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Radio Frequency and Optical Communication Link Trade Studies Between Earth, Deep Space Gateway, and Lunar Surface

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Summary

Efficient and accurate communication are two of the most important aspects in a communications system. Hence, it was pertinent that radio frequency (RF) and optical link budget analyses were understood inside and out by the two young careerists when performing this study. This report covers RF and optical trade studies performed between Earth, Deep Space Gateway (DSG), Orion, and the Moon's lunar surface. Using criteria provided by NASA Headquarters, the links were statically driven allowing review of the systems without bandwidth limitations, spectrum allocations, and hardware implementations. This provided the chance to review the efficiency of the links as technology improves throughout the decades. A few select RF links were analyzed using repeaters while select optical links were compared with coded and uncoded modulation schemes. The results from these analyses again prove the tradeoff theories in communications systems.

1.0 Introduction

As young careerists in communications research, it was pertinent to understand the analysis of radio frequency (RF) and optical communication links. Since NASA Glenn Research Center has a core competency in communications, we were paired with a mentor, Bryan Welch, to teach us the basics of these systems. At the beginning of the mentorship, a study arose requiring link data analyses of potential communication links between Earth, the Deep Space Gateway (DSG)[1], the Orion crew module, and the lunar surface of the Moon. Throughout the study, specific variables within the link budget were varied and analyzed depending on the designated link. The results shown within this report are answers to questions from NASA Headquarters (HQ), as they take on the strenuous task of the Space Policy Directive 1 (Ref. 1).

There were four major communication links analyzed. These were between (1) Earth and the lunar surfaces, (2) Earth and DSG, (3) DSG and the lunar surface, and (4) DSG and Orion, refer to Figure 1. Each link analyzed contained different changed parameters and constraints based on the interest in that particular module, relay satellite, or station. The shown data results within this document are of importance to NASA HQ.

2.0 Static Radio Frequency Trade Studies

These tests were conducted with the notion of unconstrained data rates. This was implemented by increasing the bandwidth to extreme values during calculations. The RF bands analyzed were S, X, and Ka band.[2] The forward link frequencies for S, X, and Ka band were 2.028, 7.213, and 22.85 GHz, respectively. In continuance, the return link frequencies for S, X, and Ka band were 2.203, 8.475, and 26.25 GHz, respectively.[3] All links were unidirectional when analyzed.

[1]DSG is also named "Gateway".
[2]In Section 2.4, only the S band was investigated.
[3]In Section 2.3, the S band return frequency was calculated at 2.245 GHz.

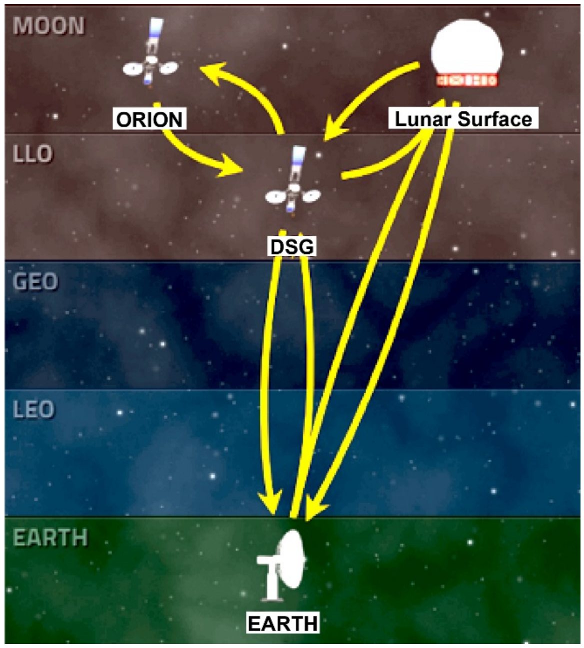

Figure 1.—Communication links analyzed.

TABLE 1.—INPUTS FOR FORWARD AND RETURN LINKS BETWEEN DSG[a] AND LUNAR SURFACE

Distance, km	70,000
Required bit error rate	1×10^{-9}
Modulation and coding	OQPSK[b] and LDPC 1/2 rate[c]
Elevation angle, deg	10
Implementation loss, dB	–3
Loss before antenna, dB	–3
Pointing losses, dB	–3
Antenna efficiency, percent	55
System temperature, K	316.23
Link margin, dB	3

[a]Deep Space Gateway.
[b]Offset quadrature phase shift keying.
[c]Low density parity check 1/2 rate.

2.1 RF Links Between DSG and Lunar Surface

Here the forward link is designated from the DSG to the lunar surface, and the return link is from the lunar surface to the DSG. Both the forward and return links varied the transmitted power and the transmitted and returned antenna diameters to calculate the unconstrained data rate. The antenna diameter facing the lunar surface was varied from 0.5 to 3 m. The transmitted power varied at 10, 50, and 100 W for the forward link and 10, 40, and 100 W for the return link. Table 1 presents other inputs that coincide with each analysis.

In the results, several observations were noted. First, the higher transmitted power values analyzed on the smaller antenna sizes offer better data rates than the lowest transmitted power calculated on the larger antenna sizes. Antenna size and system power are directly equivalent when the equivalent isotropic radiated power (EIRP) stays the same. If the scenario requires a smaller antenna, more power is required. If the scenario requires a larger antenna, less power is required. The larger the antenna, the beam is more directed and, as a result, is more efficient. However, the results show the smaller antenna performing better than the larger antenna. This is because the EIRP is not equivalent. Second, the forward and return links for each frequency band's results are different from each other (Figure 2). For the S band, the forward link performed worse than the return link. However, for the X band, the forward link performed better than the return link. For the Ka band, both forward and return links performed the same. All results were assessed in terms of data rate and for the Ka band, the higher the frequency, the higher the data rate. However, the data rates do not vary much. Lastly, the Ka band yields the highest data rates for both forward and return links. Since the link is space to space, there is a lack of atmosphere attenuation due to the link direction between the terminals allowing the Ka band to perform much better than its counterparts (Figure 2).

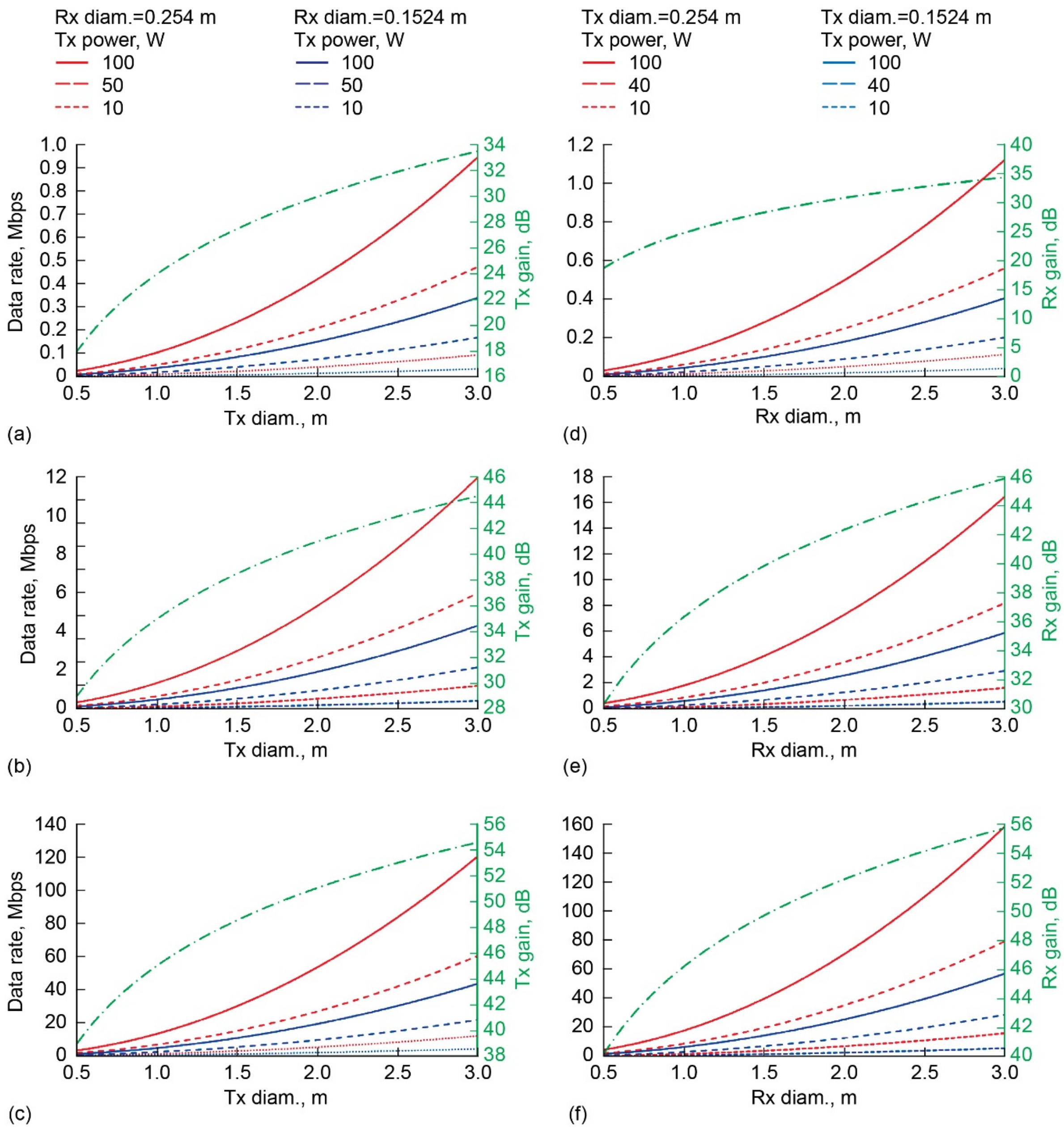

Figure 2.—Data results of varying antenna diameter and transmitting (Tx) power for the forward and return links between Deep Space Gateway (DSG) and the Moon. Power Propulsion Element (PPE) is a module of the DSG. Forward link = PPE to the lunar surface. Return link = the lunar surface to PPE. Rx = receiving. (a) S-band forward link. (b) X-band forward link. (c) Ka-band forward link. (d) S-band return link. (e) X-band return link. (f) Ka-band return link.

2.2 RF Link Between Earth's Surface and DSG

The links observed here are the forward and return links between the DSG and Earth's surface. Like the previous section, the antenna sizes varied on the DSG side ranging from 0.5 to 3 m, whereas the Earth's antenna sizes were taken as discrete values of 11, 18, and 34 m. The ground station locations for the 18- and 34-m dish sizes was White Sands Complex (WSC) in White Sands, New Mexico,[4] and the 11-m antenna size used was the Alaska Satellite Facility (ASF) in Fairbanks, Alaska (Refs. 2 and 3). Other parameters for this study are stated in Table 2. Distance was taken just above a maximum distance of 450,000 km. The forward link used static power levels comparable to their discrete transmission antenna sizes and frequencies, represented as EIRP in Table 3. This subsection's study follows baseline assumptions that the antenna gains for S- , X- , and Ka-band frequencies were 0, 34, and 45 dBi, respectively. With this, the majority of the resulting EIRP was calculated by the interpolation from the highest antenna sizes in each frequency band.

TABLE 2.—INPUTS FOR FORWARD AND RETURN LINKS BETWEEN EARTH'S SURFACE AND DSG[a]

Distance, km	450,000
Required bit error rate	1×10^{-9}
Coding scheme	LDPC 1/2 rate[b]
Elevation angle, deg	10
Implementation loss, dB	–3
Loss before antenna, dB	–3
Pointing losses, dB	–3
Antenna efficiency, percent	55
System temperature, K	316.23
Link margin, dB	3

[a]Deep Space Gateway.

[b]Low density parity check 1/2 rate.

TABLE 3.—EIRP VALUE PER ANTENNA SIZE AND FREQUENCY FOR EARTH SIDE OF FORWARD LINK

Antenna size, m	Equivalent isotropic radiated power (EIRP), dBW		
	2.028 GHz (S band)	7.213 GHz (X band)	22.85 GHz (Ka band)
11	64.80	73.82	66.69
18	81.00	84.83	77.98
34	98.70	110.00	103.80

[4]The 34-m antenna is on the Deep Space Network (DSN).

The values for the return link's receiving antenna gain-to-noise temperature, G/T (referred to as "G-over-T"), were comparable to the associated receiving antenna sizes and frequencies. The G/T values on the Earth side fall under the same baseline assumptions for the antenna gains and wattage levels. In Table 4, the G/T values are shown for the antenna size and frequency band associations. Unlike the forward link, the return link varies the transmitting power levels. The varied transmit power was analyzed through three values 10, 100, and 200 W for each antenna size and frequency band pair.

For both the forward and return links, the modulation used was offset quadrature phase shifting key (OQPSK) for the Ka band and binary phase shifting key (BPSK) for the X band. For the S band, spread spectrum unbalanced quadrature phase shifting key (SS–UQPSK) was used for the forward link while staggered quadrature phase shifting key (SQPSK) was used for the return link.

These constraints lead to several observations. For example, increasing the antenna size at both ends of the forward link increased the data rate, with a range of values as displayed in Table 5. These results are the product of the unconstrained bandwidth over the links. Thus to display the desired mathematical properties of the entire range of the varying parameters, an extremely large bandwidth was considered. See Figure 3 for a graph displaying these findings.

The return links exhibited expected behaviors in relation to each parameter (i.e., 10, 100, and 200 W transmit powers, with 11-, 18-, and 34-m received antenna sizes, at S-, X-, and Ka-band frequencies). The higher frequency bands produced higher data rates, larger receiving antennas received larger data rates, and a greater power generated greater data rates. As such, the range of the data rates are displayed in Table 6. If more clarification is needed, see Figure 4 for a detailed graph of X- and Ka-band trials.

TABLE 4.—G/T[a] VALUE PER ANTENNA SIZE AND FREQUENCY FOR EARTH SIDE OF RETURN LINK

Antenna size, m	G/T, dB/K		
	2.203 GHz (S band)	8.475 GHz (X band)	26.25 GHz (Ka band)
11	17.50	29.20	39.02
18	21.78	33.48	43.30
34	27.30	39.02	48.82

[a]Antenna gain-to-noise temperature.

TABLE 5.—DATA RATE MAXIMUM AND MINIMUM VALUE PER ANTENNA SIZE AND FREQUENCY FOR EARTH-TO-DSG[a] FORWARD LINK

Antenna size, m	Data rate	Frequency, GHz		
		2.028 (S band)	7.213 (X band)	22.85 (Ka band)
11	Min.	2.2 Mbps	17.1 Mbps	1.5 Mbps
	Max.	80.2 Mbps	616.0 Mbps	52.8 Mbps
18	Min.	93.0 Mbps	218.0 Mbps	21.5 Mbps
	Max.	3.4 Gbps	7.9 Gbps	776.0 Mbps
34	Min.	5.6 Gbps	74.7 Gbps	8.8 Gbps
	Max.	201.0 Gbps	2.7 Tbps	316.0 Gbps

[a]Deep Space Gateway.

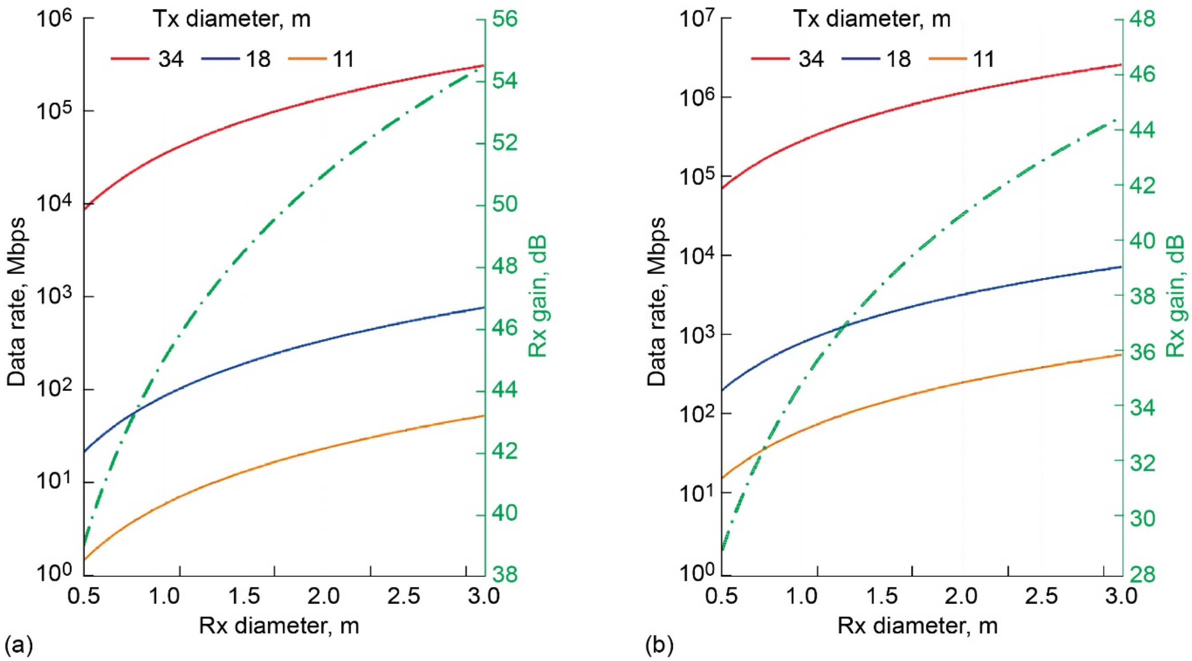

Figure 3.—Results of varying antenna diameters for the forward link between Earth and Deep Space Gateway (DSG). Tx = transmitting. Rx = receiving. (a) Ka band. (b) X band.

TABLE 6.—DATA RATE MAXIMUM AND MINIMUM VALUE PER FREQUENCY BAND FOR DSG[a]-TO-EARTH RETURN LINK

Data rate	Frequency, GHz		
	2.203 (S band)	8.475 (X band)	26.25 (Ka band)
Min.	133.0 kbps	1.9 Mbps	12.5 Mbps
Max.	104.0 Mbps	1.5 Gbps	11.2 Gbps

[a]Deep Space Gateway.

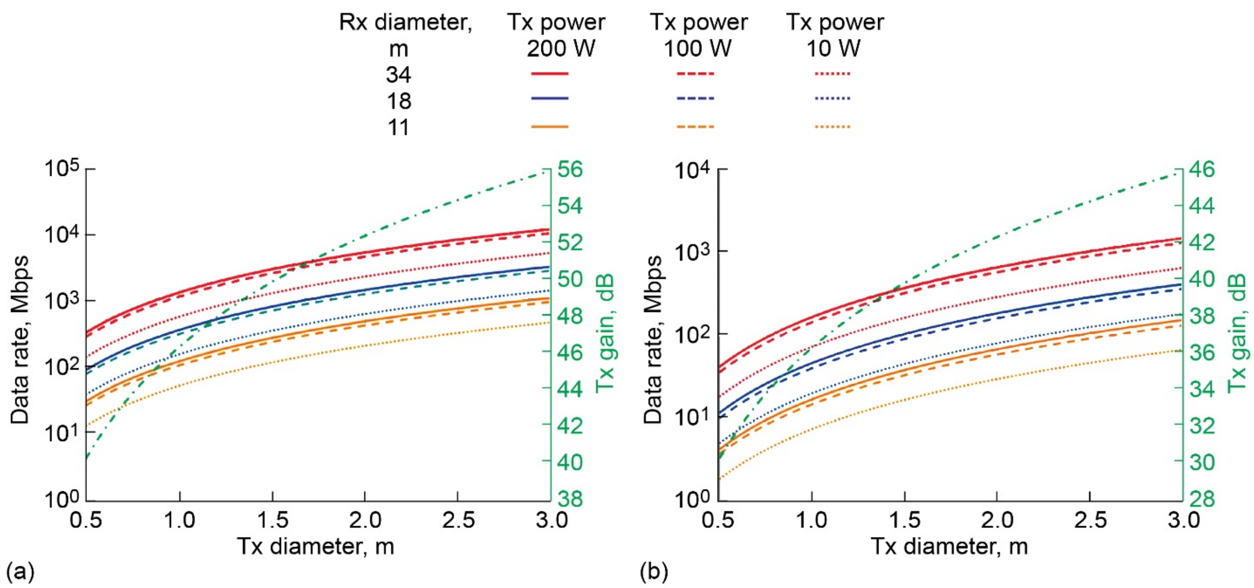

Figure 4.—Results of varying antenna diameters for the return link between Earth and Deep Space Gateway using receiving (Rx) antenna diameters of 34, 18, and 11 m and power transmitted (Pt) of 200, 100, and 10 W. Tx = transmitting. (a) K band. (b) X band.

2.3 RF Link Between Earth and Lunar Surfaces

The forward link is designated as from Earth's surface to the lunar surface and the return link is from the lunar surface to Earth's surface. These analyses traded transmitted and received antenna diameters in respect to the calculated data rate. The transmitted antenna diameter was statically varied between 11, 18, and 34 m and the received antenna diameter was varied from 6 to 23.7 in. The ground station location parameters are the same as those in Section 2.2.

In this case, the return S-band frequency was altered to be 2.245 GHz. All other bands and frequency values remained the same as the previous sections. Since the power levels remained static in this scenario, the EIRP and G/T were kept static for each frequency link. Refer back to Table 3 for the forward link's EIRP values and Table 4 for the return link's G/T values. Modulation for the S-band links, as well as X- and Ka-band links, can be found in Table 7. Variable inputs that are consistent throughout the calculations are shown in Table 8.

TABLE 7.—MODULATION SCHEME PER LINK AND FREQUENCY BAND

Link	Band		
	S	X	Ka
Forward	SS–UQPSK[a]	BPSK[b]	OQPSK[c]
Return	SQPSK[d]	BPSK	OQPSK

[a]Spread spectrum unbalanced quadrature phase shifting key.
[b]Binary phase shifting key.
[c]Offset quadrature phase shifting key.
[d]Staggered quadrature phase shifting key.

TABLE 8.—ANALOG REPEATER INPUTS FOR FORWARD LINK BETWEEN EARTH AND LUNAR SURFACES

Distance, km	390,000
Required bit error rate	1×10^{-9}
Coding scheme	LDPC 1/2 rate[a]
Elevation angle, deg	10
Implementation loss, dB	–3
Probability of exceedance, percent	10
System temperature, dBK	25
Link margin, dB	3

[a]Low density parity check 1/2 rate.

Results of these inputs and calculations are displayed as a spread of the data rates in Table 9 for the forward link and Table 10 for the return link. Yielding similar findings as in Section 2.2:

- X band yields the highest data rates for the forward link (Figure 5)
- Ka band yields the highest data rates for the return link (Figure 6)

The reasons for the X band's superior performance is that it is better for longer distances and is less affected by poor weather conditions. Also, the Ka band has a narrower beam pattern and less power output. The distance here is very large; therefore, the X band performs better. In addition, the forward link resulted in higher data rates than the return link equivalent because the transmitting antenna size is larger. When you have a larger antenna, the beam pattern is more directional based.

TABLE 9.—DATA RATE MAXIMUM AND MINIMUM VALUE PER ANTENNA SIZE AND FREQUENCY FOR EARTH-TO-LUNAR SURFACES FORWARD LINK

Antenna size, m	Data rate	Frequency, GHz		
		2.028 (S band)	7.213 (X band)	22.85 (Ka band)
11	Min.	275.00 kbps	2.17 Mbps	182.00 kbps
	Max.	4.41 Mbps	33.87 Mbps	2.90 Mbps
18	Min.	11.54 Mbps	27.05 Mbps	2.67 Mbps
	Max.	184.69 Mbps	432.76 Mbps	42.66 Mbps
34	Min.	690.93 Mbps	9.24 Gbps	1.09 Gbps
	Max.	11.05 Gbps	147.87 Gbps	17.38 Gbps

TABLE 10.—DATA RATE MAXIMUM AND MINIMUM VALUE PER ANTENNA SIZE AND FREQUENCY FOR LUNAR-TO-EARTH SURFACES RETURN LINK

Antenna size, m	Data rate	Frequency, GHz		
		2.245 (S band)	8.475 (X band)	26.25 (Ka band)
11	Min.	152.00 kbps	2.31 Mbps	15.40 Mbps
	Max.	607.00 kbps	36.96 Mbps	246.39 Mbps
18	Min.	441.00 kbps	6.28 Mbps	45.71 Mbps
	Max.	7.06 Mbps	100.55 Mbps	731.29 Mbps
34	Min.	1.58 Mbps	22.72 Mbps	166.51 Mbps
	Max.	25.30 Mbps	363.53 Mbps	2.66 Gbps

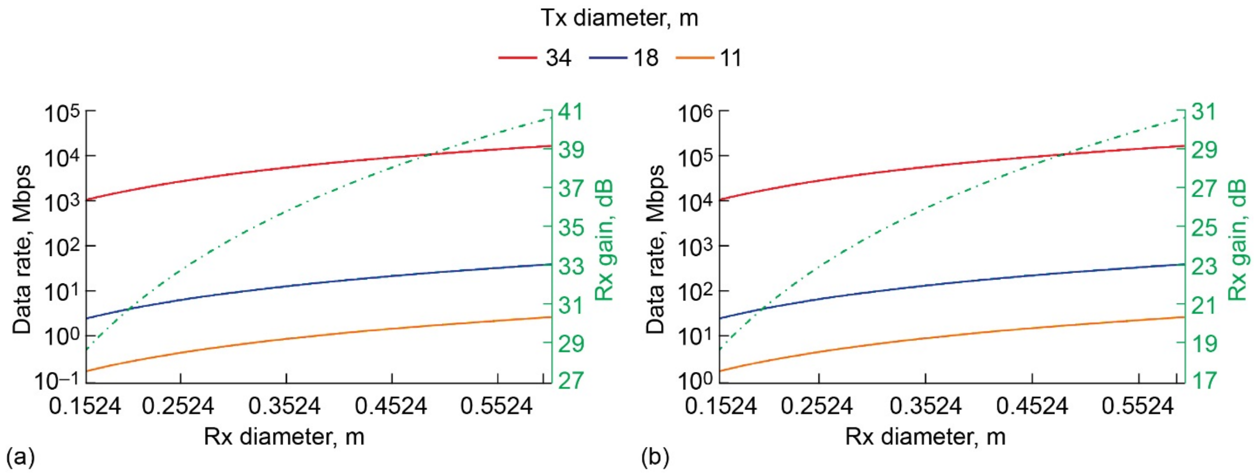

Figure 5.—Results of varying antenna diameters for the forward link between Earth and lunar surfaces using transmitting (Tx) antenna diameters of 34, 18, and 11 m. Rx = receiving. (a) Ka band. (b) X band.

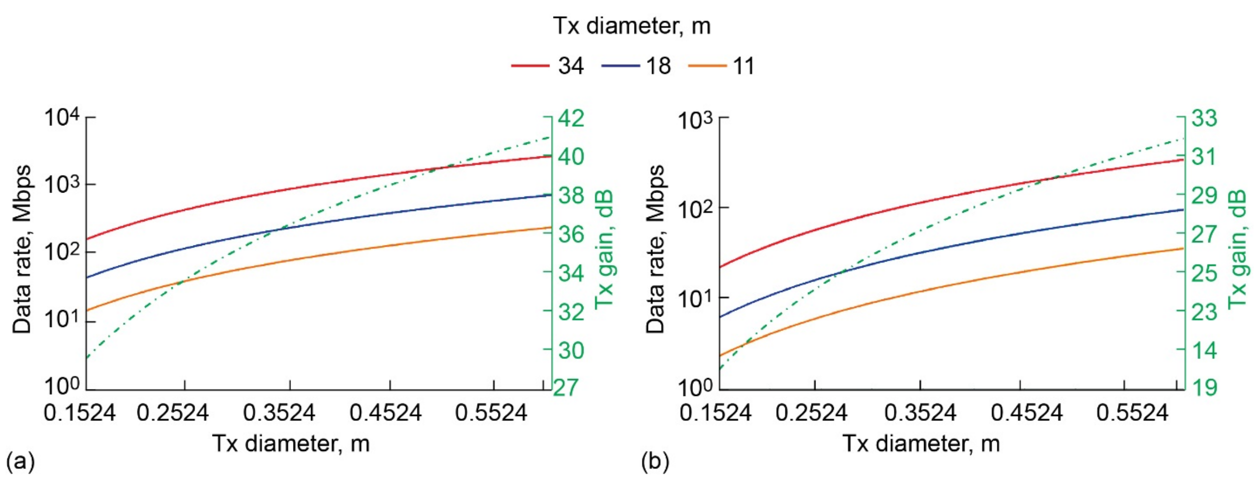

Figure 6.—Results of varying antenna diameters for the return link between the Earth and lunar surfaces using receiving (Rx) antenna diameters of 34, 18, and 11 m. Tx = transmitting. (a) Ka band. (b) X band.

2.4 RF Link Between Orion and DSG

The forward link is designated as the Orion capsule to the DSG and the return link is from the DSG to Orion. The analysis traded the distance between Orion and the DSG with different coding schemes and modulation techniques. All the calculations were done in the S-band frequency, from 2.028 to 2.203 GHz for the forward and return links, respectively. The distance was varied 1 to 400 km for both uncoded and coded links. The modulation techniques analyzed were SQPSK, staggered quadrature phase noise (SQPN), and SS–UQPSK. In the results, SQPSK and SQPN are grouped together because they provided the same curve. For the coding schemes, a coded link means a low density parity check 1/2 rate (LDPC 1/2 rate) and an uncoded link means an uncoded coding rate. The forward link had an EIRP input of 13.7 dBW. For the return link, the input power was varied at 10, 20, 50, and 100 W. In addition, the G/T input was set at –21.1 dB/K and a received antenna loss value of –3 dB was added. Refer to Table 11 for other inputs that coincide with each analysis.

After analyzing the data results, the forward link using the SS–UQPSK modulation and having LDPC 1/2 rate coding provided a higher data rate than the uncoded signal with the same link margin. Coding is used to help increase the bit error rate (BER). By using a coding scheme, the data rate will also increase if the BER improves. Other observations include

- A coded return link can make 6 Mbps at 100 W of transmitted power at 400 km range
- The choice of SQPSK versus SQPN modulation scheme for the return link did not affect the data rate versus distance results (Figure 7)

TABLE 11.—INPUTS FOR FORWARD AND RETURN LINKS BETWEEN ORION AND DSG[a]

Required bit error rate	1×10^{-9}
Gain, dB	0
Elevation angle, deg	10
Implementation loss, dB	–3
Loss before antenna, dB	–3
System temperature, K	316.23
Link margin, dB	3
Link margin, dB	3

[a]Deep Space Gateway.

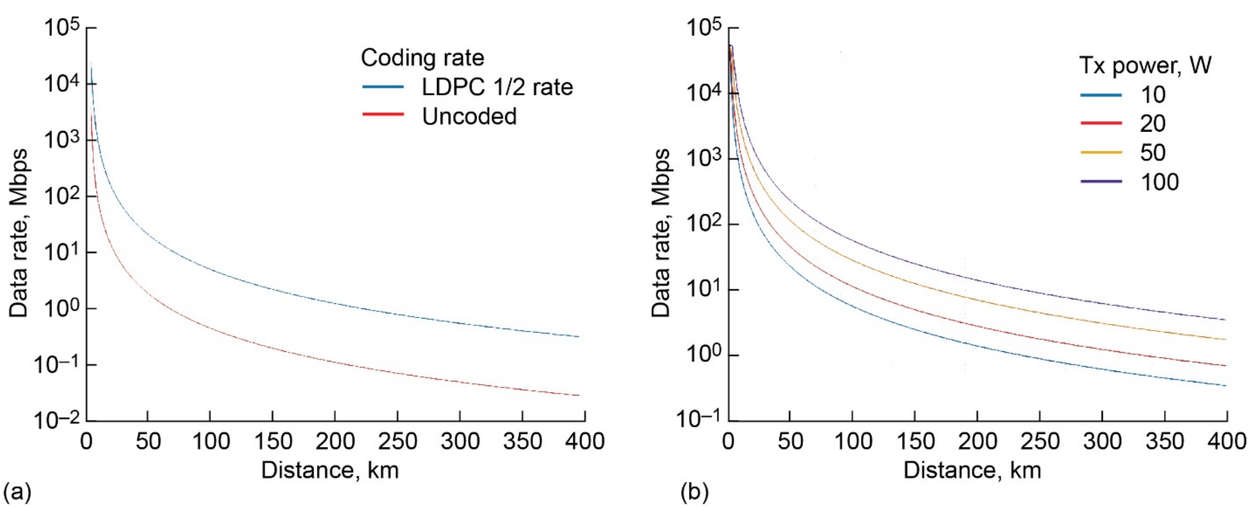

Figure 7.—Modulation data results of forward and return links between Deep Space Gateway (DSG) and Orion. Tx = transmitting. (a) Forward link = Orion to DSG. LDPC = Low-density parity-checked code. (b) Return link = DSG to Orion.

3.0 RF Static Repeater Trade Studies

The designated forward link is from the Earth's surface through the DSG to the lunar surface. The static repeater trade studies were used to explore the Ka-band forward link by varying received and transmitted antenna diameters on the DSG. This resulted in a bandwidth limit of 600 MHz.

3.1 Analog Repeater Ka-Band Forward Link

The results are calculated data rates versus antenna diameters when using an analog repeater between the Earth and lunar surfaces. The antenna on Earth was statically varied at 11, 18, and 34 m and the antenna on the lunar surface was varied as 6 and 10 in. For both antennas, the transmitting power was statically varied in different combinations of 10, 100, and 200 W. By changing the antennas statically, the limiting link was found. For other inputs that coincide with each analysis, refer to Table 12.

Based on these values, the limiting link is from the DSG to the lunar surface. Analog repeaters measure the C/N_0 relation. This relation is between the power of the modulated carrier, C, and the noise power spectral density, N_0. As seen in Figure 8, the Earth-to-DSG link had an increased data rate for the smaller antenna diameters when the transmitting power or the transmitting antenna diameter on Earth was increased. As more power is available and the lower antenna diameters increase, the upper limits of the system are reached. Please note, the static variables in Table 12 are used. If the variables were altered, the results shown would change. Also seen in Figure 8, the system's maximum data rate with the constrained parameters is 119.75 Mbps. Since the DSG to the lunar surface is the limiting link, the highest power level available, 100 W, will provide the best data rate and show the system's maximum.

TABLE 12.—INPUTS FOR ANALOG REPEATER FORWARD LINK BETWEEN EARTH AND LUNAR SURFACES

Earth-to-DSG[a] distance, km	450,000
DSG-to-Moon distance, km	70,000
Required bit error rate	1×10^{-9}
Modulation	OQPSK[b]
Coding	LDPC 1/2 rate[c]
Elevation angle, deg	10
Transmitting (Tx) pointing loss, dB	–3
Receiving (Rx) pointing loss, dB	–3
System temperature, K	316.23
Link margin, dB	3
Frequency, GHz	22.85
Ground station	White Sands, NM

[a]Deep Space Gateway.
[b]Offset quadrature phase shifting key.
[c]Low density parity check 1/2 rate.

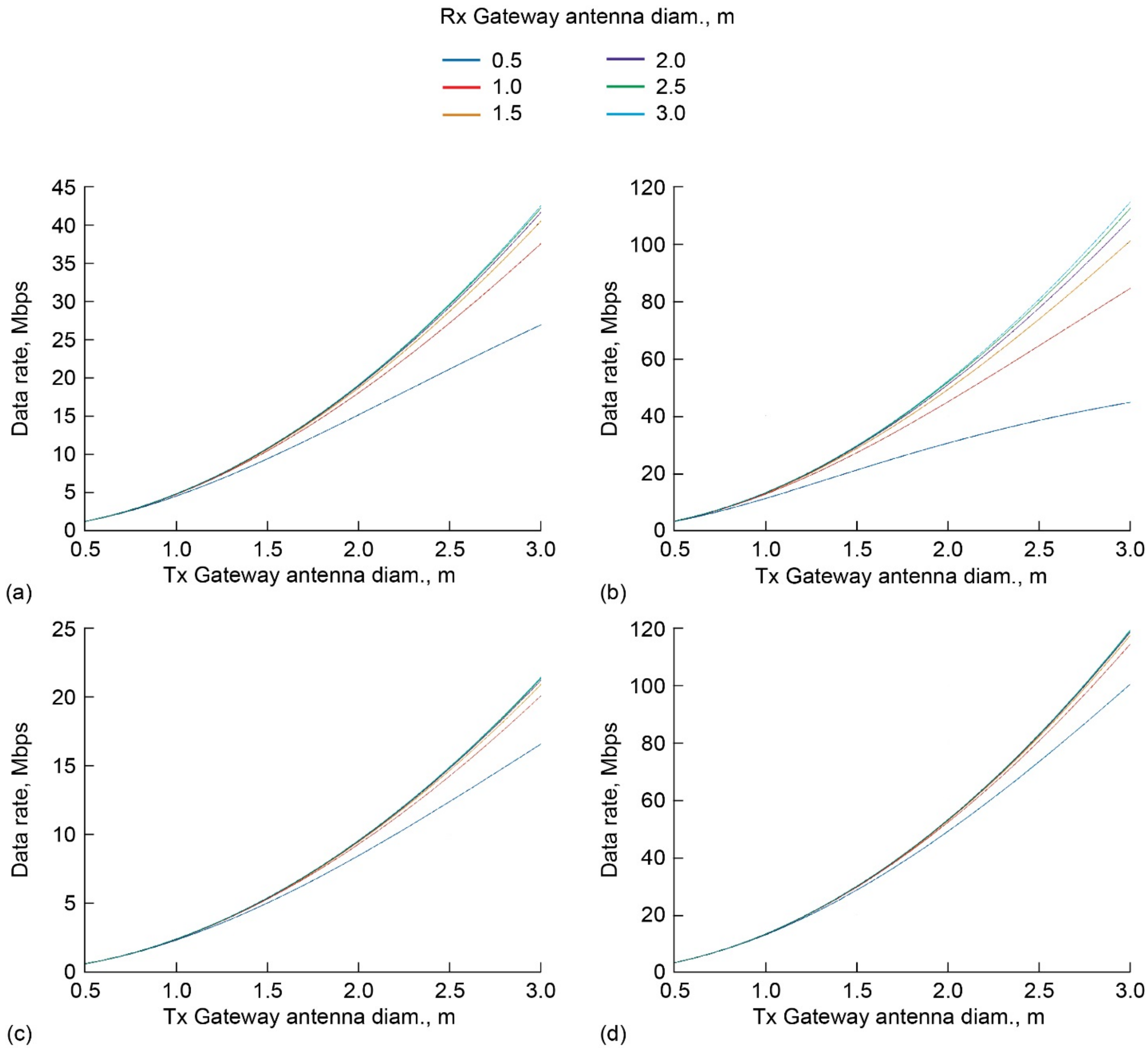

Figure 8.—Ka-band results of varying antenna diameters and power using an analog repeater for the forward link, Earth to Deep Space Gateway (DSG) to lunar surface. Tx = transmitting; Rx = receiving; Tx power, W = (link 1, link 2).
(a) Tx power, W = (100, 100); Earth Tx antenna diameter, m = 11; lunar surface Rx antenna diameter, m = 0.1254.
(b) Tx power, W = (100, 100); Earth Tx antenna diameter, m = 11; lunar surface Rx antenna diameter, m = 0. 524.
(c) Tx power, W = (100, 50); Earth Tx antenna diameter, m = 11; lunar surface Rx antenna diameter, m = 0.1254.
(d) Tx power, W = (100, 100); Earth Tx antenna diameter, m = 34; lunar surface Rx antenna diameter, m = 0.524.

3.2 Digital Repeater Ka-Band Forward Link

The digital repeater analyses varied antenna diameters and the system power to find the data rate. The two antenna diameters on the DSG were traded from 0.5 to 3 m at a step size of 0.1 m throughout the analyses. The antenna diameter of the Earth's surface varied statically at 11, 18, or 34 m whereas the antenna diameter on the lunar surface changed between 6 or 10 in. The power involved in the calculations was either 10 or 100 W. Refer to Table 13 for other inputs that coincide with each analysis.

By using a digital repeater, the BER is measured when the repeater decodes and then recodes the message. Because of this process, the digital repeater performs differently than the analog repeater, giving different but similar results to those found in Section 3.1. After reviewing the results, the limiting link is the DSG to the lunar surface. Therefore, the highest power levels available for this part of the link will provide the best data rate.

The resulting data show that using the Earth's smallest antenna size and the lunar surface's largest antenna size, unconstrained bandwidth assumptions are reached. Figure 9 shows the results from (a) a 10 W system power with an 11-m Earth antenna diameter and a 10-in. antenna diameter for the lunar surface and (b) a 100 W system power with a 34-m Earth antenna diameter and a 10-in. lunar surface antenna diameter. As the transmitted antenna diameter increases, the bandwidth constraints of the system are approached. This only happens when the received antenna diameter is at its smallest values, 0.5 and 0.6 m, because the first part of the Earth-to-DSG link is limited on its throughput. Also, the data rate increases by a factor of 2 from 10 to 100 W as shown on the y-axis in Figure 9.

TABLE 13.—DIGITAL REPEATER INPUTS FOR FORWARD LINK BETWEEN EARTH AND LUNAR SURFACES

Earth-to-DSG[a] distance, km	450,000
DSG-to-Moon distance, km	70,000
Required bit error rate	1×10^{-9}
Modulation	OQPSK[b]
Coding	LDPC 1/2 rate[c]
Elevation angle, deg	10
Implementation loss, dB	–3
Transmitting (Tx) pointing loss, dB	–3
Receiving (Rx) pointing loss, dB	–3
Probability of exceedance, percent	10
System temperature, K	316.23
Link margin, dB	3
Frequency, GHz	22.85
Ground station	White Sands, NM

[a]Deep Space Gateway.
[b]Offset quadrature phase shifting key.
[c]Low density parity check 1/2 rate.

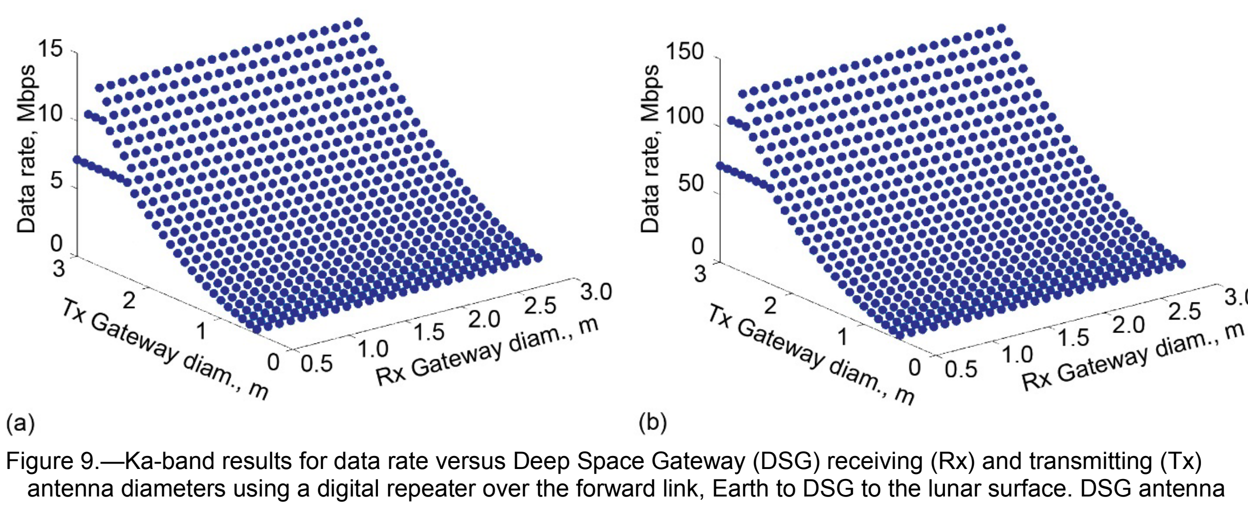

Figure 9.—Ka-band results for data rate versus Deep Space Gateway (DSG) receiving (Rx) and transmitting (Tx) antenna diameters using a digital repeater over the forward link, Earth to DSG to the lunar surface. DSG antenna diameter = 0.254 m (a) Earth antenna = 11-m diameter, 10 W power. (b) Earth antenna = 34-m diameter, 100 W power.

4.0 Optical Trade Studies

The static optical analyses were designed to show potential data rates based on varied transmitted and received aperture diameters and transmitted power using optical communications. The two wavelengths used are 1,550 and 1,558 nm depending on the forward or return link. The forward links are from Earth to DSG, Earth to the lunar surface, or DSG to the lunar surface. The return links are calculated as DSG to Earth, the lunar surface to Earth, or the lunar surface to DSG.

4.1 Coded and Uncoded Analysis

The coded and uncoded return and forward links were calculated with varying antenna aperture diameters and power, depending on the specific link. Refer to Table 14 for the three types of links that were analyzed.

The wavelength was changed between 1,550 and 1,558 nm. The 1,558-nm wavelength was used for any data coming from the lunar surface to eliminate interference since the two wavelengths maintain the same space. The detectors changed between a small cryogenic-cooled avalanche photodiode detector (APD) and a nanowire APD, for the return link between Earth and DSG. The Earth's station was designated as NASA's Table Mountain Facility in Wrightwood, California, for the optical tests dealing with the Earth. Refer to Table 15 for other inputs that remain static with every analysis.

Using the conditions from Table 15 with the 1,550- and 1,558-nm wavelengths, a couple of unexpected observations are seen within the results. Overall, the results show that the coded links perform better than their uncoded counterparts with respect to their designated wavelengths. See Figure 10 for an example of the links performance between the Earth and DSG. Coded data moves better through Earth's atmosphere, a major factor that scatters the photons in free space. The coded link's performance was sometimes more than 4 times better than that of the uncoded links (Table 16).

TABLE 14.—STATIC OPTICAL LINK TESTS BASIS

Forward and return links	Distance, km	Aperture diameters, cm	Power, W
Earth and PPE[a]	450,000	5.0 to 30.0 0.5 to 500.0	1.0 to 5.0 0.5 to 10.0
Earth and Moon	390,000	0.5 to 100.0 0.5 to 500.0	----------- -----------
PPE and Moon	70,000	5.0 to 30.0 10.0 to 100.0	1.0 to 5.0 0.5 to 10.0

[a]PPE = Power Propulsion Element.

TABLE 15.—INPUTS FOR STATIC OPTICAL TESTS

Required bit error rate	1×10^{-9}
Modulation	DPSK[a]
Elevation angle, deg	30
Implementation loss, dB	–3.5
Transmitting (Tx) pointing loss, dB	–2
Receiving (Rx) pointing loss, dB	–3
Probability of exceedance, percent	10
Link margin, dB	3
Uncoded gain, dB	0
Coded gain, dB	6.2

[a]Differential phase shifting key.

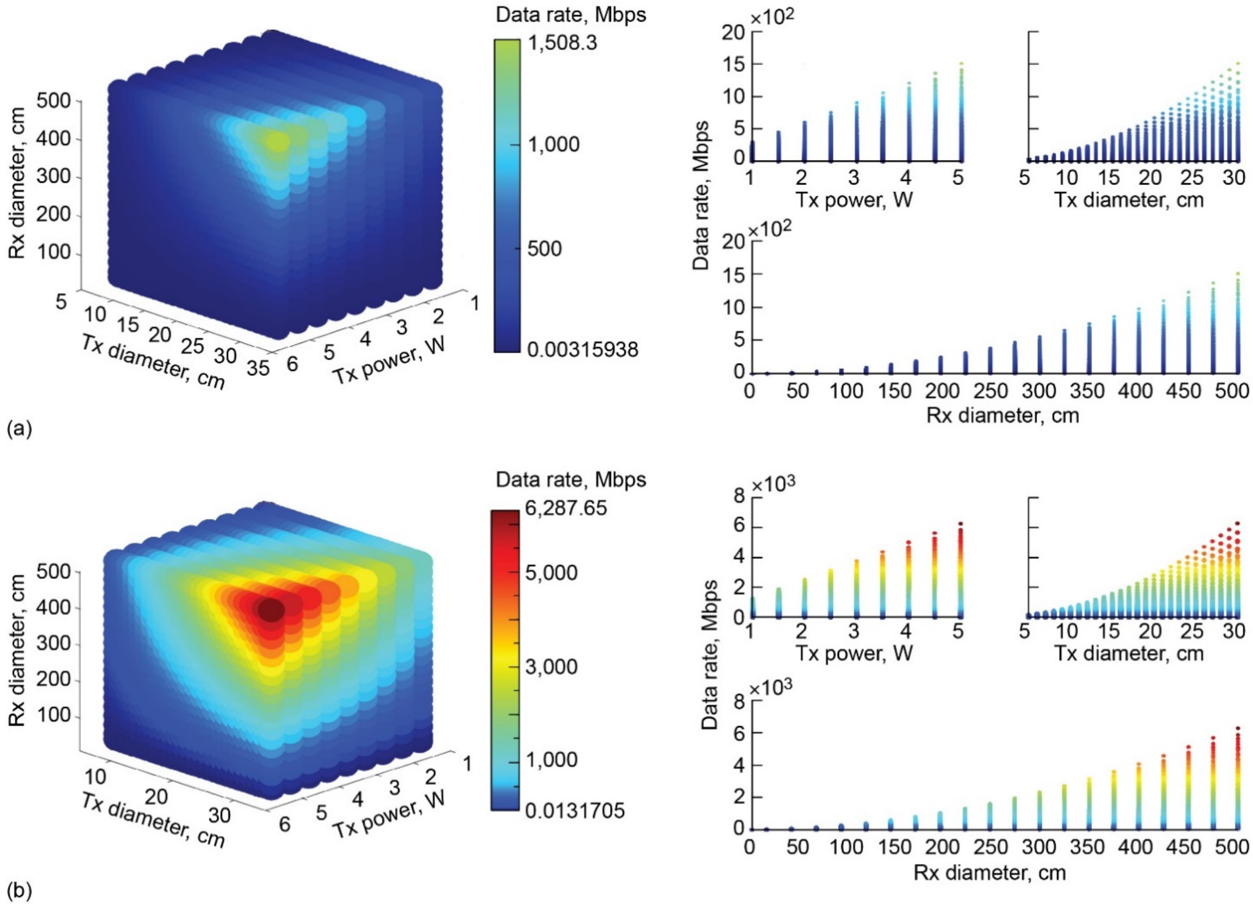

Figure 10.—Optical results for the return link between Earth and Deep Space Gateway (DSG) antennas showing the data rate versus the transmitting (Tx) power, Tx antenna diameter, and receiving (Rx) antenna diameter. (a) Uncoded. (b) Coded.

TABLE 16.—DATA RATE COMPARISON FOR STATIC OPTICAL TESTS

Link	Uncoded data rate, Gbps	Coded data rate, Gbps	Factor difference
Earth to DSG[a]	3.0	12.50	4.17
DSG to Earth	1.5	6.28	4.19
DSG to lunar surface	135.5	564.60	4.17
Lunar surface to DSG	269.5	1123.60	4.17
Lunar surface to Earth	44.6	185.95	4.16
Earth to lunar surface	44.4	185.20	4.17

[a]DSG = Deep Space Gateway.

As expected, when distance shortens, the data rate increases. The distance between the DSG and the lunar surface is the shortest at 70,000 km yielding the highest data rates. Its counterpart's distances are 450,000 and 390,000 km. Since free space path loss is always a function of distance and frequency, increasing or decreasing the range does not result in linear data rates. For the results in Figure 10 to Figure 13, the frequency was kept the same.

Based on the differences in distance, the return and forward links performed differently. For the links between DSG and the lunar surface, the return link performed better than the forward link. The lunar surface to DSG return link had higher data rates, (Figure 11). For the links between Earth's surface and the DSG, the return link performed worse than the forward link. The forward link is designated as Earth to DSG, (Figure 12). However, between Earth and the lunar surface, both the forward and return links yielded almost the same data rate results, (Figure 13). The results seen in Figure 11 to Figure 13 are due to the differences in the aperture sizes, location, and transmitted power.

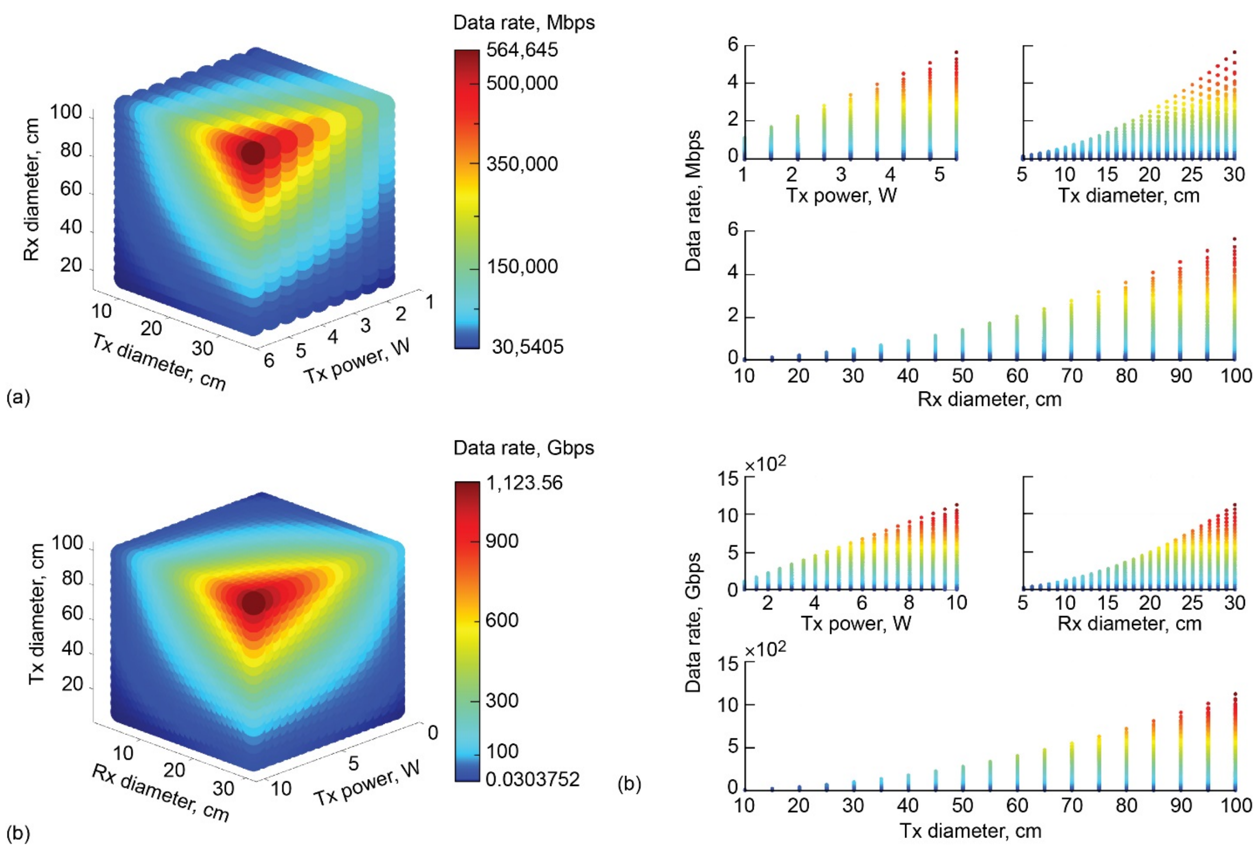

Figure 11.—Coded data results for the return and forward links between Deep Space Gateway (DSG) and the lunar surface antennas using the data rate versus the transmitting (Tx) power, Tx antenna diameter, and receiving (Rx) antenna diameter. (a) Forward link = DSG to lunar surface. (b) Return link = lunar surface to DSG.

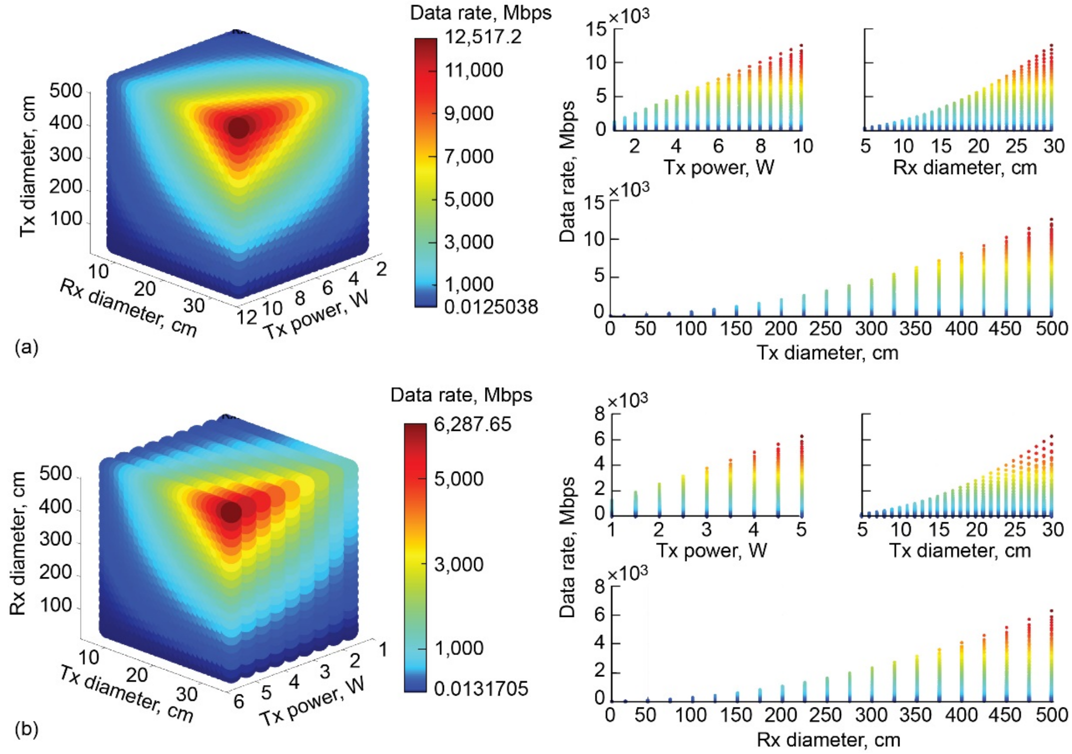

Figure 12.—Coded data results for the return and forward links between Earth and Deep Space Gateway (DSG) antennas using the data rate versus the transmitting (Tx) power, Tx antenna diameter, and receiving (Rx) antenna diameter. (a) Forward link = Earth to DSG. (b) Return link = DSG to Earth.

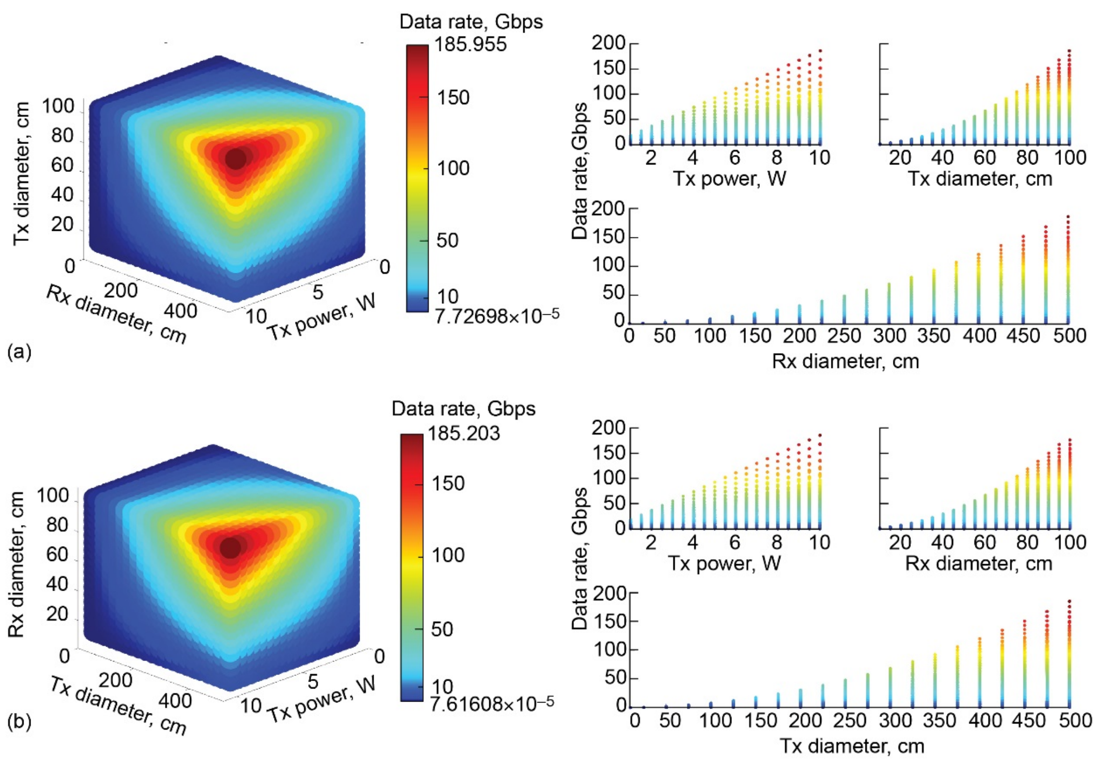

Figure 13.—Coded data results for the return and forward links between Earth and the lunar surface antennas using the data rate versus the transmitting (Tx) power, Tx antenna diameter, and receiving (Rx) antenna diameter. (a) Return link = lunar surface to Earth. (b) Forward link = Earth to lunar surface.

5.0 Concluding Remarks

The results in each section follow the tradeoff theories in communications systems. For example, the data rate increases as frequency band values or antenna power increases. There were a few unexpected results found in Section 2.1 where a smaller antenna performed better than a larger antenna and Section 2.4 where X band performed better than Ka band. For the optical study, the aperture diameter and power levels were not to extremes that would result in an unexpected phenomenon.

It should be kept in mind that the bandwidth limitations, spectrum allocations, and hardware implementations of the studied cases do not yet apply to actual systems. Throughout the Deep Space Gateway communication link analyses, knowledge of how to analyze radio frequency and optical communication links was attained. This acknowledges the succession planning that NASA Glenn Research Center has to teach young careerists about communications.

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3. Jet Propulsion Laboratory: DSN Telecommunications Link Design Handbook. TMOD No. 810–005, Rev. E, Nov. 30, 2000.