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Further advancement of wide-angle EUSO telescope with holographic and Fresnel lenses

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Air shower observations from space such as EUSO uses a remote-sensing camera for fluorescence signals. It requires wide field of view, e.g., 60-degrees Field-of-View, with relatively forgiving imaging resolution of an order of 0.1-degrees, comparable to a pixel size of the photon detector at the focal surface. The wavelength for florescence detection ranges from 330 nm to 400 nm and the camera needs to be polychromatic. The materials must be radiation hard and vacuum proof for use in space for five years or longer. The total throughput has to be optimum so that the detection threshold energy of air showers is sufficiently lower than 10^{20} eV. The Extremely Universe Space Observatory (EUSO) Optic Design Team has recently upgraded its telescope design with a holographic unit. Its characteristics and simulated performances are presented.

1. Introduction

The EUSO mission[1, 2] is to study cosmic rays with extreme energies by detecting fluorescence lights, especially, those of UV lines at 337, 357 and 391 nm that are created in an atmospheric shower event. The optical system must observe the largest possible observable area-size from the orbit with the most efficient light collection capability. Due to science requirements, EUSO's wide-field camera has a 60° Field of View (FoV) and 0.1° spatial resolution, which corresponds to 5 mm pixel size on the focal surface or 800 m on ground.[1, 2] The throughput efficiency must be > 50% overall in the FoV, designing the instrument with an Entrance Pupil Diameter (EPD) ≥ 2.3 m. This will enable EUSO to observe EHECRs with an order of magnitude larger area than what is being done with the ground-based observatories: the statistics of EHECR events will then increase above 10^{20} eV by an order of magnitude or more.[1, 2, 3]

Furthermore, the focal number F/# is 1.0 or smaller to maintain a small focal surface, which is needed for easiness, power consumption and weight constraints, but such a fast optics imposes difficulties for the imaging designs. These requirements are made within the limitations of non-deployability of the observatory. When a deployment[3] is allowed (i.e. when some major constraints of the mission can be released), a higher efficiency optics design will become usable with a larger collecting aperture and the same limited size of the focal plane.

In the last years the optical module has been designed with varieties of tools including several catadioptric systems and Fresnel lenses, exploiting the possible overall configurations. In case of a non-deployable space mission, solid monolithic Fresnel lenses are best suited,[4] otherwise a large catadioptric system is considered.[5] As of today, the baseline of the EUSO telescope is monolithic. When a deployable scheme becomes acceptable in future for in-space deployment,[3] Makustov-Pitalo catadioptric design[5] using a large mirror and two collector Fresnel lenses should become feasible.

2. The EUSO Optical System with two Fresnel Lenses

In this conception, the mission has to be carried up to the ISS through the Space Shuttle – Space Transportation System (STS), or alternatively, via other means currently under study with unmanned HTV spacecraft. Therefore the logistic boundary conditions of the allowed diameter yield no more than 2.5-m maximum diameter for a non-deployable (monolithic) instrument with STS, while it allows up to 3.5-m if it is carried by HTV Consequently, this limitation constrains the Entrance Pupil size which gives the light collection capability of the instrument not exceeding 3.5-m diameter.

If the dimension of the lens diameters is 2.5-m, the Entrance Pupil is 2.3 m for a wide-angle design and for the f/# as fast as 1.0. This is the best optimization of the optical design recently pursued as an evolution of the prior configurations. Indeed, one of the first Fresnel lens systems was designed to fit the above-mentioned dimensions.[4, 6] Due to the choices of conventional dispersive PMMA materials and corresponding optical design solutions it had smaller EPD (1.9 m) and bigger f/# (= 1.25).[4] As of today, the baseline for the EUSO telescope recommends a solution which embeds two diffractive surfaces; one on the front of the first lens and one on the back of the second one. Both lenses are curved double-sided Fresnel to yield a better imaging performance for the entire wavelengths in our concern. The addiction of holographic elements is introduced to tame the chromatic aberrations further and hence to keep reasonably small spot sizes on the curved focal surface. However, diffractive grating on curved Fresnel facets are very difficult for manufacturing.

The most recent design optimizes the performance by using two curved double-sided refractive Fresnel lenses with one free diffractive plane located between the stop and the second lens [Fig. 1], eliminating two curved diffractive lens surfaces. This choice achieves a more efficient chromatic correction, with a single and flat diffractive element which behaves also as a field lens, resulting in improved collection efficiency at large angles at all wavelengths due to reduced vignetting and dispersions. Most notable fact is that, with the best UV material considered for this configuration (CYTOP) the design exceeds EUSO requirement by over 20%. A comparative chart between the performances of the baseline and the new solution is depicted in Fig. 2. A similar design with UV-PMMA is also shown. This graph highlights the percentage of Encircled Energy (EE) that falls in a 5-mm bucket, which was corrected by vignetting and cosine of the field angle.
The optical transmittance of the latest model is presented in Fig. 3.

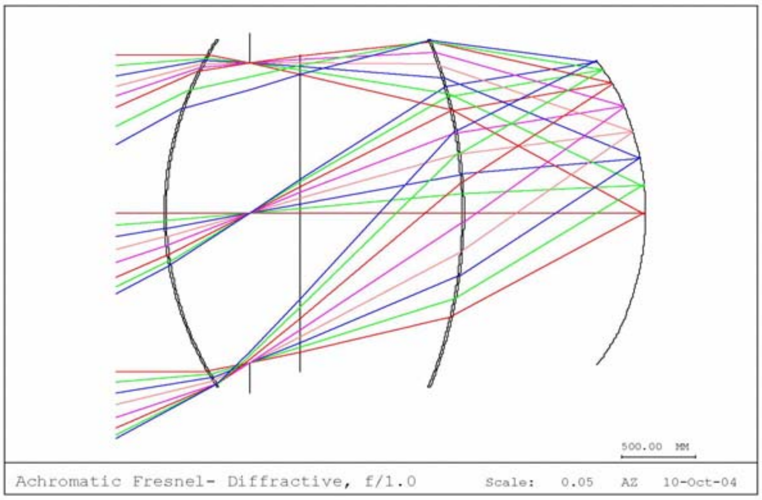

Fig. 1. The CYTOP design, having two curved Fresnel lenses and one flat diffractive plane.

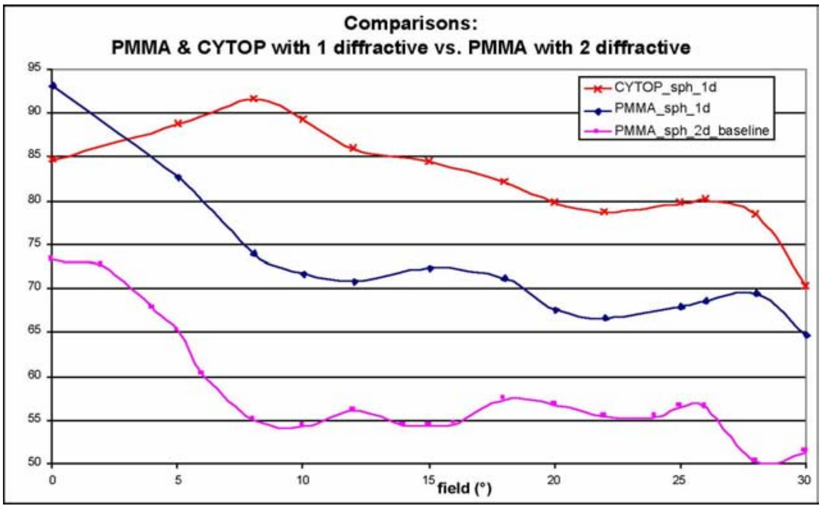

Fig. 2. Comparisons of encircled-energy (%) (within a 5-mm pixel) for three recent designs.

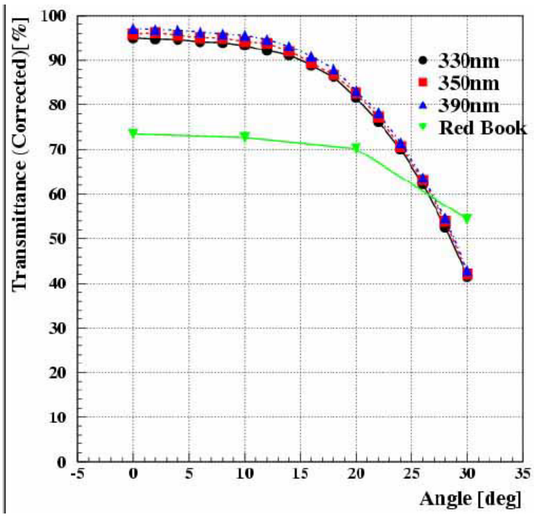

Fig.3 Transmittance including the facet-losses with the CYTOP one-diffractive design.

3. Super EUSO: An Option for a large Deployable Optic System

In case of a release of some mission constraints, a deployable catadioptric system has also been analyzed. The so-called "Super EUSO" is an option suited for much future in-space assembly of larger optics, exploiting the ISS as a space platform.[3] It was developed in the years 1996-1999, and it differs from EUSO not only for the kind of optics but also for some main parameters: this solution has in fact faster optics, F/0.6, and an Entrance Pupil Diameter > 5 m, allowing an energy threshold $<10^{19}$ eV.[3]

Fig. 4 and Table 1 depict the configuration developed, a Maksutov – Fresnel lenses – Mangin mirror combination, which we call Maksutov-Pitalo wide-angle catadioptric optics.[5]

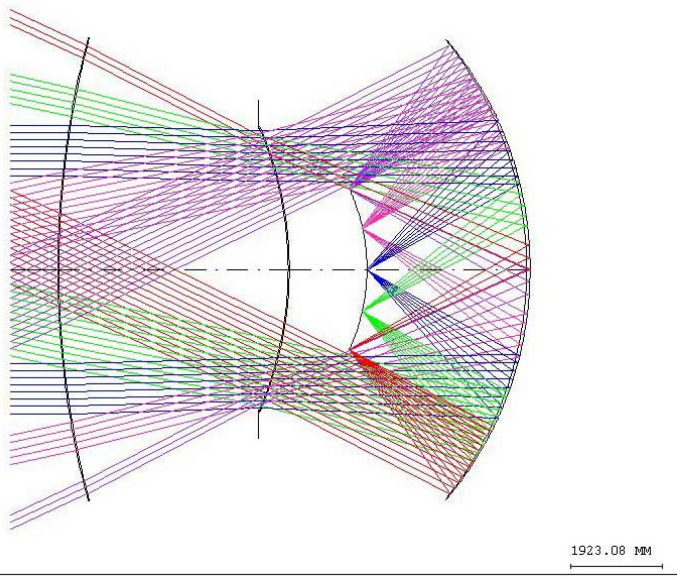

Fig.4 A fast Maksutov-Pitalo optics with f/# = 0.6 and EPD = 6-m

Table 1 Geometry of the Maksutov-Pitalo optics (F/# = 0.66) for Super EUSO. Imaging diameter for the 91% Encircled Energies are 3.01 mm and 5.12 mm, respectively, at on-axis 0° and far off-axis 25°.

Entrance Pupil Diameter	Length	Element axial thickness	1^{st} Corrector Diameter	2^{nd} Corrector Diameter	Fresnel-Mangin Diameter	Focal Surface Diameter
6 m	9.84 m	24, 24, 72 mm	9.6 m	5.9 m	9.6 m	3.35 m

4. Conclusions

Efficient optical designs became available for EHECR observations from space for both non-deployable and deployable telescopes. Technologies that enable these designs are already available for the sizes smaller than shown in this paper. Small petal segments are replicatable and allow manufacturing of large optics.[7]

5. Acknowledgements

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