the substantial uncertainties of timing and requirements for such missions, we chose to examine a set of 12 DRMs, which bound the space of potential customer requirements and encompass the wide range of applications that an optical ground segment might eventually be called upon to serve. The DRMs encompass a range of orbit types, terminal sizes, and positions in the solar system that reveal the chief system performance variables of an optical ground segment, and may be used to enable assessments of the ability of alternative systems to meet various types of customer needs.

As a result of examining the potential mission set, we have the following observations that may be helpful to guide the ground segment planning effort:

(1) The optical ground station architecture should maximize flexible utility. This is because most planetary missions are competed, and there is still significant uncertainty as to the destinations of system-driving missions. Also, there is significant annual, budget-driven variability in the both the mission composition and anticipated timeline. Some of the largest data rate drivers will be at the Sun–Earth Lagrange points or closer; but some challenging links will occur over planetary distances.

(2) The optical ground station architecture should be designed to save NASA missions money. Most missions over the next 15 years are budget-driven to be as small and low-cost as possible. Providing capability on the ground that can reduce a spacecraft's mass, power, volume "footprint" is key. A complementary effort to develop a very small, low-cost optical flight terminal may be needed. Also, larger Earth receive terminals will help to provide the best return on each mission's individual investment in optical communication, as well as the best return on investment over many future missions.

(3) The optical ground station architecture should be designed to be scalable. A significant, but uncertain potential driver is communication for human exploration. In the long-term, it potentially drives downlink, and uplink, rates more than anything else. Human exploration begins relatively close to Earth, in cislunar space. Eventually, it progresses deeper into space, with Mars as an end goal. The timing of the progression deeper into space is highly uncertain, but is likely to "push to the right" — so building the full capability upfront to service a human Mars surface expedition may not make sense. But, the architecture should be capable of scaling to that capability when it does.

(4) Overall, it is our opinion that the ability to secure future funding will depend on defining a path to a flexible, incrementally scalable capability that can adapt to changes in the NASA mission set, and that can save mission funding.

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