**Communication and Power Trade Study**

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# Acronyms and Nomenclature

DSN – Deep Space Network

BWG – Beam Wave Guide

BER – Bit Error Rate

FOM – Figures of Merit

DOD – Depth of Discharge

BOL – Beginning of Life

EOL – End of Life

RTG – Radioisotope Thermoelectric Generator

HGA – High gain antenna

MGA – Medium gain antenna

LGA – Low gain antenna

Mbps – Megabits per second

LEO – Low Earth Orbit

# Executive Summary

This report covers the Power and Communication Subsystems for a mission to Mars and the analysis to help verify the feasibility of the mission. The mission calls for an orbiter satellite along with a vehicle that lands on the surface, both of which need to collect scientific data and transmit the results back to Earth. A series of reasonable assumptions and careful analysis were used to first find the communication equipment required to transmit the data back to Earth with a high reliability. Since scientific return is the highest priority in the FOM, a high emphasis was put on the equipment used to transfer the data back to Earth. The next step was to determine the communication setup for the orbiter-lander combination, which did not require significantly more equipment to communicate, and fit well under the budgeted power and mass restraints. After the communication power requirement was found, a series of power modes could be established in order to mitigate the power needed to operate the orbiter. Since all of the equipment does not need to be on all the time, significant power saving can be found this way, thus reducing mass. Once all the power requirements for communications were set, the battery and solar array could be sized to appropriately power the orbiter until the end of life of the mission. Once all the power masses were calculated, a Monte Carlo analysis could be run on the communication system to verify the confidence level of the system if a few variables were changed. A high level of confidence was found for this mission setup. The final mass of the system allowed for a lander that is 60% of the mass of the whole system dry mass, which allows for more science to be carried out on the surface of Mars.

# Overview of approach

The first step in this procedure was to identify all constants in both the power and communication equations and verify that all numbers are within a reasonable range. All of the appropriate equations that were needed to solve the communication and power problems were then gathered, and all possible variables that need to be solved for were identified. The orbital mechanics study was then used when calculating power requirements to properly size the battery. Design variables were all identified and course of action to take on each variable was determined using a combination of the FOM and other reasonable factors. More detail on how this problem was approached can be found in the design variables section of this document. The next step was to solve for the required power for signal transmission from Mars and minimize the mass for the orbiter using common minimizing techniques for the appropriate variables. Once mass of the orbiter is at a minimum value, the Monte Carlos simulation was ran to verify that the transmitting signal will be able to be received with a high level of confidence. Any remaining mass left in the mass budget was used for the mass of the lander.

# Technical Analysis

## Communication design analysis

In this trade study, maximum tolerances are used to calculate the needed equipment for communication and power. The maximum distance from the Earth to Mars will be 2.52 AUs away, which will only happen a fraction of the time, but since the Figures of Merit put scientific data return as the highest priority, the sizing of the communication system will use this distance for calculations. Communication with Earth from the orbiter will need to be through the Deep Space Network, which restricts what frequencies that are used. There is also another restriction which states that all future space missions will not be allowed to use the S-Band carrier frequencies, which forces this craft to use X-band or Ka-band. For this mission, since the transfer bitrate is low, X-band frequencies will work, and is preferred to the higher frequencies, since they are only allowed with the 34m DSN dishes. These variables allow for the use of the 70m DSN dishes with frequencies between 7.142 and 7.235 GHz for uplink and 8.4 and 8.5 GHz for downlink. These frequencies are more than enough to support a bitrate of 256 kbps to Earth, since typical bandwidth for this carrier frequency is several Mbps according to the new SMAD reference. Since we have the ability to transfer several time faster than the orbiter-Earth maximum speed required and the fact that this data isn’t just video and is presumably important scientific data, the BER that can be tolerated can be up to 10^-6. Since there is such a high priority on scientific data and reliability in the figures of merit, there is a need to push the required Eb/No down to the lowest possible for the data transmission, by using QPSK at a coded rate of 0.8, the required Eb/No can be pushed down to 3.9 dB according to Figure 16-17 in the new SMAD reference. In order to account for small misalignments in the attitude, a pointing error of 0.25 degrees will be used, which will provide higher reliability for the data transmission to Earth by providing a relatively large window of rotation. The 0.25 degree pointing error is due to the fact that any attitude designer will not be able to exactly point the dish toward earth, so by giving the attitude systems designer some room to work with, this will help reduce the impact of pointing errors. Estimating the implementation loss and margin for the communication system, a value of 3 dB and 1.95 dB were used, respectively. Using the maximum typical ranges in each of the previous values provides for a more robust communication system. One of the last issues to consider when looking at communication with Earth is the atmospheric loss that can attribute to the attenuation of the signal back to earth. The atmospheric loss falls under -7 dB 99.8% of the time, while a loss of -2 dB is a clear day according to the data collected from the new SMAD. Since getting the scientific data transferred back to earth reliably is of such importance, a loss of -7 dB should be used when sizing the equipment. The last design variable that should be considered is the size of the high gain antenna; this will directly affect mass of the orbiter, but it can also change the gain significantly. This was also considered when sizing the batteries and solar arrays in order to minimize the mass of the system. For the Orbiter-Lander communication system, a dipole-to-dipole antenna setup was used to reduce pointing errors. The atmospheric losses on Mars were found to be sub -1dB according to NASA’s TRS document. A frequency of 250 MHz was used since it fell in the UHF region and since it has a high enough carrier frequency to transmit the required data in the specified bandwidth. A higher EbNo value was needed because of the low processing power and low gain antenna on-board the orbiter. The space loss was calculated based on the furthest the satellite can be from the lander, so the apoapsis was a good approximation.

|  |  |  |
| --- | --- | --- |
|  | |  |
| Term |  | Value |
| Frequency |  | 8.45E+09 Hz |
| Bandwidth |  | 2.56E+05 Hz |
| Transmitting antenna gain | | 44.68 dB |
| Receiving antenna gain | | 74.30 dB |
| Space loss |  | -282.51 dB |
| Atmospheric Loss | | -7.00 dB |
| Input power |  | 105.18 W |
| Received power | | 2.741E-16 W |
| Eb/No |  | 3.9 dB |
| Table 1: Orbiter-Earth Communication |  |  |

|  |  |  |
| --- | --- | --- |
|  | |  |
| Term |  | Value |
| Frequency |  | 2.50E+08 Hz |
| Bandwidth |  | 1.28E+05 Hz |
| Transmitting antenna gain | | 1.64 dB |
| Receiving antenna gain | | 1.64 dB |
| Space loss |  | -111.67 dB |
| Atmosphereic Loss | | -0.30 dB |
| Input power |  | 52.34 W |
| Received power | | 2.370E-05 W |
| Eb/No |  | 20.45 dB |
| Table 2: Orbiter-Lander Communication |  |  |

In the trade study, a discussion occurred questioning the effects of increasing the required orbiter-Earth communication link bandwidth to 1 Mbps. Since this mission used the X-band frequency, the carrier frequency is high enough to transmit this signal reliably. The predominant change required would be a need in power increase, by about 4 times, in order to transmit the signal. This will either require a larger battery and solar panels, or a larger dish on the orbiter. Either way, this translates into more mass required.

## Power design analysis

When considering design variables for the power subsystem, many options will affect the mass of the overall orbiter. First when sizing the batteries, a battery that has heritage and is known to be reliable is the important for this mission. A Li-Ion battery with a low enough DOD to last for 4 years can be used. By using this type of battery, it will allow for a reduced mass in the obiter. Unfortunately, the Li-Ion battery does not have as much heritage as other batteries, but since mass needs to be minimized and Li-Ion has seen several space flights over the course of a few years, Li-Ion batteries are the better choice. Since the orbit will only be in the shadow 14% of the time at maximum, the batteries will be sized with that in mind. The size of the batteries will also need to take into account the power draw from the system at any given time. There will need to be three different modes of operation that the satellite can operate in, which will reduce the maximum power draw on the power subsystem. Allowing for different modes will reduce the overall mass of the batteries and solar panels. Since the mission is relatively close to the sun, solar panels can be used effectively and with less mass than using RTGs, so they were chosen. Ultra Triple Junction GaInP2/GaAs/Ge solar panels with 330 W/m^2 BOL performance at 1 AU will be used for the mission. These panels provide high efficiency and reliability while keeping the mass density relatively low with a mass density of around 2.8 kg/m^2 including the supporting structure. When calculating the BOL performance at mars, an assumption for degradation rate of 2.75% for the solar panels was used. This number is an estimate found in the new SMAD book in section 21.2 for typical LEO orbits, although this is not a LEO orbit no other meaningful information for solar panel degradation was found for deep space satellites, so this assumption was used. The BOL performance at Mars was found to be around 50.35 W/m^2, which is nearly 1/6th the BOL performance at 1 AU. Since the mission is only 4 years long, the EOL performance at Mars is 45.04 W/m^2. The solar panels were sized to provide enough power until the end of life and using a Power Management and Distribution strategy to minimize the mass of the solar panels and batteries. Some time assumptions needed to be used for this calculation, so the time spent communicating with Earth was set to five hours a day, the time collecting the orbiter-based scientific data was set to five hours a day, and the rest of the time the orbiter was spent idling.

|  |  |
| --- | --- |
|  |  |
| Solar array element | Value |
| Solar array Type | Ultra Triple Junction GaInP2/GaAs/Ge |
| BOL performance at 1 AU | 330.00 W/m^2 |
| BOL performance at Mars | 50.35 W/m^2 |
| Areal density | 2.80 kg/m^2 |
| EOL performance at Mars | 45.04 W/m^2 |
| Anticipated degradation/year | 2.75% |
| Total Power supplied at EOL | 201.45 W |
| Area of solar arrays | 5.99 m^2 |
| Mass of solar arrays | 16.77 kg |
| Table 3: Solar array information |  |

|  |  |
| --- | --- |
|  |  |
| Battery element | Value |
| Battery type | Li-Ion |
| Total battery capacity | 2800 |
| Depth-of-discharge | 30.00% |
| Specific energy density | 110 W-hr/kg |
| Mass of the batteries | 25.45 kg |
| Table 4: Battery information |  |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | |  | |
| Power mode |  | | Power | |
| Communicating with Earth |  | | 269.7 W | |
| Collecting Orbiter-based scientific data | | 239.0 W | |
| Idle orbiter mode |  | | 101.0 W | |
| Table 5: Power modes for orbiter |  | |  | |

# Concept of Operations

## Orbiter-Lander communication

1. The orbiter periodically checks if orbiter can be reached.
2. If the orbiter can reach the lander, the orbiter transmits a message to the lander asking if any new data has been collected and needs to be transmitted. If so, the orbiter and lander prepare for data communication.
3. Data is transmitted to the orbiter and saved to a storage device for future transmission to Earth.
4. Once data has finished transmitting, the orbiter validates data transferred and if it is valid, does any post processing needed.
5. If the transmitted data was corrupt, repeat from step 1.
6. If the transmitted data was not corrupt, then signal to lander that the data collected earlier can be erased if needed.

## Orbiter-Earth communication

1. The orbiter periodically checks if link to DSN is established. If so, start transmitting collected data.
2. Once the transmission of data has been sent to Earth, orbiter checks if data is verified and if orbiter storage devices can be cleared for overwriting.
3. If the orbiter gets a verification message, the tapes are set to overwrite the portion of data that was verified.
4. If the orbiter does not get the verification message, the data is saved and the orbiter restarts at step 1.

# Output metrics (min/max)

The mass of the orbiter needed to be minimized, which in turn maximized the lander’s mass. Several options, many of which are coupled, needed to be taken into account in order to minimize the orbiters mass. These options include the mass and or size of the orbiters HGA dish. Although there is a need to increase the gain of the of the transmitting signal, this comes at a cost of extra mass, space, and possibly complexity. The other option would be to increase the available power in the system by increasing the size of the solar panels and battery capacity, this would allow for a higher-powered transmitter. There is a coupling between these two equations that need to have an overall minimum mass.

# Mass Properties

The mass was calculated using the overall mass of the power and communication equipment covered in this document, as well as other given pieces of information. The mass of the lander was calculated by taking the remaining mass not used by the science payload, fuel, or orbiter bus. The power mass was calculated by summing the solar panel, battery, and extra cable (10 kg) masses. The Communication mass was calculated by adding all of the communication equipment listed in the table 6.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |
| Qty | Equipment | Power | Total Power | Unit Mass | Total Mass | Notes |
| 1 | X-band High gain antenna | 0.00 W | 0.00 W | 9.00 kg | 9.00 kg | 2.5 m diameter |
| 1 | X-band Medium gain antenna | 0.00 W | 0.00 W | 1.50 kg | 1.50 kg | 0.3m waveguide horn with 5 deg beamwith (3dB) |
| 2 | UHF Low gain antenna | 0.00 W | 0.00 W | 0.70 kg | 1.40 kg | New SMAD 21-8 |
| 2 | Electra UHF transeiver | 14.00 W | 28.00 W | 4.90 kg | 9.80 kg | <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/7832/1/03-2150.pdf> |
| 2 | X-band TWTA | 150.00 W | 150.00 W | 0.97 kg | 1.93 kg | <http://www2.l-3com.com/eti/downloads/x_quad.pdf> |
| 2 | X-band SDST transponder | 14.00 W | 28.00 W | 3.00 kg | 6.00 kg | <http://descanso.jpl.nasa.gov/DPSummary/090924dawn-FinalCorrex--update5G.pdf> |
| 2 | X-band diplexer | 0.00 W | 0.00 W | 0.60 kg | 1.20 kg | New SMAD 21-8 |
| All | All Cables | 0.00 W | 0.00 W | 10.00 kg | 20.00 kg | Need cables for UHF and x-band comm |
| 2 | Ultrastable oscillator | 2.50 W | 5.00 W | 1.30 kg | 2.60 kg | New SMAD 21-8 |
|  |  |  |  |  |  |  |

Table 6: Communication equipment list

Using the information provided, a mass table for the mission can be provided below:

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| Element |  | Level 2 | Level 1 |
| 1.0 Total Payload During Earth Escape | |  | 1352 kg |
| 1.1 Orbiter Science Payload | | 73 kg |  |
| 1.2 Lander Capsule |  | 1279 kg |  |
| 2.0 Orbiter Bus (dry) |  |  | 708 kg |
| 2.1 Propulsion |  | 174 kg |  |
| 2.2 ADCS |  | 59 kg |  |
| 2.3 Communication |  | 32 kg |  |
| 2.4 C&DH |  | 63 kg |  |
| 2.5 Power |  | 52 kg |  |
| 2.6 Structure |  | 267 kg |  |
| 2.7 Pyro & Cabling |  | 61 kg |  |
| 3.0 Total System Dry Mass |  |  | 2060 kg |
| 4.0 Consumables |  |  | 0 kg |
| 5.0 Propellant |  |  | 1440 kg |
| 6.0 Total System Loaded Mass | |  | 3500 kg |
| Table 7: Mass properties for Mars mission |  |  |  |

# Design alternatives for subsystem choices

Some design alternatives include choosing a different atmospheric loss value, which would allow for communication only a fraction of the time based on weather. The lack of power transmitted could be compensated through having the orbiter transmit until it received a confirmation that the signal was received by the DSN. Allowing this would reduce the overall power needed to transmit a message, but could cost more power in storage and would have a higher chance to lose data. Another alternative could be a different battery type, like Ni-Cd or Ni-H2. These batteries can still be used for the mission, but were not chosen because of their lower energy densities and energy efficiencies. The two advantages that Ni-H2 has over Li-Ion in terms of this mission are the cycle life and heritage, but over the duration of this mission, the Li-Ion batteries can be used in such a way to reduce the chance of failure. As far as power goes, the last consideration for an alternative was the choice between Solar panels and RTGs for a main power source. Since Mars is only 1.5 AUs away from the Sun on average, it doesn’t make since to use RTGs for the orbiter since the mass per watt will be higher at that distance. RTGs are also very expensive and hard to acquire, so solar panels are the clear choice. Now for the communication, a BER of 10^-6 was chosen because of previous missions to mars that had similar data transfer rates, and the fact that a large majority of the data that is being transferred looks to like images. These bit rate errors are perfectly tolerable in this situation. If we wanted to be more careful and be sure to get less of an bit error rate, a BER of 10^-11 could be used, but this would push the Eb/No requirements to higher number. The last alternative that could be used is to switch communication frequencies to the Ka-Band. This would allow for a higher bandwidth and more data to be transferred back to earth, but would require a higher power requirement to overcome space and atmospheric losses.

# Discussion of Figures of Merit

When looking at the figures of merit, it deems scientific data return as the highest priority, which is the basis for many of the choices. Secondary importance was placed on choosing equipment with more heritage and high reliability, which appears to go almost hand-in-hand with the concept of science return. With some items, such as the battery, performance was worth the risks and equipment was chosen based off other factors. This is especially true if the risks can be mitigated using parallel and redundant setups. Schedules were not taken into consideration, since this was not high on the list. The only option affected due to cost was the solar panels, but reliability or scientific return did not suffer because of this.

# Monte Carlo Analysis

The Monte Carlo simulation that was run for this trade study varied atmospheric loss, system noise temperature, and antenna pointing error. This provides a confidence level with the parameters that have been chosen for this mission. By fluctuating the following variables, a confidence level of 99.8% was found by the simulation.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| Variable | Distribution | Nominal | 1 sigma or Min Max |
| System Noise Temperature | Uniform | 25 K | [18 40] K |
| Atmospheric Loss | Uniform | -4.5 dB | [-2 -9] dB |
| Antenna Pointing Error | Normal | 0 deg | 0.75 deg |
| Table 8: Monte Carlo Analysis |  |  |  |

The following Probability Density Function and Cumulative Density Function in figures one and two, respectively, show the analysis run on the mission parameters.

Figure 1: Cumulative Probability Function for Monte Carlo simulation

Figure 2: Probability Density Function for Monte Carlo simulation

# Orbital Mechanics study

For this type of a mission, the parameters for the orbit around Mars are set, a periapsis of 4990 km and an eccentricity of 0.76. The mission will need to span four years, which will have Mars rotate about the Sun at least twice over the mission. With this in mind and the fact that this trade study only focuses on the power and communication, the orbit only affects how long the craft will be in the sunlight at any given time. In order to cover all situations, the battery will need to be sized for the worst possible orbit, with respect to time that the sun is in view. There are other ways to account for this, like shutting off communication with the lander for a period of time, but since the Figures of Merit determine that Science return to be the highest priority, this is not a reasonable option. Now that the established course of action would be to size the battery appropriately, the longest time the orbiter will be in shadow is when the apoapsis point is exactly in the middle of the shadow cast by Mars. Since the orbit is relatively far from the sun, the shadow that is cast from Mars can be simplified to be a column instead of a cone shape. By using small angle approximations to get a true anomaly angle of around five degrees, we can plug this into the equation to get eccentric anomaly, and then plugging in the result into Kepler’s equation to get the mean anomaly. A mean anomaly of 35675 was found, and when divided by the mean motion of the orbit the time spent in the shadow can be found. When using the simplifications and the properties of the orbit, the worst-case scenario for time spent in a shadow for this orbiter is 14.4% of the orbit, or around 3.6 hours in a 25-hour orbit. The only other aspect of the orbit that can affect this trade study is the communication, which is figured into other constraints, like the minimum transfer rate, so we will not go into any further detail on this. This orbital period was probably chosen to closely match the spin rate of Mars about its axis, since the orbit period is so close to that of Mars.

# Conclusions

In conclusion, this mission seems to be viable from the standpoint of communication and power with the help of a few reasonable assumptions that other designers can work around. If a certain value was not quite able to perform as well as the other designers wanted, then another analysis could be run to see if the mission were really viable. The mass of the batteries and solar panels were kept to a minimum by using a combination of newer technology, power modes, and choices used for communication. The Communication equipment that was needed for this mission could have been modified to lower mass by removing redundant equipment, but this is necessary to provide a higher chance of mission success. Using a Monte Carlo simulation, a high confidence was found when varying the specified variables, which further increases the probability of mission success. By reducing the masses used for the orbiter, a more massive lander can be launched to collect more data on the surface.

# References

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