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Lunar-Earth Gravity Assist, a first for JUICE and for Spaceflight

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Abstract

With the Lunar-Earth Gravity Assist (LEGA), ESA's Jupiter Icy Moons Explorer (JUICE) achieved a groundbreaking milestone by performing the world's first double gravity assist manoeuvre on 19th/20th of August 2024. This complex operation allowed the spacecraft to exert a substantial amount of Δv and to divert its trajectory towards Venus, before eventually leaving the inner solar system in 2029 on its journey to the Jovian system.

The geometry of LEGA confronted the JUICE mission team with unique challenges and required close collaboration between the various contributors in both engineering and science groups within ESA and external. During the LEGA phase, the trajectory was closely monitored over a 6-week navigation campaign with daily ground station passes, employing ESA's deep space antennas in Cebreros, Malargüe, and New Norcia.
Precise navigation was crucial, as uncompensated deviations from the pre-calculated path could have been largely amplified by the fly-bys, depleting the fuel budget dedicated to the scientific mission objectives at Jupiter.
Two dedicated slots for emergency trajectory control manoeuvres allowed the ground operators to intervene in case the amplified trajectory deviations would have otherwise resulted in a large Δv penalty or in an elevated collision risk with space debris.

The Flight Control Team monitored all critical phases in real time, ready to recover the spacecraft in case of a contingency. Several measures were implemented to improve the robustness against Safe Mode entry and to facilitate a swift recovery.

This paper describes the objectives behind the LEGA phase, its operational constraints and impacts. It covers the preparation, execution and post-processing phase from the perspective of the Flight Control Team, concluding with a brief discussion on the manoeuvre's success in terms of achieved accuracy and Δv.

Keywords: JUICE, LEGA, double gravity assist

Nomenclature

Δv – delta velocity

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control System	J-MAG	JUICE Magnetometer
AU	Astronomical Unit	KaT	Ka- band transponder
BP	Breakpoint	LEGA	Lunar-Earth Gravity Assist
CA	Closest Approach	LGA	Low Gain Antenna
CDMU	Control and Data Management Unit	MAJIS	Moons and Jupiter Imaging Spectrometer
DDOR	Differential One-Way Ranging	MGA	Medium Gain Antenna
DOY	Day of Year	MTL	Mission Timeline
ESA	European Space Agency	Navcam	Navigation Camera
ESAC	European Space Astronomy Centre	PCDU	Power Conditioning and Distribution Unit

ESOC	European Spacecraft Operations Centre
ETCM	Emergency Trajectory Control Manoeuvre
FDIR	Failure Detection, Isolation and Recovery
FCT	Flight Control Team
FD	Flight Dynamics
FDT	Flight Dynamics Team
GALA	Ganymede Laser Altimeter
3GM	Gravity & Geophysics of Jupiter and Galilean Moons
HAA	High Accuracy Accelerometer
HGA	High Gain Antenna
IMU	Inertial Measurement Unit
JANUS	Jovis, Amorum ac Natorum Undique Scrutator
JUICE	Jupiter Icy Moons Explorer
JMC	JUICE Monitoring Camera
PEP	Particle Environment Package
PF	Platform
PUS	Packet Utilisation Standard
RIME	Radar for Icy Moon Exploration
RIU	Remote Interface Unit
SADM	Solar Array Drive Mechanism
SOC	Science Operations Centre
SSMM	Solid State Mass Memory
STR	Star Tracker
SWI	Sub-millimeter Wave Instrument
TMTC	Telemetry and Telecommand
TC	Telecommand
TTC	Telemetry, Tracking and Control
TCM	Trajectory Control Manoeuvre

1 Introduction

1.1 JUICE and the LEGA scenario

The Jupiter Icy Moons Explorer (JUICE) is an interplanetary satellite mission to explore three of Jupiter's Galilean Moons: Europa, Callisto, and Ganymede. It is operated by the European Space Agency (ESA) from their European Spacecraft Operations Centre (ESOC) in Darmstadt, Germany. Launched in 2023 on an Ariane 5 from Kourou, French Guiana, JUICE is currently in its cruise phase through the inner Solar system. Because a direct trajectory to the Jovian system was not within the performance regime of the launcher and due to limited fuel onboard the satellite, several gravity assist manoeuvres are required to reach its destination in 2031. More details are provided by Ecale et al. [1].

The first of these manoeuvres was planned as the World's first double gravity assist manoeuvre and was executed on the Lunar-Earth system, with a swing-by on the Moon on 19. August 2024, quickly followed by a swing-by on Earth on 20. August 2024. This novel approach of a double gravity assist provided a fuel-efficient way to achieve the required Δv and trajectory alteration. However, compared to a single flyby it required a higher precision in orbit determination and complex control that was not within the scope of earlier interplanetary ESA missions. An accurate execution of the LEGA was essential for the overall mission success, as any major deviation from the pre-planned scenario could result in large Δv penalties. The motivation and benefits of this selected approach is provided by the consolidated report on the JUICE mission analysis [2].

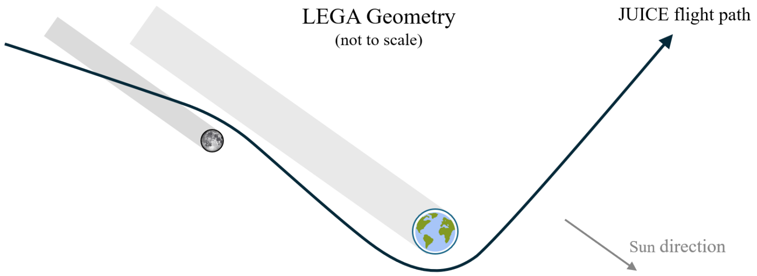

Figure 1: The Geometry of the LEGA Manoeuvre (simplified)

Figure 1 depicts the projected geometry of the LEGA manoeuvre onto the ecliptic plane and how the gravitational pull of both Moon and Earth altered the trajectory of the JUICE spacecraft. While this simplified depiction is not to scale, it helps to illustrate the required precision to make this double flyby feasible. The JUICE trajectory was bend in an L-shape with the spacecraft crossing the Moon's shadow shortly before closest approach.

1.2 Platform

The JUICE platform was manufactured by Airbus and employs an advanced design optimised for deep-space operations. It is equipped with a pair of steerable solar arrays in cross-shape configuration, which together encompass a surface area of 85m^2 and ensure efficient power generation even at large distances to the Sun. The onboard power is regulated at 28V by a Power Conditioning and Distribution Unit (PCDU) which also interfaces to a battery providing critical energy storage during eclipse phases for up to five hours.

Three-axis attitude control is achieved through the fusion of star tracker (STR) measurements and data of an inertial measurement unit (IMU) using three gyros, combined with a 4-wheeled reaction wheel assembly for fine pointing. The JUICE main engine develops 425N of thrust based on a hypergolic bi-propellant and is complemented by four 22N and six 10N thrusters per redundant branch.

The main data handling functions are performed by a powerful Control and Data Management Unit (CDMU) that communicates via the Packet Utilisation Standard (PUS) on a standard SpaceWire and MIL-Bus architecture. Units which do not have the capability of communicating via PUS by themselves are interfaced via an intermedia Remote Interface Unit (RIU). Nearly all platform units are designed with multiple cold or hot redundancies. This is necessary in view of the long mission duration combined with the highly variable thermal and radiation conditions across the Solar system.

The Telemetry and Telecommunication system features a fixed high-gain antenna (HGA) with 2.4m diameter for high-data-rate transmission at Jupiter, a steerable medium-gain antenna (MGA) for enhanced link performance during the cruise phase and two low-gain antennas (LGA) for nearly omnidirectional coverage in case of emergencies. Commanding and telemetry transmission is performed in the X-band, Payload data can be transmitted in the Ka-band.

Due to the vast distances from Earth over which JUICE has to operate, a high degree of onboard autonomy is required. Telecommands (TC) are sent by the operators in real time only while the spacecraft remains in close proximity. Otherwise different strategies are used. One of them is the execution of predefined TC files onboard, another is the employment of the Mission Timeline (MTL). In this concept defined by PUS, telecommands are uplinked in advance and scheduled for execution at a specified time-tag. This allows JUICE to operate mostly autonomously for several days, or even weeks if required.

1.3 Payload

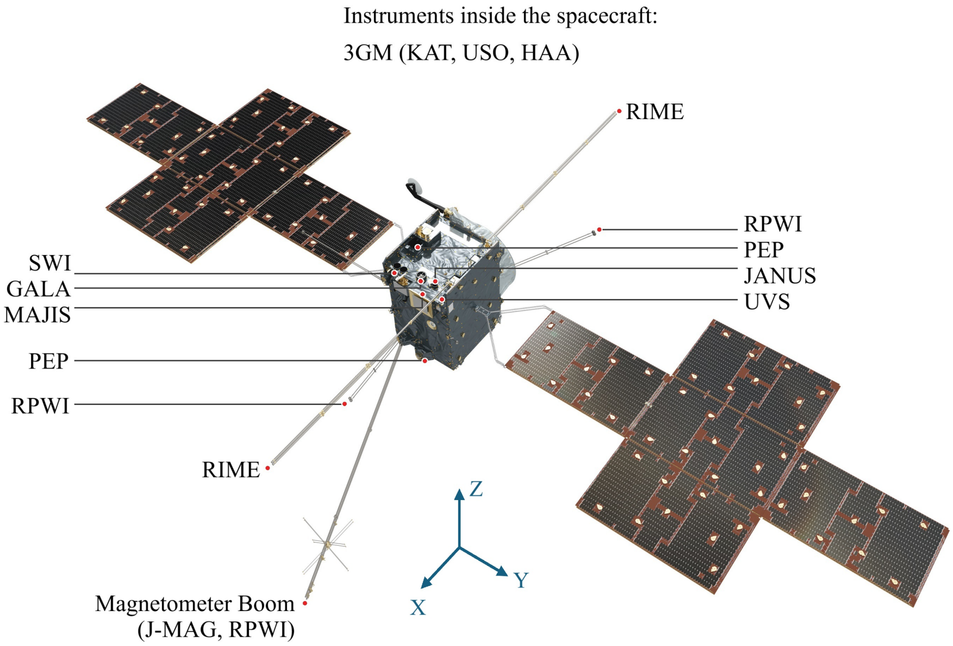

Figure 2: JUICE and its Instruments

The scientific payload of JUICE consists of several remote sensing, geophysical, and in situ instruments designed to study all aspects of the Jovian Moons. Most of the remote sensing equipment is located on an optical bench at the +Z face of the spacecraft, which is nominally kept in the Sun's shadow at all times. The corresponding electronic unit of each instrument however is mounted within one of two vaults inside the platform. These vaults offer a degree of protection against the harsh radiation environment near Jupiter. A brief description of the instruments is provided online [3][4] and is repeated hereafter.

3GM, or the Gravity & Geophysics of Jupiter and Galilean Moons, is a radio package comprising the KaT (Ka-band transponder), USO (ultra-stable oscillator) and HAA (High Accuracy Accelerometer). The experiment will study the gravity field at Ganymede, the extent of the internal oceans on the icy moons, and the structure of the neutral atmosphere and ionosphere of Jupiter and its moons.

GALA, the GAnymede Laser Altimeter will study the tidal deformation of Ganymede and the topography of the surfaces of the icy moons.

JANUS, an optical camera system, will study global, regional and local features and processes on the Moon, as well as map the clouds of Jupiter. It will have a resolution up to 2.4 m on Ganymede and about 10 km at Jupiter.

J-MAG is the JUICE magnetometer. It is equipped with sensors to characterise the Jovian magnetic field and its interaction with that of Ganymede, and to study the subsurface oceans of the icy moons. J-MAG is attached to a 10.5m long boom, in order to be electromagnetically detached from the rest of the satellite bus.

MAJIS is the Moons and Jupiter Imaging Spectrometer. It will observe cloud features and atmospheric constituents on Jupiter, and will characterise ices and minerals on the icy moon surfaces.

PEP is the Particle Environment Package. It comprises a package of six sensors to characterise the plasma environment of the Jupiter system.

RIME, the Radar for Icy Moon Exploration, is an ice-penetrating radar to study the subsurface structure of the icy moons down to a depth of around nine kilometres.

RPWI, the Radio and Plasma Wave Investigation, will characterise the radio emission and plasma environment of Jupiter and its icy moons using a suite of sensors and probes.

SWI, the Sub-millimeter Wave Instrument, will investigate the temperature structure, composition and dynamics of Jupiter's atmosphere, and the exospheres and surfaces of the icy moons.

UVS is a UV imaging spectrograph to characterise the composition and dynamics of the exospheres of the icy moons, to study the Jovian aurorae, and to investigate the composition and structure of the planet's upper atmosphere.

Apart from the scientific instruments, JUICE also has multiple platform cameras available:

Navcam is a navigation camera with a 4° field of view, delivering monochromatic images with a resolution of 1024x1024 pixels. It is a key instrument for the spacecraft navigation during its science phase at Jupiter, as it will improve the pointing accuracy and will allow for autonomous onboard guidance correction [5]. Two fully redundant units are attached to the +Z face of the spacecraft.

JMC are the two JUICE monitoring cameras. Originally designed to monitor the correct deployment of the RIME antenna and the Magnetometer boom during the commissioning phase, they were re-employed to deliver images of the Moon and Earth flybys. Two units are available, one facing in spacecraft +X direction, and another identical unit facing in +Z direction.

2 The LEGA Phase

2.1 Timeline

The cruise phase of the JUICE mission is defined as the 7.5 years long period between Near-Earth commissioning and Jupiter arrival. During this time, the scientific payloads are switched off for the vast majority of the time, with exceptions for regular checkout activities at predefined slots.
The LEGA phase was a subset of the cruise phase and covered the time frame of 24.June 2024 until 22.September 2024. Therefore, it started two months before the actual gravity assist and ended one month after its execution. This phase included several checkout activities, the two flybys, and slots for Trajectory Control Manoeuvres (TCM).

Date	Event	Notes
24. June 2024	Start of LEGA phase	
01. - 07. July 2024	Payload Checkout	including LEGA dry-run
22. July 2024	TCM -4 weeks	Slot for TCM (executed)
02. Aug 2024	Platform Units B-Side Checkout	Checkout of redundant units
05. Aug2024	TCM -2 weeks	Slot for TCM (not used)
12. Aug 2024	TCM -1 week	Slot for TCM (not used)
17. Aug 2024	TCM -3 days	Slot for TCM (not used)
19. Aug 2024	eTCM -6h	Slot for emergency TCM (not used)
19. Aug 2024	Moon flyby	Closest approach at 21:14 UTC
20. Aug 2024	eTCM -4h	Slot for emergency TCM (not used)

20. Aug 2024	Earth flyby	Closest approach at 21:56 UTC
27. Aug 2024	TCM +1 week	Slot for TCM (executed)
03. Sept 2024	TCM + 2 weeks	Slot for TCM (not used)
23. Sept 2024	End of LEGA phase	

Table 1. Key events during the LEGA phase

The key events during the LEGA phase are listed in Table 1. They are described in more detail over the course of this paper.

2.2 Operational Status and Constraints

With the LEGA phase covering a Sun distance of 1.09AU down to 0.97AU, the relatively hot environment conditions constrained spacecraft operations substantially. Three of the main considerations are listed hereafter:

1. The -X face had to remain Sun-pointed with a pointing accuracy of 2°. This way, the HGA effectively acted as protective shield against the high Solar flux. Any off-pointing was only allowed once every 24 hours for a duration of maximum 1 hour.
2. The +Z face of the S/C had to remain in the shade at all times to protect the instruments optical bench from the Sun.
3. The payloads were not allowed to operate in science mode all together for more than 8h as the waste heat of their electronic units has the capacity to considerably heat up the interior of the platform vaults. For the same reason, the MGA pointing mechanism was not allowed to operate simultaneously with combined X- and Ka-band transmission.

Apart from these thermal restrictions, the LEGA phase was characterized by rapidly varying conditions that the operators addressed by modifying the cruise configuration in numerous ways. Following, the most important configurational changes are discussed per subsystem.

2.2.1 Attitude Control

During the cruise phase, the Attitude and Orbital Control System (AOCS) is usually operated in Normal Mode – Gyroless Phase in order to preserve the three laser gyros within the inertial measurement unit as much as possible for the science campaign at Jupiter. However for the LEGA flybys, AOCS was switched to Normal Mode – Coarse Pointing to increase operational robustness. In this mode , the attitude measurements provided by the star tracker can be propagated by the now activated IMU even in phases of star tracker unavailability. This was necessary to cover an expected blinding of all three star tracker optical heads during the Earth flyby.

During the cruise phase, JUICE is nominally flipped daily around its X-axis to average out the solar radiation pressure torque experienced by its large angled solar arrays. These flips help to reduce the required size of wheel off-loadings and therefore save propellant. During the LEGA navigation campaign, these flips were stopped. The reason was that the increased station coverage would have lead to a irregular flipping pattern unable to provide the desired torque averaging. All remaining reaction wheel off-loadings were performed in a specific pure-torque mode to minimise orbit disturbances. In this mode, the Flight Dynamics team carefully selected the offloading target and the thruster compensation firings such that the resulting torque experienced by the S/C equalled close to zero with almost no parasitic forces. This came with the cost of an increased fuel consumption.

It was also expected that the high attitude dynamics during the LEGA might lead to bigger or more frequent wheel-offloadings than under nominal conditions.

2.2.2 Data Handling

To improve operator visibility, the housekeeping telemetry generation was increased onboard temporarily. During the immediate fly-bys, the solid state mass memory (SSMM) dedicated for payload science observations was switched on.

2.2.3 Power

The solar array drive mechanism (SADM) was kept in a fixed hold position with a 70° offset to the Sun direction due to thermal restrictions. This setting was also monitored by a dedicated Failure Detection, Isolation and Recovery (FDIR) algorithm onboard. The battery state of charge was increased to 95% to maximise robustness in case of Safe Mode and in anticipation of the expected eclipse entry at the Moon flyby.

2.2.4 Thermal

Apart of the already addressed thermal constraints, no specific modifications were applied to the onboard control laws, with the redundant thermistor-heater architecture being considered robust enough to keep the platform and payloads safe within their operational ranges at all times.

2.2.5 Communication

The baseline communication approach in the cruise phase through the inner Solar system is to rely on the steerable MGA, as the High Gain Antenna needs to act as a heat shield for the spacecraft and is therefore pointing towards the Sun. During the LEGA phase, the communication subsystem was switched to one of the omni-directorial Low Gain Antennas (LGA-X) three days before the Earth flyby at a distance of around one million kilometres. This allowed for bitrates between 171 and 262 kbps for downlink and 4 kbps for uplink.

2.2.6 Payloads

Spacecraft operations during the LEGA phase focussed mainly on navigation and spacecraft safety. However, the flybys were also a unique opportunity for the instrument teams to perform in situ and remote sensing measurements for the purpose of testing and calibration. Therefore, three payload observation slots for calibration purposes were defined:

1. One payload observation slot at the Moon between closest approach - 1h to closest approach + 1h, ensured circa 15 min of moon visibility for remote sensing instruments
2. One payload observation slot at the Earth between closest approach - 4h to closest approach + 3 days
3. Earth-Moon pointing campaign three weeks later

The respective payload activities were defined relative to the key LEGA events and were uplinked in advance. The operators had to respect specific thermal requirements for each payload, however their detailed description shall not be subject of this paper.

3 Planning and Preparation

3.1 Facilities and Resources

JUICE operations are nominally conducted from the dedicated control room for interplanetary missions at ESOC in Darmstadt, Germany. Routine commanding is performed by the Spacecraft Controller on shift, with support by the Spacecraft Operations Engineer on-call as part of the Flight Control Team (FCT). During the critical phase of the LEGA phase, additionally the entire FCT supported the activities in four dedicated, 8-hour shifts. Furthermore, The Flight Dynamics Team (FDT) was kept on standby for the preparation of emergency Trajectory Control Manoeuvres in two dedicated shifts. A Ground Operations Manager and the Software Support Team supported the activities on-site during working hours and on-call during the imminent flyby phase from 19.08.-21.08.2024. The JUICE Science

Operations Centre (SOC) at European Space Astronomy Centre (ESAC) in Spain supported the payload discussions and was defining the overall payload operations timeline.

To prepare the FCT for possible anomalies during the LEGA scenario, two dedicated contingency rehearsals were conducted. They involved the critical shift personnel, represented by a “Team Red” and a “Team Blue”. The rehearsals took place using the in-house operational simulator and focused on testing emergency scenarios. Key actions performed included the recovery of the spacecraft from a Safe Mode and the timely preparation and execution of an emergency manoeuvre.

Within the period of 14. - 22. August 2024, a ground segment configuration freeze was declared. During this time, no upgrade or other modification on the ground infrastructure was allowed. For the critical LEGA manoeuvre, all three deep space stations in Cebreros, Malargüe and New Norcia were employed to support JUICE operations. For the three days preceding and succeeding the flyby dates, almost continuous ground station coverage was provided by ESOC's Network Operation Centre.

3.2 Payload Checkout

Nominally, the scientific payloads of JUICE are switched off during the cruise phase through the inner Solar system. Therefore, it was important to provide an opportunity for the science teams to validate the health and nominal performance of their instruments in preparation for the LEGA observations.

A payload checkout was scheduled for the week of 01.-07. July 2024. While most activities were uplinked in advance and executed autonomously on-board, some delta-commissioning activities, application software updates and FDIR updates were conducted manually by the FCT with direct support by the instrument teams.
This included a MAJIS software update, a PEP-Hi software update, and a PEP-Lo high voltage commissioning activity staggered over the first 5 days of the week. Following, a 12-hour interference campaign of nearly all payloads with the RIME instrument was executed autonomously on board.

Additionally, a condensed LEGA dry-run with focus on payload operations was performed. It covered 2 hours of Moon flyby and 34 hours of Earth flyby operations.

The large majority of all activities were executed successfully and illustrated the instrument complement to be in a good condition. Several issues and anomalies have been identified for mitigation during the critical LEGA operation.

3.3 Platform Units B-Side Checkout

As part of routine operations, the FCT regularly performs checkouts of redundant platform units to validate their nominal performance. Given the potential impact of anomalies and onboard reconfigurations during the LEGA phase, a redundancy checkout was conducted on 02. August 2024 in preparation for this critical period. The activity involved powering on several redundant units, including the star tracker electronic unit, IMU, PCDU, and RIU. The spacecraft exhibited nominal behaviour throughout the checkout, which included:

- Communication subsystem swap to the redundant chain including deep space transponder and travelling wave tube amplifier, both with nominal performance
- RIU controller B activation, confirming nominal readings of the redundant sun acquisition sensors
- Antenna pointing mechanism switchover, with redundant position readings identical to nominal ones
- Solar array drive electronics switchover, with redundant position readings matching nominal ones
- IMU B activation, confirming quasi-inertial rate measurements consistent with IMU A
- STR 2 electronics unit power-up, confirming nominal startup and initialisation.
- Reconfiguration to redundant propulsion chain, including successful open/close operations of latch valves on the B-side. No actual thruster firings were executed on the redundant branch.

4 LEGA Execution

4.1 Navigation Campaign

The LEGA phase was highly sensitive to targeting and trajectory prediction errors, making precise spacecraft navigation critical, even more so than in typical planetary swing-by scenarios. To mitigate those risks, meticulous planning was applied to navigation, orbit determination, and manoeuvre optimization systems as part of the ground segment preparation. Accurate dynamic modeling and calibration of non-gravitational accelerations were essential to minimizing ΔV penalties and ensuring the success of the combined LEGA.

Starting 45 days before the Moon swing-by, the FDT started a dedicated navigation campaign over a span of two months, employing an increased frequency of ground station passes and rigorous orbit monitoring around the closest approaches. In addition to the regular Telemetry, Tracking and Control (TTC) passes, 13 ranging passes and four Delta - Differential One-way Ranging (DDOR) passes were utilised to support the navigation campaign. DDOR is a technique to further improve spacecraft navigation by measuring the difference in arrival times of the satellite's ranging tone at multiple ground stations at once [6][7]. A more comprehensive description of the JUICE navigation campaign including its employment of the DDOR technique is provided by Syndercombe et al. [8].

4.2 Trajectory Control Manoeuvres

During the radiometric tracking campaign, multiple slots for potential trajectory control manoeuvres (TCM) were defined to allow for the correction of navigational errors.
One of these manoeuvres was performed four weeks before the fly-bys (TCM -4 weeks) on the 22. July 2024 with a small Δv of 3.8 cm/s. This was enough for JUICE to enter a precise ballistic trajectory that would allow for the LEGA geometry to be feasible. Three more slots for potential manoeuvre executions were originally envisaged at the -2 weeks, -1 week, and at the -3 days mark. These slots would have allowed the operators to correct for any unforeseen imprecision in the flight path. However, the Flight Dynamics Team precisely tracked the spacecraft's orbit and those manoeuvres could be skipped.

Two additional slots for emergency TCM (eTCM) were allocated at the -6 hours mark before the Moon flyby and the -4 hours mark before the Earth flyby, respectively. These slots would have allowed the operators to quickly react to any emergency scenario, e.g. the occurrence of a satellite safe mode with high parasitic forces or a collision warning around the Earth from the space debris office.

A flight rule was defined for the execution of an eTCM. It would be executed if, based on the latest orbit determination and trajectory optimization, the nominal mission around Jupiter could not be reached within the given mission constraints. This translated into a Δv penalty of more than 100 m/s, which is also the overall reserve for mission contingency.
Any decision for the execution of emergency manoeuvres had to be taken on short notice and would have interrupted payload operations. For the case of the Earth flyby, the decision loop duration was defined to 12hrs from the decision point to the actual execution. This took into account: Five hours for the Flight Dynamics products preparation and delivery, 4 hours for interrupting the MTL onboard and uplink of the new manoeuvre commands, 3 hours for the actual manoeuvre sequence execution onboard.

Several preparatory measures were taken in advance, irrespective of the actual Go/NoGo decision for the execution of an eTCM:

1. Due to its long warm-up duration, Helium tank preheating started 24h before the first eTCM slot on 18/08/204 to ensure a potential eTCM could be executed with optimal performance.
2. The S/C was set into a semi fail-op configuration to increase the robustness against Safe mode entry by switching on redundant units and allowing local reconfiguration of the key units IMU, PCDU and RIU.
3. A streamlined recovery procedure was defined to enable the FCT to recover the spacecraft from a potential Safe Mode and re-configure it for an eTCM execution within two hours.
4. A special MTL strategy was used with breakpoints where emergency TCM products delivered by the Flight Dynamics Team would become valid. This allowed to split the MTL into three parts, with the second and third part re-filling the MTL onboard at the mark of these breakpoints.

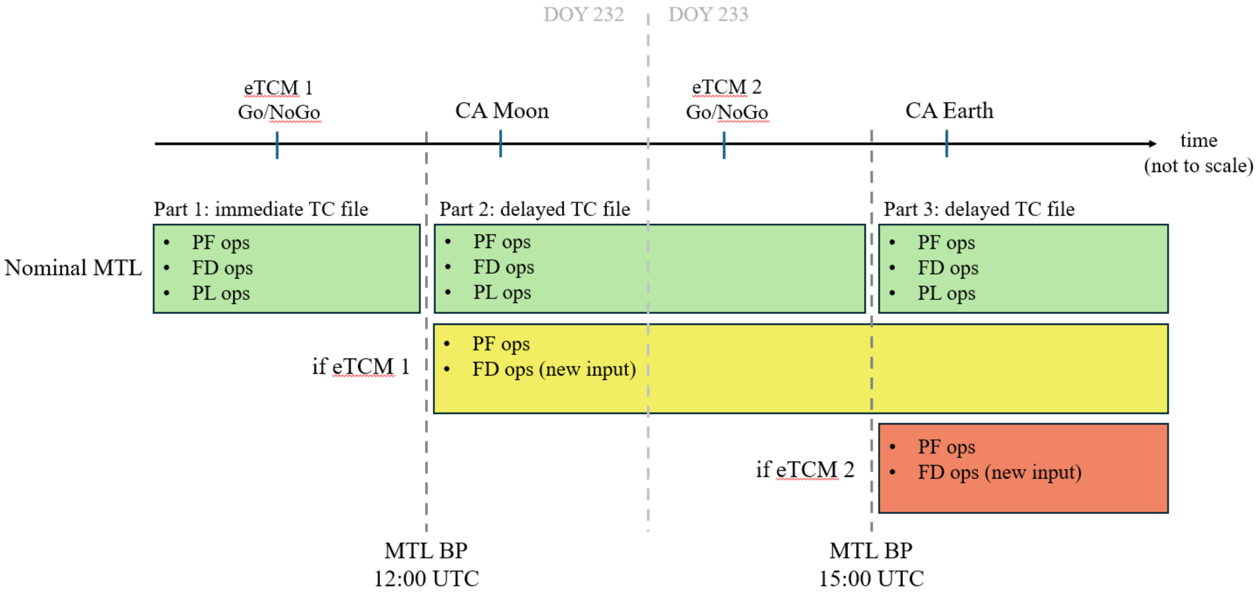

Figure 3: MTL strategy for eTCM execution

Figure 3 illustrates the MTL strategy. The nominal operations are depicted as a green bar and included platform operations commands (PF ops), Flight Dynamics operations commands (FD ops) and payload operations. The three parts were valid between the two MTL breakpoints (BP). Those breakpoints mark the times, when emergency TCM products from Flight Dynamics would have become valid. Part 1 was executed immediately after uplink of a TC file onboard. MTL parts 2 and 3 could then be loaded automatically via execution of a delayed TC file on-board, re-filling the Mission Timeline at the specified mark. The yellow and red bars only became relevant in case a decision for the execution of an eTCM was made. They show the eTCM products superseding the nominal MTL commands. Those products would only include basic platform operations and the Flight Dynamics delivered eTCM products. Those products cover the manoeuvre and basic attitude guidance. Execution of an eTCM would consequently delete all payload operations without re-uplink. To avoid the need for manual payload switch-off in case of an eTCM execution, all payloads were nominally scheduled to be off at the time of MTL breakpoints,.

4.3 Moon Flyby

On the evening of the 19. August 2024, observers could experience a full Moon, with Sun, Earth, Moon and JUICE aligned in a line. JUICE approached the Moon from its dark side and entered the shadow of the Moon at 20:36 UTC shortly before the closest approach. During 32 minutes of eclipse, the spacecraft batteries discharged by around 6%. During this time, no radio contact was possible due to the occultation by the Moon at the same time.

The spacecraft's attitude timeline during the post-flyby phase was primarily driven by thermal constraints, particularly the requirement to maintain the -X face with the HGA pointed toward the Sun. With any off-pointing from this orientation being limited to a maximum of 45 minutes, all planned activities had to accommodate this constraint, especially when scheduling payload observations. Moreover, maintaining margins for potential eTCMs was a critical consideration as they required preserved off-pointing windows.

Due to these limitations, the spacecraft maintained its Sun-pointed orientation while optimizing the phase angle around the Sun to enable limited scientific operations with direct Moon visibility. This approach allowed for payload activity without compromising thermal safety or manoeuvre contingency planning.

Around 37 hours prior to Moon closest approach (CA), a specialised attitude was assumed. While still adhering to the strict Sun-pointing constraint, the spacecraft's +Z axis was maintained within the orbital plane during its passage through the Moon's sphere of influence. This configuration provided a 15-minute long window of Moon visibility along the +Z axis around the time of closest approach, enabling brief but valuable observation opportunities.

One out of the three star tracker optical heads was blinded by the Moon for roughly 13 hours, coinciding with high levels of stray light, however this had no impact on the overall STR tracking status.

The CA with the Moon occurred at 21:14 UTC with the perilune altitude measuring as low as 752 km from the surface. The JMC camera facing the Moon was able to take multiple pictures during the flyby, one of them is depicted in Figure 4.

Figure 4: JMC Image taken shortly after Moon Closest Approach

During a predefined slot of two hours around the time of closest approach, all payloads were autonomously switched on onboard, increasing the temperature within the instruments vaults by roughly 2°C. This was within the limits of the onboard failure monitoring and no FDIR triggered.

For a few minutes around the closest approach, RIME was the only active payload with the other instruments in quiet mode to limit interference. The RIME antenna was used to send transmissions to the Moon's surface and record their echo. Afterwards, JANUS acquired spectacular images of the Moon's surface that are are accessible online [9].
A complete description of all payload activities during the Moon flyby would exceed the scope of this paper and shall therefore not be provided here.

4.4 Earth Flyby

Twelve hours before Earth closest approach, JUICE performed a 180° roll around the -X axis to ensure roughly 30 min of direct Earth visibility for the instruments on the optical bench at the +Z face. The Z axis was kept within the orbital plane around Earth whilst in its gravitational influence.

The CA with Earth occurred outside of ground station visibility over the Pacific Ocean on 20. Aug 2024 at 21:56 UTC. The perigee altitude measured as low as 6839 km.

To meet international radio frequency regulations that limit high power transmission below 45 000 km [10], the X-band transmitter was switched off between 19:30 and 00:00 UTC. Therefore, no communication was available for several hours around the Earth flyby. Afterwards, an unfavourable LGA visibility further prolonged the radio silence, such that first telemetry data was received back only at 04:16 UTC via the New Norcia ground station. No critical events or failed commands were observed for this period in playback telemetry.

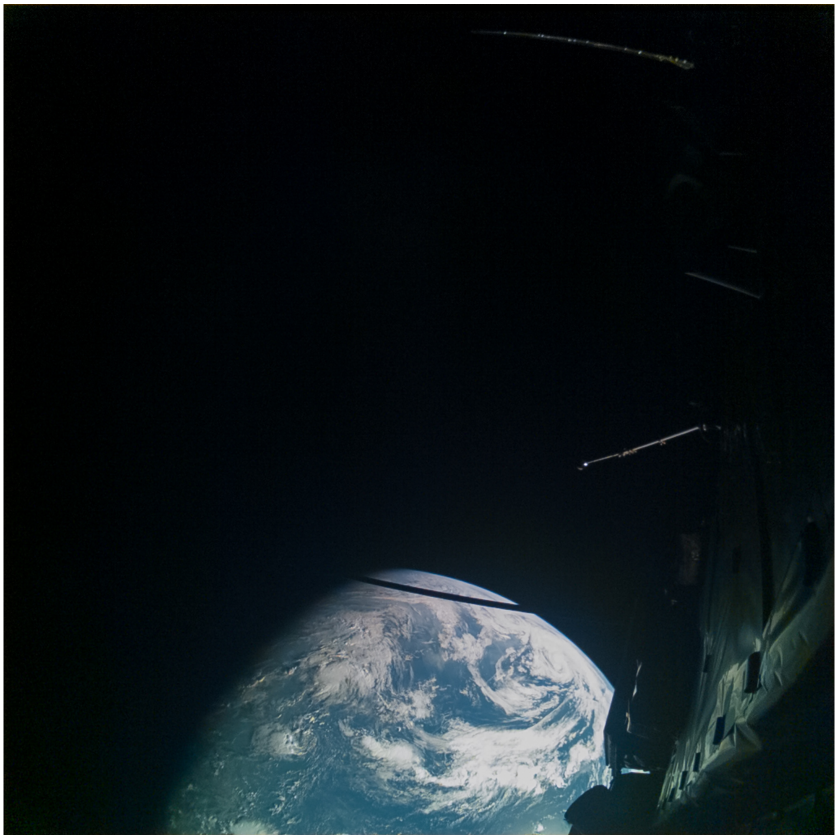

Figure 5: JMC Image taken shortly before Earth Closest Approach

All three star tracker optical heads were blinded by the Earth for roughly two hours, however never all of them at the same time. With one remaining non-blinded optical head at all times, there was no impact on the overall tracking status. At no point in time the spacecraft attitude had to be propagated using only the IMU.

Two hours after the Earth CA, JUICE performed another 180° roll around the –X axis to keep +Z at an angular distance of around 5° from the Earth direction.

All payloads were active during a dedicated slot between CA -4 hours and CA +3 days. While not all instrument activities can be described here, some remarkable results shall be mentioned:

- RPWI performed measurements for the full allowed duration. A sound representation of the radio wave environment around Earth was published online [11].
- During Earth science observation, SWI was able to detect water and ozone molecules in the Earth's atmosphere [12]. Together with the observations of the MAJIS instrument, this once and for all proved that Earth is indeed habitable [13].
- While JUICE crossed the Van Allen belt, its internal radiation detector was able to record the increased radiation background [14].
- RIME performed passive acquisitions to detect natural and man-made radio emissions from Earth. The activity was extended to attempt reception of a test signal transmitted by the HAARP experiment in Alaska [15].
- Overall, 140 images with JMC1 and 144 images with JMC2 were taken and downlinked. A short clip of the processed colour images can be found at ESA's web representation [16].

4.5 Post-Flyby Observations

Payload observation activities resumed shortly after Earth closest approach. At CA +2 days and 6 hours, the spacecraft executed one full 360° roll around its X axis. This manoeuvre was designed to support the calibration of the MAG and RPWI instruments. By CA +3 days, JUICE returned to its nominal attitude with the Earth positioned in the spacecraft's X-Z plane. The spacecraft's -X axis remained Sun-pointed.

Figure 6: Moon and Earth as observed by JANUS [17]

On September 9, 2024, at the outbound arc of the LEGA, a dedicated slew was performed to observe the Earth-Moon system from afar, with the spacecraft's +Z axis aligned towards the Earth centre. The total dwell time lasted only about 20 minutes. During this observation, multiple payloads were active, including JANUS, GALA, RPWI, and PEP-Lo. This event marked the only deviation from the standard -X Sun-pointing attitude during the LEGA phase.

4.6 Trajectory Evolution

The ballistic trajectory of JUICE throughout the LEGA proved to be precise and no emergency TCM was required. The Space Debris Office in collaboration with the United States Space Command performed multiple collision avoidance screenings that revealed no significant collision risk.

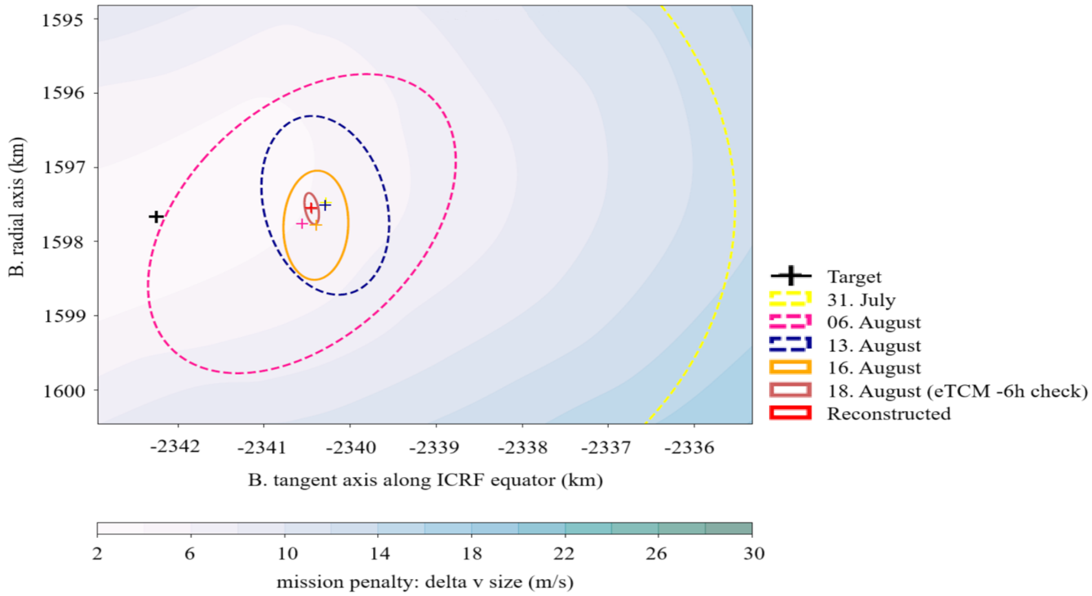

Figure 7: Chronological Evolution of the Trajectory Determination

Figure 7 visualises the evolution of the trajectory determination precision achieved by the Flight Dynamics Team. The target trajectory is depicted as black cross within the B-plane of the Moon, with the uncertainty ellipsis decreasing in size over time. The B-plane here denotes the plane perpendicular to the line connecting the spacecraft's trajectory to the centre of the Moon at closest approach. The Δv penalty is depicted as concentric rings around the target. At no point in time after the execution of the TCM -4 weeks manoeuvre, the penalty exceeded the 100 m/s threshold. In fact, the uncertainty in the trajectory determination decreased over time and eventually, an accumulated deviation of only around 3 m/s from the optimal trajectory was reconstructed after the double flyby.

On August 27, 2024, approximately one week after the LEGA, the spacecraft performed a planned correction manoeuvre (TCM +1 week), applying a Δv of 1.6 m/s. Rather than fully correcting the deviation from the nominal trajectory right away, this manoeuvre only served as a partial compensation. The Flight Dynamics Team opted for a more fuel-efficient strategy, scheduling an additional manoeuvre of 1.78 m/s at perihelion to be executed on January 1, 2025. Consequently, a previously considered TCM +2 weeks manoeuvre was omitted from the plan.

5 Results

5.1 Observations and Anomalies

Overall, JUICE performed exceptionally well during the LEGA phase. The meticulous preparation activities and simulation campaigns proved to be effective. Nevertheless, some minor anomalies and observations shall be reported here.

Shortly before the Moon flyby, one TC did not reach the spacecraft. This was due to high noise levels on the X-band receiver caused by the Sun standing in opposition with respect to Earth and the Spacecraft. Fortunately, this missing command was not critical and no mitigation action was necessary.

The Flight Dynamics Team reported a small, unexpected torque and Δv starting five minutes after Moon CA. While small enough to not cause any major impact, the deviation was visible in navigational data and lasted around 20 min. The root cause was suspected to be out-gassing processes, as Sun light reflected from the Moon's surface briefly illuminated the +X face of the spacecraft, which is usually facing the dark of deep space. This assumption was confirmed by the instrument teams that observed a cloud of water vapor after the event.

Several anomalies occurred as part of the autonomous payload commanding.
The GALA laser altimeter experienced an unexpected unit reboot at Moon flyby and lost its science data. The root cause is under investigation.
In addition, the thermal limits of the JANUS instrument were incorrectly set during the payload checkout. This caused a failed mode switch which subsequently lead to the JANUS cover remaining open during a wheel-offloading. In response, the JANUS team scheduled an additional decontamination activity after the Earth flyby to mitigate any potential impact.
During the Earth flyby, SWI transitioned to a unit safe mode at 22:56 UTC due a science script error. The cause of the script error is under investigation but had no impact on hardware. It was decided to resume SWI operations 14 hours after the safe mode entry.

The ground station performance was mostly nominal with two exceptions. On 20. August, the Malargüe ground station showed a degraded performance due to a heavy snow load covering the antenna dish, which resulted in a performance drop of approximately 9dB. However, at close distance to Earth, the margin in the link budget was large enough such that no telemetry loss occurred and the radiometric data showed no further degradation.
Ranging calibrations over Cebreros failed altogether, without impact on the orbit determination process by the Flight Dynamics Team. Maintenance activities were scheduled after the JUICE ground segment configuration freeze was lifted.

5.2 Lessons Learned

Though the LEGA activities were completed successfully, many lessons could be learned from an operational standpoint. Without a doubt, they will improve the implementation of further flyby operations both in the continued JUICE mission, but also for other ESA missions. Following, only the most significant and general applicable lessons shall be noted.

Autonomous payload activities that are scheduled relative to mission events should be planned with enough margins as the exact timing of these events can shift over the time of the long planning process. In the worst case, some payload activities overlap in an undesired fashion, have to be re-planned or in the worst case, need to be de-scoped completely. For the same reason, the planning of payload activities needs to respect the execution duration of command sequences, not only the start time.

The configuration of instrument heater and FDIR settings should be unified, as this task proved to be highly complex in regard to the large number of payloads onboard of JUICE. With each instrument possessing its own requirements, this can easily lead to operator errors during phases of high workload.

5.3 Conclusion

The Lunar-Earth gravity assist was performed successfully. The manoeuvre effectively increased the spacecraft's heliocentric velocity while reducing propellant consumption for the interplanetary cruise phase. Detailed trajectory analyses by the FD team confirm that the gravity assist optimized the orbital trajectory, thereby enabling the further journey to Venus and later, to Jupiter.
For all combined correction manoeuvres during the LEGA phase, 75 m/s of Δv were originally allocated, however only about 3.4 m/s were spent. This was only possible due to the exceptionally accurate manoeuvre performance combined with precise pure-torque wheel off-loadings. From initially eight possible manoeuvre slots, only two were actually needed.

This outcome not only validates the feasibility of complex multi-body gravitational manoeuvres but also reinforces ESA's strategic capability in deep-space navigation.
With the Lunar-Earth system behind it, JUICE is projected to reach Venus on 31. August 2025. Its ongoing journey through the Solar system can be followed closely online [18] to ever answer the question: "Where is JUICE?"

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