International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia

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icso proceedings

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127777H · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691445

HEXABLACK - COMBINING MACRO, MICRO AND NANO DESIGN TO ENABLE VANE-FREE STAR TRACKERS AND TELESCOPES

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ABSTRACT

One of the most important challenges for star trackers and telescopes is eliminating stray light generated by reflections from the walls and other optical elements of the device. Most black coatings are not sufficiently efficient at grazing angles, and the most common solution is the incorporation of blackened vanes in the design.

Acktar black coatings exhibit particularly low residual reflectance and have been implemented in various instruments. The new proposed material, commercially known as HexaBlack, exhibits particularly low hemispherical and specular reflectance – especially at grazing angles. This material consists of a 3D-structured substrate coated with a well-known Acktar black coating.

This new solution makes new baffle designs possible with a minimum of vanes. In this article the BRDF, specular and diffuse reflectance data and specular simulations for these suggested designs for VIS and IR wavelengths.

1. INTRODUCTION AND DEFENITIONS

Stray light is a significant issue in almost any optical design, especially in space applications that require high-performance, long-life stability and maintenance free solutions. The problem takes place mainly in telescopes, star trackers and other sensing devices of the satellite. With 17,000 satellites anticipated to be launched within the next decade [1], minimizing the optical noise in satellite components is essential.

Currently, the best solution for eliminating stray light is to incorporate vanes into the baffles and optical housings of the device, which allow high reduction ratio of specular reflection from the optical components.

Besides design-focused solutions, new blackening technics and materials are developed to minimize the optical noise in the systems.

Two relevant terms when discussing stray light in star trackers and telescopes are angle of incident and specular reflectance. **Angle of Incident (AOI)** is angle between the beam and the surface normal. **The specular reflectance of a surface** is defined as the specularly reflected power normalized to the incident power [2], see Fig. 1.

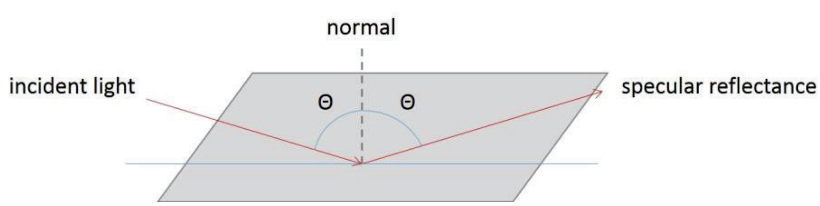

Fig. 1. Specular reflectance from a surface. Reflected angle equals to the incident angle

Most of the stray light in star trackers and telescopes is at grazing angles of incident, when the beam is nearly parallel to a surface.

2. VANES SOLUTION FOR STRAY LIGHT REDUCTION

The most prominent solution today for stray light is baffles with vanes. When using baffles with vanes, the stray light that arrives mainly at grazing angles is blocked by the vanes, while the direct rays pass to the detector without obstacles. The vanes protect light from reaching the detector, by reducing the light's intensity as much as possible.

In the first step, the field of view (FOV) of the detector placed at the end of the tube is determined. The most critical surfaces for stray light are those found outside of FOV and can be seen from the detector position or focal surface. These should be removed from the field of the detector.

In the next step, the optimal number of vanes should be calculated and placed in the inner diameter of the tub.

While baffles with vanes can offer a stray-light solution, to achieve the best performance the design must take into consideration several aspects such as optimum number of vanes, easy installation, low-reflectance coatings and production prices. These aspects increase the system's complexity, weight, size and cost.

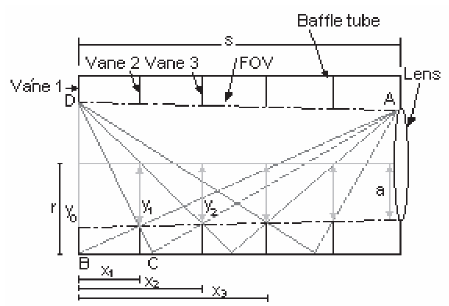

Fig. 2. General design of a baffle tube with vanes, with main dimensions and ray trace of incident light **[3]**

3. NEW LIGHT ABSORBING STRUCUTRE FOR GRAZING ANGLES

A simpler, more effective solution for stray light is the light-trapping material suggested in this article. This solution focuses on specular reflectance from grazing angles, but absorbs stary light from any incident angle. In this solution, many small vanes are places on the baffle using honeycomb structure surface [2].

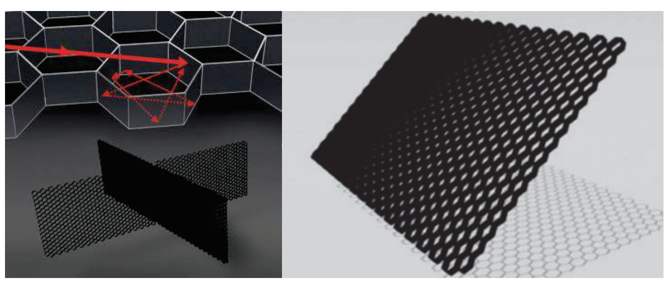

Fig. 3. The honeycomb structure of the absorbing material

DETERMINING THE CELL'S GEOMETRY

To determine the optimal height and size of the cells following factors were considered:

a) <u>Structure flexibility</u>

b) <u>Minimization of direct reflectance to the detector</u> – from certain angles on incidents and sloping edges.

c) <u>Structure strength</u>

d) <u>Generic design</u> – to minimize calculations and mechanical designing for every unique system.

Structure flexibility

The flexibility of the structure is important to enable to bend and insert the cells into the baffle. To maximize the flexibility of the material, the height of the cells has been reduced to 2mm, which is the minimum height for production.

Minimization of direct reflectance to the detector

After the height of the cell was determined to comply with flexibility requirements, the size of the cell is chosen to allow the best specular performance. As mentioned above, direct reflectance to the detector can be caused by certain angles of incident or sloping edges. Both of these factors were taken into account in the chosen geometry.

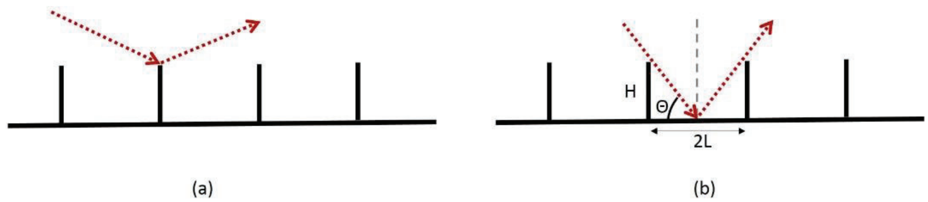

Fig. 4. Edge mode of the stray light paths – specular reflectance directly to the detector. Path (a) reflected from the sloping edge. Path (b) reflected from the baffle wall

While the cell's walls block stray light in large angles of incident, at narrow angles some stray light may encounter the baffle walls and, if not absorbed, be reflected directly to the detector. For a constant cell height, the larger the cell the larger AOI's range that could reflect directly to the detector. Taking into account the BRDF behavior of the surface (regardless of what kind of surface it is) we see that smaller AOI range results in smaller specular reflectance. It means that when considering direct reflectance from the baffle's walls alone, Θ1 (Fig. 5a) is the better choice.

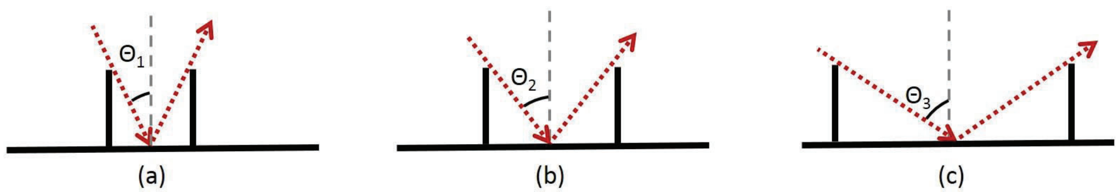

Fig. 5. Cell size influence on maximum AOI from baffle wall: $\Theta_1 < \Theta_2 < \Theta_3$.

On the other hand, smaller sized cells increase the total number of cells in the structure and therefore increase the number of sloping edges. To minimize the number of sloping edges, Θ_3 (Fig. 5(c)) is the better choice.

In order to determine the optimal cell size, we examined BRDF measurements made on a flat surface with Acktar coating. The measurements were performed at Fraunhofer IOF in Jena [4], [5].

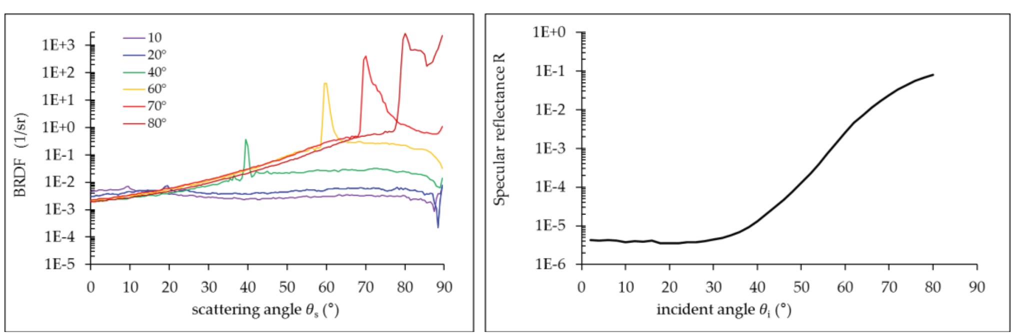

Fig. 6. Left: BRDF measurements at 4.6µm wavelength on Acktar black coating at different incident angles (only positive angles shown). Right: Measured specular reflectance of the same surface as a function of the incident angle

As seen in Fig.6, at angles smaller than 40° the specular reflectance doesn't significantly change. Therefore we will define cell size at which maximum AOI is close to 40°. Using a simple geometric calculation, we can calculate the required cell size:

$$cell\ size = 2 \cdot cell\ height \cdot tg(40°) = 2 \cdot 2 \cdot tg(40°) = 3.36mm$$

Taking into account the standard cells available, the final size was defined as 3.2mm.

In addition to reducing the total number of sloping edges, we also want to minimize the reflectance from a single sloping edge. The slimmer the width of the wall the lower the specular reflectance will be. Therefore, a thin foil of less than 40µm was chosen for the structure. This thickness provides high-enough mechanical strength while minimizing the surface of impact with the stray light. The 40µm foil was coated with Acktar, which add just a few microns to the thickness of the material, allowing extremely low reflectance.

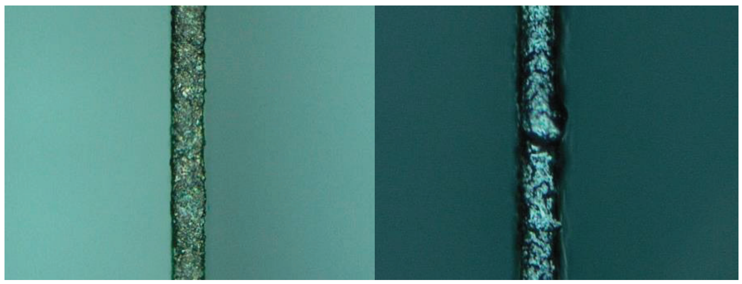

Fig. 7. Cross section of a 38µm aluminum foil coated on both sides, magnification of x100. Left: Acktar Magic Black coating. Right: Black paint.

BLACK COATING FOR HIGH PERFORMANCE

The honeycomb structure allows better stray light reduction due to its macrostructure. However, the black coating of the structure is of great significance and should be carefully examined for different applications. In our research we used Acktar Magic Black coating, which is one of the blackest coatings in the world. Having nearly 1% of hemispherical reflectance at VIS-NIR spectrum, this coating has many advantages that makes the material unique:

a) **Extremely low reflectance** - as mentioned above, having a lot of small vanes results in a great number of sloping edges that leads to specular reflectance that cannot be neglected. Low reflectance coating will reduce this unwanted reflectance.

b) **Thin coating layer** – a thin coating layer will minimize the surface area of the sloping edges (coating thickness about 1µm, see Fig. 7) and reduce the specular reflectance directly to the sensor.

c) **Low outgassing** – low outgassing is an extremely important property for space, and vacuum applications. Many treatments are developed to reduce the outgassing of materials, however these treatments usually also reduce the material's reflectance properties. Using Magic Black we avoid any treatments, having outgassing of 0.001% CVCM, 0.2% RML [6].

d) **Space qualified** – Acktar black coatings were qualified for space environment and space applications [7].

e) **Resistant to UV** – being an inorganic coating, the performance doesn't change even after long exposure to UV light.

f) **Light weight** – having a very low and uniform layer, the coating doesn't contribute much weight to the structure, resulting in low total weight.

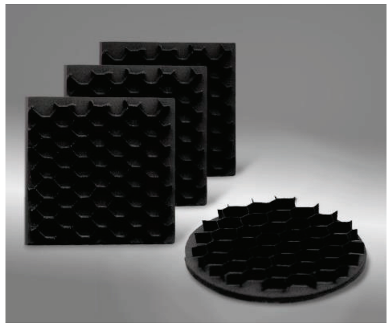

Fig. 8. The proposed absorbing material, HexaBlack

4. BRDF MEASUREMENTS

At the previous tests we performed BRDF measurements using ALBATROSS scatterometer developed at Fraunhofer IOF in Jena [4], [5]. The illumination range of the instrument is between 325 nm and 10600 nm.

Characterization of this kind of structure (see Fig.8) is especially challenging as (i) the light scattering distribution is expected to be anisotropic, which would require angle resolved measurements in the full reflection hemisphere. However, hemispherical measurements are especially comprehensive for infrared wavelengths. Moreover, (ii) the lateral dimension of the honeycomb cell size is larger than the illumination spot diameter. In order to get sample representative measurement data with reasonable effort, BRDF and reflectance was averaged from measurements performed at 5 different locations on first sample measured at 4.6µm, a relevant wavelength for space telescopes such as the James Webb Space Telescope.

Assuming the reflectance performance of nearly any material is better at visible wavelengths compared to infrared, our first evaluation was at wavelength of 4.6µm. The BRDF data as received on the first measurements is shown on Fig. 9.

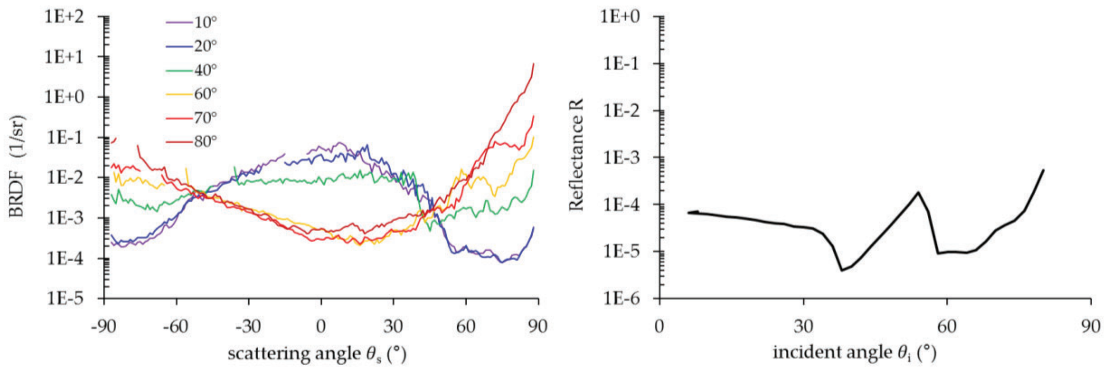

Fig. 9. BRDF (left) and specular reflectance (right) averaged from 5 different measurement positions at wavelength of 4.6 µm

After the evaluation in 4.6µm, another test was made in illumination wavelength of 640 nm with 45° linear illumination polarization, and spot diameter of about 3 mm. The results are shown on Fig 10. This time specular reflectance was not measured as the sample did not show any specular behavior. Hence, the specular reflection (R) in the VIS will be highly sensitive to the used detector aperture, i.e., R is nearly proportional to the detector solid angle for diffuse scattering sample.

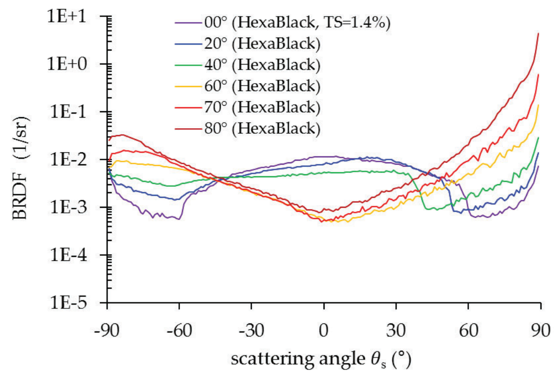

Fig. 10. BRDF averaged from 2 different measurement positions at wavelength of 640 nm

This time, based on experience from the previous measurements at IR, BRDF was averaged from measurements performed at 2 different locations on the sample.

It is easy to see that the performance of the material is similar at both IR and VIS ranges. The main difference is at small AOI where IR behavior is better at grazing angles, while VIS behavior is more flat and angle independent.

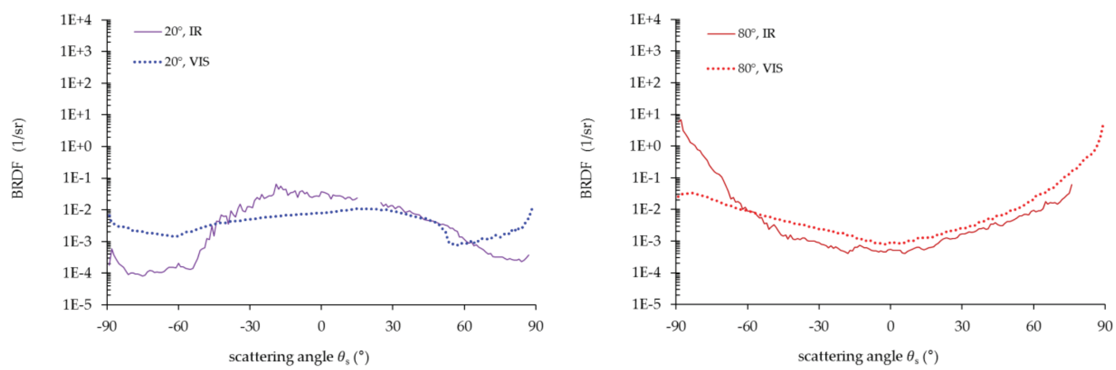

Fig. 11. BRDF comparison of IR and VIS measurements. Left: AOI = 20°. Right: AOI = 80°.

It should be noted that besides these 2D tests performed at Fraunhofer IOF in Jena, recent 3D measurements have been done which are not presented in this article. These tests display improved BRDF measurements when considering a 3D model.

2D SIMULATION

To verify the new coating's effectiveness at grazing angles three simulations using TracePro were performed at 512 nm and AOI 80: standart black, Acktar coating, Acktar coating with honeycomb structure.

Using a standard black, the total integrated relative flux was 46%, with maximum radiant intensity of 0.95. When the Acktar black coating without the honeycomb structure was simulated, the total integrated relative flux was reduced to 21%, with max radiant intensity of 0.8. When combining the Acktar coating with the honeycomb structure, the flux was reduced to 1.4%, and the max radiant intensity to 0.021.

Table 1. Specular reflectance simulation results at AOI 80

Surface coating	Wavelength		Total Integrated relative flux %	Max radiant intensity
Standard black	512nm		46	0.95
Acktar black coating	512nm		21	0.8
Hexa Black	512nm		1.4	0.021

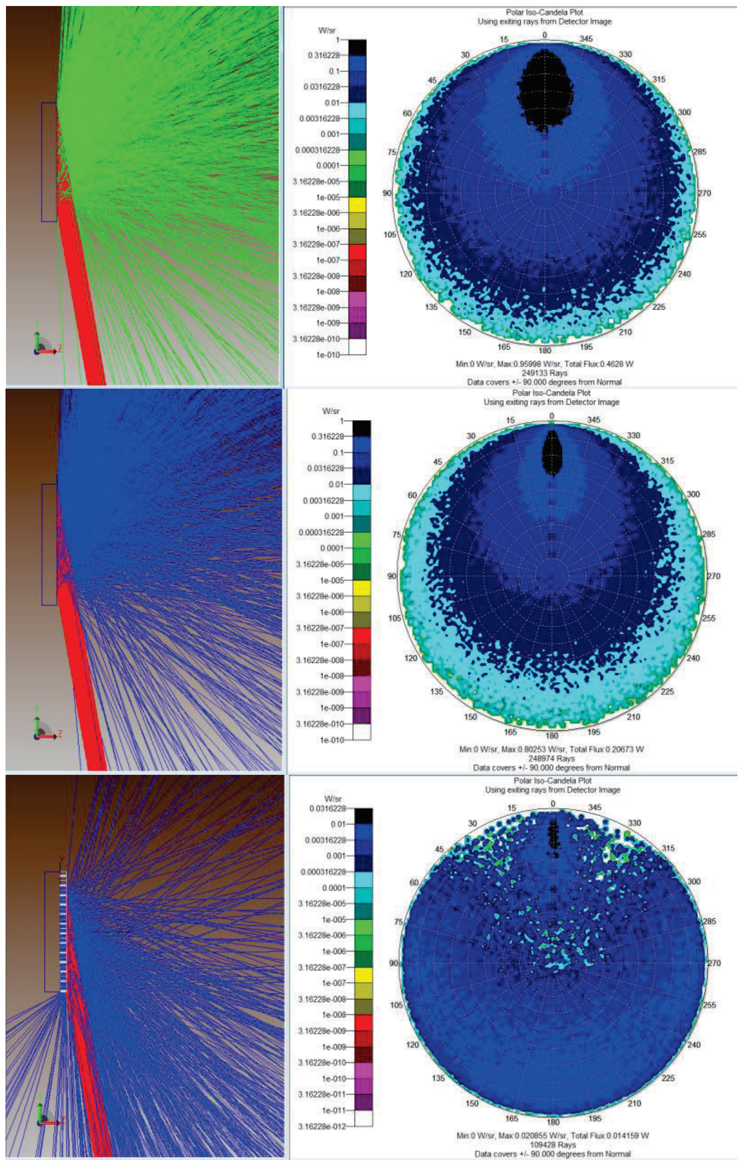

Fig 8. Specular reflectance simulation at AOI 80. Top to bottom: (a) Standart black, (b) Acktar coating, (c) Acktar coating with honeycomb structure (HexaBlack)

3D SIMULATION

Besides the 2D simulation at grazing angles, a 3D simulation of AOI 30 and 60 in VIS (white light) and IR (1.55 micron) was made using the optical design software ZEMAX and Synopsys 3D measurements:

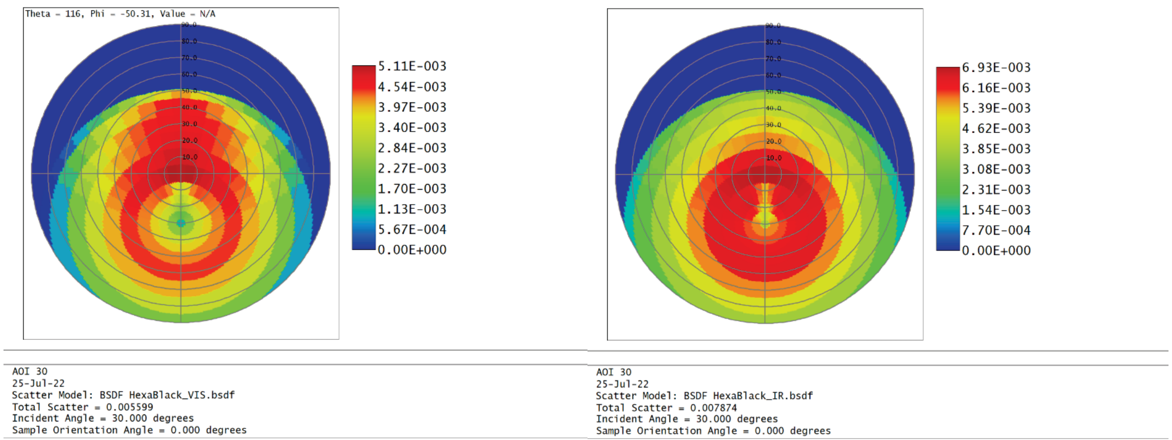

Fig 9. HexaBlack 3D simulation at AOI 30: a.VIS (left) b. IR (right)

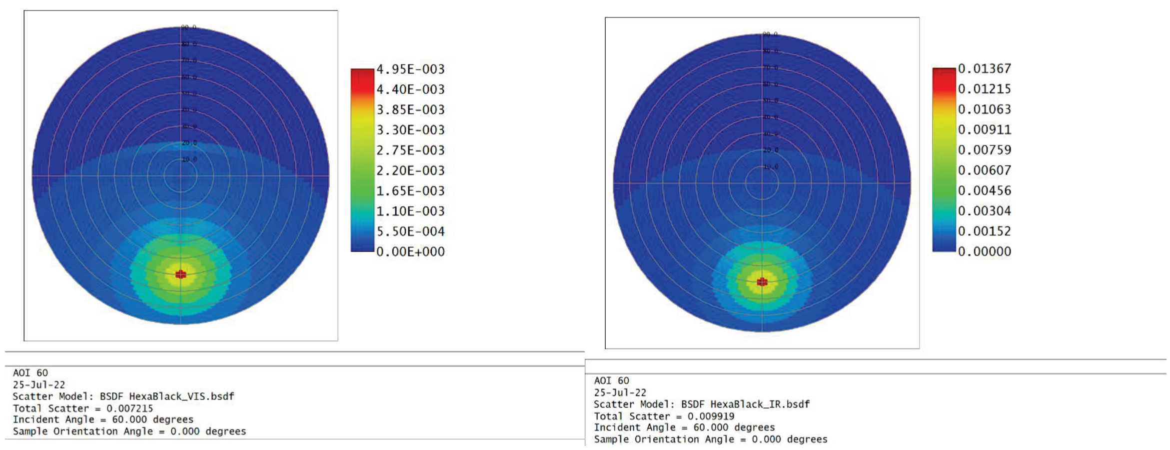

Fig 10. HexaBlack 3D simulation at AOI 60: a.VIS (left) b. IR (right)

The total integrated relative flux at AOI 30 was 0.56% in VIS and 0.79% in IR. At AOI 60, the total integrated relative flux was 0.72% in VIS and 0.99% in IR.

As seen in previous results, these measurements demonstrate extraordinary specular reflectance performance in both VIS and IR. Specular reflectance in AOI 80 will be performed in the near future.

5. CONCLUSIONS

In this paper we presented the characteristics of the HexaBlack, a novel black absorbing material that demonstrates low reflectance at any angles of incidence. It has been shown that the performance of HexaBlack at grazing angles was forty times better than standard coating, and that the optical performance of the material was similar in VIS and IR range of wavelength. This allows future designs to use the same material and design for optical systems working at any wavelength from VIS to IR.

Comparing the results to the optical performance of vanes in star trackers and telescopes, we suggest this material as a good alternative to common vanes design.

For more information on the HexaBlack and purchasing options, please visit Acktar's website in the following link:

https://acktar.com/product/hexa-black-absorbing-sheets/

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