

MATER Mission Communications Subsystem Concept of Operations

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I. Nomenclature

<i>MATER</i>	=	Mars Advanced Tanking and Extraction Resource
<i>RF</i>	=	Radio Frequency
<i>DSN</i>	=	Deep Space Network
<i>UHF</i>	=	Ultra High Frequency
<i>BER</i>	=	Bit Error Rate
<i>SNR</i>	=	Signal to Noise Ratio
<i>SNSPD</i>	=	Superconducting Nanowire Single-Photon Detector
<i>MAV</i>	=	Mars Ascent Vehicle
<i>MCL</i>	=	Mars Communications Lander
<i>MRN</i>	=	Mars Relay Network
<i>CONOPS</i>	=	Concept of Operations

II. Introduction-TH

THE MATER mission focuses on development of in-situ liquid propellant using martian subsurface ice and atmospheric carbon dioxide with its main objective being to prove technological feasibility of Mars refueling. In order to successfully demonstrate refueling capability and fulfill all mission requirements, reliable and continuous communication needs to be provided for all Martian surface assets in order to properly coordinate rover mining operations, remote propellant production, and helicopter data retrieval. The requirements highlighted in Table 1 enables MATER to monitor propellant production and send commands for mining and launch operations with minimal signal error.

A. Subsystem Mission Requirements-TH

ID	Requirement	Rationale
COMM-1	The MATER orbiters shall maintain radio frequency or optical communications within all communication links (both Earth and Mars ground stations) with a maximum BER of 10^{-6} and a minimum link margin of 3 dB.	COMM-1 requirement ensures that mission critical operations (HIAD deployment, rover deployment, etc.), emergency protocols, and propellant monitoring has reliable communication from Earth to Mars stations. Minimal bit errors results in fewer retransmissions and thus carries out commands with minimal latency.

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COMM-2	The MATER orbiters shall maintain radio frequency or optical communications with both Earth and Mars ground stations at a data rate of at least 100 kbps.	COMM-2 requirement minimizes incomplete data transmissions over the deep space channel and provides MATER with high data transmission rates for low-latency propellant monitoring. This ensures emergency protocols and commands for propellant production can be relayed with minimal interrupts and latency.
COMM-3	MATER communications with both Earth and Mars ground stations shall maintain a minimum transmission of 1 relay per hour within every 24 hour period on Mars.	COMM-3 provides multiple transmission windows for MATER. Each subteam is provided frequent status updates for Martian surface operations such that data relays, commands, emergency protocols, and/or mission staging operations can be decided.

Table 1 Communications Subsystem L1 Requirements

Table 1 requirements will be achieved by deploying three additional half-duplex orbiters into the Mars Relay Network (MRN), all of which will be phased apart such that any orbiter eclipsed by Mars can relay data to a nearby orbiter with line of sight to Earth. Additionally, orbiters will be synchronized to pass over the over the rover charging station 2-3 times per day for frequent data uplink and downlink. Surface relays between the rover charging station (also known as the MCL: Mars Communications Lander), rovers, helicopter, propellant factory, and MAV are modeled after the multi-agent autonomy project CADRE, in which the MCL will be designated as leader of a mesh network relay equipped with an omnidirectional UWB antenna to communicate with surface vehicles and the propellant station.[1] Data from ground assets is sent to the MCL through the mesh network and then uplinked to one orbiter utilizing a half-duplex Electra UHF radio. Orbiters will also be equipped with two Electra UHF radios for Martian downlink to the MCL, as well as an X-band HGA for communication with Earth DSN ground stations. For redundancy, the MCL is equipped with two radios and will also have a backup low data rate HGA for DSN uplink in case of an orbiter communications blackout. The MATER relay architecture is illustrated in Fig.1. This architecture not only provides MATER with multiple opportunities for uplink and downlink between Earth and Mars ground stations, but utilizes high performing flight heritage technology that can satisfy COMM-1 and COMM-2 requirements in Table 1.

B. Communications CONOPS-TH

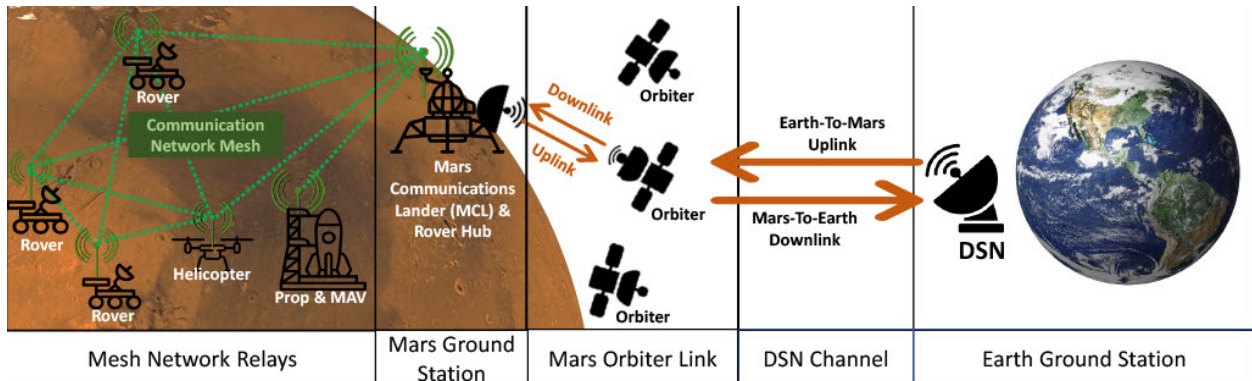


Fig. 1 Overview of Communications Relay

C. Deep Dive Requirements - JM

This report will conduct a deep dive into the two following topics:

1. Primary Communications Design from Mars to Earth

For each link in our design, we will discuss a trade study comparing RF and Optical communications to motivate our selection. Following each RF vs Optical discussion, we will outline our link budgets and hardware and software specifications.

2. Backup Communications Design from Mars to Earth

We will outline a backup communications link from the MCL to the Deep Space Network. This will include a link budget and lander specifications for hardware and software.

III. Communications Design from Orbiters to Earth

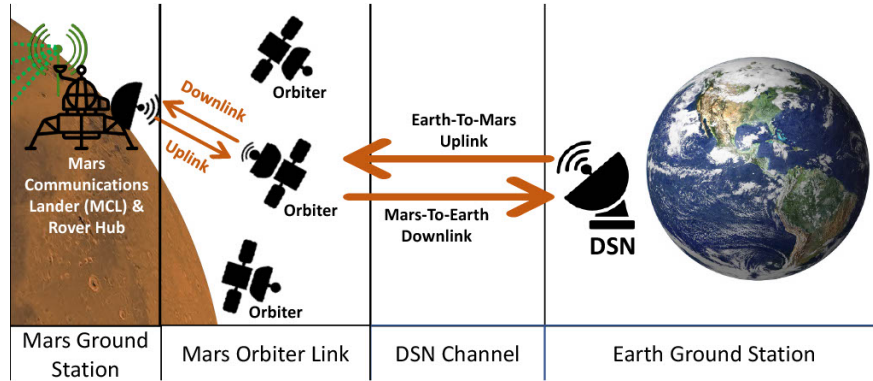


Fig. 2 Overview of Communications From MCL to Earth

A. Link Budget-TH

Since BPSK is commonly used to modulate satellites, we will use it to fulfill our BER requirement of less than $10e-6$ and set the required E_b/N_0 (dB). Using Fig.8 we determine that approximately **11 dB** would be required. In order to find data rate we need to use equation 1:

$$\frac{E_b}{N_0} = \frac{P_r}{R_b N_0} \quad (1)$$

This requires that we establish what our received power (P_r) is, our noise power density (N_0), and our received SNR (E_b/N_0).

$$P_r \text{ [dBW]} = P_t \text{ [dBW]} + G_t \text{ [dBi]} + G_r \text{ [dBi]} - L_{fs} \text{ [dB]} - L_{Scin} \text{ [dB]} - L_{Atm} \text{ [dB]} \quad (2)$$

Where P_t is transmit power, G_t is transmit gain, G_r is receiver gain, and L_{fs} is free space loss, modeled by

$$L_{fs} \text{ [dB]} = 10 \log_{10} \left(\left(\frac{4\pi R}{\lambda} \right)^2 \right) = 20 \log_{10} \left(\frac{4\pi R}{\lambda} \right) \quad (3)$$

In our model, we also include minimal scintillation (L_{Scin}), and atmospheric/multi-path losses (L_{Atm}). The impact of these losses are further discussed in each individual link analysis, since they can change based on the transmitted frequency or whether RF or optical communications are used. Equations (1), (2) and (3), are the driving equations behind our link budget analysis and are used in a link budget spreadsheet (see appendix) to determine whether our MCL or orbiter design can meet our performance requirements.

1. MCL-Orbiter Link

For our MCL-orbiter link, we use the Electra UHF radios exclusively for both uplink and downlink. We selected a transmit frequency of 430 MHz, a transmit power of 7 W, and the maximum receiver and transmitter gains of 5 dBi (no

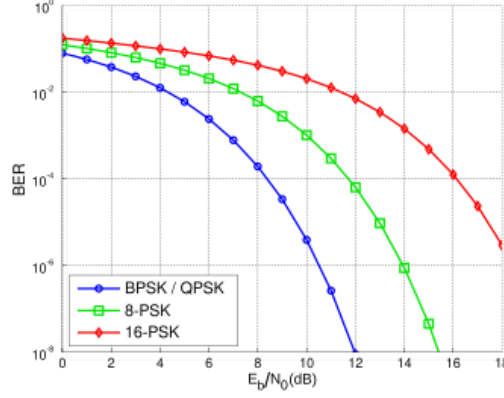


Fig. 3 Modulation Scheme: BPSK and QPSK BER vs Eb/No Chart

boresight). [2] As with the Mars Reconnaissance Orbiter, ESA Trace Gas Orbiter, and other satellites currently in the MRN constellation, our orbiters will also function in LEO (400 km - 600 km), which will ultimately result in a lower free space loss. [3] However, the total system noise temperature for this system is higher due to the use of the UHF frequency (approximately 155 K) and noise temperature of the LGA (approximately 100 K).[2],[4] Additionally, the Electra UHF transceivers have a higher max noise figure of about 3.9 dB which further adds to the noise temperature. We see by using equation (4)

$$T_{\text{sys}} = T_{\text{ant}} + T_{\text{amp}} \quad [\text{K}] \quad (4)$$

Where: $T_{\text{ant}} = T_{\text{sky}} + T_{\text{loss}}$ and $T_{\text{amp}} = \left(10^{\frac{NF}{10}} - 1\right) T_0$, NF is the noise figure in dB, and T_0 is the reference temperature (typically 290 K for Earth and 210 K for Mars[5]) Our downlink total noise temperature will be approximately: $T_{\text{sys}} = 255 + \left(10^{\frac{3.9}{10}} - 1\right) * 210 = 560.4 \text{ K}$ This leads to a noise power density being $N_0 = k T = 7.7\text{E-}21 \text{ [W/Hz]}$ where $k = 1.38 \times 10^{-23} \text{ J/K}$ (Boltzmann constant). Using equation (2) and (3) from above, we can calculate the free space loss and received power for RF communications, and then use equation (1) to calculate data rate performance. Thus with $P_t = 8.45 \text{ dBW}$ (converted from 7 W), $G_t = G_r = 5\text{dBi}$, $\lambda = c/430\text{e}6 \text{ m}$, $N_0 = 7.73\text{E-}21 \text{ W/Hz}$, and $L_{\text{Scin}} = -0.5 \text{ dB}$ and $L_{\text{Atm}} = -1 \text{ dB}$ due to relatively small losses in Mars atmosphere [4], we see in table 2 that we successfully meet COMMS-1 and COMMS-2 requirements for BER, link Margin, and data rate performance.

Parameter	Short Distance	Nominal	Long Distance
Distance (km)	400	500	600
Free space loss (dB)	-137.1583522	-139.0965524	-140.6801773
Received Power (dBW)	-119.7934449	-121.7316452	-123.3152701
Received E_b/N_0 (dB)	18.82650279	18.7147891	18.62132985
BER (BPSK)	2.29E-35	1.61E-34	7.94E-34
Data rate (kbps)	10769.84438	6892.700405	4786.597503

Table 2 Orbiter to MCL Downlink

Given that the MCL uses identical frequency, gain, and transmission powers, most parameters stay the same except for the total system noise temperature. This is due to far higher receiver noise temperature on the surface of Mars (450 K) [4]. The resulting N_0 is $1.71\text{E-}20 \text{ W/Hz}$ and will yield slightly lower data rates, as seen in table 3. (Note: Free space loss is the same)

Parameter	Short Distance	Nominal	Long Distance
Distance (km)	400	500	600

Received Power (dBW)	-119.7934449	-121.7316452	-123.3152701
Received E_b/N_0 (dB)	18.62628975	18.50923376	18.41119314
BER (BPSK)	7.30E-34	5.14E-33	2.53E-32
Data rate (kbps)	4879.169284	3122.668342	2168.519682

Table 3 MCL to Orbiter Uplink

RF vs Optical Link Trade Study

In recent years, optical communication for satellites has improved significantly and consistently demonstrates high data rates for mission relays.[6],[7] Implementing lasercom into the MCL and MATER orbiters has been considered for this mission, given that lasercom would encounter very little interference due to narrow beamwidth and have lower overall SWaP demands. However, there are many reasons why RF for the MCL-orbiter link is advantageous, one of them being that RF can more easily penetrate atmospheric conditions, while lasercom is susceptible to large amounts of attenuation due to moisture in clouds, dust, and other atmospheric conditions. [7] With lasercom, the required pointing of the beam is strict and would require an additional beacon laser for alignment with orbiter telescope apertures. This would not only put more pointing constraints on the pointing budget for our ADCS team, but this would also limit us to only communicating with our own MATER orbiters. With UHF RF communications, we can also transmit to the other 5 orbiters currently in the MRN, which may be necessary in order for requirement COMM-3 in table 1 to be fulfilled and thus the RF link budget in table 2 and 3 will be used.

2. Orbiter-DSN Link

The transmission downlink and uplink in the orbiter- DSN link varies significantly in distance, with the maximum distance being 400e6 km. Our absolute minimum distance being approximately 55e6 km. [8]. For the communications link to successfully close between MATER orbiters and the DSN, we based our orbiter design on the ESA Trace Gas Orbiter ([3]), and used an 8.4 GHz HGA with a diameter of 2.5 m, and a 70 W TWTA to transmit power, resulting in a transmit antenna gain of 46.8 dBi. Using a system noise temperature of 222.2 K as found for X-bands ([4]) we get the results in table 4. For uplink to a MATER orbiter from Earth, we use the 20kW 32-m HGA from the DSN. The resulting uplink results are shown in table 5.(Note: Free space loss is the same)

Parameter	Short Distance	Nominal	Long Distance
Distance (km)	55e6	225e6	400e6
Free space loss (dB)	-265.7406227	-277.9770193	-282.9745688
Received Power (dBW)	-133.9757155	-146.2121121	-151.2096615
Received E_b/N_0 (dB)	18.20582716	17.31763226	16.89522908
BER (BPSK)	6.38E-31	1.45E-25	2.26E-23
Data rate (kbps)	1037.063408	61.96773945	19.60698006

Table 4 Orbiter to DSN Downlink

Parameter	Short Distance	Nominal	Long Distance
Distance (km)	55e6	225e6	400e6
Received Power (dBW)	-113.5163959	-125.7527925	-130.750342
Received E_b/N_0 (dB)	19.39716378	18.73919605	18.43889966
BER (BPSK)	4.76E-40	1.06E-34	1.62E-32
Data rate (kbps)	127042.7275	7591.195076	2401.901567

Table 5 DSN to Orbiter Uplink

From table 5, we succeed in maintaining performance requirements set in COMM-1 and COMM-2 for uplink with the DSN, even exceeding 120 Mbps for the short distance case. However, table 4 shows us that we are not meeting our 100 kbps requirement for the nominal and long distance cases.

RF vs Optical Link Trade Study In order to reach 100 kbps on our orbiter to Earth downlink, we could implement one of two solutions to fulfill requirements. Firstly, we could use lasercom on our MATER orbiters for specifically the downlink case. Here we could use parameters from the Psyche mission to reach data rates of up to 8.3 Mbps.[6] For our trade study, we used a laser transmit power of 5W at wavelength of 1550nm and assuming a receiving telescope aperture diameter of 5m (Hale Caltech Telescope) [6], and a divergence of 0.1 mrad. In order to minimize the overall shot noise in the optic system, we would use an SNSPD, which would provided a very low noise-equivalent power (NEP) on the range of $10e-19$ W/Hz-2. [9]. This would result in an E_b/N_0 of 25.32 dB, BER of $2.94E-24$, and a real data rate of 16.8 Mbps. While this is great in terms of performance, there are still some trade-offs. Implementing this system would increase the orbiter payload by 29 kg, and pointing errors would need to be very small. The MATER orbiter system complexity would also increase with an optical package as such, not to mention the requirement for cryogen cooling on the SNSPD. [9] Instead, to fulfill COMM-2 requirements, we can hop relay information to the other MRN orbiters with higher data rate at the nominal and long distance parameters. This prevents further system complexity and follows the Proximity-1 protocol. (For the math in this section, please view the appendix for link budget data sheet and divergence vs received power plots)

B. MCL-Orbiter Link Specifications -JM

1. Hardware and Optical Link Equipment

Our 3-orbiter system will utilize flight heritage: each orbiter will use hardware and optical link equipment previously used on ESA and NASA orbiters for the Mars Relay Network. For each orbiter's link to our surface lander, we will use twin Electra UHF transceiver radios, which are currently in use by 3 orbiters of NASA's Mars Relay Network. ([3],[2]) Each orbiter will also be equipped with a low-gain UHF antenna for this link.

Our selection of the Electra UHF radios is motivated by flight heritage and the services they support. In both the EDL and Surface phases of the mission, these radios offer critical communication services. Throughout both stages, forward and return link communications, orbit determination, tracking during events such as EDL, and a basic time service for event timing and reconstruction, clock correlation, and 1-way ranging are enabled by Electra radios. During the Surface phase, specifically, surface asset position determination is also available, which is useful in determining the position of the lander. ([2])

The hardware specifications of the Electra radio and its antenna can be found in the table below (Table 6).

SWaP	Electra (transceiver, antenna, cabling)	Payload low-gain	Transceiver	Low-Gain Antenna
Size [cm]	–		21.7 l x 20.1 w x 12.2 h	26.1 dia x 30.5 h
Mass [kg]	6.5		–	–
DC Power [W]	–		77.8 W max	–

Table 6 Electra Payload Specifications

Our anticipated failure modes for orbiter hardware are summarized in the following table (Table 7).

Failure Mode	Description
Radio Malfunctions	A radio malfunctions or a link cannot otherwise be established.
Electromagnetic Interference (EMI) Issues	EM generation by other subsystems may degrade Electra relay communications at relay frequencies.

Electromagnetic Compatibility (EMC) Issues	Electronic devices are causing or being affected by EMI from other devices, which would degrade our orbiter's relay link.
Bus Failure	A component of the communications subsystem fails.

Table 7 Anticipated Orbiter Hardware Failure Modes

The redundancy plans to address the outlined failure modes are summarized in Table 8 below.

Failure Mode	Redundancy Plan
Radio Malfunctions	Each orbiter will be equipped with a back-up radio.
Electromagnetic Interference (EMI) Issues	Equip orbiter with EMI/EMC specifications as a guideline for allowable electric field strengths from other subsystems. If limits are exceeded, offending instruments may potentially have to be powered off during relay periods.
Electromagnetic Compatibility (EMC) Issues	Same as EMI redundancy plan above.
Bus Failure	Cross-strapped bus topology allows for continued communication because it will allow for data to be transmitted over the other bus lines.

Table 8 Anticipated Orbiter Hardware Redundancy Plan

2. Software and Data Handling

To handle data properly, our subsystem will work with the command and data handling subsystem. Each orbiter will have the following interface between its COMM subsystem and CDH subsystem:

- **Command and Control:** The CCSDS Proximity-1 Space Link Protocol is a protocol for a short-range, bi-directional, fixed or mobile radio link. Previous Mars Relay Network Orbiters equipped with the same Electra radio, such as ESA TGO, NASA MAVEN, and NASA MRO, have used this protocol.
- **CDH Interface:** Our interface will use a redundant, cross-strapped MIL-STD-1553B interface, where two or more bus lines are connected at a central point, allowing for redundancy and increased bus length.
- **Proximity link data:** Our orbiters will use a Forward and Return protocol for handling data. Redundant, cross-strapped High-Speed, Low-Voltage Differential Signaling (HS-LVDS) will be used for this.

Like with hardware, these selections are based on flight heritage, namely the MRN orbiters such as the ESA TGO and the NASA MRO. ([10], [11])

C. Orbiter-DSN Link Specifications - JM

1. Hardware and Optical Link Equipment

Each orbiter will be equipped with an X-band capable radio, a 2.5 m high-gain antenna, and a 70 W Traveling Wave Tube Amplifier (TWTA) as seen on the ESA Trace Gas Orbiter (TGO) ([10]). No major modifications will be made to the heritage radio system, as we anticipate the need for the same services that this radio provided for the ESA TGO.

The hardware specifications for the X-band radio system on each orbiter are outlined in the following table (Table 9).

SWaP	X-band Radio System	High-Gain Antenna	Low-Gain Antenna	X-band TWTA
Size [cm]	–	250 cm dia	–	–
Mass [kg]	–	17.5	–	–
DC Power [W]	–	–	–	70 W

Table 9 Orbiter X-Band Radio Specifications

Our anticipated failure modes are outlined in the table below (Table 10).

Failure Mode	Description
Component Failures	Any component of the radio system malfunctions or fails, leading to a degraded signal or complete radio failure.
Interference	Other radio signals, weather phenomena on Earth, and other electronic devices may interfere with the radio and degrade signals.
Environmental Conditions	Rain, fog, or other atmospheric conditions on Earth can affect radio performance.

Table 10 Anticipated Orbiter-DSN Hardware Failure Modes

Given that our primary failure modes concern our X-band radio, our main redundancy plan to address these failure modes is to have a backup link from the MCL to the DSN. This link is also an X-band link and allows a direct relay between the MCL on Mars and the DSN on Earth. This link is further detailed in our Backup Communications Design found in the next section.

2. Software and Data Handling

Following flight heritage from the Mars Reconnaissance Orbiter (MRO), we will follow a forward and return protocol to handle incoming and outgoing data. ([11]) Data from DSN will be stored by the orbiter until it can be transmitted by the Electra radio onboard at overflight time. Then, on the return link to DSN, data from surface assets will be downlinked twice at the earliest opportunity.

D. Surface Communication Network - JM

1. Hardware

To handle communication between the mission’s surface assets, we will use a mesh communication network. To enable this network, mesh radios from Doodle Labs, which are radios tested by NASA for mesh communication networks, will be utilized. This hardware selection is also based on NASA’s upcoming CADRE mission, which utilizes mesh radios to support communication between its multiple surface agents (in this case, four-wheeled autonomous A-PUFFER robots) and its lander on the Moon. ([1], [12])

2. Software and Data Handling

A wireless mesh communication protocol between the MCL, rovers, and helicopter will be used to handle the communication traffic on the surface. Based on NASA studies, a TDMA-based, peer-to-peer topology would be a suitable option for this mesh communication. This topology means that there will be no master or central node and allows for easy removal or addition of communication nodes. This protocol is also hardware-agnostic, which allows for flexibility with chosen hardware and allows us to avoid a single point of failure. ([13], [14])

To handle urgent situations or emergencies on the surface, our communication system will use the MCL X-band radio to communicate directly to Earth. However, the specific implementation of this protocol will need to be further fleshed out with CDH down the line.

IV. Backup Communications Design from Surface Lander to DSN

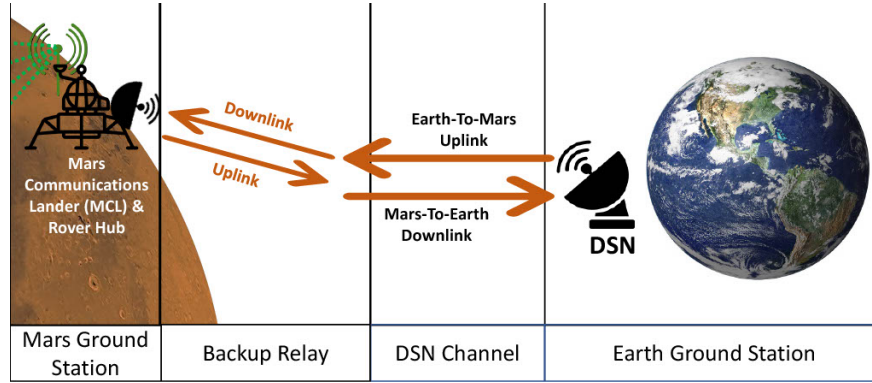


Fig. 4 Overview of Backup Communications from MCL to DSN

A. Link Budget - TH

In the instance of an orbiter communications blackout (i.e. no relays can be established with any of our own orbiters or MRN orbiters) the MCL shall communicate with the DSN directly using a HGA X-Band antenna. We chose a 25 dBi transmission gain for our antenna, comparable to that of the Curiosity rover. [3] However, due to high total system noise, our data rate may only reach up to 6 kbps when Mars and Earth are at their closest. Uplink from the DSN to the lander antenna ranges between 12 to 671 kbps, with the lowest kbps being at the largest distance away. (Check appendix for math and spreadsheet) In this case, the COMM-2 mission requirements would not be met for the MCL to DSN downlink, but it would be able to provide reasonable data transfer rates for helicopter scientific data as opposed to offering high speed sensor updates.

B. Lander Specifications - JM

1. Hardware and Optical Link Equipment

For a backup relay to DSN, the MCL will be equipped with an X-band radio system, as seen on the Spirit and Opportunity rovers. The modification made to this heritage system is a larger High Gain Antenna: the lander will be equipped with a 30 cm diameter HGA as opposed to the original 28 cm diameter antenna. ([15]) The table below (Table 11) outlines the specifications of our X-band radio payload along with its antennas. This link serves as the redundancy plan for our Mars-Earth link in the event of failure for our Orbiter-DSN relay link.

SWaP	X-band Radio System (SDST, SSPA, Coupler, Switches)	High-Gain Antenna	Low-Gain Antenna
Size [cm]	–	30 cm dia	60.2 x 3.1
Mass [kg]	5.367	1.4	0.775
DC Power [W]	71.8	–	–

Table 11 Lander X-Band Radio Specifications

2. Software and Backup Protocol

The X-band radio system will interface with the MCL's Electra radio and avionics components. The main interface will be a telecommunications card (MTIF card) that is responsible for all data transfer functions. Key characteristics of the MCL-DSN relay link, such as data rate, frame size, and encoding, will be determined by either the small deep space transponder (SDST) of the X-band radio system or the MTIF card. ([15])

V. Conclusion-TH

A. Future Work

To fully confirm that our COMM-3 requirement is fulfilled, a more in depth analysis of solar conjunctions and orbiter passes is needed. Additionally, in order to better accommodate our orbiter to Earth downlink data rates, a resizing and re-analysis of the orbiter X-Band HGA may be required. A better backup lander-DSN relay should also be studied to provide more appreciable data rates.

B. System Overview

From current findings and analysis, our current relay architecture meets COMM-1 and COMM-2 requirements. Further analysis is required to confirm success with our COMM-3 requirement. The current relay architecture relies most heavily on the Electra UHF transceiver and RF radios for half duplex communication relays using BPSK modulation. Our orbiters will also be equipped with a high-gain X-band antenna, akin to that of the ESA ExoMars Trace Gas Orbiter (2016). A mesh network will be used on the Martian surface and allow rovers, the propellant factory, and the helicopter to forward and store data to the MCL.

Appendix

C. Link Budget Calculations & Key Equations-TH

1. Noise Power Density

$$N_0 = kT \quad [\text{W/Hz}] \quad (5)$$

Where:

- N_0 is the noise power density
- $k = 1.38 \times 10^{-23} \text{ J/K}$ (Boltzmann constant)
- T is the equivalent noise temperature in kelvin (K)

2. Total System Noise Temperature

$$T_{\text{sys}} = T_{\text{ant}} + T_{\text{amp}} \quad [\text{K}] \quad (6)$$

Where:

- $T_{\text{ant}} = T_{\text{sky}} + T_{\text{loss}}$
- $T_{\text{amp}} = \left(10^{\frac{NF}{10}} - 1\right) T_0$ where NF is the noise figure in dB and T_0 is the reference temperature (typically 290 K for Earth and 210 K for Mars[5])

3. Friis Transmission Equation (Linear Form)

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad (7)$$

Where:

- P_r is received power
- P_t is transmitted power
- G_t, G_r are transmitter and receiver antenna gains (linear scale)
- λ is the wavelength
- R is the distance between antennas

4. Power Received in Decibels

$$P_r [\text{dBW}] = P_t [\text{dBW}] + G_t [\text{dBi}] + G_r [\text{dBi}] - L_{\text{fs}} [\text{dB}] \quad (8)$$

5. Free Space Path Loss (FSPL)

$$L_{\text{fs}} [\text{dB}] = 20 \log_{10}(R) + 20 \log_{10}(f) - 147.55 \quad (9)$$

Where:

- R is the distance in meters
- f is the frequency in Hz

6. Antenna Gain (Transmitter or Receiver)

In linear form (based on effective aperture):

$$G = \frac{4\pi A_e}{\lambda^2} \quad (10)$$

Or in decibels:

$$G [\text{dB}] = 10 \log_{10} \left(\frac{4\pi A_e}{\lambda^2} \right) \quad (11)$$

Where A_e is the effective aperture.

8. Bit Energy-to-Noise Density Ratio

$$\frac{E_b}{N_0} = \frac{P_r}{R_b N_0} \quad (12)$$

Where:

- E_b is the energy per bit
- N_0 is the noise power spectral density (W/Hz)
- P_r is the received power (W)
- R_b is the bit rate (bps)

D. Link Budget Spreadsheet

E. Python Script Plots for Lasercom Received Power

The following are plots that indicate the received power at different divergences for uplink and downlink. different elevation angles are considered, but the link budget spreadsheet uses NADIR pointing (90 degrees). The values used in the link budget spreadsheet are received power at approximately 0.1 mrad.

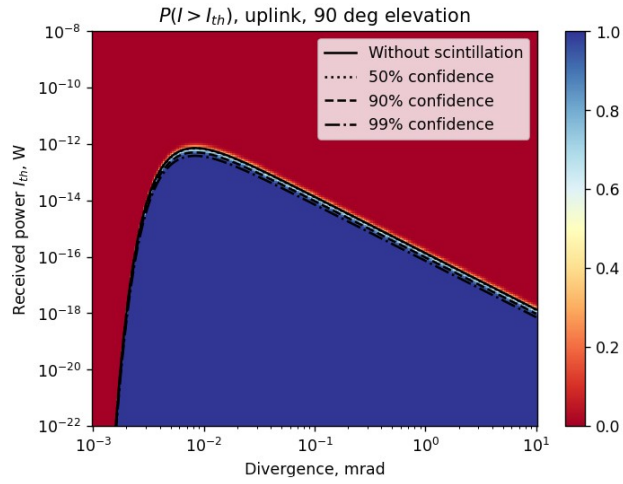


Fig. 5 Low Pointing Error Received Power- Orbiter to Earth Downlink for Lasercom

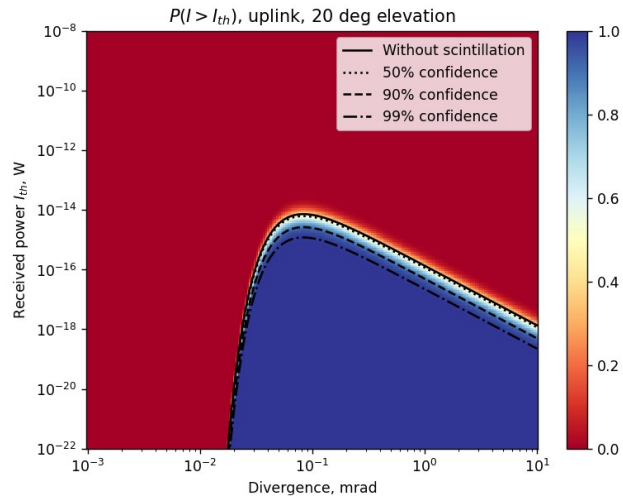


Fig. 6 20 Degree Elevation- Orbiter to Earth Downlink for Lasercom

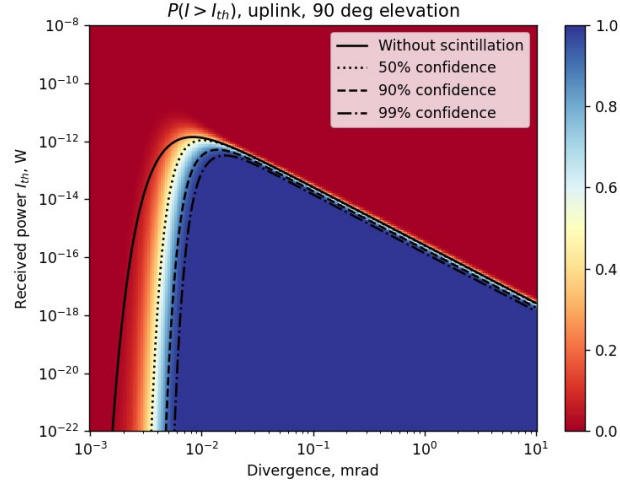


Fig. 7 Received Power- Earth to Orbiter Uplink for Lasercom

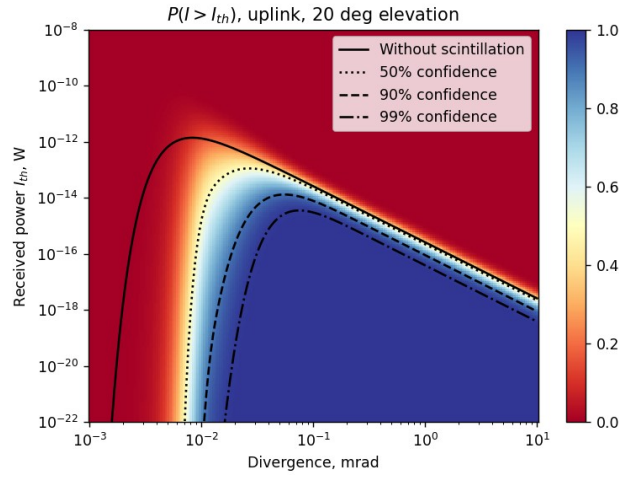


Fig. 8 20 Degree Elevation- Earth to Orbiter Uplink for Lasercom

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