Politecnico di Milano

`Third Assignment`

Space Systems Engineering and Operations

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Change log	
§1	pp. 1: more details about the frequency selection
§2	Fig.1 caption revised
§3.2	pp. 5: added explanation about the Phased Array Antenna gain estimation.
§3.3	pp. 5: better justification for the link budget margin, for the zero peaks the procedure in the computation of the link budget in Fig.2a and Fig.2b
§3.3	pp. 6: added analysis on the bandwidth
§3.4	removed

1 TTMTC Architecture

The MESSENGER Radio Frequency (RF) telecommunications system is based upon a complete and redundant, yet not undue configuration of antennas, X-Band transponders and amplifiers both for uplink, downlink and radiometric tracking data.

The choice of frequency and band for the mission was dictated by the available operating frequencies of NASA's DSN, which can operate in the S-Band (2.1 GHz Uplink, 2.3 GHz Downlink), X-Band (7.2 GHz Uplink, 8.4 GHz Downlink), and Ka-Band (34.2 GHz Uplink, 32.0 GHz Downlink).
Given the high required datarate of the mission, the S-Band was not chosen as it could not satisfy the needs of the mission in terms of datarate and it is in general used for missions traveling to the outer planets of the Solar system thanks to the lower free space losses, or for missions where achieving a high bitrate is not a concern.
At the same time, the Ka-Band would allow for higher bandwidth and datarate but its higher frequency would lead to high free space losses due to the high maximum distances achieved during the mission's lifetime, resulting in an increased required transmitted power; it will also be very strongly affected by rain and the atmosphere.
On the other hand, the frequencies used in the X-Band, lower than the Ka-band but higher than the S-band, show a very resilient behaviour with respect to the atmospheric phenomena allowing for much reliable links, while guaranteeing sufficient datarate for the scientific needs of the mission and a manageable transmitter power request.
The final RF subsystem configuration for the antennas consists of: two High-Gain Waveguide-Based Phased Array antennas, two Medium-Gain Fanbeam Antennas, and four Hemispherical Low-Gain Antennas.

- The two identical lightweight, High-gain, Waveguide-Based Phased Arrays (18 cm x 76 cm) (PAAs) are used for high bit-rate science downlink. These electronically steerable antennas are mounted on opposite sides of the spacecraft. Rotating the probe on the Y-axis, they are able to cover each one one full hemisphere, with a scanning capability of +/- 60° in the XY-plane of the spacecraft, transmitting at 8.4 GHz. They are not used for reception.
  They are placed respectively, one on the sunshade and the other on the back of the spacecraft, one facing Sun, the other in the opposite direction eliminating the need for a heavy and complex mechanically gimbaled high-gain antenna (HGA). This system reduces the weight and improve overall high temperature resilience creating a low risk solution.

- The two Medium-Gain Fanbeam Antennas (MGA) are used for commanding and low bit-rate downlink purposes. They are characterized by a beamwidth of 90°, a transmitting frequency of 8.4 GHz and receiving one of 7.2 GHz. Each of these antennas provides coverage in diametrically opposite quadrants of the plane normal to the sunshade, full 360° coverage in this plane is accomplished by rotating the spacecraft along the Spacecraft-Sun line, allowing for constant view of Earth.

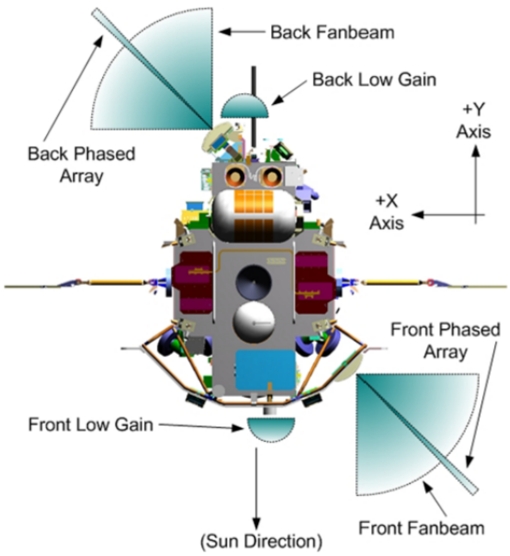
- The four hemispherical Low-Gain Antennas (LGA) are used in burn mode, emergency as well as near-Earth communications. They provide coverage in all directions, without the necessity of rotating the spacecraft in one particular direction. This aspect furthermore enables constant communications while keeping the sunshade pointed in the Sun direction. These antennas are able to transmit at 8.4 GHz and receive at 7.2 GHz.

All the selected antennas have no mechanical components, which could fail in the challenging thermal environment of Mercury. Thanks to this design choice the final configuration is able to work over a 350°C range in temperatures. Another peculiar aspect of this mission is that MESSENGER is exploring one of the inner planets of the solar system, closer than Earth to the Sun: this geometric constrain implies that the planet can be in every possible direction with respect to the spacecraft, requiring antenna coverage in all the possible directions. Furthermore the antennas are located at the ends of the shade to give a clear view to space for backside heat radiation.
The system is completed by a set of:

- General Dynamics Small Deep Space (X-band) Transponders (SDSTs) in redundant quantity. Responsible for receiving and modulating the RF uplink signal, generating and modulating the RF downlink signal, and turning around uplinked ranging and Doppler components. Each SDST's downlink signal (only one is active at any given time) is routed via a passive hybrid coupler to both solid-state power amplifiers (SSPAs).

- Solid-State Power Amplifiers (SSPAs), at least one for each phased-array antenna.
  A Solid-State solution was preferred over Travelling Wave Tube Amplifier (TWTA) because of the

reduced weight and the sufficient output power radio, despite being smaller compared with the one provided by TWTAs. The lower efficiency is not a concern for the mission, as at the distance of Mercury solar power is abundant but weight is a critical element of the design process.
Each SSPA can be in one of four modes: “distributed front,” “distributed back,” “lumped,” and “off.” The “distributed” modes of the SSPAs feed the RF downlink signal to either the front or the back PAA; the “lumped” mode of the SSPA feeds the RF downlink signal, via the two RF switch assemblies, to the fanbeam antenna or the LGAs. In the “distributed” mode, the RF signal is split in eight ways and routed to eight “stick amplifiers.” Each stick amplifier consists of a four-bit phase shifter (that controls the steering of the phased-array antenna beam), a small-signal amplifier, a driver amplifier, a power amplifier, and an isolator. The output power of each stick amplifier is approximately 34 dBm; in a distributed mode, a total of four sticks are operational per SSPA, yielding an output power of approximately 40 dBm. The “lumped” mode of the amplifier offers a 40 dBm power output for the fanbeam and low-gain antennas.



2 Mission phases and operations

Contact strategy for the MESSENGER mission is dependant on a variety of factors, such as distance between spacecraft and ground station, main disturbances, and type and rate of data to be transferred to and from the spacecraft at each mission phase.

- During the launch and early phase of mission, uplink and downlink are expected to be at least 31.25 bps and 1000 bps respectively.
  The small distance from Earth is not imposing peculiar solutions regarding the signal reception, nevertheless connection with the spacecraft cannot afford to be lost. Thus, all the four LGAs are on, providing omnidirectional coverage, being in fact less susceptible than high gain antennas to loss of signal. Moreover, data to be transmitted are expected to be less than the other phases, not rappresenting the focus of this phase.

- The cruise phase is designed for minimizing human intervention on the spacecraft control thus preserving resources. Orbit determination during the cruise phase relies primarily on the Deep Space Network (DSN) Doppler and ranging tracking data. On approach to the Venus and Mercury flybys, these data will be augmented with both DSN Delta Differential One-Way Ranging (ΔDOR) and optical navigation measurements. The solution for signal receiving and spacecraft tracking is a 34 m DSN antenna.

- In the orbital period the primary focus shifts on science data to be collected and transmitted.
  During on-orbit operations rotation about the Sun line is required to accommodate instrument viewing, since the instrument-view direction is normal to the spacecraft-Sun line and opposite the LVA direction (the direction of the main thruster, Large Velocity Adjust). Although thermal requirements are always met high-rate downlink communications are not maintained during the rotation periods. A 34 m DSN

antenna is used for the receiving with an average of 6.5 hours time window per day. Once in Mercury orbit, the RF configuration will route the uplink through the most favorable fanbeam antenna and the downlink via a phased array for high-rate data-transmission passes. LGAs are not normally on during this phase. The total amount of scientific data retrived in this phase is expected to be more than 100 Gb during the first year of operations.

- During both cruise and orbital operations, periods of solar conjunction precludes communications. Prior to these times, the spacecraft is placed into a safe-hold mode. No events requiring communications for ground commands occur during solar conjunction periods.

- In the case of an emergency communication, LGAs are used to withstand possible attitude malfunctioning, and so inaccurate pointing, granting 7.8 bps for uplink and 10 bps for downlink, while maintaining sunshade attitude requirements and 3 dB link margins. The use of LGAs in this phase requires the switch of ground station antenna from the DSN's 34 m parabolic antenna to the larger 70 m parabola, to guarantee adequate communication to and from the spacecraft.

The 34 and 70 m antennas of NASA Deep Space Network are located in Goldstone, California; Madrid, Spain; and Camberra, Australia.
These three locations are spaced almost 120° apart, and thanks to the wide field of views they can achieve, guarantee full coverage of the Messenger spacecraft with at least one antenna at every moment of the mission. High bit-rate is required by the presence of many onboard scientific instruments, as well as by the fact that information downlink is only available for a maximum of a 8-hour time window each day.
Information gathered by the instruments is stored onboard on internal memory before being downlinked at the following available opportunity, furthermore a data prioritization scheme will assist in managing the downlink phase. Moreover, control signals must be considered as important as scientific data retrieval, thanks to the system configuration, described above, operators are able to send commands at 7.8 to 500 bits per second.
Average datarate over the first year of the mission is in the order of 35 MB/day.

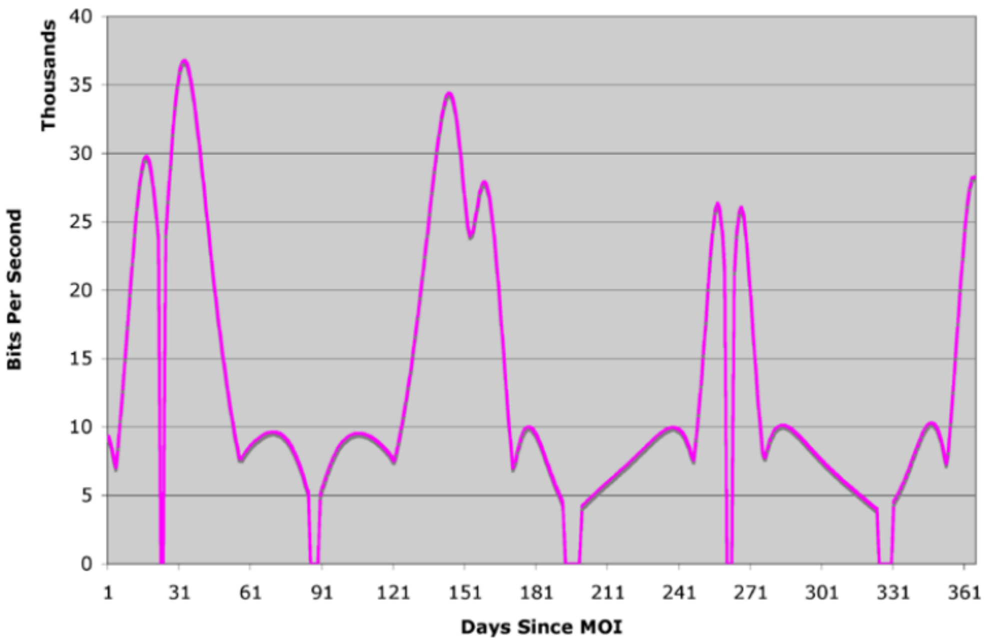


Figure 1: Downlink datarate: peaks in the curve correspond points near Mercury inferior conjunctions while the data rate drops to zero during the inferior conjunction since it is not possible to maintain the RF link due to high disturbances connected to the solar radiation aligned with the beam. Longer segments with zero data rate instead correspond to Mercury superior conjunction.

3 Reverse Sizing

In this section a preliminary reverse sizing of the TTMTC subsystem will be discussed taking into account its most important aspects.

3.1 Losses

The channel losses computation involves four types of contributions: free space, pointing, cable and atmospheric losses have been taken into account.
Free space losses have been computed as:

$$L_{free\ space} = 20 \cdot log_{10}\left(\frac{c}{4 \cdot \pi \cdot f \cdot r}\right)\ [dB] \tag{1}$$

while pointig losses are:

$$\begin{cases} L_{point} = -12 \cdot \left(\frac{\eta_p}{\theta}\right)^2\ [dB] \\ \theta = 63.5\frac{c}{f \cdot D}\ [deg] \end{cases} \tag{2}$$

where: c is the speed of light, f is the wave frequency, r is the Earth-SC distance, D is the antenna diameter and η_p is the antenna pointing efficiency. D has been assumed to be 34 m in the downlink case to be consistent with the DSN antenna dimension used considered in the literature; in the uplink case D is considered equal to $2 \cdot \lambda_{UL} = 0.0833\ m$ since the antenna here considered is the MGA.
Considering that the transmission both in uplink and in downlink occurs using the X-band, atmospheric losses has been estimated as $L_{atm} = -0.045\ dB$ while the passive L_{cab} have been considered equal to $-2\ dB$ for the spacecraft according with the literature, and $-1\ dB$ for the DSN antennas.
The previous equations leads to the following results. Notice that in the downlink case η_p has been estimated

	Computed	Real
	Downlink	
$L_{free\ space}$ $[dB]$	-270.0	-270.0
$L_{point+atm}$ $[dB]$	-0.3	-0.3
	Uplink	
$L_{free\ space}$ $[dB]$	-268.7	NA
$L_{point+atm}$ $[dB]$	-0.0483	NA

Table 1: Losses considering Earth range = 0.6 AU

equal to 0.01 considering the relative error between the electronically steerable phased array antenna and the DSN antenna while, in the uplink case, the same parameter η_p has been considered equal to 0.1 since the MGA is not steerable.

3.2 Antennas

The analysis has been performed considering the two main different antennas mounted on Messenger: the high gain phased array (PAA), considered for downlink communications, and the medium gain fainbeam antenna (MGA) taken into account in the uplink phase.
Knowing the power of each amplifier it is possible to estimate its efficiency and the corresponding transmitted power.

$$P_{Tx} = \mu_{amp} \cdot P_{In} \tag{3}$$

The gain of each antenna has been estimated as follows:

$$G = 10 \cdot log_{10}\left(\mu \cdot \left(\frac{\pi \cdot D \cdot f}{c}\right)^2\right)\ [dB] \tag{4}$$

where:

D is the characteristic dimension of the antenna (DSN: 34 m, MGA: $2 \cdot \lambda_{UL} = 0.0833\ m$)

μ is the antenna efficiency ($\mu_{para} = 0.55$, $\mu_{helix} = 0.70$)

Finally, the system noise density related to the receiving antenna is:

$$N = 10 \cdot log_{10}(kT_s)\ [dB] \tag{5}$$

where:

k is the Boltzmann constant

T_s is the system equivalent temperature

This process leads to the following results:

Input power $[W]$	Efficiency	Computed P_{tx} $[W]$	Real P_{tx} $[W]$
52	0.22	11.44	11

Table 2: Downlink PAA transmitted power

In this case, further losses are to be expected due to the presence of other electrical components.
Each antenna gain has been computed as aforementioned except for the PAA, whose gain cannot being computed using simplified formulas, the correct value retrieved from literature [1] has been therefore accounted for the following computation.

	Computed	Real
	Downlink	
$G_{Tx,HGA}$ $[dB]$	NA	+27.3
$G_{Rx,DSN}$ $[dB]$	+66.95	+68.41
	Uplink	
$G_{Tx,DSN}$ $[dB]$	+65.59	+67.05
$G_{Rx,MGA}$ $[dB]$	+14.4	+15.0

Table 3: Antenna gains for uplink and downlink

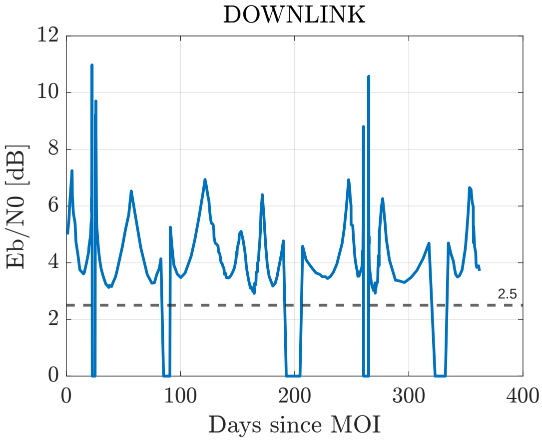
Notice that the computation of the DSN antennas gain always underestimate the real value, this is probably due to an underestimation of the antenna efficiency in Eq4.

3.3 Link budget

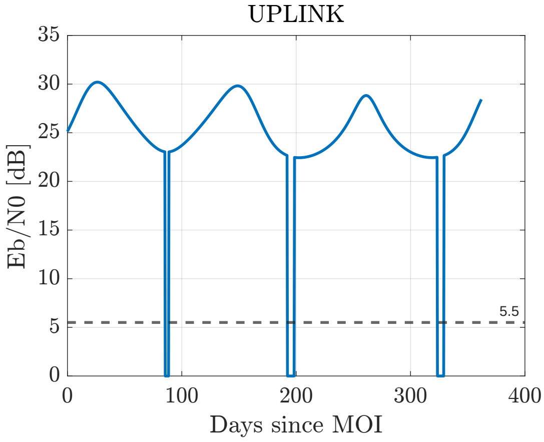
The use of a $R = 1/6$ and $k = 15$ convolution encoding, together with a Reed-Solomon modulation allows for a downlink $BER \approx 10^{-5}$ with a minimum link budget of just 1 dB, a margin of 1.5 dB is then added on top of that as a safety factor; despite according with literature the margin in the link budget in a preliminary analysis shall be 3 dB, this specific encoding and modulation allows to use lower safety margins [1]; uplink instead considers $BER \approx 10^{-7}$ as commands need higher accuracy. This yields a minimum $E_b/N_0 = 2.5\ dB$, with a safety margin of 3 dB.
Computing the total link budget is possible by using the following formula:

$$\begin{cases} \dfrac{E_b}{N_0} = 10 \cdot log_{10}(P_{Tx}) + G_{Tx} + G_{Rx} + L_{Total} - N_0 - 10 \cdot log_{10}(R) \quad [dB] \\ N_0 = 10 \cdot log_{10}(kT) \quad [dB] \\ L_{total} = L_{free\ space} + L_{point+atm} + L_{cab} \quad [dB] \end{cases} \tag{6}$$

where k is the Boltzmann constant, L_{total} and the datarate R vary over time in relation to the distance between Earth and Mercury that is computed considering the ephemerides of Earth and Mercury in the corresponding period.
In particular, for the downlink analysis the datarate considered is the one obtained through Fig.1 while, in the uplink case the datarate has been considered as a fixed worst case scenario of 500 bps. Also the DNS antenna has been considered in the worst case scenario of 34 m diameter. All the other data necessary to fulfill the equation: have been derived through the previous computations: losses: Tab.1, power: Tab.2 and gains: Tab.3. The antenna temperature in the N_0 computation, has been considered equal to 21 K for the DNS and 373 K for the spacecraft antenna since it is expected to work at high temperatures.
Notice that longer periods with zero link budget, since this computation is based on data from Fig 1, corresponds to the major conjunctions when it is impossible to establish the RF link between the Ground Station and the spacecraft.



(a) Downlink link budget



(b) Uplink link budget

The resulting link budget both for the science data downlink and telecommand uplink, appears to be satisfied for every time instant.

The bandwidth can be computed using the Shannon-Hartley theorem:

$$C = B \cdot log_2 (1 + S/N) \tag{7}$$

where C is the channel capacity that is assumed to be equal to the maximum datarate required: 36.8 $Mbps$ in downlink according with Fig.1, and 500 bps in uplink representing a worst case scenario. The Signal over Noise ratio (S/N) is required to be equal to 13 dB according with standard literature for a preliminary sizing. The required bandwidth results to be equal to 8.38 MHz in downlink and 114 Hz in uplink. Considering that the frequency separation between channels in the X-Band is equal to 1.358 MHz in downlink and 1.173 MHz in uplink [12], the required downlink bandwidth imposes either to use more contiguous channels or to increase the requested S/N and the corresponding transmission power according to the formula $SNR = P_{carrier} - N0 - 10 \cdot log_{10} (B) \quad [dB]$.

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