Politecnico di Milano

`First Assignment`

Space Systems Engineering and Operations

Prof. Roberta Michèle Lavagna

(A.Y. 2022/23)

Group: 39

Pietro Bosco (10643020)
Tommaso Brombara (10682041)
Riccardo Cadamuro (10702567)
Álvaro Flórez González (10911708)
Emanuele Marzorati (10724126)
Daniele Peruzzotti (10702005)

October 14, 2024

POLITECNICO
MILANO 1863

Contents

Change log	
§3.2	pp. 2-3: made explicit that requirements have been derived by the team, -not copied- from literature and the link between them and the functionalities
§4	pp. 4: added Gantt chart for ConOps, added link between phases and functionalities
§4.2	pp. 4-5: update ConOps, added spacecraft deployment and activation, science during flybys, DSM duration
§5.2.3	pp. 7: added details about payload ConOps in Mercury orbit
§6.4	pp.9: added details on the ΔV reverse sizing and Keplerian elements used

1 Introduction

MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) belongs to the NASA *Discovery* program, founded in 1990 that aims to investigate specific scientific questions about the Solar system but with lower costs with respect to previous programs like *New Frontiers*. Even though Mercury had already been reached by Mariner 10 in 1973, in that occasion the spacecraft was only able to perform three flybys of Mercury and to map the $40 - 45$ % of its surface, while Messenger aimed to orbit around Mercury for one Earth year, which was later extended to just over four years.
The mission was launched on 3 August 2004 on a Delta II 7925 launch vehicle form Cape Canaveral and reached the heliocentric orbit 57 minutes later.
Messenger reached Mercury on 18 March 2011, after almost seven years of interplanetary travel that involved one flyby of the Earth, two flybys of Venus, three flybys of Mercury itself and five Deep Space Manoeuvres.

2 Mission goals and drivers

MESSENGER mission is designed to answer six fundamental questions regarding Mercury: (1) What planetary formational processes led to Mercury's high ratio of metal to silicate? (2) What is the geological history of Mercury? (3) What are the nature and origin of Mercury's magnetic field? (4) What are the structure and state of Mercury's core? (5) What are the radar-reflective materials at Mercury's poles? (6) What are the important volatile species and their sources and sinks near Mercury?
These guiding questions can be translated into six objectives[1][2]:

1. Map the elemental and mineralogical composition of Mercury's surface;
2. Image globally the surface at a resolution of hundreds of meters or better;
3. Determine the structure of the planet's magnetic field;
4. Measure the libration amplitude and gravitational field structure;
5. Determine the composition of the radar-reflective materials at Mercury's poles;
6. Characterize exosphere neutrals and accelerated magnetosphere ions;

Due to the high complexity of the mission, both in terms of ΔV required to follow the interplanetary trajectory and for station-keeping (2300 m/s)[3][4] and in terms of survival in the harsh thermal environment around Mercury during the orbital phase of the mission, those two aspects have been pointed out as mission drivers.

3 Functional analysis

The mission requires four main functionalities which cover its complete time-span and operations. In particular the first one consists in *reaching and keeping the orbit around Mercury* that regards each aspect about the interplanetary travel and the orbiting around Mercury from the flight dynamics point of view. Moreover, in order to succeed in the high level goals, two more functionalities are needed: *collecting scientific data*, which is actually the mission main objective, and *transmitting them to the Earth*. Eventually, an *end of mission* functionality is prescribed according to the planetary protection principles, in particular, Mercury belongs to the first *COSPAR* category allowing for the disposal of the spacecraft by crushing it on the planet surface.

3.1 Functional Decomposition

This section contains a detailed functional decomposition of the mission.

1. Reach and keep orbit around Mercury
   - 1.1 Accelerate the SC out of Earth's gravity well;
   - 1.2 Guide the SC to Mercury along the interplanetary leg;
   - 1.3 Survive the interplanetary environment;
   - 1.4 Perform the capture maneuver on Mercury;
   - 1.5 Maintain the prescribed orbit around Mercury for the time necessary to complete the scientific mission;
   - 1.6 Withstand Mercury's orbit harsh environmental conditions during the whole mission;
2. Collect scientific data

- 2.1 Activate and calibrate all the scientific instruments, map the elemental and mineralogical composition of Mercury's surface;
- 2.2 Image globally the surface at resolution of hundreds of meters or better;
- 2.3 Determine the structures of the planet's magnetic field;
- 2.4 Measure the libration amplitude and gravitational field structure;
- 2.5 Determine the composition of the radar reflective materials at Mercury's poles;
- 2.6 Characterize exosphere neutrals and accelerated magnetosphere ions;

3. Transmit data to Earth
   - 3.1 Store collected data onboard until transmission window open;
   - 3.2 Transmit correctly data to Earth;
   - 3.3 Validate the data received;
4. End of the mission
   - 4.1 Stop performing propulsive orbital corrections;
   - 4.2 Complete all data transmissions;
   - 4.3 Crash into the Mercury's surface;

3.2 Requirements

The following section contains the high level requirements that have been derived by the team from the available literature by analyzing what functions needed to be performed to achieve the planned mission goals and therefore a plausible mission requirement for different subsystems. These were then divided by the previously cited functionalities [4][3]:

Reach and keep orbit around Mercury

ID	Requirement	Function(s)
R-OP-010	SC hardware components shall be picked among space-hardened ones;	1
NH-OP-011	SC hardware components should be picked among flight proven ones (TRL 9) to reduce mission cost;	
R-MA-010	Launcher choice shall provide an energy c3=16.4 km2/s2 to the SC;	1.1
R-MA-020	GNC and Propulsion systems shall allow the SC to follow the planned interplanetary trajectory;	1.2, 1.3
R-PS-010	Propulsion system shall provide at least 2300 m/s [3][4] of Δv;	
R-PS-020	Propulsion system shall be capable of performing precise impulses of more than 10m/s after years of inactivity;	
R-PS-030	Propulsion system shall be capable of periodically correcting SC orbit and attitude to account for perturbances;	1.2, 1.4, 1.5
R-EPS-010	Electric system shall be capable of maintaining SC in hibernation state for up to 7 years in deep space;	1.3, 1.5, 1.6
R-EPS-020	SC shall have enough battery power to survive 35min eclipse;	
R-OBDH-010	Electronic system (IEM, Integrated Electronics Module) should be built with redundancy;	
R-TCS-010	Thermal protection system shall protect SC components from intense heat at 0.3AU from the Sun and in proximity of Mercury's surface.	

Collect scientific data

ID	Requirement	Function(s)
R-ADCS-010	ADCS system shall be capable of orienting the spacecraft correctly to accommodate both ASP and NTSP;	2
R-EPS-030	Solar panels shall provide at least 640W of power at EOL around Mercury [3];	
R-MA-030	SC orbit shall be picked in such a way to transit through the whole magnetosphere;	2.3, 2.6
R-MA-040	SC shall be placed in an orbit that allows for an analysis of Mercury's polar regions;	2.5
R-PLD-010	Total instruments mass shall not exceed 50kg;	2
R-PLD-020	Onboard instruments shall be able to produce a global map of the surface Mercury with a resolution of at least 2.4 km/pixel in color and 500 m/pixel in B and W;	2.2
R-PLD-030	Onboard magnetometer shall be placed at least 3.5m from the main SC body;	2.3
R-PLD-040	Onboard instruments shall be able to perform altimetric measurements of the planet;	2.4, 2.5
R-PLD-050	Onboard instruments shall be able to perform UV, gamma-ray and neutron spectrometry of the polar regions;	2.1, 2.5
R-PLD-060	Onboard instruments should be picked such that measures can be crosschecked with the data from other onboard instruments.	2.1

Transmit data to Earth

ID	Requirement	Function(s)
R-OBDH-020	SC shall have at least 8GB internal memory storage to store scientific data until transmission;	3.1
R-OBDH-030	SC shall be able to perform data collection autonomously;	3
R-TTMTC-010	Communications system shall be capable of communicating both near Earth (hundreds of Km) and at 1.4AU;	3.2
R-TTMTC-020	SC shall be able to transmit and receive telemetry data and commands;	
R-TTMTC-030	Telemetry downlink shall have adjustable bit rate depending on mission phase and SC state;	
R-TTMTC-040	Transmission system shall be able to encrypt and decrypt data;	3.2, 3.3
R-TTMTC-050	Transmission system shall be able to communicate with Earth through DSN.	3

End of the mission

ID	Requirement	Function(s)
R-MA-050	SC shall be placed in an orbit that will cause it to fall on Mercury to safely dispose of itself;	4
R-FUN-010	SC shall be designed in such a way not to leave any debris in Mercury's orbit.	

4 Phases and Concept of Operations

The mission profile has been divided by the team into four main phases based on a literature survey [5][6][7], for each of them the Concept of Operations (ConOps) has been derived.

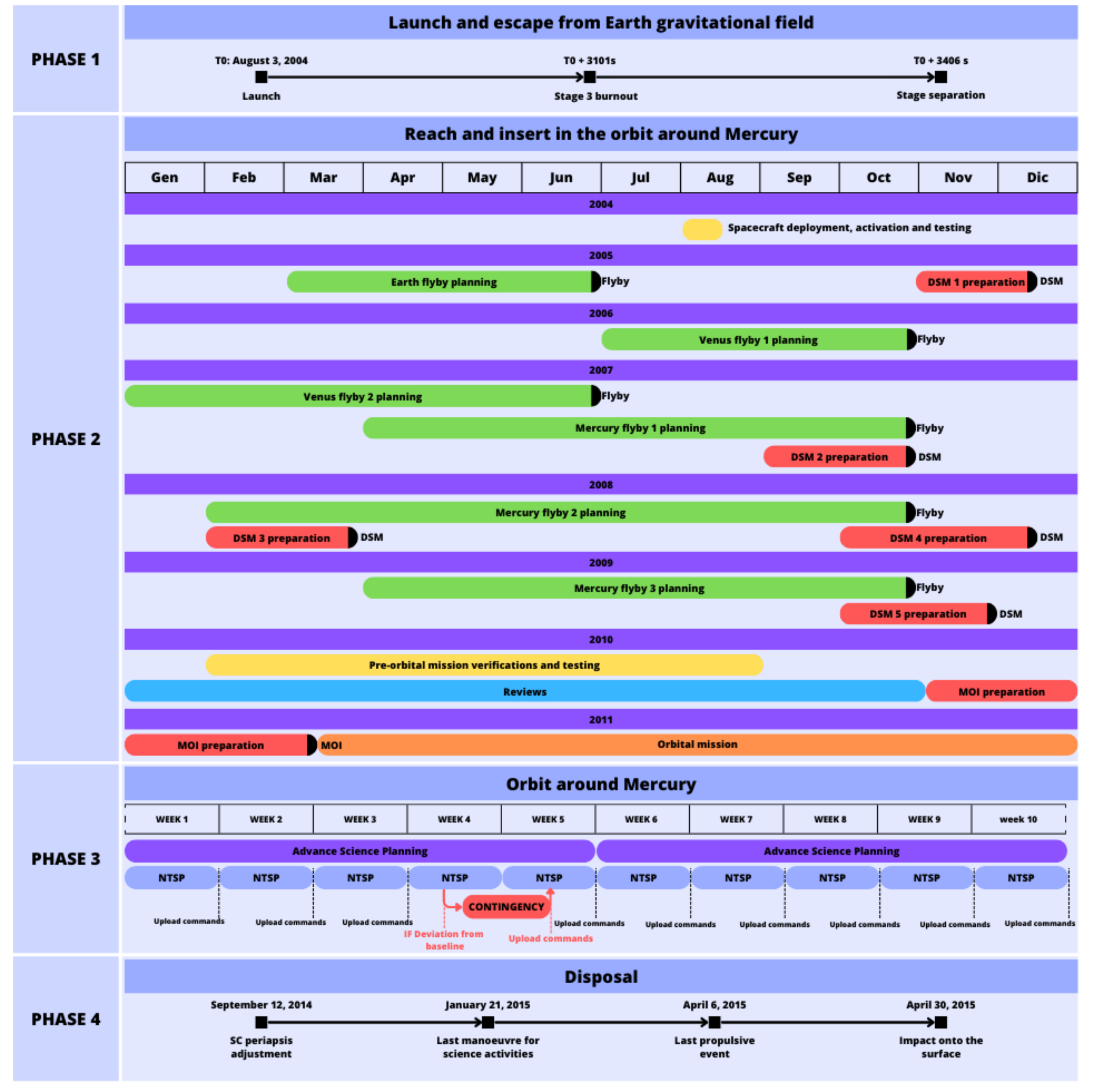

Figure 1: Messenger ConOps Gantt chart

4.1 Launch and escape from Earth gravitational field

- Launch, *T + 0s, August 3, 2004*: the launch will occur from Cape Canaveral, Florida on a Delta II 7925 launcher;
- Stage 3 burnout, *T + 3101s*: the last stage of the launcher finishes its propellant after having placed the spacecraft in the heliocentric trajectory;
- Stage 3 separation, *T + 3406s*: the spacecraft detaches from the launcher and is ready to begin its mission.

The operations described in this phase fulfill the functionalities 1.1, 1.2 and 3 (it is always necessary to maintain communication between the SC and the GS) .

4.2 Reach and insert in the orbit around Mercury

- Spacecraft deployment and activation, *August 3/6, 2004*: Spacecraft is brought under full 3 axis control, solar panels are deployed and onboard systems are powered up one by one on orbit for the first time. Contact with the ground station is established through omnidirectional antennas;

- Testing of onboard systems, *August 3/9, 2004*: the SC will perform tests on the onboard systems and instrumentation for the first 6 days of flight before being considered fully operative;
- Earth flyby, *August 02, 2005*: decreases the heliocentric orbit periapsis to follow its interplanetary path;
  - Science during Earth flyby: perform instruments calibration, Earth and Moon imaging and observations, magnetic field measurements and testing of the RF subsystem.
- DSM 1, *December 12, 2005, Duration: 522 s*: corrects the heliocentric trajectory to perform correctly the first rendez-vous with Venus;
- Venus flyby 1, *October 24, 2006*: increases SC orbit inclination and reduces its period to almost exactly the Venus orbit period;
- Venus flyby 2, *June 5, 2007*: lowers the orbit periapsis enough to enable Mercury flyby;
  - Science during Venus flybys: instrument testing, measure the atmospheric species and their chemical properties, the interplanetary magnetic field and perform observation on the charged particles at the Venus bowshock.
- DSM 2, *October 17, 2007, Duration: 518 s*: corrects the trajectory and encounter Mercury for the first flyby;
- Mercury flyby 1, *January 14, 2008*: reduces the SC arrival velocity to Mercury;
- DSM 3, *March 17, 2008, Duration: 150 s*: major trajectory correction after the flyby;
- Mercury flyby 2, *October 6, 2008*: reduces the SC arrival velocity to Mercury;
- DSM 4, December 4/8, 2008, Duration: 385 s: major trajectory correction after the flyby;
- Mercury flyby 3, *September 29, 2009*: reduces the SC arrival velocity to Mercury;
  - Science during Mercury flybys: partial mapping of the surface of Mercury, measurements of the magnetic field and of the chemical species in the exosphere and in the magnetotail.
- DSM 5, *November 24, 2009, Duration: 245 s*: major trajectory correction after the flyby;
- Mercury Capture, *March 18, 2011, Duration: 885 s*: capture manoeuvre and insertion in the orbit around Mercury enabling the primary science mission to begin.

The operations related to the payload activities ad scientific observations performed during flybys and during the orbital phase around Mercury are more in depth analyzed in section 5.2.
During the interplanetary cruise, the concept of operations prescribes a moderate DSN tracking in quiet cruise periods and additional tracking near critical events such as gravity assist flyby and deep space maneuvers. Communications are established well in advance of each critical activities such as deep space maneuvers or fly-bys. Orbit determination in this phase relies primarily on the DSN, on approach to Venus and Mercury, this data will be augmented with DeltaDOR and optical navigation measurements. The DSN long range planning includes periods for obtaining measurements each week starting five weeks prior to each flyby.
After each Orbit Determination solution, the navigation team will perform a mapping of the trajectory and its uncertainties.
After each propulsive maneuver, the remaining trajectory is re-optimized to obtain the most fuel efficient and lowest risk solution possible. The operations described in this phase fulfill the functionalities 1.2, 1.3, 1.4, 2.1 and 3.

4.3 Orbit around Mercury

In this phase, all the activities are scheduled and performed in two modes: the Advanced Science Planning (ASP) regarding long term period operation, this assessment will be performed every 5 weeks, each time producing an updated baseline for the remainder of the mission; and a short-term scheduling process known as Near Term Science Planning (NTSP).

ASP: the output of ASP process is the long-range plan of all instruments and associated spacecraft GNC activities that span entirely the nominal one-year orbital mission, in this process it is defined the set of measurement requirements to fulfill the mission science goals considering that very often the pointing and orientation of one instrument will conflict with those of another. The ASP will in general deal with the required Orbital Correction Maneuver to be performed every 88 Earth days to recover the orbital path from the solar radiation perturbation.

NTSP: it contains the short term optimized scheduling for the orbital ConOps. In this mode, command sequences are sent to operate the spacecraft subsystems considering weekly updates. The preparation of each one-week command sequence requires three weeks of planning. Each request of change in the spacecraft pointing is referred to the ASP process.

CONTINGENCY PLANNING: due to the harsh environment in the vicinity of Mercury and the mission profile that heavily constrains the spacecraft control, power generation, data downlink and observation opportunities, deviations from the baseline may result in very problematic situations. Contingency plans, once devised, can be directly inserted into the next ASP cycle or, for more pressing cases, being immediately inserted into the upcoming NTSP cycle.
The operations described in this phase fulfill the functionalities 1.5, 1.6, 2, 3.

4.4 Disposal

- SC orbit periapsis adjustment *September 12, 2014*: the periapsis altitude is set to 25 km;
- Orbit rising *January 21, 2015*: last maneuver to raise SC orbit for science activities;
- Last propulsive event, *April 6, 2015*: SC runs completely out of propellant, pressurizing Helium is used for propulsion, SC speed is increased by 8.9 m/s;
- Disposal, *April 30, 2015*: impact onto the surface of Mercury with velocity 3.911 km/s.

The operations described in this phase fulfill the functionalities 4.

5 On board instruments

5.1 Payload

MESSENGER carries seven scientific instruments and a radio science experiment in order to return the data collected from Mercury orbit[8] [9].

	Mass	Power	Development
MDIS	8.0 kg	7.6 W	The Johns Hopkins University Applied Physics Laboratory
GRS	9.2 kg	16.5 W	The Johns Hopkins University Applied Physics Laboratory, Patriot Engineering, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory
NS	3.9 kg	6.0 W	The Johns Hopkins University Applied Physics Laboratory, Patriot Engineering, Los Alamos National Library
XRS	3.4 kg	6.9 W	The Johns Hopkins University Applied Physics Laboratory
MAG	4.4 kg	4.2 W	NASA Goddard Space Flight Center and the Johns Hopkins University Applied Laboratory
MLA	7.4 kg	16.4 W	NASA Goddard Space Flight Center
MASCS	3.1 kg	6.7 W	Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder
EPPS	3.1 kg	7.8 W	The Johns Hopkins University Applied Physics Laboratory and University of Michigan, Ann Arbor

Table 1: *Payload specifics*

- **MDIS**: Mercury Dual Imaging System, with a wide- and a narrow- angle cameras, will map the landforms and spectral variations on the planet's surface in monochrome, color, and stereo. Multispectral imaging will help scientists investigate the different rock types which form Mercury's surface;
- **GRNS**: the Gamma-Ray Spectrometer (**GRS**) measures gamma rays emitted by the nuclei of atoms on the surface that are struck by cosmic rays, while the Neutron Spectrometer (**NS**) maps the variations in the fast, thermal and epithermal neutrons emitted by the surface. The device will look for hydrogen and other geologically important elements;
- **XRS**: the X-Ray Spectrometer will map the elements in the top millimeter of Mercury's crust detecting the x-ray emissions coming from the surface when solar x-rays hit the planet;

- **MAG**: a Magnetometer which will help the scientists to characterize Mercury's magnetic field in detail;
- **MASCS**: the Mercury Atmospheric and Surface Composition Spectrometer combines an ultraviolet spectrometer and infrared spectrograph, measuring the abundance of atmospheric gases around Mercury, determining the composition and structure of the planet's thin exosphere, and detect minerals in its surface materials;
- **MLA**: the Mercury Laser Altimeter uses an infrared laser transmitter and a receiver in order to map Mercury's landforms. Moreover, the data will also be used to track the planet's libration - a wobble around its spin axis - which will tell the researchers about the state of Mercury's core;
- **EPPS**: the Energetic Particle and Plasma Spectrometer is meant to measure the mix and features of charged particles in and around Mercury's magnetosphere;
- **Radio Science Experiment**: the Radio Science observations will precisely measure MESSENGER's speed and distance from Earth. This will help the researchers to compute Mercury's gravity field and to support the laser altimeter investigation to determine size and condition of the planet's core. The investigation through the Radio Science experiment is conducted by NASA's Goddard Space Flight Center.

5.2 Flybys and orbital operations

The onboard instruments will allow MESSENGER to reach its mission's high level goals, returning the researchers data about Mercury. However, the whole payload apparatus is meant to operate throughout the entire mission flow[10].

5.2.1 Earth flyby

The event provided important calibration opportunities for four MESSENGER instruments. **MDIS** will take images of both the Moon and the Earth; **MASCS** will perform spectral observations of the Moon and of the Earth's hydrogen corona; **MAG** will measure the magnetic field and charged particles characteristics; **MLA** will test the efficiency of the transmitter and the receiver, even though it will have already started working before the flyby event.

5.2.2 Venus flyby

Elements of MESSENGER's equipment will be tested during the second Venus flyby. **MDIS** will image both the approaching and departing emispheres; **MASCS**'s ultra-violet and infra-red spectrometers will make profiles of the atmospheric species and sense their chemical properties; **MLA** will serve as a passive radiometer; **EPPS** will observe charged particles acceleration at the Venus bowshock and elsewhere; **MAG** will provide measurements of the upstream interplanetary magnetic field.

5.2.3 Mercury flybys and orbit

Science observations will take place during the three Mercury flybys and in the orbit, involving all the components of the MESSENGER's payload; previously unseen regions of the planet will be mapped during the flybys, while the remaining data will be obtained over the four Mercury years (one Earth year) to be spent on orbit. The spacecraft orbital period is 12 hours; science data will be collected for 16 hours of each 24 hours period (two orbits) and then downlinked during a tracking pass which is planned for a time window of 8 hours. The selection of the payloads is driven by the functionalities that depend on the main goals of the mission. In Table 4.1 the main relations between the instruments and the functionalities are presented.

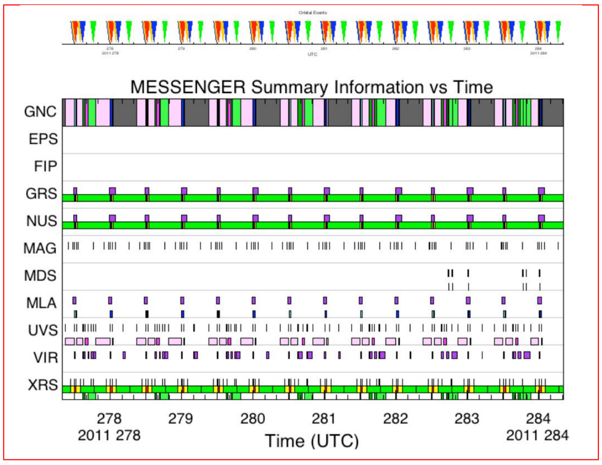

Figure 2: Example of Payload ConOps during the orbital phase

Figure 2 shows the Concept of Operations for the different instruments onboard the spacecraft during an average week in Mercury orbit. Not all instruments can be used simultaneously due to their relative positions and their different targeting needs, but overlap between different instruments measurements can occur. Different colors refer to different functions performed by the same instrument [5].

Map the elemental and mineralogical composition of Mercury's surface	**MDIS, XRS, GRNS, MASCS**
Image globally the surface at a resolution of hundreds of meters or better	**MDIS**
Determine the structure of the planet's magnetic field	**MAG, EPPS**
Measure the libration amplitude and gravitational field structure	**MLA, RS**
Determine the composition of the radar-reflective materials at Mercury's poles	**GRNS, EPPS**
Characterize exosphere neutrals and accelerated magnetosphere ions	**MASCS, EPPS**

Table 2: *MESSENGER science goals and related instruments*

6 Mission Analysis

6.1 Launch and Earth escape

Given the necessity of C3 energy for the mission, the launcher picked for the mission is the Delta II 7000 series by Boeing Integrated Defense Systems. This was the only possible choice of launcher that would have been able to provide the 1100 kg SC with a final C3 energy of 16.4 $\frac{km^2}{s^2}$. The launch sequence consisted of a direct injection into the heliocentric orbit, following a burn sequence that lasted 57 minutes.

6.2 Interplanetary leg

To achieve the goal of reaching Mercury and successfully injecting into a closed orbit around the planet, a very precisely calculated sequence of gravity assists was deemed necessary.
This is since no form of propulsion could feasibly inject the SC directly into an interplanetary arc that intersects Mercury's path in such a way to make a capture at the planet possible in terms of ΔV due to technological constraints.
The final interplanetary trajectory developed by Johns Hopkins University's APL [11][12] makes use of 6 flybys before the final Mercury Orbit Injection (MOI), 1 at Earth, followed by 2 at Venus, then 3 at Mercury. This allows to significantly reduce the cost of the transfer in terms of ΔV needed to only $\approx 1100\ \frac{m}{s}$, as well as in terms of mission cost and complexity of the spacecraft itself, at the expense of total transfer time.
Particular attention was placed into crafting a trajectory that would not need the spacecraft to maneuver during solar conjunctions (Sun-Earth-SC angle < 3 deg) and that would allow the SC to perform the necessary Deep Space Maneuvers (DSMs) in an orientation that allowed the heat shield to be pointed sunward when the probe is closer than 0.85AU from the Sun, thus protecting the sensitive components onboard from direct exposure to the Sun's heat and radiation. Because of its inner complexity, the trajectory was quite sensitive to the departure date, reason why three launch opportunities were found in 2004 with varying combinations of Venus, Mercury and Earth flybys; eventually the launch occurred during the last window.

6.3 Mercury orbit

The orbit around Mercury was chosen to be a highly elliptical one, with a minimum height above the surface of 200 km and a maximum one of almost 15200 km, an inclination of 82.5° to Mercury's equator and a low point in the orbit that was reached at a latitude of 60° N.
This was done to optimize different aspects of the mission [10][13]: this maneuver limits the propellant and ΔV that must be expended to inject into orbit, requiring 31 % of the onboard fuel reserves and a ΔV of 860 $\frac{m}{s}$. This choice also leaves time for the spacecraft to cool down between perihermion passes, where heat radiated from the surface of Mercury causes an increase in total thermal flux on the SC.
The high inclination allows both to observe and study the polar regions of the planet as well as to map the whole surface of the planet.
The low periapsis leads to a higher resolution in terrain scanning, while the high apoapsis and eccentricity allow the SC to frequently pass through different strata of the magnetosphere of Mercury to study the interaction between the magnetic field of the planet and of the Sun.
The Injection burn is also planned to happen in such a way to be executed while pointing the sunshield sunward to protect the SC.

6.4 ΔV estimations

All gravity assists performed by Messenger during its transfer to Mercury were unpowered Fly-Bys. The ΔV cost of the transfer is mainly due to the Deep Space Maneuvers that Messenger performed between planetary encounters to adjust the trajejctory ahead of the following scheduled Fly-By.
Retrieving the post-flight Keplerian elements[11][14] of the interplanetary arcs between Fly-Bys and DSMs, some of which are shown in table 3, it is possible to estimate the ΔV cost of each DSM as a single impulse burn by taking the norm of the difference of the velocity vector before and after the maneuver.

ID	$a\ [km]$	$e\ [-]$	$i\ [rad]$	$RAAN\ [rad]$	$\omega\ [rad]$	$\theta\ [rad]$[1]
Pre DSM-1	1.2101e8	0.2550	0.0442	2.2743	0.0365	6.1384
Post DSM-1	1.2406e8	0.2732	0.0450	2.2720	0.0315	6.1455
Pre DSM-2	8.0570e7	0.3836	0.1182	0.8780	6.2201	2.5754
Post DSM-2	7.9949e7	0.3917	0.1187	0.8751	6.2071	2.5914
Pre DSM-4	6.9753e7	0.3516	0.1222	0.8435	0.3393	2.9851
Post DSM-4	7.0308e7	0.3413	0.1221	0.8433	0.3468	2.9781

Table 3: Interplanetary leg keplerian elements

This analysis shows that the impulse approximation is quite precise as a first estimate of the ΔV cost for this phase of the mission as reported in Tab.4.

Maneuver	DSM-1	DSM-2	DSM-4
Computed $\Delta V[\frac{m}{s}]$	313.6	227.6	246.3
Real $\Delta V[\frac{m}{s}]$	315.6	227.4	246.8

Table 4: Calculated vs real costs of some DSMs

The accuracy of the previous results is not surprising since the team computed the ΔV using the post-flight Keplerian elements related to the points right before and after the manoeuvre reported in Tab.3.
Performing simulations for the ΔV cost of the launch phase or the Mercury Injection Orbit (MOI) results in some misleading results, as those maneuvers are much longer in duration and as such the hypothesis of impulsive burn cannot be applied. In particular, the calculated MOI burn is 295.9 $\frac{m}{s}$, where in reality the correct value is 861.7 $\frac{m}{s}$. This difference is to be expected due to the movement of the spacecraft along its hyperbolic trajectory around Mercury during the $\approx 885\ s$ burn.
A more refined model is needed to correctly estimate the cost of this maneuver.

6.5 Δt estimations

An estimation on the time required for the interplanetary leg of the mission can be retrieved by analyzing the Keplerian elements [11] of the various legs of the transfer. Computing the time needed to travel through all of them under the hypothesis of unperturbed Keplerian motion it is possible to get estimates for the different arcs that match closely with the real timeline of the mission.

Interplanetary leg	Launch - Earth FB	Earth FB - Venus FB1	Mercury FB1 - Mercury FB2	Total time
Computed $\Delta t[days]$	366.47	448.78	266.94	2444.4
Real $\Delta t[days]$	364.49	447.56	265.57	2417.7

Table 5: Calculated vs real transfer times for some interplanetary legs

[1] θ refers to the true anomaly

Bibliography

[1] Sean C. Solomon. *The MESSENGER mission to Mercury: scientific objectives and implementation.* Tech. rep. 2000.

[2] Eric J. Finnegan Peter D. Bedini. *MESSENGER: An Extreme Systems Engineering Challenge.* Tech. rep. 2010.

[3] Robin M. Vaughan. *Return to Mercury: The MESSENGER Spacecraft and Mission.* Tech. rep. 2006.

[4] Katie Dommer Sam Wiley. *MESSENGER Propulsion System Flight Performance.* Tech. rep. 2000.

[5] Deborah L. Domingue Alice F. Berman. *Orbital Operations Planning and Scheduling for the MESSENGER Mission.* Tech. rep.

[6] Deborah L. Domingue Alice F. Berman. *Testing and validation of orbital operations plans for the MESSENGER mission.* Tech. rep.

[7] Brian R. Page. *MESSENGER NAVIGATION OPERATIONS DURING THE MERCURY ORBITAL MISSION PHASE.* Tech. rep.

[8] NASA. *Messenger mission.* `https://solarsystem.nasa.gov/missions/messenger/in-depth/`.

[9] JHUAPL NASA. *MESSENGER Mercury Orbit Injection Press Kit.* Tech. rep. 2011.

[10] Sean C. Solomon. *MESSENGER Mission Overview.* Tech. rep. 2007.

[11] John Hopkins University Advanced Physics Laboratory. *MESSENGER.* `https://messenger.jhuapl.edu/`.

[12] James V. McAdams. *MESSENGER Mission Design and Navigation.* Tech. rep. 2007.

[13] Andrew G. Santo. *The MESSENGER mission to Mercury: spacecraft and mission design.* Tech. rep. 2000.

[14] John Hopkins University Advanced Physics Laboratory. *Messenger Orbital Elements.* `https://messenger.jhuapl.edu/About/mission-design/details-propulsion-activity/MOE.xls`.