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Optical design and stray light analysis for the JANUS camera of the JUICE space mission

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ABSTRACT

The JUICE (JUpiter ICy moons Explorer) satellite of the European Space Agency (ESA) is dedicated to the detailed study of Jupiter and its moons. Among the whole instrument suite, JANUS (Jovis, Amorum ac Natorum Undique Scrutator) is the camera system of JUICE designed for imaging at visible wavelengths. It will conduct an in-depth study of Ganymede, Callisto and Europa, and explore most of the Jovian system and Jupiter itself, performing, in the case of Ganymede, a global mapping of the satellite with a resolution of 400 m/px. The optical design chosen to meet the scientific goals of JANUS is a three mirror anastigmatic system in an off-axis configuration. To ensure that the achieved contrast is high enough to observe the features on the surface of the satellites, we also performed a preliminary stray light analysis of the telescope. We provide here a short description of the optical design and we present the procedure adopted to evaluate the stray-light expected during the mapping phase of the surface of Ganymede. We also use the results obtained from the first run of simulations to optimize the baffle design.

1. INTRODUCTION

Jovis Amorum ac Natorum Undique Scrutator (JANUS) is a high resolution camera designed to be part of the instruments suite of the ESA's space satellite JUICE (JUpiter ICy moons Explorer). JUICE is a large-class mission of ESA planned for launch in 2022 and arrival at Jupiter in 2030 [1]. During the mission, the satellite will perform several fly-bys and orbits around Jupiter's moons and will allow a detailed study of the Jovian system. The instrument set of JUICE is quite wide and includes 11 instruments ranging from spectrometers to laser altimeters, magnetometers and other instruments that will observe in a broad wavelength range from UV to radio. JANUS is an optical camera intended to provide excellent imaging capabilities in the visible - NIR band [2,3]. During the whole operational phase, JANUS will acquire panchromatic and narrow-band images of many targets within the Jovian system: the Galilean satellites surfaces and exospheres, Jupiter atmosphere, minor and irregular satellites and the ring system.

To meet the scientific requirements, JANUS will have a set of 13 filters, a 1.7x1.3 degree field of view, and a plate scale of 15 microrad/pixel. Another key requirement for JANUS is the need to prevent contamination by stray light in order to capture the faintest features possible of the satellites' surface. During observations, a source of stray light is represented by the satellite itself: when observing the surface of a satellite during an orbit, a non-negligible flux comes from both the in-field and the out-of-field portions of the surface and gets scattered by the optics and mechanical structure eventually reaching the detector.

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In order to estimate and minimize the stray light impact on the performance, we have undergone a series of preliminary computer simulations based on ray-tracing. The goals of the simulations were: (1) to determine the mean stray light irradiance on the detector expected during the mapping of satellites surface (2) To evaluate the contribution of different physical parameters (mirror micro-roughness, particulate contamination (PAC) and scattering from mechanical components) (3) To identify critical light paths and optimize the baffle design.

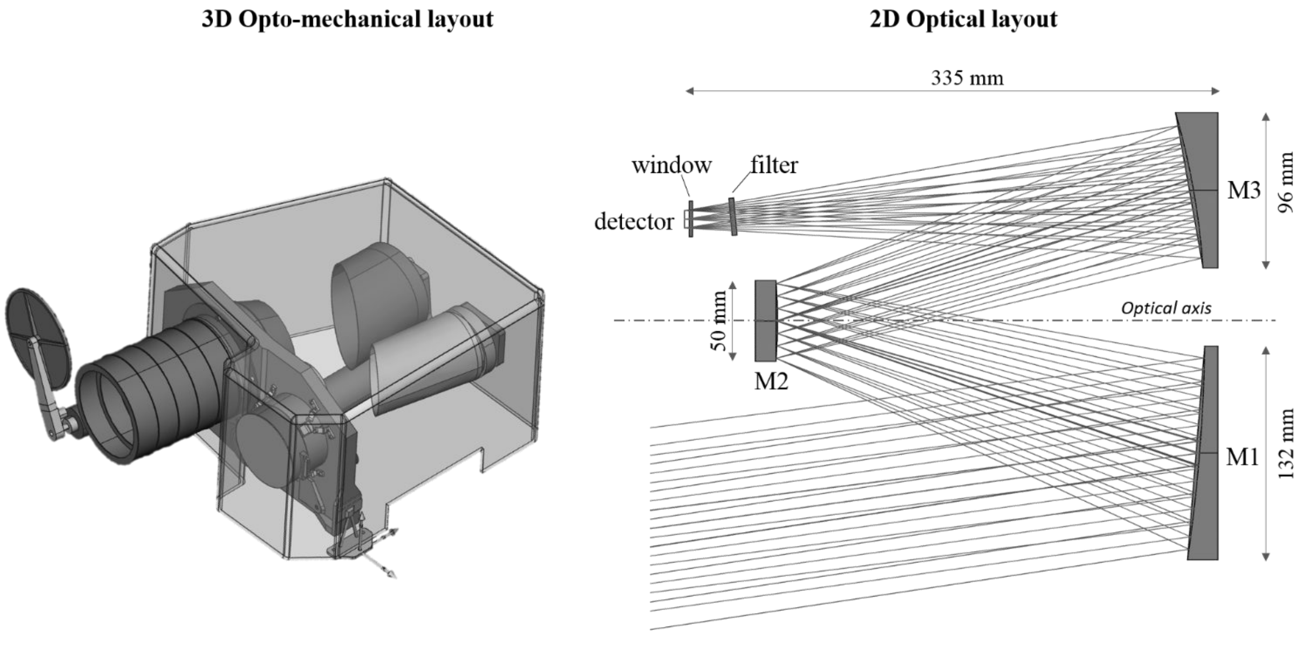
We begin by presenting a brief description of the optical design (a more detailed description can be found in [4]) and of the baffles configuration and next, we present the strategy adopted to calculate the stray light along with the results of the simulations. Finally, we use the results to optimize the design of the internal baffles and we give an estimate of the expected stray light flux.

2. INSTRUMENT DESIGN

2.1 Optical design

The optical unit of JANUS is a three mirror anastigmatic telescope. It has an entrance pupil diameter of 100 mm (corresponding to a total collecting area of 7854 mm^2) and an equivalent focal length of 467 mm, leading to an F/4.7 focal ratio. The telescope is coupled to a 2000x1502 E2V-CCD with 7µm pixel pitch [5] that covers a field of view of 1.7x1.3 deg. The quite broad spectral range (λ=350-1050 nm) led to the choice of an all-reflective design to limit chromatic aberration and the number of optical elements.

The optical configuration is similar to the one used in the Narrow Angle Camera (NAC) of the Rosetta spacecraft [6]: the system works with an off-axis field of view to avoid obscuration from the secondary mirror and an on-axis pupil placed on M2. The optical layout is shown in Figure 1: the primary and tertiary mirrors are off-axis portions of a hyperboloid and an ellipsoid respectively, while the secondary mirror is spherical. The axis of symmetry of all the three mirrors is coincident with the optical axis. The mirrors' diameters lie in the range 50-150 mm and the overall optical train occupy a very small and compact volume. Between the tertiary mirror and the detector are placed a filter wheel hosting 13 broadband and narrowband filters for waveband selection and a window to protect the detector from the strong radiation present in the surroundings of Jupiter.


3D Opto-mechanical layout

2D Optical layout

Figure 1. Left: JANUS 3D opto-mechanical layout. Right: 2D optical layout

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The all-reflective design and the use of three mirrors give enough degrees of freedom to obtain a diffraction limited optical quality over the whole spectral range and field of view (see the spot diagram in Figure 2 left). During the optimization of the optical system, the nominal performance has been estimated by mean of MTF at the Nyquist frequency for the given pixel size (71.4 cycles/mm). Figure 2 (right) shows that the polychromatic modulation transfer function is always above 63% over the whole field of view for frequencies smaller than 72 cycles/mm.

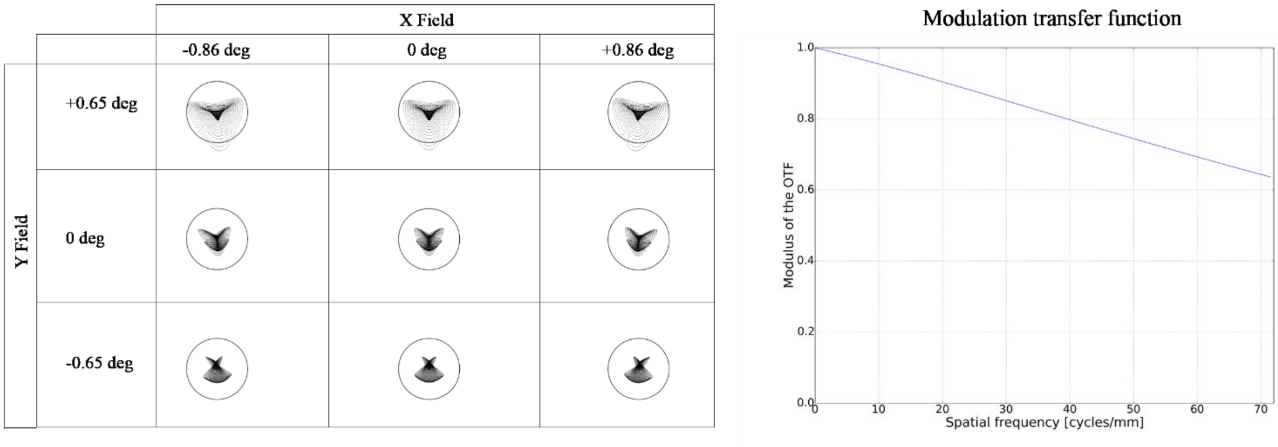

Figure 2. Left: spot diagram for 9 field positions. The circles represent the Airy disk at λ=0.7µm. Right: polychromatic modulation transfer function for a representative field position. The curves relative to other field positions (not represented in figure) are almost overlapping indicating a uniform optical quality across the field of view.

2.2 Baffles design

During the optimization process a trade-off between the camera dimensions, performances and capability to reject first-order stray light has been carried out. In particular, via internal baffling system, this optical configuration can be made robust for stray light rejection. The solid angle through which the external baffle will see M3 has been minimized and it is possible to completely shield the filters and the detector from light scattered by M1.

The baseline baffling configuration adopted for JANUS is visible in Figure 3: it is composed by an external cylindrical baffle with vanes and three internal baffles (one for each mirror) with conical shape. The baffles length and shape are such not to vignette the beam and the depth and position of the vanes in the external baffle have been optimized in order to block first order scattering from the baffle to the primary mirror. The detector is enclosed in a dedicated housing and the whole telescope is protected by an external cover.

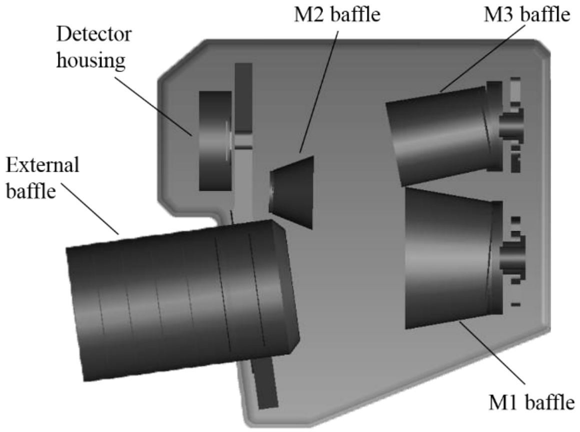

Figure 3. Scheme of the baffling system

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3. STRAY LIGHT ANALYSIS

3.1 Stray light simulations approach

Since the stray light signal depends obviously on the observing conditions (i.e. position and power of light sources), a commonly adopted method for the characterization of the stray light performance of an instrument is to calculate its Point Source Transmittance (PST). PST is defined as the amount of stray light incident on the focal plane divided by the amount of light incident on the entrance aperture of the system ([7]):

$$PST = \frac{E_{SL}}{E_{inc}} \tag{1}$$

where E_{SL} is the irradiance on the focal plane due to stray light, and E_{inc} is the irradiance from a point source at infinity incident on a plane normal to the incident beam and placed at the entrance aperture of the instrument. The PST can be used to calculate the irradiance on the focal plane due to any distribution of sources just by summing up the contribution of stray light of each point source or integrating the PST over the projected solid angle of any extended source. The method adopted in our simulations is to calculate the PST for a set of entrance angles via ray-tracing techniques and use this information to calculate - by numerical integration - the stray light irradiance on the detector expected when observing the surface of Ganymede from 500 km of altitude (at the moment supposed to be one of the most extreme observing environments).

3.2 Theoretical model and assumptions

To calculate the stray light irradiance generated by an extended source like the surface of Ganymede, it is necessary to multiply the PST by the irradiance at the entrance and integrate it over the solid angle $d\Omega$ subtended by the satellite:

$$E_{SL} = \int PST\,(\theta,\varphi)E_{Gan}(\theta,\varphi)\,d\Omega = \int_0^{2\pi}\int_0^{\vartheta_{lim}} PST\,(\theta,\varphi)E_{Gan}(\theta,\varphi)\,\sin\theta\,d\theta\,d\varphi \tag{2}$$

Where E_{Gan} is the irradiance of Ganymede and the integration is performed over the portion of surface visible by JANUS. We can parametrize the portion of visible surface via the use of two angular spherical coordinates, θ and φ: where θ is the angular distance between the direction correspondent to the center of the JANUS field of view and the line joining a point on the surface and the entrance of the system, while φ is the azimuthal angle. In general both E_{Gan} and PST will be dependent on φ and θ. We can suppose that the PST will be strongly dependent on θ end less on φ (in a rotationally symmetric optical system there would be no dependence on φ).

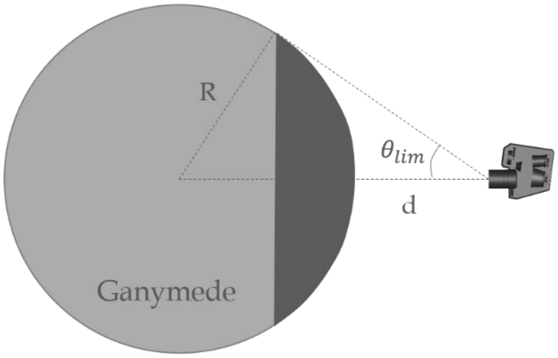

Figure 4. Scheme of the observing configuration between JANUS and Ganymede. R is the radius of the satellite, d is the distance between the telescope and the surface and θ_{lim} is the maximum angle from which light coming from Ganymede enters the telescope.

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Also E_{Gan} is variable across the surface of the satellite because it depends on the physical characteristics and features of the surface itself. There are different laws to model scattering from the surface of a planet (some examples are provided in [8]). For our simulations we assumed the satellite to emit like a lambertian sphere. With this assumption the incoming irradiance can be expressed as:

$$E_{Gan}(\theta,\varphi) = L \tag{3}$$

Where L is constant and represents the radiance of Ganymede on the aperture of JANUS. The relation between the radiance L and the total power emitted by Ganymede depends on the geometrical configuration of the system and is expressed by the configuration factor F between the source and the collecting surface [7]:

$$L = \frac{P_{Gan}}{\pi\, A_{Ent}} \cdot F \tag{4}$$

Where P_{Gan} is the total power emitted by Ganymede and A_{Ent} is the area of JANUS entrance aperture. In the case of a circular aperture placed at a distance d from a spherical source of radius R, the configuration factor is given by [9]:

$$F = \frac{A_{Ent}}{A_{Gan}}\left(\frac{R}{R+d}\right)^2 \tag{5}$$

Where A_{Gan} is the area of Ganymede's surface. The total stray light flux incident on the detector plane is then given by:

$$\Phi_{SL} = A_{det}E_{SL} = A_{det}\frac{1}{\pi}\frac{P_{Gan}}{A_{Gan}}\left(\frac{R}{R+d}\right)^2 \int_0^{2\pi}\int_0^{\vartheta_{lim}} PST\ (\theta,\varphi)\ \sin\theta\ d\theta\ d\varphi \tag{6}$$

This last equation shows that the stray light flux on the detector is given by the product between a constant (determined by the basic characteristics of JANUS, Ganymede and their mutual configuration) and the integral of the PST over the solid angle subtended by Ganymede as seen from JANUS. The equation is further simplified if we consider the ratio between the total stray light flux and the flux of the scientific image on the detector. The flux of the image depends on the field of view of the telescope and is given by:

$$\Phi_{Sci} = \frac{1}{\pi}\frac{P_{Gan}}{A_{Gan}}A_{Ent} \cdot FoV_x \cdot FoV_y \tag{7}$$

where FoV_x and FoV_y are the dimensions of the field of view (expressed in radians) respectively in the x and y directions. If we take the ratio between equations (6) and (7) and express the field of view as a function of the characteristics of the telescope we get the following, very simple relation:

$$\frac{\Phi_{SL}}{\Phi_{Sci}} = \frac{4}{\pi}\ F/\#^2\left(\frac{R}{R+d}\right)^2 \int_0^{2\pi}\int_0^{\vartheta_{lim}} PST\ (\theta,\varphi)\ \sin\theta\ d\theta\ d\varphi \tag{8}$$

The equation tells that, when observing a sphere (Ganymede) emitting like a lambertian surface, the ratio between the stray light flux and the image flux on the detector is given by the product between three factors:

1. the square of the telescope focal ratio
2. a geometrical factor determined by the radius of the sphere and the observing distance from the surface
3. the integral of the PST over the solid angle subtended by the sphere.

Moreover the ratio is independent from the total power emitted by the sphere. In the following sections we will explain the procedure used to calculate the PST and we will use equation (8) to calculate the expected stray light flux.

3.3 Point Source Transmittance calculation

To calculate the PST we used ray-tracing simulations performed with a non-sequential model. We set up a simplified model of the telescope including all the main opto-mechanical components. To simulate the scattering properties of each surface we considered three different phenomena of scattering:

1. scattering from micro-roughness of the optical surfaces (micro-roughness=2 nm rms for each surface)
2. scattering from PArticulate Contamination (PAC) of the optical surfaces (PAC =500ppm)
3. scattering from mechanical surfaces (we assumed them to be black-coated with Aeroglaze z306)

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The rays were generated with a collimated source of unit irradiance aiming at the entrance aperture of JANUS (as shown in Figure *5*) that simulates the light coming from a point source at infinity that enters the instrument and get scattered, eventually reaching the detector plane. Since the source has unit irradiance, the value of the PST (in the direction of the source) is simply given by the power recorded by the detector divided by the area of the detector itself.

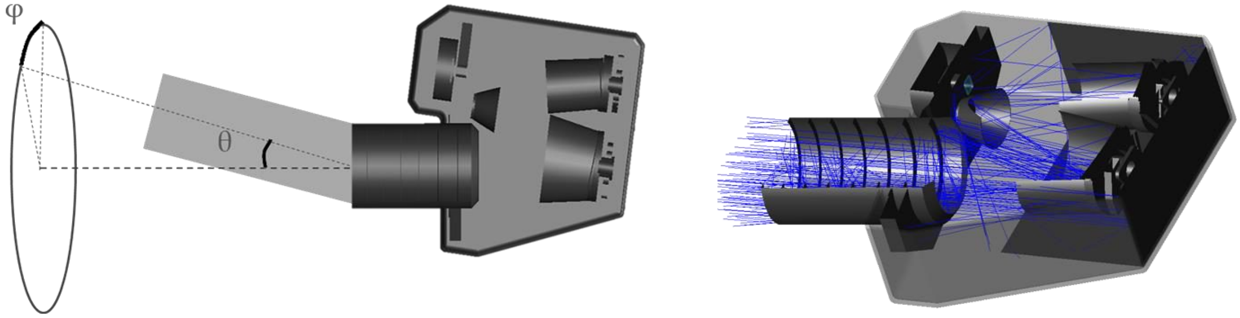

Figure 5. Left: collimated beam of light entering JANUS with the definition of the off-axis angle (θ) and the azimuth angle (φ). Right: Zemax model of the telescope with a few rays traced through the system.

The simulations are made with monochromatic light at the wavelength λ=400nm, corresponding to the bluest part of the observing wave-band of JANUS. Since the total scatter due to micro-roughness has, approximately, a λ^{-2} dependence from the wavelength [7], our simulation conditions correspond to a worst-case scenario for what concerns micro-roughness. Particulate contamination and scattering from mechanical surfaces are also wavelength dependent, but the variation is not as strong as in the case of micro-roughness.

The PST is calculated by running several simulations with different entrance angles θ and φ (see Figure *5*) for the source. In this way, we sample the PST at different entrance angles and we estimate the real PST interpolating between the data-points. To sample the (θ, φ) parameters space we chose a uniform spacing in φ (with a $\Delta\varphi$=30 deg) and a non-uniform spacing in θ with a more dense sampling inside or near the field of view. The total number of directions for which we calculated the PST is 195.

3.4 Preliminary results and design optimization

The results of the PST calculation are summarized in Figure *6*. They take into account only scattering due to micro-roughness and mechanical surfaces, while particulate contamination is considered in another set of simulations for which we only give the results. On the left is represented the PST as a function of the entrance angle θ (note that the scale on the x-axis is logarithmic). The different colors represent the PST at different azimuth angles between 0 and 360 deg. Inside the field of view ($\theta < 0.85$ deg) the PST value is larger, and drops rapidly outside the field of view suggesting that most of the stray light will be generated within the field. Anyway, since the solid angle inside the field of view is much smaller than the total solid angle subtended by Ganymede, also the light coming from outside the field of view can contribute significantly to the total stray light budget. To see the effective contribution as a function of the entrance angle it is necessary to calculate the integral of equation (8). Figure *6* (right) shows the cumulative integral of the PST assuming it to be constant at different azimuth angles. In practice, we are just integrating along θ, while the integration along φ yields a factor 2π. Again, the colors refer to the PST profile of different azimuth angles. The major contribution to stray light comes from angles between 0.5 and 10 deg. Indeed, for $\theta < 10$ deg the primary mirror is still directly illuminated from outside and reflects/scatters light inside the telescope dominating the contribution to the stray light flux on the detector. From the right panel of Figure *6* is also clear that the integral of the PST changes up to a factor of 2-3 among the different

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azimuthal angles. Of course, it is possible to take into account this variation just by calculating the integral in the 2-D parameter space, but we asked ourselves if it is possible to optimize the baffling design and obtain a more uniform behavior of the system with respect to stray light.

A more detailed analysis showed that most of the difference were arising from rays striking the cover from inside and reaching the detector directly or via multiple scattering events. A possible way to partially block these rays is to split the box in two parts: one containing the detector and the tertiary mirror, and another one containing the primary mirror and the external baffle so that rays scattered by the cover cannot reach the detector by first order scattering. A possible implementation of this solution is shown in Figure *7* where the internal baffles are replaced by a curtain (red in figure) with a central hole to let the in-field light pass through without vignetting. We computed the cumulative integral of the PST also for this configuration (Figure *7* – right) and, as expected, the dependence on the azimuth angle is greatly reduced.

We now use this last configuration to calculate the ratio between stray light flux and scientific flux on the detector expected when observing Ganymede at a distance of 500 km from its surface. According to equation (8) we simply need to multiply the PST integral by a constant factor:

$$\frac{\Phi_{SL}}{\Phi_{Sci}} = 19.87 \int_0^{2\pi} \int_0^{\vartheta_{lim}} PST\ (\theta, \varphi)\ \sin\theta\ d\theta\ d\varphi \tag{9}$$

Using the highest value of Figure *7* for the PST integral (2.29 10^{-4}) we obtain a ratio equal to 0.5%. This value takes into account only the scattering from mechanics and micro-roughness. For the scattering from particulate contamination, the simulations indicate that the amount of stray light is almost the same, so we expect the total ratio between stray light flux and scientific flux to be of the order of ≈ 1%.

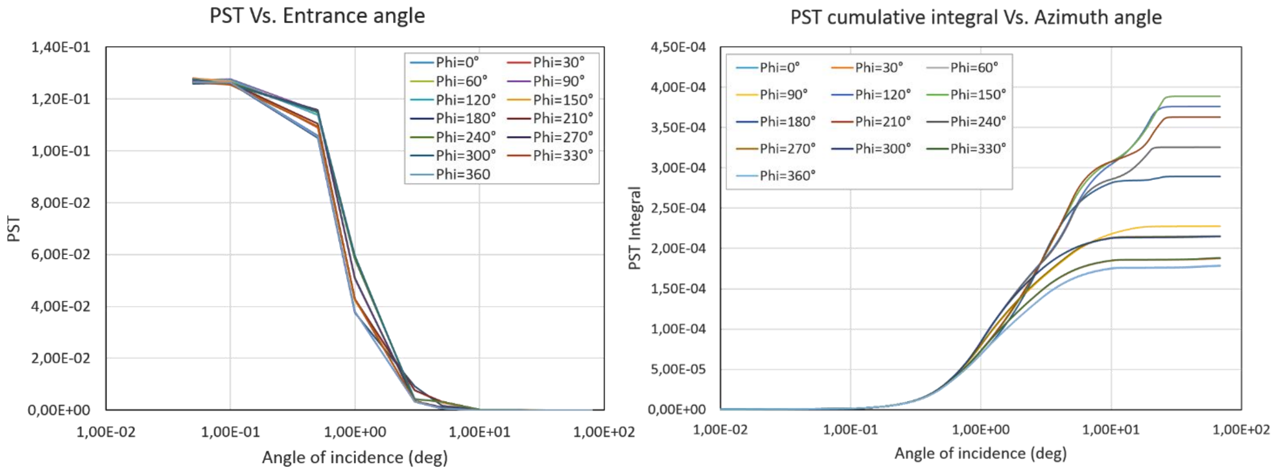

Figure 6. Left: point source transmittance as a function of the entrance angle θ. The different curves represent the PST for different values of the azimuth angle φ. Right: cumulative integral of the PST over the solid angle as a function of θ assuming a fixed profile for every azimuth angle ($2\pi \int_0^{\vartheta} PST\ (\theta)\ \sin\theta\ d\theta$). The different curves represent the PST for different values of the azimuth angle φ

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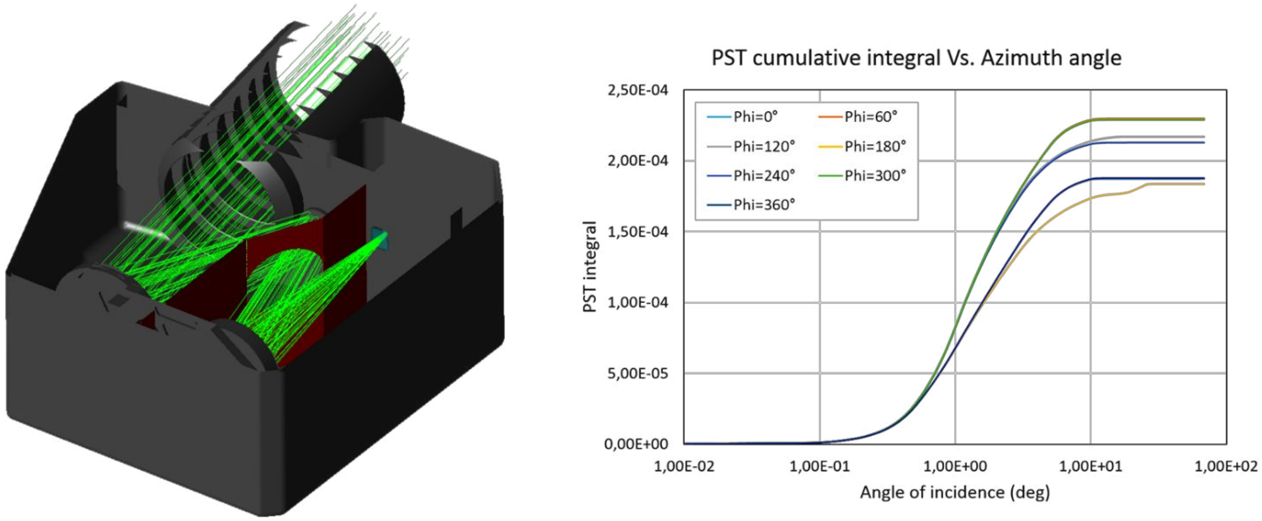

Figure 7. Left: layout of the optimized internal baffling configuration. Right: the same as Figure 6 (right) but for the new baffling configuration.

4. CONCLUSIONS

After giving a brief description of the scientific goals of JANUS, we have presented the opto-mechanical design of the telescope and the procedure adopted for the estimation of the stray light irradiance expected during the mapping phase of Ganymede from a distance of 500 km from the satellite's surface. Given the high complexity of the problem and the high variability of the observational scenario, our results are based on some assumptions and simplifications. Nevertheless, they provide a useful tool for the estimation of the system performance and its optimization. To calculate the ratio between the stray light and the in-field image fluxes, the adopted theoretical model only requires the knowledge of the PST of the telescope and the geometrical parameters of the observation. The PST for different entrance angles was estimated via ray-tracing simulations. The results showed that there was a non-negligible dependence from the azimuthal angle, indicating a non-rotationally symmetric behavior of the telescope wrt incoming stray light. A more detailed analysis of the data allowed to identify the light paths responsible for this difference and to optimize the internal baffling configuration. The new baffle design indicates a better performance for some azimuthal angles and a more uniform PST. Feeding the data in the analytical model, we were able to obtain an estimate of the ratio between stray light flux and scientific flux on the detector when observing Ganymede at a distance of 500 km from its surface.

5. ACKNOWLEDGMENTS

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