Wide-angle Optical Telescope for the EUSO Experiments

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Abstract

Future space-based air shower experiments, including the planned EUSO mission, require a wide-angle telescope in the near-UV wavelengths 330 - 400 nm. Widest possible target aperture of earth's atmosphere, such as $> 10^5$ km^2 sr, can be viewed within the field-of-view of 30° from space. EUSO's optical design is required to be compact, being constrained by the allocated mass and diameter for use in space. Two double-sided Fresnel lenses with 2.5-m diameter are chosen for the baseline design. It satisfies the imaging resolution of 0.1 degree over the 30-degree field of view.

1. Introduction

Extreme Universe Space Observatory (EUSO)[1] is the first space mission to observe extreme energy cosmic rays (EECRs) above 10^{20} eV with a single telescope on orbit. It uses a wide-field Fresnel lenses[2,3,4] to detect fluorescence lights at near-UV wavelengths (NUV: 300 - 410 nm) emanating from air showers passing in atmosphere. The EUSO optics evolved from the wide-angle optic design studies conducted at the University of Alabama in Huntsville (UAH) since 1995 under the NASA Cross-Enterprise-Technology-Development (CETD) programs.[2,3,4] This paper describes the baseline optic design and performance of the system.

2. Requirements for Imaging Characteristics

Optical Subsystem Requirements have been determined for the detailed instrument requirements as follows:

- A 2-m entrance pupil diameter (EPD): This is the minimum size required to collect fluorescence signals from EASs with energies 3×10^{19} eV.
- A 60° full-angle FOV: This is required to collect sufficient samples of events.

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- A 6 arcmin resolution: This resolution matches the desired pixel size.
- A 330-400 nm optical bandwidth: This contains prominent N2 fluorescence lines represented by 337, 357, and 391 nm
- Fast optics with f/1.0 - 1.25: This is required to minimize the size and width of the focal plane for use in space, for which weight and size are constrained.

Early on in this investigation we ruled purely reflective systems unsatisfactory. For a reflective surface in air the effective refractive index changes from 1 to -1 (i.e. D(1/n)=2), while the refractive case the change is less 1 (i.e. for n=1.5, D(1/n)=1/3). A catadioptric system uses both reflective and refractive optics such as in the Schmidt or Maksutov camera. The high symmetry around the center of the entrance pupil makes this system almost free from aberrations. The main trouble of this solution is the obscuration of mirror made by the focal plane, which becomes important at large FOV. The main drawback of this design is that the correcting element is highly aspherical, then difficult to build for a space use. Although the modified Maksutov/Schnmidt designs have many merits, it is considerably more complex and larger than the double Fresnel refractive system.

By using Fresnel lenses in place of standard lenses, we can achieve a large-aperture, wide-field systems with drastically reduced mass and absorption. Based upon the light-weight low dispersion polymer, PMMA grade#000, we have designed an optic system that uses two Fresnel lenses and meets all of the EUSO specifications. Each Fresnel lens is cut on a spherical substrate and has grooves in both sides. The system has been optimized for polychromatic acceptance throughout 330-400 nm with 90% of encircled energy focused within a focal surface pixel size 4-7 mm.

Fresnel lenses do have drawbacks. The faceted nature of the Fresnel surface causes a portion of the incident light to deviate from its intended imaging path. In addition to reducing the signal available to the photon detector, this results in scattered light and a reduction in overall image contrast. These effects have been analyzed via computer modeling using the program ASAP (Breault Research Corp., Tucson, AZ) and the fabrication and testing of prototype optics in the EUSO configuration.[2, 3, 4] The results of this analysis indicate that the effects are predictable using computer models and that the signal losses are acceptable.

3. Designing Principles

EECR science objectives require the combination of large opening angle ($\pm 30^\circ$) and large collecting power ($>$ 2 meter diameter, $\sim$ 6.25m^2 area) for the telescope, and it is unique to EUSO or any future space-oriented EECR observatories. Our concept is optics with forgiving imaging demands. The aperture we seek is 2 meter, but with an image quality only 0.001 of the diffraction limit.

Chromatic aberration of the refractive system limits the performance at the 337 and 391 nm wavelengths. However, more than 85 percent of the energy from the luminous disk of the EAS in the 330-400-nm band is contained within the central pixel. This allows sufficient image quality to yield a reliable trigger. Faster and more precision designs have been made with f/1.0 using lower dispersion materials such as CYTOP, and other special PMMA materials, which enabled to extends the EPD to 2.3-2.4-m for the lens diameter 2.5-m.

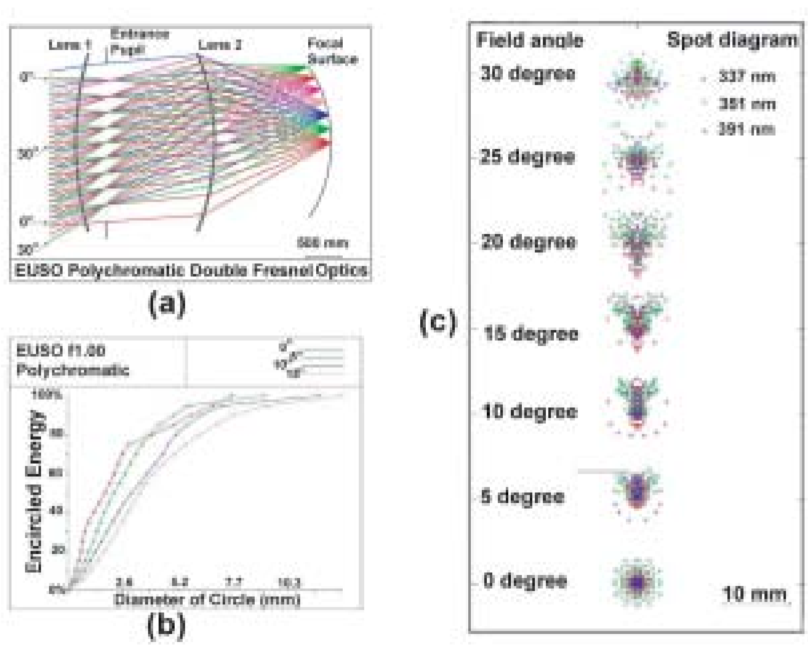

Fig. 1. (a) Layout of Fresnel lenses, (b) spot diagram and (c) Encircled energy as a function of the spot diameter (mm).

4. Baseline Design and Performance.

Most of available degrees of freedom are utilized in order to accomplish suitably small imaging spot sizes for all the NUV wavelengths. These include a use of two Fresnel lenses, double-sided for each lens, base curvatures of a lens with spherical or aspheric shape, and with or without diffractive fine gratings. We present here in Fig.1(a) polychromatic baseline optic design, and in Figs.1(b) and (c), imaging characterization with f/1.0 having gratings. The spot diameters for RMS and 90% encircled energy are given in Table 1.

Table 1. Polychromatic Design of EUSO LENS. Two double-sided Fresnel elements with diffractive grating on the front surface of Element 1 and on back surface of element 2. EPD = 2.3 m, and the spot measurements for all wavelengths 337 - 391 nm.

Field angle	0°	5°	10°	15°	20°	25°	30°
RMS diameter (mm)	2.7	3.5	4.5	4.7	5.0	4.7	5.1
90% encircled diameter (mm)	4.3	5.3	6.5	6.9	7.7	7.9	8.1

5. Conclusions.

A wide-angle, large-aperture space telescope has been designed and prototyped to enable the first generation observatory for exploring the EECR air showers above 10^{20} eV. A light-weight, single telescope enables an observation of the earth's area size $> 10^5$ km^2 from an ISS orbit at $\sim$400 km. Fine-tuning is continuing with the maximization of the optical throughput.

6. Acknowledgments

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1. L. Scarsi et al, EUSO Collaboration, and other related papers, in this Conference, 2003.
2. L.W. Hillman et al., in this Conference, 2003.
3. D.J. Lamb and L.W. Hillman, SPIE, 1999.
4. D. J. Lamb, 1999, Ph. D Dissertation, the University of Alabama in Huntsville.
5. D.J. Lamb, in "Space Factory on International Space Station," eds. T. Ebisuzaki et al., pp. 93 - 105, (2000), Universal Academic Press, Tokyo; Thesis, University of Alabama in Huntsville, 1999.