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THE JUICE NAVIGATION CAMPAIGN FOR THE FIRST COMBINED LUNAR-EARTH GRAVITY ASSIST

Thomas Syndercombe[a], Francesco Castellini[b], Frank Budnik[c], Raffaele Meles[d]

[a] *Telespazio GmbH, located at ESA/ESOC, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany, thomas.syndercombe@telespazio.de*
[b] *Telespazio GmbH, located at ESA/ESOC, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany, francesco.castellini@telespazio.de*
[c] *ESA/ESOC, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany, frank.budnik@esa.int*
[d] *GMV, located at ESA/ESOC, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany, raffaele.meles@ext.esa.int*

Abstract

This paper presents the Lunar Earth Gravity Assist (LEGA) navigation strategy defined for the JUICE mission at the European Space Operations Centre by the Flight Dynamics (FD) team. The key challenges of such a complex manoeuvre are discussed, along with the main results achieved during the navigation. Emphasis is given to the planning of the navigation campaign, stochastic Trajectory Correction Manoeuvres (TCMs) and emergency manoeuvres for anomaly recovery or space debris collision avoidance, as well as to the orbit determination setup and to the sensitivity of the trajectory to various dynamical and observable modelling details. Results from the LEGA are discussed, showing how careful planning and execution of the double swingby allowed a significant saving of propellant, which can be used to enhance the scientific return of the JUICE mission once in the Jupiter system.

Keywords: Navigation, Flight Dynamics, JUICE, Lunar-Earth Gravity Assist

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control System
CEB	Cebreros
COLA	Collision Avoidance
DCO	Data Cut-Off
DDOR	Delta Differential One-way Range
ESB	Earth Swingby
ESTRACK	ESA Tracking station network
FCT	Flight Control Team
FD	Flight Dynamics
FDT	Flight Dynamics Team
HGA	High Gain Antenna
IERS	International Earth Rotation Service
IMCCE	Institut de Mécanique Céleste et de Calcul des Ephémérides
ITP	InTerplanetary Phase
ITRF	International Terrestrial Reference Frame
JOI	Jupiter Orbit Insertion
JUICE	JUpiter ICy moons Explorer
LEGA	Lunar-Earth Gravity Assist
LGA	Low Gain Antenna
LIC	Launcher Injection Correction
MLG	Malargüe
MGA	Medium Gain Antenna
MSB	Moon Swingby
NAVCAM	Navigation Camera

NNO	New Norcia
OD	Orbit Determination
SAA	Sun Aspect Angle
SDO	Space Debris Office
SRP	Solar Radiation Pressure
SSE	Sun-Spacecraft-Earth
TCA	Time of Closest Approach
TCM	Trajectory Correction Manoeuvre
TTCP	Tracking, Telemetry and Command Processor
V_∞	Infinite Velocity
WOL	Wheel Off-Loading

1. Introduction

The JUpiter ICy moons Explorer (JUICE) is the European Space Agency's first mission to Jupiter and will perform detailed investigations of the Jovian system. JUICE aims to provide a comparative picture of the Galilean moons and their potential habitability, with particular emphasis on Ganymede. Launched on April 14th 2023 by an Ariane 5 rocket, it will arrive at the Jupiter system in 2031, performing a Ganymede gravity assist prior to the Jupiter Orbit Insertion to reduce the size of the capture manoeuvre. In the following years, until 2034, it will then perform a so-called "Jupiter Tour" with a total of 35 fly-bys of Ganymede, Europa and Callisto, before becoming the first mission to ever enter orbit around a moon in the Outer Solar System, reaching a 500-km circular orbit around Ganymede as final target for its nominal mission. Reference [1] provides a generic overview of the JUICE mission, while reference [2] focuses on the trajectory design aspects – giving details on both the interplanetary trajectory and the Jupiter Tour.

In August 2024, JUICE also became the first mission to perform a Lunar-Earth Gravity Assist (LEGA), i.e. a swingby at the Moon followed just one day later by one at the Earth, allowing it to save a significant amount of propellant on its way to Jupiter. The rationale for the introduction of the LEGA and the Mission Analysis work that led to its exploitation are described in Reference [3]. The LEGA manoeuvre is extremely sensitive to targeting errors and, as such, the accuracy of spacecraft navigation is more critical than for other planetary swingbys. For this reason, extreme care was paid to the operational implementation of the LEGA, in terms of navigation and overall operations planning as well as in the setup of the Orbit Determination (OD) and manoeuvre optimisation systems. This culminated in an intense LEGA campaign lasting roughly two months, from the start of the period with increased stations passes until the execution of a clean-up manoeuvre one week after the LEGA, spanning several trajectory correction manoeuvre slots; tight orbit monitoring and collision screening activities around the two closest approaches; and the a-posteriori reconstruction of the double swingby trajectory in the OD.

The LEGA manoeuvre was comprised of a Moon Swingby (MSB) with a perilune altitude above the Moon surface of approximately 750 km in the evening of the 19th of August 2024, followed ~24.5 hours later by an Earth Swingby (ESB) at a perigee altitude of 6807 km. The infinite velocities (V_∞) were respectively of 3.65 km/s and 3.30 km/s, with semi-deflections of 7.4 and 42.1 degrees, resulting in heliocentric vectorial velocity changes of 0.9 km/s and 4.8 km/s respectively. The navigation campaign, starting roughly 45 days before the LEGA, entailed a higher frequency of the standard radiometric tracking passes and a limited number of Delta-DOR measurements, added to provide robustness to the overall navigation strategy. Slots for stochastic Trajectory Correction Manoeuvres (TCMs) were foreseen 4 weeks, 2 weeks, 7 days, and 3 days before the MSB, as well as 1 and 2 weeks after the ESB for clean-up of the navigation errors. Due to the limited time, no nominal TCM slots were planned between the Moon and Earth closest approaches, which were therefore targeted in open loop without nominal ground intervention in between. Nevertheless, emergency TCM slots were included 6 hours before the MSB, as well as 4 hours before the ESB. These slots were only to be used in case of unforeseen circumstances (e.g. safe mode with large parasitic ΔV) resulting in a mission ΔV penalty higher than 100 m/s, or if a potential collision had been identified by the Space Debris Office during the close approach phase to the Earth.

This paper provides a more in-depth overview of the overall navigation strategy and setup, showing how the very high sensitivity of trajectory prediction errors results in large mission ΔV penalties even for small Moon B-plane errors. Particular focus is also given to the dynamic modelling and calibration of non-gravitational accelerations, key to the successful execution of the combined swingby. Finally, the paper presents the actual flight results from the LEGA, highlighting the main achievements and challenges from a navigation perspective of this complex manoeuvre, which allowed JUICE to save precious propellant for its valuable scientific investigations in the Jupiter system.

2. Interplanetary and LEGA Trajectory Design

Given the complexity and numerous constraints inherent to the full JUICE trajectory, the mission is divided into two primary segments: the interplanetary phase (ITP) and the subsequent tour of the moons. Although the ITP nominally concludes at the Jupiter Orbit Insertion (JOI) manoeuvre, robustness is enhanced by extending the operational trajectory to include the second Ganymede swingby (2G2). By targeting the outgoing conditions of 2G2, the optimisation of the ITP can be decoupled from that of the tour, thereby reducing computational demands during real-time operations and allowing greater flexibility in subsequent tour adjustments.

The launch window spanned two weeks, during which the overall ITP ΔV progressively increased from 202 m/s to 379 m/s [4], due to schedule delays that moved the launch window forward resulting in an atypical, non-symmetric, ΔV profile over the possible launch days. Despite suboptimal weather conditions, a successful launch was achieved on the second day of the window. This not only maintained low overall ΔV costs (around 209 m/s), but also a flawless flight of the Ariane 5 resulted in an accurate injection of the spacecraft into its hyperbolic trajectory. Consequently, the planned Launcher Injection Correction (LIC) manoeuvre, intended to address V_∞ errors immediately after launch, was rendered unnecessary. Following launch, a series of test manoeuvres were executed to verify the proper functioning of all on-board thrusters, ensuring that the spacecraft could perform any necessary stochastic manoeuvres while still satisfying the illumination constraints imposed by the spacecraft.

During the ITP, JUICE is subject to several attitude constraints that vary with its distance from the Sun and limit the achievable ΔV direction during manoeuvres. These constraints can be condensed into a single requirement on the angle between the applied ΔV and the Sun–spacecraft direction, known as the Sun aspect angle (SAA).

Within the ITP, two deterministic manoeuvres are executed during the initial Earth-to-Earth arc, preceding the ballistic sequence of LEVEE (Luna-Earth-Venus-Earth-Earth) flybys that deliver the spacecraft to Jupiter. The execution of the first deterministic manoeuvre (DSM-1), which provides a ΔV of 208 m/s, is critical for establishing the desired conditions at the LEGA. The second deterministic manoeuvre (DSM-2), contributing an additional 0.35 m/s for the flight launch date, refines the targeting and corrects residual errors a few months after DSM-1. Because DSM-1 represents the first—and only—significant use of the main engine in the ITP, it was deliberately split into two portions (95% and 5% of the total ΔV) to enhance robustness against execution errors. Afterwards, JUICE's trajectory is ballistic until JOI, with stochastic TCMs planned to address navigation uncertainties during flybys and to minimize their impact on the overall ΔV budget.

During the JUICE ITP design, it was decided to introduce the LEGA (see Reference [5] for an in-depth explanation of this technique), with a low altitude Moon flyby over the trailing side increases the relative velocity magnitude with respect to the Earth, which the Earth flyby itself cannot do. The geometry of the trajectory designed for the LEGA is presented in Figures 1 through 4, which show the Sun and Earth distance throughout all the ITP, a zoomed-in portion in the Earth-Moon system of the interplanetary trajectory swing-by on the ecliptic plane, and three-dimensional views of both the Earth and the Moon B-planes. The most important parameters of the Moon and Earth swingbys are summarised in Table 1 for the nominal trajectory. For the JUICE case, the Moon swingby allows to increase the Earth relative velocity by about 300 m/s. This corresponds to a saving in deterministic ΔV of approximately 150 m/s at DSM-1, due to its leveraging factor of ~2, compared to a trajectory with a conventional Earth gravity assist. However, due to the high sensitivity to navigation errors, the stochastic ΔV allocated pre-launch for the LEGA was 75 m/s, i.e. 60 m/s higher than that of a standard Earth gravity assist, with a theoretical overall saving of about 90 m/s [4].

Preparation for the LEGA involved scheduling TCM slots both before and after the flyby. Comprehensive analyses were performed to assess the sensitivity of the swingby to navigation errors by perturbing the Moon-arrival B-plane impact point and evaluating the resulting effect on the overall ITP ΔV. While V_∞ perturbations could significantly affect the ESB altitude - resulting in a substantial ΔV penalty with post–swingby corrective manoeuvres requiring nearly an order of magnitude more ΔV than the perturbation itself—the error sources associated with V_∞ were minimal, given the nearly perfect execution of the launch and DSMs. The primary source of error was in fact found to be perturbations in the Moon B-plane. To address these, the TCMs described above were analysed; in particular, those in the week before and those after the LEGA. As expected, the analysis indicated that early TCMs effectively mitigate large B-plane errors with relatively modest ΔV, proportional to the perturbation magnitude, whereas "clean-up" manoeuvres performed after the swingby demand substantially higher ΔV. Figure 5 shows an example of how position errors in the most sensitive direction exceeding 25 km rapidly surpass the nominal ΔV budget of 75 m/s, when corrected for after the ESB.

Further refinement of the strategy focused on reducing the total ΔV required by incorporating additional free manoeuvres throughout the Earth–Venus arc, optimizing both their number and magnitude. This refined approach resulted in implementing two free TCMs - one executed near perihelion and the other near aphelion – and yielded an approximately 45% reduction in ΔV compared to the original strategy with a single manoeuvre 8 days after the LEGA. The slot at –3 days was the last one allocated to nominal trajectory corrections, the one at –6 hours relative to the MSB was designated exclusively for emergency manoeuvres, while the slot at +20 hours (positioned between the two closest approaches) was reserved for collision avoidance, as described in the dedicated section below.

Table 1. LEGA Moon and Earth Swingby nominal parameters

	Moon Swingby	**Earth Swingby**
Time of Closest Approach	2024-08-19T21:16 UTC	2024-08-20T21:57 UTC
Eclipses	31 min from 20:38 UTC	None
Occultations	34 min from 20:35 UTC	N/A
Pericentre altitude	755 km	6807 km
Pericentre latitude	-12.4 deg	24.1 deg
Infinite Velocity (V_∞)	3.65 km/s	3.30 km/s
Semi-deflection	7.4 deg	42.1 deg
Heliocentric ΔV	0.9 km/s	4.8 km/s

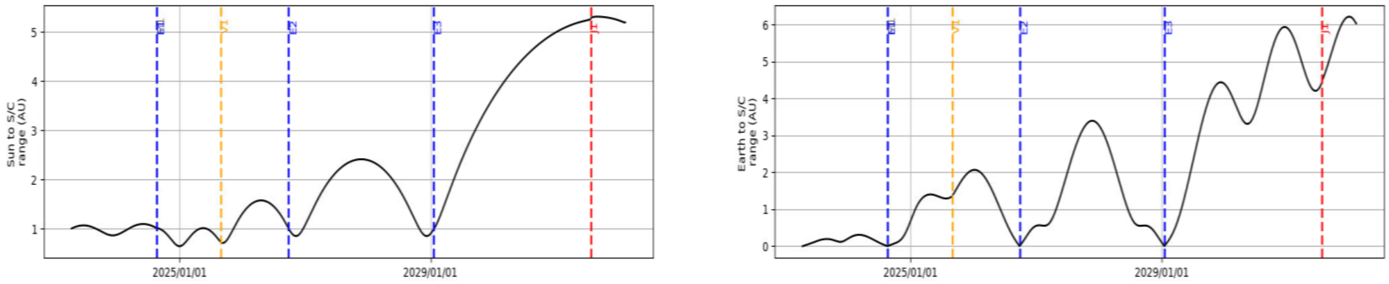

Fig. 1. Sun (left) and Earth (right) distances in AU during the JUICE Interplanetary Trajectory.

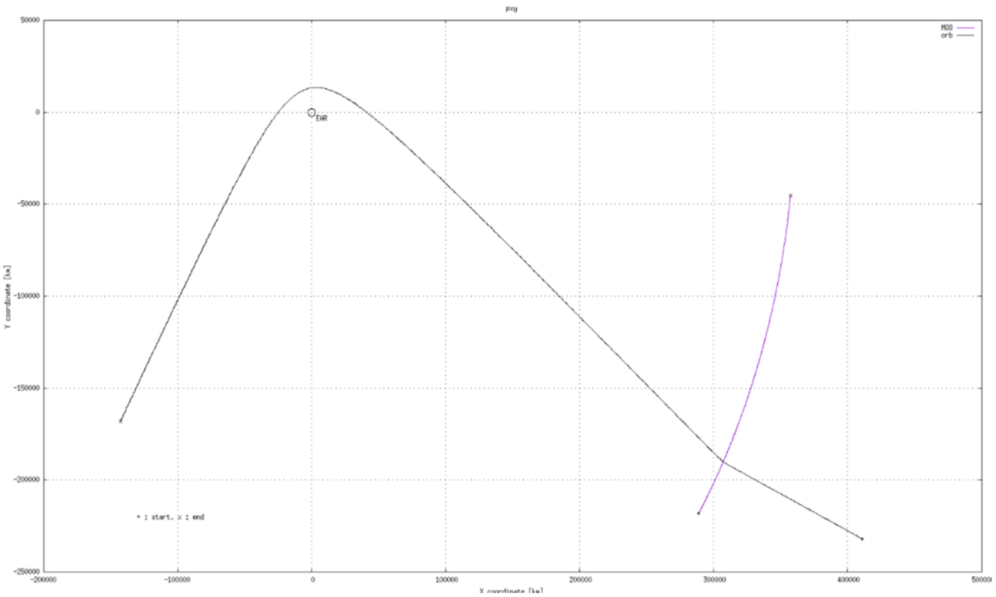

Fig. 2. LEGA, projection on the Earth Mean Ecliptic J2000 plane.

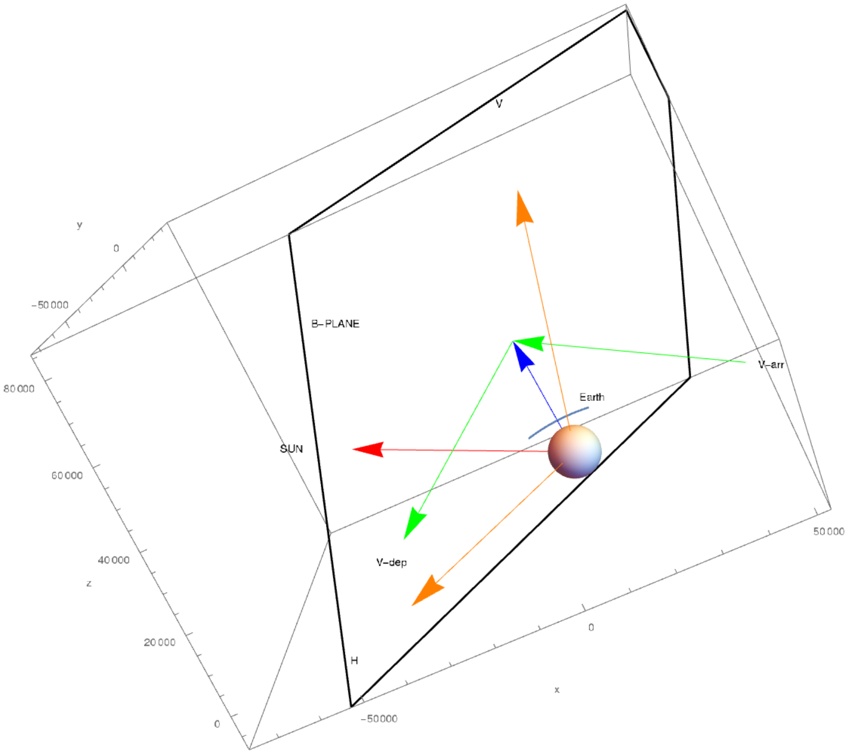

Fig. 3. LEGA, arrival Earth B-plane

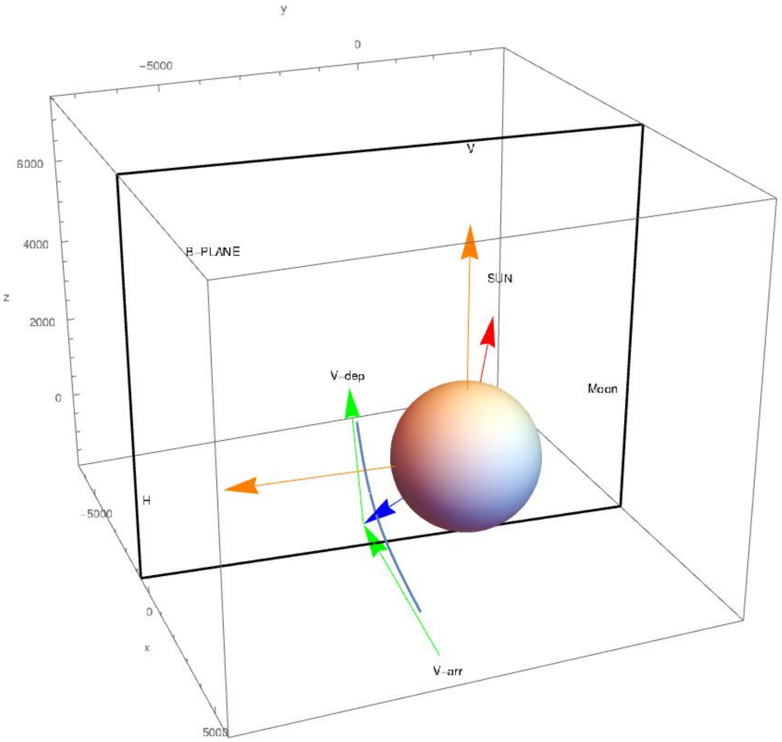

Fig. 4. LEGA, arrival Moon B-plane

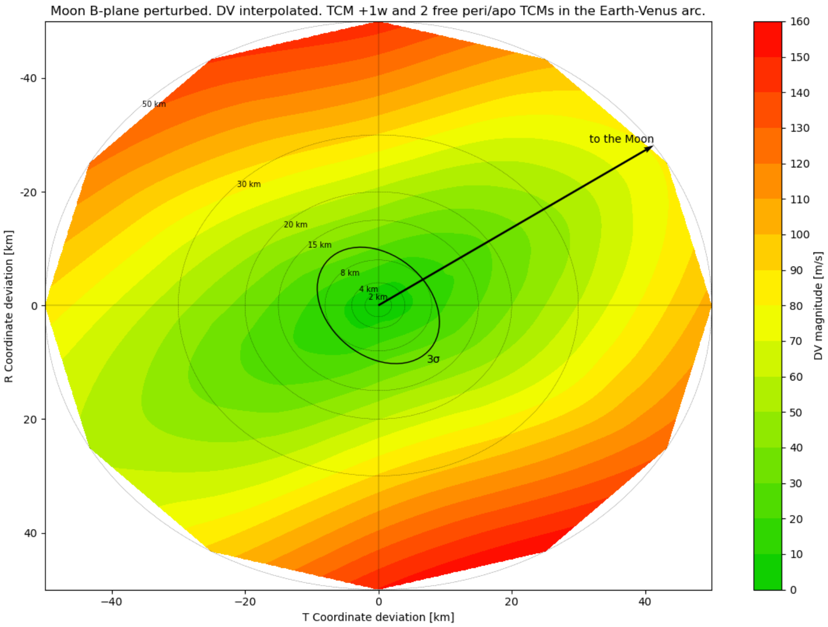

Fig. 5. DV required to correct perturbations at the Moon B-plane. The bullseye corresponds to the nominal impact point. Perturbations are in Km and are corrected post-ESB. The black ellipse represents the 3-sigma uncertainty on the Moon closest approach, as given by pre-launch navigation studies.

3. LEGA Navigation Campaign Operations

The JUICE LEGA represented a complex operation from many different perspectives, not only for the challenging navigation and overall Flight Dynamics activities, but also for complex spacecraft and payload operations. While this paper is focused on the former, reference [6] presents the LEGA from the point of view of the JUICE Flight Control Team (FCT), hence providing a more comprehensive description of the latter.

Spacecraft navigation is however deeply connected with spacecraft and payload operations; hence a brief overview is provided here for the most relevant aspects, in particular attitude and communications strategy, with a sketch of the JUICE spacecraft shown below in Figure 6. Due to thermal constraints, JUICE must keep its body-mounted, 2.4-meter, High Gain Antenna (HGA) on the -X face permanently Sun-pointed while in the inner Solar System, as this acts as Sun shield in the hot cruise phase. The roll around the sun line is therefore the only attitude degree of freedom. The baseline cruise profile has the Earth in the X/Z plane, such that the rotating solar panels mounted along the Y axis can steer following the Sun, although these are constantly offset by 70 deg in the inner cruise phase. Regular 180 deg flips around the Sun line are done in cruise, balancing the effect of the Solar Radiation Pressure (SRP) torque. The flipping attitude was however suspended throughout the LEGA campaign to simplify operations, resulting in a stable quasi-inertial pointing, referred to from now on as "LEGA attitude". For the same reason, Wheel Off-Loading (WOLs) in this period were set to execute as pure-torque, as opposed to the default non force-free mode which saves propellant during the long cruise to Jupiter but results in residual ΔVs which are less predictable, due to non-balanced thruster actuations.

Once close to the Earth-Moon system, within 48 hours of the MSB, communications were switched from the MGA to the Low Gain Antennas (LGA) and the freedom in roll around the Sun line started to be exploited to maximize the scientific return of the double fly-by. Since both the science and navigation cameras of JUICE are aligned with the +Z axis of the spacecraft, this was kept via a slow roll in the plane of the orbit around the Moon, as close as possible to the Moon nadir direction. This ensured about 30 minutes of visibility of the Moon surface around closest approach, i.e. with the payloads boresights falling within the disc of the Moon. In a similar way, the next day, +Z was kept in the plane of the orbit around the Earth, also ensuring about 30 minutes of visibility of the Earth surface before the Earth closest approach – although unfortunately the geometry of the fly-by did not allow visibility at TCA.

Throughout the MSB and ESB, the full set of payloads were activated for testing purposes via dedicated payload commands provided by the scientific teams (see reference [6] for more details). The JUICE Navigation Camera (NAVCAM) was instead operated directly by ESOC Flight Dynamics Team (FDT), to gain operational expertise for future use of the instrument in the Jupiter system. Due to the geometric constraints described above; the fact that both the Moon and the Earth were approached from the dark side; and that a "quiet time" with the NAVCAM inactive was requested by one of the payloads around the Moon TCA; only a limited number of NAVCAM images could be commanded. Nevertheless, this proved very useful for exercising the FD ground processing chain. Numerous other images were also obtained by the scientific instruments and by JUICE's Monitoring Cameras, of which an inspiring example is shown at the end of this paper (see Figure 12).

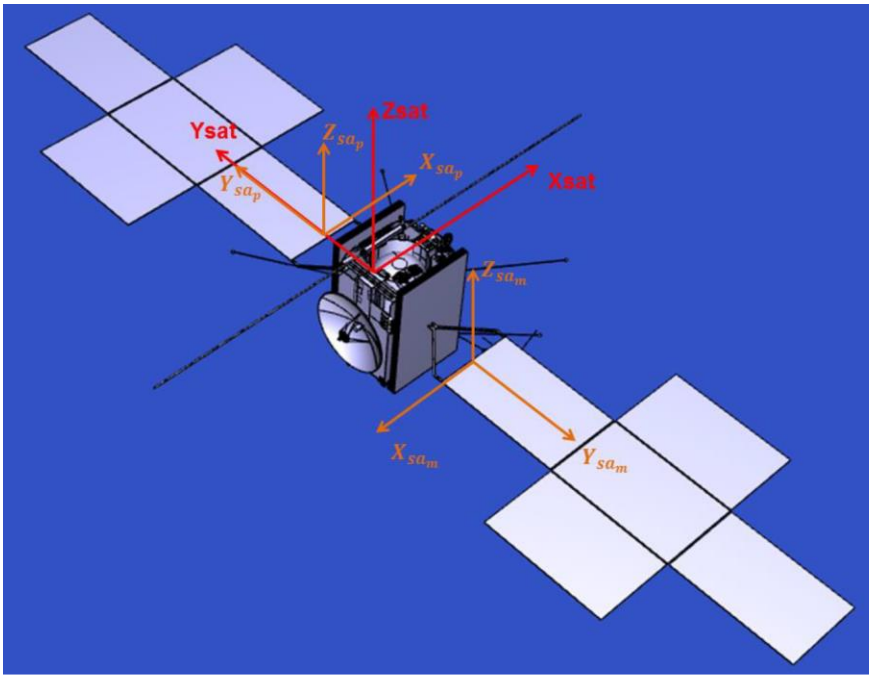

Fig. 6. Sketch of the JUICE spacecraft with the spacecraft reference frame depicted in red.

3.1 Navigation Campaign Planning

The operational planning of the navigation campaign involved three main aspects: tracking data availability, TCM slot allocations and ground commanding cycles timeline definition.

According to pre-launch Mission Analysis work, nominal TCM slots for the LEGA navigation were defined at –4 weeks, -2 weeks and -5 days with respect to MSB and at +1 week with respect to ESB. While TCM-4w, TCM-2w and TCM+1w were adopted in the operational planning, for operational robustness the TCM-5d was split in two slots. These were respectively 1 week and 3 days before MSB, with the latter used mainly as backup of the former and with low likelihood that both would be executed under nominal conditions. An additional clean up TCM+2w was also added for fine-tuning and operational robustness. As for other navigation campaigns carried out by ESOC FD, the decision to execute or not a nominal TCM is taken during operational briefings with the full team. The decision is based on the navigation needs, in particular the distance from the B-plane target compared to the 3-sigma uncertainty ellipse and the total ITP ΔV penalty compared to the LEGA budget, associated to operational considerations such as the minimum practical manoeuvre size and the inherent risks associated with performing a manoeuvre. The main difference with respect to other swingby navigation campaigns resides in the fact that the last nominal TCM slot is allocated only 3 days before the MSB, while this is typically one week out. The reason for this is the very high sensitivity of the post-LEGA trajectory to Moon B-plane targeting errors, as described above, which suggested a more robust approach. Note that, in addition to nominal TCMs, "emergency TCM" (eTCM) slots were also introduced as last resort for contingencies, 6 hours before the Moon's and 4 hours before the Earth's TCA. These are described further in Section 3.2.

Regarding tracking data acquisition, a similar approach was followed to that previously employed by ESOC FDT for other swingbys. The frequency of station passes for range & Doppler data collection was increased from 2-3 per week to daily passes for the duration of the navigation campaign, from 45 days before the MSB to 10 days after ESB. Additionally, continuous station passes covering 24 hours/day were arranged for the 5 days directly surrounding the LEGA, allowing continuous monitoring of the spacecraft during this critical phase. This provides extra data close to the Earth and Moon, which constitutes the most valuable information for trajectory reconstruction purposes. Finally, additional Delta-Differential One-Way (DDOR) measurements from both the Cebreros–New Norcia and Cebreros-Malargue baselines of the ESA tracking network were added, before the OD Data Cut-Offs (DCO) for the TCM-4w, TCM-2w and TCM–1w slots. Although these are not strictly necessary for an Earth swingby, they provide additional operational robustness, to allow for further consistency checks, especially for the dynamic model used in the OD.

Based on station scheduling and TCM/eTCM slots, ground activities were defined in coordination between the FDT and FCT, as reported in Table 2. On FD side, TCM preparation activities involve a so-called 'FD cycle' starting at the DCO with the orbit determination; followed by manoeuvre optimisation and the operational briefing to decide whether to execute the TCM; and to be concluded with the generation of all the Attitude and Orbit Control System (AOCS) commands for the spacecraft, (including any TCM commands). These are consequently delivered to the FCT by the end of the following working day. After the delivery of FD commands, more activities are required on FCT side, for example merging these with the rest of the platform and payload commands, before uplink to the spacecraft. To keep both a nominal and a backup uplink pass opportunity, and accounting for weekends, this results in JUICE having approximately 5 days between DCO and execution of a manoeuvre. For the emergency TCMs, the whole timeline is extremely compressed due to the limited available time, with work outside of normal working hours and an allocation for the full FD cycle limited to 10 hours.

Table 2. Planning Cycles, DDOR observations and TCM slots

Period	Main activities	Radiometric data	TCM slots
6th July	Navigation campaign start	Start of daily range & Doppler passes	
8th - 13th July		DDOR measurements, 3 x 2 baselines	
17th – 22nd July	TCM-4w preparation		TCM-4w 22/07 03:00z
26th – 30th July		DDOR measurements, 2 x 2 baselines	
31st – 5th August	TCM-2w preparation		TCM-2w 05/08 09:00z
5th – 7th August		DDOR measurements, 2 x 2 baselines	
7th – 12th August	TCM-1w preparation		TCM-1w 12/08 03:00z
13th - 17th August	TCM-3d preparation LEGA command preparation		TCM-3d 17/08 03:00z
17th August		Start of 24x7 station coverage	
18th August	eTCM MSB-6h preparation		eTCM-6h 19/08 15:00z
19th August	MSB monitoring		
20th August	eTCM ESB-4h preparation ESB monitoring		eTCM-4h 20/08 18:00z
21st August	LEGA reconstruction start		
22nd August		End of 24x7 station coverage	
22nd - 27th August	TCM+1w preparation		TCM+1w 27/08 22:00z
30th August	Navigation campaign end	End of daily range & Doppler passes	

3.2 LEGA timeline with Emergency TCMs and COLA screening

As described above, emergency TCM slots were added to the LEGA timeline but would only be exercised in case of very severe contingency resulting in major or catastrophic deviation from the nominal trajectory. While eTCMs are typically foreseen for any swingby navigation campaign, additional considerations were required for the JUICE LEGA. In fact, due to the relatively low altitude of the ESB and the proximity of the hyperbolic arc to the geostationary orbital plane, a collision avoidance (COLA) procedure had to be established to mitigate risks associated with debris and satellite collisions. The ESOC Space Debris Office (SDO) was hence involved in the planning and operations, with the agreement that COLA screening would be performed for the nominal trajectory as well as several alternative COLA trajectories, which could be flown in case of collision possibility. Following a previously exercised procedure, immediately prior to the Moon swingby, together with the latest optimized nominal trajectory, four additional trajectories were submitted to the SDO. These trajectories included precomputed COLA manoeuvres executed in the eTCM slot ESB-4h and their predicted effect on the orbit and its covariance. The manoeuvres were designed such to either delay or advance the ESB closest approach by ±3 and ±9 seconds. The TCM+1w slot would then to be used to correct the induced perturbation which is by design small since mainly changing the arrival time leaving the impact parameter unchanged. This resulted in along-track deviations of up to 30 km at GEO altitude, at the cost of 3 to 8.5 m/s ΔV, while simultaneously simplifying the operational setup and reducing optimisation time.

Given the COLA procedure and additional operational considerations, rigorous flight rules were defined in advance for the LEGA eTCMs at MSB-6h and ESB-4h. This was to ensure avoidance of doubt while making critical operational decisions under time pressure. The flight rules dictated that an eTCM would be executed if, based on the latest OD and trajectory optimisation, Jupiter could not be reached within the given mission constraints, or, if by doing so a ΔV penalty of more than 100 m/s would have to be spent. The 100 m/s correspond to the available reserve for mission contingency, hence any penalty less than that would still ensure a nominal science mission at Jupiter. Moreover, in case of nominal trajectory with a collision probability above 10^{-4}, the COLA trajectory with cheapest mission ΔV and collision probability below 10^{-6} would be flown.

The timeline of the last week prior to the LEGA and of double swingby itself is summarised in Figure 7, where the nominal TCM-3d and the two eTCMs are clearly indicated. Note that the COLA screening cycle with the SDO was also carried out for the TCM-3d slot, purely for the sake of exercising the procedure and interfaces. Overall, the developed LEGA timeline was intense but allowed for a robust plan covering contingencies on the spacecraft, ground systems, and the trajectory itself. In flight, no contingencies materialized, none of the manoeuvres shown in Figure 7 were required, and JUICE ran smoothly through all planned LEGA activities.

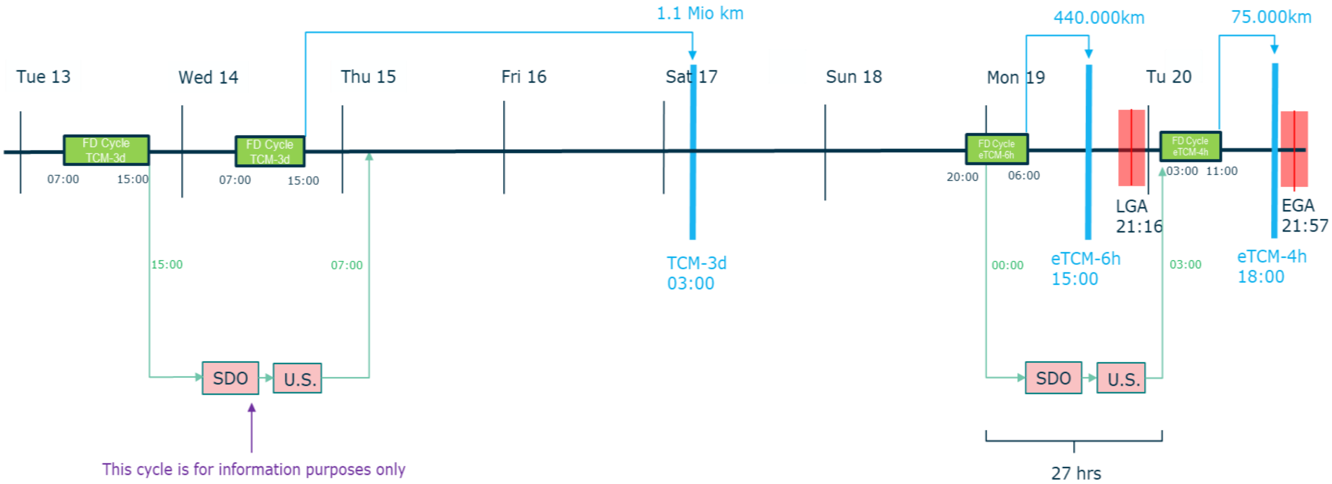

Fig. 7. Timeline leading up to the LEGA, including emergency TCM slots and COLA screening process

4. Orbit Determination Setup

A single Orbit Determination team, located at ESOC, performs OD support across all ESA interplanetary missions. The JUICE orbit determination setup described in this section is therefore rooted in the lessons learnt and experience obtained from ESA's past and present interplanetary missions. It should also be noted that each step of the FD cycle is independently checked by the FD Test and Validation Team, which operates an independent software suite to minimise potential errors. These checks cover also the OD process, ensuring that the appropriate setup is used.

4.1 OD Software

JUICE's OD has been performed since launch using a new deep space orbit determination system which has been developed by the ESOC FDT and is now being used to operate all new ESA missions. This is based upon GODOT - the Generic Orbit Determination and Optimisation Toolkit. After decades using legacy software developed in 90s for the first ESA deep space missions, ESOC FDT started a large development effort to design and implement a common software infrastructure for a variety of different software applications used across many different sections. Such effort has been conceived from the start with an ambitiously wide scope, aiming at providing in GODOT a modular, extensible, common library to form the core of all orbit related tasks, primarily within the ESOC FD division but also for a larger community in Europe. On top of the GODOT infrastructure, additional OD-dedicated libraries were developed and are now shared between the Earth Observation and Deep Space FD teams, while an application layer tailored for non-Earth orbiting missions was implemented to cope with virtually any mission scenario. The resulting Deep Space OD system has gradually been replacing the legacy software, with Solar Orbiter, Exomars Trace Gas Orbiter (TGO), JUICE, Euclid and Hera now running on the GODOT-based software.

As this paper's focus is on the Juice LEGA, the interested reader should refer to reference [7] for an introduction to the overall GODOT infrastructure and to references [8] and [9] for an overview of the Deep Space OD system used in this work.

4.2 Dynamics setup

JUICE is utilising the INPOP19a planetary ephemerides, as provided by the IMCCE and described in reference [10]. Newtonian gravitational effects of all major bodies are computed including relativistic effects from the Sun, Earth and Moon. The Earth gravity field is modelled with an order and degree 32 spherical harmonics within a distance of one million km and as point mass beyond this, while the lunar gravity is modelled with an order and degree 64 spherical harmonics, in light of the much lower flyby altitude. While higher orders are available it was noted during internal tests that these values were sufficient in terms of accuracy and the system runtime was considered reasonable.

SRP acceleration is modelled from industry provided optical properties of spacecraft faces. Given the predefined LEGA attitude described above, the primary component of the SRP force lies in the Sun-Spacecraft direction. The 70-deg solar arrays tilt in inner cruise causes a meaningful force in the spacecraft Z direction, approximately one order of magnitude smaller than the primary Sun-Spacecraft direction. SRP force along the panel rotation axis (Spacecraft Y axis) is modelled to be effectively zero, due to the symmetric nature of the spacecraft.

No spacecraft thermal re-radiation force model was implemented, under the expectation this will be small and constant – thanks to the fixed attitude guidance relative to the Sun - and effects will hence be absorbed by the SRP estimation in the OD filter (see section 4.4).

4.3 Observables setup

Data are collected from three different ESTRACK deep-space antennas located at Cebreros (CEB), Malargue (MLG) and New Norcia (NNO), all of which are well characterised through their use in routine operations. Accurate station positions are known, with additional tectonic plate motion and solid earth tide effects also being modelled. Tracking data are recorded by the TTCP – ESA's deep-space tracking receiver - from three stations. A raw 2-way Doppler data point is acquired every second and integrated over a 60 second count time during preprocessing. 2-way range data are collected at 1 s raw and down-sampled to 1 point per 20 minutes.

DDOR data are collected from two different baselines: Cebreros-Malargue and Cebreros-New Norcia, with quasar selection performed in advance. Three scans were collected per DDOR observation session from the two stations of the baseline, all being of the "Spacecraft-Quasar-Spacecraft" type, with one hour of station time (per station) being allocated for the whole session.

The received raw data, summarised in Table 3, are pre-processed into an internal observations file format. Before any orbit determination fit, an unfitted passthrough is performed of the latest tracking data against a priori orbit prediction to observe any unexpected signatures, features, or trends that exist in the raw data and – if applicable – edit them. After this the data is fed into the orbit determination filter, with the parameter configuration outlined in the next sub-section.

Notable in the observables modelling is the antenna switch from MGA to LGA on August 17th, and back to MGA on August 23rd, as introduced in Section 3. This caused a visible range jump in the observables, coming from different antenna delay corrections being applied, however this jump is within the uncertainty given by industry. Later, a correction was identified which improved the modelling and reduced this jump.

Table 3. Tracking data types and OD filter settings

	Bias (1σ)	Random (1σ)	Frequency
Range	10 m	5 m	Subsampled at 20 min
Doppler	None	0.2 mm/s	Compressed at 1 min
DDOR	None	0.1 ns	As per Section 3.1

4.4 OD parameters summary

OD parameters are outlined in Table 4 below. The associated sigmas were derived via a combination of quantitative analysis and historical values derived from the Flight Dynamics team's operational experience.

Although JUICE WOLs throughout the navigation campaign were commanded to be force-free, small parasitic ΔV were expected nevertheless and therefore the WOLs ΔV components were solved for in the OD. Conservatively, an a-priori 1σ uncertainty of 0.3 mm/s was used, since more actuations were expected in the LEGA attitude than in previous cruise with attitude flips, where an order of magnitude lower values had been observed from OD estimates and Doppler residuals of WOLs during passes.

For each orbit determination, there were additionally several WOLs outside of reconstruction arc (namely, in the future) but before the flyby itself. These were scheduled to occur daily at around midnight. For future WOLs that were already commanded, a zero-ΔV manoeuvre with a considered spherical 1σ of 0.3 mm/s was inserted at the exact commanded time. Beyond the commanded period, a zero ΔV manoeuvre was placed at midnight every day, again with a 0.3 mm/s considered 1σ.

For the TCMs, reconstruction was done with wide a-priori uncertainties of 3% and 1.7 deg (1σ), to avoid constraining the filter. For future TCMs instead, uncertainties to be applied when mapping to the B-plane were treated differently depending on whether the manoeuvre cut-off onboard was decided based on pulse-counting or accelerometers. For manoeuvres with a total ΔV above 10 cm/s (hence using accelerometers), a magnitude error of 2% and direction error of 0.33 deg would be applied (1σ). Meanwhile for manoeuvres with a total ΔV below 10 cm/s (hence using pulse counting) a spherical 2 mm/s uncertainty (1σ) would be applied. These values are selected to be intentionally larger than from industry documentation, in order to be conservative in the B-plane ellipse estimation, given the limited flight data available. All manoeuvres were modelled as impulsive, instantaneous velocity changes for simplicity, though the option exists in the software for finite duration manoeuvres, if doubts were to arise over this approximation.

The SRP force was calibrated in two degrees of freedom through a linear scaling along two axes. The primary X axis of the calibration frame was defined to be in the Sun-Spacecraft direction, while the secondary (Z axis) was defined as the projection of the spacecraft Z axis into the plane perpendicular to the primary (X direction). Given the nominal spacecraft attitude during this hot cruise period was anyway with spacecraft -X Sun-facing, this calibration frame in practice aligned with the spacecraft frame. The final Y axis of this 'SRP calibration frame' was not given freedom in the OD fit as no meaningful net force is expected for the given attitude. As part of the OD fit a linear scaling was applied to the model derived from pre-launch industry provided values for both the primary and secondary SRP components. These were given a-priori values based upon a calibration assessment performed during quiet cruise and an a-priori 1σ of 1% of the spacecraft main component, based upon the observed variation of these values.

For each ground station pass, a range measurement bias is estimated as part of the OD fit to account for unmodelled effects and uncertainties in the electronic delays onboard and at the station. Based on historical experience for periods far from superior solar conjunctions, a 1σ a-priori of 5 meters was selected.

A number of consider parameters were also included in the OD in order to estimate a meaningful uncertainty. These parameters do not affect the estimated parameters but their uncertainties are taken into account when computing the a-posteriori parameter covariance. Tropospheric corrections, ionospheric corrections, station position and Earth orientation parameters were included as considered parameters only, the set uncertainties listed in Table 4 are derived from historical experience and analysis. Transponder delays were also given considered sigmas consistent to the industry design requirements.

After an exchange with the IMCCE, an analysis was performed to assess the effect of the covariances associated to the INPOP19a ephemerides for the Earth, Moon and Earth-Moon Barycentre relative to the Sun and Solar System Barycentre. Incorporating these uncertainties into the system was found to have a very minor direct effect on the resulting covariance. The indirect effect on the dynamics from a perturbed body state on the order of the provided covariances was also considered to be negligible. In the interest of computational runtime, solar system body states were therefore neither estimated nor considered in the OD filter.

Table 4. OD parameters summary

	A-priori value	A-priori sigma (1σ)	Type
Initial spacecraft orbit state	Taken from previous OD solution at a reference epoch.	Unconstrained	Solve-For
SRP	As calculated by ground model, calibrated against in-flight data.	Spherical 1% of the magnitude of the main component (Sun-Spacecraft Direction)	X and Z Solve-For Y Consider Future X, Y, Z Considered
1-way Range biases (per pass)	Zero	5 meters	Solve-For
Manoeuvre ΔV within reconstruction arc	Commanded value.	3% in magnitude and 1.7 deg in direction.	Solve-For
WOLs ΔV within reconstruction arc	Zero parasitic ΔV	0.3 mm/s	Solve-For
Manoeuvre ΔV outside reconstruction arc	Commanded value.	Commanded ΔV > 10 cm/s: - Magnitude: 2% - Direction: 0.33 deg Commanded ΔV < 10 cm/s - 2 mm/s spherical	Consider
WOL ΔV outside reconstruction arc	Zero parasitic dV	0.3 mm/s spherical, daily at midnight	Consider
Tropospheric Delay	From GNSS-based calibrations, when available. Modelled from weather data recorded by ground station otherwise.	- Dry Zenith correction: 1cm - Wet Zenith correction: 4cm	Consider
Ionospheric Delay	Global ionosphere model	- Ionosphere scale 25%	Consider
Transponder Delay	Industry Provided	- Group delay: 1e-8 s - Phase delay: 1e-7 s	Consider
Station Position in ITRF	Ground Station Defined.	10 cm spherical	Consider
Earth Orientation Parameters	As per IERS provided data	X: 7e-9 rad Y: 7e-9 rad Z: 18e-9 rad	Consider
Earth State	From INPOP19a	None	Fixed
Moon State	From INPOP19a	None	Fixed
Eart/Moon GM values	From INPOP19a	None	Fixed

5. Results

The results from the LEGA navigation are described in this section, with particular focus on the approach navigation in the first sub-section and a brief overview of the post-LEGA reconstruction in the second.

5.1 Evolution of B-plane results during the Navigation Campaign

The evolution of the OD results mapped to the lunar B-plane can be seen below in Figures 8, 9 and 10, with the zoom level increasing. Seven orbit determination solutions are displayed in different colours with the central cross marking the trajectory's impact point and the surrounding ellipse indicating the 3σ uncertainty associated to the solution. Also plotted: in dashed grey is a circle indicating the Moon impact radius; a black cross indicates the optimal target impact point; and a teal spectrum is used to shade the post LEGA Delta-v penalty. Alongside the operationally selected orbit determination solution, multiple variations and consistency checks with different OD settings were performed. Displayed below are the selected solutions that were used to decide whether a TCM slot would be exercised or released. The Earth B-plane was also generated but closely reflects the pattern seen on the lunar B-plane, hence was not the primary subject for analysis. Figure 11 nevertheless shows the Earth B-plane corresponding to the same zoom level as in Figure 10 for the Moon, which is useful to visualize the amplification effect of the Moon swingby. For instance, the blue ellipses representing the prediction uncertainty at the TCM-1w decision point, are such that ~2 km of error ellipse semi-major axis on the Moon B-plane map to almost 100 km on the Earth B-plane.

As described in section 3.1, the navigation campaign formally began on July 6th, 2024. Eleven days later, on July 17th, the 48th orbit determination cycle for JUICE was performed, upon which was based the decision on whether to implement a TCM in the pre-determined TCM-4 week manoeuvre slot. The orbit determination for this TCM-4w decision point had a data cut-off of 2024-07-17 06:00 UTC. Since the start of the navigation campaign six DDOR measurements had been collected (three from CEB-NNO baseline and three from CEB-MLG baseline). In conjunction with this, a ten-week arc was taken consisting of 35 2-way range and Doppler passes involving all three ESTRACK deep space stations, with most of these tracking passes lasting around 9 hours and being recorded by the New Norcia ground station.

The resulting solution can be seen on upper right of Figure 9 in solid dark pink, the only ellipse clearly separated from the others. The ellipse shows a 11 km 3σ semi-major axis, with a 3 mm/s velocity 3σ uncertainty at the time of (potential) TCM-4w and a lunar flyby distance of 2399.9 km from body centre. The expected lunar B-plane impact point is seen to lie around 100km away from the optimal target point.

Given this trajectory and uncertainty, a decision was made in favour of utilising the TCM-4w manoeuvre slot by commanding a 3.8 cm/s ΔV magnitude TCM. Clearly the magnitude of the TCM was much larger than the trajectory uncertainty and it was known from previous in-flight experience that JUICE could accurately perform TCMs of this magnitude. To wait until TCM-2w to perform the correction would double the required manoeuvre size to 7.6 cm/s, while the ΔV penalty for correcting this after the flyby would be well beyond 100 m/s, as is clear from the sensitivity in Figure 5.

The dotted dark pink ellipse indicates the effects on the B-plane from including this TCM in the prediction assuming a 2 mm/s 1-sigma spherical uncertainty in the manoeuvre's ΔV components (as agreed upon in the filter parameters setup). By design, the lunar B-plane impact point moves directly to the target, with the 3σ ellipse semi-major axis growing to 19 km, TCA on 2024-08-19 21:14:55 UTC with a 5.5 second 3σ uncertainty and a closest lunar approach distance of 2490.9 km.

Over the next two weeks radiometric tracking support continued and a further 4 DDOR measurements were collected, showing a very nominal performance of TCM-4w and shrinking the error ellipse. The manoeuvre ΔV direction was at 61 degrees from the Earth line of sight, hence reasonably observable especially when including DDORs. The resulting calibration showed a very small underperformance of 0.5 mm/s and a small angular error of 0.5 deg, both with relatively large a-posteriori uncertainties of 0.9 mm/s and 1.1 deg. Such good performance of the manoeuvre execution allowed to reach an impact point on the B-plane close to the target, already comfortably within the propellant budget allocation of 75 m/s. The predicted lunar B-plane impact point afterwards drifted very little when more tracking data were added, such that by the TCM-2w decision point, the impact point was only 3km from the target, and well within the approximately circular 4.7 km 3-sigma error ellipse. Given this, the TCM-2w slot was released.

Tracking support continued nominally over the following two weeks, with the TCM-1w, TCM-3d and eTCM-6h slots being similarly released based upon the solutions presented as lilac, green, and purple ellipses respectively (see Figures 9 and 10). The successive solutions are notably consistent, with the impact points remaining tightly bunched within a few hundred meters of each other and the error ellipse shrinking over time. Even though the optimal target point lies outside all these ellipses, the ΔV penalty for not performing these TCMs was small, in the order of 2 m/s hence significantly below the allocated LEGA ΔV budget. Hence given the lower execution accuracy of small manoeuvres, the operational risk of manoeuvring in a critical phase before a swingby and the very limited propellant penalty, it was decided to skip all remaining TCM slots.

The initial post-LEGA solution is highlighted in bright red, about 2 km away from the optimal target and only few hundred meters from the prediction for the TCM-1w decision point. This is entirely consistent with the previously solutions and was used to justify a decision in favour of exercising the TCM+1 week slot. The manoeuvre optimisation team analysed several options to optimally absorb the deviation from the nominal trajectory. Ultimately an optimal solution was found to place a 1.6 m/s TCM in the +1 week slot, along with a secondary manoeuvre of 1.77 m/s close to the upcoming perihelion, 4 months later (with the exact magnitude to be reviewed at implementation time). This manoeuvre was successfully executed on 2025-01-01T00:00 UTC to bring JUICE entirely back on track.

Overall, the B-plane evolution showed subsequent ellipses fully contained within the uncertainties of the prior ellipses. This is a positive indicator that the spacecraft modelling has been performed accurately, that no systematic errors in neither the dynamics nor the measurements are present, and that the OD system is producing solutions consistent to real life. All SRP estimates also remained consistent with the values estimated previously in cruise, with WOLs ΔV estimates all well within 0.1 m/s, providing further confidence in the navigation solutions.

More details on the post swingby reconstruction are provided in the next section.

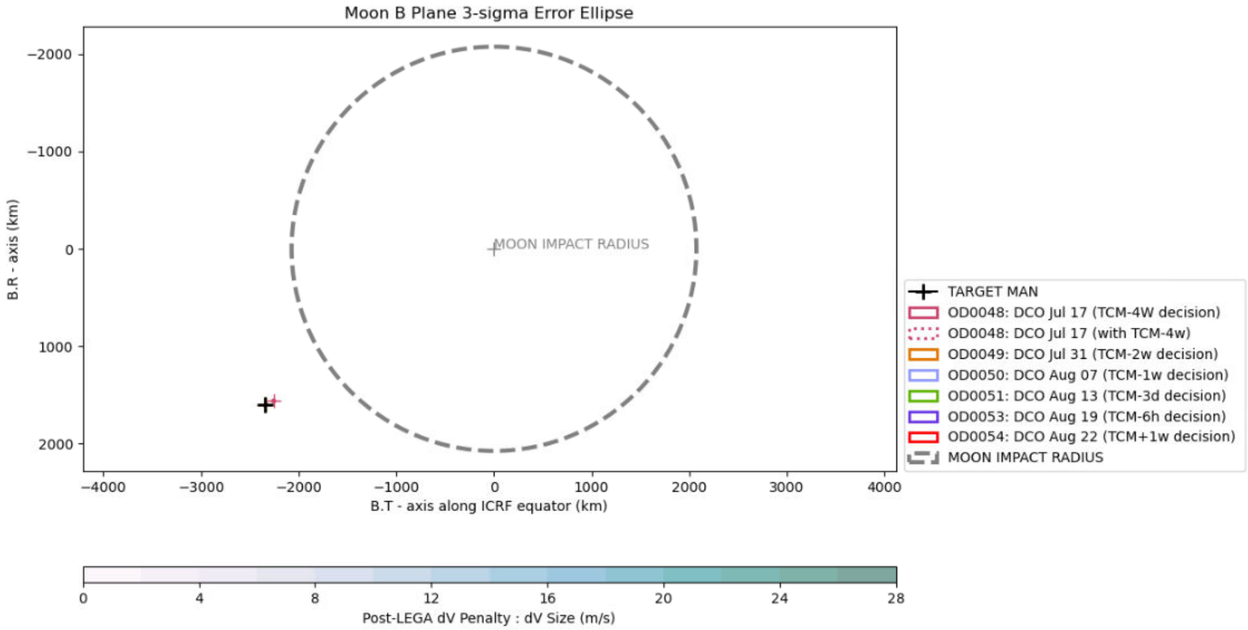

Fig. 8: Moon B-plane, zoomed out to highlight the Moon-relative position.

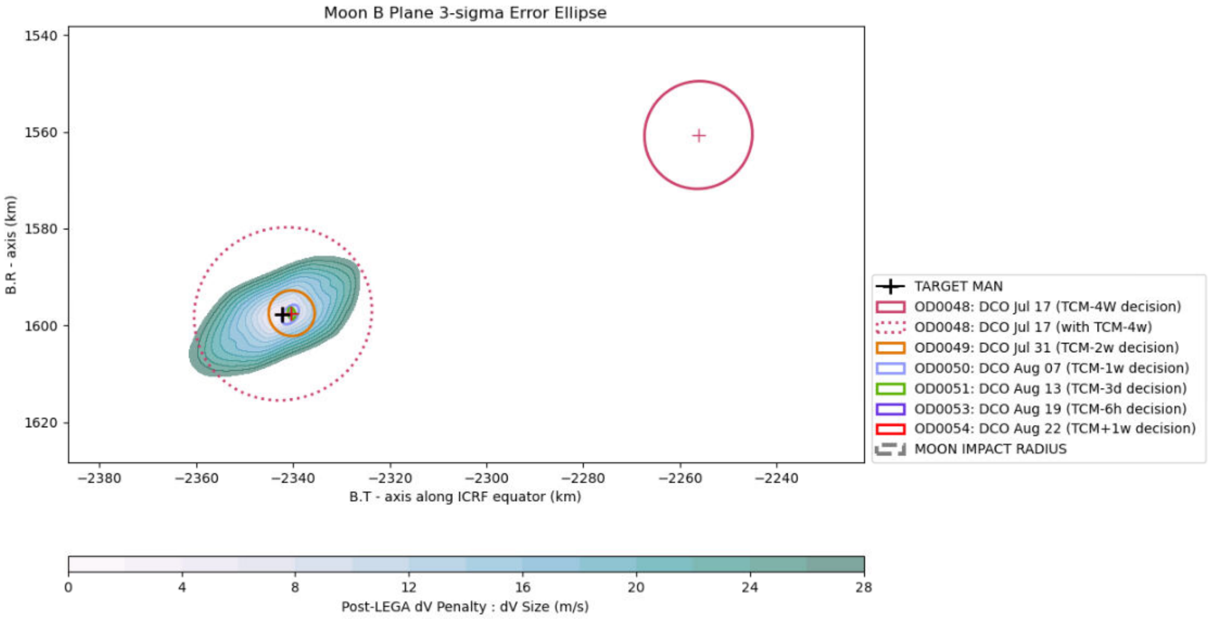

Fig. 9: Moon B-plane, zoomed to clearly highlight the effect of TCM-4W.

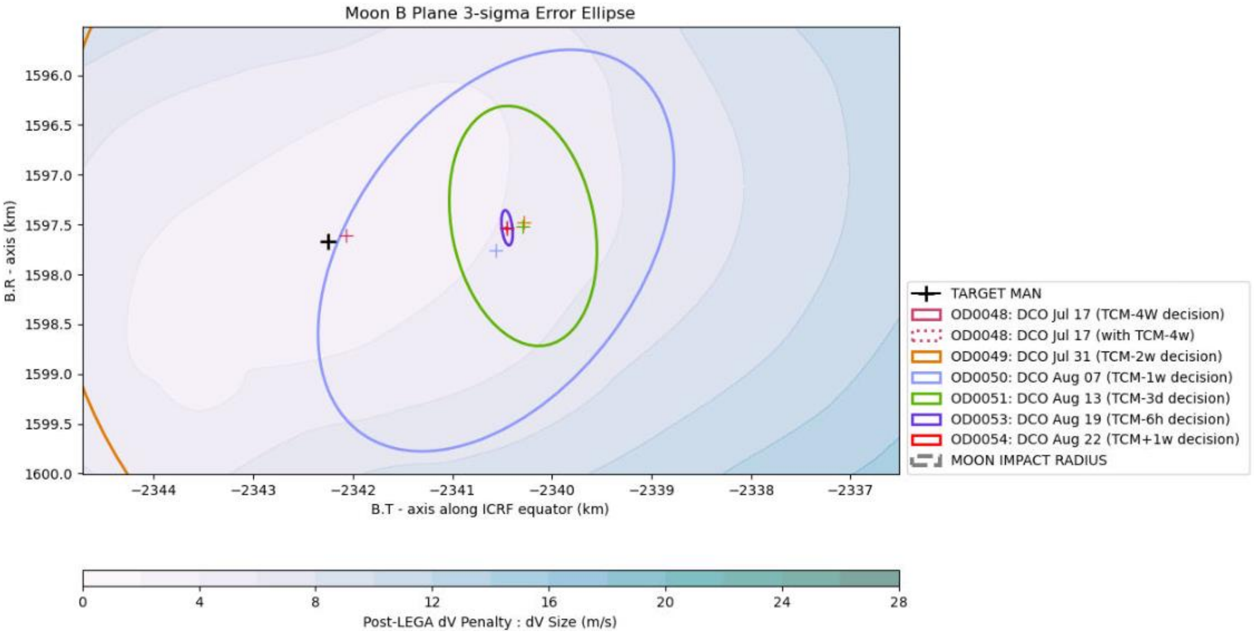

Fig. 10: Moon B-plane, final zoom in to emphasise the final three predictive ellipses and the first reconstruction.

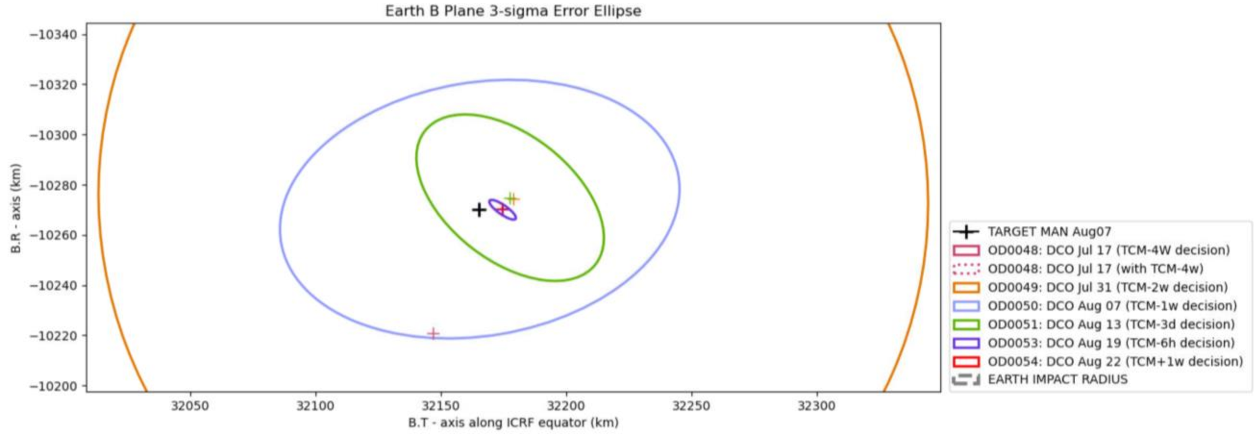

Fig. 11: Earth B-plane, similar zoom level as for the Moon B-plane in Fig. 10.

5.2 A-posteriori reconstruction of the LEGA trajectory

After the LEGA, an effort was spent to attempt to improve the reconstruction to better model the series of events. While not of critical need from the perspective of navigation and operations, this gives the opportunity to test our models and ensure the implemented characterisation is correct at a time where, thanks to the flybys, many values should be more resolvable. There is also the opportunity to uncover surprising spacecraft behaviour that may be relevant for future flybys.

In the case of the Moon swingby, it was clear that there was an initially unmodelled dynamic effect in the OD reconstruction. This was most visible in the Doppler data acquired around Moon closest approach where a clear signature was visible. A realistic fit could be found by giving the OD filter freedom to estimate a small ΔV in spacecraft -Z/-X direction, however an exact time of this ΔV around perilune could not be resolved. The ΔV direction could align with outgassing on the usually shaded spacecraft faces which are exposed to the lunar albedo during the swingby. From telemetry, higher wheel torques than predicted were also seen just after perilune, giving confidence that this was a real physical effect. The current operational reconstruction is estimating the event with a small ΔV of 0.5 mm/s in spacecraft -Z and 0.2 mm/s in spacecraft -X, a short time after perilune in the order of 7 minutes, though the exact time is not well observable.

At the Earth, a second ΔV event appears to occur. Even giving significant freedom at the Moon flyby, when the Earth flyby is also included in the reconstruction arc, the fit becomes less convincing and suggests an extra dynamic event. This is harder to resolve due to the tracking data gap around closest approach (from the transponder being switched off due to ITU regulations). When given freedom at Earth closest approach time to estimate a tangential ΔV, a resulting 0.1 mm/s prograde ΔV significantly improves the observed signatures. This suggests the existence of a small unmodelled dynamic event causing a small prograde velocity change around the Earth swingby, however details on the direction or time are not resolvable and a physical justification wasn't identified.

6. Conclusions

In August 2024, ESA's JUICE mission successfully performed the first Lunar Earth Gravity Assist manoeuvre ever attempted. By combining a low altitude Moon swingby with an Earth swingby one day later, roughly 150 m/s of deterministic ΔV was saved in the interplanetary phase of the mission. Due to the very limited time between Moon and Earth closest approaches, both manoeuvres and their full operational timeline had to be commanded in open loop, posing a significant challenge for the navigation team. In this very sensitive environment, even small errors in Moon B-plane targeting would be amplified by the double swingby, resulting in the risk of losing the deterministic ΔV advantage. This paper showed how very careful planning of the navigation campaign and overall operations, extreme attention to the orbit determination setup and modelling of non-gravitational accelerations, and an excellent behaviour of both the spacecraft and the ground segment allowed for the completion of the LEGA with approximately 3.4 m/s of correction manoeuvres – against a stochastic ΔV budget of 75 m/s. During the approach, a single correction manoeuvre was executed approximately 4 weeks out, with the decision to call off the following opportunities due to both the very small manoeuvre execution error and the very accurate and consistent orbit predictions. The a-posteriori reconstructed impact point on the Moon B-plane was about 2 km away from the approach optimal target and only few hundred meters from predictions in the week before the fly-bys.

Overall, the planning and execution of the challenging LEGA navigation and operations was flawless, resulting in an extra propellant saving equal to almost the entire stochastic ΔV budget for the LEGA. This ΔV is now available to enhance the scientific return of the JUICE mission once in the Jupiter system, which will be reached in July 2031 after an upcoming Venus swingby in August 2025 and two more Earth gravity assists in 2026 and 2029.

Fig. 12: JUICE Monitoring Camera 1 image taken at 21:25 UTC on 19th August 2024, soon after Moon TCA.

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