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Mio-First Comprehensive Exploration of Mercury's Space Environment: Mission Overview

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Abstract:

Mercury has a unique and complex space environment with its weak global magnetic field, intense solar wind, tenuous exosphere, and magnetospheric plasma particles. The first Mercury orbiter, MErcury Surface, Space ENvironment, GEOchemistry, and Ranging (MESSENGER), was highly informative of the dynamic nature of Mercury's magnetosphere. However, due to the highly elliptical orbit with north-south asymmetry and limited capability for plasma measurements of the probe, many science questions raised by the MESSENGER mission remain unsolved. BepiColombo, a joint mission to Mercury by European Space Agency and Japan Aerospace Exploration Agency, will address these open questions using two spacecraft, Mio and Mercury Planetary Orbiter. Mio is a spin-stabilized spacecraft designed to investigate Mercury's space environment, with a powerful suite of plasma instruments, a spectral imager for the exosphere, and a dust monitor. Because of strong constraints on operations during its orbiting phase around Mercury, sophisticated observation and downlink plans are required in order to maximize science outputs. This paper gives an overview of the Mio spacecraft and its mission, operations plan, and data handling and archiving.

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1 **Mio—First comprehensive exploration of Mercury’s space environment: mission overview**

2

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37 **Abstract**

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39 solar wind, tenuous exosphere, and magnetospheric plasma particles. The first Mercury orbiter,
40 MErcury Surface, Space ENvironment, GEOchemistry, and Ranging (MESSENGER), was highly
41 informative of the dynamic nature of Mercury's magnetosphere. However, due to the highly elliptical
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43 science questions raised by the MESSENGER mission remain unsolved. BepiColombo, a joint
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45 these open questions using two spacecraft, Mio and Mercury Planetary Orbiter. Mio is a spin-stabilized
46 spacecraft designed to investigate Mercury's space environment, with a powerful suite of plasma
47 instruments, a spectral imager for the exosphere, and a dust monitor. Because of strong constraints on
48 operations during its orbiting phase around Mercury, sophisticated observation and downlink plans are
49 required in order to maximize science outputs. This paper gives an overview of the Mio spacecraft and
50 its mission, operations plan, and data handling and archiving.

51

52 **Keywords**

53 Mercury; Magnetosphere; Exosphere; BepiColombo; Mercury Magnetospheric Orbiter (MMO); Mio;
54

55 **1. Introduction**

56 Mercury is the innermost planet in the Solar System and has a unique space environment. Mercury
57 possesses a weak global magnetic field and is subject to the intense solar wind due to its proximity to
58 the Sun (0.31-0.47 AU). In such conditions, Mercury formed a small but highly dynamic
59 magnetosphere. Because of its small size and its proximity to the Sun, Mercury was unable to retain
60 the bulk of its atmosphere but formed instead a tenuous exosphere, which is continuously refilled and
61 eroded from the surface by interactions with solar winds, magnetospheric particles, and micro-
62 meteoroid flux, etc. This complex system, characterized by surface-exosphere-magnetosphere-solar
63 wind interactions, makes Mercury's space environment unique and an excellent science target for
64 comparative study with Earth [Milillo et al., 2005]. In addition, recently many Earth-type exoplanets
65 orbiting in habitable zones very close to cool stars (M-dwarfs) have been found [e.g., Gillon et al.,
66 2017]. Such exoplanets are exposed to extreme stellar winds and ultraviolet radiations, and thus,
67 investigating Mercury's complex system is key to understanding the extreme exoplanetary
68 environment and its habitability conditions against strong stellar winds [e.g., Mura et al. 2011; Dong
69 et al., 2017; 2018].

70 The first Mercury orbiter, MESSENGER (MErcury Surface, Space ENvironment, GEOchemistry,
71 and Ranging) [Solomon et al., 2007], explored this innermost region of the Solar System during 2011–
72 2015 and provided a number of new findings. For example, Mercury's magnetosphere is much more

73 dynamic than had been predicted. Magnetic field measurements indicated Dungey cycles on Mercury
74 with a period of a few minutes [Slavin et al., 2010]. MESSENGER detected many energetic electron
75 events also with periodicities of a few minutes [Lawrence et al., 2015]. Electron precipitations at the
76 nightside were discovered using X-ray and gamma-ray fluorescence [Lindsay et al., 2015; Dewey et
77 al., 2018]. In addition, MESSENGER succeeded in measuring certain components of the exosphere,
78 e.g., Na, Ca, and Mg [McClintock et al., 2008, 2009]. These measurements showed surprisingly
79 constant year-to-year variations with strong seasonal dependence and no strong episodic events
80 [Cassidy et al., 2015].

81 The MESSENGER mission addressed science aspects of Mercury using only one spacecraft and thus
82 faced some constraints and limitations on investigating the environment. Its capability for plasma
83 measurements was constrained because of the lack of low-energy electrons and plasma wave
84 measurements and the limited field of view (FOV) of plasma particle measurements due to the three-
85 axis attitude control of spacecraft. The MESSENGER orbit was highly elliptical with north-south
86 asymmetry and detailed measurements in southern hemisphere were not achieved. Because of these
87 constraints, many science questions remain unsolved even after the success of the MESSENGER
88 mission (see details by Millilo et al. [this issue]).

89 The next Mercury exploration mission, BepiColombo, will address remaining open issues and will
90 provide great improvements in knowledge through comprehensive complementary investigations.
91 BepiColombo is an international joint project between European Space Agency (ESA) and Japan
92 Aerospace Exploration Agency (JAXA) [Benkhoff et al., 2010], consisting of two spacecraft
93 successfully launched on 20 October 2018 by an Ariane-5 launch vehicle. ESA's Mercury Planetary
94 Orbiter (MPO) is a three-axis-stabilized, nadir-pointing module. MPO is dedicated to geology,
95 planetary composition, inner structure, and the exosphere, and its low-eccentricity polar orbit will
96 provide an excellent spatial resolution over the entirety of the planet's surface. The JAXA spacecraft
97 "Mio"—Mercury Magnetospheric Orbiter (MMO)—is a spin-stabilized spacecraft to be placed in an
98 eccentric polar orbit [Hayakawa et al., 2004; Yamakawa et al., 2008]. Mio is equipped to study the
99 space environment of Mercury with its science instrument suite comprising a complete package of
100 plasma instruments, a sodium exosphere spectral imager, and a dust monitor and is expected to extract
101 essential elements of space plasma physics that become visible in Mercury's environment.

102 Mio will enable comparative studies of terrestrial planetary environments. Its main scientific
103 objectives are to understand:

- 104 (1) the structure and origin of Mercury's magnetic field;
- 105 (2) the structure, dynamics, and physical processes of Mercury's magnetosphere;
- 106 (3) the structure, variation, and origin of Mercury's exosphere;
- 107 (4) the physical environment of inner heliosphere.

108 Table 1 describes the success criteria of the Mio mission.

109 As described in science target (4), the BepiColombo mission can analyze heliospheric physics in the
110 inner Solar System in addition to conducting Mercury science. It will thus complement NASA's Parker
111 Solar Probe, launched in 2018, which is currently orbiting the Sun (~ 0.05 AU at perihelion) [Fox et
112 al., 2016], and ESA's Solar Orbiter [Müller et al., 2013], which will be launched in 2020 and will have
113 a highly elliptic orbit between 1.2 AU at aphelion and 0.28 AU at perihelion. During the cruise phase,
114 BepiColombo will cover the inner heliosphere between 1.2 and 0.3 AU and will perform some science
115 observations (see details by Mangano et al. [this issue]). Even after the insertion of BepiColombo into
116 Mercury orbit in December 2025, Mio will provide almost continuous in-situ measurements of the
117 solar wind. Therefore, we will have a first chance to investigate the inner heliosphere with three points
118 of measurement.

119 Here we focus on an overview of the Mio spacecraft, its operations, science operations plan, and
120 science data handling and archiving. The overall BepiColombo mission overview is described by
121 Benkhoff et al. [this issue] and the Mio-MPO coordinated observation plans are reported by Millilo
122 et al. [this issue].

123

124 **2. Spacecraft overview**

125 Mio is an octagonal spin-stabilized satellite designed to measure in-situ plasma and electromagnetic
126 fields from the orbit of Mercury. Figs. 1(a) and 1(b) show schematic drawings of Mio in its
127 observational configuration. High-gain antenna (HGA) will be deployed before separation from MPO.
128 After separation, medium-gain antenna (MGA) will be deployed and two pairs of electric field antenna
129 and two extendable masts will be extended. Fig. 1(c) shows the flight model with both HGA and MGA
130 deployed. The main structure of Mio consists of two panels (upper and lower), a central cylinder (thrust
131 tube) and four bulkheads. Inside the central cylinder the batteries, nutation damper, and a tank for the
132 cold N_2 gas jet system are located. A helical array antenna of 80 cm diameter excited by the radial line
133 is adopted for the HGA system. The external appearance has an octagonal shape, which can be
134 surrounded by a 1.8 m diameter circle. The height of the side panel is 1.1 m, with an upper portion
135 covered up to 70% by solar cells and up to 30% by optical solar reflectors (OSRs). The lower portion
136 is covered by OSRs and conductive white paint as seen in Fig. 1(c). The upper panel is located behind
137 the boundary of the upper and lower portion of the side panel. Instruments are located on the upper
138 and lower panels with an interval of 40 cm. The surface of the cover glass of solar cells and OSRs is
139 coated by conductive material and connected to the spacecraft body in order to satisfy science
140 requirements. The nominal spin period is 4-5 s (spin rate of ~ 15 rpm). The spin axis is pointed nearly
141 perpendicular (92.5° [nominal] or 90° [alternative] depending on the orbital phase of the Mercury
142 Revolution) to Mercury's orbital plane. Nominally Mio's spin axis will be controlled to satisfy the sun
143 angle of 92.5° in order to prevent the shadow on the probe antennas due to the spacecraft body, which
144 degrades the science return. During hot seasons near perihelion (true anomaly angle (TAA) $< \pm 45^\circ$),

145 the spacecraft attitude will be changed to satisfy the sun angle of 90° in order to reduce solar heat
146 inputs. Mio has four tangential thrusters on its side panels to control spin rate and two axial thrusters
147 mounted at the bottom of the spacecraft to control the spin axis. These thrusters work only for attitude
148 control and Mio thus does not have the capability to change its orbit. The spin axis direction is
149 monitored by a star scanner located on the bottom of the spacecraft and spin rate is measured by a sun
150 sensor on the side panel. The total mass of Mio at launch is 255 kg, including 3.7 kg N_2 gas for attitude
151 and spin rate control. The total mass of the science payloads is 40 kg. The nominal mission of Mio is
152 one Earth year and an extension of 1 year (or more) is expected. Technical point of view, the mission
153 life will be determined by a lack of N_2 gas storage for attitude control or an impact of the spacecraft
154 onto Mercury's surface because of gradually decreased periapsis altitude. Detailed specifications of
155 Mio are given in Table 2.

156 Figure 2 shows the system block diagram of Mio. Special features of Mio's system design are as
157 follows:

- 158 1. Unification of Data Handling Unit and Attitude Control Electronics into Data Management
159 Controller (DMC).
- 160 2. The HGA can be pointed toward the Earth by the antenna despun motor (ADM), an elevation
161 control mechanism, and the antenna pointing mechanism (APM).
- 162 3. Two types of MGA: one for command reception only (MGA) and another (MGA-TX) for data
163 transmission using on-off keying. The beacon signal transmitted from MGA-TX is received on
164 the ground for a short duration every one spin. MGA-TX transmits data by using on/off
165 sequence of beacon signal modulation.
- 166 4. Power and telemetry/command interface to MPO for the cruise phase, since Mio does not
167 generate power and both HGA and MGA are stowed. There are converters between MPO and
168 Mio to adjust the bus voltage of MPO (28 V) to that of Mio (50 V). MIL-STD-1553B is used for
169 command/telemetry data transmission between MPO and Mio. The bitrate for Mio telemetry data
170 through MPO is 1 kB/s.
- 171 5. Thermal design to survive under Mercury's harsh environment. Figure 3 shows the concept of
172 the thermal design of Mio. The basic concept of the thermal design is to minimize heat input from
173 the environment and reject heat from the radiator. To realize this concept, the following design is
174 used: a) side panels are thermally disconnected from the upper and lower panels by high-
175 temperature conductive multilayer insulation (MLI); b) solar cells are mounted where the rear
176 part of the side panel is exposed to space and covered by conductive OSRs to lower the
177 temperature of the solar cell; c) lower parts of the side panels are covered by conductive OSRs
178 or painted using conductive white paint; d) upper panel and HGA pedestal are covered by
179 conductive high temperature MLI; e) HGA is painted by conductive white paint; and f) lower
180 panel is covered by conductive OSRs and used as radiator.

181 6. There are two types of heater: a survival heater and an operational heater. The survival heater is
182 regulated by a mechanical thermostat, whereas the operational heater is controlled by a software
183 running on DMC according to the temperature sensor reading. Survival heaters are used when
184 Mio is switched off (mainly in the cruise phase), and operational heaters are used when Mio is
185 switched on (mainly after separation).

186 Mio carries five science instruments: Mercury Plasma Particle Experiment (MPPE), Magnetic Field
187 Investigation (MGF), Plasma Wave Investigation (PWI), Mercury Sodium Atmosphere Spectral
188 Imager (MSASI), and Mercury Dust Monitor (MDM). MPPE studies plasma and neutral particles
189 from the planet, the magnetosphere, and interplanetary solar wind using seven sensors, i.e., Mercury
190 Electron Analyzer (MEA1 and MEA2), Mercury Ion Analyzer (MIA), Mercury Mass Spectrum
191 Analyzer (MSA), High-Energy Particle instrument for electron (HEP-ele), High-Energy Particle
192 instrument for ion (HEP-ion), and Energetic Neutrals Analyzer (ENA) [Saito et al., 2010]. MEA1, MEA2,
193 MIA, and MSA can cover 4π steradians using spacecraft spin. MGF studies the magnetic field of the planet,
194 its magnetosphere, and interplanetary solar wind [Baumjohann et al., 2010]. MGF has two pairs of tri-axial
195 flux magnetometers able to separate the natural magnetic field from the artificial field generated in the
196 spacecraft. The inboard magnetometer (MGF-I) is mounted at the middle of a 5 m extendable mast for the
197 magnetometer (MAST-MGF), and the outboard magnetometer (MGF-O) is mounted at the tip of MAST-
198 MGF. PWI studies electric field, electromagnetic waves, and radio waves from the magnetosphere, as well
199 as solar wind [Kasaba et al., 2010]. It uses two pairs of 15 m tip to root antenna (WPT and MEFISTO) to
200 measure electric field. PWI also has a tri-axial search coil (SC) to measure the AC magnetic field. SC is
201 mounted at the tip of 5 m extendable mast for SC (MAST-SC). MSASI studies the thin sodium exosphere
202 of Mercury [Yoshikawa et al., 2010]. MDM studies dust, both from the planet and from interplanetary and
203 interstellar space [Nogami et al., 2010]. Figure 4 shows the location of each sensor and a summary
204 specification of all science instruments is given in Table 2. The Mio spacecraft coordinate system is
205 also indicated in Figure 4. Figure 5 summarizes the field of view of each MPPE sensor. Details of each
206 instrument are described in the papers of this issue [Kasaba et al., Saito et al., Kobayashi et al.,
207 Baumjohann et al., Murakami et al.]. Through combining data from MPPE, MGF, and PWI, full
208 plasma parameters can be obtained with high time resolution. This reflects a significant improvement
209 from MESSENGER, which did not carry wave instruments and for which the field of view of the
210 particle instrument was limited. Hence many of the questions arising from MESSENGER observations
211 are expected to be solved by Mio observations. The spin-stabilized spacecraft is, for example, the ideal
212 platform for plasma measurements.

213 Mio has a highly elliptical polar orbit with initial periapsis and apoapsis heights of 590 and 11,649
214 km, respectively. The initial periapsis and apoapsis are close to the equatorial plane of Mercury and
215 rotate slowly because of the gravitational coefficient. The relation of Mio's orbital plane and
216 Mercury's orbit around the Sun is shown in Figure 6(a). The orbital plane of Mio is along the Sun-

217 Mercury line at perihelion (true anomaly angle (TAA) = 0°) and aphelion (TAA = 180°), and is
218 perpendicular to the Sun-Mercury line at TAA = 90° or 270°. The apoapsis of Mio's orbit is at TAA
219 = 0° for dayside and TAA = 180° at nightside. This orbit configuration was selected to relax the heat
220 input from the hot surface of Mercury. Orbital configuration for TAA = 0°, 90°, and 180° are shown
221 in Figures 6(b), 6(c), and 6(d), respectively. As shown in Figures 6(b) and 6(d), Mio has a long eclipse
222 (maximum of 2 h) several days around TAA = 180° and short eclipse several days around TA = 0°.
223 Mio stays in the upstream region of the solar wind most of the time and passes the nightside region
224 close to the Mercury at TAA = 0° (Fig. 5(b)), therefore a small TAA would have been suitable to
225 investigate upstream solar wind. While at TAA = 180° (Fig. 5(d)), Mio stays close to the magnetopause
226 or in the magnetotail, giving a unique opportunity to investigate solar wind-magnetosphere interaction.
227 As shown in Figure 6(c), Mio passes the duskside magnetosphere close to Mercury at TAA = 90°.
228 Hence, Mio observes the magnetosphere close to Mercury as the planet revolves. Combining
229 observations at TAA = 0° and 180° gives the distance dependence in the magnetosphere.

230

231 **3. Operations overview**

232 **3.1 Mission scenario (phase definition)**

233 Mio was launched on 20 October 2018 (Coordinated Universal Time, UTC) from the Guiana Space
234 Center located in French Guiana by an Ariane 5 launcher. The Mercury Transfer Module (MTM),
235 MPO, Mio and MMO sunshield and interface structure (MOSIF) are integrated together in the
236 Mercury Composite Spacecraft (MCS) configuration, where Mio is positioned inside the MOSIF.
237 Figure 7 shows the configuration of MCS for launch. Mio was not powered during launch, but survival
238 heaters were activated as a part of the launch separation sequence.

239 Following the launch and early orbit phase, the mission moved to the near-Earth commissioning
240 phase dedicated to the checkout of each spacecraft system, science instruments, and MCS performance
241 evaluation. The first electrical propulsion arc started in December 2018, marking the beginning of the
242 interplanetary cruise phase, which will last 7 years with nine planetary flybys in total.

243 The Mercury approach phase and Mio separation phase will be the most critical periods of activity
244 for Mio throughout the whole mission. After MTM jettison, Mercury orbit insertion will start in
245 December 2025. MPO thrusters will be used to bring the remaining composite spacecraft to Mio orbit,
246 where Mio will be separated. MPO will then jettison the MOSIF and continue transitioning to its target
247 orbit. Mio will execute critical post-separation operations autonomously, after which the two
248 spacecrafts will start the Mercury orbit phase with a nominal duration of one Earth year.

249

250 **3.2 Mode definition**

251 The Mio operation mode in the MCS configuration is described below.

252 - Cruise Dormant: In this mode, only the survival heaters are powered by MPO to keep Mio

253 temperature within the non-operational range. Mio itself is off, therefore no telemetry is generated.
254 - Cruise Initial: This is the initial state after switching Mio power on. Most survival heaters are off in
255 this mode, as the power is directed to Mio's components. Only DMC, Power Control and Distributer
256 (PCD), X-band Transponder (XTRP-A/B) and converters are powered on. System Housekeeping (HK)
257 telemetry is generated every second.
258 - Cruise Standby: In this mode, Mio operational heaters are activated and maintains the spacecraft in
259 its operational temperature range. System HK telemetry is generated every 64 s, and command
260 reception/execution is possible.
261 - Mio Cruise maintenance and checkout: This is the mode for conducting subsystem and science
262 instrument checkout operations. Telemetry is generated every second and contains either System HK
263 data or Mission HK/science data.
264 Transition between modes is performed using a dedicated Onboard Control Procedure (OBCP),
265 which contains the necessary MPO and Mio command sequence and telemetry status checks. There is
266 also a Mio emergency switch-off OBCP to quickly transfer to the dormant mode in case of major
267 anomalies at MCS/MPO level.
268

269 **3.3 Mission phase and Operation plan**

270 The operations planned for each mission phase are explained below.
271

272 3.3.1 Near Earth commissioning phase

273 This phase was dedicated to initial checkout of the Mio spacecraft system and science instruments.
274 In November 2018, Mio was brought into cruise maintenance and checkout mode for the first time
275 after launch. The initial checkout was successfully completed by end of November 2018, and high-
276 voltage checkout for the MPPE and MSASI instruments were conducted in June-August 2019. Launch
277 lock release activities were also performed during this time. The checkout operations during this phase
278 were mostly interactive, carried out at ESOC with real-time data transfer to the Sagami-hara Space
279 Operation Center (SSOC)/JAXA.
280

281 3.3.2 Interplanetary cruise phase

282 During the interplanetary cruise phase, operations are mainly executed by ESA ground stations
283 [Montagnon et al., this issue]. Mio is kept in the dormant mode for the majority of the interplanetary
284 cruise phase, except for the following activities:

285 (1) Cruise checkout

286 This is a periodic maintenance/checkout activity scheduled every 6-8 months. The main objective for
287 Mio is a battery health check and, if required, charging. A functional check of all science instruments
288 is also performed. These activities are executed using the MPO mission timeline and nominally

289 concludes within 1 day.

290 (2) Cruise science, flyby science observation

291 Mio is surrounded by MOSIF in cruise configuration, but some instruments have openings within
292 their field of view and thus the opportunity for science observation during the cruise phase. Planetary
293 flybys and interplanetary solar wind observations are under discussion. The observation sequence will
294 be optimized based on trajectory prediction and the plasma region that the cruise composite will pass
295 through. As a baseline plan, PWI (magnetic field), MGF, and MPPE- ENA/MSA/MIA/MEA/HEP-ele
296 will be used for science measurements during planetary flybys.

297 (3) Maintenance/troubleshooting activities

298 Any other commissioning activities that are out of the scope of cruise checkout and science
299 observation are discussed with the ESOC Flight Operations Team and implemented in the schedule as
300 appropriate.

301

302 3.3.3 Mercury approach phase and separation

303 Mio will conduct the final system checks to prepare for separation, including charging the onboard
304 battery, which is estimated to take 1 to 5 days depending on the charging current. After the MTM
305 separation, the Marman clamp in Mio's spin ejection device will be released. The HGA is also
306 deployed. The final separation tasks are executed by an OBCP, which will turn off the power to Mio
307 (at this point, Mio is running on its own batteries), check the Mio separation readiness status, fire
308 NEAs for harness separation, and finally fires the pyros to release Mio.

309 The Mio post-separation operation is initiated once mechanical separation is detected. All tasks are
310 executed as onboard functions until a communication link to ground is established using the
311 MGA/MGA-TX.

312 Once this link is made, interactive operations will proceed to confirm the spacecraft status and upload
313 parameters for attitude control. The communication link will then be switched to HGA, and the
314 extension sequences of MAST-SC, MAST-MGF and two pairs of wire antennas will be executed as
315 follows: (1) Mio spin-up to 20 rpm, (2) wire antennas (MEFISTO-1, -2, WPT-1 and -2) deployment
316 with 5 m steps, (3) MAST-SC and MAST-MGF deployment resulting in spin-down to ~9 rpm, and (4)
317 spin-up to 15 rpm.

318

319 3.3.4 Mercury orbit phase

320 In this phase, the initial checkout of both the spacecraft bus system and science instruments are
321 performed. For many instruments, this will be the first time in 7 years that full detailed functional
322 checks are possible. The nominal operation of the Mio bus system can be categorized in routine
323 operations. Daily tasks are the HGA pointing control and spin frequency control. Eclipse and Mercury
324 occultation tables are updated every few days. Attitude (spin axis) control, battery reset operation, and

325 solar array panel UV level updates are each performed a certain number of times during each Mercury
326 year (approximately 88 Earth days). There are also maintenance operations such as ACS timer reset,
327 thrust parameter update, and heater control table updates, which will be performed as required.

328 The nominal science operations of Mio will be controlled at SSOC in JAXA/ISAS with
329 communication from the Misasa Deep Space Station at Usuda Deep Space Center. The
330 possibilities for future support by other ground stations are still under discussion. There
331 are two kinds of operations plans: a long-term operations plan for one Mercury year and
332 a short-term operations plan for one Earth week. The mission timeline will be updated
333 with short-term planning twice per week.

334

335 **4. Science operations plan at Mercury orbit phase**

336 **4.1 Baseline observation plan**

337 Mio's main science target is Mercury's space environment, including solar wind and dust conditions.
338 In order to maximize scientific outputs, continuous monitoring along the whole spacecraft orbit is
339 important. Therefore, the baseline observation plan requests that all science instruments will be kept
340 on, except for MSASI, a remote sensing instrument and the field of view will be directed downward
341 from the bottom of the spacecraft such that its observation timing is limited from specific orbital
342 positions [Yoshikawa et al., 2010; Murakami et al., this issue]. However, there are several major
343 constraints for operations during Mercury orbit phase, and continuous measurements will not always
344 be possible. Figure 8 shows Mercury's orbit and highlights periods of major constraints for Mio's
345 science operations. One of the most critical constraints is temperature of the spacecraft and its
346 instruments. Our thermal calculation for the Mercury orbit phase predicts that, during perihelion
347 season, continuous operations of the payload will increase the temperature up to the unsustainable
348 high values. To avoid this overheating, it is necessary to cease observations and turn off the science
349 instruments during one to two orbits per three orbits, depending on TAA. We will update our thermal
350 calculation using the latest thermal models and in-flight performances.

351 Another major constraint is electric power. Near aphelion the Mio spacecraft will experience a long
352 eclipse with a duration of up to 120 min per orbit for ~7 Earth days. In order to keep the state of charge
353 of the battery and to save its lifetime, science observations will be highly limited during this period.
354 Battery charging requires about three times as long as the eclipse duration. Therefore, in the current
355 baseline plan, no science observations are expected during this period. The aphelion season, however,
356 is important from the scientific point of view, because Mio will normally be inside Mercury's
357 magnetosphere and will cross the magnetotail region as shown in Figure 6d. The feasibility of science
358 observations during an aphelion season will be carefully discussed and updated by checking the latest
359 performance of battery, thermal characteristics, and electric power available and required for science
360 instruments.

361 The science instruments have several observational modes that will be switched depending on the
362 geometrical position of the spacecraft. For example, PWI and MPPE-MIA/MSA/MEA have a solar
363 wind mode and magnetosphere mode. MPPE-ENA has three modes: periapsis mode, apoapsis mode,
364 and a low-resolution mode for other regions. MSASI has a normal FOV mode (45° for spin scan) and
365 wide FOV mode (90°). The timing of each mode change will be optimized at the initial phase of
366 nominal operations, approximately one Mercury year after the start of science observations.

367 Nominal science operations will be performed by stored commands according to the onboard mission
368 timeline. The number of commands for the mission timeline is limited to 512. The timeline will be
369 updated twice per week, and one timeline sequence covers 1 week of operations for redundancy. Mio
370 will have ~ 18 orbit revolutions per week, such that the upper limit for all instruments and spacecraft
371 bus system will be about 28 commands per orbit on average. This limitation will not allow the
372 observation modes to be changed many times during each orbit, and thus, careful observation planning
373 is required. Some instruments requiring long observation sequences (e.g., MSASI) use long macro
374 commands (the fixed sequence of commands stored in the onboard memory) to reduce the number of
375 commands necessary.

376

377 **4.2 Downlink strategy and baseline plan**

378 Another important constraint on Mio's science observation is imposed by the downlink data rate from
379 the spacecraft to the ground station, which varies strongly during the orbit phase. It is not possible to
380 downlink all science data obtained by the payloads; rather, it is a necessary need to select a part of
381 them. In order to maximize science output against such a limitation of downlink data size, we have
382 three data modes with different resolutions and downlink priorities: low-resolution (L-) mode for
383 continuous monitoring and event survey, nominal (M-) mode for standard science analysis, and burst
384 (H-) mode for high-quality analysis. All scientific instruments generate L-mode data, all of which will
385 be downlinked in quasi-real time (within 1 day). M-mode data are generated at the same time (except
386 for MDM, MPPE-ENA, PWI-AM2P, and MSASI) and can be stored in the spacecraft data recorder
387 for ~ 9 days. Because of the constraint on a downlink data rate, only 20%-30% of the M-mode data
388 can be downlinked. Thus, the strategy to mitigate this constraint is to downlink L-mode data first and
389 then select M-mode data to be downlinked by checking the L-mode data quick-looks. The plasma
390 measurement suite (MGF, PWI, and MPPE) has the H-mode based on 4-20 min interval data sets. The
391 H-mode data is taken by a preset mission timeline or by onboard automatic triggering. In order to
392 optimize the parameters and thresholds for automatic trigger detection, we need to investigate data for
393 at least one Mercury year during the Mercury orbit phase. All science data processing is performed by
394 the Mission Data Processor (MDP) [Kasaba et al., this issue].

395 Based on the assumptions shown in Table 4, the downlink data rate for the Mercury orbit phase can
396 be estimated. The average downlink rate for science data is 3.7 kbps (38 MB/day). Figure 9 shows the

397 result of our data rate calculation. The thick black line shows the total data size that can be downlinked
398 each day. The daily-averaged downlink rate depends on the distance between Earth and Mercury,
399 Mercury occultation, and thermal and electric power constraints for spacecraft communication. The
400 red and blue lines in Figure 9 show the data production rate of L-mode and L- and M-mode,
401 respectively. Figure 9 clearly indicates that all L-mode data can be downlinked but M-mode data
402 require a selective downlink. The original design of the downlink plan for each data mode is described
403 by Kasaba et al. [this issue].

404 As shown in Figure 9, the downlink data rate is highly variable in time. For example, during Mercury
405 year (MY) #1 and #2, we can downlink a huge volume of data, but on the other hand we will have
406 very low downlink rates in MY #3 and #4. Table 5 shows the summary of averaged downlink data
407 rates for each observation period. It is necessary to establish an optimized plan to downlink science
408 data effectively for each period. In order to deal with this strategy, we have two kinds of operations
409 plan: a long-term operations plan with a duration of one Mercury year and a short-term plan for 1-
410 week operations, planned to be uploaded twice a week.

411 We need to decide which M-mode (and H-mode) data should be downlinked as early as possible,
412 because the onboard data recorder can store only ~9 days' data. In order to achieve this selective
413 downlink quickly and effectively, we have a strategy of downlink request with several priorities as
414 follows. We prepare a baseline long-term plan for downlink every Mercury year, on the basis of the
415 spacecraft position along the orbit and expected downlink rate. A few days after the observation,
416 additional downlink requests with higher priority will come from event detection by the L-mode data
417 survey if that period is not covered in the baseline plan. In addition, if any Mio-MPO-coordinated
418 observations are planned, the data resulting from this period has the highest priority for downlink.

419 In order to prepare a baseline downlink plan, the spacecraft position is most important, especially
420 relative to Mercury's magnetosphere. The duration of the period when Mio is inside the magnetosphere
421 is shown in Figure 10. We used the KT17 model [Korth et al., 2017] with a disturbance index of 50%
422 for calculating the location of the magnetopause. As shown in Figure 10, Mio stays within the solar
423 wind most of the time and inside the magnetosphere just ~11% of the time, except for during near
424 aphelion season ($TAA = 180^\circ$). Thus, we can downlink most M-mode data obtained inside the
425 magnetosphere. During periods of high downlink rate such as MY #1 and #2, we can add the solar
426 wind M-mode and H-mode data to the selective downlink requests. On the other hand, when a very
427 low downlink data rate exists, as in MY #4, specific parts of magnetospheric M-mode data must be
428 selected. Downlink strategies will be prepared in more detail after the thermal analysis update.

429

430 **5. Data handling and archiving**

431 **5.1 Data pipeline and archiving plan**

432 Figure 11 shows the outline of the science data pipeline. Science data obtained by Mio is

433 automatically stored into the scientific information retrieval and integrated utilization system
434 (SIRIUS), the telemetry database of JAXA [Nomura et al. 1983]. All telemetry data from Mio are
435 compliant with the CCSDS-binary format. Instrument teams retrieve the raw CCSDS-binary data
436 (Level-0 data) from SIRIUS and process these data to make Level-1 data. Level-1 data carry time
437 labels in UTC, whereas observed data are uncalibrated (instrument-dependent units.)
438 Level-1 data are converted to Level-1p (calibrated) data in standard physical units by the
439 instrument teams. ISAS converts Level-1p data to official public-open version data (Level-2 data).
440 The adequate metadata (e.g., rules of the road) are attached to the Level-2 data. Level-2 data are in
441 accordance with the PDS4 convertible format (see Section 5.2 for data formatting). Level-2 data are
442 made available to users on a dedicated server soon after data processing and are archived in the data
443 archives and transmission system (DARTS) for long-term archiving. All generated Level-2 data are
444 converted to the PDS4 format for planetary research users. The converted Level-2 PDS4 data are
445 archived in DARTS. Level-3 data reflect the combined products of multiple Level-2 data from
446 different instruments (e.g., pitch angle distributions of particle fluxes.) The basic idea of data level
447 definition is based on the Arase case [Miyoshi et al. 2018a, 2018b]. A summary of the definition of
448 the science data level is shown in Table 6.

449 We perform time labeling in UTC when we generate Level-1 data. A time index (TI), which is a time-
450 sequential counter (LSB = 31.25 ms) using the internal clock of the spacecraft bus-system, is attached
451 to every data packet from Mio. A corresponding UTC can be calculated from attached TI using a time-
452 calibration table. An MDP-TI (LSB = 1.95 ms) is also attached to every mission packet to determine
453 the time label.

454 Raw CCSDS binary data (Level-0 data) nominally become available within 1-2 working days after
455 receiving telemetry data from Mio. The daily tasks of Level-1, Level-1p, Level-2, and Level-3 data
456 generation are automatically processed on the workstation after Level-0 data become available on
457 SIRIUS. Processed Level-2 data will be publicly available on both the dedicated server and DARTS
458 according to a project-agreed schedule.

459 We provide orbit, attitude, and other ancillary data as a SPICE kernel. SPICE is developed by the
460 Navigation and Ancillary Information Facility team of the Jet Propulsion Laboratory (NASA) and
461 widely used to determine observation geometry for planning and analyzing space science observations.
462

463 **5.2 Data format**

464 We adopt the common data format (CDF) as the standard format of Level-2 science data products.
465 CDF is proposed by the National Space Science Data Center/NASA and is commonly used for
466 archiving solar-terrestrial physics data (e.g., Arase (Miyoshi et al. 2018a), Van Allen probes (Mauk et
467 al. 2012), MMS (Burch et al. 2016), and many other solar-terrestrial physics missions). In the case of
468 Arase, all of science data (plasma wave data and plasma particle data) are archived in CDF and

469 distributed by the ERG Science center (Miyoshi et al. 2018b). Because the basic design of plasma
470 particle and wave instruments aboard Mio is almost the same as that of Arase, a part of the existing
471 tools and technique can be used for Mio data processing and archiving.

472 On the other hand, there are cases in which CDF is not suitable when we archive image-like data.
473 For archiving imaging observation data, the flexible image transport system (FITS) is widely used
474 (e.g., Hisaki mission; Yoshikawa et al. 2014). Therefore, we have adopted the FITS format for data
475 obtained by MSASI. Regarding the MDM data, we provide Level-2 data in the ASCII format because
476 they have a relatively simple list of dust detections.

477 All Level-2 CDF/FITS/ASCII data are converted into PDS4 format for users in the field of planetary
478 research. The contents of Level-2 PDS4 data are the same as those of Level-2 CDF/FITS/ASCII data.

479

480 **5.3 Data analysis tools**

481 All Level-2 CDF/FITS/ASCII data can be analyzed by the Space Physics Environment Data Analysis
482 Software (SPEDAS) (Angelopoulos et al. 2018). SPEDAS is a suite of scientific analysis routines
483 written in Interactive Data Language (IDL), and widely used in solar-terrestrial physics. Users can
484 easily download Level-2 data via the internet using the load procedure and create combined plots using
485 multiple data products. The SPEDAS will be also used for the generation of quick-look plots.

486

487 **6. Conclusions**

488 The BepiColombo mission will provide the first comprehensive investigation of Mercury with two
489 spacecraft. The Mio spacecraft is designed to analyze Mercury's environment, one of the most unique
490 and complex systems in the Solar System featuring a range of interactions between the intense solar
491 wind, planetary surface, weak global magnetic field, tenuous exosphere, and dynamic magnetosphere.
492 The main science targets of Mio are (1) to assess the structure and origin of Mercury's magnetic field;
493 (2) to analyze the structure, dynamics, and physical processes in Mercury's magnetosphere; (3) to
494 study the structure, variation, and origin of Mercury's exosphere; and (4) to determine the physical
495 environment of the inner heliosphere. Mio will address unsolved questions on these targets raised by
496 MESSENGER with new investigations focusing on plasma waves, energetic neutral atoms, low-
497 energy electrons, and dust monitoring, and with higher instrumental capabilities such as wider energy
498 ranges of plasma particles and a higher resolution of spectral imaging in the exosphere. The spin-
499 stabilized platform also significantly enhances the capability of plasma particle measurements relative
500 to other three-axis stabilized spacecraft.

501 After the launch of BepiColombo on 20 October 2018, initial checkout operations of the Mio
502 spacecraft system and science instruments were successfully performed. During the 7 years cruise
503 phase, periodic maintenance/checkout activities of the spacecraft bus system (mainly the battery) and
504 instruments are planned to take place every 6-8 months. Though the capabilities of the science

505 instruments are limited during the cruise phase because of the stacked spacecraft configuration and
506 unextended wire antennas and masts, we plan science observations for planetary flybys at the Earth,
507 Venus, and Mercury. Solar wind measurements during the cruise can also contribute to inner-
508 heliospheric science in coordination with other spacecraft such as NASA's Parker Solar Probe and
509 ESA's Solar Orbiter and ground-based observations. After the Mercury orbit insertion, most critical
510 operations such as spacecraft separation and the extension of wire antennas and masts will be executed.

511 Nominal science operations during the Mercury orbit phase are strongly constrained by the thermal
512 condition during the aphelion season and electric power during the long eclipse period in the perihelion
513 season. The baseline observation plan of Mio will conduct continuous measurements as long as
514 possible against the major constraints above (except for MSASI). The downlink plan is more
515 complicated and requires optimization. On the basis of the highly variable expected downlink data
516 rate due to the distance between the Earth and Mercury, we have prepared the downlink strategy for
517 each Mercury year. All low-resolution (L-mode) data and 20%-30% of nominal resolution (M-mode)
518 data will be downlinked. The downlink plan plays a key role in maximizing the science outputs of
519 Mio, and we will continue to discuss and update it within the science working group. Science data will
520 be processed based on heritages from the past missions and high-level products will be prepared in
521 both CDF/FITS/ASCII format and PDS4 format.

522

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530

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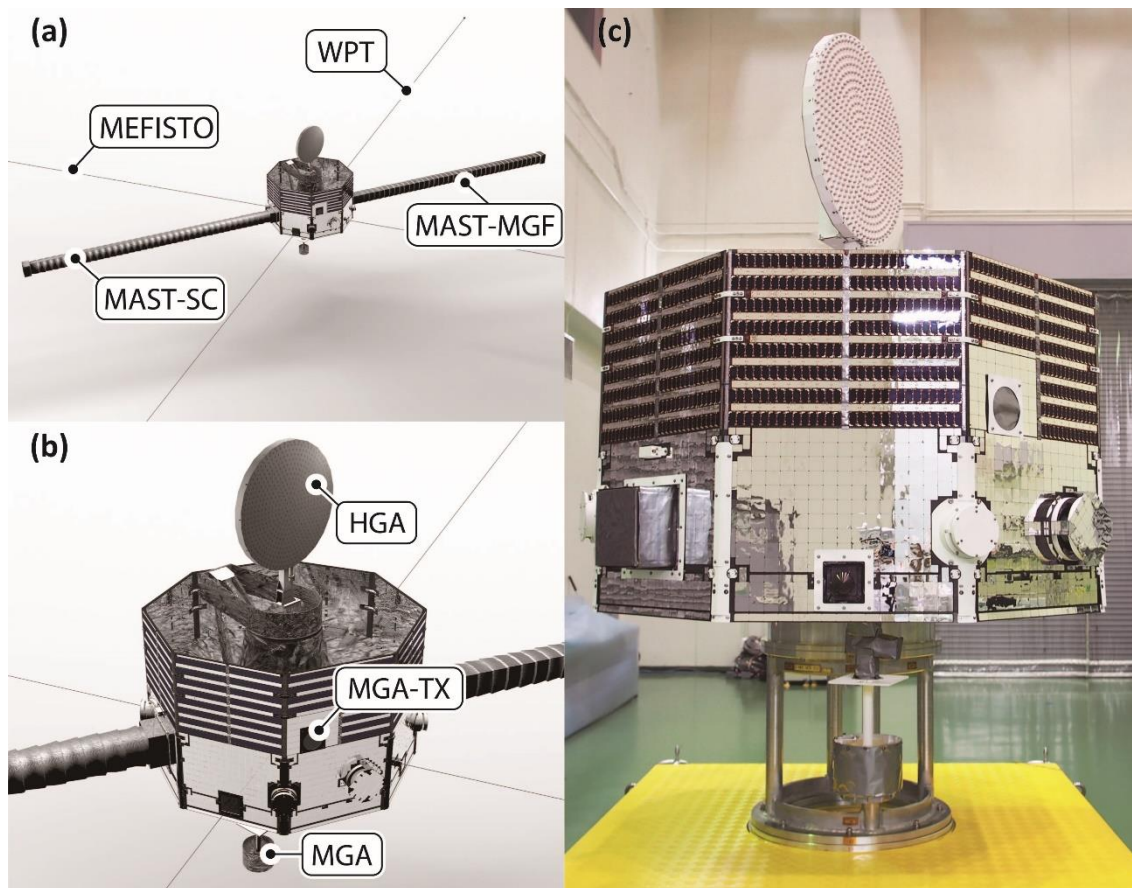
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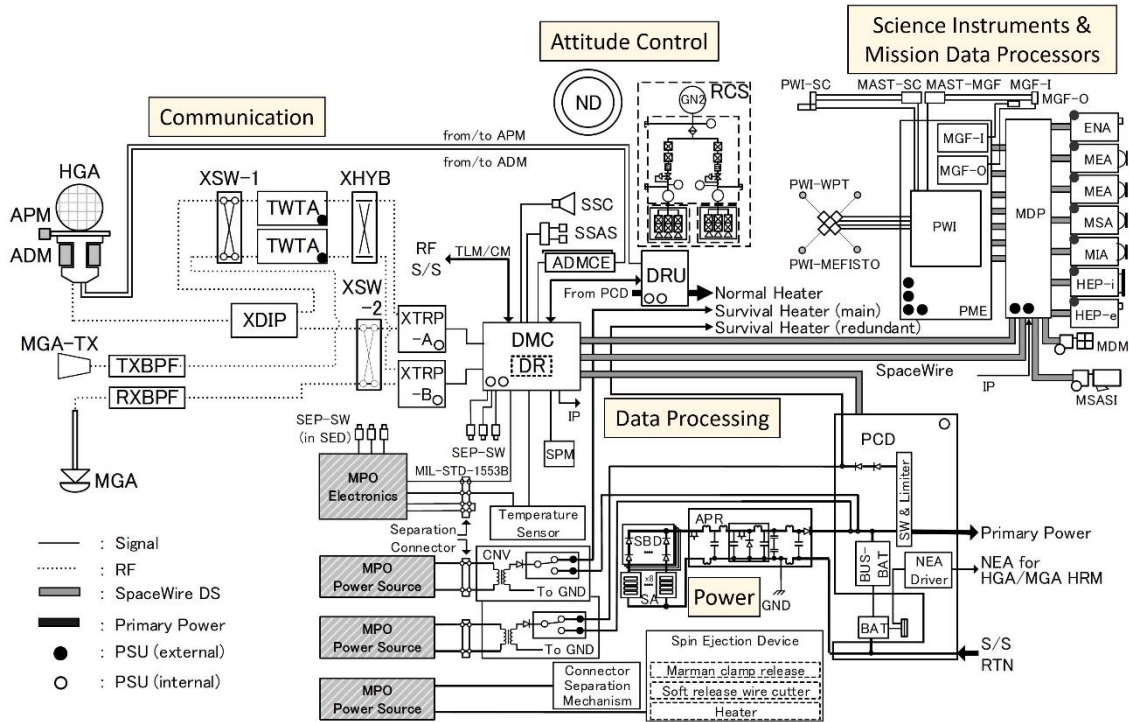
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Figure 1: Schematic views (a, b) and photograph (c) of the Mio spacecraft.

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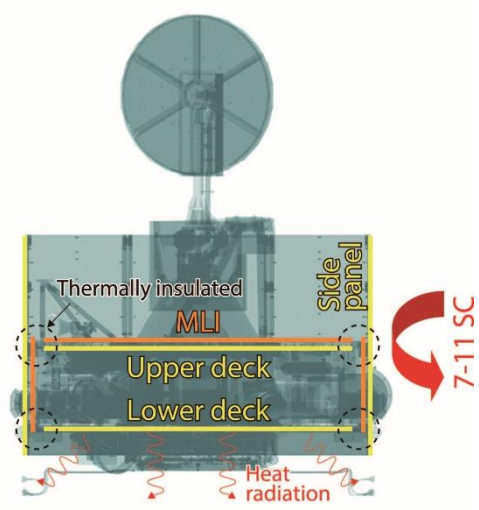
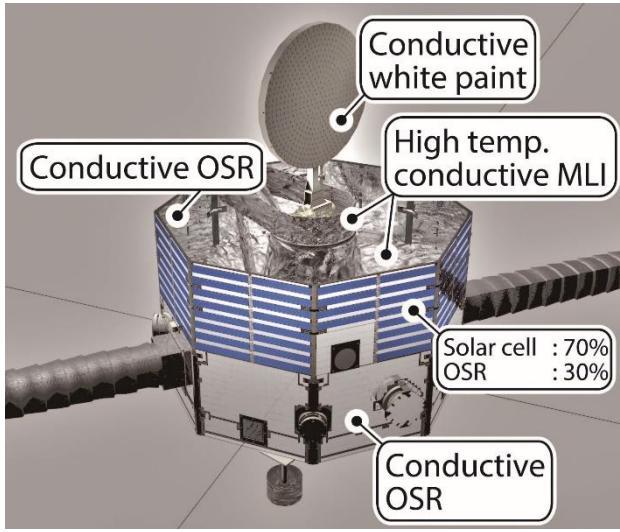
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Figure 2: Block diagram of the Mio spacecraft system.

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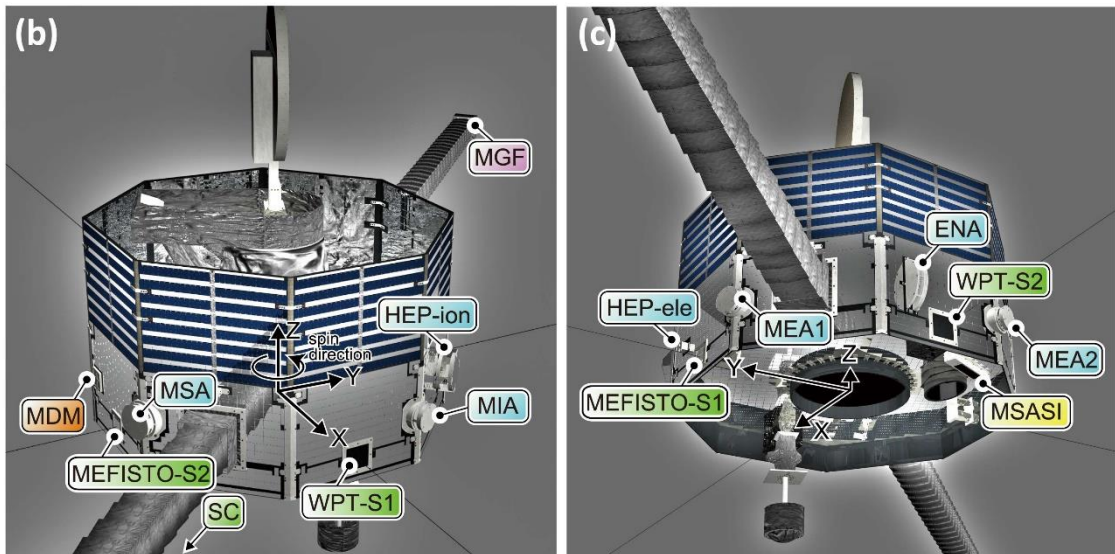
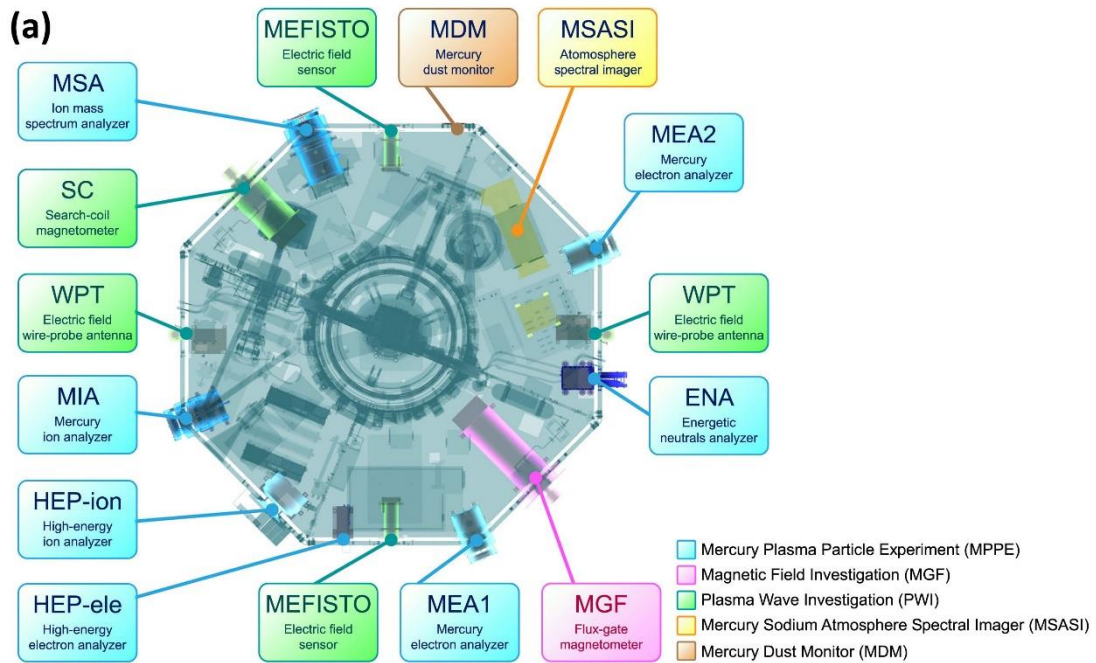
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Figure 3: Thermal design of the Mio spacecraft.

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Figure 4: Schematic views of the Mio spacecraft identifying the science instruments. The location of each instrument and sensor is indicated from top (a), side (b), and bottom (c) views. The spacecraft coordinates and spin directions are indicated in (b) and (c).

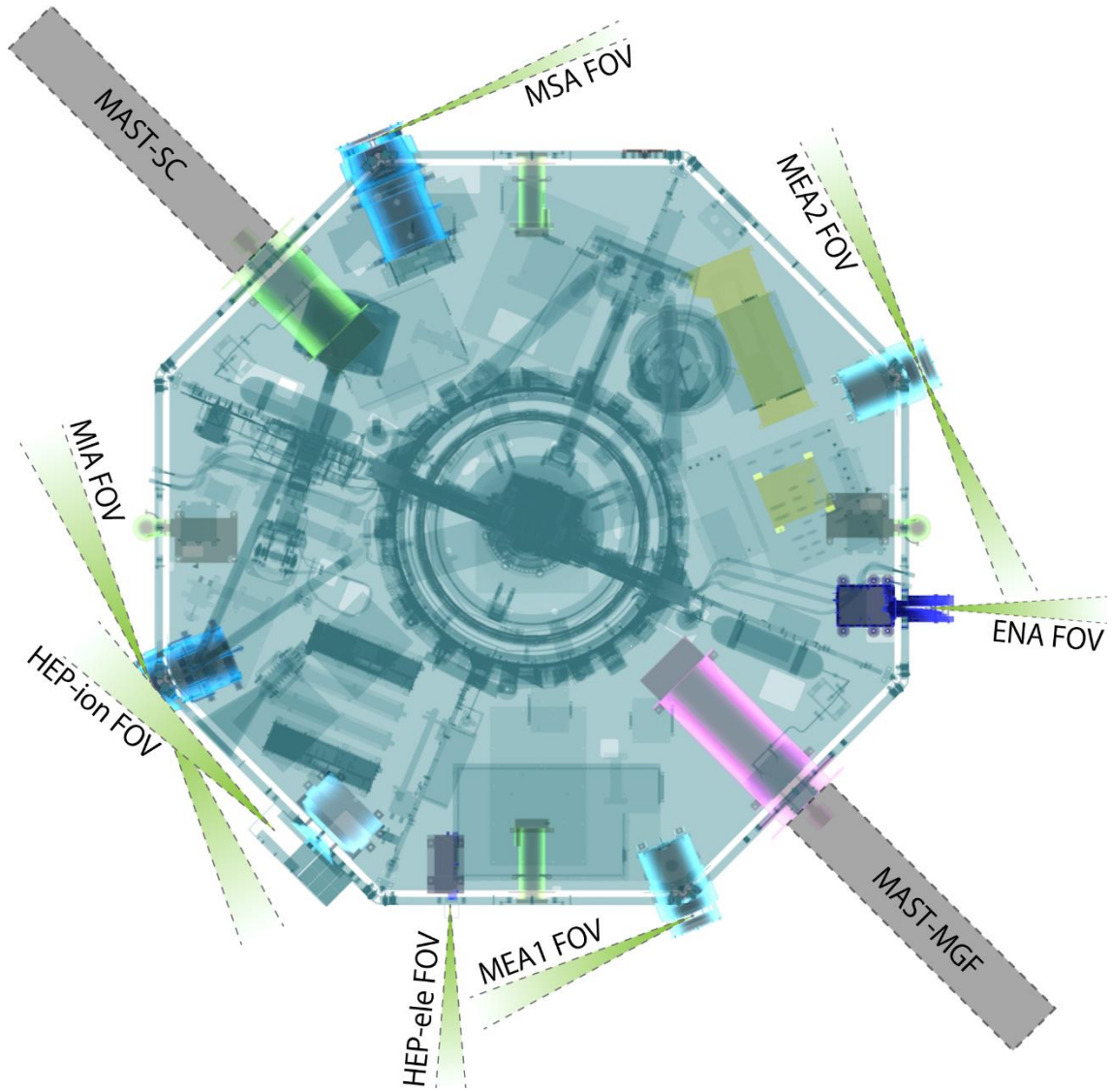
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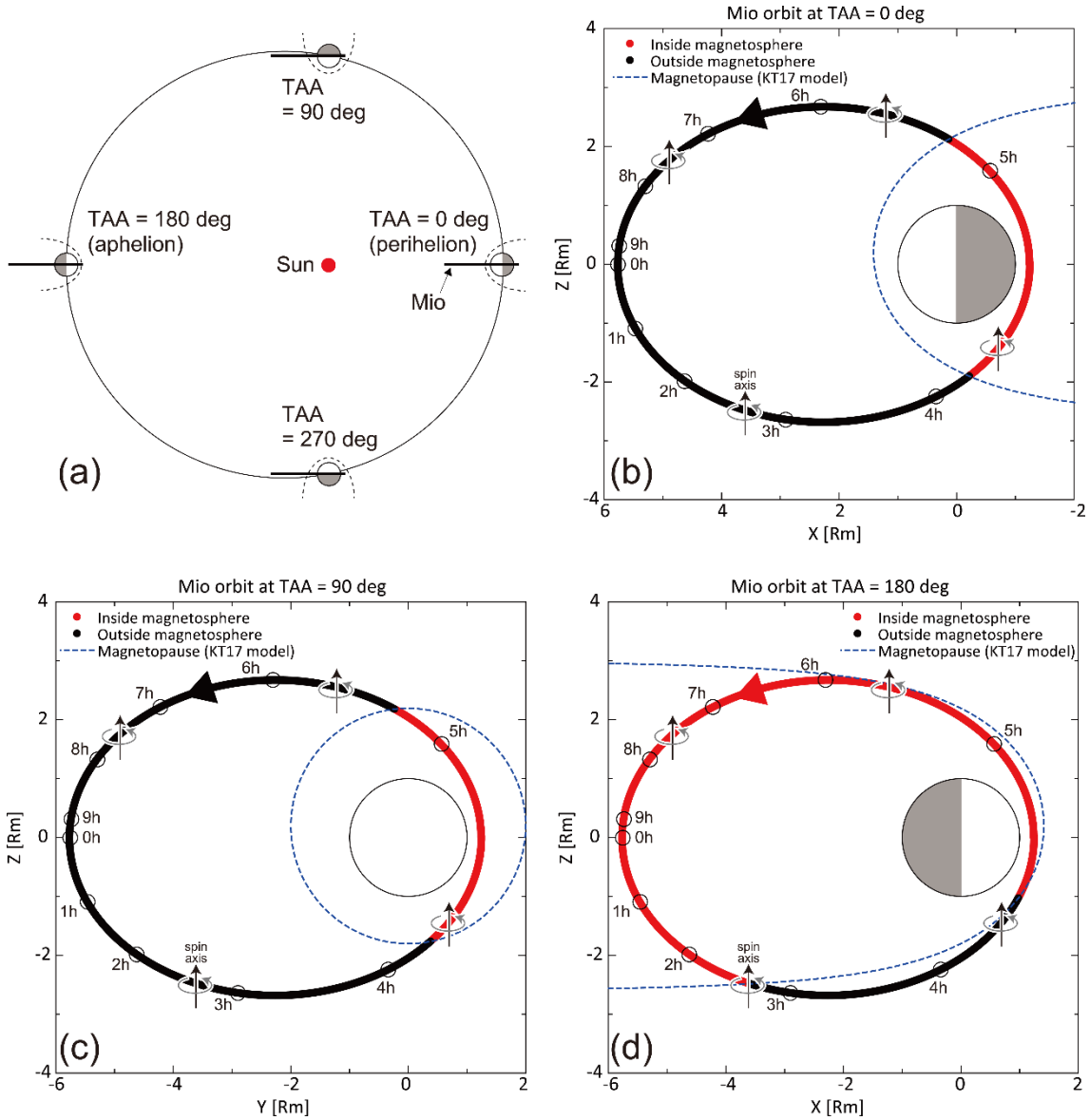


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732 **Figure 5:** A schematic of the field of view of each MPPE sensor.

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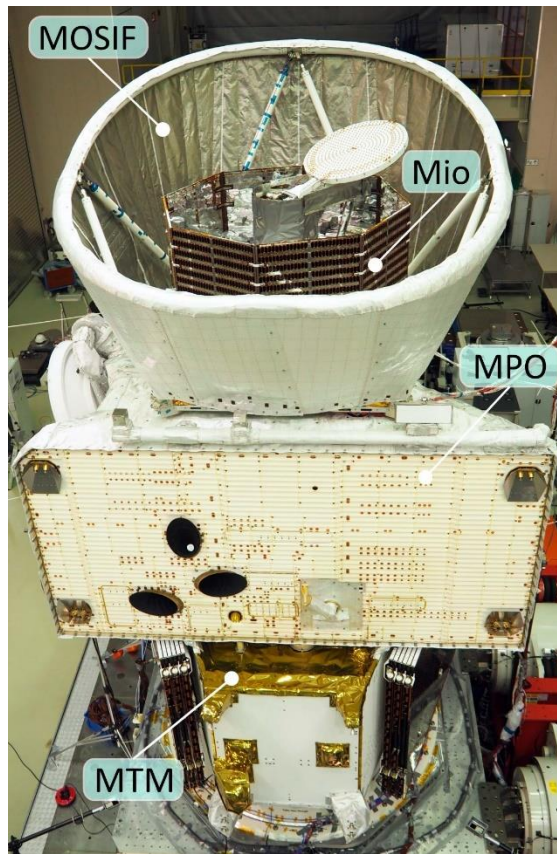
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737 **Figure 6:** Orbits of Mio on Mercury's orbital plane (a) and the polar orbit at a true anomaly angle of
 738 0° (b), 90° (c), and 180° (d). Mio's spin axis (almost same as Mio's z-axis shown in Figure 4) and spin
 739 spin direction are also shown in (b-d). The spacecraft locations every 1 hour from the periherm are indicated
 740 by black circles along the orbits in (b-d).

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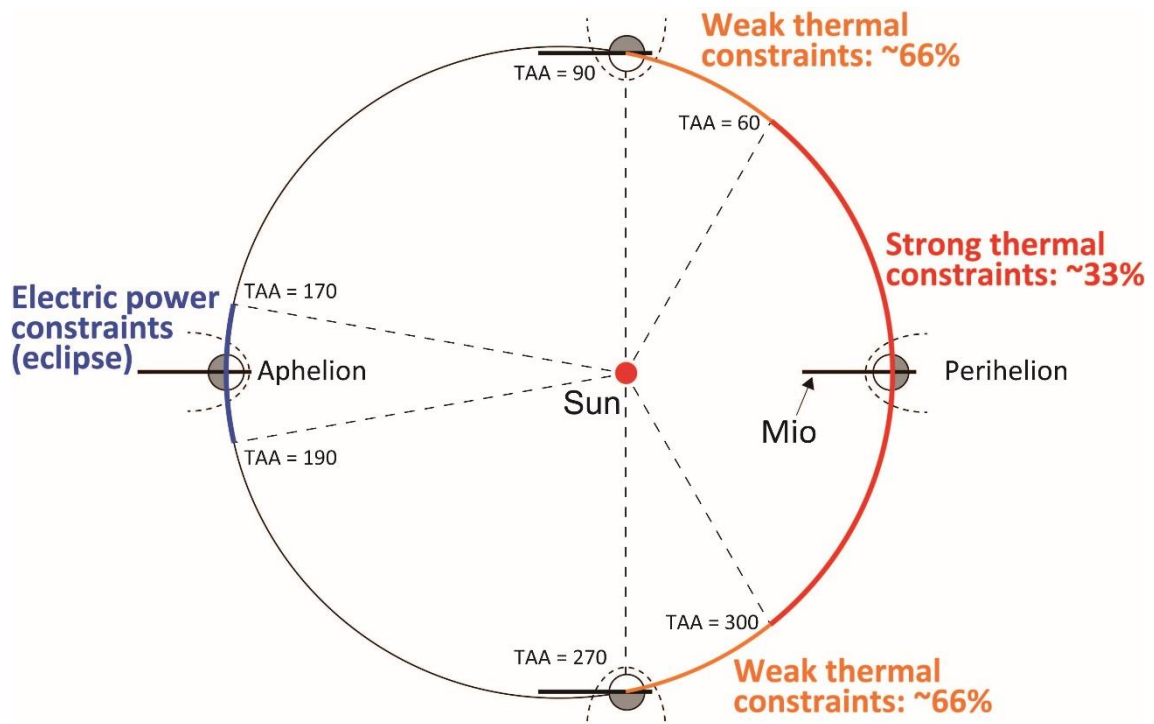
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745 **Figure 7.** Configuration of the Mercury Composite Spacecraft (MCS) during vibration tests (same
746 condition as during launch). Mio is located at the top of MCS and surrounded by MOSIF.

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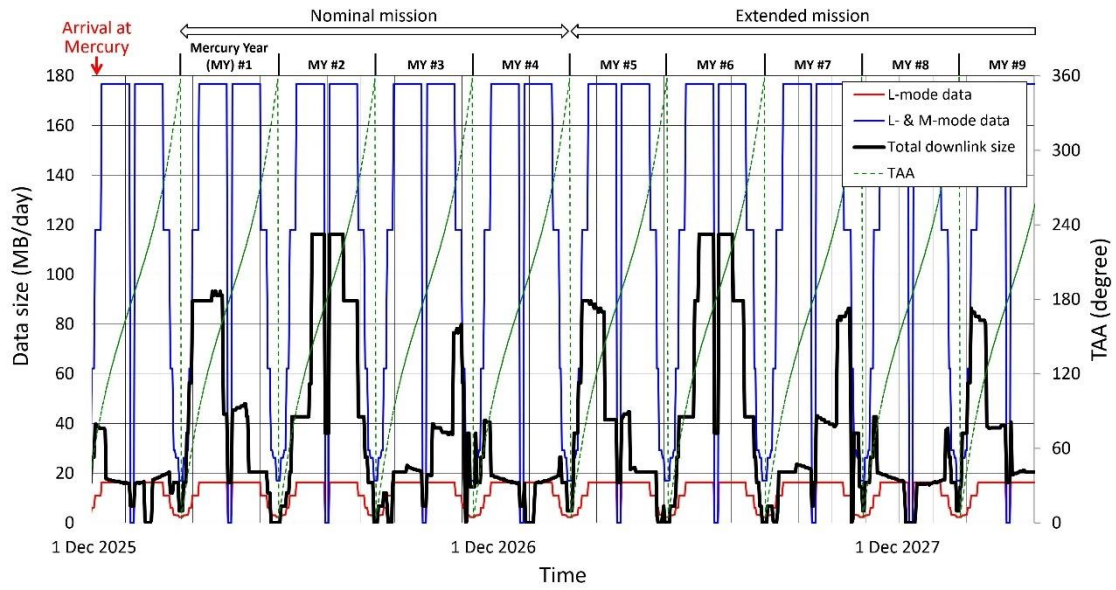


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751 **Figure 8.** Schematic view of orbital phases with major operational constraints for Mio science
 752 operations. Science instruments will not be fully operable because of thermal constraints during the
 753 perihelion season and because of electrical power constraints in aphelion seasons.

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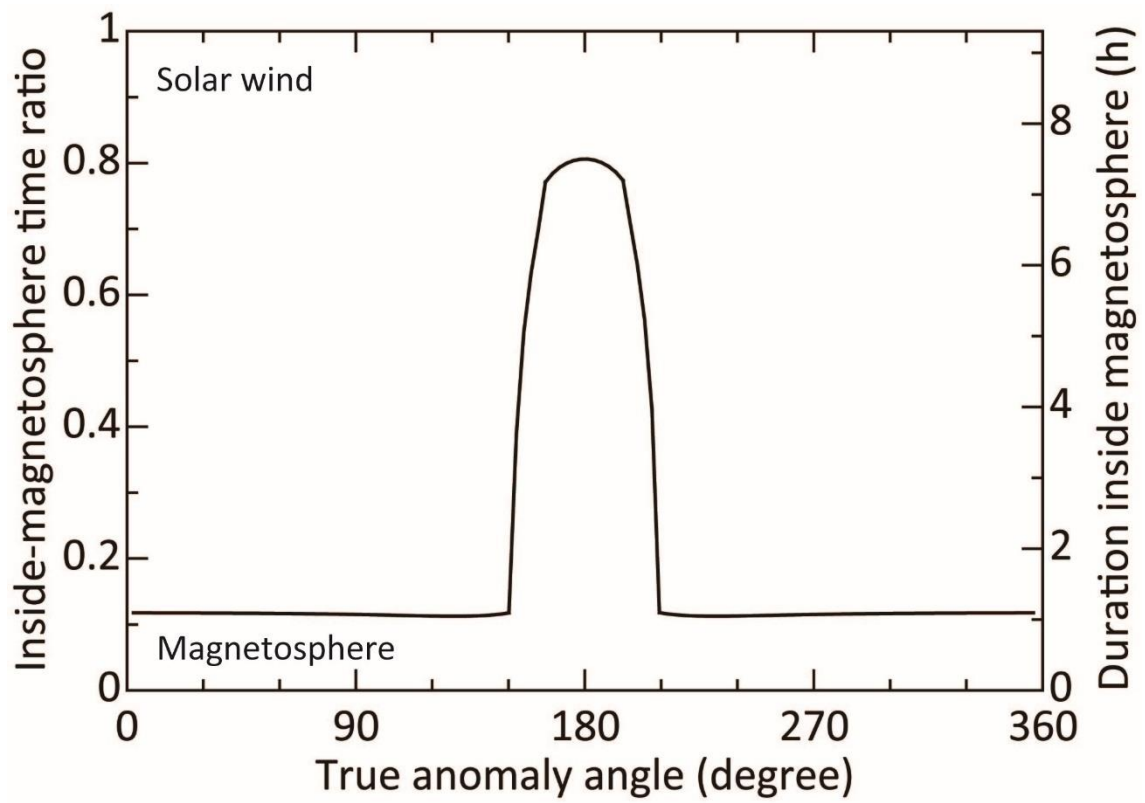
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757 **Figure 9.** Expected temporal evolution of the data rates for total downlink size (black) and science
 758 data production with L-mode (red) and L- and M-mode (blue) during the nominal and extended
 759 mission phases. The green dashed line shows the true anomaly angle.

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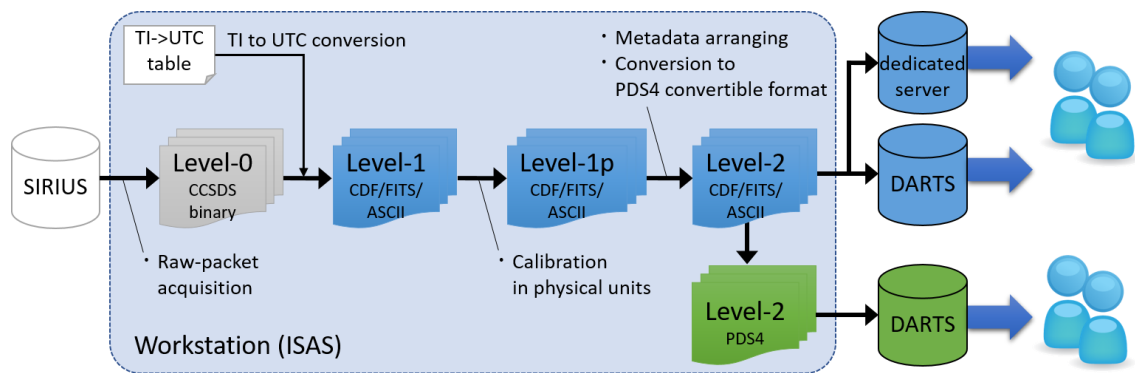
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764 **Figure 10.** Seasonal variation of duration inside Mercury's magnetosphere in each spacecraft orbital
 765 evolution.

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770 **Figure 11.** Outline of the science data pipeline.

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Table 1. Success criteria of BepiColombo/Mio

	Minimum success	Full success	Extra success
Magnetic field	Confirm presence of the intrinsic magnetic field by MGF measurements for more than 88 Earth days (one Mercury year)	Perform global mapping (>80% coverage) with accuracy of <1 nT or <2% within one Earth year and obtain useful information to infer the origin of the magnetic field.	Separation between internal and external sources. Insight into planetary internal structure (collaboration with MPO)
Magnetosphere	Identify structure of the magnetosphere by either MPPE or PWI measurements for more than 88 Earth days.	Identify the effect of solar wind condition on magnetospheric structure from plasma density and temperature profiles with resolution of several hundred km within one Earth year. Understand the plasma dynamics with data of 10 s time resolution or higher.	Comparative magnetosphere theme: understanding common and unique features
Atmosphere	---	Observe variation of the sodium exosphere for several hours with a few minutes time resolution, more than once in every quarter orbital position within one Earth year. Identify the effect of solar radiation and solar wind.	Understanding of source and loss mechanisms of the Mercury's atmosphere by collaboration with MPO and/or dust distribution information
Shock wave	---	---	<i>In-situ</i> observations of very high (Ma ~ 40) and/or low (Ma<1) Mach number shocks in the inner-heliosphere

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Table 2. Specification of Mio

Shape	Octagonal shape within a 1.8 m diameter circle with two 5 m extendable mast and four 15 m (from tip to root) electric field antenna
Height	1.52 m (launch configuration) 2.66 m (observational configuration)
Mass	255 kg (including 3.7 kg N ₂ gas) excluding 20 kg separation mechanism which remains on MMO sunshield interface (MOSIF)
Power (spin averaged)	≥ 271 W (periapsis at aphelion) ≥ 368 W (average at aphelion) ≥ 530 W (average at perihelion)
Designed mission life	One Earth year observation at the Mercury orbit
Thruster	6 \times 0.4 N N ₂ cold gas jet
Spin rate	15 rpm (4 s/spin)

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779 **Table 3.** Summary of the science instruments onboard BepiColombo/Mio, compared with the
 780 MESSENGER mission

Target	BepiColombo/Mio			MESSENGER		
Plasma	MPPE	MEA	Low-energy electrons	3 eV-26 keV	-	
		MIA	Low-energy ions	15 eV-29 keV	FIPS	50 eV-13 keV 1-40 amu/e
		MSA	Ion mass spectroscopy	1 eV-38 keV 1-60 amu/e $m/\Delta m = 40 (<13 \text{ keV})$ $m/\Delta m = 10 (>13 \text{ keV})$		
		HEP-ion	High-energy ions	30 keV-1.5 MeV	EPS	25 keV-1 MeV
		HEP-ele	High-energy electrons	30 keV-700 keV	EPS	25 keV-1 MeV
		ENA	Plasma imaging	10 eV-3.3 keV	-	
	MGF	Magnetic field	DC – 64 Hz (sampling) L: <0.25 Hz, M: 8 Hz	MAG	DC – 20 Hz (sampling)	
	PWI	Electric field, plasma wave, radio wave	DC – 10 MHz (E) few – 640 kHz (B)	-		
Exosphere	MSASI	Na-exosphere image	Spatial resol.: 3-30 km R = 65000	MASCS	Spatial resol.: 25-800 km R = 1000	
Dust	MDM	Dust environment	10s pg*km/s	-		

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Table 4. Assumptions for downlink rate estimation of science telemetry data

Ground station	Misasa Deep Space Station (one station)
Coding	Turbo code
Geometrical constraints	Communication is available at Sun-Earth-Mercury angle $> 3.0^\circ$
	Communication is available at the antenna elevation angle $> 10^\circ$
Pass assignment for downlink	Everyday
	No conflicts with other spacecraft operations during Mio's visible pass
Spacecraft thermal constraint	Communication time = 2 h/day at $TAA < 15^\circ$ (~4 days)
	Communication time = 4 h/day at $15^\circ < TAA < 45^\circ$ (~10 days)
	Communication time = 6 h/day at $45^\circ < TAA < 60^\circ$
Spacecraft electric power constraint	Communication time = 4 h/day at $TAA > 175^\circ$ (~3 days)
Ranging operations	1 h/week (50% data rate during RNG)
Station availability factor	85% (one Earth year average)
HK telemetry rate	64 s period (= ~0.5 kbps for real time and reproduct)

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Table 5. Summary of averaged downlink rate for each period during Mercury orbit phase

Mercury year (MY)	Average DL rate (MB/day)	Period
0	18.4	24/11/2025–19/02/2026
1	47.1	20/02/2026–18/05/2026
2	62.9	19/05/2026–14/08/2026
3	26.6	15/08/2026–10/11/2026
4	16.9	11/11/2026–06/02/2027
5	40.5	07/02/2027–05/05/2027
6	65.1	06/05/2027–01/08/2027
7	31.6	02/08/2027–24/01/2028

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Table 6. Definition of the science data level

Level	Contents	Scope	File format
Level-0	Raw-telemetry	Internal	CCSDS-Binary
Level-1	Observed data in instrument-dependent units	Internal	CDF, FITS, ASCII
Level-1p	Calibrated data in physical units	Internal	CDF, FITS, ASCII
Level-2	Calibrated data in physical units with appropriate metadata	Public	CDF, FITS, ASCII PDS4
Level-3	Processed data combining data from different instruments	Public	CDF, FITS, ASCII PDS4

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