



Planning of the JUICE/JANUS camera observations during the first ever Lunar-Earth Gravity Assist

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Abstract. The Jupiter Icy Moons Explorer (JUICE) spacecraft, launched in April 2023, will reach the Jovian system in July 2031 and will conduct an extensive science campaign of the Jupiter system, with a strong focus on Jupiter itself and of its icy Galilean satellites. During its cruise phase the spacecraft performed a double gravity assist maneuver (Moon–Earth) in August 2024, followed by a “farewell” observational sequence on 9 September 2024. These events constitute the Lunar Earth Gravity assist (LEGA) campaign. JANUS, the high resolution optical camera of JUICE, used this opportunity to perform an imaging campaign under realistic illumination, viewing geometry and thermal conditions that closely mimic the forthcoming Jupiter operations. JANUS acquired a total of 461 images in full frame, lossless mode, covering the complete set of 13 spectral filters (340–1080 nm). This paper summarizes the end-to-end workflow from the definition of scientific and engineering constraints, through the design and ground-segment validation of the observation sequences, to the acquisition, processing and preliminary analysis of the LEGA data. The campaign demonstrated that a thermal-pre-warm strategy using the spacecraft survival heaters can bring the JANUS optics to the required -20°C thermal stability significantly limiting the power draw but preserving image quality. Exposure times were limited by a 1/4-pixel smearing criterion; nevertheless, exposure times ranging from 0.22 ms to 163 ms yielded adequate signal-to-noise ratios across all filters, and full 13-filter colour sequences were successfully obtained at high ground-track speeds. A series of images acquired with increasing compression ratios showed no perceptible degra-



15 dation, establishing a realistic data-volume budget for the science phase. Simultaneous measurements by MAJIS, NavCam
and the external Earth-observation satellites enabled a three-way cross-calibration that will improve the absolute radiometric
accuracy of JANUS. The LEGA experience shows that extending payload operations during cruise-phase flybys dramatically
enhances calibration quality, cross-instrument synergy and scientific return. These lessons will directly inform the planning of
the remaining JUICE Earth flyby windows (September 2026 and January 2029) and provide a best-practice template for the
20 Jupiter phase of the mission.

1 The JUICE mission and the Moon-Earth gravity assist

The JUICE (Jupiter Icy Moons Explorer) mission is the first Large (L-class) mission selected for the European Space Agency
(ESA) Cosmic Vision 2015-2025 program. Its main goal is the exploration of the Jupiter system and the investigation of its icy
Galilean satellites Europa, Ganymede and Callisto (Grasset et al., 2013). JUICE has been successfully launched on 14 April
25 2023 from Europe's Spaceport in Kourou, French Guiana, on an Ariane 5 launcher and, after its 8 years journey throughout
the inner Solar System, it will reach the Jupiter system in July 2031. During its nominal science phase, JUICE will spend
many months orbiting around Jupiter, performing flybys of Europa, Ganymede and Callisto, and finally conducting an orbital
tour of Ganymede. During the cruise phase, JUICE performs a number of gravity assists to change the spacecraft's speed and
direction, allowing it to reach its destination with less fuel consumption: the first ever performed Moon-Earth flyby in August
30 2024, a Venus flyby in August 2025, an Earth flyby in September 2026 and a final Earth flyby in January 2029.

The JUICE spacecraft performed its first gravity assist maneuver with Moon and Earth on 19 and 20 August 2024 (Dietz
et al.). It was the first-ever done double gravity assist maneuver: the spacecraft passed by the Moon and then Earth in rapid
succession (less than 24 hours), using the Moon's gravity to fine-tune the Earth flyby (Fig. 1). The closest approach (CA) to
35 the Moon occurred on 19 August at 21:15 UTC and the one to the Earth the following day at 23:56 UTC, at a distance of 752
km and 6839 km, respectively (Dietz et al.). This was the first opportunity since launch in which all on-board instruments,
including JANUS (the scientific high-resolution camera system), had the possibility to perform observations similar to those
that will occur during the science phase at Jupiter, simulating in particular both low and high-altitude flybys at icy satellites
and observations of the Jovian atmosphere. It therefore provided, for the first time, insights into the instrument performances
40 under nominal operation conditions. The primary purpose of the observations was to perform an in-depth check of instrument
operational capabilities, performances and calibration. However, the dataset acquired allowed also studies of the Moon's surface
and of the Earth's atmosphere and surface.

On 9 September 2024, while on its way to Venus following the Moon-Earth flyby, JUICE looked back to the Earth and the
Moon from a distance of 5.7 and 5.3 million km, respectively. JANUS observed the Moon-Earth system for 10 minutes,
45 tracking the Earth. Those observations are proxies for the Jupiter distant monitoring that will be performed regularly during
the science phase.

Details about the gravity assist and the farewell images are summarized in Table 1.



This paper describes how the JANUS observations were planned and acquired under the limitations imposed by multiple constraints and it highlights how such activities are proxies of the operations during the science phase and are essential for its success. Agostini et al. presents the calibration of the JANUS data and improvements that shall be investigated based on the LEGA and farewell data. A study of the Moon’s surface is presented by Lucchetti and et al. and Hueso et al. (2026) presents the investigation of the Earth observations.

Table 1. Information about the Moon and Earth flybys and the Moon-Earth farewell. Object in FOV: time interval in which the observed object (Moon or Earth) was in the JANUS FOV. Phase angle: is the boresight intersect phase angle (or surface phase angle). Distance: is the slant distance, i.e. the distance between the camera and the surface along the line of sight (target - boresight intersection). Relative speed: maximum relative velocity during the CA. Operation: time interval in which the instrument was switched ON.

	Moon	Earth	Moon-Earth
Date	19 Aug 2024	20 Aug 2024	9 Sep 2024
Closest Approach [UTC]	21:14:55 (752 km)	21:56:14 (6839 km)	–
Object in FOV	21:10:59 - 21:26:11	21:18:52 - 21:50:08	09:51:00 - 10:01:00
Phase Angle [deg]	90	90	72
Distance [km]	870 - 3005	8404 - 16550	5.7×10^6 (E), 5.3×10^6 (M)
Resolution [m/pix]	13 - 590	134 - 1167	
Relative speed [km/s]	4.2	8.4	–
Operations	CA \pm 1 h	CA - 2 h to CA +13 h	-001.21:46:00 - 000.10:06:00
Acquired images	204	173	84

2 The JANUS camera system

JUICE carries 10 state-of-the-art instruments, comprising the most powerful remote sensing, geophysical and in situ payload suite ever flown to the outer Solar System. Among those, JANUS (Jovis Amorum ac Natorum Undique Scrutator) is the scientific optical camera system. The scientific objectives together with a comprehensive overview of the instrument design and performances are summarised in Palumbo et al. (2025). Here we describe JANUS, highlighting the aspects that are relevant to the LEGA operations and acquired dataset.

JANUS is a modified Ritchey-Chretien telescope with a nominal focal length of 467 mm, an aperture of 103.6 mm and a rectangular field of view (FOV) of $1.72 \times 1.29^\circ$. Its focal plane employs a 2000×1504 pixel CMOS sensor, yielding an angular sample (instantaneous field of view (iFOV)) of $15 \mu\text{rad}/\text{pix}$, which results in images with 7.5 m/pixel resolution at a distance of 500 km. The CMOS sensor uses a rolling shutter readout strategy, which means that JANUS does not produce an instantaneous image where all pixels are exposed at the same time, but the exposure happens row by row with a delay of 0.2215 ms between the exposure of one row and the following one. The main consequence is that a geometric distortion is introduced when there is a relative motion between target and S/C. The camera is equipped with a filter wheel with 13 filters (Table 2),

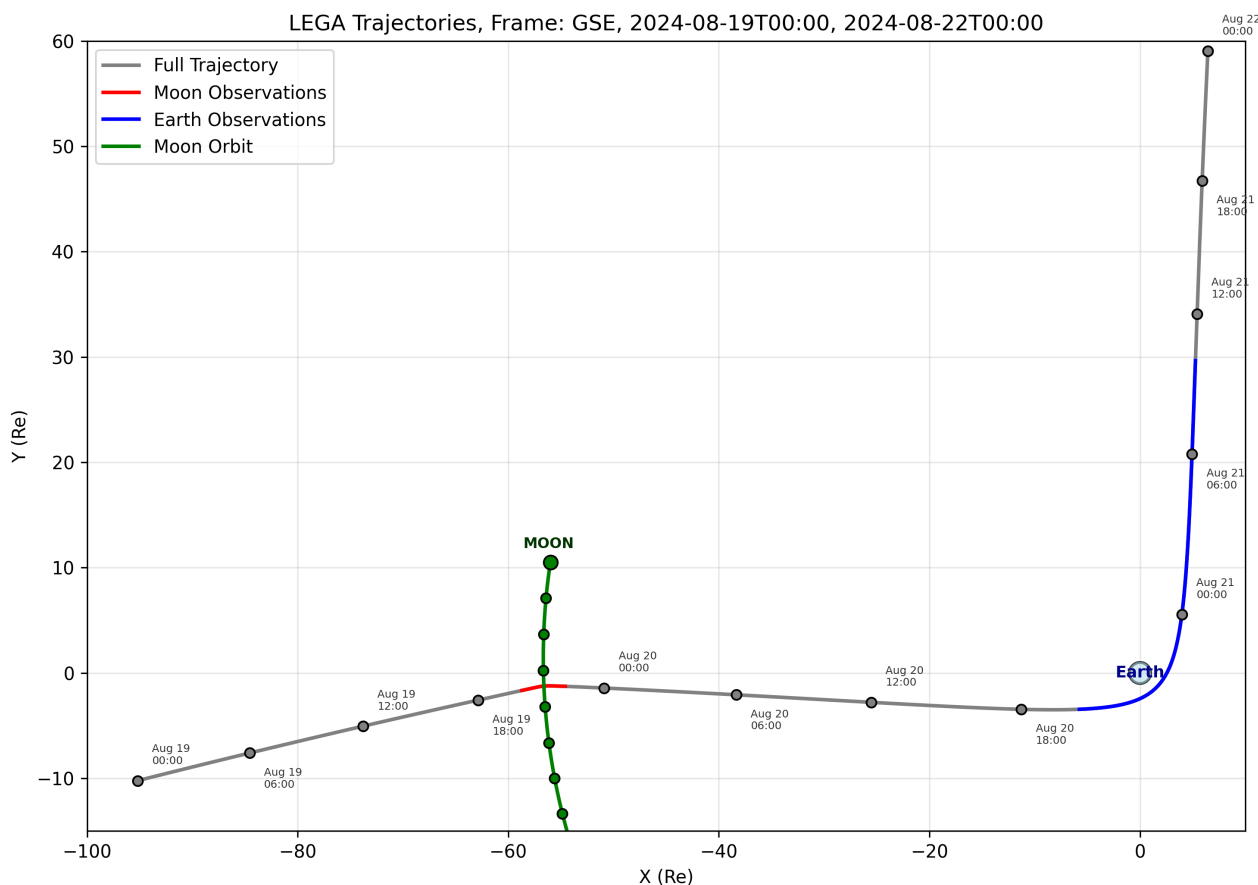


Figure 1. JUICE and the Moon trajectory during LEGA. The trajectory is drawn in the Geocentric Solar Ecliptic (GSE) frame, which is a Cartesian coordinate system with the +X axis pointing from the Earth to the center of the Sun, the +Z axis is normal to the ecliptic plane, pointing towards the North Ecliptic Pole, while +Y completes the right-handed system, pointing towards the dusk side (opposite to the direction of Earth’s orbital motion). JUICE approaches from -X moving towards +Y after the Earth flyby. Markers are shown every six hours, and the total interval plotted is indicated on the plot title. Highlighted periods in red and blue show the operational segments of JANUS. The off-pointing period (farewell images) is not shown here, due to its large distance from Earth (towards +Y).

which allows JANUS to acquire multi-spectral images in the 340–1080 nm wavelength range. The very different bandwidths, coupled with the system response at the different wavelengths, result in a wide range of exposure times to be used to achieve a similar signal-to-noise ratio (SNR).

JANUS has a COVer Mechanism (COM) which provides external closure of the telescope and protects its optical parts from sunlight and contamination.

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For best image quality, the JANUS telescope shall be thermally stabilized at -20°C before the beginning of the imaging sequence. Thermal stability is reached, in about 12 hours, and maintained by the JANUS thermal control which is activated just



after the instrument is powered ON.

Table 2. The JANUS filters with their main characteristics: central wavelength (λ_C), bandwidth ($\Delta\lambda$) and typical exposure time for Moon and Earth images.

Position	Filter ID	$\lambda_C/\Delta\lambda$ [nm]	$t_{exp,M}$ [ms]	$t_{exp,E}$ [ms]
F1	PAN	650/500	0.4	0.2
F2	BLUE	450/60	5.3	0.4
F3	GREEN	540/60	2.7	0.4
F4	RED	646/60	2.6	0.4
F5	CMT medium	750/20	5.3	1.1
F6	Na	590/10	10.6	1.1
F7	MT strong	889/20	10.6	2.6
F8	CMT strong	940/20	10.6	4.4
F9	MT medium	727/10	10.6	1.2
F10	Violet	380/80	10.6	0.5
F11	NIR 1	910/80	5.3	0.9
F12	NIR 2	1015/130	10.6	1.3
F13	H α	656/10	10.6	1.3

75 3 Development of LEGA observational concept

The observation strategy was developed to perform an in-depth check of operational capabilities, camera performances, calibrations and data quality in a science-phase like scenario. The Moon, thanks to its well known surface properties, was a perfect calibrator that could be used to validate and improve the JANUS radiometric calibration. The Earth was a proxy for Jupiter's atmosphere observations. To plan the observations, a number of constraints had to be taken into account: Moon and Earth
80 brightness, rapid motion of the S/C, fixed S/C attitude, encounter geometry, data volume limitations, instrument constraints and capabilities.

The overall design was subject to a number of technical and mission/spacecraft constraints that we describe below.

3.1 Constraints and Operational Environment

3.1.1 Thermal

85 During the hot cruise phase (heliocentric distance < 1.34 au) the spacecraft -X axis (i.e., the side where the large High Gain Antenna is mounted (Sarri et al., 2026)) is maintained pointed to the Sun to use the High Gain Antenna as a sun shield, to protect the spacecraft body from direct high solar flux. The same configuration was used during LEGA. As a consequence of



the fixed attitude, surface tracking (nadir pointing) was not possible. Instead, the camera operated with a slanted pointing, with the camera boresight sweeping the target at constant surface phase angle of approximately 90° . The observation window began when the JANUS boresight, approximately aligned with the S/C +Z axis (i.e. the nadir direction (Sarri et al., 2026)), crossed the surface target. The main consequence of the fixed attitude is that the exposure times had to be limited to avoid smearing.

3.1.2 Payload operation windows

All instruments, including JANUS operated during the Moon and Earth flybys. The Mission Operation Control (MOC) defined two payload operation windows: CA \pm 1 hour for the Moon flyby and from CA - 4 hours to CA + 3 days for the Earth flyby. CA stands for Closest Approach, i.e. the shortest distance between the S/C and the target surface. JANUS was powered ON at CA - 1 hour for the Moon flyby and CA - 2 hours for the Earth flyby, respectively 1 hour and 1.3 hours before the beginning of image acquisition. The nominal 12 hours for thermal stabilization were not possible, thus, the S/C survival heaters (which can be operated when the instrument is switched off) were used to warm up the JANUS telescope to the -20°C , allowing to acquire images under thermally stable conditions at the desired temperature. The S/C survival heaters were switched ON about 12 h before the beginning of the imaging sequences.

This approach was first implemented during LEGA (and initially tested during its full rehearsal one month before) and has the advantage of significantly reducing the power consumption. JANUS requires between 10 and 20 W when it is powered ON to reach and/or keep thermal stability, while the survival S/C heaters, which are operated with JANUS off, require significantly less power (about 3 W).

During the science phase, periods of observations will be interleaved with periods of very limited power availability, e.g. down-link windows, in which instruments might be requested to be switched off. In the cold space environment, JANUS drifts away from thermal stability very quickly as soon as the thermal control is switched off. Therefore, different strategies, such as the use of survival heaters, which reduce power consumption assuring image quality, are very important alternatives which shall be tested and optimised to assure the best image quality within the available power envelope.

3.1.3 RIME "quiet time"

The Radar for Icy Moon Exploration (RIME) instrument (Bruzzone et al., 2015) was granted to operate alone for a few minutes around the Moon closest approach to perform some tests of electro-magnetic cleanliness. All other payloads, including JANUS, had to be in quiet mode to ensure that no interference was introduced by the subsystems. JANUS operations began as soon as the "RIME quiet time" was concluded, 30 seconds before terminator crossing.



3.1.4 JANUS-specific operational constraints

In addition to the aforementioned constraints posed by the S/C and the other instruments, JANUS had its own constraints that had to be accounted for during the sequence design.

Smearing: because of the fixed spacecraft attitude requirement described in Sec. 3.1.1, surface tracking was not possible and the camera boresight swept the target at constant velocity during the flybys. The image exposure times had to be limited to avoid smearing. The smearing limit was set to a motion of the JANUS boresight of below 1/4 pixel. Typical exposure times are summarised in Table 2.

Filter change time: the time needed to change filter of one position is 0.5 s. This time interval plays a critical role in multifilter sequences for color cubes when the spacecraft is in motion, as in the LEGA case, and the JANUS FOV continuously shifts across the surface. The maximum number of filters that could be used was thus determined by the time that color sequence footprint moved of maximum 60-70% of the JANUS FOV, assuring an overlap of 20-30% between the footprints in all filters. An example is shown in Fig. 2, where the footprints of F2, F4, F11 and F12 overlap on about 20-30% of the FOV.

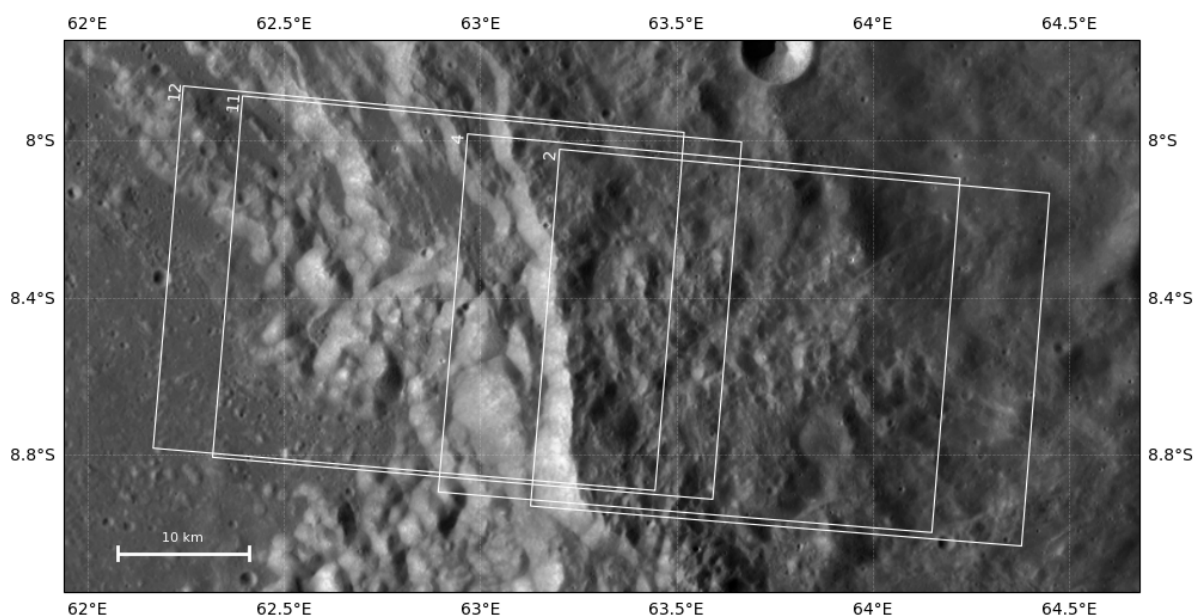


Figure 2. Example of multifilter sequence. The footprints of F2, F4, F11 and F12 (indicated on the image) overlap on about 20-30% of the FoV.

3.2 JANUS Campaigns

This section described the design and testing capabilities of the JANUS LEGA campaign.



3.2.1 Overall design

During LEGA, JANUS acquired 204 image of the Moon and 173 images of the Earth. All images were in full frame and resolution (not binned/down-sampled) and commanded lossless, to assure maximum data quality. Figure 3 and Figure 6 show the JANUS footprints plotted over Moon and Earth maps, respectively.

All sequences were rehearsed on the JANUS Ground Reference Model (GRM), which is representative of the flight unit in both hardware and onboard software. The timing between images as well as the duration of the sequences was simulated. This was especially important for flyby operations, where precise time synchronization between the image sequences and the footprint on the surface was critical. No command errors occurred during LEGA, confirming that a full chain rehearsal is a prerequisite for any time critical cruise or science phase campaign.

The images were processed using the nominal JANUS calibration pipeline (Agostini et al.).

Each flyby was divided in segments within which different instrument settings were tested: single filter imaging, multi-filter imaging and acquisitions with different compression factor. The objectives of each segment are described below.

145 Moon flyby:

Moon observations were acquired over an elongated stripe from the nightside to the dayside (Fig. 3).

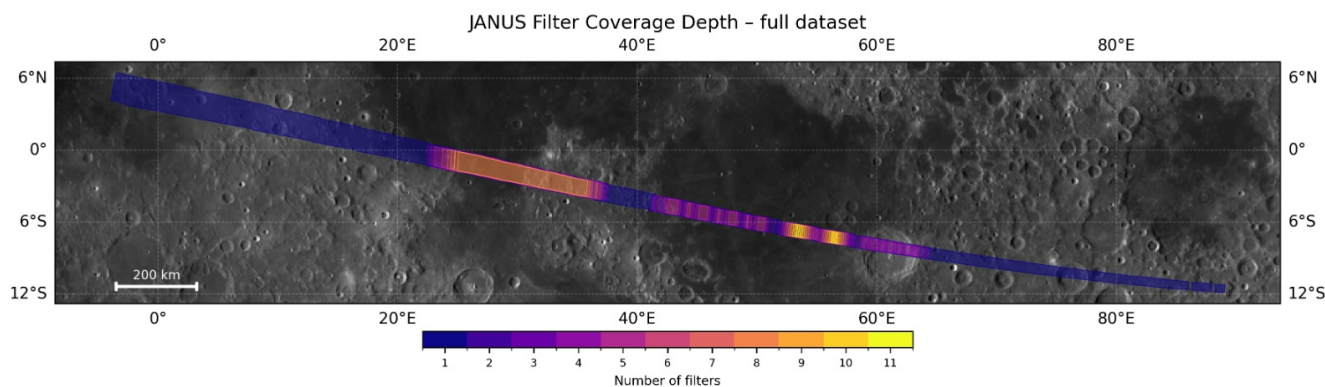


Figure 3. Footprints of the JANUS FOV on the Moon map. Footprints are moving from right to left.

A total of 204 images were acquired over the target. While observing the nightside, we attempted to observe the Ganymede Laser Altimeter (GALA) spot on the Moon's surface to test the alignment of the two instruments boresights (Seq. 1, Table 3). For this purpose we acquired a number of images in the near-IR filter (F12, $\lambda_c = 1015$ nm). This measurement was inherently difficult due to the marginal sensitivity of JANUS at the edge of its spectral range and to the non-ideal geometry and limited time both instruments could operate. In particular, due to the RIME quiet time constraint (Sec. 3.1.3, this observation could only be performed in the 30 seconds before the terminator crossing.

After the terminator crossing, dayside lunar surface observations were constrained by geometry, relative speed and radiometry,



which together determined the usable filters and corresponding exposure times.

155 The first two sequences in daylight (Seq. 2 and 3, Table 3) are characterized by high incidence angle and were acquired in a single filter (F1, $\lambda_c = 650$ nm). The cadences were chosen to have overlap between consequent footprints, providing up to fourfold redundancy in surface coverage along the track. These images enable validation of the radiometric performance and post processing techniques, e.g., to correct image smearing and improve resolution.

The subsequent 3 sequences (Seq. 4, 5 and 6, Table 3) were multi-filter acquisitions using a variable number of filters. Those
160 sequences allow to extend performance and calibration verifications to the entire wavelength range. While flying over the Mare Fecunditatis all 13 filters were used (Fig. 5). The relative uniformity of the Mare Fecunditatis allowed the comparison of images with non-overlapping footprints, enabling the validation of the radiometric performance to the entire wavelength range covered by JANUS. In addition, it enabled the assessment of straylight contributions from areas outside the JANUS FOV.

A compression test was carried on over a cratered area (Seq. 7, Table 3): images with increasing compression were acquired to
165 evaluate the information loss as function of the used compression. While flying over the region north of Rimae Gutemberg we acquired a sequence of 14 images in the panchromatic filter (F1, $\lambda_c = 650$ nm) with increasing compression ratio from 1:1 to 33:1. The images were acquired as fast as possible, to ensure a significant overlap between the footprints. (Fig. 4).

From a first and very preliminary analysis, the information loss is not as drastic as feared as function of the used compression. This result, even though, preliminary, allows to set realistic expectations of the compression that can be used during the science
170 phase, preserving the image quality but at the same time complying with a limited mission-wise data volume availability .

Two final sequences on the Moon surface (Seq. 8 and 9, Table 3), one multifilter and one with single filter were carried on while flying towards the Moon limb.

After limb crossing, a number of images with long exposure times (Seq. 10, Table 3) were acquired to characterize the stray-
175 light originating from an out-of-field source at increasing angular distance and with decreasing apparent size.

Earth flyby:

A similar approach was used to plan the Earth observations. Given the higher flyby altitude, image timing was less stringent constraint compared to the Moon flyby, enabling full multifilter observations on several footprints.

180

Earth observations were acquired over an elongated ground track extending from nightside to dayside with the sub-spacecraft point moving from North of Madagascar to central Pacific over a distance of 18,700 km (Fig. 6). JUICE's trajectory over the Earth allowed to test the design of very different exposure times for the changing illumination conditions, test for smearing effects associated to short dwell times, check the performance of the onboard image compression algorithm and obtain radio-
185 metric data to be compared with data from Earth satellites. Hueso et al. (2026) describe the analyses of these observations. A total of 173 images were acquired, with an average ground sampling resolution of 140 m/pix. Since the spacecraft velocity over the target varied from 5.0 to 6.8 km/s this resulted in dwell times of 18 to 44 ms. For the nightside images, short dwell times limited the possibilities to obtain well-exposed images in other filters than the panchromatic (F1). Thus, nightside images

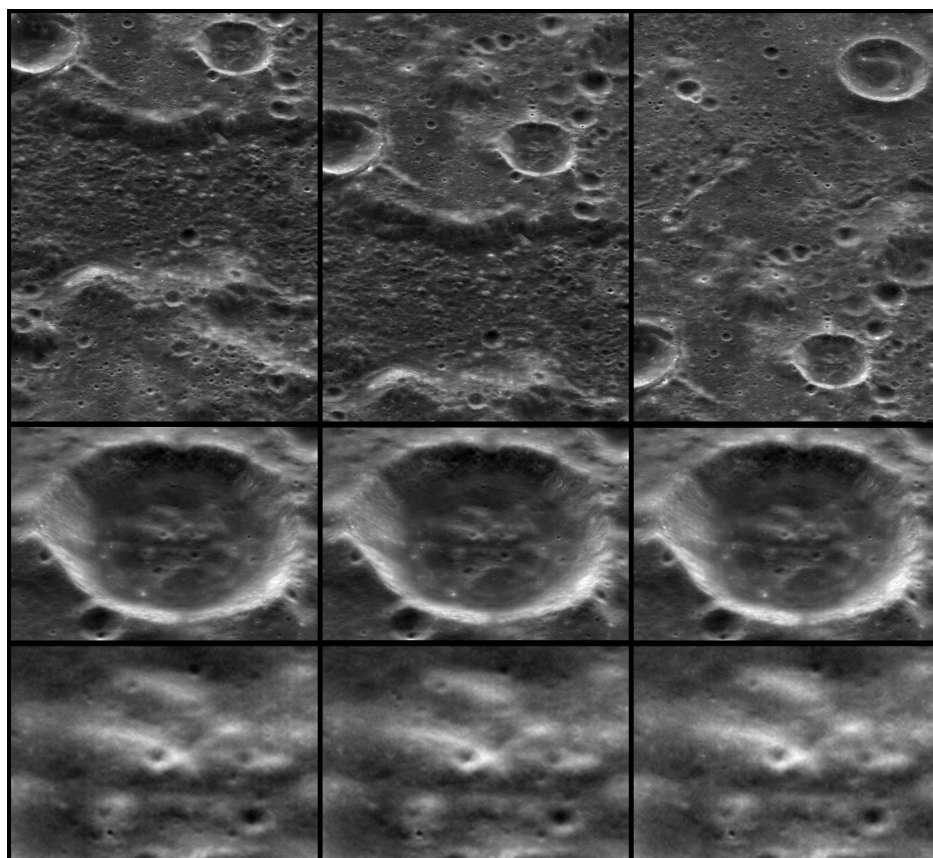


Figure 4. Images acquired during the compression test with compression 1:1 (left), 3.5:1 (center) and 10:1 (right). From top to bottom full JANUS FOV images (top), images shown with a zoom x 3 (center), images with a zoom x 10 (bottom). All panels are contrast stretched to maximize visibility of small-scale features.

were acquired only with the panchromatic filter (F1) to maximize the visibility of surface features illuminated by the Moon.

190 For the dayside images the high velocity flyby limited the capability to plan for repeated observations of the same areas.

The first two images targeted Earth's limb over Madagascar and the Indian Ocean. Their exposure times were chosen to accommodate to the dwell time of nearly 35 ms of that period and test the visibility of Madagascar's north coast over the dim illumination provided by the Moon. The night-time sequence included 24 images that targeted potential observations of lightning over tropical latitudes and the detection of city lights over Cambodia and Vietnam (Seq. 1, 2, 3 and 4, Table 3). Most images were acquired with the panchromatic filter (F1, $\lambda_c = 650$ nm) and short exposure times to avoid smearing effects. Two images (Seq. 2, Table 3) were instead acquired with the near-IR filter (F12, $\lambda_c = 1015$ nm) and longer exposure times (140 ms equivalent to 5 times the dwell time) to test image quality under smearing conditions.

The transition across the terminator was monitored using sequences of short-exposure monochromatic images (Seq. 3 and 4,

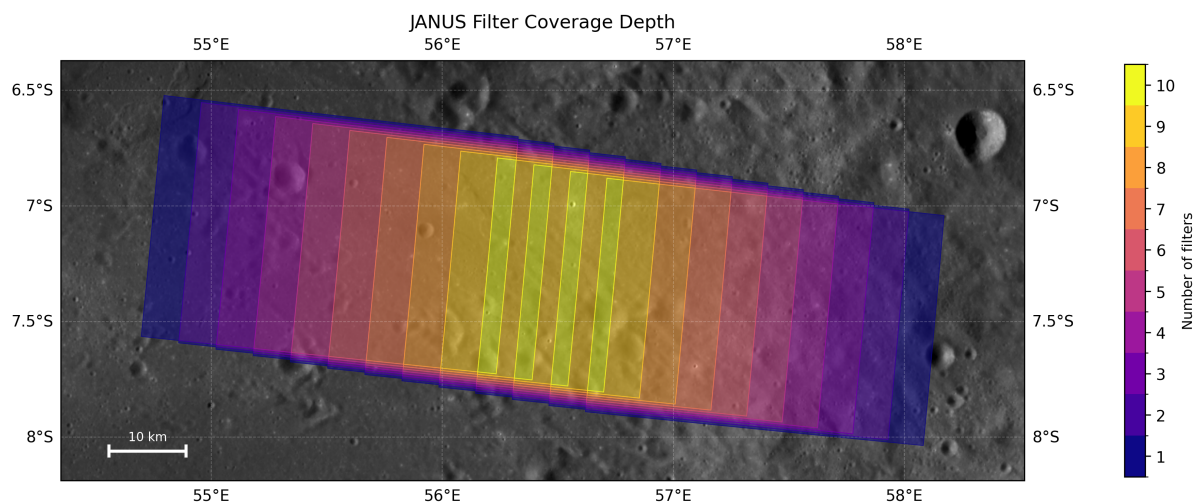


Figure 5. JANUS footprints while flying over the Mare Fecunditatis. The color scale indicates how many filters imaged, during the sequence, that part of the Moon surface.

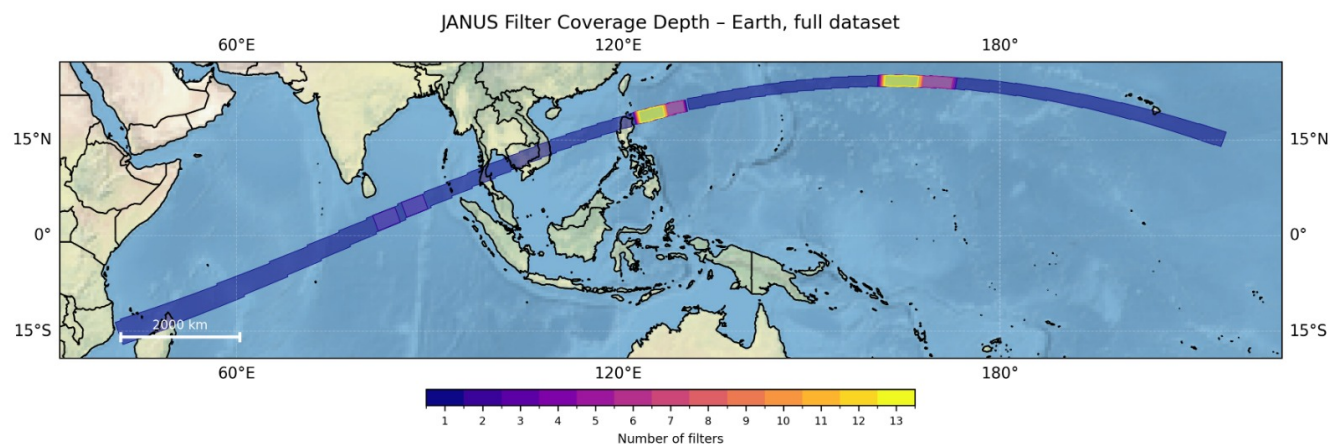


Figure 6. Footprints of the JANUS FoV overlapped on the Earth map. Footprints are moving from left to right and from nightside to day-side with a terminator crossing just east of the Philippines shortly before the first multi-filter sequence.

200 Table 3), including four panchromatic images with 25 ms exposure time to capture the rapid change in illumination. JANUS
acquired 116 images of Earth's dayside (Seq. 7 to 12 and 4, Table 3). These observations covered tropical latitudes over the
ocean and included several multi-filter sequences. Two of the multi-filter sequences targeted an area of the Pacific Ocean also
observed with two Earth observing satellites: EnMap and PRISMA (Caporusso et al., 2020) both obtaining high-resolution
hyperspectral data of the area covered by JANUS to compare the radiometric quality of the observations (Hueso et al., 2026).
205 Most other daytime observations used the green filter (F3, $\lambda_c = 540$ nm) alternating exposure times that varied by a factor of



3-5 to obtain images well exposed for the dark ocean and bright clouds. This filter was preferred over the panchromatic one, as the latter would have saturated even at the minimum exposure time of 0.2215 ms due to its broad spectral bandwidth.

All images were acquired with lossless compression: in addition to preserving the highest images quality, it allowed to investigate the effective compressions under a wide range of illumination conditions.

210 3.3 Synergistic Instrument Campaigns

One of the strengths of LEGA is that it was a synergistic instrument campaign, in which several instruments operated at the same time acquiring simultaneous datasets which can be compared. MAJIS, the visible and infrared imaging spectrometer onboard JUICE (Poulet et al., 2024), observed the Moon and the Earth during the same time intervals as JANUS, acquiring 4 hyperspectral cubes targeting the lunar surface and 19 targeting the Earth (Poulet et al., 2026). The overlap between the datasets
215 allows to compare, for example, the geometric and radiometric calibrations of JANUS with the ones of MAJIS.

The navigation camera (Gorog et al., 2019; Cornet et al., 2026) performed 6 observations on the Moon. 3 of them were evenly spaced between the terminator and the illuminated limb. The observation over Mare Fecunditatis overlaps the JANUS and MAJIS footprints. The observation on the limb matches the JANUS one but with a larger FOV (Figure 7). The partial overlap with JANUS observations provides additional opportunities for cross-calibration between the two imaging systems. In
220 particular, the images acquired over the Mare Fecunditatis are an excellent dataset for a radiometric cross-calibration because JANUS used all 13 filters.

On the Earth, NavCam performed 8 observations from the night limb (over Madagascar) to the illuminated limb in the Pacific Ocean (over Hawaii). All footprints overlap with JANUS images. The footprint over the Pacific, overlap with a multfilter JANUS sequence and very nicely shows the same cloud features.

225 Through coordination during the LEGA planning, the two Earth-observing satellites Environmental Mapping and Analysis Program (EnMAP) and PRecursoRe IperSpettrale della Missione Applicativa (PRISMA), operated by the German (DLR) and Italian (ASI) space agencies respectively, observed an area over the Western Pacific Ocean which was also imaged by JANUS. The closest in time EnMAP hyperspectral observation took place 21 hours before the JANUS one, while the PRISMA data were acquired 2 hours after the JANUS images. A comparison between the JANUS, EnMAP and PRISMA observations is
230 presented in Hueso et al. (2026).

4 Moon-Earth farewell

On 9 September 2024, about 20 days after the Moon-Earth flyby, JUICE looked back to the Earth and the Moon from a distance of 5.7 and 5.3 million km, respectively.

Despite still being in the hot cruise phase, a deviation of up to 45 minutes from the S/C -X axis pointed to the Sun was allowed. An off-pointing of about 17 deg, maintained for about 20 minutes, allowed both bodies to enter in the JANUS FOV.
235 JANUS switched on 12 hours before the observations to thermally stabilize and observed the Earth-Moon system for 10 minutes, while the S/C was tracking the Earth, acquiring 84 images in all 13 filters.

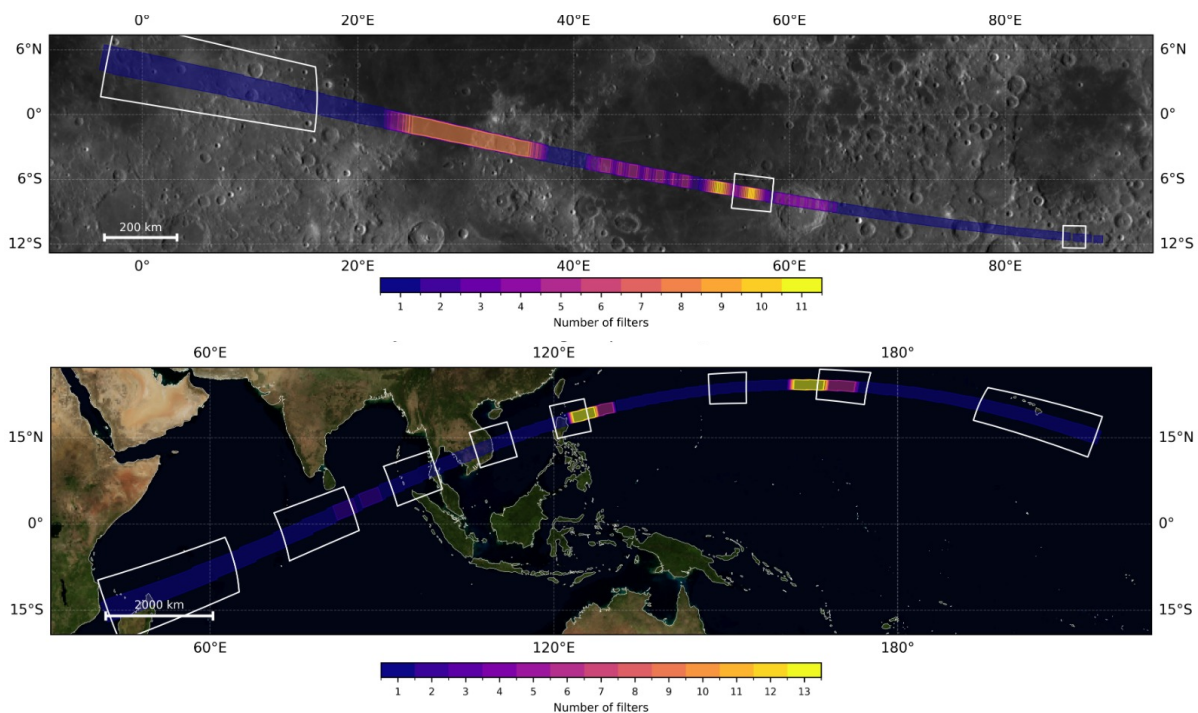


Figure 7. Footprints of the JANUS FoV overlapped on the Moon map (top) and on the Earth map (bottom). The NavCam footprints are shown, indicating when the two instruments have observed simultaneously.

Since the S/C was tracking the Moon-Earth system, the exposure times were not constrained. For each filters 6 images with increasing exposure time, going from 20% to 100% saturation level, we acquired. For one filter (F6, $\lambda_c = 590$ nm) we acquired 6 additional images with exposure time complementary to the ones used in the previous sequence. An example of RGB color composite image is shown in Fig. 8.

Those images enable the evaluation of the radiometric calibration as well as the characterization of ghosts generated by the optics. In addition the presence of two resolved objects not on the same image line, allows to characterize the Signal Dependent Baseline Shift (SDBS), a detector effect that is affecting each image, as described in Agostini et al..

245 5 Lessons learned

Some highlights and lessons learned from these campaign are summarized below:

Ground segment validation is essential. All sequences were rehearsed on the JANUS Ground Reference Model (GRM). The timing between the acquired images as well as the duration of the sequences was as planned. No in flight command errors occurred, confirming that a full chain rehearsal is a prerequisite for any time critical cruise or science phase campaign.

250 **Thermal strategy validated.** The spacecraft survival heaters, which can operate when the instrument is switched OFF and



Figure 8. The Moon-Earth system as seen by JANUS on 9 September 2024. Left: Full frame; Right: Zoom on the Moon-Earth system. A gamma curve correction is applied.

use significant less power than JANUS, were successfully used to warm up JANUS to the desired temperature of -20°C . This allowed to power ON the instrument between 1 and 2 hours before the beginning of the imaging sequence, reducing the overall power budget while preserving image quality.

Exposure time and smearing. The $1/4$ pixel smearing limit dictated the exposure time ranges that could be used in the different phases of the Moon and Earth flybys. This in turn defined which filters could be used to reach a reasonable SNR.

13 filter colour sequences. 13 filter sequences were acquired over the Mare Fecunditatis and over a Pacific Ocean swath, confirming that a full colour cube acquisition with (some) overlap between the individual frames is feasible in this range of ground-track speeds.

Compression performance. A very preliminary analysis of the images acquired with different compression ratios indicates that compression can be used during the science phase, preserving the image quality but at the same time complying with a limited mission-wise data volume availability.

Synergistic observations. The simultaneous MAJIS, NavCam and JANUS measurements enabled a three way cross-calibration that will help to improve the absolute radiometric calibration.

More broadly, the LEGA campaign highlights the value of maintaining an active science payload during cruise phase flybys and opportunistic encounters.



6 Conclusions

In the section above we described the activities that JANUS carried on during the Moon and Earth flybys and during the Moon-Earth farewell, highlighting the process that went into their planning and the scientific and technical objectives of the acquired observations.

270 The LEGA campaign served simultaneously as a unique calibration opportunity and as a full-scale rehearsal of the science phase operations that will be performed during JUICE’s Jovian tour. By exploiting the Moon and Earth flybys, and the subsequent “farewell” imaging sequence, JANUS was exercised under a wide range of realistic illumination, viewing geometries and thermal conditions. The resulting high-quality dataset (204 lunar, 173 terrestrial, and 84 farewell images) not only supports scientific investigations, but also provides the reference measurements needed to refine JANUS radiometric and geometric
275 calibrations and to carry out cross-calibrations with MAJIS, NavCam and additional Earth-observation systems (EnMAP, PRISMA). The campaign validated the instrument design, the on-board processing chain, and the operational concept.

For deep-space missions, whether they involve planned planetary flybys or chance encounters with comets, asteroids, or other bodies, maintaining an active science payload during these windows dramatically expands the calibration and science
280 return. In cruise, cameras are typically limited to stellar observations that deliver stability, radiometric, and geometric checks. In contrast, LEGA allowed JANUS to acquire resolved images of planetary surfaces and Earth’s atmosphere, thereby testing the full end-to-end imaging chain including exposure-time management, smear mitigation, multi-filter colour sequences, compression, stray-light, all under conditions representative of the forthcoming Jupiter operations.

In short, the LEGA experience demonstrates that a modest increase in cruise-phase operational flexibility can lead to a substantial
285 gain in calibration fidelity, cross-instrument synergy, and scientific value—insights that will directly inform the planning of the remaining JUICE Earth flyby windows in September 2026 and January 2029, and will serve as a best-practice template for future cruise checkout operations of JANUS.



Table 3: JANUS sequences executed during the Moon and Earth flybys and during the Moon-Earth farewell observation. For each sequence a description if provided together with the exposure times used for each filter. $\text{t}_{\text{exp}}\{\text{i}\}$ and $\text{t}_{\text{exp}}\{\text{e}\}$ indicate, respectively, the incidence and emission angle ranges during each sequence.

Seq #	Description	T_{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
Moon flyby							
1	Single filter (F12), full frame, lossless compression. Images acquired as fast as possible.	10000, 5000, 1000, 1000, 1000	2024-08-19 21:18:07 [00:00:21]	5	1-3	91-93	Surface, nighttime
2	Single filter (F1), full frame, lossless compression. 3 s cadence.	3.5	2024-08-19 21:18:35 [00:00:34]	12	0-5	86-90	Surface, daytime
3	Single filter (F1), full frame, lossless compression. 2.5 s cadence.	0.7	2024-08-19 21:19:14 [00:01:59]	48	5-21	69-85	Surface, daytime
4	Sequence of 4 filters (F2, F4, F11, F12), full frame, lossless compression. 4 repetitions, 10 s cadence.	2.7 (F2), 1.3 (F4), 2.7 (F11), 5.3 (F12)	2024-08-19 21:21:18 [00:00:38]	16	22-27	63-68	Surface, daytime
5	Sequence of 13 filter (F1 to F13), full frame, lossless compression. 2 repetitions, 20 s cadence.	0.4 (F1), 5.3 (F2), 2.7 (F3), 2.7 (F4), 5.3 (F5), 10.6 (F6), 10.6 (F7), 10.6 (F8), 10.6 (F9), 10.6 (F10), 5.3 (F11), 10.6 (F12), 10.6 (F13)	2024-08-19 21:22:03 [00:00:34]	26	28-33	57-62	Surface, daytime



Table 3 continued from previous page

Seq #	Description	T _{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
6	Sequence of 5 filters (F2, F4, F10, F11, F12), full frame, lossless compression. 4 repetitions, 15 s cadence.	3.1 (F2), 1.5 (F4), 6.2 (F10), 5.3 (F11), 6.2 (F12)	2024-08-19 21:22:46 [00:00:54]	20	35-44	47-55	Surface, dayside
7	Single filter (F1), full frame, 14 compression factors: 1:1, 1.5:1, 2:1, 3.5:1, 4:1, 5:1, 6:1, 7:1, 8:1, 9:1, 10:1, 15:1, 20:1, 33:1). Images acquired as fast as possible.	0.2	2024-08-19 21:23:50 [00:00:14]	14	46-48	42-45	Surface, dayside
8	Sequence of 8 filters (F2, F3, F4, F5, F7, F10, F11, F12), full frame, lossless compression. 4 repetitions, 14 s cadence.	1.8 (F2), 1.8 (F3), 1.8 (F4), 5.3 (F5), 7.1 (F7), 5.3 (F10), 3.5 (F11), 5.3 (F12)	2024-08-19 21:24:12 [00:00:52]	32	50-61	29-41	Surface, dayside
9	Single filter (F1), full frame, lossless compression. 9 s cadence.	0.2	2024-08-19 21:25:12 [00:00:55]	7	64-86	6-27	Surface, dayside
10	Single filter (F1), full frame, lossless compression. 8 repetitions, 2 min cadence.	1000, 10000, 50000	2024-08-19 21:26:13 [00:15:03]	24	-	-	Limb and out of limb
Earth flyby							
1	Single filter (F1), full frame, lossless compression. 50 s cadence.	36	2024-08-20 21:19:03 [00:05:01]	7	45-78	135-167	Nightside



Table 3 continued from previous page

Seq #	Description	T _{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
2	Single filter (F12), full frame, lossless compression. 50 s cadence.	140	2024-08-20 21:24:15 [00:00:51]	2	39-44	129-134	Nightside
3	Single filter (F1), full frame, lossless compression. 50 s cadence.	25	2024-08-20 21:25:13 [00:02:31]	4	27-39	117-129	Nightside
4	Single filter (F1), full frame, lossless compression. 40 s cadence.	25	2024-08-20 21:27:52 [00:06:41]	11	0-27	90-117	Nightside
5	Sequence of 13 filters (F1 to F13), full frame, lossless compression. Images acquired as fast as possible.	3.8 (F1), 26.6 (F2), 17.7 (F3), 15.9 (F4), 66.4 (F5), 70.8 (F6), 121.8 (F7), 162.7 (F8), 70.8 (F9), 24.3 (F10), 28.8 (F11), 48.7 (F12), 46.5 (F13)	2024-08-20 21:34:44 [00:00:15]	13	1-2	88-89	Dayside
6	Sequence of 13 filters, full frame, lossless compression. Execute 30 s after the beginning of the previous sequence to have partial overlap.	0.7 (F1), 5.8 (F2), 4.2 (F3), 4.2 (F4), 17.7 (F5), 20.8 (F6), 39.8 (F7), 57.6 (F8), 24.3 (F9), 8.9 (F10), 11.1 (F11), 18.8 (F12), 19.0 (F13)	2024-08-20 21:35:14 [00:00:14]	13	3-4	87-87	Dayside



Table 3 continued from previous page

Seq #	Description	T _{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
7	Sequence of 6 filters (F1, F2, F3, F4, F7, F8), full frame, lossless compression. Images acquired as fast as possible.	0.4 (F1), 3.5 (F2), 2.66 (F3), 2.66 (F4), 26.6 (F7), 26.6 (F8)	2024-08-20 21:35:40 [00:00:08]	6	4-5	85-86	Dayside
8	Sequence of 6 filters (F1, F2, F3, F4, F7, F8), full frame, lossless compression. Execute 30 s after the beginning of the previous sequence to have partial overlap between.	0.2 (F1), 2.4 (F2), 1.8 (F3), 1.8 (F4), 18.8 (F7), 26.6 (F8)	2024-08-20 21:36:10 [00:00:08]	6	6-7	83-84	Dayside
9	Single filter (F3), full frame, lossless compression. 12 repetitions, 36 s cadence.	2.2	2024-08-20 21:37:00 [00:06:38]	24	10-37	53-81	Dayside
10	Sequence of 13 filters, full frame, lossless compression. 2 repetitions, with 30 s cadence.	0.2 (F1), 0.2 (F2), 0.2 (F3), 0.2 (F4), 1.1 (F5), 1.3 (F6), 2.7 (F7), 4.4 (F8), 1.8 (F9), 0.7 (F10), 0.9 (F11), 1.6 (F12), 1.6 (F13)	2024-08-20 21:43:58 [00:00:44]	26	39-43	48-51	Dayside
11	Sequence of 6 filters (F1, F2, F3, F4, F7, F8), full frame, lossless compression. 2 repetitions, 30 s cadence.	0.2 (F1), 0.2 (F2), 0.2 (F3), 0.2 (F4), 2.7 (F7), 4.0 (F8)	2024-08-20 21:44:59 [00:00:38]	12	44-48	43-46	Dayside



Table 3 continued from previous page

Seq #	Description	T _{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
12	Single filter (F3), full frame, lossless compression. 8 repetitions, 36 s cadence.	0.2, 0.7	2024-08-20 21:45:50 [00:04:14]	16	49-80	10-41	Dayside
13	Single filter (F1), full frame, lossless compression. 8 repetitions, 2 min cadence.	1000, 10000, 50000	2024-08-20 21:50:20 [00:15:03]	24	-	-	Limb and out of limb
14	Single filter (F1), full frame, lossless compression. 3 repetitions, 2 min cadence.	1000, 10000, 50000	2024-08-21 10:56:14 [00:05:03]	9	-	-	Limb and out of limb
Moon- Earth farewell							



Table 3 continued from previous page

Seq #	Description	T _{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
1	Sequence of 13 filters, full frame, lossless compression. 6 images per filter with increasing exp time from 20% to 100% saturation. Images acquired as fast as possible.	F1: 0.2, 0.4, 1.1, 2.2, 4.4, 22.2 F2: 0.2, 0.4, 0.9, 1.8, 3.5, 5.3 F3: 0.2, 0.4, 0.9, 1.8, 2.7, 4.4 F4: 0.2, 0.4, 0.9, 1.6, 2.2, 3.1 F5: 0.9, 1.8, 4.4, 6.6, 8.9, 13.3 F6: 1.1, 2.2, 4.4, 7.6, 13.3, 17.8 F7: 2.2, 4.4, 7.8, 13.3, 16.6, 22.1 F8: 2.2, 4.4, 8.9, 14.4, 19.9, 28.8 F9: 1.3, 2.2, 4.4, 7.8, 13.3, 17.7 F10: 0.4, 1.3, 3.3, 5.6, 7.8, 11.1 F11: 0.7, 1.3, 2.2, 3.3, 4.4, 6.7 F12: 1.1, 2.2, 4.4, 6.6, 8.9, 11.1 F13: 1.1, 2.2, 4.4, 6.6, 8.9, 11.1	2024-09-09 09:51:00 [00:06:00]	78	-	-	Moon and Earth



Table 3 continued from previous page

Seq #	Description	T_{exp} (ms)	Date and Time	# of images	i (deg)	e (deg)	Context
2	Single filter (F6), full frame, lossless compression. Images acquired as fast as possible.	0.2, 0.7, 1.6, 3.3, 5.5, 11.1	2024-09-09 09:58:00 [00:03:00]	6	-	-	Moon and Earth



Data availability. JANUS data are in the team proprietary period until the data release through ESA Planetary Science Archive (PSA). The first delivery of JUICE cruise data to PSA will occur in 2029.

290 *Author contributions.* CT led the science operations, desing of the sequences and the writing of the manuscript. LP contributed to the design of the operations and of the sequences and to different parts of the manuscript. LA, AA, MA, KDM, MR, TB, EK, RP, FT contributed to the definitions of the parameters needed for the observations and data processing. RH and AL provided scientific inputs for the observations. PP designed the observations. RY, AD, IB made the observations possible. All other authors reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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300 at https://gitlab.gwdg.de/juice/science_planning.



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