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Faculty of Electrical Engineering
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BACHELOR'S THESIS

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ÚSTAV JAZYKŮ

SPACE MISSIONS TO MERCURY
VESMÍRNÉ MISE NA MERKUR

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Bakalářská práce

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Vesmírné mise na Merkur

POKYNY PRO VYPRACOVÁNÍ:

Cílem semestrálního projektu je výzkum minulých i současných vesmírných misí na planetu Merkur. Výzkum bude zaměřen na předchozí misi NASA na Messenger a současnou misi BepiColombo, společnou misi dvou kosmických lodí Evropské kosmické agentury (ESA) a japonská letecká kosmická agentura (JAXA)

DOPORUČENÁ LITERATURA:

Eric H. Christiansen and Braxton Spilker, Exploring the Planets v18.1,, 2018.

http://explanet.info (see Chapter 5, Mercury)

Unlocking the Mysteries of Planet Mercury.

https://messenger.jhupl.edu

European Space Agency: BepiColombo.

https://www.esa.int/Science_Exploration/Space_Science/BepiColombo

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Abstract

This Bachelor's thesis focuses on the past and present space missions to planet Mercury, particularly NASA's earlier Messenger mission and the present joint mission of ESA and JAXA, BepiColombo. The thesis deals with the objectives, timelines, challenges and science results gained during both of these missions. The chapters comprise a comprehensive description of the scientific technology, instrumental payload and construction design; furthermore, the paper outlines the differences between them as well as the progress in technology.

Key words

Mercury, Messenger, BepiColombo, spacecraft, mission

Abstrakt

Tato bakalářská práce sa zaměřuje na minulé a současné vesmírné mise na planetu Merkur, na dřívější misi Messenger uskutočněnou kosmickou agenturou NASA a současnou společnou misi dvoch kosmických sond Evropské kosmické agentury ESA a japonské letecké agentury JAXA, BepiColombo. Výskum je zejména zaměřen na cíle, časový harmonogram, výzvy a vědecké výsledky získanými během těchto misí. Kapitoly obsahují podrobný popis vědecké technologie, vědeckých instrumentů a konstrukci sond. Dále tato práce zdůrazňuje rozdíly mezi nimi a také pokrok v technologii.

Klíčová slova

Merkur, Messenger, BepiColombo, sonda, mise

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Vedoucí bakalářské práce: M. A. Kenneth Froehling

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V Brně dne ....

Jakub Novák

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Table of Contents

INTRODUCTION

Mercury is the innermost terrestrial planet in our Solar System, with a distance three times closer to the Sun than Earth. Among scientists, it is often called the "World of brutal extremes". As the closest planet to the Sun, it experiences enormous temperature variations, from about -180°C on the night side to +430°C on the dayside. The uniqueness of this planet is not only due to its position, but it is also the smallest planet in our Solar System, with a length of diameter over 4800 km, which is the size about the continental United States.

It is very complicated to observe Mercury from Earth because its view is fleeting, considering that it is orbiting our solar system star at an average speed of 47 km/s, resulting in the year lasting only 88 days. Even the Hubble space telescope is forbidden from viewing the Mercury; due to the Sun's proximity, our eyes may be damaged.

This Bachelor's thesis deals with the past and present missions to Mercury and investigates the science behind the used technology as well as the gained data. So far, it is has been visited by only two spacecraft, NASA's MESSENGER and its predecessor Mariner 10. Those missions were essential regarding the facts we know today. The first chapter sums up the fundamental discoveries provided by Mariner 10.

Mission MESSENGER successfully accomplished its objectives, determined the surface composition and geological history as well as discovered details about magnetic field and polar deposits. Consequently, it revealed a number of stunning results that raised many questions, which now remain to be answered. This mission is the main topic of the second chapter.

The third chapter is dedicated to future observations which depend on the mission BepiColombo, provided by ESA and JAXA. The spacecraft, consisting of two scientific orbiters, Mercury Planetary Orbiter and Mercury Magnetospheric Orbiter, both equipped with cutting-edge technology, is expected to observe the planet's interior, surface, exosphere and magnetosphere. With its seven-year cruise, the spacecraft should arrive in orbit at the end of 2025.

The last chapter describes the comparison between science and technology behind each mission. Furthermore, I will specify and comment on the most significant deployed improvements that helped to enhance the development and functionality of the succeeding mission.

1. EARLY HISTORY

1.1. Mariner 10

Mariner 10, the seventh successful launch in the Mariner series, performed the very first close flyby of the planet Mercury. The Mariner program was a series of interplanetary probes designed to explore Mercury, Venus and Mars, from 1962 to 1973. NASA's spacecraft was launched on November 3, 1973, in order to fly by and pioneer planets Mercury and Venus. On route to Mercury, the spacecraft completed a gravity-assisted Venus manoeuvre to direct its course toward the orbit of Mercury. According to Dunne and Burges (1978), "The technique allows a spacecraft to change both its direction and speed without the expenditure of propellant, thereby saving time and increasing scientific payload on inter-planetary missions" (p. 11).

This concept of a gravity-assist technique has been known since the 1920s and '30s. However, cosmologists and trajectory designers could not develop an appropriate mathematical solution regarding the matching velocities and time. Consequently, after decades of speculation, a detailed Venus-Mercury navigation strategy was prepared, providing practical feasibility as an interplanetary space mission.

The Mariner 10 spacecraft commenced the Mercury observations, providing the crucial development in terms of technology since being the first spacecraft to use the gravitational pull of one planet to reach another, as well as the first spacecraft to visit two planets. Furthermore, the mission was performed very economically, with its total cost of roughly 100 million dollars, including research, development, launch and other support costs (Murray and Burgess, 1977). The spacecraft was equipped with several scientific instruments to provide the measurements of the planet's physical characteristics; comprising two cameras, infrared radiometer, ultraviolet airglow spectrometer, ultraviolet occultation spectrometer, magnetometer, charged particle telescope and plasma analyser. The primary objectives of the mission were to measure Mercury's environment, atmosphere, surface, and body characteristics and conduct similar research of Venus. Secondary objectives were to execute experiments in the interplanetary medium and to gain experience with a gravity-assist.

The spacecraft completed, three encounters with Mercury at six-month intervals, due to the fortuitous gravity of the planet. They were performed in sequence: first on March 29, 1974, at an altitude of 704 km, second on September 21, 1974, at an altitude of 48,069 km, and the third and last encounter occurred at a distance of 327 km on March 16, 1975. Eight days after the final encounter on March 24, 1975, the supply of altitude-control gas was exhausted, thus leaving the spacecraft orbiting the Sun, and the mission was terminated (Dunne and Burges, 1978).

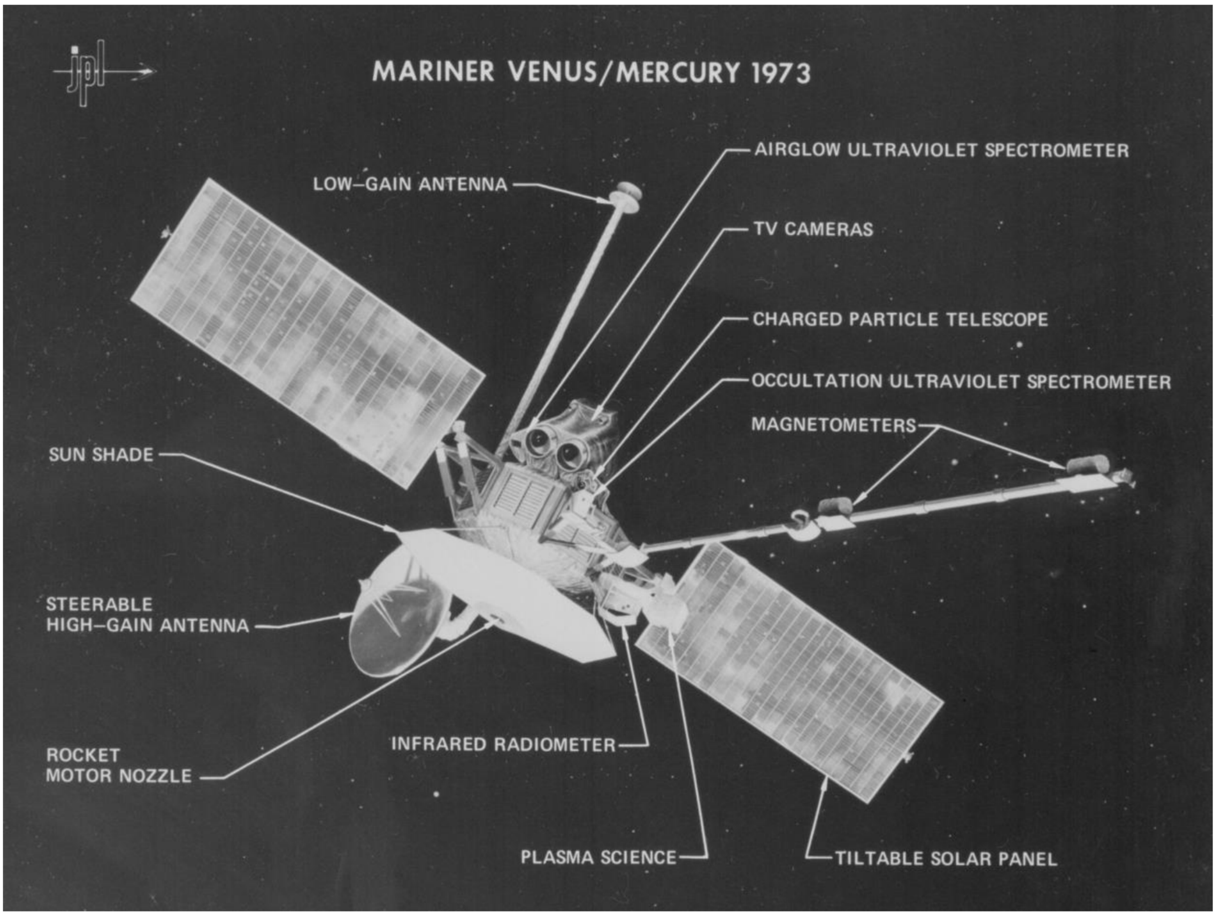


Figure 1: The spacecraft Mariner 10 with its scientific instruments

1.2. First discoveries

Prior to the Mariner 10 mission in 1973, the earth-moon system had been studied, and only one planet was being investigated, Mars. Despite relatively little scientific evidence, scientists agreed that there had been five major epochs in planet-building: accretion, melting, bombardment, volcanism and finally, plate tectonics (Shirley, 2003). Questions were raised on whether this evolutionary process is universal to all the inner planets. Little did the scientists know about Mercury before the mission was introduced, since only this planet was totally unexplored.

Despite a number of failures on the route, such as malfunctioning high-gain antenna and altitude control system, the Mariner 10 mission provided significant discoveries, including the presence of the small magnetic field, the absence of atmosphere and the occurrence of a heavy meteoric bombardment approx. 3.5 billion years ago. Mercury was also shown to have a relatively iron-rich core, comprising about 80 per cent of Mercury's mass and a cratered, dormant Moon-like surface (Shirley, 2003). In total, Mariner 10 provided more than 2,700 pictures during its flybys, covering almost half of the planet's surface. These images were essential in terms of planet investigation, perhaps the most significant discovered feature on the surface was the Caloris basin. In geologists' terminology, the basin is simply a crater larger than about 300 kilometres in diameter, whereas Caloris measures approximately 1,640 kilometres (Cunje and Ghent, 2016).

As a result of the successful Mariner 10 mission, scientists collected valuable scientific data concerning not only the planet's surface but also surrounding interplanetary space, as well as specific information about the solar system environment. Ultimately, the engineering, know-how and experience acquired during this mission have laid the groundwork for all the upcoming space exploration missions, especially for its successor MESSENGER.

2. MESSENGER MISSION

The MESSENGER (MErcury Surface, Space ENvironmnet, GEochemistry, and Ranging) spacecraft is a part of the Discovery Program of the U.S. National Aeronautics and Space Administration (NASA). Since the planet Mercury was the least studied planet of the inner Solar System, it was essential to explore further details in terms of understanding how the terrestrial planets were formed.

2.1. NASA

The National Aeronautics and Space Administration (NASA) was established in 1958, succeeding the National Advisory Committee for Aeronautics (NACA) and other U.S. government organisations (Garber, 2005). NASA conducted several major space missions, including Project Mercury, Project Gemini and finally Project Apollo, which pushed the boundaries of aeronautics research concerning space exploration (Dunbar, 2018). Up to the present day, NASA remains a global leading force with regard to space science and aerospace technology.

2.2. Mission objectives

In accordance with the NASA Discovery Program guidelines, Sean C. Solomon is the Principal Investigator for this mission. As the person with the overall responsibility for the execution and the success of the mission, Solomon and his co-workers published an article in which they summarize that the MESSENGER mission has six fundamental science objectives to accomplish: (Solomon et al., 2001)

1. Planetary formational processes that led to Mercury's high ratio of metal to silicate

   In contrast to other terrestrial planets, Mercury's uncompressed density (approximately 5.3Mg/m^3) is by far the highest of any planet. The density implies that Mercury's core covers approximately 75% of the planetary radius, and the fractional core mass about 65% of the total mass – more than twice as much as for Earth, Venus or Mars.

2. Geological history of Mercury

   Prior to the MESSENGER mission, only 45% of Mercury's surface had been documented by the Mariner 10 mission. However, in combination with the images from MESSENGER's three Mercury flybys, approximately 98% of the surface has been seen in detail. A majority of Mercury's surface is covered with heavily crater regions, as a consequence of a period of heavy bombardment about 3.8 billion years ago.

3. The nature and origin of Mercury's magnetic field

   According to the information gathered by Mariner 10, Mercury has a small magnetosphere similar to the one on Earth – very dynamic and with significant changes in response to the activity of the Sun. However, Mariner 10 had not managed to measure Mercury's magnetic field well enough to characterise it properly, thus the origin of Mercury's internal magnetic field was still not well understood.

4. The structure and state of Mercury's core

   Prior to the mission, scientists had only been hypothesising regarding Mercury's extensive iron-rich core. However, an observation would yield an unambiguous determination of the existence of the liquid core and provide a measurement of the radius of the liquid outer core as well. Thus, the observation would provide crucial information concerning the planet's evolution and core composition.

5. The radar-reflective materials at Mercury's poles

   In 1991, essential radar images of Mercury discovered high-reflexivity and high polarisation regions near Mercury's poles, showing similar properties with the polar cap of Mars and the icy moons of Jupiter and thus suggesting the indication of surface or near-surface ware ice.

6. The important volatile species and their sources and sinks near Mercury

   Unlike the atmospheres of Venus, Earth or Mars, Mercury's atmosphere is extremely thin and is a surface-boundary exosphere, consisting of six elements: hydrogen, helium, oxygen, sodium, potassium and calcium. However, prior to the MESSENGER, the source of these elements was still unanswered.

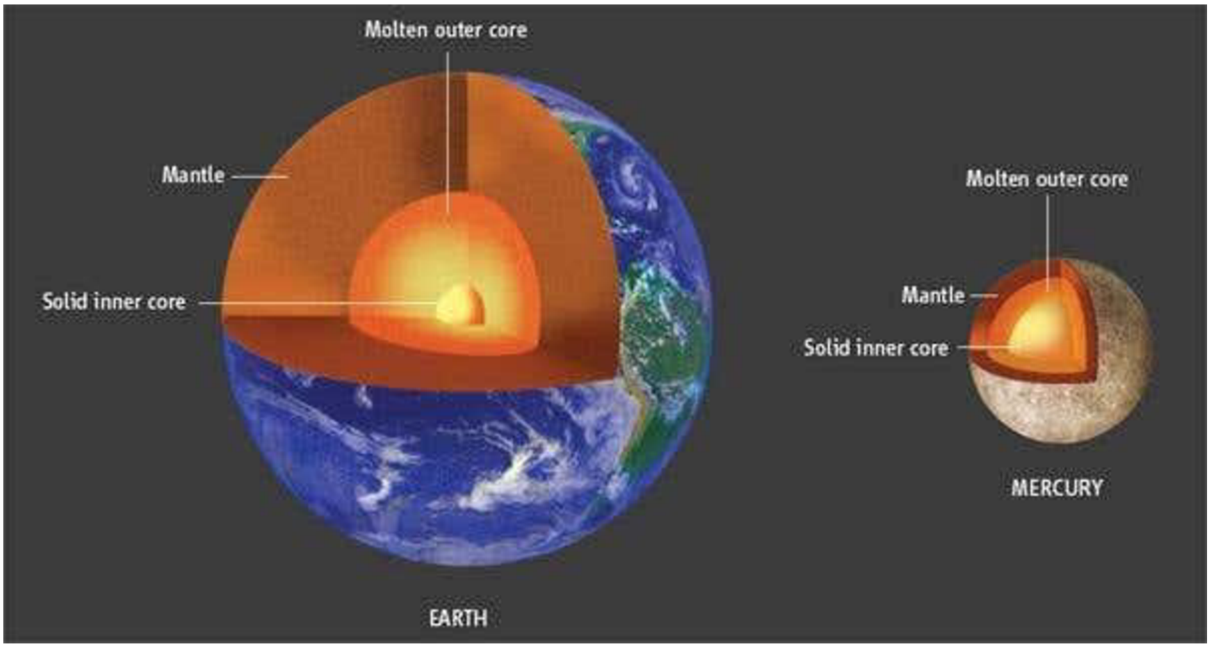


Figure 2: Interior of Earth and Mercury

2.3. Mission timeline

McNutt et al. (2005) suggested that the first concept of the MESSENGER mission should be conceived in March 1996, and proposed the concept to NASA in December of the same year. However, the project formally started in January 2000. The spacecraft was designed and operated by The Johns Hopkins University Applied Physics Laboratory (APL) and directed by the Principal Investigator, Sean C. Solomon. The prime launch opportunity was planned for March 2004, with backup launches identified in May 2004, July-August 2004. Finally, after schedule slips caused by necessary spacecraft testing, the spacecraft successfully launched from Cape Canaveral, Florida, on August 3, 2004. The spacecraft had to complete five large deep space manoeuvres, one Earth flyby, two Venus flybys, three Mercury flybys and one orbit-correction manoeuvre.

EARTH FLYBY

On August 2, 2005, MESSENGER accomplished the first flyby of the heliocentric trajectory at an altitude of 2347 km above Earth. The Earth flyby was performed flawlessly, and with the help of gravity-assisted manoeuvre, the spacecraft targeted towards Venus. (Moessner and McAdams, 2015)

VENUS FLYBYS

The first Venus encounter occurred on October 24, 2006, within 2987 km of the surface. On June 5, 2007, MESSENGER flew by Venus for the second time at an altitude of 338 km. (Moessner and McAdams, 2015)

MERCURY FLYBYS

After a number of trajectory-correction manoeuvres, on January 14, 2008, MESSENGER executed its first Mercury flyby at the closest approach altitude of 201.4 km. On October 6, 2008, MESSENGER accomplished its second flyby at 202 km periapsis altitude, with an impressive 1.406 km altitude error. The third and the last Mercury flyby occurred on September 29, 2009, at the lowest altitude above the planet of 227.5 km. (McAdams, Moessner and Dunham, 2011)

MERCURY ORBIT INSERTION

After more than six and a half years in cruise toward its destination, on March 18, 2011, MESSENGER successfully completed its orbit insertion manoeuvre and became the first spacecraft to orbit Mercury. Throughout the first year of orbiting Mercury, spacecraft maintained altitudes between 200 km and 506 km, and an orbital period of approximately 12 h. In mid-April 2012, the orbital period was reduced to 8 h and gradually decreased. In its final 44 days of the mission, MESSENGER maintained the minimum altitudes of 5.4 and 34.2 km. Finally, on April 30, 2015, the spacecraft impacted Mercury's surface with a speed of 3.912 km/s. (McAdams, Moessner and Dunham, 2011)

2.4. MESSENGER spacecraft

The MESSENGER spacecraft is equipped with the various vital innovations making the mission possible (Gold et al. 2003):

1) A ceramic-cloth sunshade
2) Three large, low-mass fuel tanks
3) Solar panels composed of 2/3 second-surface mirrors and 1/3 cells
4) A low mass composite structure
5) A pair of phased array antennas

The spacecraft structure is primarily light-weight composite material. The main size of the body is 1.44 meter tall, 1.28 meters wide, and 1.85 meters deep, with a front-mounted ceramic-cloth sunshade eliminating most of the solar input and two rotatable solar panels.

Thermal design

While orbiting Mercury, the harsh environment around the Mercury is significantly hotter than the one around Earth. Mercury's orbit swings the planet to within 46 million km of the Sun – about two-thirds closer to the Sun than Earth. MESSENGER uses a completely passive thermal design; no other mechanisms or lovers are required. A heat-resistant and highly effective sunshade provides thermal defence. The sunshade is made from 3M Nextel 312 ceramic cloth with an excess rate of 1000°C; under worst-case conditions, a 400°C temperature difference may occur between the sunshade and the spacecraft. (Santo et al., 2001)

Power

The spacecraft's primary source of electric power is two single-sided panels, thus the power generation increases as the spacecraft moves sunward. The power system comprises a power-system electronics system, a power distribution unit, a common-pressure vessel 23-ampere-hour nickel-hydrogen battery, and a solar array 5m2 in extent. (Santo et al., 2001)

Propulsion

The state-of-the-art, dual-mode propulsion system is designed to provide 2,250 m/s velocity change and incorporates a 645-N bipropellant thruster for large manoeuvres, four 22-N monopropellant thrusters for smaller trajectory adjustments, ten 4-N monopropellant thrusters for altitude control, plus two more providing velocity in the sunward direction. (Santo et al., 2001)

Telecommunications system

MESSENGER's X-band coherent communications system includes redundant Motorola small deep-space transponders, two light-weight phased arrays for downlink – the first electronically steered antennas used on a deep-space mission; and two medium-gain and four low-gain antennas for uplink and downlink communications. (Santo et al., 2001)

Command and data handling

Integrated Electronics Module (IEM) comprises the spacecraft's core avionics into a single box. Via Command and Data Handling (C&DH) subsystem, MESSENGER receives the operating commands from Earth that can be executed in real-time or stored for later execution. The spacecraft is also equipped with several vital techniques providing both a fault-protection and a high degree of redundancy, e.g. IEEE-1394 serial bus interface. (Santo et al., 2001)

Guidance and Control

To keep the precise orientation relative to Mercury, Earth and the Sun, MESSENGER uses the Guidance and Control (G&C) subsystem consisting of a suite of sensors for altitude determination, actuators for altitude corrections, and algorithms executed in the IEM, for continuous, closed-loop altitude control. The G&C sensor suite includes an Inertial Measurement Unit (IMU), which contains gyroscopes and accelerometers, two star trackers, five Sun sensors, and two Sun-sensor electronics units. (Santo et al., 2001)

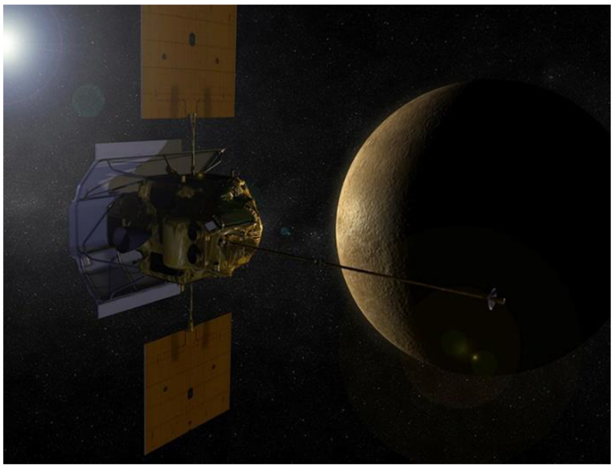


Figure 3: The MESSENGER spacecraft in deep space

2.5. Science payload

The MESSENGER spacecraft's payload consists of seven instruments and radio science. The instruments include a Gamma-Ray and Neutron Spectrometer (GRNS), an X-RAY Spectrometer (XRS), a Mercury Dual Imaging System (MDIS), a Magnetometer (MAG), a Mercury Laser Altimeter (MLA), a Mercury Atmospheric and Surface Composition Spectrometer (MASCS), and an Energetic Particle and Plasma Spectrometer (EPPS) (Gold et al. 2003). To ensure full connectivity, the instruments communicate through fully redundant Data Processing Units (DPUs). The process of selecting the scientific instrumentation is based on a total availability of mission resources, such as mechanical accommodation, power, mass and cost. In the case of MESSENGER, the significant constraints concerning mechanical accommodation and mass issues have already occurred during the preparation, since the payload mass was limited to only 50kg. Moreover, due to unique thermal constraints, all of the instruments are designed to withstand an extreme temperature range in a harsh environment, where the spacecraft's sunward face reaches temperatures above 350°C (Gold et al. 2003).

Instrument	Mass[a] (kg)	Power[b] (W)
MDIS	8.0	7.6
GRNS	13.1	22.5
XRS	3.4	6.9
MAG	4.4	4.2
MLA	7.4	16.4
MASCS	3.1	6.7
EPPS	3.1	7.8
DPUs	3.1	12.3
Miscellaneous[c]	1.7	
Total	47.2	84.4

[a] Mass includes mounting hardware and captive thermal control components. The mass for MDIS includes the calibration target. The MAG mass includes the boom

[b] Nominal average power consumption per orbit; actual values will vary with instrument operational mode and spacecraft position in orbit

[c] Includes purge system, payload harnesses, and magnetic shielding for the spacecraft reaction wheels

Figure 4: MESSENGER payload characteristics

Gamma-Ray and Neutron Spectrometer (GRNS)

The GRNS (Goldsten et al., 2007) consists of two sensors, a Gamma-Ray Spectrometer (GRS) and a Neutron Spectrometer (NS).

The Gamma-Ray Spectrometer sensor is a cryo-cooled, high-purity germanium detector with an active shield and measures the abundances of geologically essential elements such as oxygen, silicon, sodium, iron, hydrogen, as well as naturally radioactive elements, potassium, thorium and uranium.

The Neutron Spectrometer sensor consists of two lithium glass scintillators, separated by a thick slab of neutron-absorbing, borated plastic scintillator on both ends. The glass scintillator plates are loaded with lithium to measure thermal and epithermal neutrons.

X-RAY Spectrometer (XRS)

The X-RAY Spectrometer (Schlemm et al. 2007) is an improved version of Near Earth Asteroid Rendezvous (NEAR) Shoemaker X-ray spectrometer to detect atomic surface abundances in the 1-10keV energy range – specifically, magnesium, aluminium, silicon, calcium, titanium and iron by solar-induced X-ray fluorescence.

Mercury Dual Imaging System (MDIS)

The Mercury Dual Imaging System (Hawkins et al., 2007) is constructed with both wide-angle and narrow-angle cameras (the "WAC and "NAC", respectively) with an on-board pixel summing capacity providing images of nearly uniform resolution throughout the elliptical orbit while minimising downlink requirements. The MDIS is the only instrument with a pointing independent of the spacecraft altitude, thus enabling the pivot to point 50° toward the Sun and to 40° anti-sunward centred on nadir.

The WAC has a 10.5° field of view (FOV) and can observe Mercury through a 12-position filter providing full-colour mapping.

The NAC can take high-resolution images through a single band-limiting filter and its 1.5° field of view.

Magnetometer (MAG)

The magnetometer (Anderson et al., 2007) is a three-axis, ring-core, fluxgate detector of the same basic design as its predecessors that have flown on a number of planetary missions. The sensor is mounted on a light-weight 3.6-m long carbon-fibre boom that keeps it away from the spacecraft's own magnetic field. MAG characterises Mercury's magnetic field in detail, thus providing the scientist with the crucial information of the field's source, specific strength and how it varies with position and altitude.

Mercury Laser Altimeter (MLA)

The MLA instrument (Cavanaugh et al. 2007) consists of a diode-pumped, Q-switched, Cr:Nd:YAG laser transmitter operating at 1064 nm, delivering eight pulses per second, and four receiver telescopes with sapphire lenses. The altimeter maps Mercury's landforms and provides a high-precision measurement of surface topography in order to determine the planet's forced physical librations.' The combination of a silicon avalanche photodiode and a time-interval unit – based on an application-specific integrated circuit (ASIC) chip – measures altitudes up to 1200 km with a 30-cm resolution.

Mercury Atmospheric and Surface Composition Spectrometer (MASCS)

MASCS is a combination of an Ultraviolet-Visible spectrometer (UVVS) and a Visible-Infrared Spectrograph (VIRS); both spectrometers are contained in the same package and fed by a single front-end telescope. (McClintock and Lankton, 2007)

The UVVS is a 125-mm focal length spectrometer providing the measurement of the altitude profiles in order to determine the composition and structure of Mercury's exosphere.

The VIRS is a 210-mm focal length spectrometer that detects minerals in Mercury's surface materials in order to obtain a mineralogical composition on spatial scales up to 5 km.

Energetic Particle and Plasma Spectrometer (EPPS)

The EPPS instrument (Andrews et al., 2007) measures characteristics of charged particles in and around Mercury's magnetosphere via the combination of an Energetic Particle Spectrometer (EPS) and a Fast Imaging Plasma Spectrometer (FIPS).

The FIPS measures the energy spectra, angular, and compositional distributions of the low-energy components – energy ions with low energy per change.

The EPS observes ions and electrons accelerated in the magnetosphere and measures the energy spectra, angular, and compositional distribution of these ions and electrons.

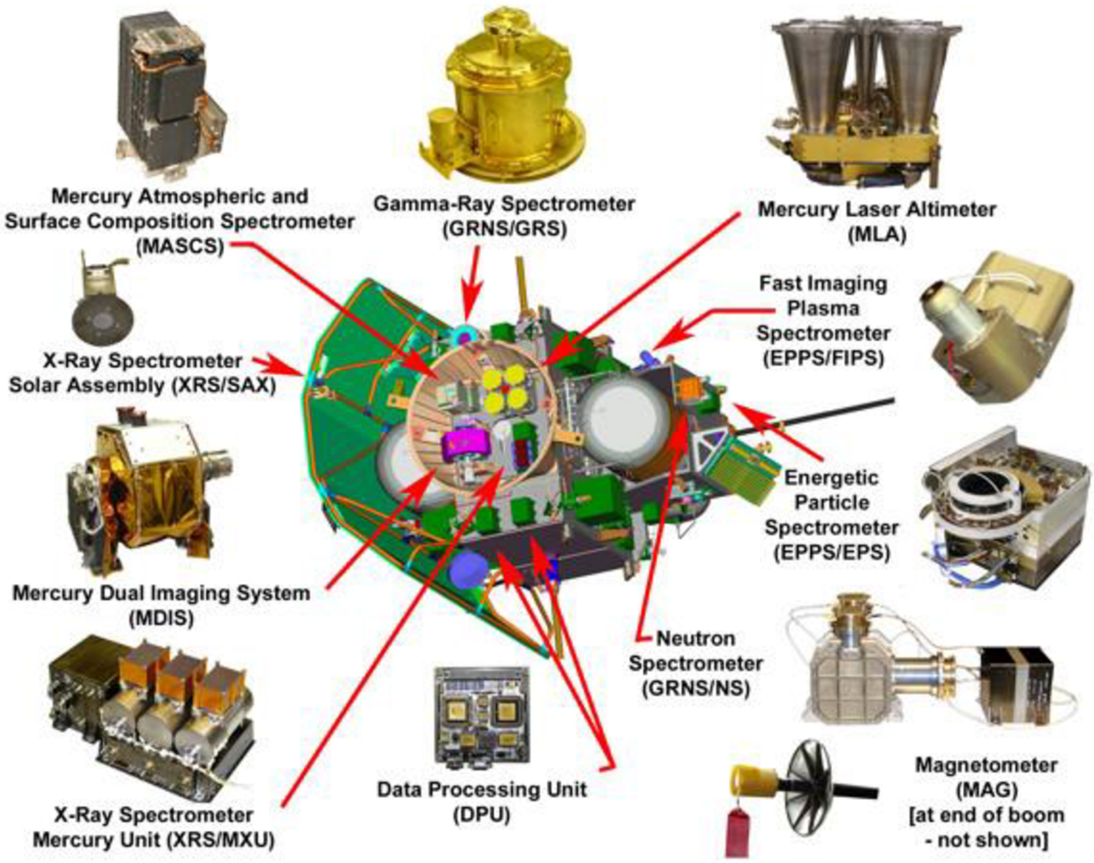


Figure 5: MESSENGER payload instruments and their location

2.6. Science results

Volatile-Rich Planet

Mercury is noticeably rich in volatile elements that evaporate at moderately higher temperatures than scientists expected prior to the mission. The MESSENGER's X-ray spectrometer provided vital chemical information from the surface, discovering the abundances of volatile elements like sulphur, sodium and chlorine. Additionally, the high sulphur contents combined with low amounts of iron on the surface indicate that Mercury was formed from materials with less oxygen compared to the other terrestrial planets.

Ice on Mercury

Both of Mercury's Polar Regions are permanently shaded from the heat of the Sun contain water ice. Despite being the closest planet to the Sun, Mercury's low axial tilt results in the existence of Polar Regions that experience an average temperature of about - 70°C. Based on MESSENGER's data, neutrons signals were detected and confirmed the presence of water ice in larger craters.

Magnetic field

Mercury's magnetic field is offset from the centre of the planet by approximately 20%. Due to the fact that Mercury experiences strong solar wind, which then interacts with the planetary field, it generates current in the magnetosphere, which results in induction of external magnetic fields with magnitudes equal to or higher than the planetary field in much of the magnetosphere.

Furthermore, among mission accomplishments, we can also include the discovery of the highly dynamic magnetosphere, which is mainly a result of a small magnetic field and proximity to the Sun.

Hollows

Hollows were first noticed in Mariner 10 images, but the resolution was not high enough to study them. Mercury's hollows, in other words, irregular depressions, were likely formed as a result of the loss of a volatile constituent from the surface by sublimation. What is more, hollows are thought to be the youngest features on Mercury's surface.

Volcanic Deposits

It comes as no surprise that volcanism had played a crucial role in shaping the planet's surface. As a result of MESSENGER's data, not only a number of valleys formed by quickly flowing lava were examined, but also large volcanic deposits were discovered on Mercury's surface. According to the results from Byrne et al. (2016), major volcanism on Mercury stopped at around 3.5 billion years ago, proving that there is a huge geological difference between Mercury and Earth, Mars or Venus.

Energetic Electrons

Already Mariner 10 in 1974 discovered that energetic particle bursts were present inside the miniature Mercury magnetosphere. Decades later, the combined data from MESSENGER's multiple instruments detected the presence of energetic electrons, whose energy ranges from a few keV to several hundred keV in electron kinetic energy (Baker et al., 2016).

Mercury's Contraction

Mercury has experienced radial contraction primarily driven by interior cooling. As a result, it has shrunk in radius by 7 kilometres – the most significant global contraction among terrestrial planets. However, according to the latest study provided by Watters (2021), it is not that accurate. Furthermore, Watters argues that a number of faults occurred during the estimation of the total magnitude of contraction, resulting in a considerable radius reduction. In his work, he ultimately states the radius change did not exceed 2 kilometres.

Exosphere

In fact, Mercury has an extremely tenuous atmosphere; as a consequence, it has only an exosphere, which is mainly composed of atoms and molecules released from the surface of the planet, like oxygen, sodium, hydrogen, helium and potassium.

Caloris Basin

The MESSENGER spacecraft continued and broadened the exploration of the Caloris Basin. Its fairly advanced technology compared to Mariner 10 provided essential high-resolution images used to determine the structure and formation of this unique crater more precisely. Through the use of MESSENGER's wide-angle and narrow-angle cameras, scientists discovered a complex arrangement of tectonic landforms. The uniqueness of this basin that makes it different from other impact features on other planets and moons is the presence of both the contractional wrinkle ridges and extensional graben. According to Cunje and Ghent (2016), there are three distinct structural classes, the radial graben of Pantheon Fossae located from the basin centre to 400 km outward, the concentric graben and randomly oriented troughs between 350 km to 600 km from the centre of the basin, and the wrinkle ridges. Moreover, various regions throughout the basin show mutual interactions and relationships that proved the forecasts about the sequence of tectonic events. Despite a number of gained data, an additional examination is needed, thus future data from BepiColombo will be essential in terms of further understanding of the tectonic complexity of the Caloris Basin.

3. MISSION BEPICOLOMBO

The BepiColombo mission to Mercury, launched in October 2018, is a collaboration of ESA (European Space Agency) and JAXA (Japan Aerospace Exploration Agency), with the objective to study the planet and its environment in order to provide further details concerning Mercury's interior, surface, exosphere and magnetosphere. According to Benkhoff et al., 2010, the name of the mission honours a well-known scientist, Giuseppe Colombo: "The mission has been named in honour of Giuseppe (Bepi) Colombo (1920–1984), who was a brilliant Italian mathematician, who made many contributions to planetary research, celestial mechanics, including the development of new space flight concepts." (Benkhoff, p. 2)

3.1. International endeavour

3.1.1. JAXA

The Japan Aerospace Exploration Agency (JAXA) is the Japanese national aerospace and space agency, formed in 2003 through the merger of three institutions (the Institute of Space and Astronautical Science, the National Aerospace Laboratory of Japan and the National Space Development Agency of Japan). Prior to JAXA, the preceding agencies focused on robotic space missions, aerospace technology, vehicles launch, as well as spaceflights to conduct research on the ISS.

3.1.2. ESA

The European Space Agency (ESA) was established in 1975 as a merger of its predecessors, the European Space Research Organisation (ESRO) and the European Launcher Development Organisation (ELDO). ESA is an inter-governmental organisation, currently comprising 22 member states, including the Czech Republic, and together with NASA and JAXA, it also participates in the International Space Station program.

3.2. Mission objectives

Balogh et al. (2007) emphasises that the primary goal of the BepiColombo mission is not to discover new features of Mercury, although it cannot be excluded, but instead provide the comprehensive set of observations and thus bring the necessary knowledge of the origin and evolution. The mission will complement the work of MESSENGER and focus on five major areas – interior, surface, exosphere, magnetosphere and fundamental physics.

Benkhoff et al. (2010) pointed out the main scientific objectives:

1. Study the origin and evolution of a planet close to its parent star.

   Although the Moon has often been used as a comparison to Mercury, the surface of Mercury was by a greater degree modified by heavy bombardment and solar wind particle precipitation due to its proximity to the Sun. The new discoveries may provide crucial data not only about Mercury's origin but also about the origin of the other terrestrial planets in our solar system.

2. Determine Mercury's figure, interior structure and composition.

   There are plenty of formation models of Mercury's interior structure, and however, even after the results published by the MESSENGER team, they are still inconclusive. New findings may give a clue regarding the detailed formation of the crust, mantle and metallic core.

3. Detect exogenic and endogenic surface modifications, cratering, tectonics, volcanism.

   Although the knowledge of Mercury's surface is based on the Mariner 10 and MESSENGER data, it is not that sufficient. Denevi et al. (2009) found that 40% of the Mercury surface is covered by smooth plains. However, without the BepiColombo mission, it is not possible to conclude the exact details about the composition of volcanic deposits.

4. Analyse composition, origin and dynamics of Mercury's exosphere and polar deposits.

   Measurements of MESSENGER provided the crucial findings of Mercury's atmosphere, which is tenuous to a great degree that it is called an exosphere. However, due to possible anomalies in specific geographic locations, it is essential to observe as many different spots as possible.

5. Examine the structure and dynamics of the planet's magnetosphere.

   Little to nothing has been known about the physics of Mercury's magnetic field. Therefore, in order to gain the required information, BepiColombo is expected to examine the kinetic correction, solar wind and magnetosphere coupling to the planet, the substantiality of heavy ions and how much the boundary condition at the planet's surface matters.

6. Perform a test of Einstein's theory of general relativity.

   MPO will provide a test of general relativity to a level better than 10^{-5} by the measurement of time delay and Doppler shift of radio waves and the precession of Mercury's perihelion.

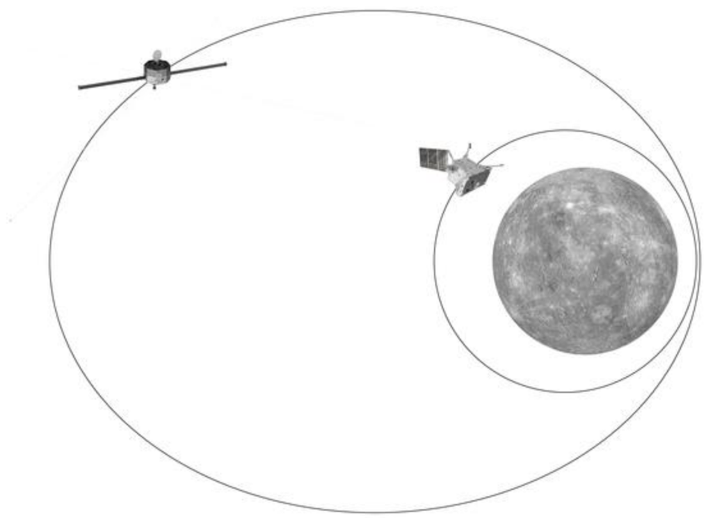


Figure 6: MPO and MMO in their elliptical polar orbits around Mercury

3.3. Mission timeline

The first discussion concerning the possible collaboration was initiated in November 1999. Almost one year later, in July 2000, the official request was sent, and ESA approved the BepiColombo as a cornerstone-class mission (Balogh et al., 2007). The payload selection took place in 2005 and the initial launch was planned for October 2013. After several delays, the BepiColombo was finally launched into an Earth escape orbit on October 20, 2018, with Ariane-5 from Kourou (Steiger et al., 2020).

The Launch and Early Orbit Phase (LEOP), as the initial phase, lasted for the first 2.5 days and consisted of critical activities to ensure communication and normal behaviour as well as orbit control test manoeuvre. From October 22 to December 20, 2018, the first part of the Near Earth commissioning phase (NECP) took place, intending to perform a complete checkout of the spacecraft. The second part of NECP was used to perform investigation activities for issues encountered in part one. Besides the commissioning operations, two electric propulsion thrust arcs took place in the first year of flight. The second solar electric propulsion arc of the mission took place in November 2019 (ESA).

The Earth flyby occurred on April 15, 2020. According to the ESA, the spacecraft headed toward the Venus orbit, where it successfully executed the first Venus flyby on October 15, 2020, within the closest approach of 10,720 kilometres above the planet's surface. The next Venus flyby is expected on August 10, 2021, with a much lower altitude above the surface – 552 km, allowing a great range of investigations (ESA).

More importantly, in the upcoming 5 years, BepiColombo will execute 6 flybys around Mercury, planned for August 2021, October 2021, June 2022, June 2023, September 2024, December 2024 and the final sixth flyby for January 2025. Ultimately, after completing the cruise phase lasting 7.2 years, BepiColombo will enter Mercury's orbit, without an orbit insertion manoeuvre being required, on December 5 2025. Nominal mission science operations will last one year, with a planned extension of another year (Steiger et al., 2020).

3.4. BEPICOLOMBO SPACECRAFT

3.4.1. Mercury Planetary Orbiter (MPO)

ESA's MPO (Benkhoff et al., 2010) carries mainly remote sensing and radio science instrumentation, accommodating a total of 11 scientific instruments. MPO has a box-like shape with a size of 3.9 x 2.2 x 1.7m and a dry mass of approximately 1080kg. Two tanks of propellant are located in the centre of the orbiter, for the propulsion system.

Power

MPO's average power demand in Mercury orbit, while conducting scientific measurements, is approximately 1300W – provided via 28V regulated power bus by the solar array, single 3-

panel wing, and a battery during eclipse phases. Due to proximity to the Sun, high intensity of solar irradiation occurs. Therefore, incident angles of solar arrays must be precisely set in order to generate enough energy but not to exceed the maximal limit of the solar array.

Thermal design

The harsh environment near Mercury creates the need to provide the spacecraft with a complex passive thermal design to ensure that the payload will be able to withstand such high temperatures. The passive control elements include a second surface mirror (SSM), multi-layer insulator (MLI), thermal shield, paints and films. The temperatures inside the spacecraft are kept within the range of 0°C and 40°C. Nevertheless, in the case of specific instruments, temperatures are kept below -10°C. This is provided by the heat pipes embedded in the double-H panels and radiator.

Communications

For communication with Earth, MPO uses a high-gain antenna, used for science data transmission, a medium-gain antenna, providing global coverage and two low-gain antennas. The high-gain antenna not only provides data transmission but also supports uplink and downlink in both frequency bands for Mercury Orbital Radio Science Experiment (MORE).

Altitude control

The altitude is controlled by three star trackers, sun sensors and a high precision gyroscope package. Through the combination of these systems, precise altitude is determined within seconds – which is also required for several experiments.

Propulsion

The propulsion system operates in a “dual-mode” since it uses various fuels based on the operation modes. It comprises four redundant 22N thrusters, located in the nadir face of the spacecraft, and four 10N thrusters mounted on the radiator. The 22N thrusters use hydrazine as a fuel and nitrogen tetroxide (NTO) as the oxidiser, whereas the 10N thrusters use only pure hydrazine.

3.4.2. Mercury Magnetospheric Orbiter (MMO)

MMO (Yamakawa et al., 2008), provided by JAXA, is an octagonal spin-stabilised spacecraft carrying mainly instrumentation for fields and particle science. The main structure of MMO has an octagonal shape, which can be surrounded by a 1.8 m diameter circle and is 0.9 m in height, and comprises two decks, a central cylinder and four bulkheads. The total mass of MMO, including payload and N_2 gas, is 250 kg.

Power

Since MMO is not exposed to the direct solar flux during the cruise phase, the heater power is provided by MPO. After the separation, the solar cells will ensure the energy source; the voltage of the bus is 50 V. A Li-Ion secondary type battery has an initial capacity of 28Ah and is designed to cope with the maximum eclipse condition around Mercury lasting 2 hours, and thus provide the required energy.

Thermal design

Like MPO, MMO is also provided with the passive thermal design in order to withstand high temperatures at Mercury's orbit. The passive control elements include a thermal shield, SSM, paints, films and MLI blankets. The external surface of the upper deck, central cylinder and thermal shield are covered with the MLI to ensure the protection of internal equipment. More significantly, in order to equalise internal temperature, most of the internal components have a surface of high emissivity (i.e. black paint).

Communications

The communication with Earth is provided by a helical array antenna (HAA). The main benefits of deploying the HGA (high gain antenna) system are high efficiency, low weight, wide frequency band, simple flat structure and avoidance of solar flux concentration. At Mercury's orbit, the telemetry rate will change as the distance from Earth will differ; the average bit is 16 kbps, resulting in approx. 40 Mbyte sent per day.

Altitude control

The altitude is ensured by a pair of sun sensors and a star scanner, and controlled by the propulsion system with a cold gas jet. The cold gas jet system consists of one propellant tank, piping, six 0.2N class Nitrogen gas jet thrusters, valves, and the equipment for thermal control (e.g. sensors and heaters). The volume of the tank is 14.7 l, consists of titanium alloy liner and carbon fibre shell and is loaded with 4.25 kg of nitrogen.

3.4.3. Mercury Transfer Module (MTM)

The MTM (Benkhoff et al., 2010), developed by ESA, provides electrical and chemical propulsion means – acceleration and braking – for the cruise towards Mercury. To supply the high power demand (i.e. up to 10kW) for the propulsion, the dedicated propulsion module uses its large solar arrays covering over 40 m^2, delivering up to 14 kW at their peak. The MTM is equipped with a bi-propellant propulsion system consisting of 10N thrust used either for altitude control or navigation manoeuvres during the cruise. Once close to Mercury, the MTM will separate from the spacecraft stack; subsequently, the remaining modules will drift into Mercury's orbit.

3.4.4. MMO sunshield and interface structure (MOSIF)

Similarly to MPO and MTM, MOSIF (Benkhoff et al., 2010) was also developed by ESA. Its only task is to protect MMO from the full intensity of the Sun until the final separation at operational orbit. The sunshield, located between MPO and MMO, has a metal truss structure covered with MLI and thus ensures suitable temperatures for MMO.

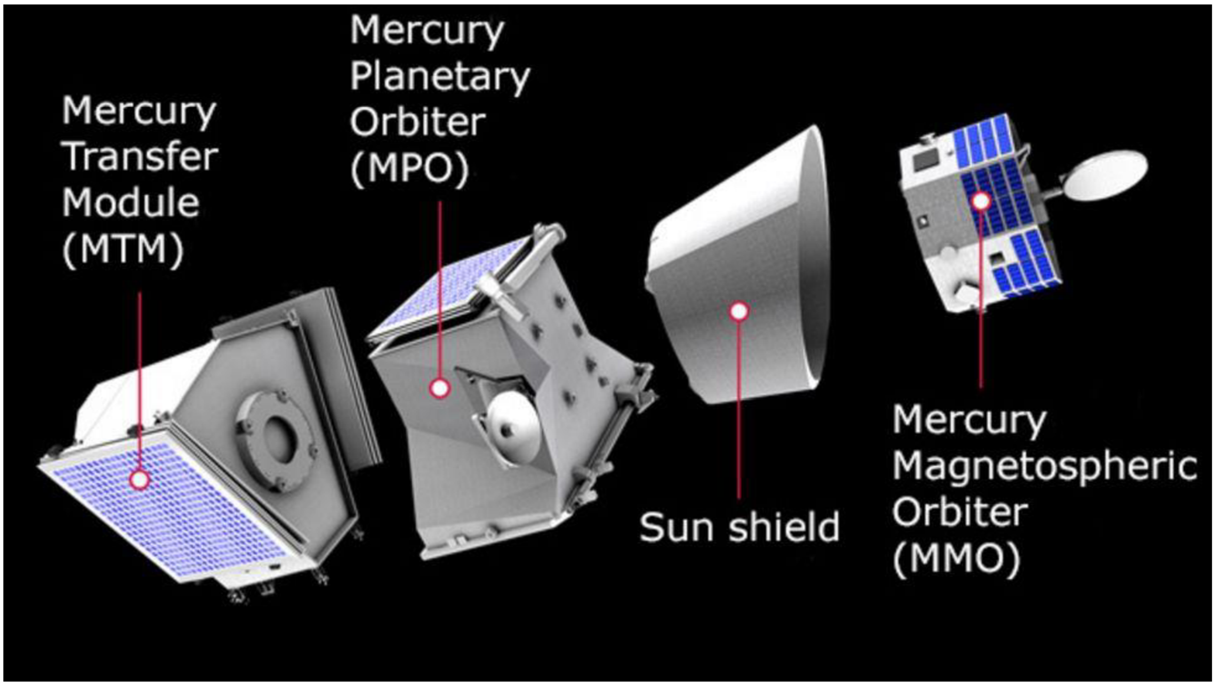


Figure 7: Elements of the BepiColombo Mercury Composite Spacecraft

3.5. SCIENCE PAYLOAD

3.5.1. Mercury Planetary Orbiter (MPO)

BepiColombo Laser Altimeter (BELA)

The BepiColombo Laser Altimeter (Gunderson and Thomas, 2009) is, generally speaking, a classical laser altimeter with the same approach as Mars Orbiter Laser Altimeter (MOLA). BELA will perform the measuring of the topography, figure and surface morphology of Mercury. Consequently, in synergy with other instruments, BELA will provide the scientists with the opportunity to explore the interior structure and geologic evolution in detail.

Italian Spring Accelerometer (ISA)

The Italian Spring Accelerometer (Iafolla et al. 2009) is a three-axis accelerometer devoted not only to measurements concerning the planet but also to test Einstein's theory of general relativity in unprecedented accuracy.

Magnetic Field Investigation (MPO-MAG)

The Magnetic Field Investigation (Glassmeier et al. 2009) includes a dual fluxgate magnetometer system, which is able to measure 3D magnetic fields, and two sensors, used for the determination of magnetic contamination. The primary objective is to measure the planetary magnetic field, the interaction of the solar wind and the formation, and the dynamics of the magnetosphere. Thus, it provides the possibility of understanding the origin, evolution and current state of Mercury's interior.

Mercury Radiometer and Thermal Imaging Spectrometer (METRIS)

The Mercury Radiometer and Thermal Imaging Spectrometer (Hiesinger et al. 2009) were built up with the micro-bolometer technology – for this reason, no cooling is required. As the essential part of the upcoming mission, METIS will deal with the surface composition, mineralogy of the planet in high-spectral resolution. Furthermore, METRIS will provide the study of surface temperature variations and thermal inertia.

Mercury Gamma-ray and Neutron Spectrometer (MGNS)

The Mercury Gamma-ray and Neutron Spectrometer (Mitrofanov et al. 2009) is designed to measure the elemental composition of the surface and subsurface of Mercury, and identify the regional distribution of volatiles in permanently shadowed polar areas.

Mercury Imaging X-ray Spectrometer (MIXS)

The Mercury Imaging X-ray Spectrometer (Fraser et al. 2009) consists of two channels – the MIXS-C, used to separate the significant Mercurian terrains and the MIXS-T, an imaging telescope for high-resolution measurements of the surface. The MIXS will perform an X-ray fluorescence analysis of the surface, and consequently, the combination of both channels will help to determine rock types, the surface evolution and ultimately reveal the formation process of the planet.

Mercury Orbiter Radio science Experiment (MORE)

The Mercury Orbiter Radio-science Experiment will not only characterise the most advanced interplanetary tracking system ever built but also determine the gravity field of Mercury, the size and physical state of its core, whether it is molten or not, as well as provide the radius of this molten core. In addition, MORE will measure the gravitational oblateness of the Sun.

Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS)

The Probing of Hermean Exosphere by Ultraviolet Spectroscopy (Chassefière et al., 2009) includes three detectors to detect emission lines – EUV detector for the range 25-155nm, FUV for 145-315nm and additional low-resolution NUV detector to cover the 404 and 422nm. PHEBUS is devoted to characterising Mercury's exosphere composition and dynamics.

Search for Exosphere Refilling and Emitted Neutral Abundances (SERENA)

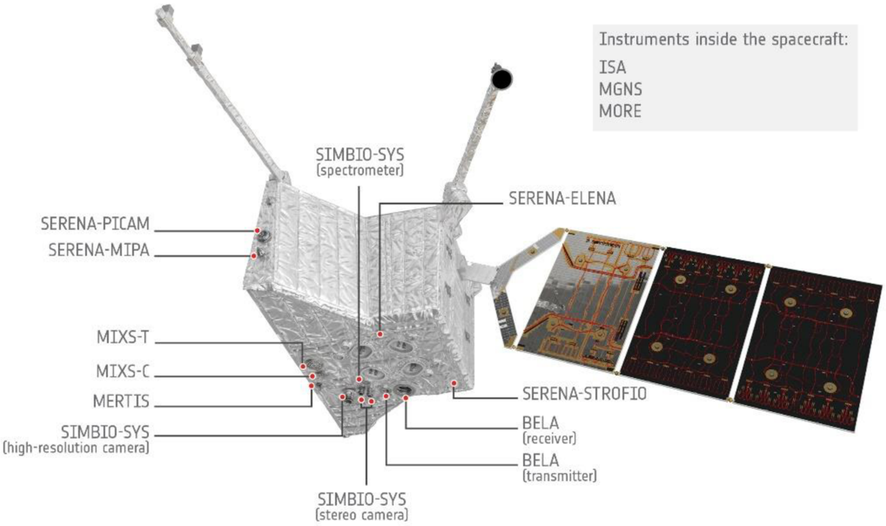
The primary scientific objective of the Search for Exosphere Refilling and Emitted Neutral Abundances (Orsini et al. 2009) is to collect data about the global surface-exosphere-magnetosphere system and its interaction with the solar wind. The SERENA instrument includes four units – (1) the Emitted Low-Energy Neutral Atoms unit (ELENA) to measure energetic neutral particles that escape from Mercury's surface, (2) the Start from a Rotating Field Mass Spectrometer unit (STROFIO) to monitor the cold exospheric gas composition, (3) the Miniature Ion Precipitation Analyser unit (MIPA) to measure ions that precipitate towards the surface, and (4) the Planetary Ion Camera unit (PICAM).

Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System (SIMBIO-SYS)

The Spectrometer and Imagers for MPO BepiColombo Integrated Observatory System (Flamini et al. 2009) are used to spectroscopically investigate Mercury, including the surface geology, volcanism, global tectonics, surface age, surface composition and geophysics. The system consists of: (1) the Stereo Channel, which provides the global colour coverage of the surface; (2) the High Spatial Resolution Imaging Channel that characterises surface targets with high-resolution images; and (3) the Visible Infrared Hyperspectral Image Channel, which provides the global mineralogical composition of the surface.

Solar Intensity X-ray and particle Spectrometer (SIXS)

The main objective of the Solar Intensity X-ray and particle Spectrometer (Huovelin et al. 2009) is to monitor the flux of X-rays and energetic particles of solar origin, and thus, study the interaction of the radiation with Mercury's surface, exosphere and magnetosphere.



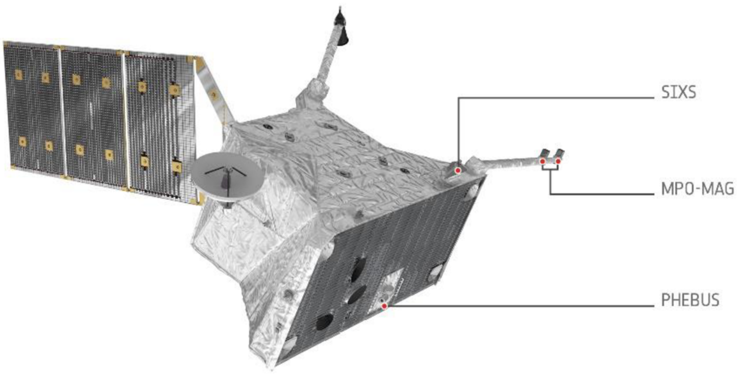


Figure 8: The science instruments of MPO

3.5.2. Mercury Magnetospheric Orbiter (MMO)

Mercury Magnetometer (MMO-MAG)

The Mercury Magnetometer (Baumjohann et al. 2009) is used to collect Mercury's magnetic field measurements. The magnetometer includes two sets of fluxgate magnetometers, MGF-O (digital-type) for the external sensor and MGF-I (analogue-type) for the internal sensor.

Mercury Plasma Particle Experiment (MPPE)

The Mercury Plasma Particle Experiment (Saito et al. 2009) consists of seven sensors: two Mercury Electron Analysers (MEA1 and MEA2), Mercury Ion Analyser (MIA), Mercury mass Spectrum Analyser (MSA), High Energy Particle instrument for the electron (HEP-ele), High Energy Particle instruments for ion (HEP-ion) and Energetic Neutrals Analysers (ENA). The MPPE was proposed to investigate plasma and energetic particles in the magnetosphere and the interaction between the solar wind and the magnetosphere.

Mercury Plasma Wave Instrument (PWI)

The Mercury Plasma Wave Instrument (Kasaba et al. 2009) will analyse electric fields, plasma wave and radio waves in Mercury's plasma environment. The PWI comprises three sets of receivers, connected to two sets of electric field sensors, and two kinds of magnetic sensors.

Mercury Sodium Atmosphere Spectral Imager (MSASI)

The Mercury Sodium Atmosphere Spectral Imager (Yoshikawa et al. 2009) will address a number of fundamental scientific questions concerning Mercury's exosphere. Due to the tenuous atmosphere, Mercury has a substantial sodium component. Therefore, MSASI, as the first instrument to provide high-spectral performance in planetary science, will measure the abundance, distribution and dynamics of sodium in Mercury's exosphere.

Mercury Dust Monitor (MDM)

The Mercury Dust Monitor (Nogami et al. 2009) consists of a PZT sensor unit mounted to the outside panel and the electronics unit installed inside the spacecraft. The primary objective of this system is to obtain new data concerning the dust environment at Mercury's region of the solar system. It is also capable of detecting the impact momentum, crude direction and the number density of the dust.

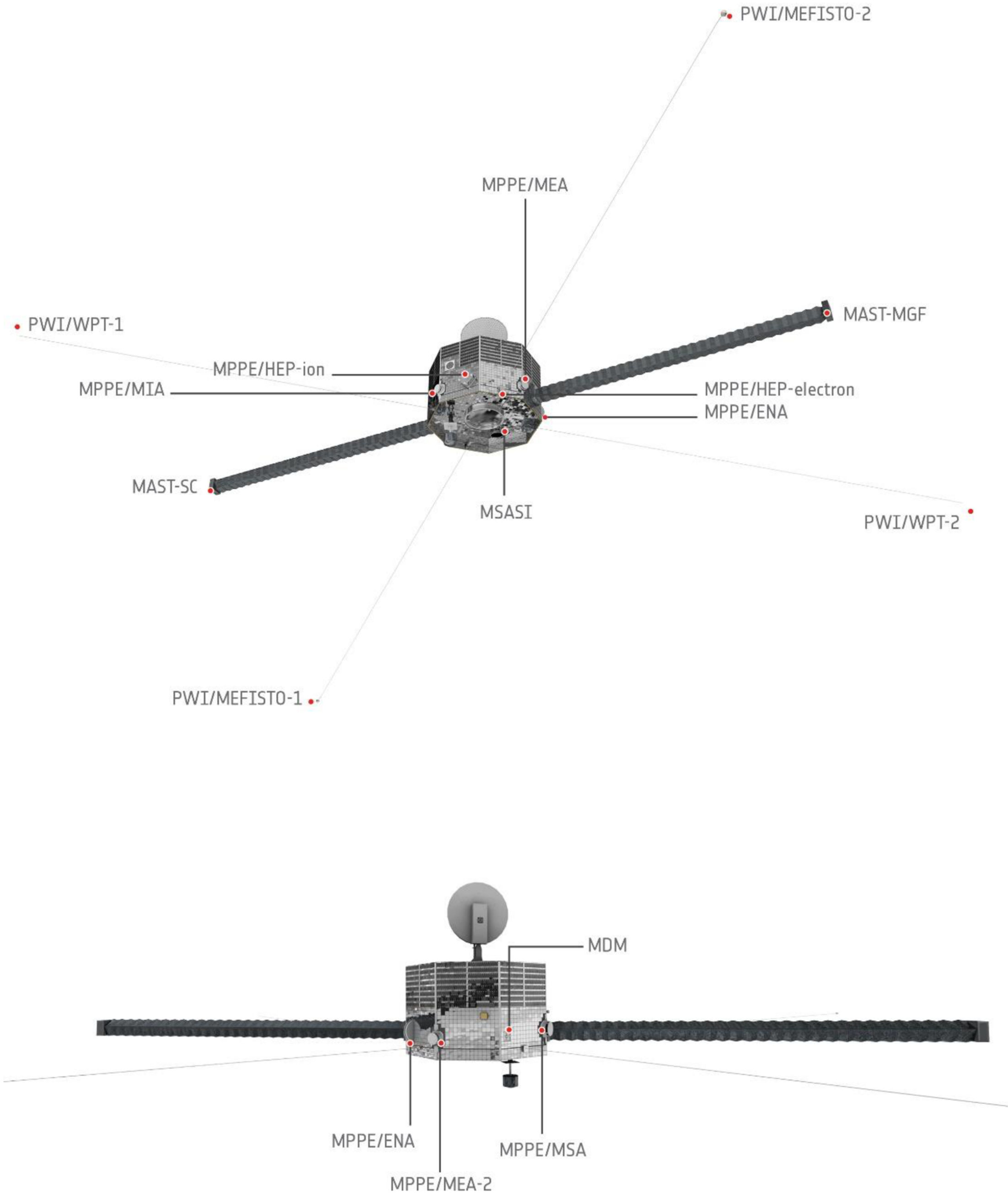


Figure 9: The science instruments of MMO

4. FROM MESSENGER TO BEPICOLOMBO

MESSENGER was considered a crucial mission since it was the first spacecraft to visit Mercury since Mariner 10 in 1976. Despite the fact that this mission was the least expensive among NASA´s Discovery missions, it was an incredible success. MESSENGER carried seven science instruments and provided not only a tremendous global photographic colour map of Mercury, but also crucial discoveries about the planet's topography, gravity and surface composition.

In contrast, the BepiColombo mission is a significant degree larger mission than MESSENGER, with a total cost of over 2 billion dollars. Furthermore, it is essential to mention that the ESA and JAXA contributed to this mission together by a great degree. Both of these space agencies consider BepiColombo to be their flagship mission. Although a variety of instruments are very similar to ones carried by MESSENGER, they are more advanced. Therefore, the BepiColombo mission has a higher capability to provide more details and contribute as indispensable evidence to furthering the planet research (McNutt et al., 2004). The variance in used technology is one of the major differences between the missions. It comes as no surprise that technology is evolving at a tremendous pace. The fact that the BepiColombo was launched more than a decade later indicates the difference in the spacecraft´s instruments.

In the case of MESSENGER, the payload selection process had severe constraints, as mentioned in previous chapters, for instance, the payload comprised seven instruments, and the mass was limited to 50 kilograms. The more sophisticated payload of BepiColombo includes the MPO´s 11 instruments and mass of 80 kilograms, and MMO´s five instruments and mass of 40 kilograms. In total, BepiColombo carries 16 relatively advanced instruments with a mass of 120 kilograms, which is more than twice the mass of MESSENGER.

As for the actual mass of science payload, the enlargement of the spacecraft's mass proportionally leads to an increase in the amount of fuel needed. The implementation of all the required equipment results in more challenging propulsion as well as power design. The total launch mass of BepiColombo is 4,100 kilograms. In particular, for MMO, the mass is 255 kilograms, for MPO 1200 kilograms, for MOSIF 125 kilograms and the mass of MTM is 1,100 kilograms (ESA). In contrast, the launch mass of the MESSENGER spacecraft was almost four times lower, only 1,107.9 kilograms. As mentioned earlier, for power supply and propulsion during the cruise, BepiColombo uses MTM. To power more than 4 tons of mass, BepiColombo is equipped with 1,400 kilograms of propellant. This is a crucial point as regards the progress in used technology. Specifically, the propellant load of MESSENGER spacecraft was 600 kilograms, which is 54 per cent of the total spacecraft launch mass. Whereas, in the case of BepiColombo spacecraft, the propellant mass takes up only 34 per cent of its total launch mass. This increased efficiency is provided as a result of the application of Monomethylhydrazine (N_2O_4-MMH) as a fuel, compared to hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) used for MESSENGER´s propulsion.

The branch of communications is also crucial in terms of development between the two missions. MESSENGER´s communications system was based on X-band, which was described in the chapter dealing with MESSENGER Spacecraft. The transmission comprised status data, operating command, emergency communications etc. This was performed at a downlink rate from 9.9 bps to 104 kbps, and uplink 7.8 to 500 bps. The rates varied according to spacecraft distance from ground-station on Earth. In the case of BepiColombo, it uses two distinctive technologies for each spacecraft. For MMO, the average bit rate is expected to be about 16 kbps, which is slightly higher than in the case of MESSENGER - this bit rate for the proper functionality of MMO is more than sufficient. Moreover, the main advantage is that the communications are extremely stable. MPO uses a state-of-art dual uplink-downlink X/Ka-band with an average data rate of 50kbps. As a consequence, the higher data rate has a direct impact on spatial resolutions.

Another difference between the two missions is that BepiColombo consists of two different spacecraft, which will be disjoined from MTM after orbit insertion. Both of them will be orbiting Mercury in different orbits and altitudes, and thus they will have a considerably better reach of the planet than MESSENGER. Consequently, this ensures new investigation opportunities. MESSENGER was orbiting Mercury with its lowest altitude over the northern hemisphere and provided deep investigation of this part of Mercury. However, unlike MESSENGER, both MPO and MMO will orbit over the southern hemisphere and at significantly lower altitude. In particular, MMO´s orbit is more elliptical with an altitude range of 400 kilometres to 12,000 kilometres, while the MPO´s periapsis will be over the equator approaching the planet closely at all latitudes ranging from 400 kilometres to 1500 kilometres. Therefore, more detailed observations in this hemisphere will complement and enlarge the planet’s information as a whole. Figure 10 clearly demonstrates the relative latitudes of each spacecraft.

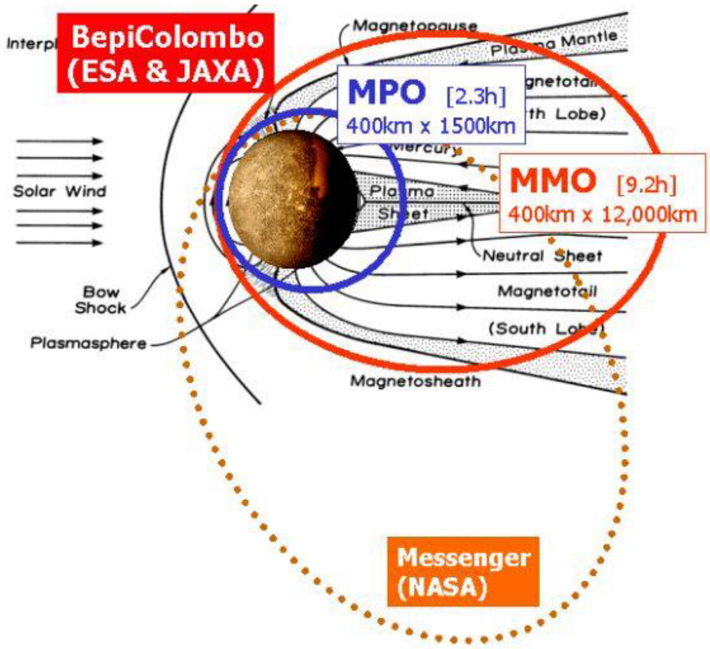


Figure 10: The relative latitudes of each spacecraft

CONCLUSION

The primary objective of this thesis was to describe and research past and present space missions to the planet Mercury, including the goals of each mission as well as their actual success. The secondary objective was to compare the scientific technology used by NASA, ESA and JAXA. Based on the review literature in this thesis, it is crucial to mention that up to now, Mercury is still the least explored terrestrial planet in our Solar System. There have been only two missions completed so far, compared to other terrestrial planets like Mars or Venus.

The very first mission to Mercury, Mariner 10, took place almost a half-century ago. The mission consisted of three flybys around Mercury in 1974 and 1975 and returned the first images of the planet, together with indispensable evidence of the planet structure and surrounding environment. Despite a number of failures on the route, Mariner 10 was able to discover the presence of the small magnetic field, the iron-rich core, the dormant Moon-like surface and the absence of atmosphere, as well as the occurrence of a heavy meteoric bombardment 3.5 billion years ago. Moreover, for the first time in history, the Mariner 10 spacecraft accomplished the gravity-assisted manoeuvre, which was later used for both succeeding missions. As a result of the Mariner 10 mission, scientists collected fundamental data concerning the planet and thus have laid the groundwork for its successor Messenger.

The mission Messenger, which was a part of NASA's Discovery Program, was first conceived and proposed in 1996 and formally started in 2000. The spacecraft was finally launched in 2004, three decades after Mariner 10. MESSENGER successfully completed six flybys of Mercury, and after four years of operation, it crashed onto the surface in 2015. The Messenger mission had several objectives to accomplish, most of which were the answers to questions raised from the previous research. This paper sums up six scientific areas for the research: (1) formational process of the planet; (2) geological history; (3) magnetic field; (4) core structure; (5) materials at poles and (6) volatile species. Generally speaking, the mission was an incredible success; not only it has attained its stated goals, but it also has discovered notable features. As for the outcomes, among the major science results, this paper concludes: (1) the discovery of water in the form of ice in permanently shaded Polar Regions; (2) the noticeable number of volatile elements; (3) the offset of magnetic field from the centre of the planet; (4) the presence of irregular depressions called *Hollows*; (5) the presence of volcanic deposits on the surface; (6) the discovery of energetic electrons; (7) the existence extremely tenuous atmosphere; (8) the significant global contractions and (9) the exploration of Caloris Basin. The spacecraft

Messenger was equipped with several technical innovations that enabled it to gain the required data and create essential images for detailed research of the planet – for instance, the ceramic-cloth sunshade, the advanced solar panels, or the low mass composite structure. Regarding the science payload, not only had MESSENGER significant constraints concerning the limitation of the payload mass, but it also had to withstand an extreme temperature range. Despite these obstacles, the spacecraft was ultimately equipped with state-of-the-art technology, consisting of seven instruments and radio science. The instruments were precisely selected to perform necessary measurements – they are principally similar to those on the Mariner 10 but significantly enhanced.

The BepiColombo mission, a joint mission of ESA and JAXA, was after several delays, finally launched in 2018. The spacecraft is currently on its way towards Mercury, with planned orbit insertion on August 2021. BepiColombo is expected to complement Messenger's work and thus enlarge the knowledge of what we know about Mercury so far. There are six main scientific objectives pointed out in this paper: (1) study the origin and evolution; (2) determine the structure and composition; (3) detect surface modifications; (4) analyse exosphere and polar deposits; (5) examine magnetosphere and (5) test theory of relativity. Due to these objectives, both BepiColombo spacecraft are equipped with appropriate technology, which is advanced by a significant degree than the one in its predecessor MESSENGER.

There is an essential difference in technology between these two missions due to the fact that BepiColombo was launched more than ten years later than MESSENGER and disposed of a 20-times greater budget, which was subsequently demonstrated in the payload selection process. For instance, more effective fuel or enhanced communications system.

To conclude, we can consider previous missions to Mercury highly successful. In spite of the limited budget, NASA did a great job and undoubtedly gained important information about what we know about Mercury so far. The mission BepiColombo is notably different since it is recognised as a flagship mission with a smarter and bigger budget – and therefore expectations are much higher.

EXTENDED ABSTRACT

Tato bakalářská práce se zabývá minulými i současnými vesmírnými misemi na planetu Merkur. Cílem práce je provést výzkum předchozí mise Messenger uskutečněnou kosmickou agenturou NASA a současnou společnou misi dvou kosmických sond Evropské kosmické agentury (ESA) a japonské letecké kosmické agentury (JAXA), BepiColombo. Výzkum je především zaměřen na podrobný popis a srovnání každé mise, včetně cílů, časového harmonogramu a použité vědecké technologie.

V první kapitole se rozebírá historie planety Merkur, nakolik tato planeta byla až do příletu kosmické sondy Mariner 10 v roce 1974 absolutně neprozkoumaná. Merkur totiž není pouze nejbližší planeta ke Slunci a nejmenší planeta ve sluneční soustavě, ale zároveň se řadí i mezi planety podobné Zemi. Z tohoto důvodu bylo získávání informací o vývoji a současném stavu planety klíčové v oblasti porozumění formování Země. Kosmická sonda Mariner 10 provedla několik obletů kolem Merkuru, během nichž se zaměřovala na výzkum atmosféry, povrchu a vnitřní struktury. Na tuto oblast navazuje podkapitola o prvních nálezech, ve které jsou popsány důležité objevy, které položili základy výzkumu této planety.

Následující kapitola se věnuje v pořadí druhé misi na planetu Merkur, misi Messenger. Tato mise byla provedena až tři dekády po misi Mariner 10, a to v roce 2004. Jejím hlavním cílem bylo mimo nových objevů i poskytnout odpovědi na otázky, které vyvolal předchozí výzkum. Příprava mise trvala několik let a skládala se z teoretických výpočtů možné trasy až po pokročilé technické vybavení sondy. Kosmická sonda Messenger byla vybavena několika technickými inovacemi, které jí umožňovaly zpracovat potřebná data a vytvořit záběry nezbytné pro podrobný výzkum planety. Do toho počítajíc sluneční štít z keramické tkaniny, pokrokové solární panely, zda kompozitní strukturu použitého materiálu. Následně jsou diskutovány vědecké přístroje na sondě Messenger, které byly přesně vybrány k provádění fundamentálních měření na základě specifických údajů získaných z předchozí mise Mariner 10. Přístroje se ve své podstatě do určité míry neliší od těch použitých v sondě Mariner 10, avšak z praktického hlediska jsou propracovanější a výrazně užitečnější. Sonda se skládá ze sedmi přístrojů určených k explorace planety a rádiových přístrojů pro komunikaci. V neposlední řadě se tato kapitola věnuje shrnutí nejdůležitějších vědeckých objevů, které byly získány právě vědeckým týmem mise Messenger. Tyto nálezy jsou nejen považovány za průlomové v oblasti planetární vědy, ale náležitě posloužily i jako zdroj odborného zájmu pro následující misi BepiColombo.

Třetí kapitola se věnuje současné misi BepiColombo, která je momentálně na trase k planetě Merkur s plánovaným dovršením orbity v srpnu 2021. Cílem této mise je navázat na úspěch mise Messenger a tak rozšířit dosavadní poznatky o planetě Merkur. Primárně se zaměří na pět oblastí - vnitřek planety, povrch, exosféra, magnetosféra a fundamentální fyzika. Výsledky této mise mají přispět k sumarizaci poznatků a následně k vytvoření podrobného obrazu o této planetě. Společná mise BepiColombo se skládá ze dvou sond, Mercury Planetary Orbiter (MPO) a Mercury Magnetospheric Orbiter (MMO). Mise je velmi očekávaná a považována za vlajkovou loď obou podílejících se agentur, co se prokázalo i na nesrovnatelně vyšším rozpočtu oproti předešlé misi Messenger. Obě sondy jsou vybaveny nejmodernější technologií, která má poskytnout očekávané výsledky. Sonda MPO je pod záštitou ESA a je určena na komplexní studii planety. Druhá sonda MMO je postavena agenturou JAXA a bude se zabývat především výzkumem magnetického pole. Dále v této kapitole jsou popsány technologické výzvy, včetně unikátního pohonu pro správnou korekci trajektorie, pasivního tepelného designu pro udržení potřebné teploty přístrojů, komunikačních technologií pro spojení se Zemí a ovládáním řízení směru letu. Jelikož jednotlivé sondy jsou sestaveny nezávisle od sebe různými výrobci, jsou obě separátně popsány v různých podkategoriích. Každá sonda obsahuje specializované příslušenství dedikované na konkrétní předměty výzkumu. Sonda MPO je podstatně sofistikovanější a skládá se z jedenácti vědeckých nástrojů, druhá sonda MMO obsahuje pět nástrojů. Zmiňované nástroje jsou diskutovány a popsány spolu s jejich praktickým využitím v kontextu vědecké kooperace.

Ve čtvrté části jsou diskutovány rozdíly mezi jednotlivými misemi s důrazem kladeným na pokrok ve vědecké technologii. Vzhledem k tomu, že mezi misemi je několikaletý rozdíl a obě disponují diametrálně odlišným rozpočtem, se jedná o signifikantní odchylky. S ohledem na rozdílné cíle misí, jsou následně popsány odlišnosti týkající se cesty k planetě a trasy letu po oběžné dráze.

V závěru práce jsou postupně shrnuty hlavní poznatky z obou misí, které obsahují primární i sekundární cíle, harmonogram od počátečních příprav až po současný stav a použité vědecké přístroje. Dále je zde rozebrán a vysvětlen rezultát z porovnání vědeckých technologií a nakonec jsou zde zhodnoceny i dosavadní výsledky obou misí a s nimi spojené konsekutivní kroky.

LIST OF FIGURES

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