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VANE-FREE DESIGN FOR STAR TRACKERS AND TELESCOPES

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I. INTRODUCTION AND DEFINITIONS

Stray light is a significant issue in optical design and can dramatically influence the performance of the optical system. Stray light reduces the dynamic range and the SNR (signal to noise ratio) in the device. The effect is caused by light scattering, ghosting in refractive optics, diffraction and etc.

Using proper design and black surfaces are the most popular ways for stray light reduction. In this paper we will deal with the blackening solution. A lot of blackening methods are available today, such as black anodized aluminum, black paints, flock paper, Acktar black and others.

Black coatings are usually characterized by specifying the specular reflected and the diffuse scattered components. The hemispherical reflectance of a surface is defined as the ratio of the total energy reflected into the subtending hemisphere to the energy incident on the surface and hence contains both components. Direct measurement is usually performed by integrating spheres.

The specular reflectance R of a surface is defined as the specularly reflected power P_R normalized to the incident power P_i. Total backscattering TS_b is defined as the backscattered power P_s normalized to P_i, where the range of scattered radiation to be detected (range of acceptance angles) is $\theta_s = 2^\circ...85^\circ$ and $\varphi_s = 0^\circ...360^\circ$ [1]. Hence, other than the hemispherical reflectance, TS_b excludes the power contained in the specular reflectance. TS_b can be determined by direct measurement or through numerical integration of angle resolved quantities as the Bidirectional Reflectance Distribution Functions (BRDF).

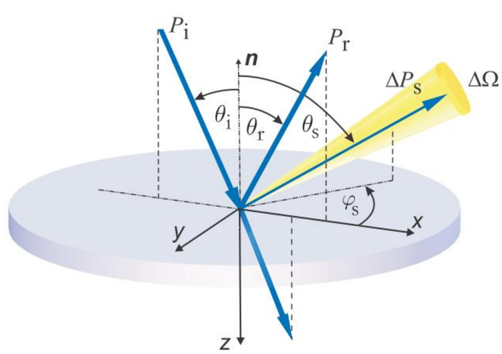

Fig. 1. Geometry for the definition of light scattering and specular quantities: **n** sample normal; P_i – incident light power at the incidence angle θ_i; P_r – specular reflected light power; ΔP_s – scattered light power into detector solid angle $\Delta\Omega$.

The BRDF is the fundamental way to describe the distribution of light scattered from an optical or non-optical surface or material [2]. BRDF data is also used in optical engineering software to model the propagation of stray light in optical systems and its impact onto the image properties during the design phase.

The BRDF is defined as the power ΔP_s scattered into the solid angle $\Delta\Omega_s$ normalized to the solid angle and the incident power P_i:

$$BRDF(\theta_s, \phi_s) = \frac{\Delta P_s(\theta_s, \phi_s) / \Delta\Omega_s}{P_i \cos\theta_s} \qquad (1)$$

θ_s and ϕ_s are the polar scatter and azimuthal scatter angles (see Fig. 1), respectively. The BRDF also depends on other parameters such as the angle of incidence θ_i, polarization, and wavelength. The cosine factor originates in the radiometric definition of the BRDF. It is sometimes omitted; the resulting function being called Angle Resolved Scattering (ARS) or cosine-corrected BRDF.

For black coatings, the hemispherical reflectance can reach values of less than 1% for quasi normal incidence or for near VIS illumination wavelengths. The specular reflectance is relatively low and has no significant influence on the hemispherical reflectance. However, for gracing angles of incidence and for infrared illumination wavelengths, the specular reflectance increases and the surface tends to behave more as a mirror (see Fig. 2).

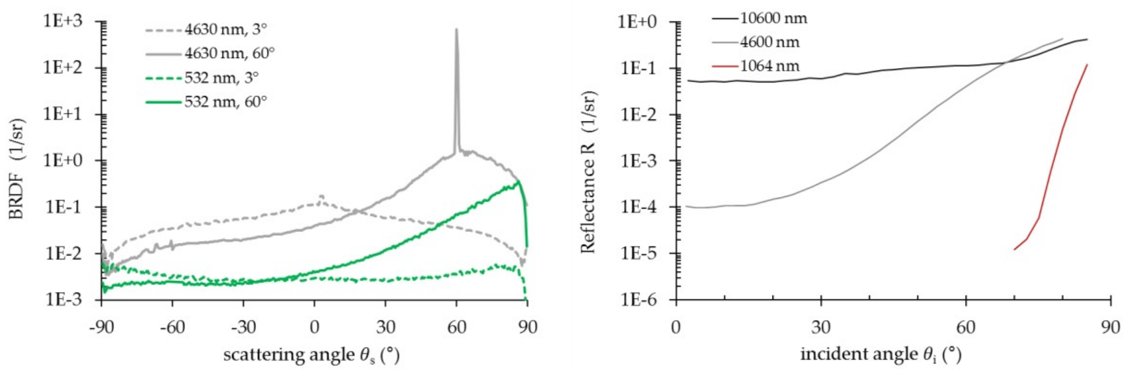

Fig. 2. Left: BRDF measurements at 532 nm and 4630 nm illumination wavelength on a black coating (Acktar Magic Black^{TM} [3]) at different incident angles (3° and 60°). TS values were determined to 1% (532 nm, quasi normal incidence) and 15% (4630 nm, quasi normal incidence). Right: Measured specular reflectance (Acktar Magic Black^{TM}) as a function of the incident angle for different illumination wavelengths.

The purpose of this paper is to describe a new black surface that will minimize the mirror-like effect of the surface, allowing to use this in star trackers and telescopes.

II. VANES AS STANDARD STRAY LIGHT SOLUTION

Most of the star trackers and telescopes use baffles as a solution for stray light problem. The idea of this design is to allow the light pass directly to the detector, but prevent any reflections from the internal walls of the telescope tube. The baffle made from a tube, which has vanes in internal walls. The vanes protect unwanted light from reaching the detector, by reducing it 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 tube.

Several issues should be considered for best performance:

1. The optimum number of vanes. Less will reduce the efficiency, more will be costly and heavy.

2. Installation of the vanes efficiently and without harm to the system and the coating.
3. Vanes make the system larger for certain FOVs and add weight to the application.
4. Price of the design and the implementation is usually high.
5. Installation time for vanes is not negligible.

The design variables for the baffle are determined by the following vane parameters: vane aperture, distance from the detector, spacing between the vanes, edge radius of vane aperture, bevel angle, angle relative to main baffle, and coating type [3], [5].

If the design has been properly chosen, stray light that enters the baffle is attenuated by several orders of magnitude before it reaches the detector.

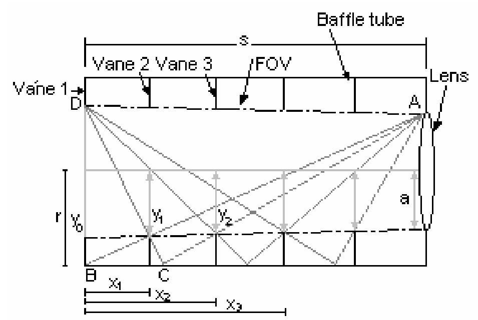

Fig. 3. Ray trace for determining the position of the vanes in the case of diffusely reflecting surface [4]

III. NEW BLACK SURFACE TO MINIMIZE THE AMOUNT OF VANES

As described before, vane based design is an efficient way for stray light elimination, but often it may be not easy to implement or can be too costly. Using the same idea of vanes we will suggest an alternative design, fast and easy to implement, light weighted and with reduced cost.

Assume we can place as many vanes as we can, for example every 10 mm. This means the detector to be well protected from stray light. Now let us make the vane height very small, namely large aperture, for example 20 mm less than the tube internal diameter (10 mm vane wall height).

This design will allow the use of very thin vanes, as small forces will act on every single vane. Thus the sloping edge will be very small, depending on the ability to produce such thin vanes. In our investigation, the smallest thickness was 20 µm. This will reduce the problem of edges that reflect light directly onto the detector, as the signal from such small areas is very small.

The next step is to find the proper black coating to reduce the reflectance as much as possible. Several points should be taken into account:

1. Low hemispherical reflectance (to attenuate the stray light hit the vanes surface)
2. Low specular reflectance (to ensure the smallest reflection from the sloping edges).
3. Thickness of the coating should be very small (to achieve sharp edges). If the coating will not be suitable, as happens with many paints, the edge will not be sharp enough (as shown in Fig. 4) and the total specular reflection to the detector will not be negligible.
   Most of vane based designs contain edges of at least 150 µm, thus using more vanes require thinner edges.

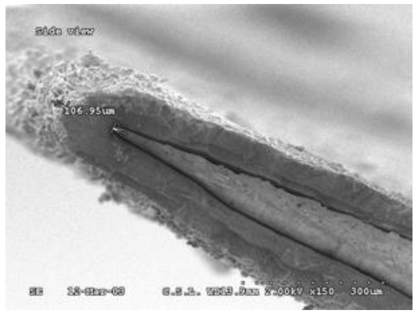

Fig. 4. Non sharp sloping edges - painted aluminum sheet [5]

4. Low outgassing and resistant to UV (important for space applications).

Considering all the specifics discussed above, we developed a unique honeycomb structured surface made of thin aluminum foil with an Acktar Magic Black^{TM} absorbing coating.

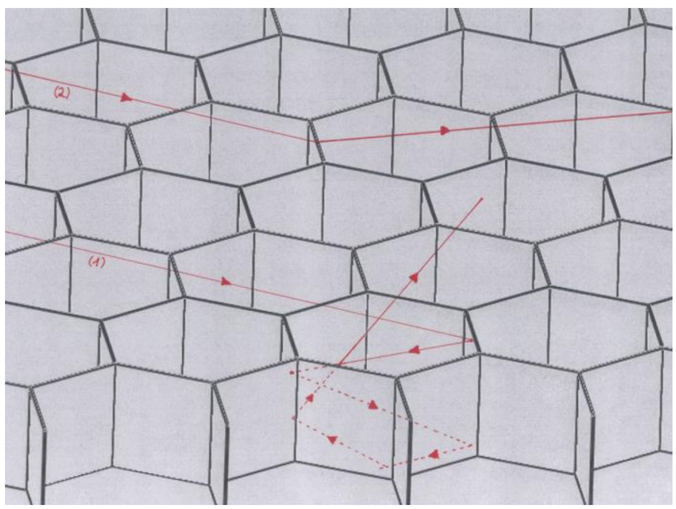

Fig. 5. Path of the stray light as reflected from the honeycomb structured surface. Path (1) will lose most of the power after 4 reflection from honeycomb wall (reflection from bottom plane not counted as not coated with Acktar Magic Black^{TM}). Path (2) will lose 0.01 of the power and reflected directly to the detector.

The unique properties of the black surface:

1. Acktar Magic Black^{TM} coating delivers extra low reflectance (1% hemispherical reflectance for near VIS illumination wavelengths), combined with a very small thickness. It reduces the reflected light radiance by 0.01 at every reflection, thus after several reflections the light radiance will significantly decreased. For example, a beam that is reflected 5 times from the walls will return with a power of 10^{-10} relative to the initial power.
2. Very small thickness of the material, allowing minimum specular reflectance from the sloping edges. The honeycomb made from thin foil (thickness 18 µm) which is coated with 1 µm thick layers, which results in a total thickness of 20 µm.

Fig. 6. Cross section of a 25 µm thick aluminum foil, coated on both sides by Acktar black, magnification of x100

3. Evenly covering the surface (compared to paint where the edges usually become very thick, as showed in Fig. 4 above).
4. Sloping edges with tooth shape – a special treatment of the wall tops reduces scattered light and specular reflection from the edges.

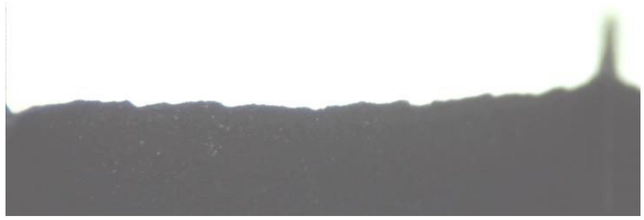

Fig. 7. Wall tops of the black surface, magnification x100

5. Ultra-light weight – as the material is made from thin foil and has small height, the total weight is very low compared to the usually 0.5-1 mm thick vanes in ordinary designs.
6. Low outgassing and resistance to UV radiation –this is a basic property of Acktar coatings, which enables using the material in space applications.
7. Easy to install – it is possible to simply apply the structured and coated sheet to the inner surface of the tube.

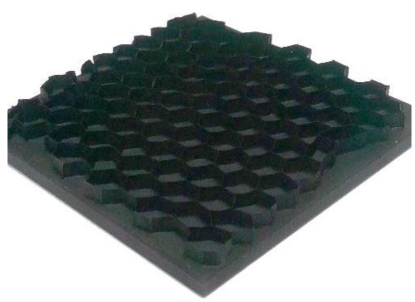

Fig. 8. The black surface on an aluminum substrate (for illustration contrast and brightness of the picture were enhanced)

IV. BRDF MEASUREMENTS

BRDF measurements on high-end absorbing surfaces like Acktar black coatings require scatterometers with capabilities far beyond conventional photometers. Only few instruments exist that meet these demands. The measurements described in this section were performed using the ALBATROSS scatterometer developed at Fraunhofer IOF in Jena [6], [9]. The instrument is located in a clean room (ISO 7) under laminar flow boxes (effective ISO 5) and capable to perform measurements ranging between 325 nm and 10600 nm illumination wavelength. The scatterometer achieves the sensitivities and dynamic ranges necessary to characterize high end optical components, materials, and black coatings [8].

Characterization of the honeycomb 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 the sample. An illumination wavelength of 4.6 µm was chosen, with 45° linear illumination polarization, and with an illumination spot diameter of about 3 mm.

Fig. 9 displays the BRDF and the reflectance measurements that were performed at 5 different measurement positions on the sample, respectively. The missing data points at $\theta_i \approx \theta_s$ are a result of the detector blocking the incident beam. It can be observed that for different measurements positions the BRDF changes especially for scattering angles between 30° to 60°. The reflectance measurements at different positions show highest variation also for incident angles of about 30° to 60°. These effects can probably be related to changing obscuration conditions inside the honeycomb structure.

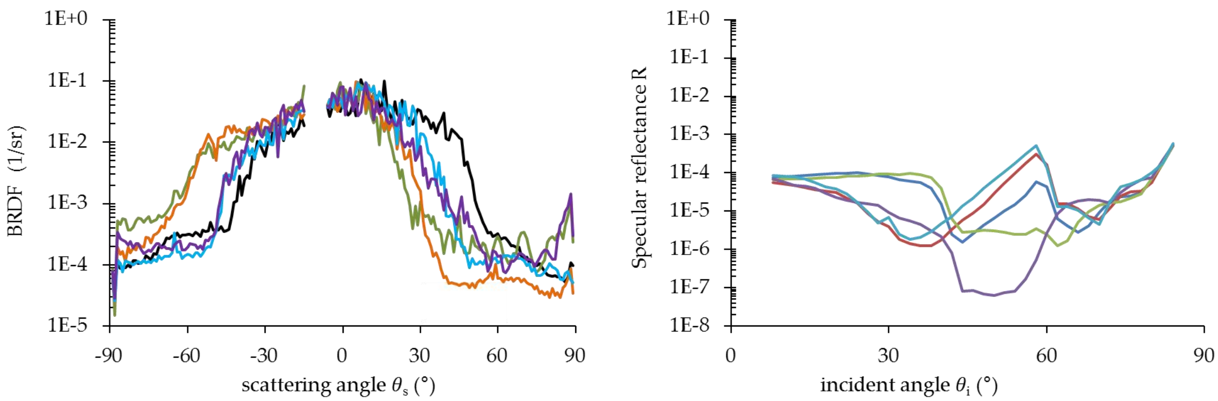

Fig. 9. BRDF (left, 10° angle of incidence) and reflectance (right) measurements performed at 5 different measurement positions, respectively

Fig. 10 displays the averaged data from the measurements described above. Different azimuthal orientations would probably lead to different obscuration conditions; however, both BRDF and reflectance now represent a much closer approximation to the overall performance of the honeycomb structure.

Compared to conventional black coated surfaces, the honeycomb structure is capable to effectively reduce specular reflectance at gracing angles of incidence even for infrared illumination wavelengths.

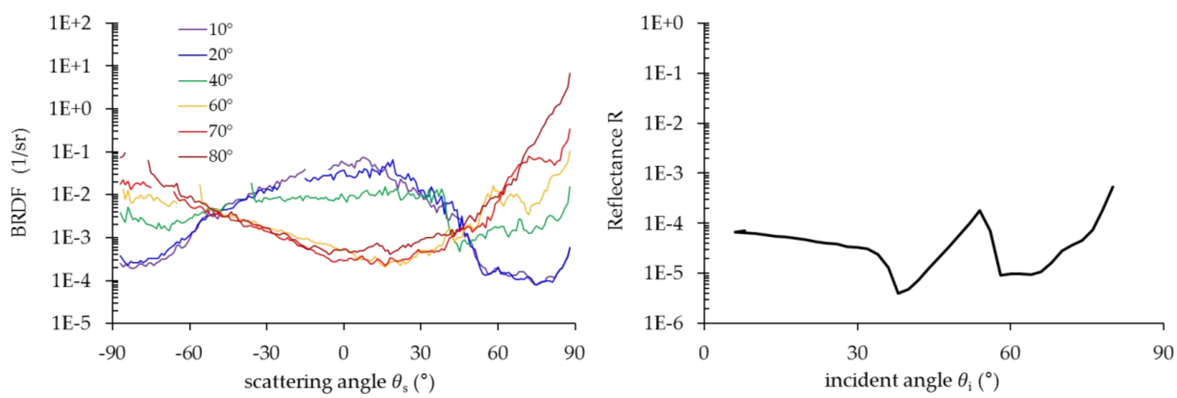

Fig. 10. BRDF (left) and reflectance (right) averaged from 5 different measurement positions, respectively

V. SIMULATION OF THE DESIGN USING OPTICAL DESIGN SOFTWARE

Two simulations were performed using the optical design software - TracePro. The goal of the simulations was to compare a standard design of a baffle with vanes to a design of a baffle with the surface presented in this paper.

a. Simulation of the baffle with Acktar proposed surface

A tube with the suggested material in the inner surface was tested. At the entrance a lens doublet with EFL=150mm was placed. For the light source, a collimated beam out of the FOV (9° off axis) was used. The result is shown in Fig 11. The ray tracing simulation shows that only a very small number of the input rays reaches the detector. The total rejection ratio of the system was $7.9 \cdot 10^{-7}$.

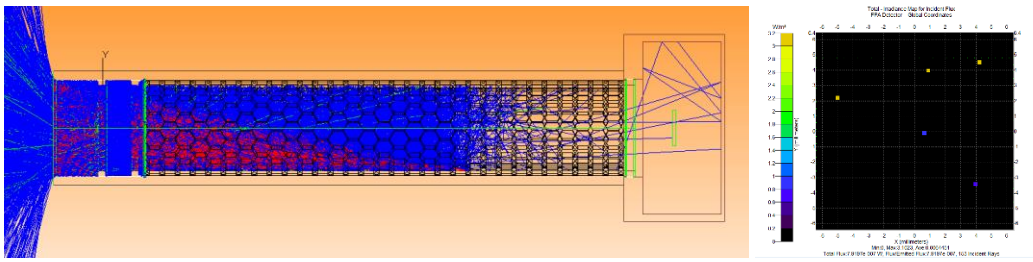

Fig. 11. Ray tracing simulation (left) - A lens doublet was placed in the left side of the tube, the detector was placed in the right side. Total irradiance map of the incident flux on the detector (right).

b. Simulation of standard baffle with vanes

A similar simulation was made for a standard design of a baffle with vanes. Five vanes were placed inside the same tube to achieve the same FOV as before. The result is shown in Fig 12. The ray tracing simulation shows as before, that only a very small number of the input rays reaches the detector. The total system rejection was $3.3 \cdot 10^{-5}$, concentrated in the arch shape at the middle. Therefore, Acktar proposed surface improved the rejection to stray light by 2 orders of magnitude compared to the vane design demonstrated here.

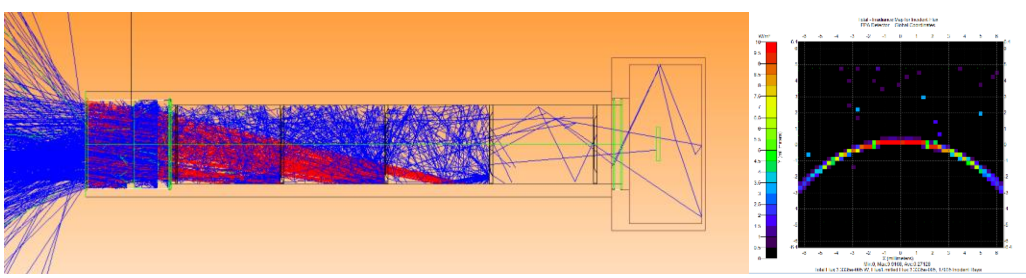

Fig. 12. Ray tracing simulation (left) - five vanes were placed in the tube to achieve the same FOV as in the first simulation. The detector was placed in the right side. Total irradiance map of the incident flux on the detector (right).

VI. CONCLUSIONS

In this paper we presented a novel black absorbing surface revealing reduced specular reflectance at high angles of incidence. It has been shown to perform at least comparably to vanes in star trackers and telescopes. In some cases it will show enhanced performance of stray light reduction as compared to common vanes.

As a conclusion of this study, we suggest this new development as a replacement of a part of the vanes in a variety of space designs and even all the vanes in some of the systems. This will reduce costs, weight and add flexibility to many designs.

Future work will include further investigation in order to determine the best choice of the honeycomb dimensions (wall height and cell size) for different types of tubes.

VII. AKNOWLEDGMENT

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REFERENCES

[1] ISO 13696:2002, *Optics and optical instruments - Test methods for radiation scattered by optical components,* 2002.

[2] J. C. Stover, Optical scattering: Measurement and analysis, 3rd ed., Bellingham, Wash.: SPIE Press, 2012.

[3] Acktar Ltd, [Online]. Available: http://www.acktar.com.

[4] E. C. Fest, "Baffle and Cold Shield Design," *Chapter 9 - Stray Light Analysis and Control SPIE Press,* 2013.

[5] V. Latendresse, D. Katsir, K. Shabtai, J. McKeever, V. Isbrucker, J. Lavoie, R. Kruzelecky and W. Jamroz, "High Absorbance Coatings For GHGSat Nanosatellite," in *13th ISMSE - International Symposium on Materials in a Space Environment*, Pau, France, 2015.

[6] C. N. S. Lucimara, É. G. Carvalho, L. F. Santos, F. M. M. Yasuoka, M. A. Stefani and J. C. Castro, "Baffle Design and Analysis of Stray-light in Multispectral Camera of a Brazilian Satellite," *Annals of Optics XXIX ENFMC,* 2006.

[7] J. Y. Plesseria, E. Mazy, J. Defise, P. Rochus, E. Lemmens and D. Vrancken, "Optical and mechanical design of a straylight rejection baffle for COROT".

[8] S. Schröder, T. Herffurth, H. Blaschke and A. Duparré, "Angle-resolved scattering: an effective method for characterizing thin-film coatings," *Applied Optics,* vol. 50, pp. C164-C171, 2011.

[9] S. Schröder, A. von Finck and A. Duparré, "Standardization of light scattering measurements," *Advanced Optical Technologies,* Vols. 4(5-6), pp. 361-375, 2015.

[10] M. Hauptvogel, S. Schröder, M. Trost and A. Duparré, "Light scattering characterization of optical components for space applications," in *ICSO - International Conference on Space Optics*, 2016.