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JUICE Navigation camera design

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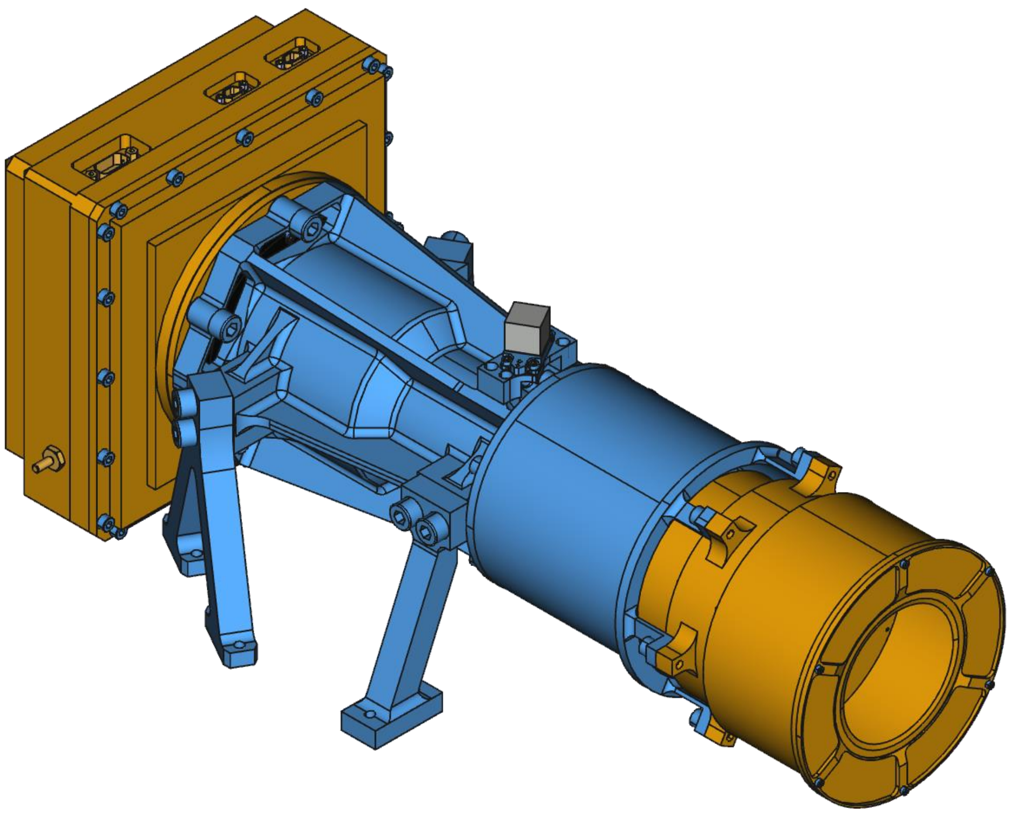

ABSTRACT

The Jupiter Icy Moon Explorer (JUICE) is an ESA mission whose aim is to study the Jovian system : Jupiter itself, its icy moons (Europa, Ganymede and Callisto) and the magnetosphere. For this challenging mission, Sodern was selected to provide the Navigation Camera (NavCam).

NavCam is a key instrument for the spacecraft navigation. During its lifetime JUICE does numerous fly-bys, however the delta V is limited by the available propellant in the spacecraft. To achieve such precise navigation in Jovian environment, ground based radiometric measurements are not sufficient, therefore it is paramount to measure the position of the Jupiter moons in-flight, with high accuracy,.

To achieve this measurement, **the NavCam assesses the position of the moon and stars in its field of view** in an inertial reference frame. The combination of these two measurements gives the accurate position of each of Jupiter icy moons. The stars processing is similar to that of a star tracker and is performed inside the camera, whereas the moons detection is done on-ground from images captured by the camera. In addition to the above primary mission, the navigation camera will also be used by the spacecraft attitude control loop during close fly-bys in order to improve the spacecraft absolute pointing performance.

Jovian environment is particularly severe. The mission profile imposes considerable radiations constraints on the spacecraft, which are uncommon in typical space programs. Jupiter magnetic moment is the largest of the solar system (over 10,000 times higher than the Earth's). It induces a high total dose exposure at electronic parts level (100krad), high number of Single Event Effects and internal charging effects. Furthermore, to achieve the best performances, the NavCam is mounted on the optical bench near sensitive instruments; so it must comply with stringent thermal control and magnetic cleanliness to avoid disturbances to the other instruments. Finally, the measurements of moons and stars in the same field of view induce complex optical design to mitigate stray light.

Star trackers and instrument experience paired with radiation and optical engineering know-how have put Sodern in the position to solve all these challenges. JUICE NavCam is at the moment at PDR stage, the paper describes the current features and the ongoing model activities.

Keywords: Sodern, ESA, JUICE, Jupiter, Camera, Navigation, star tracker

1. OVERVIEW

The JUICE Navigation camera (NavCam) is composed of three main subassemblies, the detection unit, the lens assembly and the baffle. The development of this camera was made possible thanks to the high heritage of Sodern on both star trackers and space optical instruments. This allowed re-using well known technologies to build a NavCam that withstands the Jovian environment, spacecraft constraints and reach the expected performances while delivering in time of the spacecraft launch.

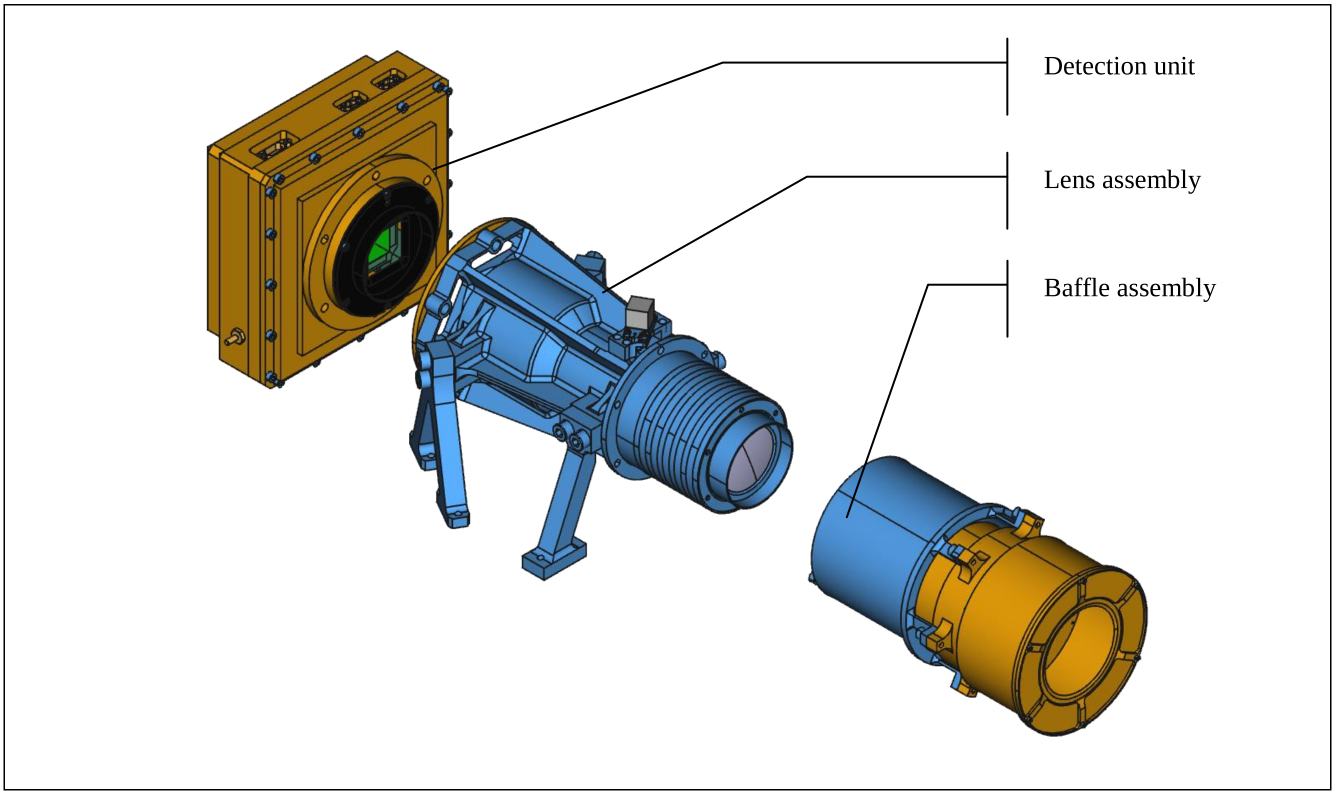

Figure 1: Exploded view of the JUICE Navigation camera

The baffle technology is inherited from HYDRA star trackers. The same design rules are applied and the same high performances coatings are used allowing a high out of field stray light mitigation.

The lens assembly uses Rad hard glasses specifically developed and used by Sodern in its star trackers to minimize performance degradation during the mission and to benefit from the radiation characterization already performed. Furthermore, the optics mounting is inherited from space optics technology already space qualified that provides very high mounting precision and stability. This allows achieving the image quality requested for moons detection. Finally, the bipod design is inspired by other space instruments and uses the same design rules. It is, however, specifically adapted to meet the JUICE spacecraft constraints.

The detection board includes the HAS2 (High Accuracy Sensor) APS combined with a thermo electrical cooler. The HAS2 is a CMOS Image Sensor (CIS) developed by ON-SEMI under an ESA contract and designed in order to withstand harsh radiation environment. This assembly, (APS and TEC) is identical to the one in HYDRA star tracker; however, the detector is maintained down to 0°C in order to minimize the detector dark current.

The current mass estimation of the NavCam is around 8kg with a detection unit of 3.3kg a lens assembly of 4kg and a baffle assembly of 0.7kg.

2. RADIATION CONSTRAINTS

Intense radiation belts composed of protons and high energy electrons are found around Jupiter, which are seldom experienced on Earth-orbiting missions. In consequence, several characteristics of the JUICE environment are unique, however, a good understanding of the related physical processes allows for an effective mitigation of their effects.

2.1 Electron flux and background noise:

As the spacecraft closes on Jupiter, the electron fluxes increase and reach values that are many orders of magnitude above those encountered around Earth. Impinging particles create electron-hole tracks in the image sensor, which act as a background parasitic signal and interfere with the detection of objects in the instrument field of view. This effect is considered as a design driver, as it directly affects the accuracy and robustness of the Navigation Camera. An accurate simulation of charge deposition is required to assess correctly the performance of the instrument.

The electron flux depends on the spacecraft distance to Jupiter and peaks during the Europa fly-bys at 9.3 R_J. In consequence, a detailed analysis taking into account the spacecraft position during the different mission phases is also needed.

Concerns over the accuracy of the JOREM environmental model used to assess the electron fluxes in the environmental specification have led ESA to mandate a 300% design margin on the radiation-induced background noise.

A detailed characterization of the behavior of the detector (HAS2) has been performed under electron flux at multiple energies during LAPLACE studies providing inputs for a high fidelity simulation taking into account electron energy spectrum and detector effects. This allowed developing and testing electron filtering algorithms based on image sensor timing adaptations.

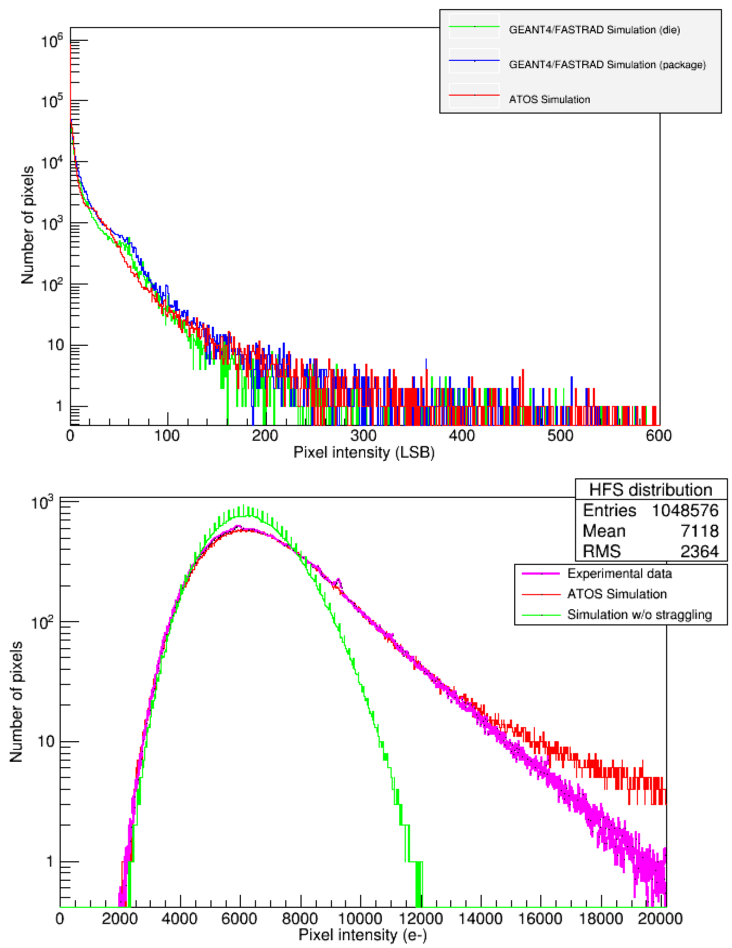

Figure 2: The ATOS simulation tool for performance assessment simulates at high speed the electron flux impact to perform extensive performance campaign. Compared to GEANT4 Monte-Carlo simulation under Europa worst case conditions (top) or experimental 12 MeV electron irradiation (bottom), it shows a near-perfect match confirming the high accuracy of the simulation.

2.2 Total Ionizing Dose (TID) levels on EEE parts and optics:

As energetic electrons can penetrate deeply in the matter, the TID exposure of components and optics can reach very high levels if the instrument is not adequately shielded. However surface materials are exposed to TID levels lower than those experienced on geosynchronous orbit, as a benefit for qualified material reuse.
Because of the fluctuations in the observed particle fluxes, an environmental design margin of 100% is mandated on the considered TID.
This is the main driver to select EEE parts tolerant up to 100krad and the mechanical shielding of the detection unit. Rad hard glasses specifically developed and used by Sodern in its star trackers are chosen to minimize performance degradation during the mission and to benefit from the radiation characterization already performed.

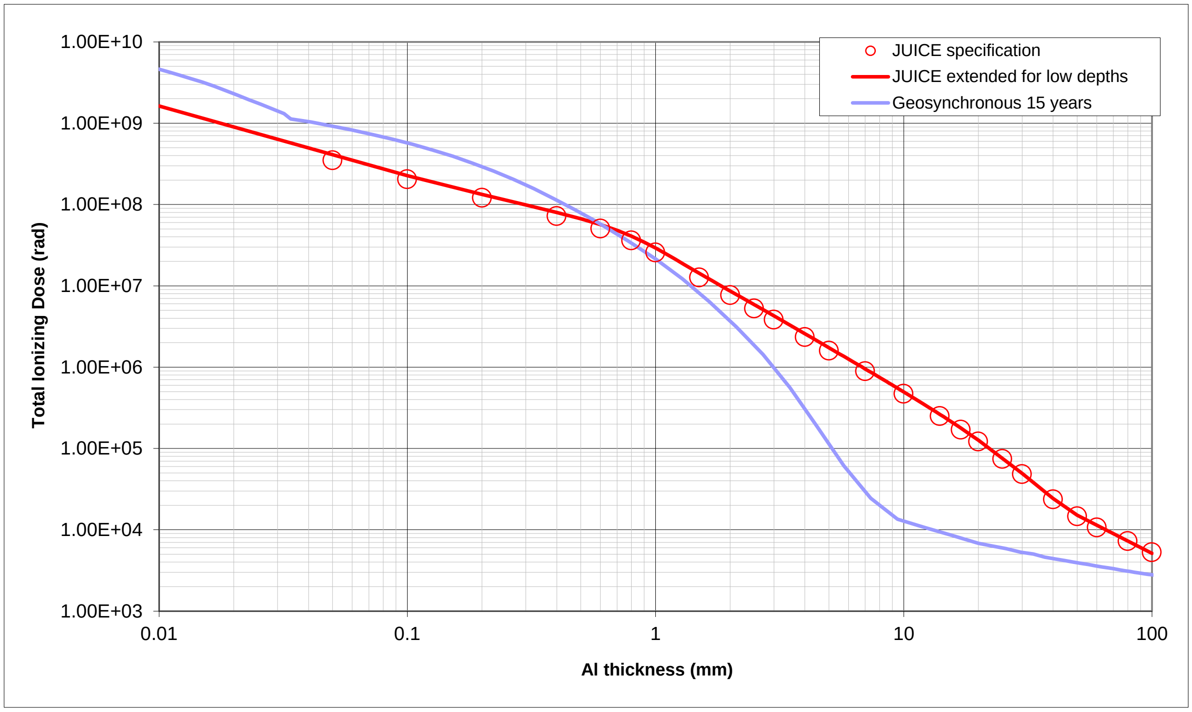

Figure 3: Comparison between the total ionizing dose constraints of JUICE and Earth geosynchronous orbit missions. The margin of 100% is included for JUICE curve. As seen on the dose dose-depth curve, energetic electrons deposit very high amounts of total ionizing dose on shielded electronics, which is the main radiation challenge of the mission.

2.3 Internal charging

High electron fluxes also cause internal charging effects which can trigger electrostatic discharges, especially in high-resistivity dielectrics such as optical materials.
Charging tests have been performed at high current and representative temperatures and analysis performed using ESA-supplied data on material resistivity in vacuum.

2.4 Photonic secondary effects:

Energetic electrons generate visible light in the instruments optics through the Cherenkov and luminescence effects. This glow acts as stray light or ungrounded conductors. Representative tests have been carried out to take into account these effects in our simulation tools.

2.5 Displacement Damage levels:

The mission is exposed to significant levels of Total Non-Ionising Dose (TNID), which mainly degrade the performance of optoelectronic parts through an increase of dark signal. For JUICE mission, the displacement damage is mainly electron-induced, and scales differently than the proton-induced displacement damage encountered on Earth orbit.
Representative tests have been performed to assess the effects of electron-induced displacement damage on image sensor which are inputs for the comprehensive dark current simulation models taken into account for performance analysis.

2.6 Proton and heavy ion fluxes

Proton and heavy ion fluxes are similar or lower to those encountered on Earth geosynchronous orbit. Trapped heavy ions are present around Jupiter, but are not sufficiently energetic to reach the electronics of the instrument. In consequence, Single Event Effects are not a prime concern. The only exception would be if a solar flare occurred during the Venus gravity assist phase: the spacecraft would be exposed to fluxes twice as high as those experienced around Earth.

3. ARCHITECTURE

3.1 Detection unit

The Detection Unit contains the detector, its cooling system (TEC) and the electronic boards mounted in an aluminum structure. The Detection Unit supports all connectors necessary for NavCam command, power supply and two redundant spacewires.

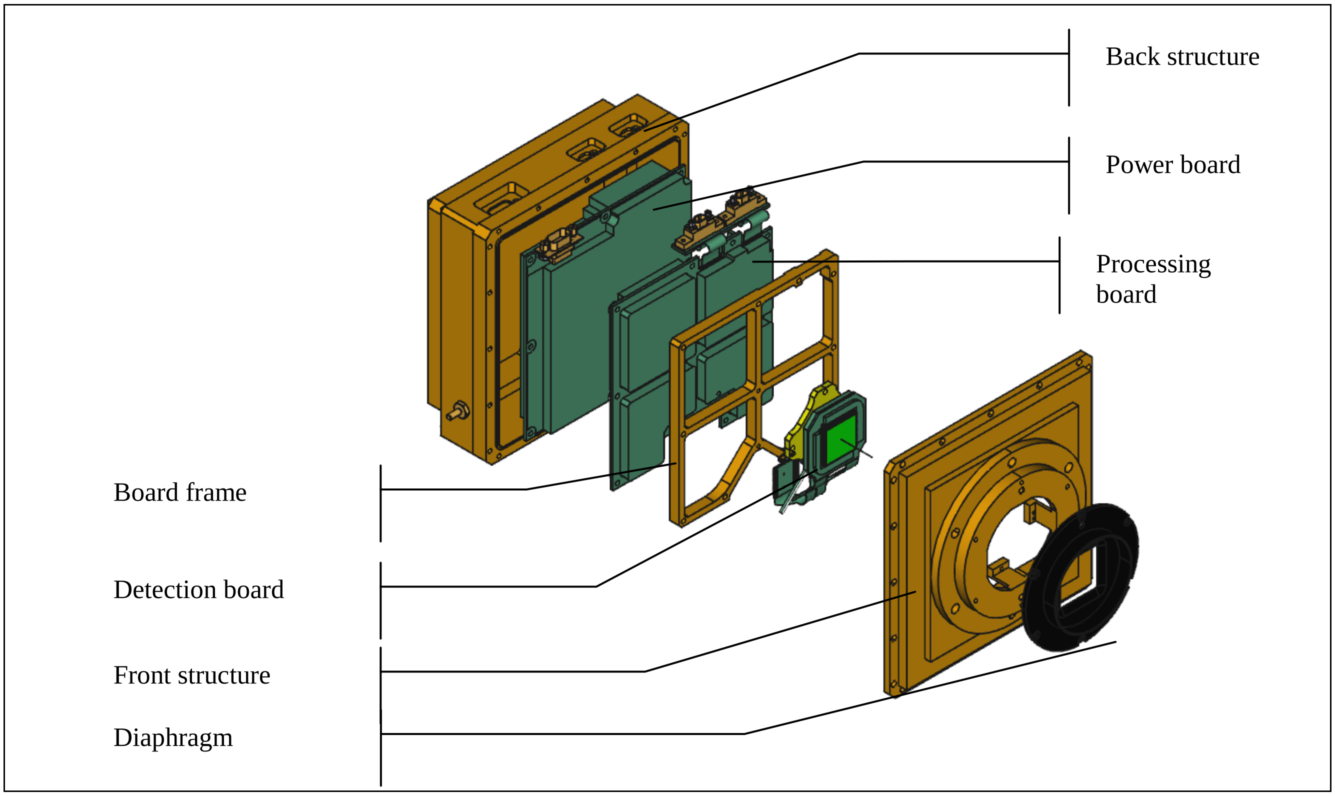

Figure 4: Exploded view of the detection unit

The structure is made of aluminum and receives a high emissivity coating so that it can be used as a radiative cooler for dissipation of boards' thermal power. For the very cold cases encountered in the Jovian environment, one heater is fixed on the structure to avoid reaching temperatures below -40°C. The high thickness of the box walls (about 9 mm) provides enough shielding for the high tolerant EEE parts (100krad) mounted on the power board and the processing board.

The processing board includes a radhard FPGA a nonvolatile 16 Mb MRAM to store the parameters and a volatile memory 1Gb SDRAM to store telemetries including images.
The extensive radiation tests performed on the HAS2 detector of the detection board allow estimating the performance degradations of the detector in the Jovian environment.

The converter and processing board are customized to comply with the requested interfaces and the harsh radiation environment by selecting parts with a radiation tolerance above 100krad.

3.2 Lens assembly

The Lens Assembly contains all the optical glass components and the alignment cube. It interfaces with the detection unit, the baffle and the optical bench. To minimize the thermal exchanges with spacecraft cavity, it is covered by MLI except for the feets.

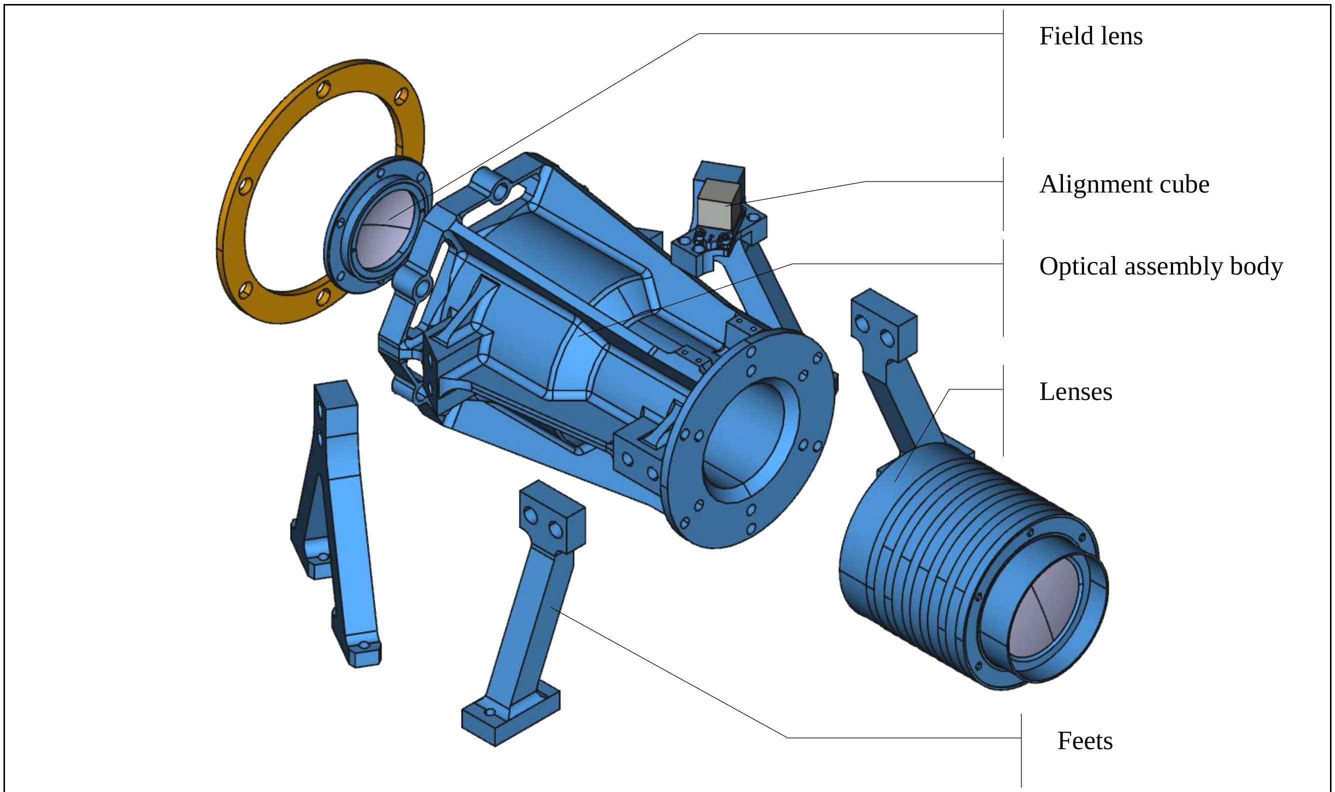

Figure 5: Exploded view of the lens assembly

The glasses are radiation tolerant (doped glasses) and the first element is made of Silica to withstand the high electron flux at the external surface. The design is customized for the Juice Navigation camera need with a pupil diameter of 50mm and a field of view of 4°. In-field stray light mitigation was a main driver as the NavCam shall be able to detect stars with a moon in the field of view.

The flexures at the interface of the detection unit allow solving the expansion mismatch between the aluminum of the detection unit and the titanium of the lens assembly body. It also decouples thermally these two elements to minimize the thermal gradients in the lens assembly.

Two heaters are necessary to drive the temperature of the lenses. One is at the front of L1 and one at the back of L6. They allow reaching a minimum temperature of -40°C compatible with Sodern qualification status and limit the gradient through the lenses.

The feet design is driven by the need of a high thermal resistance to limit the thermal flux exchanges (conductance bellow 0.075W/K) and high rigidity to minimize the amplification of the vibration at board and lens level.

4. MOON AND STARS DETECTION

The JUICE Navigation camera primary goal is to take images of the Jovian Moon and at the same time detect the background stars.

4.1 Moon detection

A field of view of 4° is specified to assess the moon position. With such a small field of view, there are small chances to have bright stars; therefore the pupil diameter is increased with regard to typical star trackers up to 50mm to detect stars up to magnitude 8.8. With such a large diameter and the requested optical precision, the lenses shall be mounted with very high precision and stability. This is achieved thanks to barrel mounting, a Sodern technology developed in the frame of space instruments already space qualified. This technology allows reaching optical performances compliant with the need for moon detection in all operational phases.

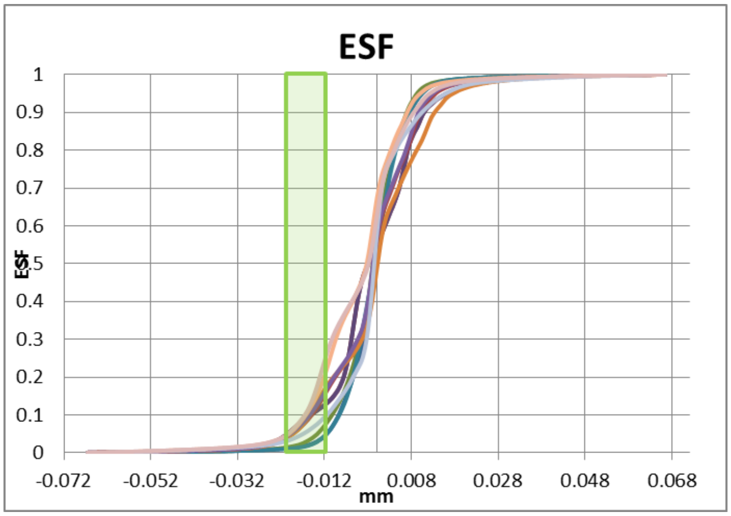

Figure 6: Edge spread function drops of 90% in less than 1.1 pixel (0.02mm) in all field of view, for all color temperature in the whole temperature range.

Furthermore, straylight has been mitigated, with the help of modelization tools like FRED, by coating all critical areas with already space qualified processed and diaphragms. The expected attenuation factor of the infield straylight is above 2000 even for a worst case moon of 500pixels.

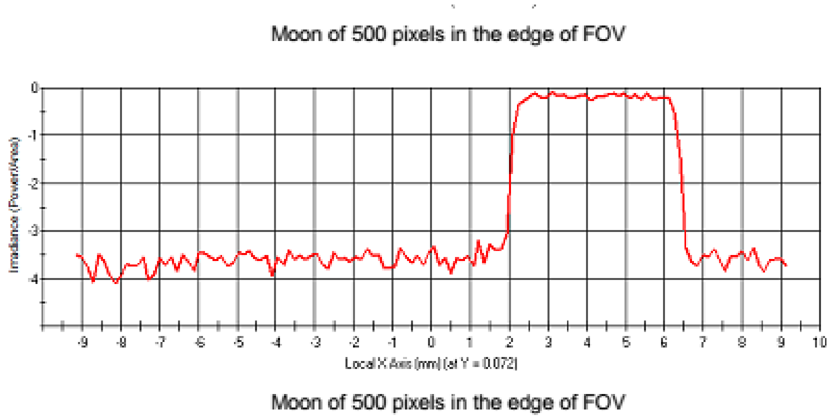

Figure 7: Straylight due to a moon of 500 pixels inside the field of view. The attenuation is above 2000.

4.2 Stars detection

Thanks to its long heritage in Star Tracker (STR) design and its deep involvement in ESA TDAs studying the effect of Jupiter harsh radiation environment on STR and Navigation Camera, Sodern has the relevant and validated simulation tools to assess the performances of the JUICE NavCam and to build the star catalogue optimized for its Star Centroiding mode.

Predicting accurately the Star Centroiding mode performance of the navigation camera requires assessing detection and measurement performance at star level, and also predicting attitude determination performance over the celestial vault from the combination of stars in the field of view. Sodern in-house simulation tools address all aspects of performance assessment.

The in house simulation tool (ATOS) simulates all effects that drive the NavCam single-star performance
ATOS accurately simulates HAS2-based detection chain and outputs star centroiding performance using a Monte Carlo approach.

All effects that impact images in the context of JUICE mission are simulated:

- Optical performances and motion blur: transmission, PSF and straylight.
- HAS2 electro-optical performances: photo response, cross-talk, full well capacity, readout noise, dark current, FPN, PRNU, photonic noise, ADC quantification and saturation.
- HAS2 readout modes: rolling shutter, full frame and windowed sequencing.
- Radiation induced cumulative effects: optical transmission loss, HAS2 dark current, DSNU, spikes.
- Radiation induced transient effects: Cherenkov and luminescence photons, Jovian electrons induced ionization effects of HAS2 3D pixel array.

The highly realistic images are pre-processed for radiation electrons filtering, spikes filtering and background signal correction before star centroiding is performed. ATOS typically outputs star detection probability, star position bias and NEA, and star signal bias and noise as a function of magnitude.

ATOS has been used for more than one decade for both commercial and military projects. The simulation of Jovian electrons interactions with HAS2 detector was validated in the frame of ESA "Evaluation of STR performance in high radiation environment" study against heavy GEANT4/FASTRAD physics radiation codes and ground tests. ATOS showed very good compliance with both physics simulations and experimental tests. In particular, the simulation helped develop a filtering algorithm which mitigates the impact of the electron flux and at the same time avoids saturation due to the straylight of the Moon.

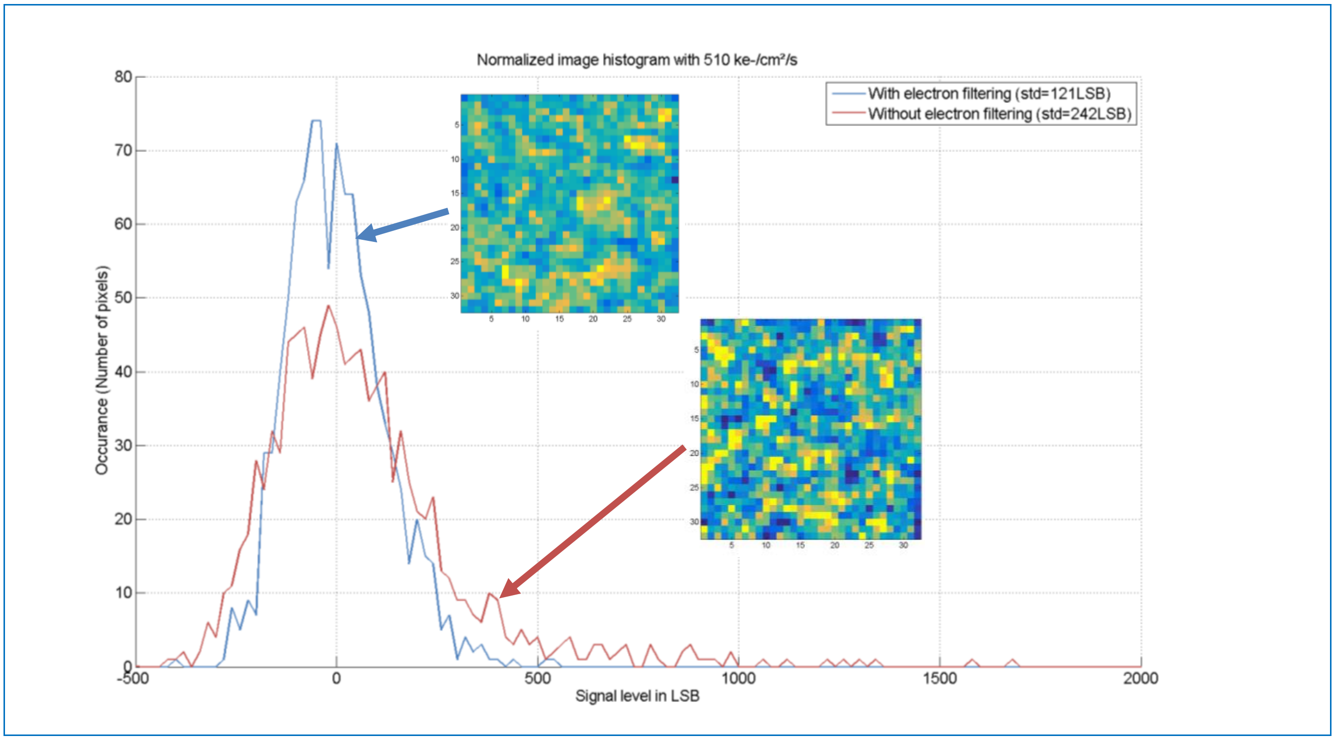

Figure 8: The electron filtering algorithm is highly effective on the most energetic impacts which are the most problematic for the centroïding algorithm.

The performances achieved at end of life are compliant with the expectations:

Short term bias stability	X=0.2 arcsec Y=2.1 arcsec Z=0.2 arcsec
Field of view error on 99% of the vault	X=1.1 arcsec Y=1.1 arcsec Z=47.4 arcsec
Noise on 98% of the vault	X=4.4 arcsec Y=4.4 arcsec Z=190 arcsec

5. CONCLUSION

Sodern designed a Navigation camera that withstands all the constraints imposed by the Jovian environment while achieving the expected performances. In the brief allowed development period, this has been possible thanks to the reuse of several brick technologies mastered by Sodern on various projects, in particular star tracker and space optics. The main challenge was to find a design that comply with all the constraints, radiation, EMC, thermal, mechanical and performances as all of them are particularly stringent on JUICE mission.

6. ACKNOWLEDGMENTS

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