The JANUS camera onboard JUICE mission for Jupiter system optical imaging

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ABSTRACT

JANUS (Jovis, Amorum ac Natorum Undique Scrutator) is the visible camera selected for the ESA JUICE mission to the Jupiter system. Resources constraints, S/C characteristics, mission design, environment and the great variability of observing conditions for several targets put stringent constraints on instrument architecture. In addition to the usual requirements for a planetary mission, the problem of mass and power consumption is particularly stringent due to the long-lasting cruising and operations at large distance from the Sun.

JANUS design shall cope with a wide range of targets, from Jupiter atmosphere, to solid satellite surfaces, exosphere, rings, and lightning, all to be observed in several color and narrow-band filters. All targets shall be tracked during the mission and in some specific cases the DTM will be derived from stereo imaging. Mission design allows a quite long time range for observations in Jupiter system, with orbits around Jupiter and multiple fly-bys of satellites for 2.5 years, followed by about 6 months in orbit around Ganymede, at surface distances variable from 10^4 to few hundreds km.

Our concept was based on a single optical channel, which was fine-tuned to cover all scientific objectives based on low to high-resolution imaging. A catoptric telescope with excellent optical quality is coupled with a rectangular detector, avoiding any scanning mechanism.

In this paper the present JANUS design and its foreseen scientific capabilities are discussed.

Keywords: space instruments, visible camera, planetary imaging, Jupiter system.

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1. INTRODUCTION

JUICE (JUpiter ICy moons Explorer) is a mission chosen in the framework of the Cosmic Vision 2015-2025 program of the Science and Robotic Exploration (SRE) Directorate of the European Space Agency (ESA). The JUICE mission will survey the Jovian system with a special focus on the three Galilean Moons (i.e., Europa, Ganymede and Callisto) becoming the first SpaceCraft (S/C) to orbit around a Moon (Ganymede) of a giant planet [1]. The fundamental objective of the JUICE mission is to address two key questions of the ESA's Cosmic Vision program: 1) What are the conditions for planet formation and the emergence of life? and 2) How does the Solar System work?

Two major science themes for JUICE have been developed: the emergence of habitable worlds around gas giants, and the Jupiter system as an archetype for gas giants. The JUICE mission will provide a thorough investigation of the Jupiter system in all its complexity with emphasis on the three ocean-bearing Galilean satellites, and their potential habitability. JUICE has been tailored to observe all the main components of the Jupiter system and untangle their complex interactions [1].

The observational strategy to address these objectives has three main components: 1) conduct a comparative study of Ganymede, Callisto and Europa, with an emphasis on the characterization of Ganymede as a planetary object and possible habitat, 2) provide a complete spatial-temporal characterization of the giant, rotating magnetosphere, and of the meteorology, chemistry and structure of Jupiter's gaseous atmosphere, and 3) study coupling processes inside the Jupiter system, with an emphasis on the two key coupling processes within that system: the tidal effects that couple Jupiter with ist satellites, and the electrodynamic interactions that couple Jupiter and its satellites with their atmospheres, subsurface oceans, magnetospheres and magnetodisc [1]. JUICE will perform a multidisciplinary investigation of the Jupiter system as an archetype for gas giants including exoplanets. The circulation, meteorology, chemistry and structure of the Jovian atmosphere will be studied from the cloud tops to the thermosphere. The focus in Jupiter's magnetosphere will include an investigation of the three dimensional properties of the magnetodisc and in-depth study of the coupling processes within the magnetosphere, ionosphere and thermosphere. Aurora and radio emissions and their response to the solar wind will be elucidated. Within Jupiter's satellite system, JUICE will study the moons' interactions with the magnetosphere, gravitational coupling and long-term tidal evolution of the Galilean satellites [1].

Remote sensing instruments include besides the camera (JANUS), and spectrometers/spectro-imagers (MAJIS, UVS, SWI). The geophysical package consists of a laser altimeter (GALA), a radar sounder (RIME), a radio science experiment (3GM) and Very-Long Baseline Interferometry (PRIDE). The in situ sensors include particle detectors (PEP), a magnetometer (JMAG), and the radio and plasma wave instrument (RPWI).

The configuration of the JUICE spacecraft is driven by the long distance to Jupiter, the high Δv, the need to protect equipment from the intense radiation environment. The requirement of using solar electric power generation results in a large area of solar arrays. Furthermore, to optimise the data downlink rate, a large high gain antenna is included, and to satisfy the needs of its remote sensing and in situ instruments, the spacecraft will be three-axis stabilised.

Savings of the propellant mass are achieved during the interplanetary trajectory by gravity assists (Earth-Venus-Earth-Earth for both baseline and backup launches), and, following the Jupiter Orbit Insertion (JOI), by using the two outer Galilean moons, Callisto and Ganymede, for shaping the trajectory within the Jupiter system. After reduction of the spacecraft velocity with these gravity assists, Europa flybys would be conducted, followed by a phase where repetitive gravity assists would be performed with Callisto raising the inclination of the orbit around Jupiter more than 20°. This would allow for extended observations of Jupiter's high latitude regions and Jupiter's magnetosphere over a wide range of latitudes. Finally the spacecraft would be transferred into an elliptical orbit around Ganymede, which would be circularised and reduced in altitude down to 500 km.

Trade-off between different design solutions, performed by the JANUS team in order to satisfy all JUICE mission's scientific requirements, has led to the following architectural choices:

- a catoptric telescope with excellent optical quality is coupled with a framing detector, avoiding any scanning mechanism;
- no mechanisms are implemented for yaw steering compensation;
- a fine tuning of instrument parameters coupled with the mission design allows to have an instrument designed to be fully compliant with both the high- and low-resolution imaging requirements of the mission;

- instrument operations are flexible enough to optimize the acquisition parameters with respect to the many different observation requirements and conditions that JANUS will face. The instrument design will allow to adjust the resolution through binning, the field of view through windowing, the signal levels and SNR through integration time and the instrument calibration parameters through in-flight calibration and data pre-processing. All the capabilities listed above are guaranteed without imposing any requirement on the S/C and without the use of mechanisms.

2. INSTRUMENT DESIGN

JANUS is formed by 3 units, each with an independent mechanical I/F with the S/C (Figure 1):

1. The Optical Head Unit (OHU)
2. The Proximity Electronic Unit (PEU) to be integrated on S/C close to the OHU
3. The Main Electronic Unit (MEU) to be integrated on S/C in an environment shielded from external radiation

Each unit is formed by one or several modules with different functionalities.

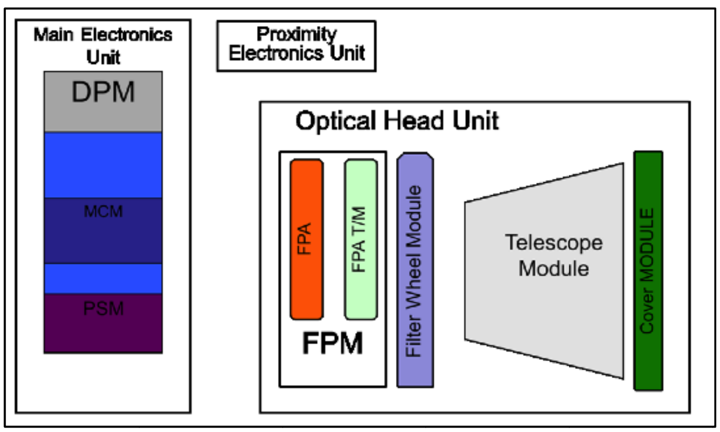


Figure 1: JANUS overall configuration.

2.1 Optical head

The OHU will be integrated on a stable platform common to star- tracker and other remote sensing instruments in order to allow co-alignment stability. It includes the optics, the external baffle, the mechanisms (filter wheel and Cover) and the thermo-mechanical module supporting and conditioning the Focal Plane Assembly (FPA). Iso-static mountings are foreseen to cope with S/C thermal and mechanical constraints (Figure 2).

The optical solution adopted as JANUS camera baseline is the Three Mirror Anastigmat (TMA). The camera is composed by three mirrors sharing the same optical axis. The first mirror is concave off-axis hyperboloid, the secondary mirror is convex with spherical shape while the tertiary mirror is a concave off-axis oblate ellipsoid ([6]) (Figure 3).

The optical system has on-centered unobstructed virtual entrance pupil and off-centered field of view, similarly to OSIRIS Narrow Angle Camera on Rosetta Space Mission ([7]).

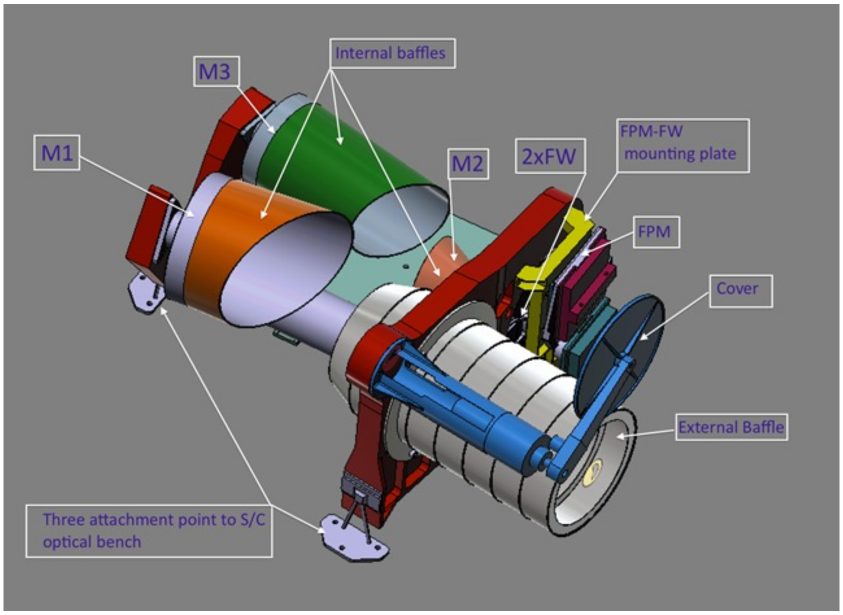
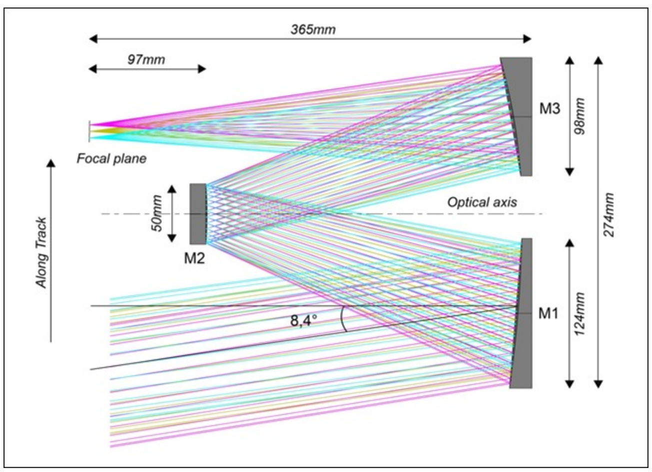


Figure 2: View of JANUS OHU with highlighted main optical and functional elements.



Specification	Value
Entrance pupil diameter	100 mm
Effective focal length	467 mm
F/#	4.67
Field of View	1.72 x 1.29 degree^2
Detector format	2000 x 1504
Pixel size	7 µm
Pixel scale	15 µrad/pixel
Spectral range	350 – 1050 nm

Figure 3: JANUS optical design layout (left) and its main parameters (right).

The focal plate module (FPM) consists of a FP baseplate which is carrying the detector PCB, the Cold-Finger (CF) I/F also acting as radiation shelter and a radiation cover for the detector The baseplate can be iso-statically mounted by using flexure-mounts in order to compensate mismatches between the mounting plate and the baseplate, but also to thermally decouple the baseplate as much as possible from the warmer environment required by the FW (Figure 4).

The baseline detector is the CIS115 [8] from e2V (Figure 5).

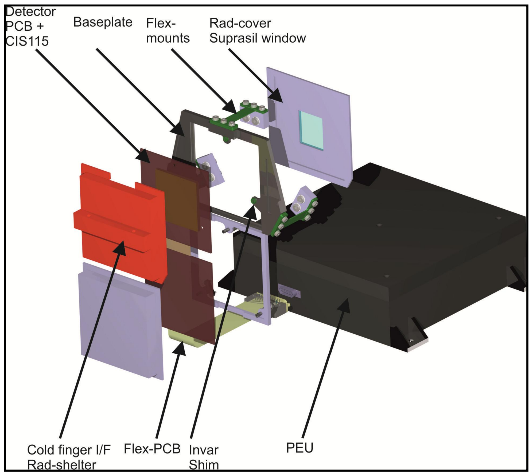
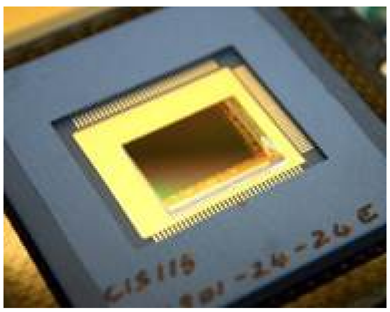


Figure 4: FPM preliminary design.



Parameter	Units	Value
Image Format	pixels	2000 (H) x 1504 (V)
Pixel Pitch	μm	7 x 7
Number of Outputs	-	4
Pixel Rate (per Output)	Mpixel/s	6-10
Operating Mode	-	Rolling Shutter
Read Noise	e^-	8
Full well	e^-	55000
Dark current @ 233K	e-/s/pixel	1
ADC bit	-	14

Figure 5: e2V CIS115 detector (front-illuminated version for testing) and its specifications.

2.2 Mechanisms

In the OHU are housed the Filter Wheel Module (FWM) and the Cover Module (COM) mechanisms. In the JANUS Camera it is foreseen a set of 13 optical filters with different bandwidth and central wavelength (

Table 1).

Table 1: Filters properties.

Filter # – Type	Central λ [nm]	Bandwidth [nm]	Min λ [nm]	Max λ [nm]
1 – Panchromatic	650	500	400	900
2 – Na D-lines	590	10	585	595
3 – Hα-line	656	10	651	661
4 – Medium Methane band	727	10	722	732
5 – Continuum for strong Methane band (geology)	750	20	740	760
6 – Strong Methane band	889	20	879	899
7 – Continuum for medium Methane band, Fe^{2+}	940	20	930	950
8 – UV slope	410	80	370	450
9 – Blue	450	80	410	490
10 – Green; also background for Na	530	80	490	570
11 – Red; also background for Hα	656	80	616	696
12 – Fe^{2+}; Io lava spots	910	80	870	950
13 – Fe^{2+}; Io lava spots	1000	150	925	1075

FWM positions the optical filters in front of the image detector with high accuracy. Its design is based on the FWM used in the OSIRIS ([9]) cameras on board the ROSETTA S/C but with better performances. The present design foresees a support structure, a common shaft with two parallel filter wheels, two stepper motors with gears and position encoders.

The present design of the mechanism provides the space for 14 filters allocated in two wheels each one containing 8 slots. Each individual filter wheel is turned by a stepper motor to position a filter in front of the detector in less than 1s (half wheel turn), that is, less than 2 s are needed to place the filters in front of the detector as due to power constraints both wheels cannot be turned simultaneously but alternatively.

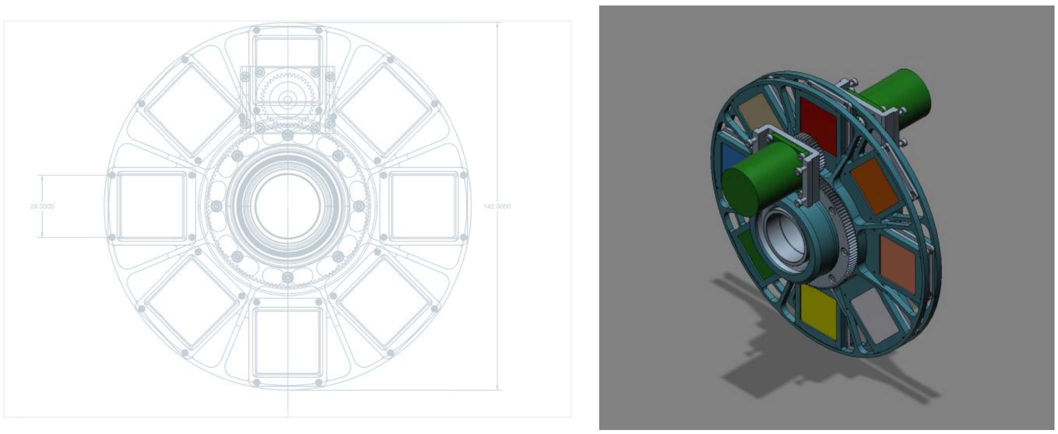


Figure 6: Filter wheel mechanism

COM was included in the design in order to mitigate the contamination risk for the optics during the non-operational phases of the mission. Possible contamination sources can be micro meteorites, dust, and volatile deposition. Moreover, the cover allows instrument protection from direct sunlight, provides a mean for calibration checking through an internal source and limits the heat dissipation during non-operative phases.

COM mechanism comprises the door, a sealing ring that attaches to the baffle to ensure proper sealing, an opening mechanism driven by a redundant stepper motor and a single-shot emergency (fail-safe) opening system.

2.3 Proximity electronics

JANUS PEU shall be integrated on the S/C close to the OHU and it is devoted to the analog signal conditioning, to the FPA driving, to the low level instrument control and data elaboration. The PEU provides all the clocks and biases required by the focal plane and digitizes (nominal 14 bits) the image sensor data. A preamplifier is located on the Focal Plane Module (FPM) to minimize the capacitive loading of the sensor's analog output(s) and drive the short length of cable between the FPM and PEU. The PEU shall have only a very limited number of active electronics in order to provide a high level of radiation tolerance. The key components are 14 bit ADCs and a radiation hard FPGA.

2.4 Main electronics

JANUS MEU design is based on the mixed heritage designs of ROLIS on ROSETTA [2], the Framing Camera Main Electronics on DAWN [3], the BELA Main Electronics on BepiColombo [4], the VEX VIRTIS Main Electronics [5]. MEU is designed fully cold-redundant and consists of a Data Processing Module (DPM) and a Power Supply Module (PSM).

DPM includes a processor that controls the complete instrument and manages the interface to the spacecraft: reception of TeleCommands (TCs), synchronization with the On Board Time (OBT), formatting and transmission of Telemetry (TM) packets (data and housekeeping). The DPM includes the interfaces to the PEU and a real-time, seamless lossless to lossy data compression of the acquired image data according to the CCSDS 122.0-B-1 standard. It is based on a three-level two-dimensional Discrete Wavelet Transform (DWT) that performs de-correlation, followed by a Bit Plane Encoder (BPE) that encodes the de-correlated data and provides simple and efficient data rate control.

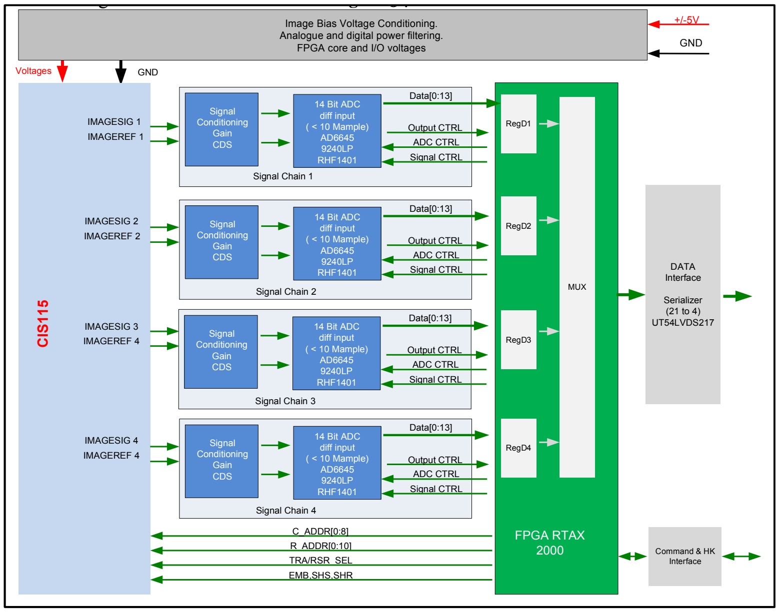


Figure 7: PEU electronic scheme.

The PSM is equipped with power line input filters and DC/DC converter(s) to provide the needed voltages. Filter Wheel and Door Controllers are integrated on the PSM PCB.

A block diagram of the MEU architecture and its external and internal signal interfaces is shown in Figure 8.

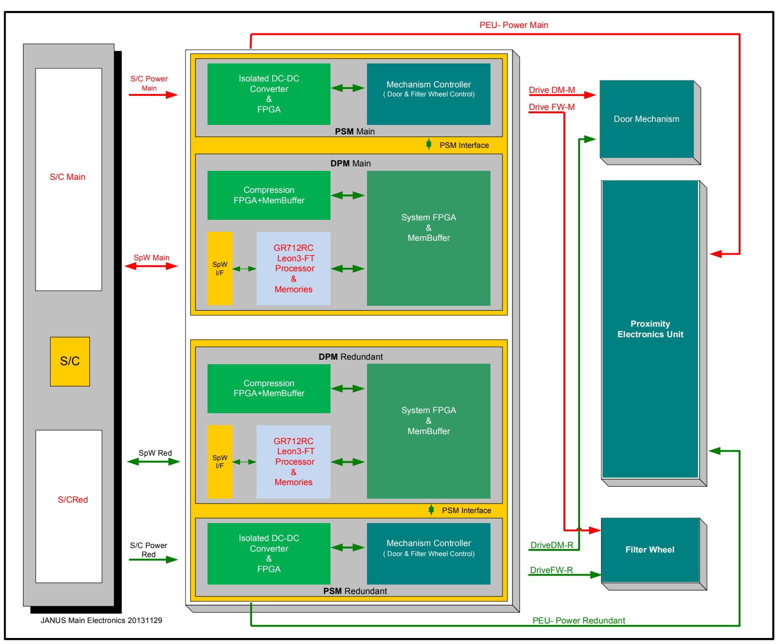


Figure 8 MEU block diagram.

3. INSTRUMENT PERFORMANCES

3.1 JANUS scientific objectives

JANUS will conduct an in-depth comparative study of Ganymede, Callisto and Europa, and explore most of the Jovian system and Jupiter itself.

In particular, the JANUS science objectives are:

- Characterize Ganymede, Callisto, and Europa as planetary bodies, including their potential habitability, with special focus on Ganymede
- Characterize and study the physical properties of other satellites of the Jupiter system, including Io, the irregular and the inner satellites
- Perform a physical characterization of the ring system
- Study the external layers (down to the troposphere) of Jupiter's atmosphere
- Study the magnetosphere in which Jupiter and its satellites are embedded, and the complex interactions taking place in the Jovian system

3.2 Science performance verification approach

JANUS capabilities to fulfill the above listed scientific objectives have been extensively evaluated by means of mathematical simulations of the JANUS images quality, in the different operation conditions to be faced during the Jovian tour, and JANUS coverage and resolution capabilities, within the JUICE nominal mission.

Proper mathematical models have been developed to simulate JANUS operations and derive expected JANUS performances in terms of SNR and coverage capabilities, taking into account both the JANUS instrument design (e.g., IFOV, optics transmission, detector quantum efficiency, noise sources, filters efficiencies) and the operative conditions in the nominal mission framework (observation geometry, constraints on operations, environmental conditions like planet and satellite albedo [10]). Like in a reverse-engineering approach, SNR estimations have been used to derive constraints for the instrument in order to guide the features selection for its design.

3.3 JANUS image quality

JANUS performances have been evaluated for all JUICE operative phases during the Jovian system tour.

Since JUICE mission foresees a complex and quite demanding observation plan during the Jovian system tour, here we only report the result obtained for the main phases around Ganymede.

Ganymede observation is dedicated to:

- accomplish a global medium-resolution color mapping to investigate the surface characteristics, and to search for past and present activity;
- understand geology, composition and evolution of selected targets on the surface with very high resolution.

The fulfillment of the above listed objective is guaranteed by exploiting the two orbital mission phases below.

GCO5000: High-latitude phase @ 5000 km:

The high-latitude phase will be devoted to multispectral (broadband) imaging for Ganymede global surface geology, for fresh ices and/or dark materials identification.

Plots in Figure 9 show the SNR achievable in the 3 filters during a fraction of orbit around Ganymede and with a pixel scale of 150 m/pixel.

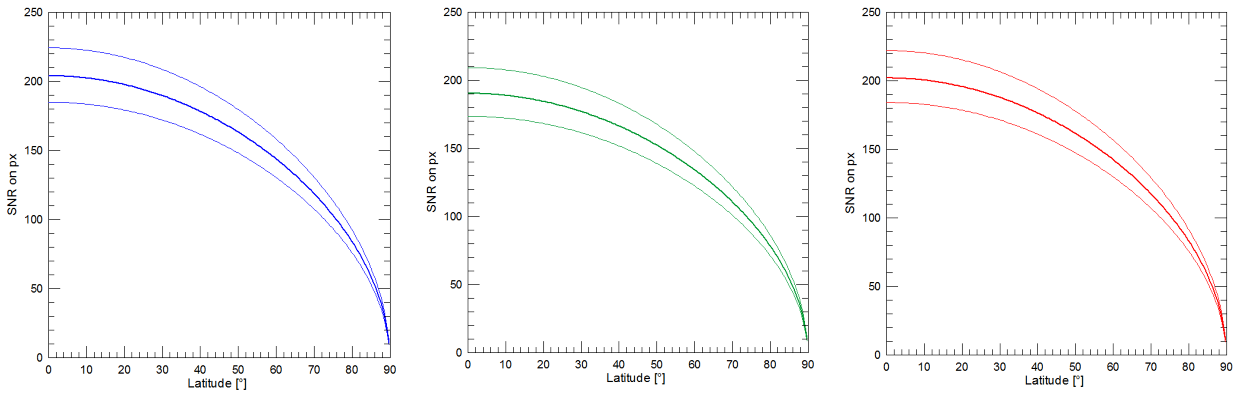


Figure 9: JANUS SNR for BLUE (left) GREEN (middle) and RED (right) filter. The exposure times are 15 ms, 9 ms and 9 ms respectively. The pixel scale is 150 m/pixel with 2x2 pixel binning. The bold line shows the JANUS SNR at phase-typical β orbital value (β = 43°). The two thin lines indicate the JANUS SNR ranges achievable during the phase (β orbital angle ranging from 28° to 52.5°).

GCO500: circular phase @ 500 km:

During the low-latitude circular orbits, JANUS will concentrate on panchromatic imaging at high spatial resolution of targeted areas.

The operative conditions during GCO500 are very demanding, due to the high S/C relative velocity and to the high β angle. Nevertheless, the JANUS performances are very good as showed in Figure 10.

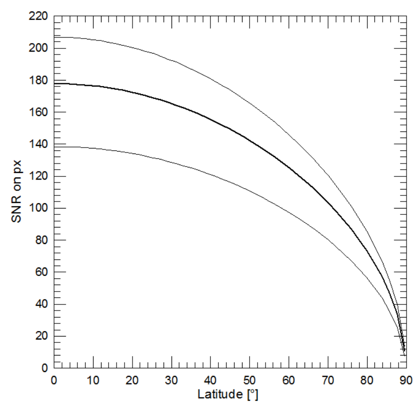


Figure 10: Expected JANUS SNR along an orbital arc during GCO500, obtained with the integration time t_{exp} = 2.5 ms and applying a 2 × 2 binning (pixel scale is 15 m/pixel). The thin lines represent the beginning and the end of the phase (β angle ranging from 62.5° to 78°), the bold line is the SNR for the phase-typical β angle (β = 70°).

3.4 JANUS spatial resolution and coverage capability

The ground sampling distance and resulting image swath capabilities of JANUS at different targets are reported in Figure 11, based on present mission design and instrument characteristics.

The available data downlink capacity of JUICE (i.e., 1.4 Gbit per day) represents a major constrain for JANUS in the fulfillment of its scientific objectives since it could limit its coverage and/or spatial resolution capabilities. For this reason, JANUS data rate / volume is defined by a multi-parameter matrix which not only depends on instrument-internal parameters like data compression (i.e., nominal compression ratio of 3.5:1) and resolution but also on mission-related parameters like distance-to-target, dwell time and illumination conditions. The most important measure to optimize data volume and coverage within the given constraints are data compression and spatial resolution tuning by pixel binning.

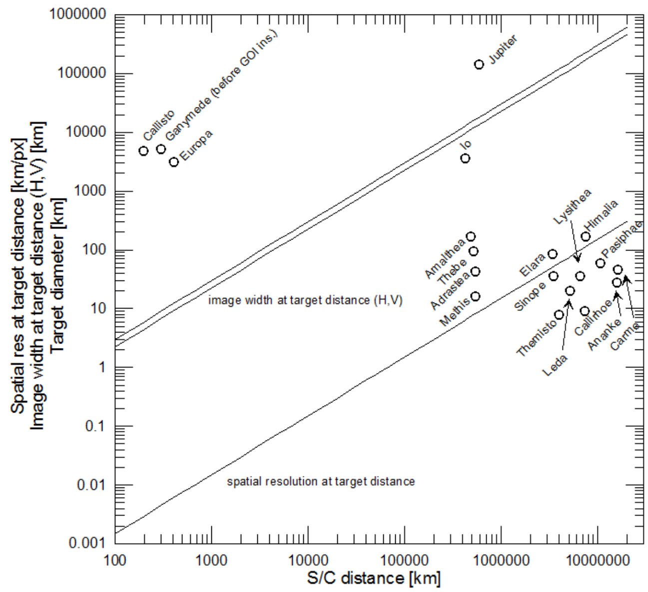


Figure 11: JANUS spatial resolution and image swaths as a function of distance from target. Circles mark the distances to the surface at closest approach (horizontal axis) and the object diameter (vertical axis) for Jupiter and several satellites based on the existing JUICE orbit predict.

Software tools have been customized on JUICE mission in order to analyze the JANUS coverage capability for all the Jovian system bodies. Inputs for the tools are the S/C and planetary SPICE kernels, JANUS instrument specifications (e.g. FOV) and observations constrains (e.g., pointing, illumination, overlap).

As outlined in previous section, JUICE has a very complex observation plan so here we report only the results for Ganymede coverage simulation.

Exploiting the JUICE orbital configuration during the operative phases around Ganymede, it is possible to evaluate the following observation results:

Global coverage at low-medium spatial resolution

During high-altitude quasi circular orbital phase (i.e., 5000 km orbit lasting for 90 days) it could be shown (Figure 12) that global coverage (> 98%) is possible neglecting any resource restrictions with respect to data volume as well as power. The coverage simulation considered only monochromatic coverage but the time from one image to the next of 180 sec leaves sufficient time to acquire the required 4-colour data. The number of images needed to cover the entire surface of Ganymede in one channel is 16,000 yielding a total of 64,000 images for all four colors. It has to be noted, however, that simple nadir pointing for the actual JUICE orbit predict was assumed in this simulation without any measures to optimize the coverage by, e.g. across-track pointing or adjustments of the orbit. The total number of 64,000 images (or 16,000 image sequences) required to fulfill the global coverage goal can, therefore, be considered as a worst-case scenario.

Taking into account the data volume downlink available for JUICE with 1.4 Gbit/day, it becomes evident that JANUS will not be able to achieve global coverage in GCO5000 alone but has to split this task over more mission phases. Pending the evolution of the JUICE mission design, we assumed a 45.7% of Ganymede surface could be imaged in GCO5000. The remaining 54.3% of the surface have to be observed during the flybys and the elliptic phases.

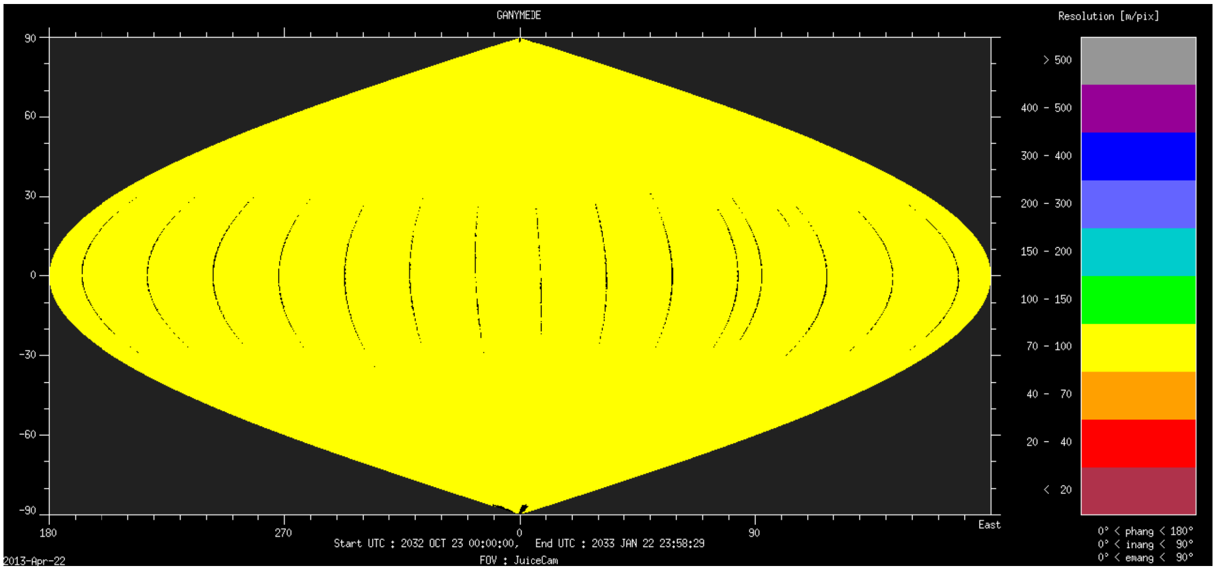


Figure 12: Ganymede surface coverage achievable during the GCO 5000 km orbit in 90 days at full spatial resolution of about 75 m/pixel. Assuming only nadir pointing and taking into account yaw steering effects by cos 45° yields a surface coverage of > 98%.

Surface coverage at high spatial resolution

During GCO-500 low-altitude circular orbits (i.e., 500 km orbit lasting for 150 days) JANUS will concentrate on panchromatic imaging at high spatial resolution of targeted areas with 7.5 m/pixel as spatial resolution. Nadir pointing is the nominal operative condition with exceptions for stereo imaging [11].

Comparison in coverage capability between JANUS and past Galileo mission is reported in Figure 13.

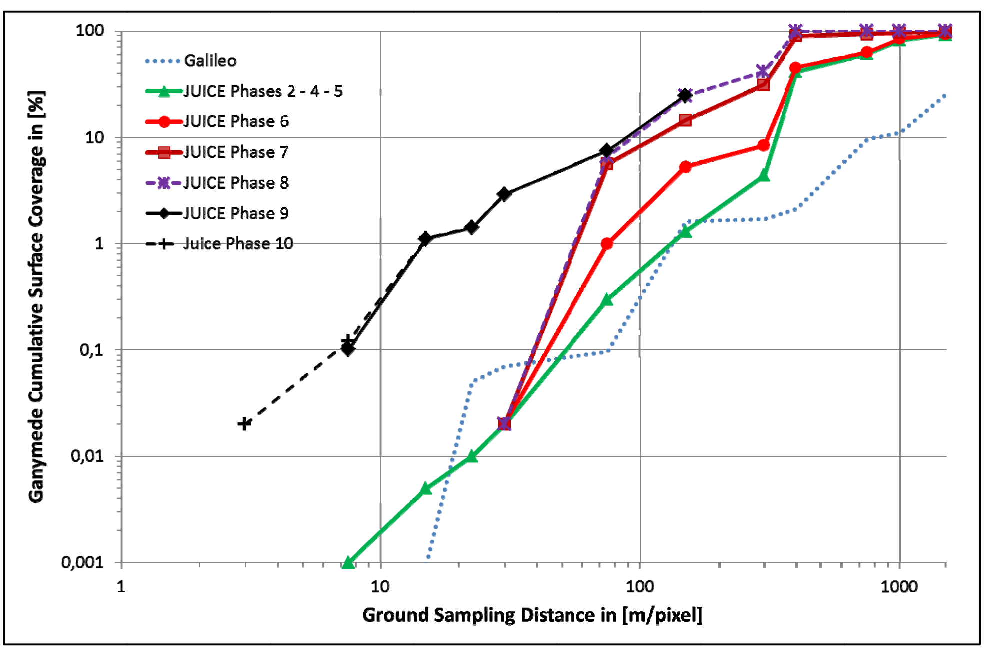


Figure 13: JANUS Ganymede cumulative surface coverage compared with Galileo mission imagery. Phase 10 (200 km elevation orbit from satellite's surface) is presently not considered in the baseline mission scenario.

4. CONCLUSIONS

JUICE is the ESA mission selected in the framework of the Cosmic Vision 2015-2025 program for the exploration of the Jovian system with a special focus on the three icy Galilean Moons, Europa, Ganymede and Callisto. Its overarching theme is to study the emergence of habitable worlds around gas giants and in particular around Jupiter.

JANUS is the imaging system aboard the JUICE mission with the aim of characterizing Ganymede, Callisto, and Europa as planetary bodies (including their potential habitability with special focus on Ganymede), studying the physical property of Io and the other small satellites and investigating Jupiter's atmosphere and its ring system.

JANUS instrument is based on an optimized telescope with excellent optical performances, coupled with a high-performance and radiation tolerant detector. The system is equipped with a Filter wheel (for color and narrow band imaging) and a Cover mechanism for contamination and safety control. Image acquisition, conversion, compression and packet-conversion are managed by Proximity and Main Electronics designs with good heritage.

Preliminary evaluation of JANUS imaging performances indicates that the present instrument design is capable to fulfill its scientific objectives with excellent quality (i.e., SNR) and completeness (i.e., coverage).

5. ACKNOWLEDGEMENT

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