



JUICE-JANUS observations of Earth in preparation for the JANUS investigation of Jupiter's atmosphere

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Abstract. JANUS (Jovis, Amorum ac Natorum Undique Scrutator), the high-resolution camera on the JUICE mission (Jupiter ICy moons Explorer), obtained observations of the Earth during and short-after a Lunar and Earth Gravitational Assist maneuver (LEGA) that was run on August 19-20, 2024. We report on the observations of the Earth that were acquired on August 20, 2024 at a closest approach to the surface of 8,408 km, and on September 9, 2024 at a distance of 564,300 km. The close approach observations covered a narrow strip of the Earth, starting in the night-side of the planet and moving over the terminator and day-side. The later observation provided a low spatial resolution portrait of the Earth and the Moon. Here we examine JANUS observations of the Earth as an example of the different science topics that will be addressed in future observations of Jupiter's atmosphere.

The Earth night-side images show atmospheric airglow, clouds illuminated by a full Moon, fires in rural areas, lights over the ocean from maritime traffic, city lights, no firm detections of lightning, and two meteor candidates compatible with meteoroids



of 1-30 g entering Earth's atmosphere. The day-side images show crepuscular rays under extreme incidence angles, atmospheric gravity waves on elevated cirrus, sun glint on multi-filter images of the tropical Western Pacific, convective storms, internal waves in the ocean and multiple cloud systems at a variety of spatial resolutions. Some images acquired with the panchromatic filter showed islands such as Luzon and the Big Island of Hawaii. We compare spectral trends of the ocean and various cloud systems extracted from JANUS multi-spectral images with spectra from the EnMAP and PRISMA satellites. JANUS images acquired on September 9, 2024 allow to form a multi-spectral view of the Earth at low spatial resolution. The data confirm the expected instrument performance in terms of optical quality and multi-wavelength radiometry precision, and the ensemble of observations contains a wide variety of features that are good analogs to multiple systems in Jupiter's atmosphere.

1 Introduction

The Jupiter ICy moons Explorer (JUICE) is the first large mission of the ESA Cosmic Vision program and will investigate the Jovian system and the potential habitability of its icy satellites (Grasset et al., 2013; Coustenis et al., 2021). JUICE was launched on April 14th, 2023, and will arrive at the Jupiter system in July 2031 after a long orbital tour that includes several gravitational assist maneuvers (Boutonnet et al., 2024). The first of these maneuvers was a Lunar and Earth Gravitational Assist (LEGA) that was run on August 19-20, 2024. Additional Earth and moon images were acquired on September 9, 2024. Both data sets provided an excellent opportunity to test the scientific payload of the mission under a real operational scenario. Two more Earth Gravity Assist maneuvers will be occurring in Sept. 2026 and Jan. 2029, and LEGA observations allow to plan future observations with hindsight on the performance of the JUICE instruments for these targets.

This paper describes the observations of the Earth during and short-after LEGA acquired with the JANUS instrument. JANUS (*Jovis, Amorur ac Natorum Undique Scrutator*) is a multi-spectral camera operating in the 340-1080 nm spectral range, and is the high-resolution instrument on JUICE (Palumbo et al., 2025). The science planning of JANUS observations during LEGA is presented by Tubiana et al. (2025). Agostini et al. (2025) detail the calibration of the data. In addition, Luchetti et al. (2025) show an analysis of JANUS observations of the Moon during LEGA and Giuseppe et al. (2025) summarize spectroscopic analyses of Earth data acquired with the MAJIS infrared spectrometer onboard JUICE.

The observations presented here cover a broad range of atmospheric phenomena observed under a variety of illumination conditions. The analysis of these data illustrates the instrument's capability to address diverse atmospheric investigations and serves as representative examples of the wide range of studies that JANUS will conduct of Jupiter's atmosphere. JUICE will perform a 3.5 yr orbital tour of the Jupiter system in which multiple science themes of the Jovian atmosphere will be investigated. For JANUS, these encompass nightside investigations of lightning and auroras and dayside investigations of winds, vertical cloud structure, color distribution, convection, and the overall behavior of atmospheric systems of multiple sizes, together with the overall evolution of atmospheric phenomena during the Jupiter orbital tour. The JANUS investigation of the Jovian atmosphere is summarized by Palumbo et al. (2025), and the overall investigation of JUICE of the Jovian atmosphere from the multiple instruments in JUICE is described by Fletcher et al. (2023).



The structure of this paper is the following: Section 2 summarizes the characteristics of the Earth data acquired. Section 3 presents an analysis of nightside observations. Section 4 explores observations of the Earth under crepuscular illumination. Section 5 presents daytime observations of the Western Pacific. Section 6 shows spectral trends from JANUS multi-filter images of the ocean and cloud systems. These spectral trends are compared with spectral observations of the same locations from near contemporary data acquired by Earth satellites. Section 7 presents a global view of the Earth obtained after LEGA observations and discusses what moderate spatial resolution can reveal for Earth. Each section contains a brief comparison with expected Jupiter observations. We summarize our conclusions on Section 8.

2 JANUS instrument and Earth observations

2.1 JANUS instrument

Palumbo et al. (2025) provide a detailed description of the JANUS instrument. Here we only give a short summary of the instrument characteristics.

JANUS is a camera with an effective focal length of 467 mm and is equipped with a 1,504 x 2,000 pixel CMOS detector, resulting in a plate scale of $15 \mu\text{rad}$ per pixel and a FOV of $1.29^\circ \times 1.72^\circ$. The rows of pixels are read out in rolling shutter mode with a line read-out time of 0.2215 ms. A filter wheel allows to select among 13 individual filters whose characteristics were selected to study the Jupiter system. Table 1 summarizes the wavelengths and band-passes of these filters.

Position	Filter id.	Central wavelength/ Bandwidth [nm]
F1	PAN	650/500
F2	BLUE	450/60
F3	GREEN	540/60
F4	RED	646/60
F5	CMT medium	750/20
F6	Na	590/10
F7	MT strong	889/20
F8	CMT strong	940/20
F9	MT medium	727/10
F10	Violet	380/80
F11	NIR 1	910/80
F12	NIR 2	1015/130
F13	H α	656/10

Table 1. Summary of JANUS filters. CMT stands for continuum near a methane absorption band, MT stands for filters in methane absorption bands.



The JANUS panchromatic filter gives access to imaging under very low illumination conditions. Broad band filters are sensitive to color, and narrow band filters are sensitive to the vertical structure of Jovian clouds through the combination of filters inside methane absorption bands and at close spectral distances. Additional filters in JANUS were selected for investigations of the Jovian moons. A relevant filter for Earth observations is the JANUS F8 filter at 940 nm. This filter lies within a strong water-absorption band and provides sensitivity to vertical cloud heights on Earth. Observations of Earth clouds in this filter play a role comparable to that of the F7 filter on Jupiter, which probes Jupiter’s atmosphere in the strong methane-absorption band at 889 nm. Additionally, filters F5, F6, F7, F11 and F12 are also weakly sensitive to water absorption bands.

2.2 LEGA Earth data

A total of 140 images of the Earth were acquired on Aug. 20, 2024 between 21:19:03 UTC and 21:50:03 UTC. At the closest approach, approximately at a distance of 8,400 km from Earth’s surface, the images achieved a spatial resolution of 125 m per pixel. During the imaging sequence, the spacecraft moved relative to Earth’s center with a horizontal velocity of 5.02–6.82 kms^{-1} . Exposure times ranged from 0.222 ms to 162 ms, generally shorter than the JANUS dwell time for those velocities. The time interval between the start of consecutive images varied from 0.46 to 50 s, depending on exposure duration and filter-change requirements. A few night-side test images acquired with narrow-band filters were smeared by 3–5 pixels due to spacecraft motion.

The high velocity flyby at a very short distance to the Earth’s surface, together with other operational constraints on the attitude of JUICE, resulted in short smearing times and in the acquisition of a small number of multi-filter sequences. These were acquired in the South China Sea and the West Pacific. Also, only a few locations were observed twice with the same filter. Those observations were separated in time by only a few tens of seconds, making wind retrievals from cloud tracking extremely challenging. Pointing was inertial and the observation sequence was constrained to phase angles of 90° due to thermal constraints on the spacecraft. The images were compressed with low compression settings to ensure lossless compression. Tables A1 to A3 in the Appendix provide a list of the LEGA images from August 20, 2024 selected for this study. Images are identified by an image ID composed of an image session ID with 10 digits, an image number during the observing sequence made from 4 digits, and two digits that code the filter used from 01 to 13.

2.3 Distant Earth data

The data acquired on September 9, 2024 consisted of a sequence of 84 images acquired at a distance of 564,300 km under a phase angle of 70.0° and with a spatial resolution of $84.66 \text{ km pix}^{-1}$ at the sub-spacecraft point. Images were obtained in the 13 filters available to JANUS using six exposure times from 0.222 to 28.795 ms. All the images kept the same pointing and included both the Earth and the Moon. We focus our attention on the portion of the images covering the Earth. Table A4 lists the distant Earth observations analyzed in this paper.

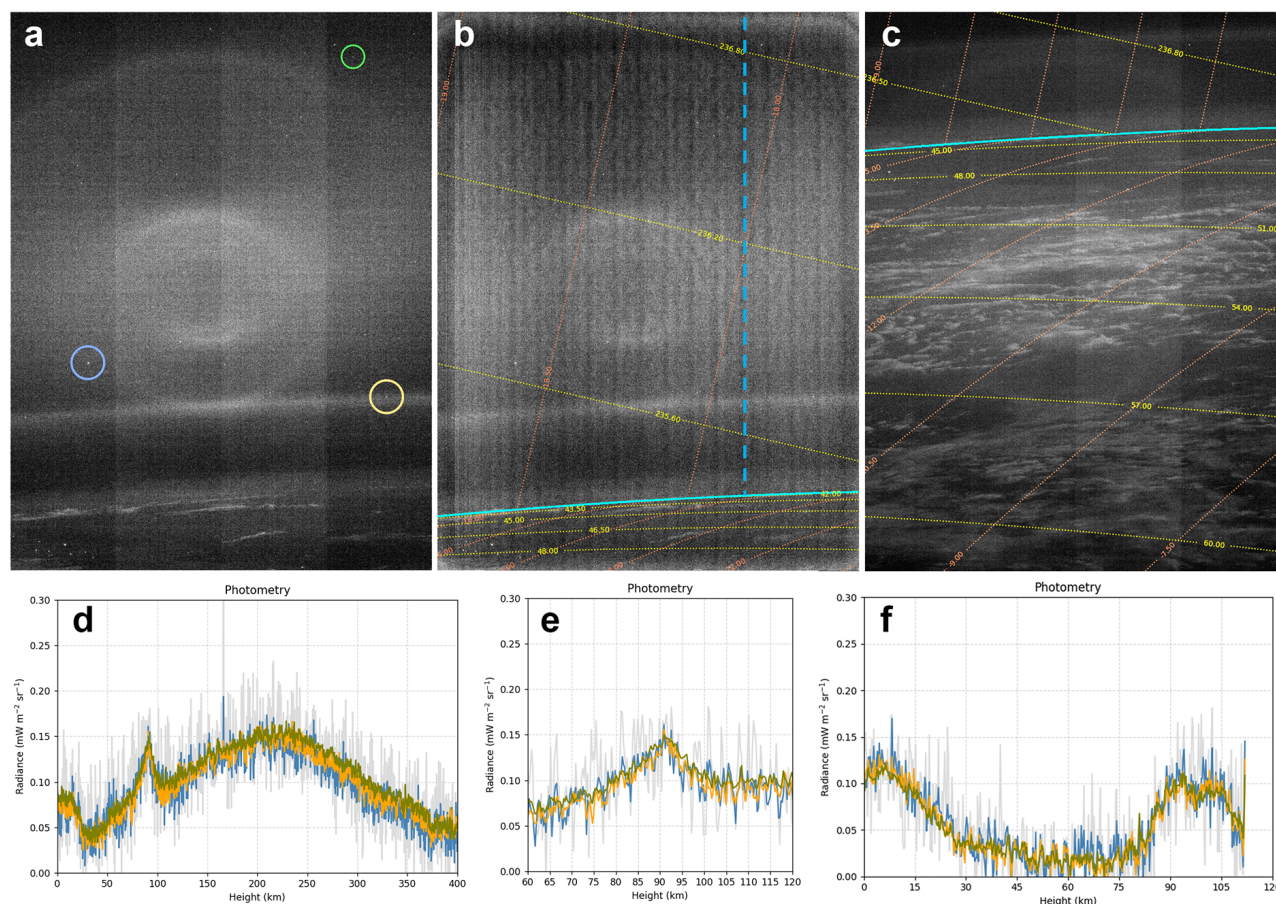


Figure 1. JANUS images of Earth's limb during nighttime. (a) JANUS image 0777503922_0000_01 after dark subtraction. Representative stars with visual magnitudes of 8.12, 9.60 and 10.18 are highlighted with blue, yellow and green circles respectively. (b) Fully calibrated image after applying flat-fielding and conversion from DNs to radiance units. The cyan solid line highlights the horizon over the surface. Longitude (yellow lines) latitude (orange lines) and RA (yellow lines) DEC (orange lines) coordinates are superimposed over the image demonstrating accurate image navigation and star identification. A vertical dashed line, outside the main artifacts in the image from stray light shows the location of photometric cuts shown in panels (d) and (e). (c) Full-size JANUS image 0777503922_0001_01 showing the same area over the horizon and clouds illuminated by the full Moon. (d) Photometric cut from the horizon to the first 400 pixels of the image. Grey lines are for a single vertical line illustrating pixel noise. Blue, yellow and green are photometric cuts averaging 30, 100 and 400 vertical lines respectively and reducing noise. (e) Zoom over the main airglow layer. (f) Photometric cut over the second image showing a similar structure of the scattered light over the horizon and of the main airglow layer.



3 Nighttime images

The inbound over the nightside of the Earth gave JANUS the opportunity to observe atmospheric airglow and search for lightning over diverse areas. Most of these observations were obtained under the illumination of the target by a full Moon. Table A1 lists the selected JANUS nighttime observations discussed in this section.

3.1 Airglow and scattered light over the limb

The first image of the Earth was an observation of the limb of the planet during nighttime at a distance to the horizon of 18,010 km (Fig. 1a). The image was acquired with a exposure time of 36.1 ms with the F1 filter (panchromatic). The short-time exposure was selected due to the short dwell-time associated to the fast flyby and the unexpected nature of what the observation would show. Above the horizon, the image shows Earth's airglow and multiple stars of magnitudes 8.1–10.8 inside and outside the mean airglow emissions. Close to Earth's horizon, the image shows clouds illuminated by the Moon and bright lights in the west coast of Madagascar. These bright lights are observed again at the same geographical positions in a JANUS image acquired 50.2 seconds later (Fig. 1c). In this second image, large cloud systems illuminated by the full Moon are visible over the Indian Ocean. From the calibrated JANUS panchromatic image, the radiance levels of these clouds and the overall Moonshine in this location is $\sim 0.3 \text{ mW m}^{-2} \text{ sr}^{-1}$, which is in overall agreements with expected values from typical ground measurements of lunar illumination (Kyba et al., 2017).

Given the low-exposure of the image, stray light from sunlight reflected by Earth's dayside resulted in a circular artifact likely created from internal reflections in the baffles of JANUS. This artifact appears in most of the nighttime images with different contrast. In the airglow image, the circular patterns created by stray light have an influence on the determined radiance of about $0.17 \text{ mW m}^{-2} \text{ sr}^{-1}$. In addition, the standard radiometric calibration process (see Agostini et al. this issue) results in the addition of a noisy regular pattern in the darkest regions of the images (see Fig. 1b). This is because of the behavior of the calibration algorithm that may introduce artifacts in case the signal is very low (less than 10 digital units in the original raw image). This effect is being studied for correction in future versions of the calibration pipeline.

Earth's airglow is the most notable feature in Fig. 1a. The airglow appears as a bright halo detached over the surface of the planet with a radiance level that peaks at 90 km above the surface with values of $0.15 \text{ mW m}^{-2} \text{ sr}^{-1}$. Additional airglow extends over altitudes around 250 km (Fig. 1d-f). A comparison with photometry of stars in the field, corrected for background contributions from airglow and stray light using aperture mask photometry results in an estimated brightness of $18 \text{ mag arcsec}^{-2}$ for the main airglow layer at 90 km height. This value compares well with typical estimates of night-sky brightness observed from the ground, with brightness values of about $21.6 \text{ mag arcsec}^{-2}$ for observations of the zenith (Patat, 2003). The extended emission at 250 km competes in brightness with stray light, and its spatial structure and overall brightness are more complex to characterize.

In the wavelength range of the panchromatic filter, the most intense emissions of Earth's airglow come from atomic oxygen (OI) at 630 nm, sodium (NaD) at 588.9–589.6 nm, and hydroxyl (OH) (all peaking near 90 km). The extended emission around 250 km is most likely contributed by OI emissions at 630.0 and 636.4 nm (Leinert et al., 1998).



Besides airglow, the JANUS Earth observations in Figure 1 show scattered light over the horizon from the surface to an altitude of about 25 km. However, the low radiance level and low signal to noise ratio of the image do not allow for further exploration of light scattering from the atmosphere on the nightside limb.

JANUS will image Jupiter's nightside limb several times on its orbital tour (Fletcher et al., 2023). The recent discovery of a
 125 widespread Jovian airglow in the near-IR by the James Webb Space Telescope (Sromovsky et al., 2022) opens the possibility to
 search for visible counterparts to those emissions. However, the key observational target on JANUS observations of nightside
 limb are auroras. So far, only the Galileo orbiter has observed auroras on Jupiter in the visible range (Ingersoll et al., 1998;
 Vasavada et al., 1999). Galileo observations showed complex structures over extended arcs 250 km above the 1 bar level. The
 auroral emissions extended over vertical distances of 120 km, and were observed at a spatial resolution of 26 km per pixel.
 130 JANUS will image Jupiter's limb at a pixel scale of 10-20 km in several perijoves over the JUICE mission. Thus, we expect
 to map not only the spatial extent of auroras, but also to characterize their vertical structure and obtain information about its
 variability at different time-scales. Jupiter auroral emissions in the visible observed by Galileo with near nadir viewing had
 intensities of ~ 80 kR ~ 300 kR (Ingersoll et al., 1998). These are about 10-30 brighter than the airglow emissions observed
 in JANUS images of the Earth. In addition, Jupiter Observations at perijove will have much larger dwell times than in the fast
 135 Earth flyby allowing for the acquisition of well exposed detailed views of the Jovian auroras.

Replicating nighttime observations of the scattering of moon light above the horizon observed on these images of Earth's
 limb might be difficult on Jupiter, where the Galilean moons receive ~ 25 times less light. However, Jupiter's extended hazes
 in the equatorial and polar latitudes will increase light scattering effects, and equivalent observations of Jupiter by JANUS will
 be run under much longer integration times. Thus, detached haze layers as those observed by Galileo at high phase angles
 140 (Rages et al., 1999) might be observed serendipitously on JANUS images of the nightside when JANUS frames include the
 limb of the planet.

Further, JANUS may be able to observe visible counterparts to the UV auroras of Ganymede detected by the Hubble Space
 Telescope and Juno (Saur et al., 2015; Greathouse et al., 2022), with auroras in the visible observable on Ganymede's nightside
 (de Kleer et al., 2023). These auroral observations will provide key information about Ganymede's internal ocean.

145 **3.2 Searches for lightning, city lights, fires and maritime traffic**

Nighttime images of the Earth were acquired over tropical latitudes from Madagascar to Thailand. Many of these night-time
 images contain bright sources. Detailed analyses show that only one of them can be considered a weak candidate for detection
 of lightning. These nighttime compact light sources illustrate the potential of the instrument to detect lightning and can guide
 the design of surveys of lightning on Jupiter.

150 Figure 2 contains a detailed view of a small section of the full JANUS image shown in Figure 1. Several compact lights can
 be seen near the horizon. Their geographical position and brightness are repeated in the next JANUS image obtained 50 s later.
 Panel (b) shows a map of the original observation in terms of longitude and geodetic latitude. Some of these compact lights
 correspond to the city of Mamoudzou in the island of Mayotte, East of Madagascar, and potentially also to the city of Andoany

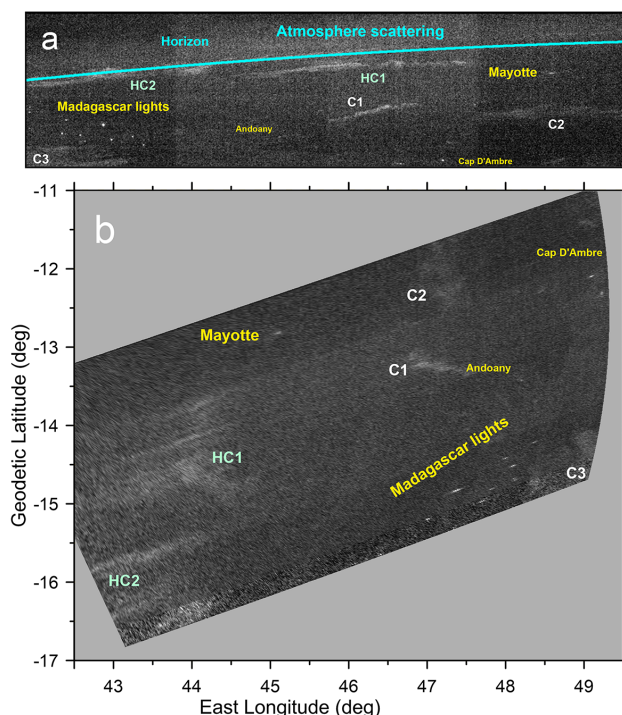


Figure 2. Lights on Madagascar. (a) A small section of image 0777503922_0000_01 showing the horizon, clouds illuminated by the Moon, and several bright and compact light sources. (b) Cylindrical map projected image. Point sources in panel (a) spread on the map projection on (b) due to the nearly limb viewing geometry. Labels C1, C2 and C3 identify clouds, labels HC1 and HC2 identify high-altitude clouds. The position of Mayotte island, Andoany and Cap d'Ambre are indicated. The shape of the west coast of Madagascar can be seen in the image competing with the noise level. All compact light sources are inside Madagascar island and are repeated at the exact same geographic positions in a second image of the area obtained 50 seconds later.

and villages around Cap D'Ambre in the north coast of Madagascar. Most other lights, including the most intense sources, correspond to fires in Madagascar (fires are common in the area at that time of the year due to farming activities). The nature of these lights as fires in rural and bush areas was verified using data from NASA's Fire Information for Resource Management System (FIRMS; see <https://firms.modaps.eosdis.nasa.gov/>), which provides daily maps of hot spots on the surface of the Earth from IR observations by Earth monitoring satellites. Similar light sources were observed in JANUS images over Cambodia and Vietnam, and again were verified to be caused by surface fires from comparisons with FIRMS data.

Nighttime observations of the Indian ocean showed an interesting case of a dim light spot over a convective cloud. Figure 3 shows a group of moderately bright pixels appearing on image 0777503922_0005_01 acquired at 21:23:13 UTC. This small light spot was located inside a convective system at 80.73°E, 2.32°N, south of Sri Lanka. An image of the same area obtained 50 seconds later (image 0777503922_0006_01) does not show the same group of hot pixels. Both images had a spatial resolution of 196 m and an exposure time of 36.1 ms. Meteorological satellites show the presence of a ~4,000-km long convective line

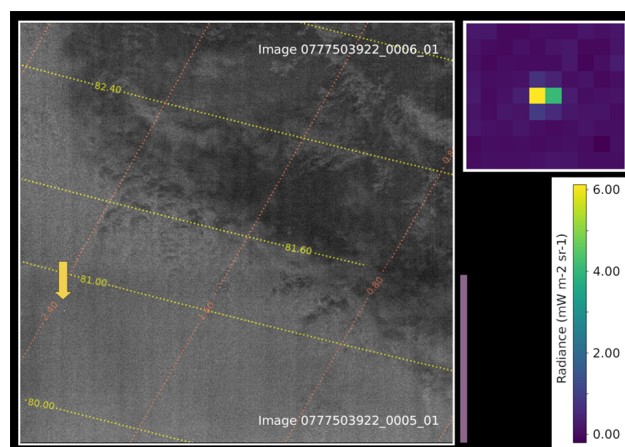


Figure 3. Sections of JANUS images 0777503922_0005_01 and 0777503922_0006_01 combined in a single image. A purple vertical line shows the area in which both images superimpose (the original images have much larger FOVs). That region is shown in this figure from image 0777503922_0005_01 containing a lightning candidate highlighted with a yellow arrow. The illumination of this scene comes from the Moon. A magnified view of the light distribution over the area covered by the lightning candidate is shown in the upper right corner.

165 at that region. In order to investigate the nature of this event we examined lightning detections of the area captured by the Earth Networks Total Lightning Network (ENTLN). This network locates lightning activity from a global array of radio sensors capturing broadband radio-frequency emissions from lightning discharges (Zhu et al., 2022). We also examined data from the popular Blitzortung network operated by volunteers (Narita et al., 2018). However, none of these networks show any signature of a lightning event in the 4 seconds around the time of the JANUS image acquisition. Also, the World-Wide Lightning Location
 170 Network (WWLLN) (Rodger et al., 2009) did not observe lightning on that specific location over the 21:00-22:00 UT time range. These negative detections imply that if there was a lightning event it should have been a very weak one.

Since all JANUS images are calibrated in radiance, the optical energy of the group of hot pixels can be estimated. To do that we integrate the total flux of the group of pixels in the image using aperture photometry to remove the background illumination ($12 \text{ mW m}^{-2} \text{ sr}^{-1}$), we multiply by the pixel area (196^2 m^2) and by the exposure time of the image (36 ms). A multiplication
 175 by a geometric correction factor 4π is also included assuming isotropic emission. This results in an estimated detection of optical energy for this event of 210 J. This evaluation of the optical energy does not take into account light absorption within the cloud. Since exposure time and lightning development time-scales are comparable, the energy associated to these bright pixels represent a lower energy limit to the energy of the lightning candidate. The optical energies of lightning flashes in the visible wavelength range is typically on the order of $1.2 - 3.6 \times 10^6 \text{ J}$ depending on lightning type (Quick and Krider, 2013;
 180 Peterson and Liu, 2013; Peterson et al., 2017), although substantially weaker flashes have also been reported. Thus, the energy detected in this event is about 4 orders of magnitude below typical values of optical energy of lightning in the visible and near-infrared. This order of magnitude estimate of the optical energy is also 2-4 orders of magnitude smaller than reported optical energies of sprites (Sentman et al., 1995; Wescott et al., 1995; Takahashi et al., 2010) and is also much smaller than other

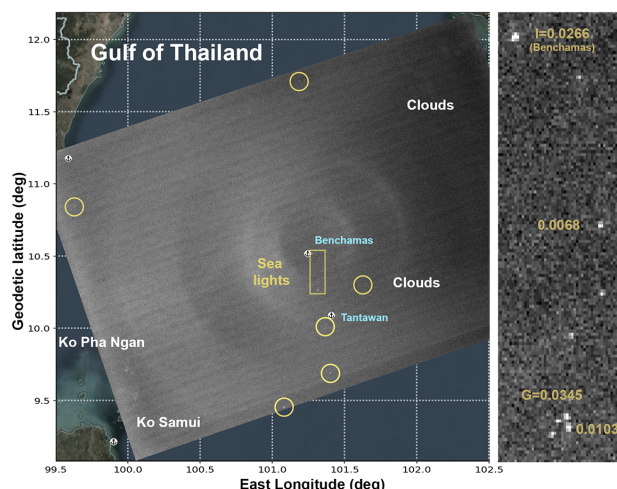


Figure 4. Cylindrical map projection of JANUS image 0777503922_0014_01 showing the Gulf of Thailand. The image was obtained with the panchromatic filter with an exposure time of 25 ms, and the pixel scale 165 m. The image has been mapped and placed on top of a map of the area to provide context. Coastal lights around the Ko Pha Ngan and Ko Samui islands are clearly visible at the spatial resolution of the original images. Compact lights in the sea are highlighted with circles. The location of Benchamas and Tantawan offshore ports and oil gas fields are indicated. A zoom of the rectangular area highlighted in the map shows the strongest lights present in the image. Numbers in the figure correspond to radiance levels calculated for individual lights using aperture photometry and given in units of $\text{W m}^{-2} \text{sr}^{-1}$. G stands for the group of 4 individual light sources in the bottom part of this rectangle.

Transient Luminous Events (TLEs) like ELVES, Halos or Blue Jets (Pasko et al., 2012). The estimated read-out noise of this
 185 image is about $0.05 \text{ mW m}^{-2} \text{sr}^{-1}$, or about two orders of magnitude smaller than the estimated radiance of this event. Since
 noise from a cosmic ray or particle hit at the detector cannot be disregarded, this event highlights the difficulties to identify the
 nature of weak light sources on nightside images. For the future JANUS investigation of Jupiter lightning, defining a detection
 threshold for lightning can be problematic when analyzing observations acquired from large distances in the more energetic
 environment of the Jovian magnetosphere. Systematic observations will acquire enough detections to provide an identification
 190 threshold based on statistics on the events observed.

Another image with interesting compact light sources is an image of the Gulf of Thailand (Fig. 4). In the image showed in
 this figure, the scene is illuminated by the Moon, which is at low elevation on the WWS direction. Stray light effects associated
 to the illumination from Earth's dayside create the large-scale circular pattern visible on the image. Several small and bright
 patches of light are observed over the sea and in coastal populations in two islands on the lower-left side of the image. The
 195 lights observed over the sea are located in densely traveled maritime routes, and the largest and brightest clusters of light are
 concentrated near the offshore Benchamas and Tantawan oil and gas fields, which suggest that the compact light sources are
 the industrial facilities of the offshore gas fields and large ships or groups of ships. The radiance of the spot identified at the
 geographical location of Benchamas is $27 \text{ mW m}^{-2} \text{sr}^{-1}$, and individual spots likely associated with individual ships or cluster

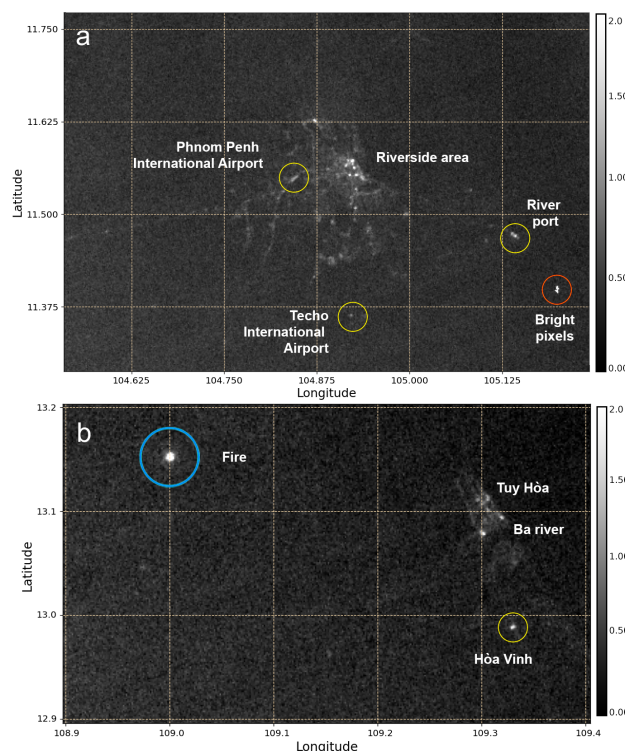


Figure 5. Sections of cylindrical map projections of JANUS images 0777503922_0015_01 and 0777503922_0017_01. (a) Cambodia’s capital, Phnom Penh. The image had a pixel scale of 160 m and a exposure of 25 ms. A group of bright pixels far from cities and villages is highlighted with a red circle and is discussed on section 3.3. (b) Tuy Hòa and surrounding area in Vietnam’s coast. The image had a pixel scale of 152 m and a exposure of 25 ms. A large and bright fire is observed at 13.15°N, 109.00°E.

of ships have radiances of $3\text{--}10 \text{ mW m}^{-2} \text{ sr}^{-1}$ (e.g. each of them are similar individually to the event shown on Fig. 3, but their alignment over a heavy traveled maritime route reveals their nature).

JANUS also captured images of bright lights in different cities. Figure 5 shows Cambodia’s capital Phnom Penh and the small city of Tuy Hòa in the coast of Vietnam. Phnom Penh and Tuy Hòa have populations of 2.0 million people and 160,000 people respectively. The city center near the riverside area in Phnom Penh and several large infrastructures can be identified in the JANUS image when comparing with maps of Phnom Penh. The Tuy Hòa image also shows a bright spot that corresponds to the most intense fire observed by JANUS, with its nature confirmed from a comparison with FIRMS data.

The image with Phnom Penh also shows two sets of bright pixels (one is highlighted in Fig. 5 and the other is outside the FOV shown in this figure). The nature of these source is discussed in the next subsection.

Values of optical energy associated to the light sources observed in these images can be calculated following the same technique used for the lightning candidate previously discussed. Integrated energy associated to the illumination of Phnom Penh and its city center are 8,080 and 5,570 J respectively (although these numbers are more uncertain than for compact light



sources due to the extended source and background illumination from the Moon). The optical energy of the intense fire near Tuy H6a is estimated as 1,500 J, which is three orders of magnitude smaller than a typical lightning flash (Quick and Krider, 2013).

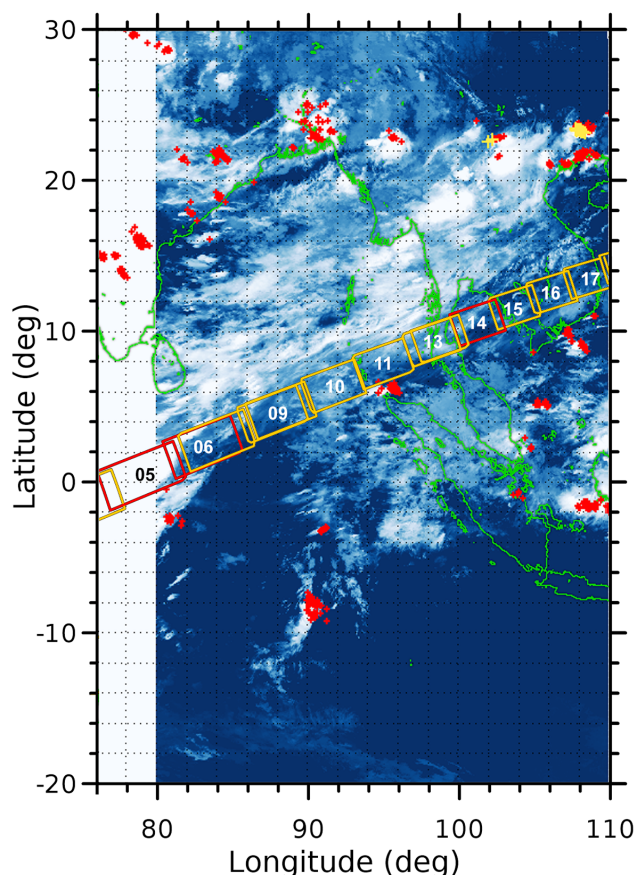


Figure 6. Locations of lightning strokes on August 20th, 2024 in the interval of 21-22 UTC from the WWLLN data (red crosses) and Blitzortung (yellow crosses) networks of radio receivers. JANUS FOV of individual images from 0777503922_0004_01 to 0777503922_0017_01 are shown in color. Images discussed in the text, like 05 and 06 with a very weak lightning candidate, and 15, covering the Gulf of Thailand, are shown with red polygons. The background is an IR image from the Himawari satellite operated by the Japan Meteorological Agency and captured at 21:20 UTC on August 20th, 2024.

Most compact light sources observed on JANUS nightside images of the Earth are created by fires or artificial sources, and the single lightning candidate observed over a convective cloud system had an estimated optical energy that even under conservative assumptions is several orders of magnitude lower than typical lightning flashes. Thus, the apparent lack of detection of lightning in the Earth nightside observations invites for an examen of strategies to search for lightning. The efficiency of a camera-based lightning search depends on the total spatial and temporal coverage of the ensemble of observations. The 20 JANUS nighttime



images of the Earth covered a total area per time of $\sim 89,000 \text{ km}^2 \text{ s}$ (assuming for simplicity nadir pointing for all images and
 220 multiplying the area covered by each image by their exposure time and adding their totals), or $\sim 2.8 \times 10^{-3} \text{ km}^2 \text{ yr}$. Extensive
 observations of lightning from space show a lightning flash frequency of 20-30 flashes $\text{km}^{-2} \text{ yr}^{-1}$ in strongly lightning active
 regions, and values of about 5 flashes $\text{km}^{-2} \text{ yr}^{-1}$ for tropical latitudes (Christian et al., 2003). Thus, the observational efficiency
 of the JANUS nighttime images is very small compared with lightning rates. For instance, image 0777503922_0014_01 (Fig.
 4) of the Gulf of Thailand, which is known to be a very active site of lightning, covered $79,300 \text{ km}^2$ and was acquired with a
 225 exposure time of 25 ms, meaning that it had an efficiency of $6.3 \times 10^{-5} \text{ km}^2 \text{ yr}$. This translates in a probability for this image
 of containing a lightning flash of only 0.2%. For the whole set of nightside observations, and considering a representative value
 of 5 flashes $\text{km}^{-2} \text{ yr}^{-1}$, we get a probability for the JANUS nightside dataset of $\sim 1.5 \%$ of containing a single lightning event.

These aspects can be further examined observing the lightning activity over the area traversed by JANUS from networks of
 lightning detection based on radio receivers. Figure 6 shows the ensemble of lightning detections from spherics detected by
 230 the WLLN and Blitzortung networks on the area of the Indian Ocean over the 21-22 UTC time range. Only a few lightning
 strokes occurred over a full hour on some of these short-exposure frames confirming the non-lightning nature of the compact
 light sources discussed previously. However, lightning activity occurring very close to the JANUS images shown in Fig. 3, and
 the nature of the local meteorological activity indicates that electric activity was indeed possible on that location. The JANUS
 image 777503922_0011_01 covered also a region of strong convection with lightning activity over the 1 hr time interval shown
 235 in Fig. 6. A close examen to this image did not show any lightning candidate to brightness levels at least four times smaller
 than the weak candidate shown in Fig. 3.

JANUS will extensively characterize lightning events in Jupiter's atmosphere. Most lightning observations will have long
 exposure times, accumulating several flashes over the same area. Jovian lightning is far more intense than lightning on Earth,
 but it will be observed from much larger distances allowing statistical mapping and determination of the size of lightning spot
 240 sizes which constrains lightning depth (Borucki and Magalhaes, 1992; Little et al., 1999; Gierasch et al., 2000; Dyudina et al.,
 2004). So far, the largest optical survey of lightning activity on Jupiter comes from the Galileo orbiter, which determined a flash
 rate above a given energy threshold of 4×10^{-3} flashes $\text{km}^{-2} \text{ yr}^{-1}$, with lightning sources concentrating on cyclonic regions
 (Little et al., 1999). A lightning survey from the Stellar Reference Unit on Juno, which is a far more sensitive instrument than the
 ISS camera on Galileo, gave 6.1×10^{-2} flashes $\text{km}^{-2} \text{ yr}^{-1}$ for lightning observations over high latitudes (Becker et al., 2020).
 245 In addition, the lightning activity detected by radio instruments can be significantly higher (Imai et al., 2020), indicating the
 difficulties to observe in the visible weak or deep atmosphere lightning events. Thus, for its survey of Jovian lightning, JANUS
 will obtain repeated observations of large and small areas of Jupiter using a combination of short and long time exposures
 to maximize the efficiency of those surveys and understand the weak light spots from statistics of the results. Observations
 of hot pixels, cosmic rays and energetic particles in the high-energy Jovian environment will characterize those effects on
 250 the detector, helping to understand the capability of the instrument to unambiguously characterize weak lightning sources.
 Observations conducted at a variety of spatial resolutions will give information about the spatial distribution of lightning
 events, their depth and energy release. Dayside and nightside observations of the same areas will be planned similarly to

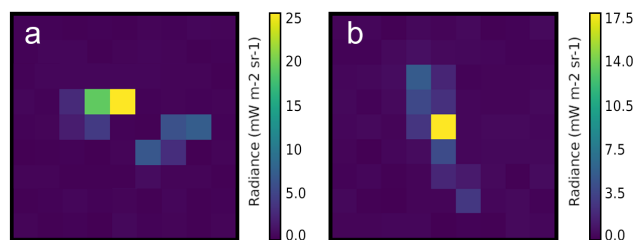


Figure 7. Hot pixels in JANUS image 0777503922_0015_01. Panel a is centered at longitude 105.20° and latitude 11.40°. Panel b is centered at longitude 104.83° and latitude 12.07°. Note the two different color scales for these two features. Pixel scale is 158 m and exposure time is 25 ms.

storms observed by Galileo (Gierasch et al., 2000) and will be a key part of the JANUS investigation of convective storms in Jupiter. In addition, synergetic observations with other JUICE instruments sounding the lower layers of the atmosphere with
 255 MAJIS (Poulet et al., 2024) and upper layers with the Ultraviolet Spectrometer instrument on JUICE (Davis et al., 2021), together with radio emissions with the RPWI (Wahlund et al., 2025) (e.g. similarly to recent multi-instrument analyses with Juno, see Brueshaber et al., 2025 or previous works in Saturn with Cassini, see Dyudina et al., 2010) will be particularly relevant to investigate the spatial distribution, energy output and impact of storms in the Jovian atmosphere.

3.3 Meteor candidates

260 JANUS images of the Earth show two moderately bright events that we could not associate to surface features, were too weak to imply lightning, and occurred in regions not covered by clouds. These two events appear on the JANUS image 0777503922_0015_01 over Cambodia. The brightest of these features is highlighted in Figure 5. A detailed image of the structure of both groups of hot pixels is shown in Figure 7. The brightest pixel in Figure 7a is ten times brighter than any pixel in the image covering the city of Phnom Penh. The total flux of this event is a third of the total flux of the large fire
 265 visible in Figure 5b. The brightest of these two groups of pixels occurred in a location that was also observed in the following JANUS image 0777503922_0016_01, where no such bright feature is observed, demonstrating a transient feature. For the second event, there is no additional JANUS image covering the same location. In addition, the elongated shape of both features is very different to areas where JANUS found fires and to the nearly circular group of pixels shown in Figure 3. JANUS did not detect cloud features in the area of these bright spots, and meteorological satellites do not show clouds, ruling out electrical
 270 activity.

An important aspect of the interpretation of features like this is the rolling shutter nature of the JANUS detector. Images are read from top to bottom with a read line time of 0.2215 ms implying that each line is read on slightly different times. The elongated structure of both events could be compatible with cosmic ray events or impacts by energetic particles. This image was captured from an altitude of 10,327 km, close to the outer altitude of the inner Van Allen belt. However, all the other
 275 images in the Earth LEGA observations were obtained from similar altitudes without showing similar features. The possibility



that these groups of hot pixels were caused by cosmic rays or energetic particles could be eventually tested comparing these features with images acquired during science operations and periodic check outs of the JUICE payload.

Alternatively, there is a second possible scenario to explain these features. From the radiance values, pixel scale of 158 m per pixel, and 25 ms exposure time, the integrated optical energy associated to the two groups of hot pixels in Figure 7 are 549 and 266 J respectively. For luminous efficiencies of 1-10% (Drolshagen et al., 2021), these values of optical energy can be released from meteors impacting Earth's atmosphere at speeds from 11-70 km s⁻¹ with masses of 1-30 g, although given the very short exposure of the image, higher masses are probably required to explain these events from meteors.

The origin of these two events cannot be totally determined. There is a considerable interest to detect and characterize impacts in Jupiter from small-size objects leaving visible traces in the atmosphere that could be similar to these two groups of pixels. Jupiter receives a flux of impacts that is much greater than that of Earth. Voyager 1 observed one small impact in Jupiter from a distance of 555,000 km and at a pixel scale over Jupiter of 20 km from an object with an estimated size of 11 kg (Cook and Duxbury, 1981). The UVS instrument on the Juno mission detected a single bolide with an estimated mass of 250-5,000 kg. The impact rate for objects of similar mass and size is considered to be around 24,000 per year (Giles et al., 2021). Juno also observed several candidates to TLEs in a proportion of 10 to 1 with respect to impacts (Giles et al., 2020). Super bolides observed in Jupiter from Earth with sizes of 5-25 m in diameter are expected to hit Jupiter 10-65 times per year lighting the atmosphere at the impact location for only a few seconds (Hueso et al., 2018).

Planned JANUS observation of Jupiter's nightside will most likely observe dozens of impacts in the size category of the one observed by Voyager 1, and many more smaller given the more sensitive camera than the one in Voyager 1 and the larger coverage over the nightside of the planet over the 3.5 yr orbital tour. It should also be able to observe several energetic impacts similar in size and energy to the one detected by Juno. Building a sufficiently large set of observations of impact events in Jupiter would help immensely in the determination of the current impact rate in the planet and their role in polluting the upper stratosphere.

4 Crepuscular illumination near the terminator

4.1 Dawn images

JANUS images obtained near dawn show illumination effects associated to tangent illumination close to the terminator. Figure 8 shows high cumulus clouds observed before sunrise, during the morning astronomical twilight. Here, scattered light from the distant dawn terminator travels over the upper atmosphere and illuminates the uppermost clouds in the scene half an hour before local sunrise. A comparison with later observations during morning hours over the tropical latitudes covered by JUICE suggests these cumulus clouds may have high cloud tops at heights of about 10-14 km. Several cloud systems are observed in the lower troposphere with very low illumination levels and without projecting observable shadows.

As the spacecraft moved towards dawn, the illumination increased rapidly and elevated clouds started to receive direct illumination from the Sun refracted on the atmosphere acquiring the capability to project shadows. Figure 9 contains two

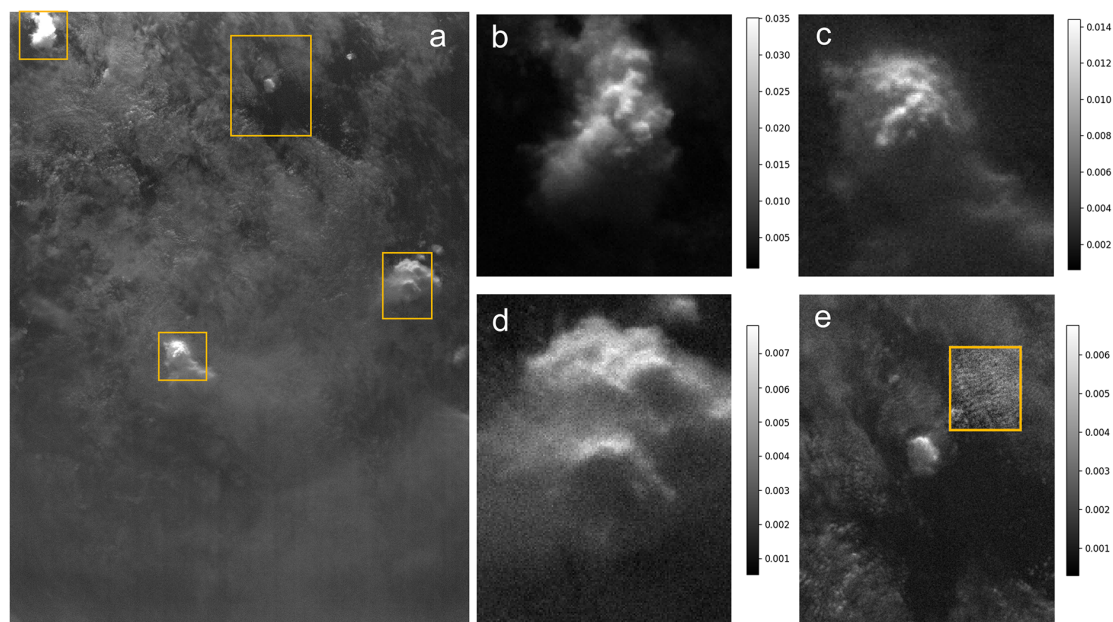


Figure 8. JANUS image of the morning twilight. (a) JANUS image 0777503922_0020_1 showing elevated cumulus clouds illuminated from sun light refracted over the upper levels of the middle atmosphere. The illumination comes from top of the image (East). The moon is setting in the West. The image is showed using a Gamma correction with $\gamma = 0.4$ to simultaneously show bright and dark features in the image. The lower clouds visible in the upper part of the image show a strong gradient in illumination, while the lower part is illuminated only by the Moon light and shows homogeneous lighting. The pixel scale is 144 mand the FOV is 288 km x 215 km centered at planetocentric latitude 16.131° and longitude 115.71° over the South China Sea. Boxes highlight regions shown in panels b-e with a zoom factor of about 6 with respect to the full image. (b) Cumulus cloud illuminated 26 min before local dawn. (c) Cumulus cloud at a location 32 min before local dawn. (d) Cumulus cloud 30 min before dawn. (e) Low elevation clouds 26 min before local dawn. Inset shows a contrast-enhanced subregion of the image where gravity waves can be observed in the background clouds. Panels (b-e) are shown in linear scale with no gamma correction. Color bars in (b-e) show radiance levels in units of $\text{W m}^{-2} \text{sr}^{-1}$.

consecutive images close to the dawn terminator showing a strong gradient in the illumination of the scene. The left panel shows that the light increases by a factor of 3.5 over a distance of 280 km approaching dawn. The next JANUS image acquired in the sequence and displayed in the center panel, shows an additional enhancement of brightness by a factor of 4.0 over the next 280 km. This image saturates near dawn (all elevated clouds and some low terrains appear saturated in the upper part of the image, closest to dawn). Both images show crepuscular rays, (CRs), which are alternating dark and light bands in the sky that take the form of light streaks as sunlight filters through cloud gaps (Minnaert, 1954; Lynch, 1987). The crepuscular rays in these two images are a combination of shadows and forward scattering on the elevated aerosols present in the images (Van Den Broeke et al., 2010). The long shadow highlighted in this figure reaches a length of 510 km.

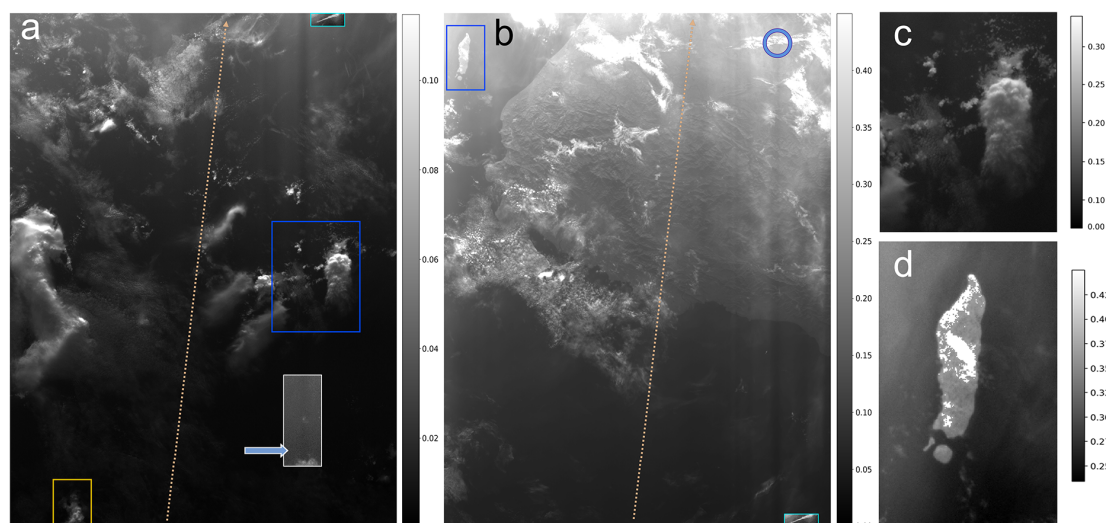


Figure 9. JANUS images near sunrise. (a) Image 0777503920_0021_1 over the South China Sea. (b) Image 0777503920_0022_1 over Luzon island. A diagonal arrow in panels (a) and (b) shows the direction of the spacecraft motion from bottom to top. A small inset highlighted in cyan in panels (a) and (b) shows a common feature in both images illustrating spatial continuity between the two images. The orange box in (a) shows the cumulus cloud showed in Fig. 8b. Blue boxes in (a) and (b) indicate regions showed in higher detail in panels (c) and (d). A blue circle in (b) and a blue arrow in (a) show the start and end respectively of an extremely elongated shadow that traces the direction of the Sun illumination and reaches a length of 512 km. A white box in (a) shows a contrast-stretched inset of the image to show the end part of the elongated shadow (a). Crepuscular rays are observable in (a) and (b) parallel to this shadow. (c) Zoom version of the cumulus cloud highlighted in (a). (d) Fuga Island, north of Luzon, appears partially saturated 3 min. before local sunrise. Color bars show radiance levels for each panel in units of $\text{W m}^{-2} \text{sr}^{-1}$. Saturated pixels on (a), (b) and (d) are shown in white.

Figure 10 shows details over the north coast of Luzon island. The lateral illumination by a rising sun shows strong contrasts associated to the mountainous terrain, visible rivers and the coast. Dense clouds appear saturated and thin cirrus with gravity waves are also visible in the image. A long-dark feature in the sea is probably an internal ocean wave, common in the Luzon strait (Yuan et al., 2006). This small portion of the original image demonstrates the high-resolution of the JANUS images, and the capacity to observe very faint contrasts as those coming from the cirrus clouds and from the linear features in the coast produced by the parallel alignment to the coast of local populations. It is remarkable that the high clouds in Figure 10 do not project shadows over the terrain because of the almost total horizontal illumination, which contrasts with the CRs on Figure 9 in which CRs propagate at altitudes near the elevation of the original clouds casting shadows and leaving gaps over thin layers of elevated aerosols. Because the terrain is mostly illuminated by the dawn light refracted in the sky, mountain shadows are not as strong as they would be if the Sun had fully risen.

Observations of the Earth terminator were acquired under a 90° phase angle. A similar illumination will be common in many JUICE perijoves in which images of the planet at spatial resolution of 15 km per pixel will be common. With Earth's

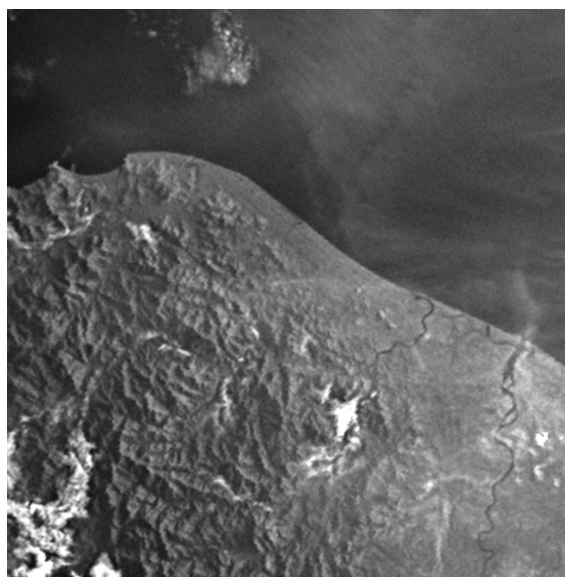


Figure 10. Details over the Cagayan province in the north coast of Luzon island at dawn from image 0777503922_0022_01. A section of about 370 x 370 pix in the original image has been mapped into a cylindrical projection with longitudes from 121.0° to 121.50° E longitudes and latitudes from 18.25° to 18.75°N. North is up and East is to the right. The image has been high-pass filtered. High clouds appear saturated.

terminator showing complex illumination effects over 500 km, and Jupiter's larger radius by a factor of 11, JANUS images of the terminator may observe similar extreme illumination conditions in Jupiter helping to identify and separate upper and lower clouds like those observed in Figs. 8 and 9. Such illumination effects at the terminator will cover a significant portion of the JANUS detector allowing to explore these effects if appropriate exposure times to the challenging illumination can be determined.

5 Daytime observations

5.1 Cloud altitudes from shadows

Earth observations obtained soon after local dawn show a variety of cirrus and cumulus clouds that project long crepuscular rays and shadows.

Two sequences of multi-filter images were obtained minutes after local sunrise with nearly tangent illumination and nadir viewing. Figure 11 shows part of one of these sequences obtained about 12 min after local sunrise. The images show cumulus clouds and elevated cirrus in color and in the JANUS filter F8 centered at 940 nm. Observations in this filter are strongly affected by the wide H₂O absorption band at 820-940 nm. The color image shows a bright convective cloud, elevated dense cirrus and multiple bright clouds reaching lower heights. Long crepuscular rays dominate the scene in short wavelengths,

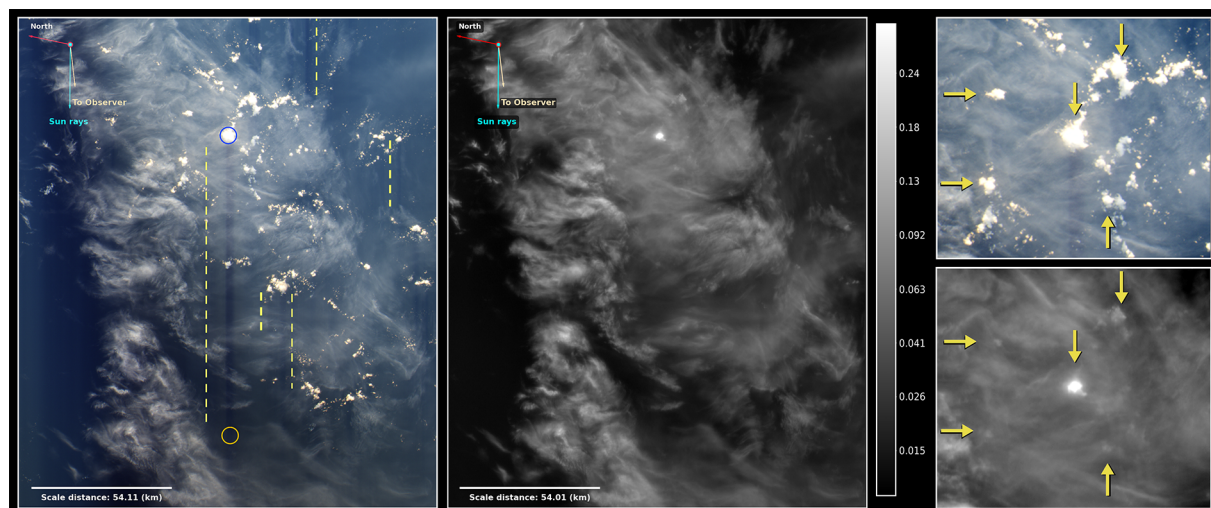


Figure 11. JANUS images of clouds and shadows. (a) Color image from JANUS images 0777503922_0039_04, 0777503922_0038_03, and 0777503922_0037_02 in red, green and blue filters respectively. The figure legend shows the North direction and the position of the sun and observer. Yellow dashed lines are shown close to shadows cast from elevated clouds. From left to right these shadows extend over 118, 16, 38, >36 and 26 km. From a geometric model of the observations these shadows lengths correspond to minimum altitudes of 5.4, 0.7, 1.7, >2.2 and 1.4 km. (b) JANUS image 0777503922_0044_08 with the F8 filter (940/20 nm) sensitive to water absorption. Only the elevated cirrus clouds and one of tallest cumulus clouds are apparent in the image. Because of the strong contrast the image is shown using a non-linear representation of the brightness levels. The gray bar shows values of radiance in units of $\text{W m}^{-2} \text{sr}^{-1}$. Panels (c) and (d) show zoom-up versions of the area around the tallest cumulus with arrows indicating common features between both images.

and shadows projected by the central cumulus cloud are clearly observable in most filters. The F8 image shows much higher contrast associated to the high dense cirrus and the bright convective system, but most other bright clouds in the color image are almost invisible in the F8 image implying shallow cumulus over most of the image.

345 No shadows are observed in the image within the F8 filter. This implies that the massive large cloud system observed in the F8 image is at altitudes comparable to or above the convective bright cumulus. The low elevation of the Sun, combined with the homogeneous distribution of brightness in the F8 image, imply that water is concentrated in the lower part of the troposphere (an equivalent image of Jupiter's high clouds with tangential illumination using the JANUS F7 filter in a methane band would result in an image with a gradient in illumination from the vertically well-mixed atmospheric methane). When examining the
 350 full multi-filter sequence, the contrast of the shadow and crepuscular rays is maximum in blue and violet wavelengths (most likely because of the forward scattering effects of the crepuscular rays), and is much lower in the F7, F11 and F12 filters, which are centered at wavelengths of 889, 910 and 1015 nm respectively, which are wavelengths also sensitive to weak water absorption bands.

A quantitative interpretation of the altitudes associated to these cloud systems cannot be directly obtained from the multi-
 355 filter observations because water abundance probably varies over the scene and the observation does not provide access to



360 shadow d as:

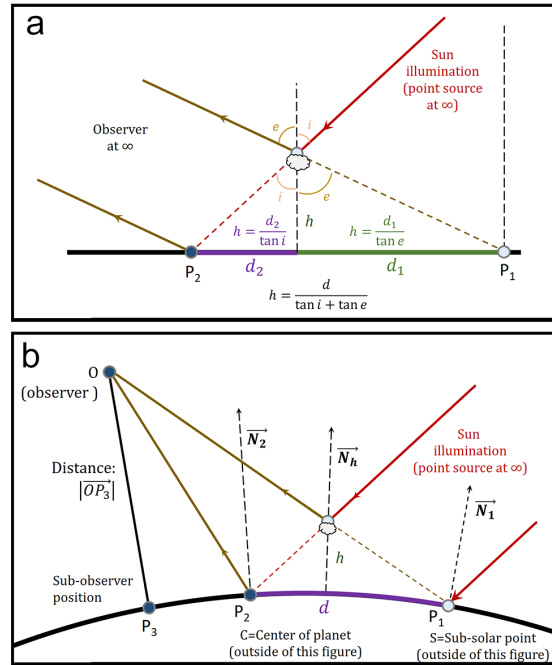


Figure 12. Geometry associated to shadow projections under extreme conditions of inclination i and e emission angles. (a) Simple geometry with no effects associated to parallax. (b) Geometry based on vector calculus. P_1 is the projected position of the bright cloud over the surface. P_2 is the position of the tail of the shadow observed over the planet's surface. The distance between P_1 and P_2 is the horizontal extent of the shadow. The figure has been greatly exaggerated, note that e is a small angle in the JANUS observations and that the distance $\overrightarrow{OP_3}$ is larger than the planetary radius and several orders of magnitude larger than the height h of the cloud sketched.

$$h = \frac{d}{\tan i + \tan e}, \quad (1)$$

where i and e are the incidence and emission angles respectively.

For a close observer (in the images shown in Fig. 11 the sub-spacecraft altitude was 9,060 km, the main incidence angle was 86.85° and the main emission angle was 3.56°), an evaluation of heights from shadows requires taking into account parallax and the ellipsoidal geometry of the surface. Figure 12b shows a sketch of the relevant geometry. The cloud altitude evaluation is solved by finding the intersection point between vectors $\overrightarrow{P_1O}$ and $\overrightarrow{P_2S}$. Here, points O and S are the positions of the observer

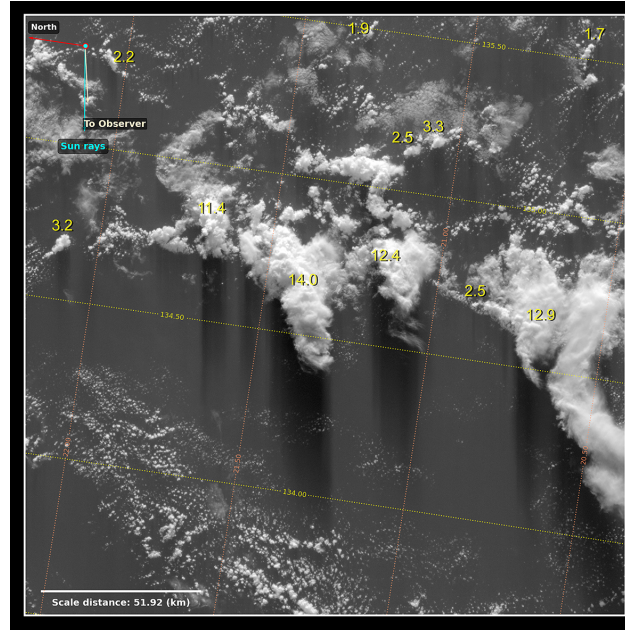


Figure 13. Deep convective cumulus from JANUS image 0777504999_0003_03. The observation has an incidence angle of 78° and an emission angle of 12° and was obtained from a distance of 8,700 km with a spatial resolution of 130 m. Numbers correspond to cloud top altitudes from shadow lengths and are centered just above the main cloud system measured in each case.

and the Sun respectively, and P_1 and P_2 are the position of the bright cloud and end of its tail respectively. Expressing vectors also with respect to the center of the planet, (i.e. transforming longitudes and latitudes of a point like P_1 into the vector $\overrightarrow{CP_1}$) then:

$$\begin{aligned} \overrightarrow{CO} &= \overrightarrow{CP_3} + \overrightarrow{P_3O} \\ \overrightarrow{P_1O} &= \overrightarrow{CO} - \overrightarrow{CP_1} \\ \overrightarrow{P_2S} &\approx \overrightarrow{CS} \end{aligned} \tag{2}$$

For an ellipsoidal planet like Jupiter the method works in the same way by taking the coordinates of points P_1 , P_2 and P_3 referred to the center of the planet and considering the local radius.

For the geometry of the observations shown in Figure 11, calculating cloud altitudes from shadows in this way results in an increase of altitudes of about 20% with respect to the use of eq. 1. Also to be noted that altitudes from shadows in this image are minimum estimates, since the end of the shadows over the ocean are difficult to define with the very tangent illumination. Several additional calculations of cloud altitudes from shadows are showed in the next section.

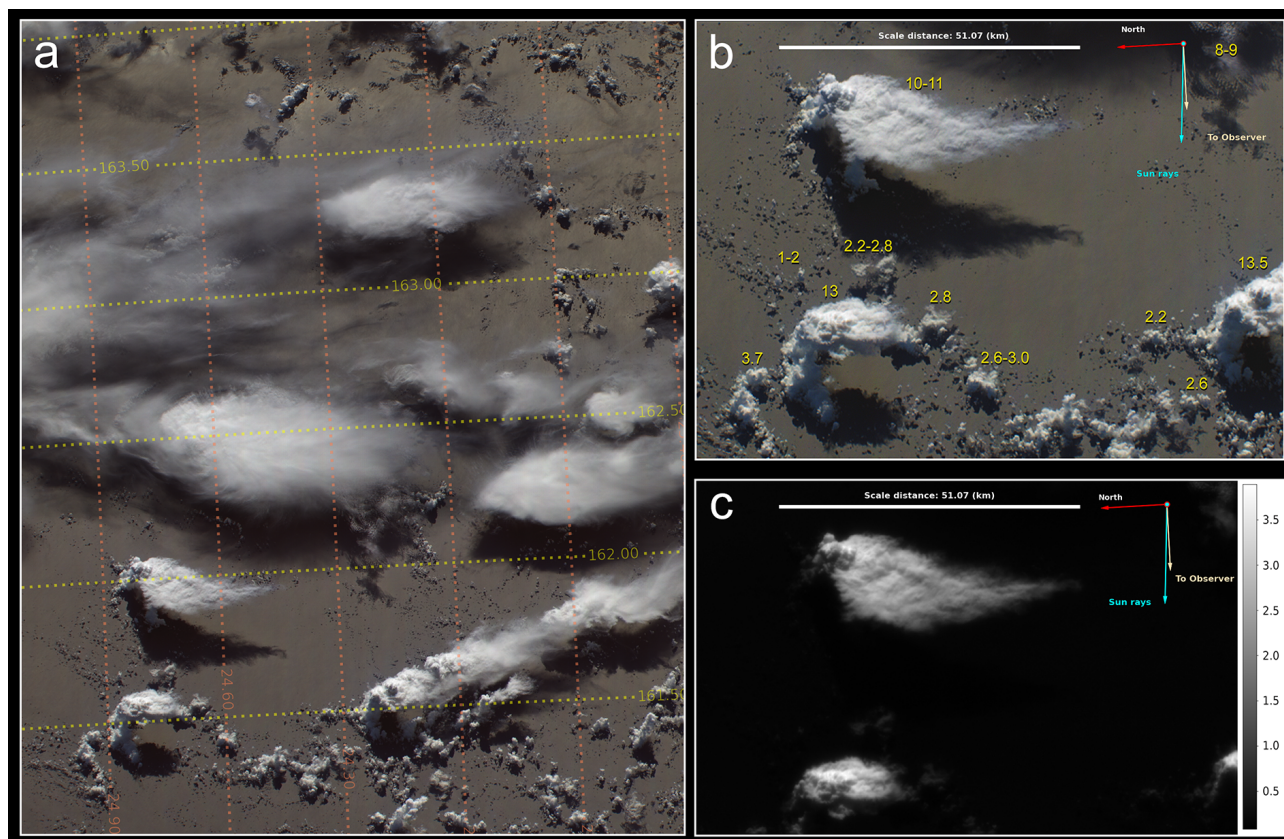


Figure 14. JANUS images of convective storms over the Pacific ocean. (a) Composite color image from images 077750499_0025_02 (blue), 077750499_0026_03 (green) to 077750499_0027_04 (red) co-registered over the green image after correcting spacecraft motion and showing longitudes and latitudes of the green image. (b) Zoom over the full color image showing altitudes of the clouds from shadows in yellow numbers. (c) F8 image of the area above from image 077750499_0031_08. Radiances are given in units of $\text{W m}^{-2} \text{sr}^{-1}$.

5.2 Deep convection

Figure 13 shows a high resolution image of active convection on cumulus clouds imaged with a spatial resolution of 130 m pix^{-1} and observed 1 hr after the local sunrise. The cumulus are projecting clouds to distances of up to 65 km, and the cloud tops reach heights above the ocean of up to 14 km. Only observations in a green filter covered this region. No anvil clouds were observed, which suggest, when combined with the early local hour, that convection had initiated near sunrise and had not reached a fully developed mature stage. Because of the illumination and viewing geometry, the cumulus appears tilted towards the bottom part of the image, and the cloud tops and east side of the clouds can be observed simultaneously nearly down to the base of the convective towers. Patchy cloud structures at 1-5 km scales indicate stratocumulus and active boundary layer convection after sunrise.

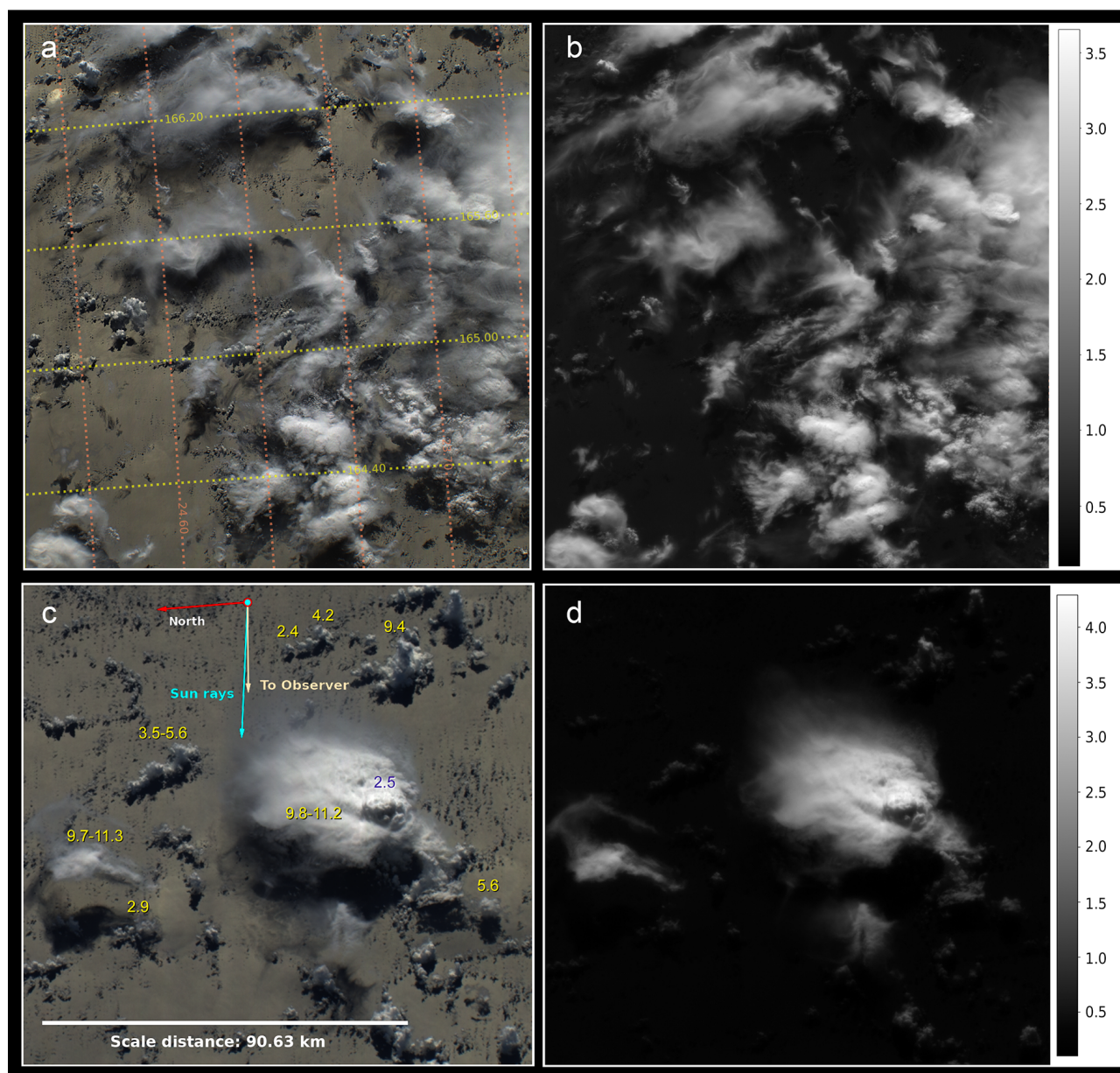


Figure 15. JANUS images of convective storms over the Pacific ocean. (a) Composite color image from images 077750499_0038_02 (blue), 077750499_0039_03 (green) to 077750499_0040_04 (red) co-registered over the green image after correcting spacecraft motion and showing longitudes and latitudes of the green image. (b) F8 image 077750499_0044_08 covering the same area as in panel (a). (c) Composite color image from images 077750499_0051_02 (blue), 077750499_0052_03 (green) and 077750499_0053_04 (red). (d) F8 image 077750499_0055_08 covering the same area as in panel (c). Radiances in panels (b) and (d) are given in units of $\text{W m}^{-2} \text{sr}^{-1}$.

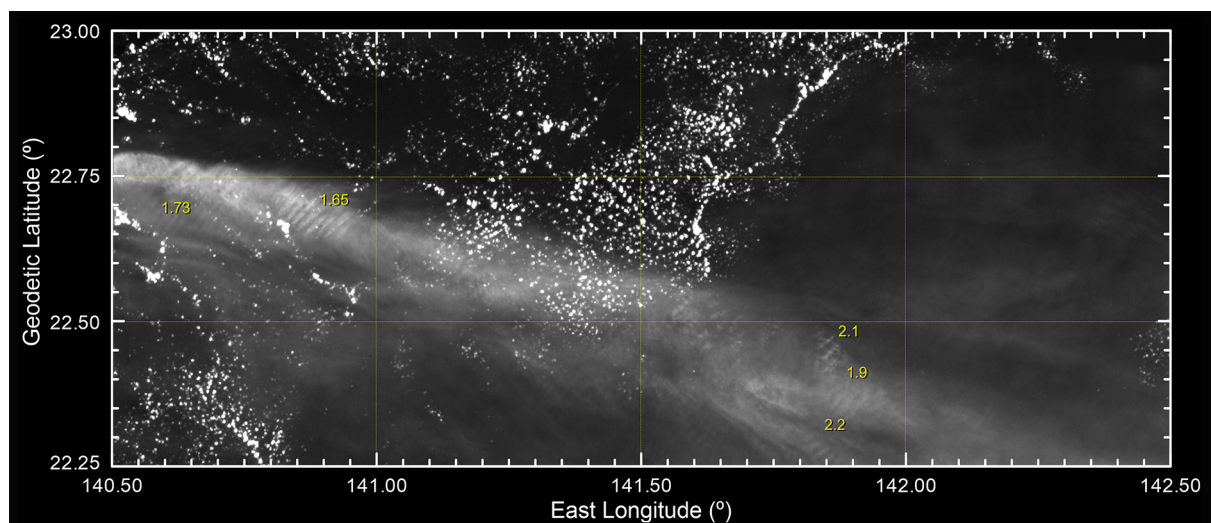


Figure 16. Longitude latitude map from JANUS image 0777504999_0008_03 showing atmospheric gravity waves on elevated cirrus. The map uses a resampled equal-distance projections for a 22.5° latitude. Yellow numbers indicate wavelengths of wave packets close to each number.

Figure 14 shows examples of mature cumulus developing active convection. The spatial resolution of these images is 126 m pix⁻¹, and the field of view covers a location 3 hr after the local sunrise. These storms are under a mature stage and show fully developed anvil clouds with longitudinal extensions of 20 to 85 km and cloud tops peaking at altitudes of 12-14 km. A multi-filter sequence of images of this area was obtained allowing to build color images. The apparent brown-red color of the ocean is due to Sun-glint conditions affecting these observations (i.e., near-specular reflection of sunlight; in these observations, the incidence angle of the central pixel was 51° and the emission angle was 40°, values close enough to induce glint effects).

In the image sequence that covered the area shown in Figure 14, two images separated by 34 seconds overlap over the three large convective cumulus cloud at the bottom of the image. Map projections of these images show strong apparent motions in the highest clouds, while features at the base near the ocean remain stationary. Those motions could be indicative of divergence and expanding clouds. With the spatial resolution of these images and the time difference between both image acquisitions, a 1-pixel motion implies velocities of 3.7 ms⁻¹. However, the strong parallax effects associated to the changing view point of the observations, and the combination of horizontal and vertical motion, do not allow to measure winds from cloud tracking, either manually or with image correlation software. The expansion of the anvil clouds appears very limited, and expansion rates larger than 30 ms⁻¹ can be ruled out.

The comparison of these color observations with images in the F8 filter in the water absorption band at 940 nm shows bright clouds at the convective cores and large anvil clouds, dark clouds for moderately elevated cumulus and a dark ocean.

Figure 15 shows a more complex scene contiguous with the one in the previous figure. Here elevated cirrus extending over a horizontal distance of 190 km appear as wispy cloud systems close to active cumulus towers. The bottom panels in this figure show a magnified view of an isolated active cumulus observed in a nearby location in the image sequence. This cloud system

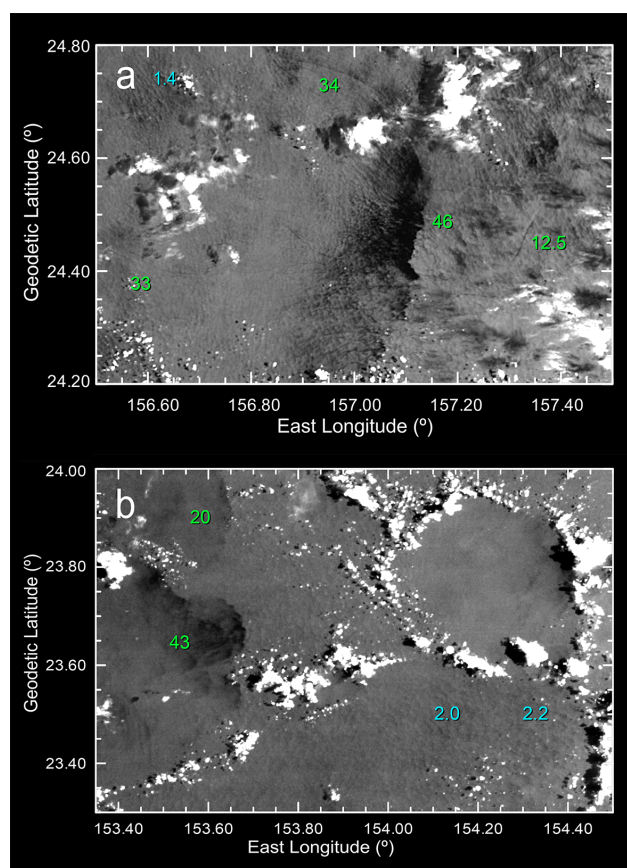


Figure 17. Longitude latitude maps from JANUS images using resampled equal-distance projections for a 24° latitude. (a) 0777504999_0020_03, and (b) 0777504999_0018_03. The images are shown with a contrast enhanced scale after some slight high pass processing to enhance the visibility of features in the ocean. Blue numbers indicate the wavelengths of regular features in the ocean. Green numbers indicate lengths in km of internal waves observed in the images. The original resolution of these images was 125-126 m. The nearly perfect ring of clouds in (b) has a diameter of 41 km and is likely a cold pool contributing to form new convective systems. Note the presence of further internal waves in the east side of the ring of clouds separated from cloud shadows.

405 corresponds to the brightest region in the F8 image, and the cloud morphology shows overshooting convection, with the F8 brightest part of the cloud ascending over the darker anvil cloud by about 2.0-2.5 km.

We were not able to identify changes in the brightness of the ocean in the F8 filter, which is strongly sensitive to water absorption. This suggests a very homogeneous distribution of water vapor over the tropics in the regions sampled by these images.

410 Large-scale storms powered by moist convection are a common feature in Jupiter's atmosphere (Vasavada and Showman, 2005) with a major role in the atmospheric dynamics (Ingersoll et al., 2000; Sánchez-Lavega et al., 2008; Siegelman et al.,



2022; Fletcher et al., 2020). JANUS will study the occurrence rate and dynamics of convective storms of multiple scales in Jupiter allowing studies of their onset, development and cycle of activity (Hueso et al., 2022; Brueshaber et al., 2025). The combination of dayside and nightside observations will allow to determine their electric activity (Gierasch et al., 2000).
 415 Observations with filters sensitive to different altitudes, combined with radiative transfer models (e.g. West et al., 1986 and Sánchez-Lavega et al., 2008) will allow us to determine their vertical structure. JANUS observations of Jupiter acquired at sufficient spatial resolution will enable to measure divergence rates and turbulent fluxes through the atmosphere (Salyk et al., 2006), including convective storms and eddies. Thus, JANUS will perform a full investigation of the role of convective storms in shaping the atmospheric dynamics of the Jovian atmosphere.

420 5.3 Atmospheric and Ocean Waves

Some of the JANUS images show gravity waves over elevated cirrus. Fig. 16 shows a long cirrus cloud system (> 160 km in length), where several gravity wave packets with wavelengths of 1.6 to 2.2 km are observable. The waves are aligned perpendicularly to the elongated cirrus suggesting a main direction for the winds flow and strong stratification. The cirrus is not dense enough to project shadows that could be used to determine its height, and this area was only observed on images
 425 using the F3 green filter. The low-level clouds present in the image are indicative of stratocumulus in the early morning, and the absence of larger vertically extended cumulus over the area also indicates local stability. The long cirrus band could be an anvil outflow from a mesoscale convective system developing in the early morning, as the convective towers shown in Fig. 13.

Figure 17 shows several dark features over the ocean with arc-shaped fronts, narrow elongated arcs and wavy dark and bright patterns. These type of features appear on multiple JANUS images of the ocean acquired with the F3 (green) filter (none of
 430 these areas was also covered by additional filters to characterize their color). The elongated arcs with scales of 30-80 km, and the regularly spaced bands of features, are consistent with internal waves in the ocean (Alford et al., 2016). Internal waves can form from interactions of sea currents along the thermocline, and by tidal interactions with the bathymetry. They can also be formed from variations in sea surface roughness created by wave currents moving with different phase speeds (Jackson, 2007). The Izu-Ogasawara Trench in the western North Pacific, which is considered to be one location driving intense internal
 435 waves generation, is located at around 1,000 km west of the location of the internal waves imaged by JANUS. In addition, the visibility of internal waves is also affected by sunglint effects and the location of these images also contains partial sunglint from differences between the incidence and emission angle of 20° .

We expect that JANUS will image several wave systems at Jupiter, characterizing their properties, physical origin, and influence on the atmosphere. Past observations show that gravity waves in the cloud fields of Jupiter can appear in the upper
 440 hazes of the planet in methane-band images (Reuter et al., 2007) and in the lower clouds in the ammonia cloud layer (Arregi et al., 2009; Simon et al., 2018). JANUS will be able to characterize their frequency, wavelength, and phase speeds allowing for several studies of atmospheric waves in Jupiter's atmosphere.

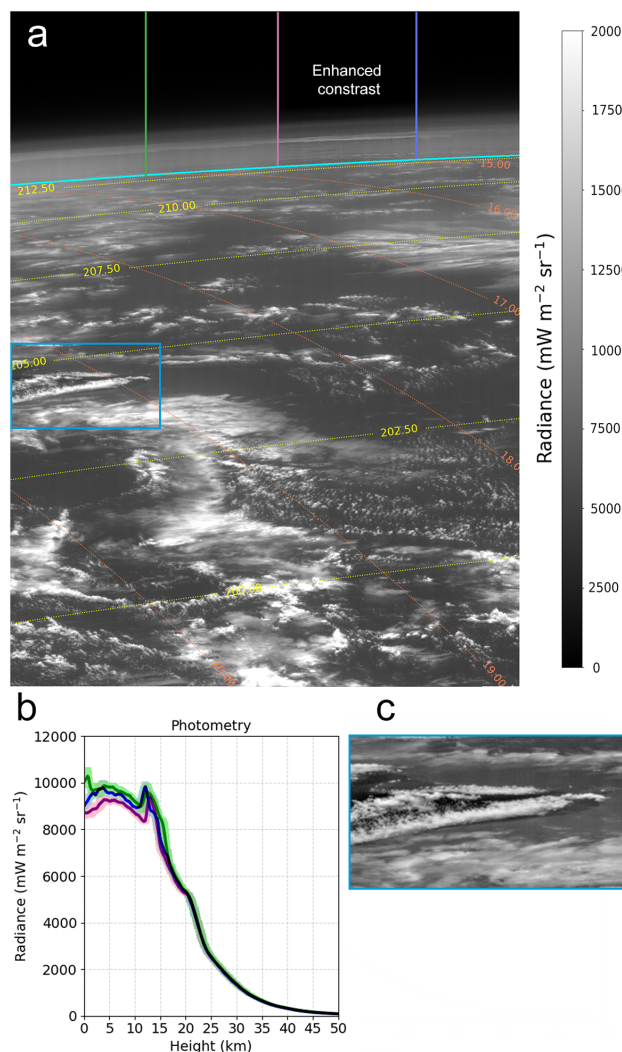


Figure 18. JANUS image 0777504999_0075_03 showing Earth's limb in the Western Pacific using a green filter. (a) JANUS image with longitudes and latitudes. A blue line shows the position of the horizon over the planet's surface. Three vertical lines show the position of three photometric cuts shown in panel b. The region between the pink and blue line shows the limb after contrast enhancement to highlight the underlying structure. A blue box highlights the position of the South coast of the Big island of Hawaii. (b) Photometric scans over the horizon obtained over vertical sections of the image at locations identified with color lines on panel (a). Error bars for each line correspond to the standard deviation over 100 nearby photometric scans. (c) Contrast-enhanced view of the South coast of Hawaii highlighted on (a).

5.4 Earth's limb during dayside

At the end of the observation sequence, JANUS imaged the limb of the Earth illuminated by a nearly zenithal sun. Figure 18
 445 shows a JANUS image of the dayside horizon with incidence angle varying from 12 to 2° over the full image. This geometry



shows extensive cloud systems over the North-Central Pacific, and scattered light over the horizon, where the vertical spatial resolution is 0.177 km. The image also shows the south coast of the Big Island of Hawaii covered by dense clouds and with a dark coast.

The structure of the atmospheric limb in this image is particularly interesting. At the spatial resolution of this image, the limb reveals the vertical structure of Earth's atmosphere. Discrete low clouds above Earth's spheroid are visible at altitudes of 1-5 km. Above these lower clouds, scattered light shows the presence of a detached double layer of aerosols at altitudes of 12-15 km near the tropopause. This overall structure is observed all over the limb. Scattered light at altitudes above the tropopause rapidly diminishes with increasing altitude. Diffuse light is observed to vary suddenly at altitudes of about 20 km, showing evidences of atmospheric structure even at that height. These results are similar to those obtained by instruments specifically designed to profile the limb and investigate the vertical structure of aerosols (Letros et al., 2025).

Dayside limb observations of the Earth are similar to Galileo observations of Jupiter's hazes under limb viewing geometries (Rages et al., 1999). Galileo showed that at high phase angles near 140-150°, the equatorial and polar hazes can exhibit their vertical structure when observed at sufficiently high spatial resolution (Galileo observed these effects with a spatial resolution of 15 km per pixel). JANUS will acquire a large number of similar observations of Jupiter's limbs in multiple filters at different latitudes and with different illumination conditions and with a sufficient spatial resolution to study the vertical distribution of aerosols. By combining these observations with radiative transfer models, we should obtain a very valuable dataset able to inform about the vertical distribution of clouds and aerosols and particle size at different heights through the planet. With a maximum spatial resolution of about 10 km in the closest perijoves, structures equivalent to one third of the vertical scale height H will be resolved. This will provide direct information on the extent and properties of the equatorial and polar hazes and above specific atmospheric systems covered by dense upper hazes like the Great Red Spot and other major ovals.

6 Spectral trends over the ocean: comparison with EnMAP and PRISMA

Multi-filter images acquired by JANUS can be used to obtain spectral trends at high spatial resolution. Three full multi-filter sequences of the Earth were acquired. The first sequence covered the region shown in Fig. 11. However, this region was very close to dawn and was illuminated tangentially making difficult to compare with spectra of the Earth acquired under similar illumination conditions. The other two sequences correspond to morning observations of a highly convective region over the Western Pacific as shown in Figs. 14 and 15. Except for the observations in the panchromatic filter that are saturated, none of the images acquired in other filters present saturated pixels. These two multifilter sequences were acquired at 21:44 UTC with all the images captured over a total time of 50 seconds with incidence and emission angles from 51-47° and 39-42° respectively under sun glint conditions increasing from west to east.

The area covered by these images was observed by two hyperspectral instruments aboard Earth-observing satellites operated by the German and Italian space agencies (DLR and ASI). These were the Environmental Mapping and Analysis Program (EnMAP) and the PRecursoRe IperSpettrale della Missione Applicativa (PRISMA) satellites carrying instruments with the same name. These instruments provide hyperspectral observations at high-spatial resolution in the visible to near infrared and

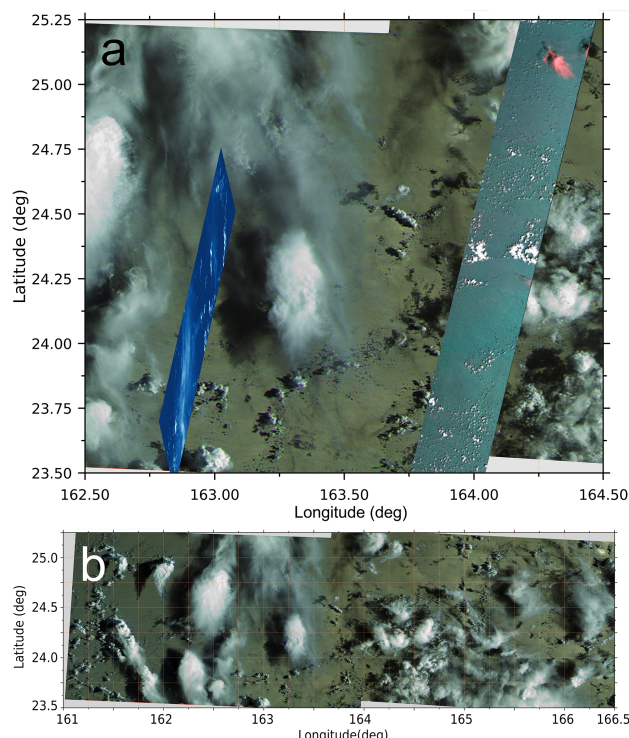


Figure 19. Map from two JANUS hyperspectral sequences superposing at around longitude 163.50° . Images were built from red, blue and green filters, but the color is altered by the sun glint conditions of the observations. (a) Central region with PRISMA and EnMAP data. PRISMA data is shown in blue. EnMAP data is shown in color with RGB channels coming from observations at 940, 890 and 540 nm respectively. Red features in this image correspond to high thin clouds. (b) Full map showing the sun glint effects associated to the variation of color of the ocean over the images.

short-wave infrared from 420 to 2350 nm and from 400 to 2500 nm respectively. Storch et al. (2023) describe the EnMAP mission and its instrument, and Cogliati et al. (2021) describe PRISMA. EnMAP obtained 15 observation tiles with data ID 888660 on 20 Aug. 2024 at 00:19:40 to 00:20:46 UTC. These images were acquired 21 hr before the JANUS data. PRISMA acquired similar data of a close area the same day but over 23:46:53 to 23:47:18 UTC. This is nearly two hours after the JANUS observations and almost one full day after EnMAP observations of the same region. Both EnMAP and PRISMA had incidence angles lower than 30° and emission angles near zero values. PRISMA data has also been compared with data obtained by the MAJIS instrument during the Earth flyby over different locations to those covered by JANUS (Oliva et al., 2025).

Figure 19 shows the collocation of these observations with JANUS data. The figure also shows the very different morphologies of the cloud systems present in the observations over the three different times covered. JANUS observed massive convective clouds in a mostly cloud covered area. EnMAP and PRISMA observed a calmer atmosphere with much lower cloud activity and no massive convection.

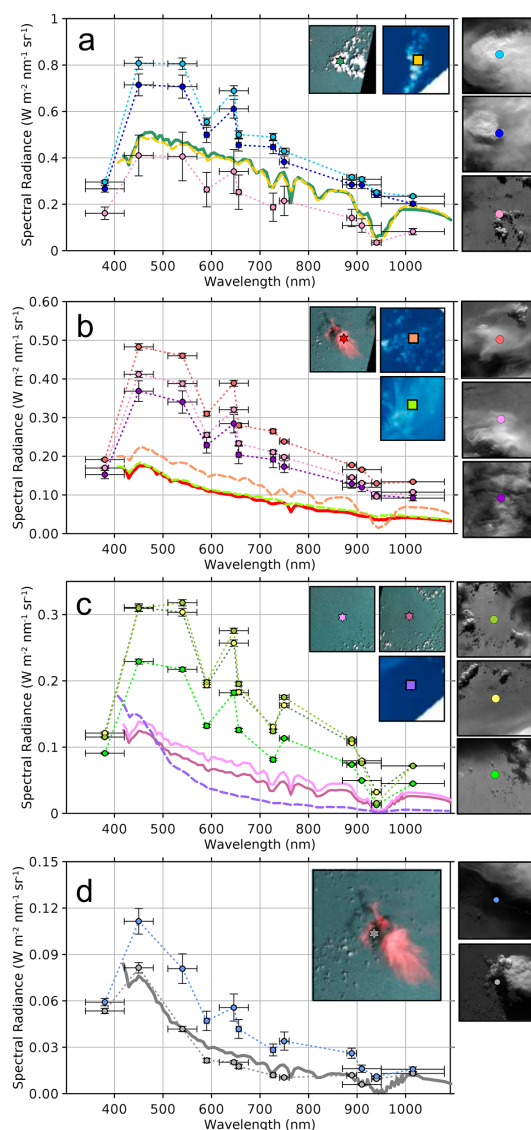


Figure 20. JANUS spectral trends and EnMAP and PRISMA spectra for different targets. (a) Bright clouds. (b) Elevated cirrus-like clouds. (c) Ocean. (d) Shadow regions. JANUS data are shown with data points and error bars. EnMAP spectra are shown with colored continuous lines. PRISMA spectra are shown with colored dashed lines. Insets show the regions where the spectra were obtained. Colored symbols highlight the locations from where the spectra were retrieved. EnMAP regions are shown in green. PRISMA regions are shown in blue. JANUS regions are shown in black and white. Error bars on JANUS spectral trends correspond to the filters effective width and the photometric variation in a circle of 8 pixels radius from where the spectra were extracted. Error bars on EnMAP and PRISMA data are comparable to the line width.

490 Figure 20 displays a comparison of spectra obtained from EnMAP and PRISMA with spectral trends from JANUS for a selection of targets. For JANUS, spectral radiances for each target are obtained from the photometric radiance in each image



divided by the effective filter width. EnMAP and PRISMA data are top of atmosphere radiances. All spectra have been corrected from geometric effects using a Lambert correction. Panels a and b show spectral trends over a variety of cloud systems. Panels c and d show spectra of the ocean under different illumination conditions.

495 Fig. 20a shows that JANUS spectral trends of high cumulus clouds are much brighter than clouds observed in the EnMAP and PRISMA field of views. Clouds present in EnMAP and PRISMA data are mostly low-level stratocumulus clouds or cirrus and have very similar spectra. An interesting characteristic of the JANUS spectra is the correlation between the depth of the water absorption band at 940 nm in the JANUS F8 filter with cloud altitude (no absorption for the high clouds and strong absorption for low-altitude clouds). This correlation also holds for EnMAP and PRISMA data when examining low-elevation
 500 clouds in panel a that show a prominent absorption band at 940 nm. We can see in Fig. 20b that non-convective but high-elevation clouds observed by EnMAP and PRISMA have different spectral characteristics that the evolved cumulus present in the JANUS sequence. The JANUS elevated clouds are much more reflective indicating higher opacity of the clouds and higher elevations from low water absorption at 940 nm.

Spectra of the surface of the ocean are shown in Fig. 20c. Here, the strong water absorptions from high water abundance
 505 near the surface is clearly observable in the F8 filter at 940 ± 20 nm. Water absorption is also evident in the weaker water absorption band at 727 nm sampled by the JANUS images in the F7 filter. It is also evident from this panel and the comparison with EnMAP and PRISMA data that the JANUS spectral trends of the surface of the ocean are strongly affected by sun glint effects at all wavelengths. The sunglint effects in JANUS increase from west to east as sun glint conditions increase (see Fig. 19). Observations of the surface of the ocean in regions under shadows casted by the upper clouds and observed in JANUS
 510 and EnMAP data (Fig. 20d) show a stronger similarity between both data sources and agree in radiance values and spectral behavior of the ocean. This is because there is no sun glint in the shadow areas and the ocean is in both cases illuminated by light scattered in the atmosphere without the direct solar illumination and reflections.

Finally, JANUS narrow filters F6 at 590 ± 10 nm (Na filter) and F13 at 656 ± 10 nm ($H\alpha$ filter) show abrupt changes in radiance compared with the nearby F3 filter at 540 ± 60 nm (green), F4 filter at 646 ± 60 nm (red), and F9 at 727 ± 10 nm
 515 (MT medium). These changes are present in all JANUS spectra and are not associated to the characteristics of the targets. EnMAP and PRISMA data do not show equivalent strong variations at these wavelengths suggesting minor corrections in the radiometric calibration of these filters. JANUS radiometric data at these filters, and the effective width of the filters used in the computation of the spectral radiance will be examined with other data sources to improve the current radiometric calibration (see Agostini et al. 2025).

520 7 Earth portrait

We selected Earth images obtained on 9 Sept. 2024 that had the maximum exposure time for each filter and did not saturate any single pixel. This was not possible for the panchromatic image, where most pixels over the Earth are saturated even at the smallest exposure time used of 0.222 ms. The images had a spatial resolution of 84.6 km pix^{-1} at the sub-spacecraft point, and the Earth has a diameter in the original images of 152 pix. The observations were acquired under a phase angle of 70.0° , and

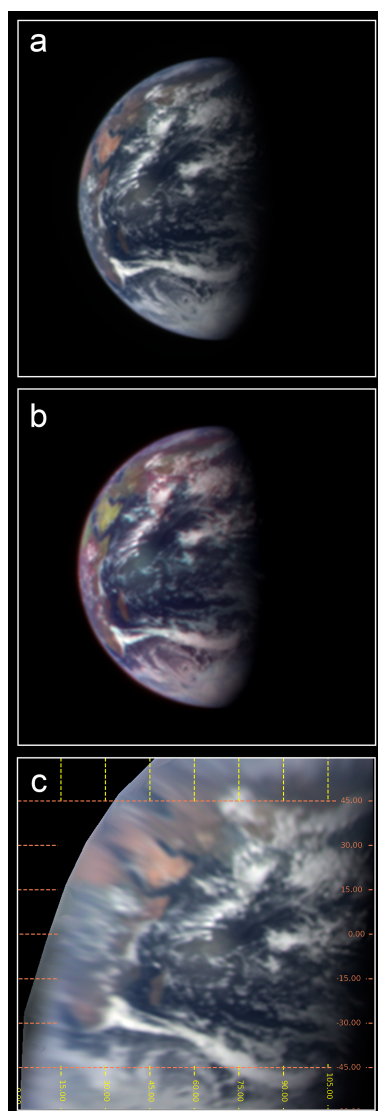


Figure 21. JANUS images of the Earth. (a) Near true-color composition from filters F5 (red), F4 (green) and F2 (blue). (b) False-color image from filters F11 (as red), F4 (green) and F2 (blue). (c) Cylindrical projection of the Earth based on panel (a). A luminance layer has been added to all images based on a high SNR image obtained from adding JANUS images in multiple filters. See text for further details about these color compositions.

the time between the first and the last image was 340 seconds in which the planet rotated $\sim 1.4^\circ$. This corresponds to a relative shift of about 2 pix at low latitudes for images acquired in different filters.

Two color compositions of the Earth are shown in Fig. 21. One of them is also mapped in cylindrical coordinates to facilitate the identification of geographical positions. The images were cubic interpolated to increase the size of the original images. The



Earth image on Panel (a) is built from images in filters F4 (red), F3 (green) and F2 (blue), and is close to a true color view of the Earth. The Earth image in panel (b) is built similarly, but using image in filter F11 as the red channel resulting in a false-color image that separates better blue hues. In order to increase the image quality, in both cases a high SNR image has been added as a luminosity channel to both color compositions. This luminosity channel was calculated from the first principal component of a principal component analysis of the 12 non-saturated images available in JANUS filters F2 to F13 (see below). The high SNR of the luminosity channel contributes to the quality of the final Earth image when compared with the coarse resolution of the original images. While we did not correct rotation effects when stacking these images, similar analyses on Jupiter's atmosphere will be run after fully correcting rotational effects.

The JANUS Earth portrait covers East Africa, the Arabic peninsula, India and South East Asia. The Bay of Bengal is covered by dense clouds from a deep atmospheric depression, and Thailand and Malaysia are difficult to see in the cloud covered region. The region of Antarctica appearing in these images is also completely covered by clouds. In the false color image shown in Fig. 21b, there is a subtle cyan color over Antarctica that could be caused by water ice, as described in the investigation of the Galileo spacecraft images of the Earth (Sagan et al., 1993). The Indian Ocean covers a large part of the image and shows a variety of clouds in terms of sizes and brightness, as well as the sun glint at 60°E, 5°S. The continents are less visible in blue wavelengths (F2 and F8) and most visible in red and near infrared wavelengths (F5, F7, F9, F11 and F12). However, narrow filters like the F6 Na and F13 H α filters did show the continents with lower contrasts. Sun glint was completely absent in the F8 filter due to the strong absorption by atmospheric water. The F12 filter showed a faint light scattering over the limb, slightly reducing the contrast in this image.

Figure 22 shows spectral trends obtained over the Earth portrait. All these spectra have been corrected using a Lambert correction. Panel a in this figure shows JANUS spectra over different cloud systems. The EnMAP spectra obtained for the Western Pacific is also shown showing very good agreement between both images. The water absorption feature at 940 nm is almost completely absent in these JANUS spectra of high clouds. Spectra of the ocean on regions without significant cloud coverage are shown in panel b. These JANUS spectra also agree with the EnMAP spectra of the ocean and show the strong water absorption at 940 nm. Spectra of different locations on the Earth from the very red Arabic Peninsula, to central Africa and Madagascar are also shown in panel c and show a larger variability than spectra of high clouds and the ocean. The three spectra over land locations show strong absorption at 940 nm, implying water absorption from the lower atmosphere in regions not covered by clouds.

The low spatial resolution, high cloud cover and relatively low presence of continents near the central meridian reduced the capability to investigate whether JANUS filters could form relevant indexes to demonstrate or display variations in vegetation. A synthetic image built from the (F4-F7)/(F4+F7) filter composition can resemble the classical NDVI (normalized difference vegetation index) filter (red-near IR)/(red+near IR) (Rouse et al., 1974). However, images obtained under this filter combination did not show relevant results in terms of detecting vegetation or display variability associated to vegetation. This was probably due to the small coverage of terrains with variable vegetation and low cloud content, since suitable areas for this experiment are only available near the limb of the Earth in this dataset.

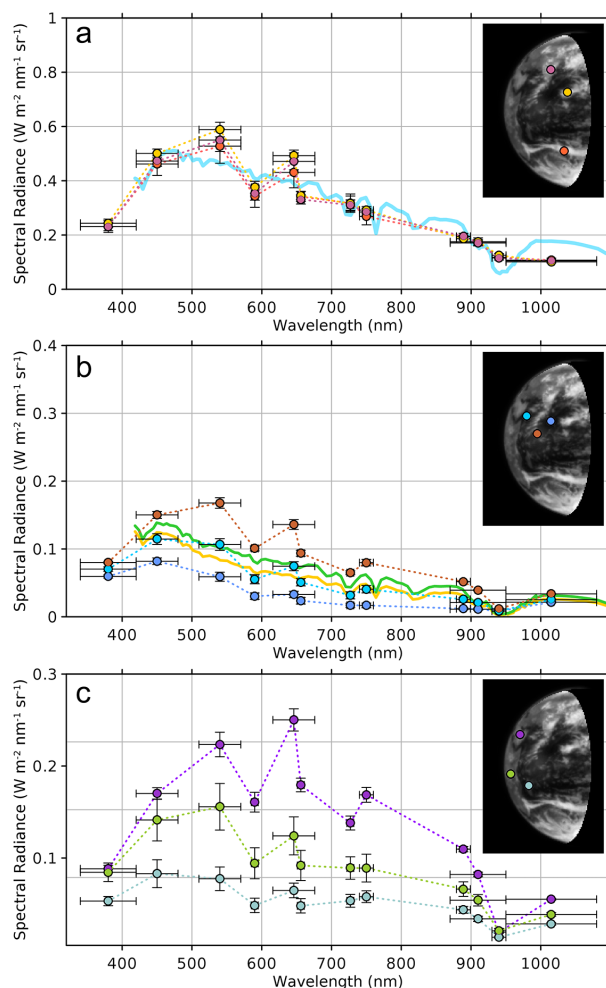


Figure 22. JANUS spectral trends of different locations on the Earth. (a) Bright cloud systems. (b) Ocean. (c) Spectra over the Arabic peninsula, central Africa and Madagascar. Colored lines in (a) and (b) are EnMAP spectra of clouds and ocean shown previously. Insets show images of the Earth and specific locations from where each spectrum was obtained using colored circles. Spectra and images in this figure have been corrected from basic geometric effects using a Lambert correction. JANUS spectra was obtained from selected regions using a radius of 2 pixel in the Lambert corrected images.

The images of the Earth in the 12 JANUS filters offer several additional image combination possibilities. A general technique that has been applied to multi-spectral data of the Earth and Jupiter is Principal Component Analysis (Singh and Harrison, 1985; Murtagh and Heck, 1987; Simon et al., 2015; Ordonez-Etxeberria et al., 2016; Biagiotti et al., 2025). This technique redistributes the information present in the images into a new base of images where each new image or component is as uncorrelated with other images as possible, forming a new set of images. The new principal components are ordered in a way in which the first principal component (PC1) contains most of the information of the original images in terms of image

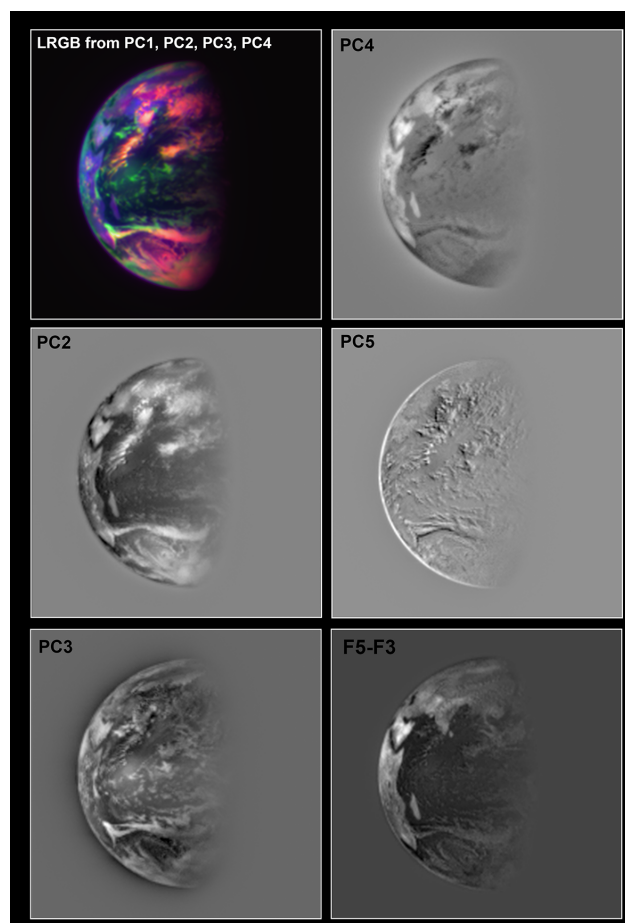


Figure 23. PCA of JANUS images using all filters from F2 to F13. The colour image shows a color composition of PC1 as luminance and PC2, PC3 and PC4 acting as red-green-blue channels. Different PCs are identified in the figure legend. The last panel illustrates a more conventional image comparison that in this case successfully removes most of the clouds present in the images.

variance. The other components are arranged in a way in which each new component contains less variance than all the previous components.

For the analysis of JANUS images we run a principal component (PC) analysis after normalizing all images to values from 0 to 1. Figure 23 shows the results of this analysis. Figure 24 shows the relative distribution of information in each component and the coefficients of the original images that are used to form the Principal Components down to PC5. Here PC1 contains 97.667% of the total information content of the 12 images, adding them with similar weights. This image provides a high SNR image that was used in figure 21 to improve the image quality. PC2 contains 0.979% of the information and separates blue wavelengths from other images with a strong participation of the F8 filter, sensitive to clouds. Clouds appear bright, continents appear grey and the ocean appears dark. PC3, PC4 and PC5 contain 0.618%, 0.459% and 0.138% of the total information

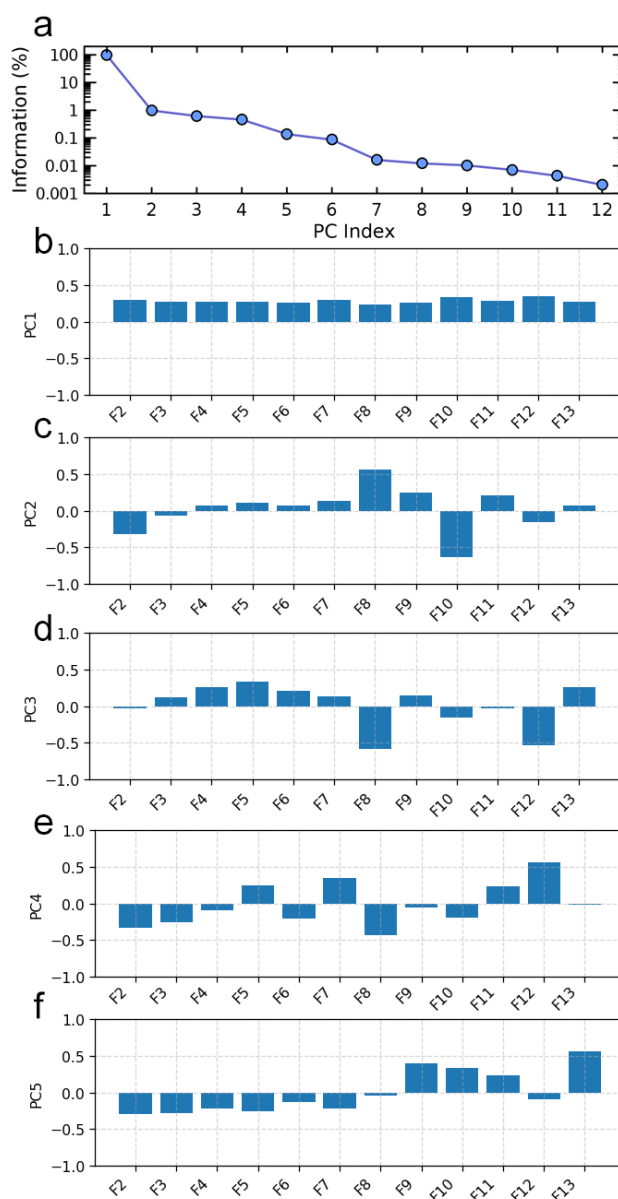


Figure 24. Relative distribution of information in the PCA of Earth images together with PCs coefficients for the first 5 PCs.

respectively, and components 6 to 12 contain together 0.5% of all the remaining information. When examining the images of these PCs in Figure 23, PC3 is an image composition where the effect of high clouds is reduced and that contains most of the sun glint. PC4 roughly separates the continents from oceans and PC5 starts to have strong effects from the rotation of the planet. PC6 and the remaining components are mostly noise.



A false color image was built from PC1, PC2, PC3 and PC4. An RGB image was built from PC2, PC3 and PC4 as channels red, green and blue and a luminosity channel was added from PC1. This false color image summarizes most of the information available in the images. The image displays terrains with no clouds in purple-blue, dense clouds appear in different shades white to red, and thinner or less dense clouds appear in green hues.

The statistical approach used by PCA generally misses meaningful image combinations. A simple combination of the F5 (near-IR with weak water absorption) and F3 (green) filter simply computing F5-F3 produces the best visualization of continents and land terrain including India, Indonesia and West Australia, even though most of India was covered by dense clouds. The image shows also clear views of large bodies of water like the Caspian sea, and the easternmost side of the Black sea. Three black spots in Africa correspond to lake Victoria, lake Tanganica and lake Malawi.

The sequence of observations of the Earth also contains the Moon, and the same techniques used here can be used to explore the overall spectral information of the Moon. However, the smaller number of pixels that cover the Moon does not result in compelling results.

The portrait of the Earth is analogous to images of the Earth obtained by the Galileo mission to Jupiter (Sagan et al., 1993; Geissler et al., 1995). Sagan et al. (1993) used the Galileo observations of the Earth to create a control experiment for the search for extraterrestrial life and understanding a complex object at a variety of spatial resolutions. JANUS images of the Earth show the capability to obtain relevant information of planetary targets even at small spatial resolution and demonstrate the feasibility of its filter set-up to provide spectroscopic data of interest even at modest spatial resolutions. Similar observations with Jupiter fitting inside one JANUS FOV will be accomplished in certain monitoring observations. Even though no specific flybys of Jupiter's moon Io will be run by JUICE, several opportunities to observe this volcanic moon at distances of around 500,000 km are possible throughout the mission.

8 Conclusions

The diversity of Earth phenomena captured by JANUS demonstrates the performance of the instrument and the range of scientific analyses that will be possible when JUICE arrives at Jupiter in 2031. Earth observations during LEGA were obtained with a spatial resolution that is roughly 80 times higher than the best spatial resolution expected for Jupiter images. Earth observations obtained during the farewell sequence are comparable to potential observations of Jupiter's inner moon Io and are much smaller than observations of Jupiter during monitoring observations on apojoves during the Jupiter tour in which Jupiter will be generally larger than the JANUS FOV.

Images of Earth's airglow are similar to expected observations of Jovian auroras in visible wavelengths (Ingersoll et al., 1998). At a large enough spatial resolution JANUS should contribute to understand the vertical structure of the auroras and their chemical impact in generating complex aerosols in the polar hazes (Hue et al., 2024). In addition, JANUS observations of Ganymede's nightside may also contribute to the characterization of Ganymede's aurora (de Kleer et al., 2023). Other potential weakly illuminated targets are Jupiter rings and Io's torus on the sodium filter (Bagenal and Dols, 2020).



Nightside images of the Earth illustrate the science goals associated to the investigations of lightning (Little et al., 1999), transient luminous events (Giles et al., 2020) and large meteors (Giles et al., 2021) on Jupiter's atmosphere. They also show the difficulties to identify physical sources associated to weak light sources. While lightning and meteors should be orders of magnitude brighter than the weak light candidates for lightning and meteor on Earth's observations, appropriate detection thresholds will need to be investigated once JANUS starts to acquire Jupiter observations.

High-resolution observations at dawn show spectacular illumination results that depend on the vertical structure of aerosols and the geometry of the observations. Similar images of Jupiter's atmosphere will be obtained over a variety of phase angles and spatial resolutions. Elongated shadows created by a low elevation sun illumination might be able to produce direct measurements of relative cloud altitudes. Limb observations at spatial resolutions of about 10 km per pixel will also contribute to a direct determination of the vertical structure of clouds and aerosols on the Jovian atmosphere. Those observations will be very helpful to constrain radiative transfer models that will determine the vertical cloud structure derived from JANUS observations under less extreme illumination conditions and using different filters including methane absorption bands.

JANUS will observe many convective and complex meteorological systems producing a rich dataset to study atmospheric dynamics, derive winds from repeated observations and investigate the overall workings of Jupiter's atmosphere.

The distant observations of the Earth show a single multi-filter portrait of the Earth. JANUS monitoring observations of Jupiter atmosphere during apojoves will reach spatial resolutions of around 50 km pix^{-1} , thus, showing a large portion of the Jupiter disk in a single JANUS frame and allowing global monitoring with relatively small resources (Fletcher et al., 2023).

Repetition of observations over the Jupiter orbiting time line or 3.5 years will be a key feature of the mission. That time line might be potentially longer if Jupiter can be observed during the last phases of the JUICE mission when the spacecraft will be orbiting Ganymede.

New Earth Gravity Assist maneuvers will be run on September 2026 and January 2029. Observations from 2024 will play a significant role in the planning of these observations and further testing the performance and instrumental limits of JUICE's payload. Such new opportunities to observe the Earth will allow to improve the planning of JANUS observations of Jupiter's nightside and to better define the best combination of multi-filter images to reach the science goals of the instrument on its Jupiter investigation (Fletcher et al., 2023; Palumbo et al., 2025).

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. The PRISMA hyperspectral data used in this study are publicly available from the Italian Space Agency (ASI) PRISMA mission data archive. EnMAP hyperspectral data are publicly available from the EnMAP data archive operated by the German Aerospace Center (DLR). Access to both datasets is subject to user registration and acceptance of the respective data use policies.



Author contributions. R. Hueso led the analysis and writing of the manuscript. A. Antuñano, L.M. Lara, K. Stephan, A. Zinzi, A. Coustenis, A. Simon, Y. Yair, M. Sato, J. Haruyama and Y. Takahashi contributed to different analyses parts of the analysis. K. Stephan and A. Zinzi also provided external data and specific analyses of EnMAP and PRISMA data respectively. Y. Yair, M. Sato and J. Haruyama examined external sources of lightning information. C. Tubiana led the science operations. L. Penasa and A. Luchetti worked on the science plan. L. Agostini led the data calibration process. M. Aye led the calculation of exposure times. R. Evill and I. Belgacem worked on science operations. A. Aboudan, E. Kersten, K.-D. Matz, F. Trauthan, and M. Patel worked on image acquisition, navigation and calibration. R. Politi participated in the data analysis pipeline and data archival. J.M. Castro-Marín, V. Della Corte, S. Hviid, T. Roatsch and N. Schmitz worked on additional aspects of the investigation. G. Portyankina played a key role in team coordination. P. Palumbo led the conceptualization of the investigation, data acquisition and team coordination. All authors critically reviewed and revised the manuscript and approved the final version for publication.

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Appendix A: Summary of JANUS images

The following tables provide a brief description of the data. The start column refers to the start of the exposure and is given with a resolution of seconds (the precision of this parameter is known for each image with a precision of ms). Longitude (Lon) and latitude (Lat) refer to the center of the image and are given in degrees, with latitudes in the table using geodetic latitude instead of geocentric latitude given in the labels of the images. Images on tables A1-A3 were all obtained on Aug. 20th, 2025. Images on Table A4 were acquired on Sept. 9th, 2025.



Table A1. Nighttime images

Image ID	Start (UTC)	Lon	Lat
0777503922_0000_01	21:19:03	45.59	-13.87
0777503922_0001_01	21:19:53	51.90	-11.39
0777503922_0005_01	21:23:13	78.95	0.45
0777503922_0006_01	21:24:03	82.96	2.43
0777503922_0014_01	21:28:32	101.24	10.67
0777503922_0015_01	21:29:12	103.65	11.66
0777503922_0016_01	21:29:52	106.10	12.63
0777503922_0017_01	21:30:32	108.57	13.62

Table A2. Dawn images

Image ID	Start (UTC)	Lon	Lat
0777503922_0020_01	21:32:32	115.69	16.27
0777503922_0021_01	21:33:12	118.10	17.04
0777503922_0022_01	21:33:52	120.56	17.83

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Table A3. Daytime images

Image ID	Start (UTC)	Lon	Lat
0777503922_0038_02	21:35:15	125.59	19.30
0777503922_0039_03	21:35:16	125.64	19.33
0777503922_0040_04	21:35:17	125.75	19.30
0777503922_0044_08	21:35:21	126.02	19.41
0777504999_0000_03	21:37:00	132.19	20.92
0777504999_0008_03	21:39:24	141.67	22.75
0777504999_0018_03	21:42:24	154.66	24.15
0777504999_0020_03	21:43:00	157.56	24.30
0777504999_0025_02	21:43:59	162.45	24.41
0777504999_0026_03	21:44:00	162.53	24.37
0777504999_0027_04	21:44:01	162.66	24.37
0777504999_0028_05	21:44:02	162.72	24.40
0777504999_0029_06	21:44:03	162.77	24.36
0777504999_0030_07	21:44:04	162.90	24.40
0777504999_0031_08	21:44:05	163.00	24.40
0777504999_0032_09	21:44:06	163.06	24.38
0777504999_0033_10	21:44:07	163.20	24.42
0777504999_0034_11	21:44:08	163.31	24.41
0777504999_0035_12	21:44:09	163.40	24.39
0777504999_0036_13	21:44:10	163.49	24.42
0777504999_0038_02	21:44:29	165.10	24.36
0777504999_0039_03	21:44:30	165.15	24.39
0777504999_0040_04	21:44:31	165.26	24.38
0777504999_0041_05	21:44:32	165.28	24.34
0777504999_0042_06	21:44:33	165.41	24.36
0777504999_0043_07	21:44:34	165.52	24.37
0777504999_0044_08	21:44:35	165.58	24.33
0777504999_0045_09	21:44:36	165.70	24.34
0777504999_0046_10	21:44:37	165.82	24.33
0777504999_0047_11	21:44:38	165.92	24.37
0777504999_0048_12	21:44:39	166.01	24.34
0777504999_0049_13	21:44:40	166.09	24.35
0777504999_0051_02	21:45:00	167.85	24.31
0777504999_0052_03	21:45:01	167.97	24.32
0777504999_0053_04	21:45:02	168.08	24.31
0777504999_0055_08	21:45:05	168.35	24.25
0777504999_0075_03	21:49:26	206.09	17.84



Table A4. Earth portrait

Image ID	Start (UTC)	Exposure (ms)
0779190669_0007_02	09:51:50	0.443
0779190669_0012_03	09:52:10	0.222
0779190669_0018_04	09:52:30	0.222
0779190669_0025_05	09:52:50	1.772
0779190669_0031_06	09:53:10	2.215
0779190669_0037_07	09:53:30	4.430
0779190909_0002_08	09:55:31	8.860
0779190909_0007_09	09:55:50	2.215
0779190909_0012_10	09:56:10	0.443
0779190909_0019_11	09:56:30	1.329
0779190909_0025_12	09:56:50	2.215
0779190909_0031_13	09:57:10	2.215