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Advancement of the wide-angle JEM-EUSO optical system with holographic and Fresnel lenses

JEM-EUSO COLLABORATION

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Abstract: JEM-EUSO is a space mission to observe extremely high-energy cosmic rays, evolved from the previous design studies of EUSO. It is adjusted for the Japan Experiment Module (JEM) of the International Space Station (ISS). JEM-EUSO uses a wide-angle refractive telescope in near-ultraviolet wavelength region to observe from ISS the time-and-space-resolved atmospheric fluorescence images of the extensive air showers. The JEM-EUSO optics is re-designed after the ESA-Phase A studies to upgrade the light-collecting-power by using a new material CYTOP, and its overall light-collecting power is about 1.5 times higher than the ESA-Phase A baseline optics. We describe in this paper an optimized optics design that maximizes the sensitivity of JEM-EUSO, and the results of the optics manufacturing tests.

EUSO optics overview

Space-based air shower experiments require a wide-angle telescope in the near-UV wavelengths 330 - 400 nm. Widest possible target aperture of earth's atmosphere can be viewed within the Field-Of-View (FOV) 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. The EUSO optical design evolved from the design studies of the Wide-angle Lens (OWL) conducted at the University of Alabama in Huntsville (UAH) since 1995 under NASA's Cross-Enterprise-Technology-Development Program (CETDP). UAH group found out that only refractive systems could satisfy the full set of the logistic constraints imposed by the EUSO requirements and the ISS transport vehicles STS and HTV. Two double-sided Fresnel lenses with 2.5-m diameter are chosen for the new baseline design with a possible option of 2-m and 3.5-m alternatives. Fresnel lenses (made of radiation hard light-weight plastic material) can provide a large aperture, wide FOV system with reduced mass and low absorption. It satisfies the imaging resolution of 0.1° over the 30° FOV[1]. The heritage of EUSO and changeover from ESA-EUSO to JEM-EUSO are shown in another paper in this conference (Ebisuzaki et al.[2]). The older design of the ESA-phase-A (EUSO) is denoted as ESA-EUSO hereafter. Explained below are the new lens materials, improved optical design of JEM-EUSO, and their manufacturing tests.

JEM-EUSO Optics

JEM-EUSO has two of a double Fresnel lens module (15 mm thickness) with 2.5m external diameter and a large-area focal surface of detectors like ESA-EUSO. JEM-EUSO's schematic is shown in fig.1. The overview of the JEM-EUSO telescope is shown in another paper in this conference (Kajino et al.[3]).

JEM-EUSO optics was re-designed from ESA-EUSO to upgrade the light-collecting-power by using a particular new material CYTOP[4]. This material is UV transmitting fluoropolymer (ASAHI GLASS CO., LTD. JAPAN). It has ∼50% smaller (hence better) dispersion characteristics than UV-PMMA-000 (ESA-EUSO optics material). Although, UV-PMMA-000 (Mitsubishi Materials Co., LTD. JAPAN) is one of the best kind of the special grade UV-transmitting polymethyl-methacrylate, its dispersion is not sufficiently small to suppress the chromatic aberration for the

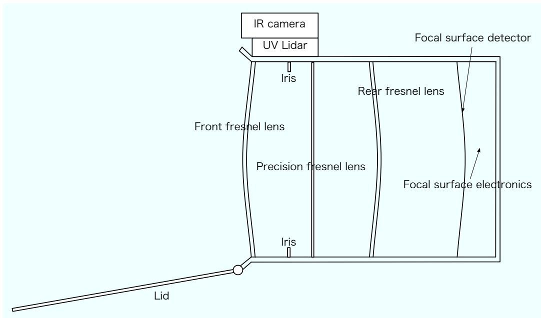

Figure 1: Cross-section of the JEM-EUSO telescope

refractive system of our concern. Fig.2 shows the refractive index dispersions of UV-PMMA-000 and CYTOP in the 330nm - 400nm wavelength region.

The diffractive technology being adopted by EUSO and JEM-EUSO helps canceling chromatic aberration of the refrative system. The ESA-EUSO baseline was designed to have two precision fresnel structures (diffractive surfaces) to control the large chromatic aberration, for which two precision fresnel structures were used on the front-surface of the first fresnel lens and the back-surface of the second fresnel lens, but JEM-EUSO is sufficient to use only one such plane.

The virtues of CYTOP are several-folds: the dispersion of refractive index of CYTOP is much smaller than that of PMMA so that the control of chromatic correction is easier than the system with PMMA.

Furthermore, CYTOP assists light-collecting-power of optics, because it is the materuial most transparent to date in the wavelength range from 200 nm to 2μm. Its transmittance is better than 95% overall and 98 - 99% in the JEM-EUSO application (see fig.3). Moreover, it is often used for anti-reflection coating and does not require any additional anti-relection coating processes. CYTOP is highly resistant to chemical such as acids, alkalis, and organic solvents, being suitable for use in a relatively dirty space environment around ISS. The reason to choose CYTOP as lens material is due to these prominent characteristics, although it is more expensive and heavier than PMMA.

The location of the precision fresnel plane is chosen in between iris and rear-lens so that it also acts as an additional field lens, making the focussing even sharper than that of the ESA-EUSO design. This arrangement is not only good for performance but will also help for an easy construction of the optical system. The material for this unit does not have to be CYTOP and it is sufficient to use UV-PMMA-000.

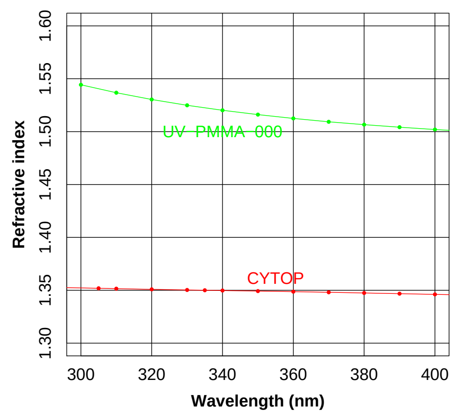

Figure 2: Refractive index of CYTOP and UV-PMMA-000.

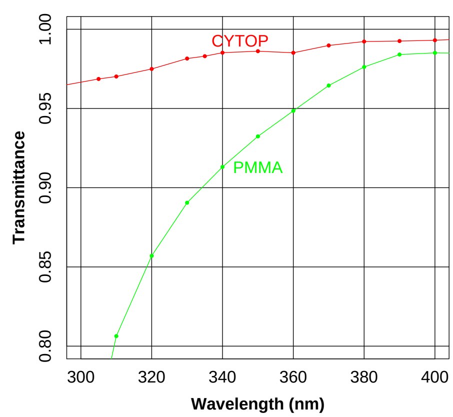

Figure 3: Transmittance (15mm thickness) of CYTOP and UV-PMMA-000.

JEM-EUSO optics performance

We estimated the JEM-EUSO optics performance by using the ray tracing simulations. Overall light-collecting power of the JEM-EUSO optics becomes about 1.5 times higher than the ESA-EUSO optics by the choice of new material CYTOP and new improved optical design. Light-collecting-powers of the ESA-EUSO optics and the JEM-EUSO optics are compared in Table1. Light-collecting-power ratio herein is defined by the fraction of the collected photons in the spot size of a circle of 5-mm diameter. The estimation includes such parameter values as Fresnel lens back cut loss, material absorption, reflectivity on the lens surface, diffractive manufacturing error, Fresnel lens manufacturing error, and support structure obscuration.

Table 1: Light-concentrating power. Its ratio is the fraction of the collected photons in the spot size of a circle of 5-mm diameter.

Field angle	ESA-EUSO	JEM-EUSO
0°	0.38	0.55
10°	0.38	0.57
20°	0.36	0.51
25°	0.34	0.51
30°	0.32	0.45

Lens fabrication

The current optics for the JEM-EUSO is 2.5m diameter monolithic lens. These lenses will be made by the diamond turning manufacturing method. This method was tested during the OWL study phase at UAH and RIKEN as well as at NASA MSFC during ESA-Phase-A studies. NASA MSFC manufactured 1-m size test article of the centerpiece; a piano-convex lens with facets on one side and a thin doubled sided meniscus during the ESA phase-A study.

RIKEN, UAH and NASA MSFC are currently studying technique of cutting CYTOP. Manufacturing tests being carried out at the RIKEN Fine-Precision Manufaturing Laboratory showed appropriate results for CYTOP manufacturing (fig.4 and fig.5). RMS roughness of the surface about 20 nm was observed in these test manufacturing, while direct diamond-turning of CYTOP had not been established in the past. This result suggests that the manufacturability of Fresnel lenses with CYTOP material is feasible with the adequate choice of the cutting speed and the tip-radius. Further optimization of the better cutting parameters is developing.

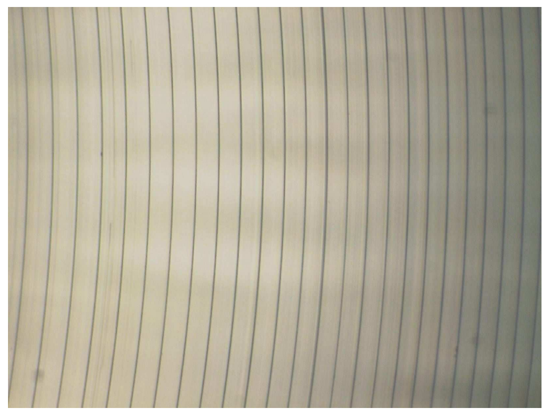

Figure 4: CCD image of the fresnel structure on the CYTOP substrate. Each facet is 70μm in pitch and in 30μm in height.

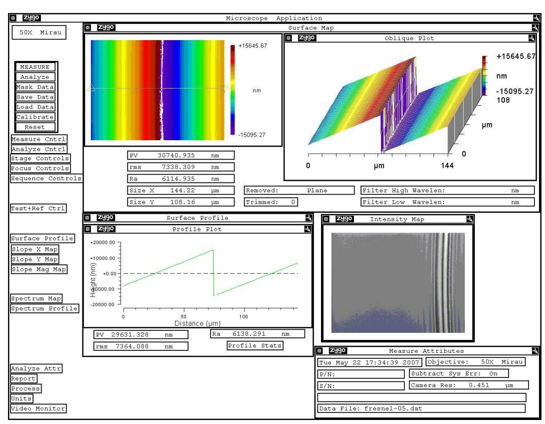

Figure 5: Measurement of fresnel structure of the fig.4.

Furthermore, another fabrication method, the laser ablation method, has been studied at RIKEN and UAH. RIKEN has the F_2 laser ablation technique for fabricating the precise micro-structure on the CYTOP film. Obata et al (Laser technology Lab., RIKEN) succeeded in fabricating a 30μm diameter hole with $\sim$20nm (RMS) surface roughness on a CYTOP substrate[5], and they applied to the fabricating of a microchip electorophoresis system for DNA analyses[6]. Its microchannel of 20mm in length, 200μm in depth, and 240μm in width on the CYTOP film was test manufactured with satisfactory precision. The Laser technology Lab. further plans to test-fabricate with CYTOP for the fine-fresnel grated structure.

Summary

The overall light-collecting power of JEM-EUSO optics is about 1.5 times higher than the past design, by adopting a new material CYTOP and new improved optical design with one fine-fresnel plane. Although the test fabrication of CYTOP lens is still on-going, its fundamental feasibility is verified and there are not big technical problems observed in these tests. RIKEN, NASA MSFC and UAH will continue further optimization of the cutting parameters and laser ablation parameters for better manufacturing of CYTOP and grated fresnel lenses.

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