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Straylight Minimization in the design of the ERO Narrow Angle Camera

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ABSTRACT

The Mars Sample Return mission is a multiple probe mission to collect rock samples from Mars and bring them to Earth. The Perseverance rover is currently collecting samples on Mars. Tasked with the recovery of the Mars samples in Mars orbit and their return to Earth, the Earth Return Orbiter (ERO) is the last probe of the mission. In order to capture the Orbiting Sample (OS), which contains the Mars rock samples, the ERO will first detect the OS at long distance using its Narrow Angle Camera (NAC). Because the OS will be a faint object of magnitude 12, its detection is a challenge. One part of this challenge is to minimize the straylight caused by the illumination of the camera by much brighter out of field sources, such as the Sun and also the planet Mars. We describe here the design steps taken to minimize straylight, starting with measurement, design principles for the baffle and the objective, then finally simulations and their results.

Keywords: Straylight**,** Navigation Camera, Detection, Mars ERO, Black coatings, Lens Construction

1. INTRODUCTION

The Mars Sample Return mission has 3 distinct phases: the collection of samples, the retrieval and Mars ascent and finally the capture in orbit and return to Earth. The collection of samples is currently underway with the Perseverance rover, with 12 tubes out of 38 already sealed as of August 1. For the retrieval and Mars ascent, another probe needs to be sent. It will carry a small rocket, the Mars Ascent Vehicle (MAV), and once on Mars load the Orbiting Sample (OS) with the tubes collected by Perseverance. The MAV will be fired with the Orbiting Sample as payload. The Earth Return Orbiter (ERO) is the 3rd probe, tasked with the capture of the Orbiting Sample and the return to Earth of the samples. The Earth Return Orbiter will need to detect the OS at distances up to 3400 kilometers, while getting closer to it. The plan is to detect the OS by optical means, the Narrow Angle Camera (NAC), a camera equipped with a teleobjective lens.

The OS design is not finalized yet, but it can be described as a canister of dimensions 230 mm x Ø185 mm. Even if the OS is coated with a very reflective material, it will necessarily remain a faint object at large distance. The current maximum magnitude to be detected is +12.6, which corresponds to an irradiance at the entrance of the system of 2.5×10^{-13} W/m².

The orbit of the ERO is planned to be fairly close to the surface of Mars, with an altitude of about 300 km. Even if the launch of the MAV from Mars will be planned to maximize the likelihood of detection, the capture of the OS will take some time. Therefore, the NAC must allow the detection of the OS in a variety of scenarios, which are not all favorable. The range of scenarios where detection is possible or likely needs to be maximized.

The NAC must not only detect a faint object but also work with other stronger light sources as close as possible to its line of sight. It is well known that the Sun, the brightest light source in Mars orbit, prevents the detection of faint objects even when outside the field of view of an optical system. In the case of the NAC, one also has to contend with light from Mars: indeed, both the ERO and the OS will be in low Mars orbit, which means that Mars will occupy a large part of the hemisphere facing the camera and the edge of the limb will be close to the line of sight. The amount of light entering the baffle due to the Sun is up to about 8W, while the total power from Mars is up to about 1.8W in some scenarios.

2. DESCRIPTION OF THE CAMERA SYSTEM

The Narrow Angle Camera system is made of 4 main parts: an electronic unit, which includes the detector, a teleobjective lens, a baffle, and a radiator.

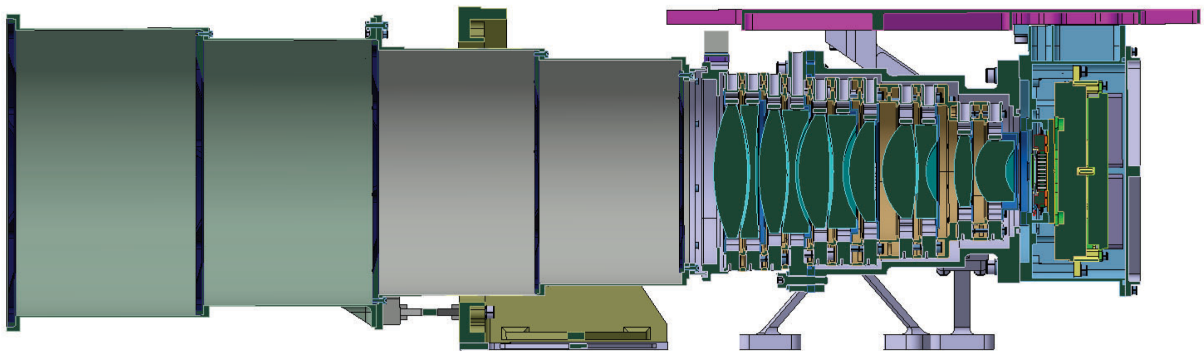

Figure 1 View of the NAC system

The characteristics of the teleobjective and of the baffle are given in Table 1

Table 1 NAC teleobjective and baffle characteristics

Teleobjective characteristics		Baffle characteristics	
Focal length	129 mm	**Exclusion angle**	13.8°
F Number	1.6	**Number of cavities**	4
Diagonal field of view	6.4°	**Length**	497 mm from entrance pupil
Length	220 mm	**Entrance diameter**	137 mm
Number of lenses	11		

The Narrow Angle Camera is based on a FaintStar FS2 CMOS detector from AMS. It is a radiation-tolerant one megapixel image sensor for use in star trackers and navigation cameras currently available and performant detector suitable for such a mission.

The focal length of the camera is determined by the need to cover the full detector matrix with diagonal field of view of ±3.2°. The entrance pupil diameter of 80mm was selected so that the amount of light will be large enough to allow detection of the OS, but is limited by constraints of size and manufacturing . The lens has been designed by Sodern to be athermalized and to achieve a nearly constant PSF size over the whole field of view.

The baffle design is a compromise between its length and diameter on one hand, and the exclusion angle on the other hand. For out of field straylight, the NAC is a two-stage system: The baffle intercepts light with an incoming angle larger than the exclusion angle and applies a strong attenuation. The objective also has features to lower straylight further as the extinction provided by the baffle is not large enough.

3. BSDF MEASUREMENTS

In order to confirm the hypotheses taken from Sodern's experience and public information on materials, a series of measurements were made on a shortlist of materials, paints and coatings.

The first goal of these measurements was to confirm the opacity of the candidate paints at all wavelengths between 400nm and 1100nm. Because most manufacturers of paints target a market centered around human vision, they do not need to care about the performance in the infrared. They may also not need a perfect opacity. The main shortlisted candidates were found to behave well and to be consistently opaque throughout the wavelength range.

Another measurement considered the BRDF of Acktar Magic Black, at various angles of incidence. Acktar Magic Black is a coating with a diffuse reflectance of 1-2% at normal incidence, even after long exposure in air. However, at high angles of incidence, like many materials, the diffuse reflectivity is higher, reaching about 20% at 80° incidence. Even if such measurements are less precise when the angle of incidence increases, this finding is particularly important, given that light entering the baffle is likely to have large angles of incidence on the critical parts of the baffle.

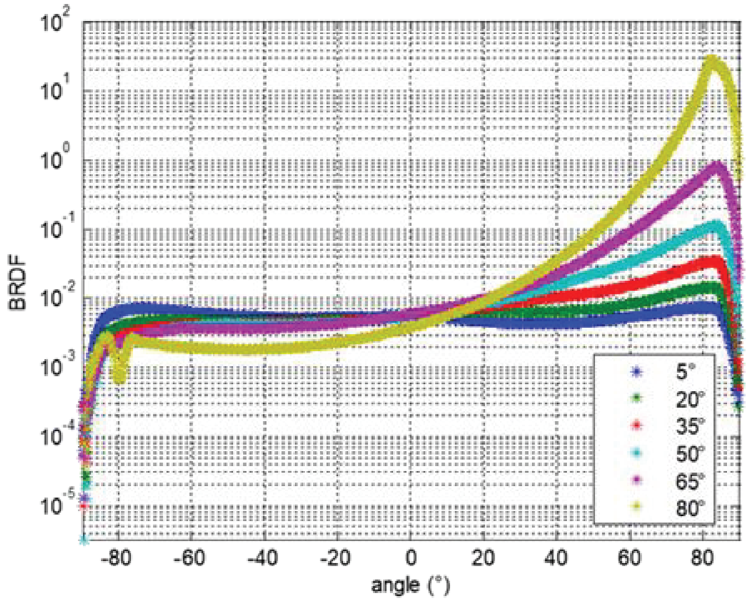

Figure 2 AcktarMagic Black BRDF mesurement results

4. BAFFLE DESIGN

When a bright source of light such as the Sun is within the field of view, the detection of such a faint object as the OS is an extreme challenge. The Sun is an extremely strong source compared to the OS, with an irradiance of the order 500W/m² at the entrance of the baffle and therefore 15 orders of magnitude stronger than the OS. With such a difference, parasitic reflections on the detector and the surfaces of individual lenses are more than enough to make the OS signal impossible to detect. But even outside the field of view, the Sun would illuminate the lenses and the effects of parasitic reflections on the polished diopters would be enough to mask the OS signal.

That is why an efficient baffle is used to reduce the amount of light coming from strong sources outside the field of view. The baffle works through a purely geometric principle, where light incoming with a large enough incidence is trapped within cavities covered with black paint or black coatings such as Acktar.

The design principle is shown on Figure 3. It starts with the selection of an Exclusion Angle, the angle above which no ray can exit without having been reflected at least twice on black coated surfaces. As the baffle must let light coming from the field of view pass through unobscured, one obtains a succession of cavities with openings of diminishing size when going towards the objective.

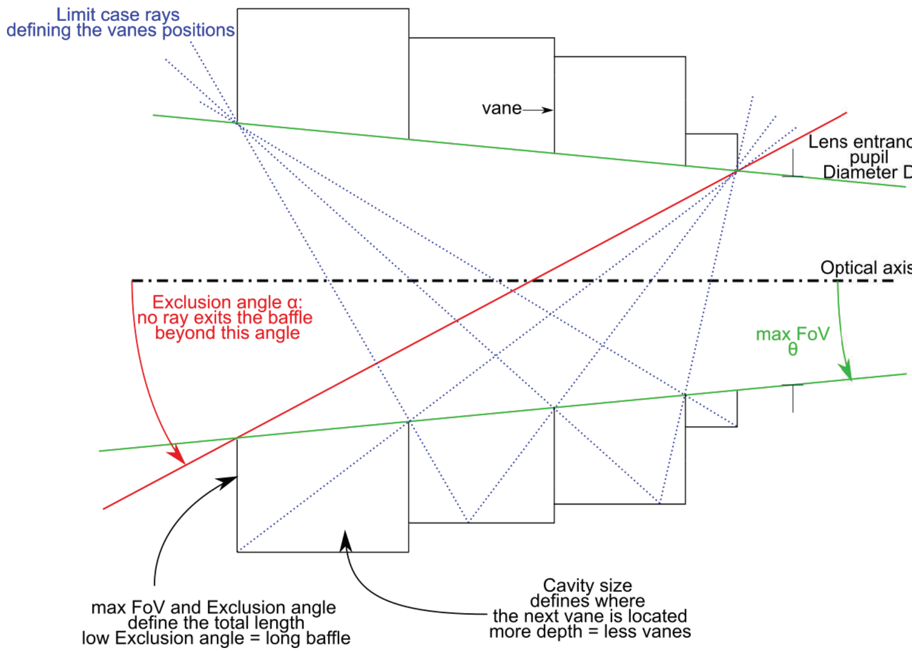

Figure 3 Baffle construction principles

The first characteristic of the baffle is that the lower the exclusion angle, the longer the baffle. From Figure 3, we can see that the length $L \geq \frac{D}{\tan\alpha - \tan\theta}$, with the actual length determined by the distance between the baffle and the entrance pupil.

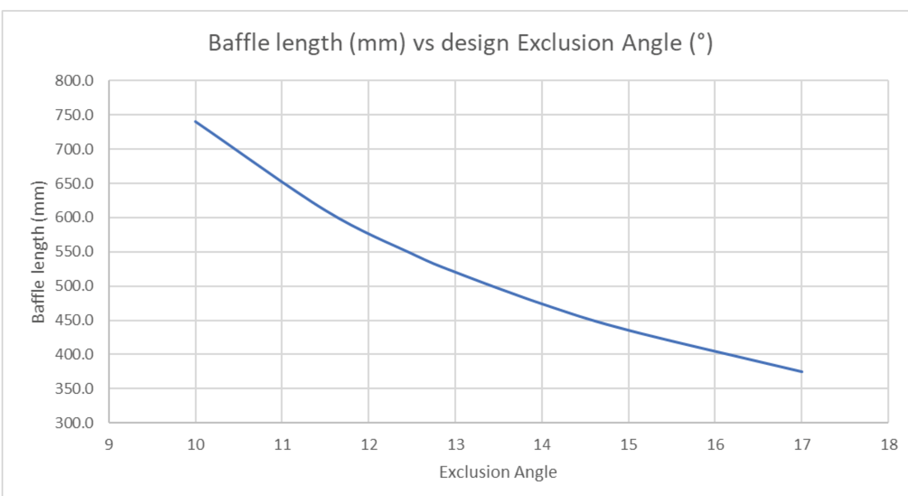

Figure 4 Baffle length vs exclusion angle relationship.
Actual length is now longer because of greater separation of the baffle and the objective

A mission requirement is that the smallest Sun angle for which the NAC must work is 30°, but because the edge of Mars may come as close as 12° to the line of sight, a small Exclusion Angle is necessary. Sodern settled on an Exclusion Angle of 14° as compromise between the length and the straylight attenuation afforded, reasoning that the unbaffled étendue of the Mars limb was small in any case.

There are unavoidable exceptions to the rule of having at least two reflections on a black diffusive surface before entering the objective: the vanes delimiting the cavities have a certain thickness. Because of the large incidence angle on the edges, the absorbing effect of the Acktar Magic Black coating is much weaker than the advertised on-axis values. In the experience of Sodern with star trackers, this thickness is enough to qualitatively explain the observed straylight. Of course, Sodern strives to reduce the thickness of these edges. Currently the thickness of these edges is around 50µm.

Under a certain thickness the light going to the objective from the cavities themselves becomes dominant; however, accumulating all this light as if it was emitted from the edge is the worst case, because it creates secondary light sources that are as close as possible to the line of sight. That is why the preferred model is to have only the edges of the vanes scattering light towards the objective, even if the modelled thickness is larger than the true thickness.

Because of its length, the baffle has its own mechanical interface to the satellite platform. A gap is necessary for assembly purposes. This gap is bridged by a labyrinth system, so that no direct illumination is possible from the sides of the lens. Furthermore, this area is covered by MLI required to achieve the required thermal performances.

5. OBJECTIVE DESIGN

The objective is built from separate barrels in which the individual lenses are glued in 3 points. The technique was selected because it guarantees a very good centering of the faces in barrel, very good stability and it was used with success on the Sentinel5 project. However, this strategy leaves a gap around most of the lens. For this reason, many diaphragms block the path of light that may happen around the lenses. They are all Acktar Magic Black coated and their edge is far from the main optical path.

Additionally, all flat closing bevels are black painted so as to prevent light scattered by these surfaces to reach the detector. If left unpainted, the amount of straylight is much larger; but the total amount of straylight depends on how much light comes from the baffle. Furthermore, the relative distribution of straylight on the detector depends mainly on this second part of the straylight generation process. Whenever light strikes a surface that can generate straylight, it tends to create similar patterns, due to its scatter characteristics and also due to the fact that the range of angles of incidence when coming from the baffle are fairly constrained.

The actual straylight performance is very sensitive to the paint deposition process. The surface that absolutely needs to be painted on the lens is often limited to few millimeters in width. The rest is often invisible from the detector due to other mechanical features, such as spacers. But then the lack of paint on a ring with a width of few dozen micrometers is equivalent to a paint with a transmittance of a few percent, even if the paint itself is completely opaque. For a project such as NAC, this would be incompatible with the stringent requirements. That is why paint will be deposited also on the outer area of the polished diopter of concave lenses, so as to be certain to leave only specular refraction on the diopter as a direct exit from the lens.

With the inclusion of diaphragms and the extensive painting of lenses, it was found that the cavities thus formed, combined with the baffle extinction, were enough for our needs. The simulations show that the effects of the anti-reflection coatings are minor compared to the scatter effects.

6. PERFORMANCE COMPUTATIONS

In order to validate the design before any test could be conducted, simulations were run in specialized software, FRED from Photon Engineering. Simulations have been used for 3 purposes: confirmation of the design hypotheses, computation of the performances of the NAC system and finally comparison of the simulation with real world performances.

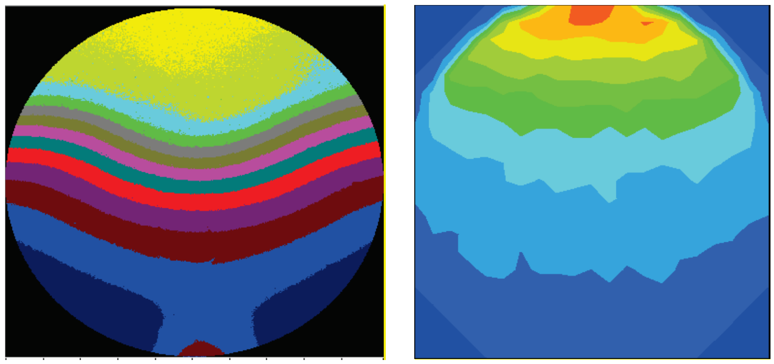

Figure 5 Straylight irradiance comparison of straylight measurements on a prototype (left) and simulations (right), for unpainted lenses. The levels displayed here are more than 100 times the requirement on the NAC

For the confirmations of the hypotheses, simulations on other projects have shown that painting the flat closing bevels of diverging lenses was mandatory with the chosen mounting strategy. Simulations showed very large straylight and a characteristic pattern. The characteristic pattern was observed on a prototype system, confirming the key role of these areas.

BSDF & BRDF measurements were used through the intermediary of fits. Not using the fitting utility resulted in some unphysical behavior (such as TIS greater than 100%), whereas using a fit gave better results closer to the expected behavior. Using fits also allows the modification of the behavior of the coatings and paints, for example to allow higher TIS at high angles of incidence, while keeping the rest nearly constant. This offers opportunities in terms of sensitivity analysis that were used during the project.

To compute the expected performances of the NAC, the first challenge to overcome is the lack of rays. Indeed, the critical areas of the baffle – the edges of the vanes – are very thin. Furthermore, as it was decided to take further steps to cover the most critical areas with black paint, the total number of rays reaching the detector of the simulation is very low. To alleviate these issues, sources target directly the critical surfaces of the baffle. Other acceleration techniques have been explored, but without much success. In particular, using GPUs proved more difficult than anticipated, due to a bug and other pitfalls of GPU simulations. As a result, the maps of straylight provide accurate average irradiance values, but the results are still noisy.

Another challenge was to simulate the effect of Mars on the straylight irradiance on the detector. The effect of the Sun can be accurately simulated by assuming that the Sun is a point source. Indeed, its size at Mars orbit is about 0.3°, whereas the changes in straylight with the angle of incidence are expected to be slow in comparison, except near the exclusion angle.

Mars, on the contrary, is expected to cover a large part of the hemisphere facing the camera, about 1/3 of the total étendue, as seen on Figure 6. In order to ensure the mission performance, various scenarios of Mars radiance at baffle entrance were also needed. To solve this issue, one can remark that Mars is at a very large distance, such that one point on Mars is related only to one direction at the entrance of the NAC. This way, any arbitrary scenario creates a straylight irradiance map on the detector which is the superposition of straylight maps created by point sources at infinity. As the designed system is rotationally symmetric, one can save on the simulations in FRED by only simulating straylight maps for angles of incidence. Maps for any direction can be deduced by appropriately rotating the simulated maps.

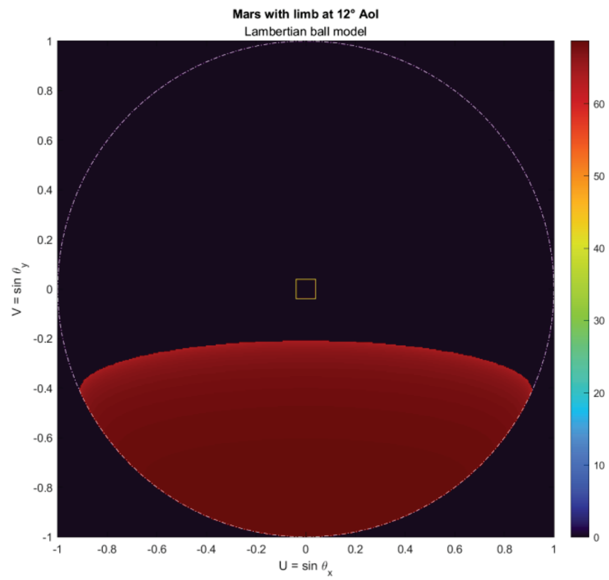

Figure 6 Radiance of Mars, with a limb limit at 12°, assuming it is a Lambertian ball of albedo 0.4. Colorbar scaled in W/m².sr. The dashed line shows the limits of the accessible étendue, the small square in the center is the NAC field of view.

These remarks provide the basis for an algorithm to compute the straylight map resulting from an arbitrary scenario. One can use FRED to compute straylight maps for a certain number of angles of incidence and then use software specialized in numeric computations such as MATLAB to compute the superposition for any scenario. As an added benefit, practically all objects can be included in the radiance map of a scenario: the Sun, but also objects on the satellite platform, etc.

As the computations in MATLAB are much less time consuming than FRED simulations, this provides an effective way to compute results for a large number of scenarios. Doing the same in FRED would require a dedicated setup for each scenario, a painstaking task. Moreover, this allows the separation of the generation of scenarios, the straylight simulations and the straylight evaluation which can then be made at different places.

Finally, simulation results were compared to real world experience. This was done with available telemetry data from other products. FRED simulation results, made along the same principles outlined in this article, were compared to the data. The simulation results matched the data quite well, except close to the exclusion angle where the sharp expected uptick in straylight occurred for slightly smaller angles than simulated.

7. SIMULATION RESULTS

A camera signal to noise ratio budget was elaborated and it allocated an irradiance level for straylight of 2 x 10^{-11} W/m² on the detector. To evaluate the straylight level various scenarios of Mars brightness were tested, ranging from the case of a uniform white cloud cover, peaking around 180W/m².sr, to the uniform Lambertian sphere of albedo 0.4, peaking around 60W/m².sr.

As the Sun is modelled as a point like source and Mars as a collection of point sources, an important characteristic of the simulation results is the impulse response, the straylight generated by a collimated source, as a function of the incidence angle. It is represented on Figure 7. One can observe that going towards smaller angles, there is a sharp change in straylight irradiance near 12°. This angle actually corresponds to the angle where light can enter the baffle and pass through the entrance pupil directly. Going towards higher angles of incidence, straylight decreases up to angles of about 70°.

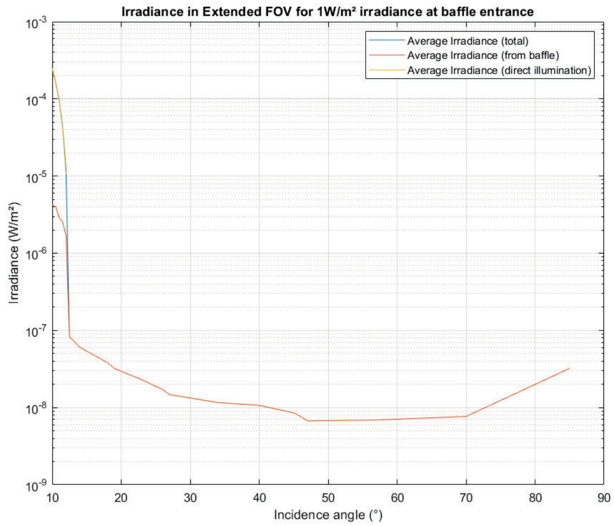

Figure 7 Average straylight irradiance over the detector area for 1W/m² at the entrance of the baffle vs the incidence angle.

Because of the large straylight irradiance for angles of incidence below 12°, the results for the scenarios with white cloud cover give large straylight irradiances, mainly because the top of the clouds extends up to 10.5° incidence. At this point the baffle does not prevent light from reaching the objective. Light directly even enters the objective beyond the aperture stop. In such scenarios, the level of straylight is 8 times the allocated budget once some design margin is considered. A typical irradiance map is shown on Figure 8.

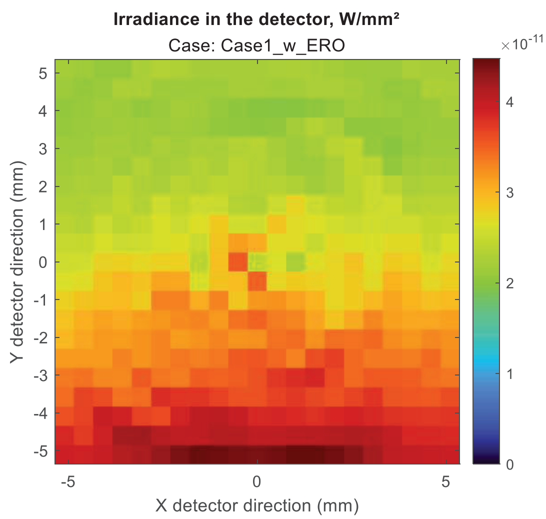

Figure 8 Straylight irradiance map due to Mars in a case with white cloud cover extending up to 10.5° incidence.

When the limb of Mars is below the required 12° and the Sun is at 60° from the line of sight, simulations give a just compliant result when the design margin is included. When the Sun is at 30° from the line of sight instead, simulations with the design margin give an amount of straylight about 2x the allocated budget. As the margin taken is a factor of 6x to take into account uncertainties linked to the difficulty of the requirements, this shows that the straylight performance is likely to meet the requirements while still remaining a challenge.

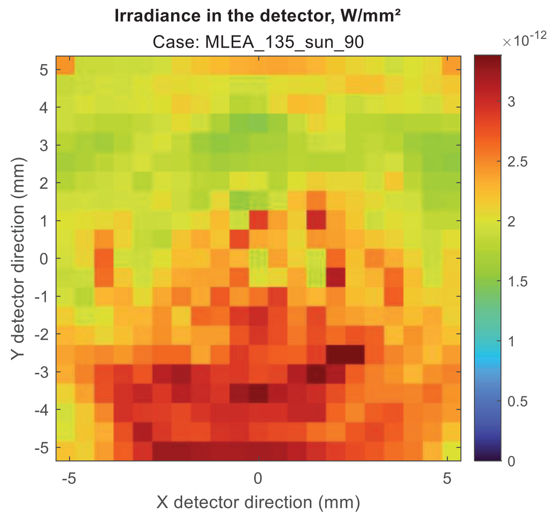

Figure 9 Typical irradiance map due to Mars, atmosphere extending up to 12° incidence.
The straylight irradiance is reduced by a factor of 10 with respect to the case of the atmosphere at 10.5°.

8. CONCLUSION

This paper presented the main steps of the design of the Narrow Angle Camera with respect to straylight, as well as the challenge represented by the faint brightness of the object to be detected (Orbiting Sample) compared to the Sun and Mars. A measurement campaign allowed to get more precise models for the paints and coatings. Extensive measures were taken to minimize straylight by reducing the size or TIS of critical objects. In order to assess the straylight level, simulations were run and an economic way of evaluating different scenarios was devised.

Looking at the performances, simulations indicate that the measures taken will allow the detection of the OS with a high probability.

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