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Optical Ground Segment Performance Summary

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ABSTRACT. — The performance of candidate optical communication systems for deep space that would use a single optical ground station in conjunction with various space terminals is reported here. We considered three potential diameters of ground receive terminals (4, 8, and 12 m) and three potential ground transmit powers (1, 5, and 10 kW). Combinations of ground receive terminals, ground transmit terminals, and spacecraft terminals were assessed for data rate and volume (both uplink and downlink), and for uplink irradiance needed to enable downlink pointing, in the context of a set of 12 design reference missions. Raw physical link performance was assessed assuming clear weather conditions with conservative desert daytime turbulence, using communication link parameters that were optimized according to previously reported methods using the Strategic Optical Link Tool (SOLT). Also, realistic bad weather conditions were considered, assuming a random process that could at any time make transitions between two states: a cloud-free state and a cloudy state that completely interrupts data transmission. We compared the link performance achievable under our assumptions to the anticipated requirements associated with the design reference missions to determine the degree of satisfaction possible with various optical segments. Nine potential operating concepts for an optical communication system were described, and two were evaluated in detail for the Mars 2022 mission opportunity: raw data delivery and automatic repeat request for complete data delivery.

I. Introduction

As a result of NASA's strategic technology investments and flight demonstration efforts[1] [1–7], optical communications are viable for operational use by NASA within a 5- to 10-year horizon. NASA's Space Communications and Navigation (SCaN) Program Office and the Deep Space Network (DSN) are therefore engaged in long-term planning for the ground segment of an initial operational capability (IOC) for deep-space optical communication. Based on previous studies, we assume for our performance analysis that the IOC will include a large-aperture ground terminal capability, perhaps organized around the equivalent of one or more 4- to 12-m-diameter class telescopes.

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* Communications Architectures and Research Section.

[1] A. Biswas, presentation for DSOC for Discovery Technology Day, April 2014.

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Accordingly, a number of studies were carried out in fiscal year 2015 to support planning of the deep-space optical ground segment, starting from previously developed concepts for optical ground apertures and flight terminal capabilities for a range of missions, including both high data rate, and low size, weight, and power scenarios. This article summarizes the performance aspect of those studies for a range of ground terminal diameters ranging from 4 m to 12 m, transmit powers ranging from 1 to 10 kW, for a set of 12 design reference missions (DRMs) selected to reveal the envelope of potential system requirements for the ground segment. We also describe here nine potential operating concepts for an optical ground segment that have significant influence over the performance of the overall optical communication system.

This summary article relies on more detailed supporting reports provided in *The Interplanetary Network Progress Reports* regarding optical link characterization [8], the assumed design reference missions [9], and automatic repeat query (ARQ) applied to a reference deep-space optical communications link [10].

We discuss below the metrics we used for assessing performance of data acquisition, the cumulative data volume we estimated for the DRMs as a function of optical ground segment sizing, and the operations concepts affecting performance estimates. We conclude with a summary of the range of performance estimated for the DRMs, and give an assessment of the ability of the contemplated ground segment to satisfy anticipated customer communications requirements.

II. Metrics of Data Acquisition

We evaluated the following data acquisition metrics for optical communication:

- Data rate
- Data volume
- Availability
- Continuity
- Latency

Our methods of evaluation covered a wide range of potential mission types and spacecraft terminals, and a range of ground-based uplink and downlink terminals, and are described below.

A. Data Rate

An inherent characteristic of optical links through Earth's atmosphere is that their performance depends on atmospheric transmittance, turbulence, and solar radiance. As a consequence, the supportable data rate in any real data acquisition will vary substantially with actual weather, range, elevation, and Sun–Earth–probe (SEP) angles.

We evaluated the supportable data rate as a function of time for the design reference missions described in [9], subject to an error rate constraint and a number of assumptions about operating conditions. The reference missions of [9] were constructed to resemble a number of potential future missions that are currently within the set of options under consideration by NASA.

To determine the supportable data rate for each design reference mission, Xie et al. [8] evaluated the link situation at fixed intervals of time ranging from 5 to 30 min, and covering relevant periods of interest. For each moment evaluated, Xie et al. optimized the data coding and rate for the link situation using the methods described in [8], resulting in a time series of supportable data rate. In most cases, the optimum data rate changed many times during a pass, as illustrated in Figure 1. We assumed initially that the operational link would follow the optimum data rate in a preprogrammed (but not adaptive) way, and consider the possibility that data rate changes might be limited to coarser steps on page 11 of this article. For the purposes of ground segment evaluation, we reduced these variations to an average data rate during a pass, by calculating the instantaneously optimized single-pass data volume, and then dividing by the pass duration based on visibility of the type of mission considered as seen from Goldstone, California. This gives a better approximation to the achievable data transport than would result from assuming a single, minimum rate for any particular pass. Use of the pass-average data rate simplified the calculation of cumulative data volume and presentation of data rate variations with the calendar. The forecasted

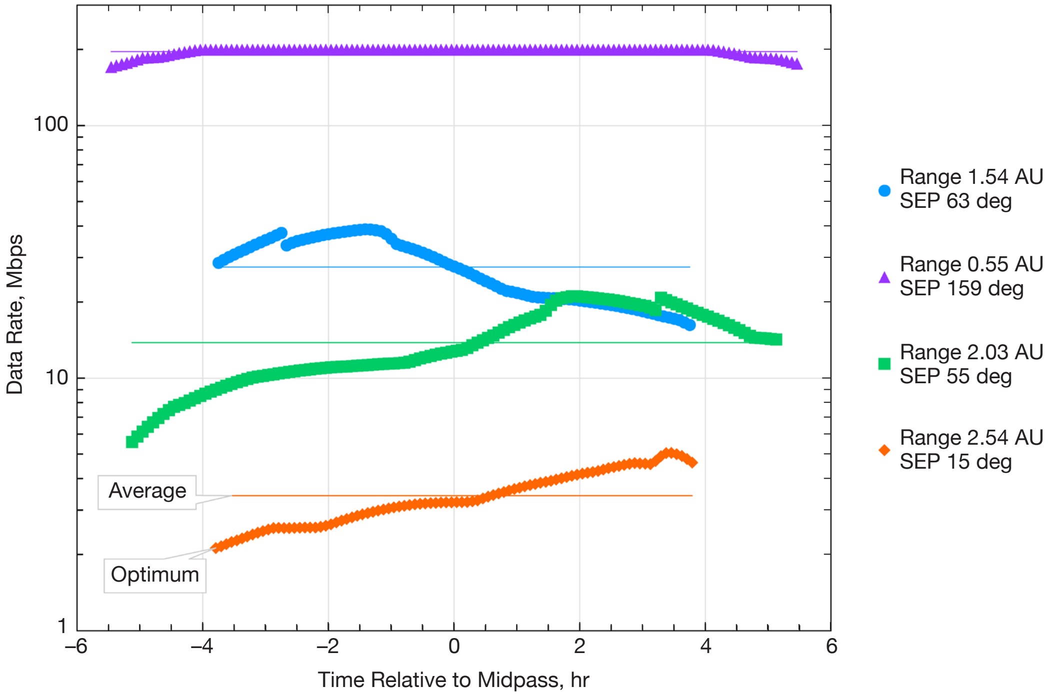

Figure 1. Samples of the variation of optimized optical data rate during a pass.

instantaneous data rates typically vary by a factor of 2 or more from the averages we used, and this should be taken into account for other system sizing considerations.

B. Data Volume

We calculated single-pass data volume by taking the average of adjacent data rates for each time interval evaluated during the pass, and then multiplying by the interval. The average of adjacent rates minimizes bias arising from evaluating at regular intervals, considering the possibility that the precise time of data rate change could occur anywhere in the interval.

We also calculated a cumulative data volume as a function of time for each mission, by summing the individual pass data volumes. We considered the cumulative data volume in two forms: ideal and realistic. For the ideal case, we assumed use of all available passes for a single receiving site, cloud-free line of sight (CFLOS); specifically, we assumed that there are no clouds of any sort, including subvisual cirrus clouds, and no losses due to weather. For the realistic case, we discounted the cumulative data volume to 67 percent of the ideal case, corresponding to historical average experience at Goldstone, California. This is a typical probability of CFLOS, corresponding to typical conditions in Hawaii and the southwestern United States. Some optical observatory sites have higher probabilities, up to 82 percent.[2] Further information regarding discount factors and long-term variability of weather is available in [10].

We calculated cumulative data volume for both the “raw data delivery” and “automatic repeat query (ARQ)” operations concepts, described in Section IV. In the case of ARQ, there is a trade-off between the offered load (as a fraction of channel capacity) and other system performance metrics. The offered load in general must be less than the channel capacity, and this may be interpreted as a deduction against the cumulative data volume, which we factored into our calculations of cumulative data volume. This topic is discussed in more detail in [10], and the results are summarized in Table 1.

C. Availability

The availability of the data under the “raw data delivery” concept is the same as the CFLOS probability, which is 67 percent for average Goldstone weather. It should be noted that seasonal and longer-term variability has been observed, and there is some chance of turbulence or wind being worse than we assumed, although we assumed desert daytime turbulence, which is conservative. This issue is discussed further in [10].

Under the “automatic repeat request” operations concept, times of unavailability are compensated by retransmission. In effect, reliability is added to the link, so that most data arrives even if some transmissions are lost due to weather. A small fraction of data (much smaller than losses due to weather) can still be lost due to buffer overflow, which is described by the “data loss performance” discussed in [10].

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[2] G. S. Wojcik, H. L. Szymczak, R. J. Alliss, and M. L. Mason, *JPL CFLOS Project Fiscal Year 2004–05 Final Report* (internal document), Jet Propulsion Laboratory, Pasadena, California, September 7, 2005.

Table 1. Cumulative data volume including weather effects.†

					Design Reference Mission											
Ground Receive Terminal, diameter	Service	Weather	Discount Factor		Small Optical Terminal at Mars	Medium Optical Terminal at Mars	Large Optical Terminal at Mars	Deep Space Ob-servatory Nighttime	Deep Space Ob-servatory Dawn or Dusk	Deep Space Ob-servatory Daytime	Medium Optical Terminal at Jupiter Distance	Large Optical Terminal at Saturn	Large Optical Terminal at Jupiter	Inner Planets	Very Small Terminal at Lunar Distance	Mars Trunk Line
12 m	Raw	None	1.00	*	5.70	1364	8937	5541	379	1442	49.4	678	1953	1490	104	2127
12 m	Raw	Las Campanas	0.80		4.56	1091	7149	4433	303	1154	39.5	542	1562	1192	84	1702
12 m	Raw	Gldstn Best	0.72		4.10	982	6434	3390	273	1038	35.5	488	1406	1072	75	1532
12 m	Raw	Gldstn Avg	0.67		3.82	914	5988	3713	254	966	33.1	454	1308	998	70	1425
12 m	Raw	Goldstn Worst	0.38		2.17	518	3396	2106	144	548	18.8	258	742	566	40	808
12 m	ARQ	None	0.80		4.56	1091	7149	4433	303	1154	39.5	542	1562	1192	84	1702
12 m	ARQ	Best	0.64		3.65	873	5719	3546	243	923	31.6	434	1250	953	67	1361
12 m	ARQ	Gldstn Best	0.58		3.28	785	5148	3192	218	831	28.4	390	1125	858	60	1225
12 m	ARQ	Gldstn Avg	0.54		3.05	731	4790	2970	203	773	26.5	363	1047	798	56	1140
12 m	ARQ	Gldstn Worst	0.30		1.73	415	2727	1684	115	438	15.0	206	594	453	32	647
8 m	Raw	None	1.00	*	2.61	770	7564	5541	180	1442	22.8	341	1068	1080	60	1435
8 m	Raw	Best	0.80		2.09	616	6051	4433	144	1154	18.2	273	855	864	48	1148
8 m	Raw	Gldstn Best	0.72		1.88	554	5446	3990	129	1038	16.4	246	769	778	43	1033
8 m	Raw	Gldstn Avg	0.67		1.75	516	5068	3713	120	966	15.3	229	716	724	40	962
8 m	Raw	Goldstn Worst	0.38		0.99	293	2874	2106	68	548	8.7	130	406	410	23	545
8 m	ARQ	None	0.80		2.09	616	6051	4433	144	1154	18.2	273	855	864	48	1148
8 m	ARQ	Best	0.64		1.67	493	4841	3546	115	923	14.6	219	684	691	38	919
8 m	ARQ	Gldstn Best	0.58		1.50	443	4357	3192	103	831	13.1	197	615	622	34	827
8 m	ARQ	Gldstn Avg	0.54		1.40	413	4054	2970	96	773	12.2	183	573	579	32	769
8 m	ARQ	Gldstn Worst	0.30		0.79	234	2299	1684	55	438	6.9	104	325	328	18	436
4 m	Raw	None	1.00	*	0.64	245	4915	5541	45	1442	5.5	88	310	547	17	506
4 m	Raw	Best	0.80		0.51	196	3932	4433	36	1154	4.4	71	248	438	14	405
4 m	Raw	Gldstn Best	0.72		0.46	176	3539	3990	33	1038	3.9	64	223	394	13	365
4 m	Raw	Gldstn Avg	0.67		0.43	164	3293	3713	30	966	3.7	59	208	367	12	339
4 m	Raw	Gldstn Worst	0.38		0.24	93	1868	2106	17	548	2.1	34	118	208	7	192
4 m	ARQ	None	0.80		0.51	196	3932	4433	36	1154	4.4	71	248	438	14	405
4 m	ARQ	Best	0.64		0.41	157	3146	3546	29	923	3.5	57	199	350	11	324
4 m	ARQ	Gldstn Best	0.58		0.37	141	2831	3192	26	831	3.5	51	179	315	10	292
4 m	ARQ	Gldstn Avg	0.53		0.34	131	2634	2970	24	773	2.9	47	166	293	9	271
4 m	ARQ	Gldstn Worst	0.30		0.19	74	1494	1684	14	438	1.7	27	94	1866	5	154

† Data volumes are expressed in terabits. Design reference missions are as described in [9], and discount factors for weather are as described in [10].
Values for ARQ service are further discounted for 80 percent offered load.

* End-of-mission cumulative data volume from Section 7.

D. Continuity

The continuity of the data under the "raw data delivery" is the same as the continuity of CFLOS, which is discussed as part of [10] under the subheading "Input Variables and Performance."

Under the "automatic repeat request" operations concept, continuity is added to the link by retransmission. Again, continuity of the small fraction of data lost due to buffer overflow is described by the "data loss performance" discussion of [10].

E. Latency

The latency of the data under the "raw data delivery" is the same as the one-way light time. Clare et al. [10] examined the "automatic repeat request" operations concept for latency. This is described by the "latency" discussion of [10].

III. Cumulative Data Volume Including Weather Effects

We applied the CFLOS statistics to determine the likely range of downlink cumulative data volume that might be achieved under realistic weather conditions. We did this by multiplying the cumulative data volumes at end of mission for each DRM as calculated by Xie et al. [8], by various discount factors ranging from no discount (near-ideal weather all the time), to the discount for the worst year observed at Goldstone. Further details on the origin of these discount factors are available in [10]. We also calculated the data volume if the ARQ operating concept were to be applied with an offered load that is 80 percent of the CFLOS. The resulting values are summarized in Table 1. A convenient reference point is the DRM for a medium optical terminal at Mars, which we estimate could transfer 914 terabits to Earth during approximately one synodic cycle, using a 12-m ground receive terminal under Goldstone average weather, and operating under the raw data delivery operating concept. We estimate that the corresponding data volume would be 731 terabits operating under the ARQ operating concept.

IV. Satisfaction of Anticipated Customer Requirements

We evaluate here the satisfaction of the anticipated customer communications requirements associated with the DRMs of [9], based on the link performance estimates of [8]. This comparison inherently relies on the spacecraft and ground terminal characteristics described in [8].

A. Downlink Data Rates — Non-Crewed

The downlink data rates desired for all the DRMs, except the crewed missions, can be supplied at closest approach to Earth within the level of technology planned for the Deep Space Optical Communications (DSOC) terminal, and with Earth receive terminals in the

4- to 12-m aperture range. However, the smaller apertures provide substantially less cumulative data volume over a mission, and a substantially smaller distance at which a given data rate can be achieved. The smaller apertures therefore dilute a customer's return on their investment in an optical terminal. Taking into account losses to weather, and using ARQ to provide reliable data delivery, we found that cumulative data volumes for reliable transport from a 22-cm, 4-W DSOC terminal over roughly a Mars synodic cycle would be approximately 730, 410, or 130 terabits, respectively, for a single 12-m, 8-m, or 4-m ground receive terminal assuming average weather at Goldstone, California. Throughout most of the synodic cycle, the range is great enough to ensure that the DSOC terminal would be operating below its maximum data rate limit. We estimate the range at which a DSOC terminal can achieve its full data rate of 267 Mbps to be approximately 0.48, 0.32, or 0.16 AU for 12-m, 8-m, or 4-m ground receive terminals. The maximum rate could be reached during cruise to Mars, or at other locations closer to Earth.

B. Downlink Data Rates — Crewed

Within our assumptions, downlink data rates from a 50-cm, 20-W large optical terminal at Mars to a 12-m ground aperture are a factor of 2 or 3 lower than the 600 Mbps at 2.5 AU upper range desired by crewed customers in the late 2030s, but above their lower range of desire for 150 Mbps at 2.5 AU. Data rates to 8-m and 4-m apertures would fall below the requirement at maximum range. The primary limiting factor in our analysis was not Earth- or space-based aperture, rather, it was detector speed on Earth and a self-imposed requirement to maintain photon-efficiency that set the upper limit on data rate. If the customer desire for 600 Mbps data rates is to be satisfied, faster detectors, larger arrays of detectors, or other means such as lowering the pulse-position modulation (PPM) order (and concomitantly link efficiency), or combinations of all of these, could be pursued. We understand that sufficient improvement in detector speed can probably be achieved with a few million dollars of technology investment, and we confirmed in a point calculation that lower PPM order and a 12-m ground aperture comes closer to satisfying the desire. If this primary limiting factor is overcome, the next limit is spacecraft laser power. This could be addressed by continued research on 20-W and 100-W spacecraft lasers capable of PPM.

C. Uplink Data Rates — Non-Crewed

Achievable uplink data rates in general are severely constrained by the modulation bandwidth and peak-to-average power ratio of the existing uplink lasers to 2 kbps, even though enough uplink power is available to achieve multi-megabit performance were faster lasers and spacecraft electronics available. With research activities already in progress for faster high-power lasers, it is conceivable that data rates could be drastically increased, to the point where the data rate would only be constrained by the power available. However, the technology maturation of faster high-power lasers will need continued attention. When this limit is overcome, the next limit is flight detector readout electronics and processing, which presently limit uplink data rate to less than about 1 Mbps at deep-space ranges.

D. Uplink Data Rates — Crewed

With improved uplink lasers and flight detector readout electronics and processing, the power-limited uplink data rates from Earth ground stations to large optical terminals at Mars are still a factor of 2 to 10 lower than the 25 Mbps minimum desired by crewed customers, even with the maximum-power (10-kW) transmitter we considered.

E. Outer Planets — Beacon

Constraints on uplink irradiance needed for the beacon mode of downlink pointing exclude the lower-power (1 kW or less) Earth transmitters we considered, but the larger transmitters (5 kW and 10 kW) satisfy the constraint in many cases. Also, the uplink irradiance requirement is not met at Saturn by the largest transmitter we considered (10 kW). As discussed in [8], a larger space terminal aperture would not directly improve this shortfall because the increased collecting area is counterbalanced by tighter pointing requirements for the correspondingly narrower beam.

F. Reliable Optical Service

Reliable data services can be provided over optical, if the customers can tolerate some latency, and the spacecraft carries enough data storage. The amount of storage needed depends on the customer's sensitivity to latency, data loss, and offered load, but it appears that satisfactory results can be obtained with spacecraft data storage that is 6 to 13 times larger than the daily data volume, at 80 percent offered load and average weather conditions. Variations of daily data volume with range, Sun angle, view period, and system sizing affect the daily data volume, and raise issues as to how the buffer should be sized for a particular mission. We described a general strategy for trading buffer size against various aspects of system performance.

G. Small Optical Terminals

Small optical terminals for CubeSats or other applications are an emerging need, but as yet are a subject of research as to their capabilities. Nonetheless, we explored small terminals in the spirit of a "what if" study, assuming the space terminal to have either a 5-cm aperture and 1 W of transmitter power, or a 2-cm aperture and 2 mW of transmitter power. We assumed diffraction-limited pointing, peak/average power ratio of the lasers greater than 128, and PPM. These characteristics are not currently achievable within mass, power, and volume constraints consistent with 5-cm or 2-cm apertures, but are used as placeholders for a "what if" study. With this in mind, we found that the hypothetical 5-cm terminal might deliver raw bit rates of 267 Mbps at 0.052 AU, 0.035 AU, or 0.018 AU to 12-m, 8-m, or 4-m ground apertures under clear nighttime conditions. We found that such a terminal might provide more than 267 Mbps from Earth–Sun Lagrange point 1 for any of the ground apertures considered, and 1 Mbps from Mars at closest approach to a 12-m ground aperture. For the hypothetical 2-cm, 2-mW terminal at lunar distance, we found that a data rate of 20 Mbps could be supported to a 12-m ground aperture. These data rates should be regarded as very approximate descriptions from a "what if" study and should only be used for broad considerations that would remain applicable when rescaled to reflect the true architecture of any particular small terminal.

V. Operations Concepts

The potential benefit of different operations concepts for optical communication surfaced first in the context of the DSN transition to Ka-band downlinks. Shambayati observed in his 2008 report on the Mars Reconnaissance Orbiter Ka-band demonstration[3] that the Ka-band frequency is more susceptible to adverse weather conditions than was X-band. He posited a new operations concept for Ka-band, focused on maximizing the average data return while maintaining a minimum link availability. Also he noted the need to design the system to diagnose weather versus outages due to other factors; and to decouple spacecraft data collection procedures from their data transmission procedures to allow a more adaptive approach to link utilization, capitalizing on weather forecasting data rate adaptation, and sophisticated onboard data management mechanisms and large buffers to ride through downlink disruptions by weather. All of these were harbingers of the same but greater issues for optical communication.

We describe in the following sections several operations concepts that may be useful for optical communication, each having characteristics that make them suited to different provider and customer needs.

A. Raw Data Delivery

Raw data delivery operates as follows:

- The receiving telescope points to the spacecraft.
- The spacecraft telescope points to the receiving telescope aided by an uplink beacon.
- The spacecraft applies forward error-correction coding.
- When link conditions meet design assumptions, the receiving telescope correctly receives data; otherwise data are discarded.

The benefit of this concept is that it is simple to operate for the customer's mission. The detriments of this concept are that it requires the optical ground segment to construct 6 to 9 telescopes to provide 24-hour service and >90 percent availability, as explained by Wilhelm and Shaik;[4] or if not done, the availability will be comparable to the CFLOS probability. Also, data transport is uncertain for low latency, although this detriment can be compensated by the RF–optical routing concept described below.

B. Automatic Repeat Request

Automatic repeat request operates the same as the raw data delivery concept, with the following additions:

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[3] S. Shambayati, *MRO Ka-band Demonstration Cruise Activities Report*, Rev. A, JPL D-31190 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 9, 2007.

[4] M. Wilhelm and K. Shaik, *Ground-Based Advanced Technology Study (GBATS)*, JPL D-11000, Release 1 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 5, 1994.

- The spacecraft buffer stores a substantial period of data as described by Clare et al. [10].
- When link conditions meet design assumptions, the receiving telescope correctly receives data, and
- The receiving telescope forwards a receipt acknowledgement to the spacecraft via a forward channel; the spacecraft discards acknowledged data, and retransmits non-acknowledged data.
- The spacecraft discards the data when its buffer overflows.

The benefits of this concept are that high availability can be achieved with only a single optical telescope to be built. The concept can provide excellent long-term availability at high latency. Data volume is high, governed by the permissible offered load discussed in [10], which is around 80 percent of maximum allowable by CFLOS.

The detriments of this concept are that the spacecraft must carry a large buffer, and the customer mission must manage that buffer. For missions that have appreciable variations of the distance to Earth, most of the spacecraft buffer is not used during most of the synodic cycle. However, the waste can be mitigated by intentional undersizing at expense of maximum data volume or availability during certain parts of the cycle. This undersizing strategy is described further by Clare et al. [10]. Also, data transport is uncertain for low latency needs, but the RF–optical routing concept can compensate for this detriment.

C. RF–Optical Routing

RF–optical routing operates the same as any other operating concept, with the additional feature that when the optical link is not available, the spacecraft routes data to RF if it is higher-priority data. Higher-priority data is a customer-determined concept, but might be associated with perishable data, high-value data, a retransmission for completeness, or data aging out of a buffer.

The benefit of this concept is that completeness of data improves faster over time than it would with optical alone. The concept may also allow a smaller spacecraft buffer. There may also be times of low Sun–Earth–probe angle when RF outperforms optical, especially if RF Earth stations can provide continuous coverage but optical is limited to a single site, or if larger RF Earth stations are scheduled when optical performance is degraded.

The detriments of this concept are that the customer mission must manage priorities and routing between RF and optical, and the ground segment must provide the function of merging data streams from RF and optical.

D. Interleaving or Disruption-Tolerant Coding

Interleaving or disruption-tolerant coding operates the same as raw data delivery, with the following additions:

- The spacecraft buffer stores up to one ground pass worth of data.
- The spacecraft applies a disruption-tolerant code, e.g., a Repeat-N or a Tornado code.

- When link conditions meet design assumptions on at least one interval out of N possible intervals, the receiving telescope correctly receives data; otherwise data are discarded.

The benefit of this concept is that availability can be increased in scattered or broken skies without much operational labor. The detriments of this concept are that a spacecraft buffer is required, though modestly sized compared to some other concepts. Also, optical ground segment study (OGSS) ground processing is more complex, and the total data volume transported falls by 1/N. If N is a small number (2 or 3), that loss can be partly made up by more optimistic weather assumptions permissible with this approach.

E. Limited Data Rate Changes

We observed in our predictions that in most cases the optimal data coding and rate (from a communications channel perspective) is constantly changing, often on a minute-by-minute basis. However, constantly changing communications configurations are considered to be a nuisance from a mission operations viewpoint, because current mission operations concepts for deep space usually have tight coupling between spacecraft activity and data transport, which are carefully crafted long in advance of operation. To simplify operations planning, it is common to limit the frequency of configuration changes to a few per pass. Xie et al.[5] have examined a number of possible strategies for reducing the number of configuration changes, and found that a strategy of selecting link configurations that are static during the first 25 percent, middle 50 percent, and last 25 percent of each pass has a relatively mild penalty of lost opportunity to collect data. For the Mars mission they examined (2009–2012), this approach typically yielded only an 11 percent lost opportunity to collect data overall, or about 40 percent worst case.

F. Dynamic Link Parameters

The converse of limited data rate changes is dynamic link parameters, constantly adjusted to the link conditions. Compared to limited data rate changes as commonly practiced in the existing RF systems, this approach could be seen as providing an 11 percent data volume advantage overall, or about 40 percent best case.

G. Weather Forecasting and Dynamic Asset Management

Weather forecasting can improve the response of the overall system to short-term weather changes, if there are multiple receiving stations. In this concept, a weather predictor forecasts link conditions at multiple receiving telescopes one round-trip light time (RTLT) prior to data transmission. Then the best receiving telescope is assigned for service, the spacecraft is informed of receiving telescope via a forward channel, and the spacecraft points the spacecraft terminal to assigned received telescope.

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

The benefits of this concept are that availability rises to ~80 percent or higher within one pass, depending on the number of telescopes available. The detriments of this concept are that the customer mission must manage a changing receive telescope on short time scales. Also, multiple telescopes with otherwise good weather will be unused, unless some means is provided to use them on a contingency basis.

H. Improved Link Management

Difficulties in Existing Approaches to Link Management

The data-rate control loop for deep-space missions, either optical or RF, involves several slow-responding control loops layered around the events of collecting data for a single pass. The outermost, and slowest to respond, is the decision about mission design for the communications function. This loop considers the most recent bulk statistics for observing conditions available at the time the mission design is decided, and selects a particular capacity range and variables of operation for the communications system. This often must be done years in advance.

Another control loop is the strategic planning loop, which decides how to exercise the variables of the communication system to achieve various goals of the mission. This is usually done months in advance.

Finally, a tactical control loop, usually in the days- to weeks-level of lead time, is used to set the final parameters of the communications system. At present, this is the fastest response time available, though in exceptional cases hours or even minutes can be achieved occasionally.

In all of these loops, the time scale exceeds the time frame within which useful predictions can be made about important features of the weather, such as clouds or haze. As a consequence, the control process must manage a trade-off between risk of losing data from the weather being worse than assumed, and the risk of losing the opportunity to collect data from the weather being better than assumed. Historically, most missions emphasize the risk of loss, and choose to operate so as to get some data, even if it means getting less when the weather is good. In other words, mission managers may choose pessimistic assumptions about data return to achieve the desired availability.

For RF, the historical habit of using pessimistic assumptions results in a penalty in lost opportunity to collect data that is not severe at S- or X-band. At K-band, the penalty is around 3 to 6 dB, which is significant but not devastating.

The problem with optical, however, is that the trade-off between the two risks is much steeper than encountered historically with S-, X-, or even Ka-band data acquisition. It is quite possible to extinguish all benefits of using optical by making early, pessimistic assumptions about future weather. It is also possible to make unduly optimistic assumptions, and be caught later by short- or long-term climate fluctuations outside the range of valid extrapolation from the available statistical information.

In all of these situations, a major underlying problem is a mismatch between the response time of the control loops, and the characteristic time frames of weather variability. This is not the only underlying problem: the cost of rapid adaptation within existing mission and network operations concepts, and the cost of acquiring sufficient expertise to respond to weather appropriately are also significant issues.

The use of optical communications, then, justifies a reconsideration of the historical habits for link management, to make it more possible to properly adjust the optical link to the actual weather. We suggest below two alternate concepts that may eventually be needed to fully capitalize on the potential of an optical ground segment.

Decoupled Data Transport

Most mission operations systems at present strongly couple spacecraft operations to on-board data store usage and communications link usage. This is typically necessary because the available capacities of the onboard data store and the communications link are small compared to short-term fluctuations in data production from spacecraft operations.

However, storage has been getting smaller, and with optical, communications links will be much more capable than previously available. It may soon be possible to decouple spacecraft activity from data transport. This concept would have the following advantages:

- Mission responsibilities could be simplified, because there is less of a data management constraint.
- Data transport could become transparent to the mission user, though with some latency.
- Excellent availability and maximum data volume are possible.

The detriments of this concept are that the ground segment responsibilities increase, though overall costs may decrease because fewer groups must maintain competency on weather adaptation.

Optical Ground Segment Control of Spacecraft Terminal

If decoupling can be achieved, then proper adaptation to weather becomes possible. In this concept, some part of the optical ground segment would take responsibility for controlling some of the spacecraft terminal communications parameters, those that do not interact significantly with coupled spacecraft resources such as power and attitude. At first blush, it may appear unusual that the optical ground segment would control spacecraft resources. Yet, in a decoupled system, detailed timing of data rate and coding can be managed freely, and probably should be managed using the shortest control loop that can be arranged, which would be the receiving system. This technique is in fact used with many terrestrial microwave and optical communications systems under the heading of “adaptive data rates.” The responsibility would be on the ground segment to keep the communications parameters compatible with weather and other ground segment conditions of the moment. This could be done by a multimission operations team, or automatically by the optical ground segment as it is done in many other terrestrial microwave or optical communications systems.

The benefits of this concept are that mission responsibilities are simplified, and that excellent availability and maximum data volume are possible. The detriments of this concept are again that the ground segment responsibilities increase, though overall costs may decrease because fewer groups must maintain competency on weather adaptation.

VI. Summary

We examined the system performance of optical communications links using a single optical ground station and various space terminals, assuming three diameters of ground receive terminals: 4 m, 8 m, and 11.8 m (nominally 12-m). Ground transmit terminals with powers of 1 kW, 5 kW, and 10 kW were considered in most cases; for the one DRM case of circumlunar communication, ground transmit powers of 10 W, 50 W, and 100 W were considered instead. The performance estimates were based on the DRMs recommended by Breidenthal and Abraham [9], which encompass the wide range of applications that an optical ground segment might eventually be called upon to serve.

Combinations of ground receive terminals, ground transmit terminals, and spacecraft terminals were assessed for data rate and volume (both uplink and downlink), and for uplink irradiance needed to enable downlink pointing. The communication link parameters were optimized according to previously reported methods, embodied in the Strategic Optical Link Tool (SOLT) as reported by Xie et al. [8].

We compared the performance estimates of [8] to the customer communications requirements associated with the DRMs of [9], and determined the degree of satisfaction that would result from various sizes of ground segment optical terminals. These assessments are summarized in Table 2. Also, we summarized the data rate as a function of distance as shown in Figure 2, and calculated the approximate maximum communication distance for different sizes of space and ground optical terminals, as shown in Table 3.

We took into account realistic bad weather conditions, based on the histories of weather at relevant sites around the world as described by Clare et al. [10].

Several potential operating concepts for an optical communication system were described, and two were evaluated in detail: raw data delivery and automatic repeat request for complete data delivery. Some observations were provided about the utility and rationale for the other operating concepts.

Table 2. Summary of performance analyses.†

Report Section/ Design Reference Mission Type	Downlink Data Rate Requirement	Satisfied by Ground Receive Terminal			Uplink Data Rate Requirement	Satisfied by Ground Transmit Terminal			Uplink Beacon Irradiance Requirement, pW/m^2	Satisfied by Ground Transmit Terminal		
		11.8 m	8 m	4 m		10 kW	5 kW	1 kW		10 kW	5 kW	1 kW
3.3.1 Small Optical Terminal at Mars	~10 kbps DTE at 2.6 AU; ~128 kbps to 2 Mbps to relay orbiter	P	P	P	[1 kbps*]	Y	Y	P	4	Y	Y	P
3.3.2 Medium Optical Terminal at Mars	~>5.2 Mbps	Y	Y	P	[100 kbps*]	Y	Y	P	4	Y	Y	P
3.3.3 Large Optical Terminal at Mars	~150 Mbps–600 Mbps	Y	P	p	~25 Mbps	P	P	N	4	Y	Y	P
3.3.4 Deep Space Observatory — Nighttime	~150 Mbps–262.5 Mbps	Y	Y	Y	[100 Mbps*]	Y	Y	Y	4	Y	Y	Y
3.3.5 Deep Space Observatory — Dawn or Dusk	~2.5 Mbps	Y	Y	P	[1 Mbps*]	Y	Y	P	4	Y	Y	Y
3.3.6 Deep Space Observatory — Daytime	~30 Mbps (possibly up to 260 Mbps)	Y	Y	Y	[100 Mbps*]	Y	Y	Y	4	Y	Y	Y
3.3.7 Medium Optical Terminal at Jupiter Distance	~12.5–30 kbps	Y	Y	P	[1 kbps*]	Y	Y	Y	4	P	N	N
3.3.8 Large Optical Terminal at Saturn	~1.6 kbps relay	Y	Y	Y	[10 kbps*]	Y	Y	Y	4	N	N	N
	[1 Mbps*]	[Y]	[Y]	[P]								
3.3.9 Large Optical Terminal at Jupiter	~134 kbps	Y	Y	Y	[10 kbps*]	Y	Y	Y	4	Y	P	N
3.3.10 Inner Planets	~25 kbps to ~14.5 Mbps relay	P	P	P	[100 kbps*]	Y	Y	Y	4	Y	Y	Y
3.3.11 Very Small Terminal at Lunar Distance	~25 Mbps; early desire for ~150 Mbps	Y	P	N	~6 Mbps	Y	Y	Y	4	Y	Y	Y
3.3.12 Mars Trunk Line	~250 Mbps	P	P	N	[100 kbps*]	Y	Y	Y	4	Y	Y	P

† Y = requirement satisfied; N = requirement not satisfied; P = requirement satisfied part of the time.

* Provisional value in absence of customer statement.

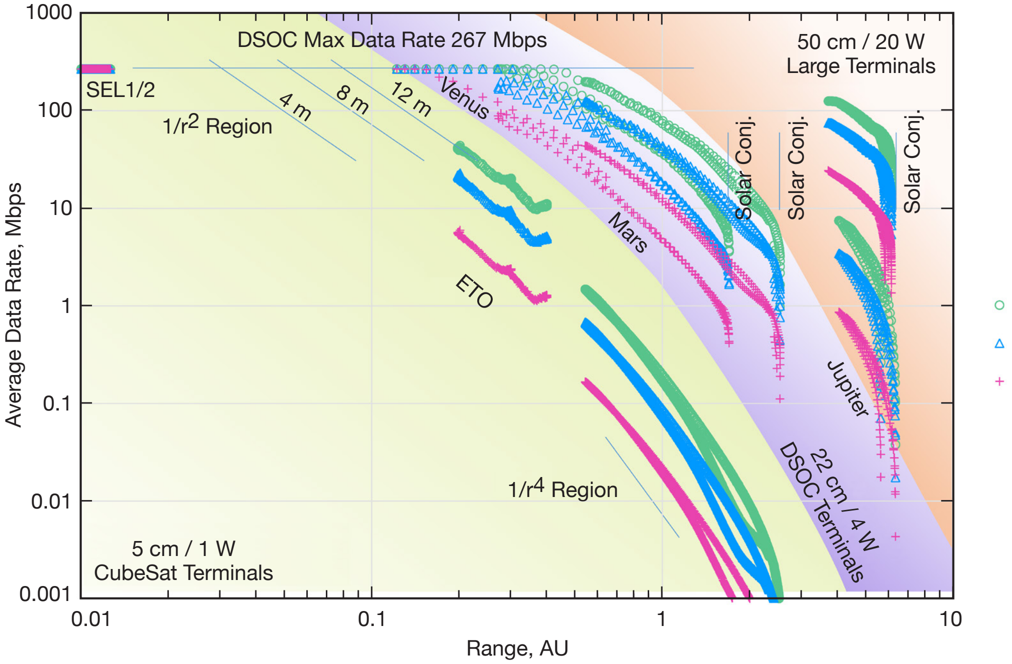

Figure 2. System performance for multiple missions as a function of communication distance (multiple missions).

Table 3. Approximate maximum communication distance for optical link to close at maximum data rates (DSOC planned upper range).*

		Ground Receive Terminal		
Terminal Type	Rate	4 m	8 m	12 m
50 cm / 20 W	267 Mbps	0.75 AU	1.5 AU	2.2 AU
22 cm /4 W	267 Mbps	0.16 AU	0.32 AU	0.48 AU
5 cm /1 W	267 Mbps	0.018 AU	0.035 AU	0.052 AU

*Values are calculated for SEP = 180 deg, zenith angle 45 deg, turbulence r_0 = 5.5 cm at 500 nm.

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