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ABSTRACT

JANUS (Jovis Amorum Ac Natorum Undique Scrutator) is a high-resolution visible camera designed for the ESA space mission JUICE (Jupiter Icy moons Explorer). The main scientific goal of JANUS is to observe the surface of the Jupiter satellites Ganymede and Europa in order to characterize their physical and geological properties. During the design phases, we have proposed two possible optical configurations: a Three Mirror Anastigmat (TMA) and a Ritchey-Chrétien (RC) both matching the performance requirements. Here we describe the two optical solutions and compare their performance both in terms of achieved optical quality, sensitivity to misalignment and stray light performances.

Keywords: JANUS, Optical design, Three Mirror Anastigmat, Ritchey-Chrétien, Optical performance, stray light, space visible camera, imaging camera.

1. INTRODUCTION

JANUS is a high-resolution visible camera and it is one of the instruments onboard the JUICE spacecraft, a large-class mission of ESA planned for launch in 2022 and arrival at Jupiter in 2030 [1], [2]. 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 main scientific goal of JANUS, and the main drivers for the design, is to observe the surface of the Jupiter satellites Ganymede and Europa, and the atmosphere of Jupiter and other satellites [3], [4]. In the case of Ganymede, in particular, it is foreseen a complete mapping of the surface with resolution higher than 400 m/px. The camera will be able to acquire both narrowband and panchromatic images by means of a dedicated set of 13 filters taking advantage of a field of view of 1.7x1.3 degrees and a plate scale of 15 microrad/pixel. JANUS is in a preliminary design phase and two design are currently under evaluation: (1) an off-axis three-mirror anastigmat and (2) an on-axis Ritchey-Chrétien telescope with field corrector. The two configurations are characterized by the same first order properties (focal length, entrance pupil diameter, field of view, waveband, etc.), both presenting their pros and cons. In particular, the study of the RC configuration is more recent and solves some practical issues related to the mass budget allocated from the spacecraft for JANUS. Although the design of every instrument is driven by its own requirements, we believe that some results of the trade-off study that we are conducting could be of general interest. For this reason, in the following sections we will briefly describe the two configurations more in detail, comparing their performance in terms of nominal image quality and stray light and providing some considerations about manufacturability, thermal/mechanical stability and alignment.

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2. DESIGN DESCRIPTION

The first configuration that we took in exam is a three-mirror off-axis telescope (Figure 1). The choice was driven by the better contrast generally achievable with un-obstructed systems in terms of Modulation Transfer Function (MTF) and by the achromaticity of an all-reflective design. The telescope optimization was based on the scientific requirements, image quality and blocking of first order stray light paths as described in [5]. It is composed by three mirrors, one spherical (the secondary), used on-axis and two with aspherical shape (primary and tertiary), used off-axis. The field corresponding to the center of the detector enters the instrument with an inclination of about 8 degrees with respect to the optical axis. Between the tertiary mirror and the detector there is a filter wheel hosting 13 filters and a flat window to protect the image sensor. The quality is diffraction limited with a nominal MTF >63% at the Nyquist frequency all over the field of view. The baffling concept is visible in Figure 1 (left): one external baffle with vanes plus three internal baffles (one for each mirror) with conical shape. All of them are black coated to reduce scattered light inside the instrument.

The second configuration has been proposed recently and it is still under optimization. It is a catadioptric design composed by a Ritchey-Chrétien telescope plus a three-lens field corrector (Figure 2). The major drivers of this solution are the compactness and ease of alignment. It is an on-axis system with central obstruction but the entrance pupil diameter is such that the collecting surface is equal to that of the TMA. Because of the obstruction, the nominal MTF is slightly lower than the TMA configuration with a value MTF>58% all over the field. Nevertheless, the strongest limit on the MTF will be given by the detector intrinsic MTF which is of the order of 15%. The system is more compact than the three-mirror solution being approximately half the size of the TMA in both length and height. The proposed baffling configuration is composed by one external baffle with vanes plus one internal conical baffle on the primary mirror obstruction that acts also as a mounting for the three-lens corrector.

It is noteworthy that both the configurations have been already used in space planetary missions like the Narrow Angle Camera [6] (TMA) in the Rosetta spacecraft or the High Resolution Imaging Channel of SIMBIO-SYS [7] (RC) in the Bepi Colombo mission.
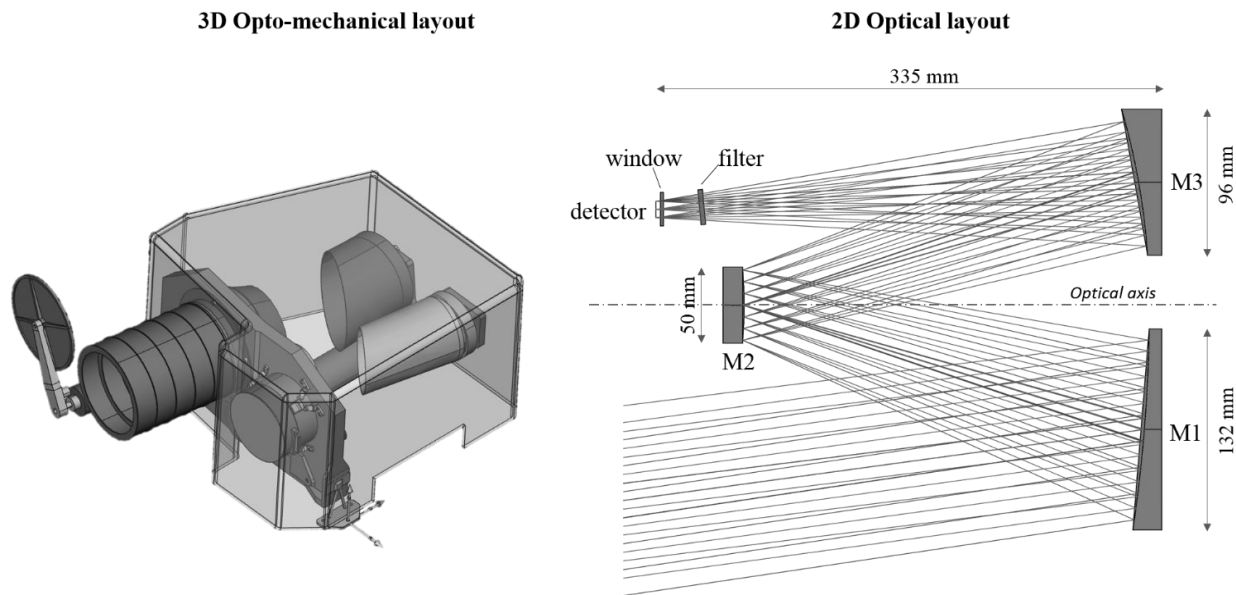

Figure 1. Left: Three Mirror anastigmat 3D opto-mechanical layout. Right: 2D optical layout

3D Opto-mechanical Layout
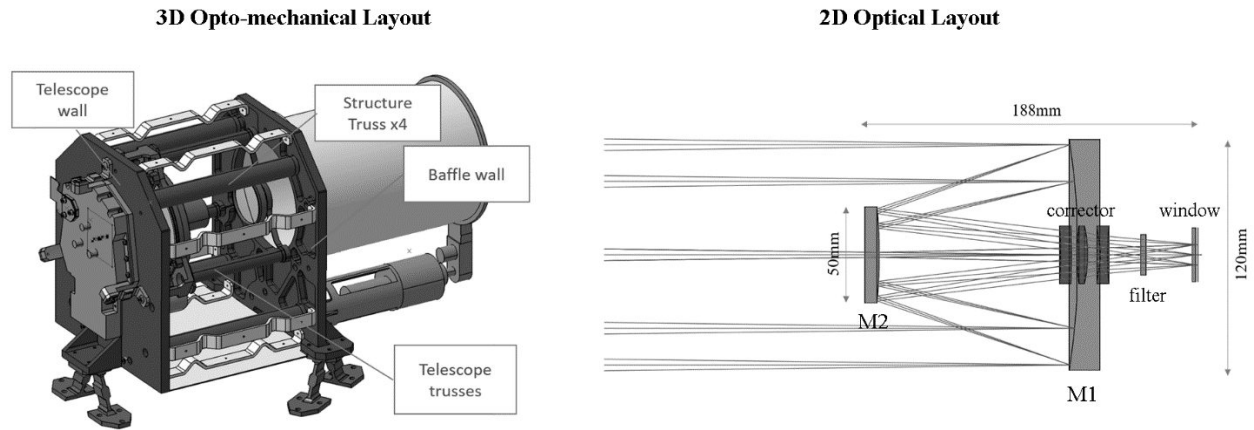

2D Optical Layout

Figure 2. Left: Ritchey-Chrétien 3D opto-mechanical layout. Right: 2D optical layout
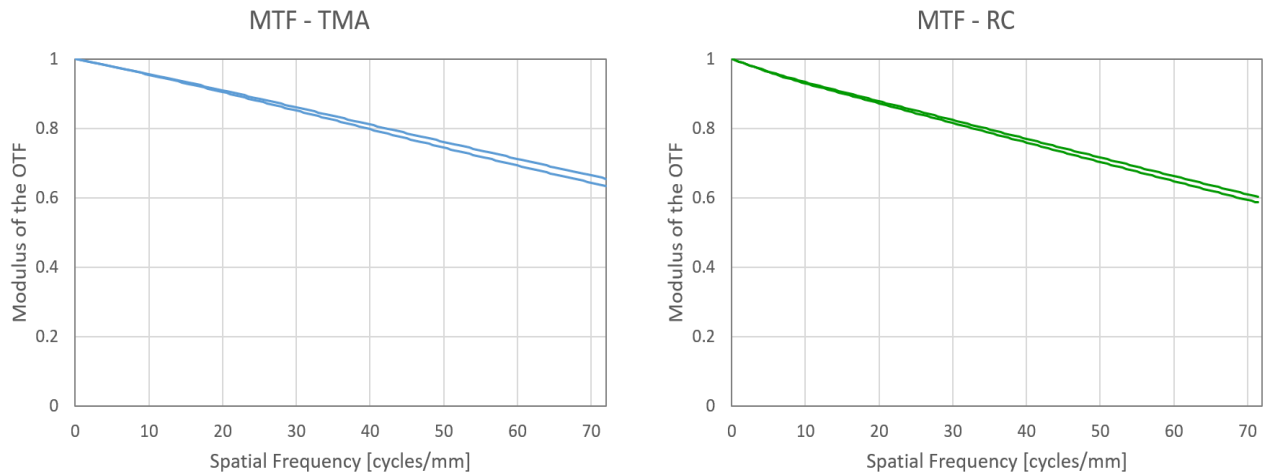

Figure 3. polychromatic modulation transfer function for two representative field positions for the TMA configuration (left) and the RC configuration (right). The curves relative to other field positions (not represented in figure) are almost overlapping indicating a uniform optical quality across the field of view.

3. STRAY LIGHT PERFORMANCE

For both the configurations, we also carried out a preliminary stray light analysis in order to derive a first guess of the expected stray light irradiance on the detector and to drive the optimization of the opto-mechanical design. For the TMA configuration, the adopted procedure for the evaluation of the stray light has been already described in [8]. Here, we follow the same procedure to evaluate also the behavior of the RC configuration. The comparison between the two solutions is made by evaluation of their Point Source Transmittance (PST) as a function of the entrance angle with respect to the optical axis. Moreover, we use the cumulative integral of the PST over the solid angle to calculate the expected ratio between stray light irradiance and scientific irradiance on the detector during the observation of Ganymede at a distance of 500 Km from its surface. This calculation, as explained in [8], is based on the following assumption:

- Ganymede emits like a lambertian surface and is the only source of stray light
- The PST is considered to be independent from the azimuth entrance angle (rotational symmetry)
- We consider only stray light from micro-roughness and particulate contamination of optical surfaces and scattering from mechanical components. Stray light from ghost reflections are evaluated in a different simulation.

The PST is calculated via non-sequential ray-tracing simulations on a simplified opto-mechanical model of the telescope. The results are reported in Figure 4. The plot on the left shows that the PST of the Ritchey-Chrétien camera is always higher than that of the TMA, indicating a worse performance in terms of stray light. For both the systems, the major contribution inside the field of view ($\theta < 1$ deg) is due to the optical components. In the RC design, although the smaller number of mirrors, the presence of three lenses (and thus 6 air-glasses interfaces) produces slightly higher values of PST than that of TMA. Between 1 and 5 degrees, in the case of the TMA the PST is dominated by light scattered from the primary mirror, while in the case of the RC the PST is dominated by light scattered from the internal baffle and reaching directly the detector. Finally, for $\theta > 10$ deg, the major contributor is light scattered from the external baffle.

When observing an extended lambertian source, the stray light is proportional to the cumulative integral of the PST over the solid angle subtended by the source itself (see [8]). The graph on the right of Figure 4 shows that, in this observational scenario, the behavior of the two configurations is quite different. The great difference is concentrated between 1 and 5 degrees and is due, in the RC configuration, to light directly illuminating the internal baffle and scattered toward the detector, which causes an increase on the total stray light by a factor of 4.

Although this limitation is somehow inherent to the on-axis optical configuration, some design strategies could be adopted to mitigate this effect. The simplest, although not trivial, solution is to use vanes on the internal baffle. The major limitation would be the maximum depth of the vanes allowed if one does not want to vignette the beam.
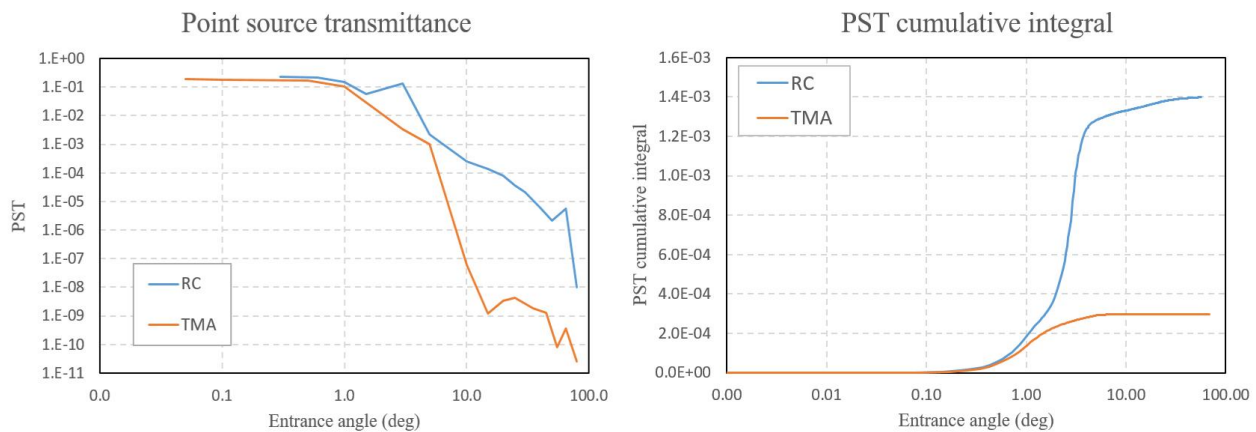

Figure 4. Left: log-log plot of the point source transmittance as a function of the entrance angle θ. Right: cumulative integral of the PST over the solid angle.

To evaluate the presence of ghost images, their irradiance and their total power, we performed a non-sequential ray-trace simulation with a collimated on-axis source of unitary irradiance (1 Watt/mm^2) illuminating the telescope. We assumed a 99% reflectivity for the mirrors, 99% transmissivity for the glass surfaces and 10% reflectivity for the detector. The results presented here account for the ghost images produced by the optical elements all together. Figure 5 shows the irradiance on the detector due to ghosts for the TMA configuration (left) and the RC configuration (right). Of course, since ghosts are usually defocused images of the object, they have different sizes and irradiances depending on how far from the detector the image is formed. Therefore, depending on the observing condition and on the science output required from an image, one should not only be concerned by the total power of ghosts, but also from their size and position with respect to the scientific target. Nevertheless, considering to observe uniform extended objects, the ratio between the total power of ghosts and the total power of the scientific image for an on-axis source gives an estimate of the order of magnitude of the ghost contribution to the total signal. Following this reasoning, we get a ratio between ghost power and scientific image power of 0.3% for the TMA and 1.2% for the RC configuration. Part of the difference between the two configurations is to be expected due to the presence of six additional glass surfaces in the RC camera however, looking at the partial contribution of each surface, we were able to detect a bad coupling between one surface of the corrector and the secondary mirror producing a single-reflection ghost path. This issue has been solved with an optimization of the optical design and, although we don't have performed a new simulation yet, we expect the ghost power to be halved to about 0.6% of the scientific signal.
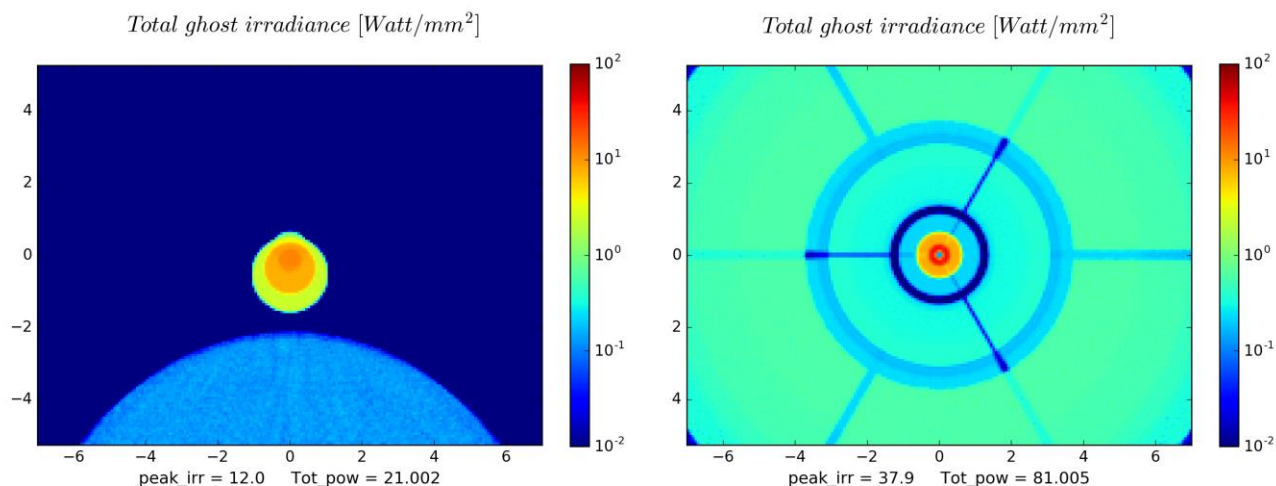
Figure 5. Ghost irradiance on the detector due to an on-axis collimated source of unitary irradiance. Left: ghost irradiance for the TMA configuration. Right: ghost irradiance for the RC configuration.

4. ALIGNMENT, MASS AND MANUFACTURING

To ensure performance stability in a broad temperature range, the choice of materials is critical. For reasons of mass budget and mechanical stability, lightweight materials with low coefficients of thermal expansion (CTE) are in general preferable. Some examples are silicon carbide or carbon fiber. However, other constraints apply like manufacturability, matching of CTE between glass and mountings, moisture release, magnetic disturbances to other instruments, etc. Considering the same composition for the structure of the two configurations, the mass of the RC system is much smaller allowing more flexibility in the choice of materials. In the TMA case, on the other hand, a structure in silicon carbide or carbon fiber was necessary to stay within the mass budget allocated for JANUS although the manufacturability of these materials is more challenging. Based on this reasoning and on the trade-off between the other design parameters, a structure in silicon carbide with Zerodur mirrors has been proposed for the TMA configuration while, for the RC configuration, different solutions are still under evaluation (all aluminum, Invar + Zerodur + Fused Silica, etc.). We recall that optimization of resources from the spacecraft (particularly mass) has been the major driver towards the RC configuration; however there are also other practical advantages with respect to the TMA solution. One obvious advantage is the easier manufacturability and alignment of optics due to their rotationally symmetric shape. This represents not only an advantage in terms of time but also in terms of optical performance of the real system.

5. CONCLUSIONS

For the design phase of the JANUS camera, we presented two possible optical configurations. The first one is an all-reflective three mirror anastigmatic telescope and the second one is a Ritchey-Chrétien telescope with a three-lens field corrector. The two solutions show a very similar performance in terms of optical quality while, regarding stray light, the RC design is slightly underperforming with respect to the TMA by a factor of 2 – 4. Anyway, we would like to stress that the RC design is still under an optimization phase and there is room for improvement. For instance, depending also on the scientific requirements, allowing to partly vignette the light at the edge of the field would lead to improvements in the stray light performance at the expense of a lower signal to noise ratio. This will be part of a trade-off study that will be conducted in the following months and that should take into account also the big advantages offered by the RC design in terms of weight, alignment and manufacturability.

6. ACKNOWLEDGMENTS

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