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Research and Development Optical Deep Space Antenna Sizing Study

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Results from this study provide a basis for the selection of an aperture size appropriate for a research and development ground-based receiver for deep space optical communications. Currently achievable or near-term realizable hardware performance capabilities for both a spacecraft optical terminal and a ground terminal were used as input parameters to the analysis. Links were analyzed using OPTI, our optical link analysis program. Near-term planned and current missions were surveyed and categorized by data rate and telecommunications-subsystem prime power consumption. The spacecraft optical-terminal transmitter power was selected by matching these (RF) data rates and prime power requirements and by applying power efficiencies suitable to an optical communications subsystem. The study was baselined on a Mars mission. Results are displayed as required ground aperture size for a given spacecraft transmitter aperture size, parametrized by data rate, transmit optical power, and wavelength.

I. Introduction

This study builds upon and continues work performed to develop a ground-based optical terminal for deep space communications, the Deep Space Optical Receiving Antenna (DSORA) [1–3]. Deep space links can utilize pulse position modulation schemes very effectively, which implies the information is contained in the energy per pulse and not in the phase of the optical beam. Thus, DSORA can use a large aperture, incoherent, photon-bucket type of telescope that is much less expensive to construct [4] than the phase-preserving Keck I and II telescopes ($93M). The nominal DSORA aperture size is 10 m. This size of aperture was found to be both technologically achievable and reasonably affordable [5]. The present study reexamined what was technologically achievable both from the spacecraft side as well as the ground receiver side and used performance parameters in a link analysis that are achievable now or in the near future (5 years) with continued development. Mission planning was reexamined as well, and this led to consideration of nominal data rate requirements much less than 1 Mbps, with a Mars mission providing the most likely opportunity of placing an optical communications subsystem on a deep space probe in the near future.

II. Mission Database

The mission database currently being maintained by the Telecommunications and Data Planning Office[1] was used as the basic source of information regarding current and near-term future mission data

[1] Data compiled and maintained by R. Cesarone, Telecommunications and Data Acquisition Planning Office, Jet Propulsion Laboratory, Pasadena, California.

rates. Of the planetary missions in the database (as of December 1993), 29 had either firm data rate requirements or projected estimates available. A distillation of this information is contained in Table 1, which categorizes missions into flyby, orbiter, lander, probe, or other, and shows the mean rate and spread. Additional mission data rates projected well into the next century (to the year 2075) were obtained from the JPL-sponsored Deep Space Relay Satellite System (DSRSS) study contracts.[2,3] Table 2 summarizes telemetry data rate requirements for primary planetary encounter science, as derived by Stanford Telecom (S-TEL).[4]

Table 1. Data rates for mission categories (29 missions total).

Mission type	Number, percent	Data rates		
		Maximum, kbps	Minimum, kbps	Mean, kbps
Flyby	31	640	0.008	86
Orbiter	38	500	3	135
Lander	7	10	1	6
Probe	7	0.5	0.35	0.5
Other	17	400	8	200

From Tables 1 and 2, it is seen that the majority of missions can be serviced by telecommunications subsystems providing 200-kbps data rates or less. Large spacecraft with multiple imaging cameras (or a smaller number of high-resolution cameras) will require data rates approaching 1 Mbps. Current NASA plans do not indicate that large, heavy spacecraft, such as Cassini, will be flown in the near future, as the trend is toward a larger number of smaller and lighter payloads. For this study, a data rate of 250 kbps was selected as a reasonable upper limit.

III. Spacecraft Optical Transmitters

To size the ground aperture, a spacecraft optical transmitter had to be conceptually devised and parametrized. Key parameters include laser power output at a specified wavelength, transmitter aperture size, and beam pointing accuracy.

The most mature technology for laser transmitters are Nd-based laser gain media operating at 1.06 μm, and the same laser frequency doubled to 0.532 μm. Adequate powers are presently available at these wavelengths (3.5 W pulsed at 0.532 μm, 11 W continuous wave (CW) at 1.06 μm [6]), the atmospheric transmittances are good, and high-performance detectors exist. A realistic transmitted optical power was obtained by first identifying the prime power required for several RF telecommunications subsystems already designed (or in process) to provide a specified data rate for the categories of missions indicated above. It was assumed that the same power was allocated to the optical communications subsystem and the same data rate requirement imposed. The laser power output was obtained by applying appropriate power efficiencies for optical and electro-optical hardware to the prime electrical power.

[2] Stanford Telecom, *DSRSS Mission Requirements TR90090 Final Report*, DSRSS Study Contract No. 958734, January 21, 1991.

[3] TRW, *Deep Space Relay Satellite System Study Final Report*, DSRSS Study Contract No. 95833, July 22, 1993.

[4] Stanford Telecom, op. cit., pp. 1–13.

Table 2. Data rate requirements projected for future missions.

Encounter type/ representative mission	Likely science objectives	Likely instrumentation	Data rate considerations and rationale	Relationship to timeline element	Derived requirements	
					Data rate, kbps	Variability
Flybys/ Pluto Flyby	Planetary figure, mass, density, magnetic field. Surface character. Atmospheric character. Solar wind interactions.	Imaging camera. Magnetometer. Plasma wave spectrometer. Ultraviolet spectrometer.	Camera data rate is 6–350 Mbps. If camera episodes are short, then data recording can be used to lower effective data rate.	4 months around primary target encounter event.	100	Moderate
Landers/ Mars Global Network	High resolution of localized sites. Perform in-situ soil analyses. Seismic studies. Meteorological studies.	Camera. Soil sampler. Magnetometer. Meteorological. Seismological.	Long-term data generation. Continuous low rate. Occasional high rate. Use of data recorders. Data transfer to Earth based on view period.	Corresponds to surface operations phase.	20	Moderate
Sample return/ Mars Rover Sample Return	Collect soil samples. Collect rock samples. Meteorological studies. Seismic studies.	Camera. Rover. Meteorological.	Low rate. Relatively short duration (several months). Communication may be relayed via an orbiting spacecraft.	8 months around primary target encounter event.	50	Moderate
Probe, penetrator/ Cassini Probe	Atmospheric studies. Lightning characteristics. Surface state composition.	Imager spectral radiometer. Gas chromatograph. Atmospheric structure instruments.	Low rate. Short duration.	20 days around primary target encounter event.	10	Moderate

Table 3 indicates four specific missions, their respective power allocations, data rates, and spacecraft attitude control capabilities. An optical communications subsystem shall require an onboard beam control assembly to increase pointing accuracy. For reference, the Defense Support Program (DSP) optical crosslink subsystem achieved optical pointing accuracy in ground simulation tests of 1.3 μrad at 1.06 μm (1ϕ value) [7]. The design data rate was 1.28 Mbps at crosslink distances of 71–84 Mm and for a ground link distance of 38 Mm. This represents older technology, frozen at approximately 10 years ago. For the link analyses of this study, 100 nrad was used [8].

Table 4 shows four optical transmitters, their power requirements, and the estimated total power consumption for the subsystem, including laser and gimbal. The 10-W class transmitter is from TRW's DSRSS study,[5] included for comparison and reference only and not used in the link analyses. The three transmitters at 0.5, 1.0, and 2.0 W use conversion efficiencies of 13 percent. The estimated total power consumed is from previous work[6] and currently ongoing work performed by JPL's Optical Communications Group. For this article, it is assumed that a gimbal for the telescope is needed. A gimbal is

[5] TRW, op. cit., pp. 5-54–5-55.

[6] H. Hemmati and C. C. Chen, "Report on the Pluto Flyby Laser Transmitter Study," JPL Interoffice Memorandum 331-92.6-143 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 1, 1992.

estimated to consume 15 W.[7] The remaining electronics use about 27 W. An optical transmitter at 2 W consumes at most 16 W of prime power, and the total subsystem consumption is 58 W, less than the power allocated to the communications subsystems of several categories of missions. For many missions, a gimbal will not be required; thus, the power for the 0.5-, 1.0-, and 2.0-W transmitters of Table 4 will each be reduced by 15 W.

Table 3. Representative missions for spacecraft categories, RF data rates, and prime power allocations.

Parameter	Spacecraft category			
	Flyby	Orbiter	Orbiter/probe	Lander
Representative mission	Pluto	Cassini	Galileo	MESUR Pathfinder
Time frame	2014–2015	2004–2008	1995–1998	1997
Distance, km/AU	6.15×10^9/41	1.58×10^9/10.5	9×10^8/6	3.75×10^8/2.5
Telecommunications rate	80 bps	250 kbps	134 kbps	1200 bps
Band	X	X	X	X
Control accuracy	1.5 mrad (1σ)	2 mrad (3σ)	3.4 mrad (3σ)	12 mrad (1σ)
Control stability	10 μrad/1 sec	4 μrad/0.5 sec	125 μrad/1 sec	1.7 μrad (knowledge)
Total spacecraft power, W	60	800	500	200
RF subsystem power, W	24	88	—	83
RF transmitted power, W	3	20	20	17

Table 4. Spacecraft transmitter power requirements.

Optical power output, W at 1.06 μm	Prime power into laser, W	Total prime power required for optical communications subsystem, W
0.5	4	46
1.0	8	50
2.0	16	58
10.0	91	133

The final parameter is the optical aperture size, and three sizes were selected: 10, 30, and 50 cm. There are several designs for 10-cm aperture telescopes in existence, and this size is appropriate for missions where size and weight are given highest priority and where the data rate is low. SSG Inc. is currently being funded under the NASA Phase II Small Business Innovative Research Program (SBIR) through the JPL Optical Communications Group to build a 30-cm silicon carbide telescope that could eventually be space qualified. It is estimated that it will weigh about 6 kg, without a gimbal. Additionally, successful demonstration of this 30-cm mirror technology would enable fabrication of a 50-cm telescope.

[7] L. A. Voisinet, "OCD Gimbal Discussion," JPL Interoffice Memorandum 331-93.6-209 (internal document), Jet Propulsion Laboratory, Pasadena, California, December 13, 1993.

IV. Link Analyses

OPTI was used for all link analyses. Inputs are shown in Table 5. Mars was selected as the candidate target for hypothetical missions: orbiters, landers, and probes. In view of the recent NASA decision to explore Mars over the coming decade [9], Mars will undoubtedly present the largest number of opportunities in the near term for a possible deep space optical communications payload.

Links were first modeled using a wavelength of 1.06 μm. A frequency-doubling conversion efficiency of 50 percent was then applied to the transmitter power at 1.06 μm and the links recomputed at a wavelength of 0.532 μm, making appropriate changes in atmospheric transmittance and detector quantum efficiency. Avalanche photodiode detectors (APDs) in a direct detection mode were used for both wavelengths. Parameters listed for hardware performance are realizable. All links are for daytime conditions and assume an atomic resonance filter is used to suppress atmospherically scattered background light.

A. Ground Aperture Sizes for λ = 1.06 μm

Table 6 gives the ground aperture diameter required in meters for values of the spacecraft transmitter aperture of 10, 30, and 50 cm, for four different data rates, and for ranges of 2.5 and 0.4 AU (for Earth–Mars at nearly the furthest separation and at the closest approach, respectively) at a communication wavelength of 1.06 μm. Figure 1 graphically displays these same results for the 2.5-AU range.

As expected, the required receiving aperture size increases with data rate and decreases with transmitter power. The U.S. Air Force Phillips Laboratory/Starfire Optical Range (SOR) operates a 3.5-m-diam imaging telescope in Albuquerque that is available to NASA and JPL. A line is drawn at 3.5 m in Figure 1 as a reference point to indicate this as the largest ground receiver immediately available for communications links (of course, apertures smaller than 3.5 m are available at a number of locations, including the Table Mountain Facility).

Results show that for a 250-kbps data rate, at least a 17-m-diam receiver is needed for the powers considered with a 10-cm transmitter at 2.5 AU. This size of receiver is not presently available. The largest optical telescope primary mirror presently in operation is 10 m. Current mirror fabrication methods may extend this size to about 12 m. For a 12-m receiver, a 10-cm/2-W transmitter provides a maximum data rate of 131 kbps. For a 3.5-m telescope, the data rate is 283 kbps for a 50-cm/2-W transmitter.

For 2-W output powers, a 30-cm spacecraft transmitter requires at least a 6-m ground receiver to attain 250-kbps data rates, and a 50-cm transmitter will reduce this ground aperture size to 3.3 m for the same data rate. A photon bucket can be made at either size of receiver aperture. The 30- and 50-cm spacecraft telescopes are under development; the 2-W power is currently available at 1.06 μm; and initial research is now proceeding on the atomic resonance filter.

For 1 W of transmitted power, the 3.5-m telescope is limited to about 150 kbps with the 50-cm spacecraft telescope. A rate of 250 kbps is achievable with a 30-cm transmitter if an investment is made in an 8.4-m ground receiver.

For 0.5 W of transmitted power, a 50-cm transmitter and 6.6-m receiver are required to attain 250-kbps rates. The small-aperture, low-power transmitter, 10 cm/0.5 W, is useful with the 3.5-m ground receiver when size and power on the user spacecraft are severely restricted; this configuration is limited to about 3 kbps.

Table 5. OPTI inputs.

Parameter	Value
Transmitter	
Power, W	0.5, 1.0, and 2.0
Wavelength, μm	1.06 and 0.532
Antenna diam, m	0.1, 0.3, and 0.5
Obscuration diam, m	0, 0.067, and 0 with respect to antenna diameters above
Efficiency	0.70
Pointing bias, 1σ, μrad	0.1
Jitter, 1σ, μrad	0.05, 0.02, and 0.01 with respect to antenna diameters above
Modulation extinction ratio	1×10^5
Receiver	
Diam, m	Variable
Obscuration diam, m	18 percent of diam ($\approx$3 percent of primary area)
Efficiency	0.70
Quantum efficiency	0.36 (at 1.06 μm) and 0.72 (at 0.532 μm)
Filter transmittance	0.30
Filter bandwidth, Å	0.01 (atomic resonance filter at 1.06 and 0.532 μm)
Detector diam, field of view, μrad	100
APD gain	200
Noise temperature, K	300
Load resistance, ohms	2000
APD ionization ratio	0.002
APD surface leakage current, nA	1.0
APD bulk leakage current, pA	1.0
Operational parameters	
Alphabet size	1024
Data rate, kbps	1.2, 50, 150, and 250
Link distance, AU	2.5
Bit error rate	0.01 (without coding)
Atmospheric transmittance	0.50 (at 1.06 μm) and 0.34 (at 0.532 μm), both at 60-deg zenith angle at 2.3 km
Dead time, μsec	Fixed; depends on alphabet, slot width
Slot width, nsec	10
Additional parameters	
Link margin, dB	3
Day sky radiance, W/m^2/sr/Å	0.054
Mars	In field of view of detector at 2.5 AU

Table 6. Ground aperture sizes for selected data rates and spacecraft transmitters at $\lambda = 1.06\ \mu m$ for daylight conditions and ranges = 2.5/0.4 AU.

Spacecraft transmitter		Ground receiver aperture size, m							
Average power, W	Aperture, cm	1.2 kbps		50 kbps		150 kbps		250 kbps	
		2.5 AU	0.4 AU	2.5 AU	0.4 AU	2.5 AU	0.4 AU	2.5 AU	0.4 AU
0.5	10	2.3	0.37	15.0	2.40	26.6	4.26	35.2	5.63
	30	0.82	0.13	5.3	0.85	9.2	1.47	12.0	1.92
	50	0.46	0.07	2.9	0.46	5.1	0.82	6.6	1.06
1.0	10	1.6	0.26	10.5	1.68	18.3	2.93	24.0	3.84
	30	0.59	0.09	3.8	0.60	6.5	1.04	8.4	1.34
	50	0.32	0.05	2.1	0.34	3.6	0.58	4.6	0.74
2.0	10	1.1	0.18	7.3	1.17	12.8	2.05	16.7	2.67
	30	0.41	0.07[a]	2.7	0.43	4.6	0.74	6.0	0.96
	50	0.23[a]	0.04[a]	1.5	0.24[a]	2.6	0.42	3.3	0.53

[a] Performance will be degraded by scintillation.

At 0.4 AU, a 250-kbps rate can be attained using the small (10-cm) transmitter with a ground receiver of less than 6 m. Using 2 W of power with this transmitter, the receiver can be reduced to 2.7 m. This indicates that with careful mission planning, high data rates (>250 kbps) comparable to that contemplated for the Cassini mission may be sustained utilizing the existing 3.5-m ground telescope as a receiver.

B. Ground Aperture Sizes for $\lambda = 0.532\ \mu m$

Table 7 and Fig. 2 present results for a wavelength of 0.532 μm. The 1.06-μm laser transmitter powers of Table 4 were retained and a frequency-doubling conversion efficiency factor of 50 percent was applied, thus halving the transmitter powers for the shorter wavelength. As the doubler does not consume prime power, the spacecraft subsystem power allocation at this wavelength will not change from the values in Table 4.

Comparing results for the two wavelengths at 2.5 AU, the ground receiver size needed at 0.532 μm is in every case smaller than that required at 1.06 μm for the same transmitted power, a consequence of the smaller divergence at the shorter wavelength. To provide the capability for 250-kbps data rates at this wavelength, a 0.25-W/30-cm transmitter must be used with a 10.3-m ground receiver. Alternatively, increasing the power to 1 W with the same 30-cm transmitter reduces the required ground receiver size to 5.3 m and in principle lowers the cost of the ground receiver by a factor of 4. The 10-cm transmitter cannot provide 250 kbps for any currently available ground receiver size at maximum range, the smallest required size being a 14.2-m diameter.

Examining what may be done with the 3.5-m telescope, we see that at the small spacecraft transmitter extreme, 0.25 W/10 cm, the link is capable of a data rate of 3.9 kbps. At the other extreme, 1 W/50 cm, the link is capable of 379 kbps. The 30-cm telescope used with the 3.5-m ground receiver will provide 29, 57, and 116 kbps for powers of 0.25, 0.5, and 1 W, respectively.

At 0.4 AU, the receiver can be even smaller than that required at 1.06 μm at 0.4 AU, again indicating that high rates can be obtained for most missions of current interest by utilizing technology readily available.

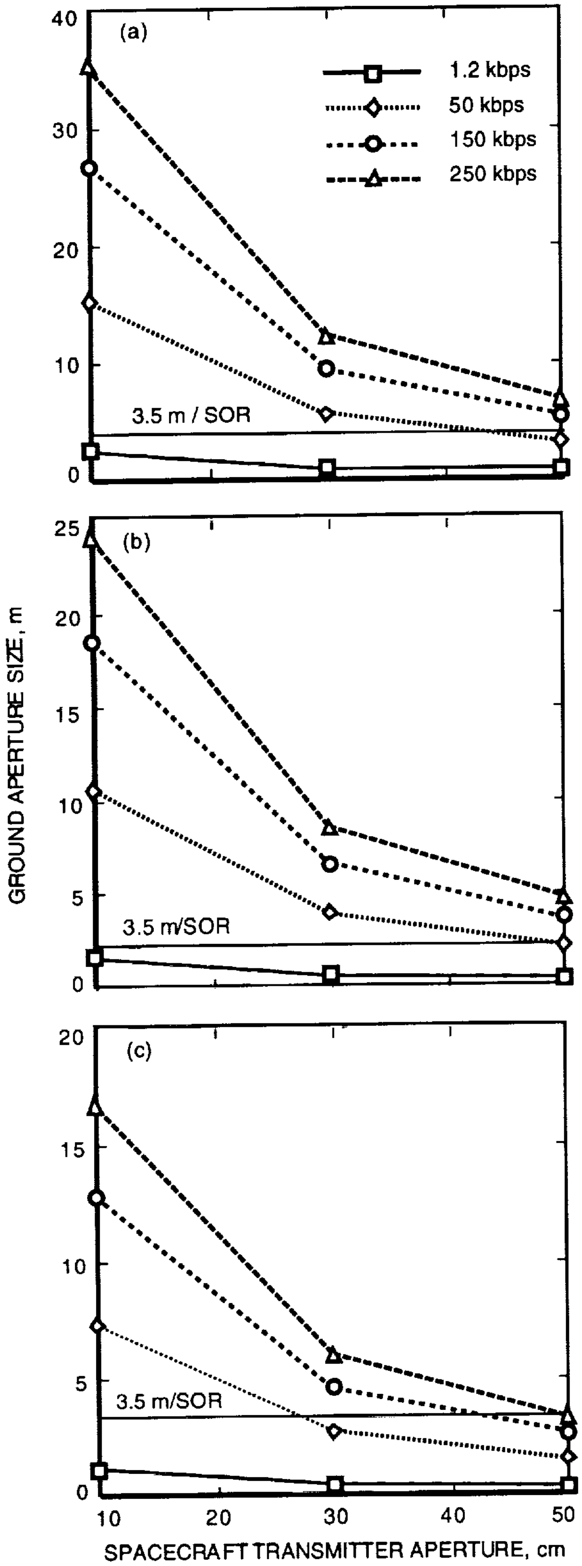

Fig. 1. Ground aperture sizes for a 1.06-μm link distance of 2.5 AU (daylight conditions) with transmitter power at (a) 0.5 W, (b) 1.0 W, and (c) 2.0 W.

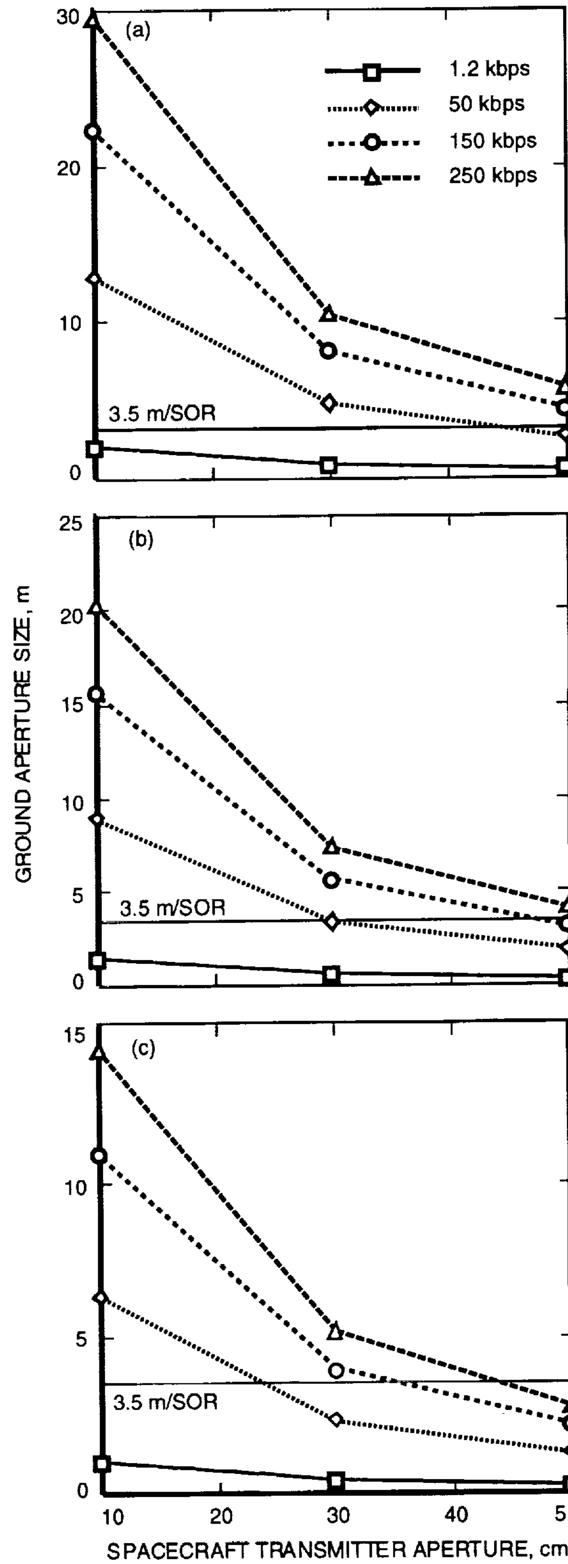

Fig. 2. Ground aperture sizes for a 0.532-μm link distance of 2.5 AU (daylight conditions) with transmitter power at (a) 0.25 W, (b) 0.5 W, and (c) 1.0 W.

Table 7. Ground aperture sizes for selected data rates and spacecraft transmitters at $\lambda = 0.532\ \mu m$ for daylight conditions and ranges = 2.5/0.4 AU.

Spacecraft transmitter		Ground receiver aperture size, m							
Average power, W	Aperture, cm	1.2 kbps		50 kbps		150 kbps		250 kbps	
		2.5 AU	0.4 AU	2.5 AU	0.4 AU	2.5 AU	0.4 AU	2.5 AU	0.4 AU
0.25	10	2.0	0.32	12.7	2.0	22.2	3.5	29.2	4.51
	30	0.71	0.11	4.6	0.74	8.0	1.28	10.3	1.65
	50	0.39	0.06	2.6	0.42	4.4	0.70	5.7	0.91
0.5	10	1.4	0.22	8.9	1.42	15.6	2.50	20.3	3.25
	30	0.50	0.08	3.3	0.53	5.6	0.90	7.3	1.17
	50	0.28	0.04	1.8	0.29	3.1	0.50	4.0	0.64
1.0	10	0.98	0.16	6.3	1.01	10.9	1.74	14.2	2.27
	30	0.36	0.06	2.3	0.37	4.0	0.64	5.2	0.83
	50	0.20	0.03	1.3	0.21	2.2	0.35	2.8	0.45

V. Summary

A spaceborne segment consisting of a 2-W, 1.06-μm laser transmitter with a 30-cm telescope and an onboard beam control assembly capable of at least 100-nrad pointing accuracy can provide at least an 86-kbps data rate from Mars at 2.5 AU using a 3.5-m receiver and an avalanche photodiode detector in the ground segment. An atomic resonance filter provides daytime operation capability. The same configuration will provide a data rate as high as 2.9 Mbps from Mars at its closest approach to Earth (0.4 AU).

By converting the wavelength to 0.532 μm while still retaining the total prime power consumption, a 1-W transmitter with a 30-cm telescope and the same pointing capability will provide 115 kbps from Mars at 2.5 AU using a 3.5-m telescope. The detector (APD) and filter (atomic resonance) are categorically the same but operate at this shorter wavelength. At the closest approach, the data rate capability is as high as 3.6 Mbps.

These optical communications segments would provide the capability to meet the telemetry data rate requirements currently envisioned for many lander, orbiter, and probe missions.

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