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The TA-EUSO and EUSO-Balloon optics designs

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Abstract: In this paper we describe the details of the design of the optics being developed for the TA-EUSO and the EUSO-Balloon experiments. These are pathfinders experiments of the JEM-EUSO mission. TA-EUSO (Telescope Array EUSO) observes the fluorescence light from extensive air showers, generated by ultra high energy cosmic rays, detected at the Telescope Array site in Utah. The EUSO-Balloon will observe extensive air showers from a gondola of a stratospheric balloon. We have developed feasible optics designs for these experiments based on the JEM- EUSO optics development. These designs are simplified version of the JEM-EUSO baseline optics design. The optics of TA-EUSO consists of two 1m square flat Fresnel PMMA lenses, while the EUSO-Balloon optics include, beside the two 1m square flat Fresnel PMMA lenses, an additional 1m square flat diffractive PMMA lens.

Keywords: JEM-EUSO, UHECR, fluorescence, TA, Balloon, optics, Fresnel lens

1 Introduction

The Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO) of the International Space Station (ISS) will be attached to the Exposure Facility on the JEM located of the ISS. Its main goal is to observe UV fluorescence images of UHECR air shower in the Earth atmosphere with a field of view of 60° [1] .

The TA-EUSO and EUSO-Balloon projects are pathfinder experiments for the JEM-EUSO, in which the manufacturing of several key components of the telescope will be tested together with the observational technique to detect the cosmic ray air shower events. The details of both missions are described in [2] and [3]. In this paper, we focus on the designs of the optics of the two pathfinders experiments.

To maximize the sharing between the two projects of the machine time required by their manufacturing, it was decided that the two projects would have used the same optical design for the front and the rear lenses. Therefore, the EUSO-Balloon optics consists of two TA-EUSO lenses and of an additional flat diffractive lens. The diffractive lens is placed between the front lens and the rear lens to produce the fine RMS spot size (< 2.8mm pixels size). The lens material is the UV transmittance grade PMMA (PMMA-000, Mitsubishi Rayon CO., LTD.). All lenses have a size of 1m by 1m shape and the thickness is 8 mm. This size was decided by the observational performance and commercial availability of PMMA base material. The details of the manufacturing of TA-EUSO/EUSO-Balloon lenses are described in [4].

2 The concept of the TA-EUSO and EUSO-Balloon optics

The TA-EUSO and the EUSO-Balloon optics is designed taking into account the optics performance and verifying the lens manufacturing technology. Since the JEM-EUSO lenses have a side cuts form, TA-EUSO and EUSO-Balloon lenses manufacturing is a good opportunity to verify how to manufacture non-circular shape lens. As far as the optics design is concerned, the front and the rear lens of both experiments have a fresnel surface, while the middle lens of the EUSO-Balloon needs a diffractive surface to obtain a small spot size (< 2.8mm pixels size). The diffractive lens counteracts the dispersion of the lens material refractive index, so it is able to reduce the color aberration. The surface roughness of the lenses should be smaller than 20 nm RMS. The photon collection efficiency (PCE) of both optics should have ∼40% for the field angle 0°. These values come from the JEM-EUSO optics requirements. PCE is calculated with a formula in our developed raytrace simulation:

$$PCE = \frac{Photon\ counts\ in\ a\ pixel\ of\ the\ detector}{Photon\ count\ hitting\ the\ front\ lens} \qquad (1)$$

To meet the observational requirements, the RMS spot size should be smaller than the pixel size of the detector for EUSO-Balloon. This requirement is the same for the JEM-EUSO optics. the Field of view (FOV) of the Photo Detector Module (PDM) of EUSO-Balloon is larger than 12°. This value comes from sciences requirements [3].

For TA-EUSO, the RMS spot size requirements are more relaxed since FOV of 5×5 pixels of Telescope Array is nearly equal to the full FOV of TA-EUSO with one PDM. PDM has 48×48 pixels. There are ∼9.6×9.6 pixels of PDM in a pixel FOV of Telescope Array. In that case, the RMS spot size should be smaller enough than ∼9.6×9.6 pixels, TA-EUSO is able to observe a resolving image in a Telescope Array pixel FOV. The FOV of the PDM is larger than 8°. This value comes from sciences requirements [2].

The entrance pupil area of both optics should be larger than an area of 1m diameter. This requirement comes from [2, 3].

3 Optics design and performance

In this section, we describe in details the TA-EUSO and EUSO-Balloon optics respectively.

3.1 Lens material

There are two candidates for the material of the lenses: the PMMA-000 and CYTOP. PMMA-000 (Mitsubishi Rayon Co, Ltd. product) is a special-grade UV transmittance Poly-methyl methacrylate [5]. The seconde candidate is CYTOP (Asahi Glass Co, Ltd. product), an amorphous, soluble perfluoropolymer. CYTOP has 95% transmittance between UV and near-IR and high resistance against space environment (bombardment with atomic oxygen and radiation dose) because of the strong chemical stability by fluoro-bond.

PMMA-000 has been selected for the TA-EUSO and the EUSO-Balloon experiments mainly for two reasons: 1) non-space mission and 2) commercial availability of the lens material.

3.1.1 Characteristic of PMMA-000

The refractive index in the near UV region for three different temperatures ($-40°$C, $20°$C and $40°$C) is shown in Fig. 1. The $20°$C curve has been measured, while the $-40°$C and $40°$C are calculated according to [6]:

$$n(t) = n_0 + at + bt^2;$$

$$a = -0.000115,$$

$$b = -5.17358 \cdot 10^{-7},$$

$$n_0 \textit{ is a reference refractive index.}$$

$$\textit{Our measured data of } 20°C \textit{ is used as } n_0.$$

The TA-EUSO and EUSO-Balloon experiments will be operated in various temperature environments. TA-EUSO is deployed at the Telescope Array site in Utah, USA. The temperature of TA-EUSO will be changed between $-30°$C $\sim 40°$C by the seasonal variation. On the other hand, the temperature of the EUSO-Balloon lenses will change with balloon flight conditions (trajectory, altitude, etc). Each lens has to withstand different temperatures. The front lens temperature will be in the range $-40°$C $\sim 0°$C, depending on flight conditions. The inner lenses' temperatures will be higher than the front lens, and with smaller variations, due to the heating by electronics components.

The PMMA transmittance with 8mm thickness in near UV region is shown in Fig. 2.

3.2 The TA-EUSO optics design and its performance

The requirements and the designed values of the TA-EUSO optics are shown in Table 1. The angular resolution has to be better than the Telescope Array Fluorescence Detector (TA-FD). The field of view of a TA-FD pixel is 1°. It corresponds to $\sim$9.6$\times$9.6 pixels for the TA-EUSO. The RMS spot size of TA-EUSO should therefore be smaller than $\sim$9.6$\times$9.6 pixels to resolve a TA-FD pixel. Our best design results in a spot size, in case of the two lenses system, of 9 mm RMS, which corresponds to $\sim$3$\times$3 pixels of PDM. Specifications of the the TA-EUSO optics design is shown in Table 2.

The front side of the front lens is a plane surface to clean dust from the surface easily. This is particularly important since TA-EUSO is going to be deployed at the Telescope Array site, where sand and dust might accumulate on the front surface of the front lens. The back side of the front lens has a Fresnel structure. The back side of the rear lens is again a plane surface that can be easily cleaned. The front side of the rear lens has a Fresnel structure.

The design was implemented for temperatures of front and rear lenses of $20°$C. This optics is insensitive to changes of temperature between $0°$C and $40°$C. Full FOV of TA-EUSO is $\pm 8°$ for two PDMs. The spot diagrams of the TA-EUSO between FOV $0°$ and $8°$ are shown in Fig. 4.

The loss factors of the optics system represent the losses of light on-axis (Table 3). The obscurations due to the back-cuts at off-axis angles are implemented in the efficiency calculations. Photon collection efficiency of the TA-EUSO is shown in Table 4.

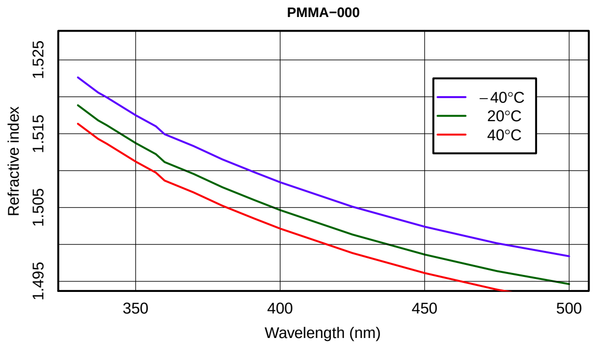

Figure 1: PMMA-000 refractive index in the near UV region with different temperatures ($-40°$C, $20°$C and $40°$C).

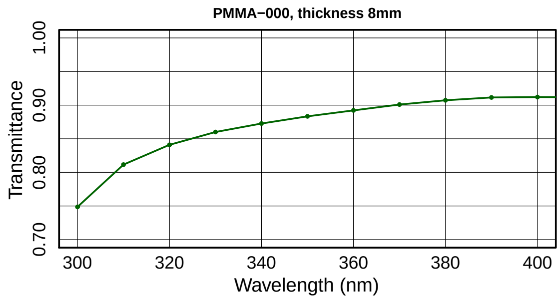

Figure 2: The 8mm thick PMMA transmittance in the near UV region.

	Requirements	Design result
Optical system	2 or 3 lenses sys.	2 lenses sys.
Focal length	-	1562.18mm
FOV for a PDM	$> \pm 4°$	$\pm 4°$
RMS spot size	$<$ PMT size	9 mm @ 0°
Entrance pupile	> 0.785 m^2	0.95 m^2
Base shape of lens	Flat type	Flat type
Lens material	PMMA-000	PMMA-000
Lens thickness	$<$ 10 mm	8mm
FS curvature	2505 mm	2505 mm

Table 1: The TA-EUSO optics design requirement parameters and designed values.

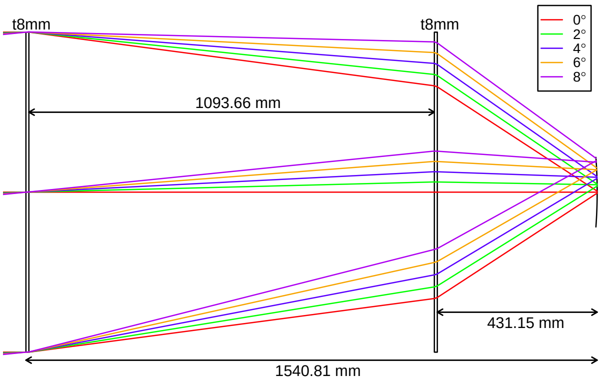

Figure 3: The optics design of the TA-EUSO.

	Front lens		Rear lens	
Material	PMMA-000		PMMA-000	
Lens shape	1m square		1m square	
Thickness	8 mm		8 mm	
Weight [kg]	9.6		9.6	
Surface type	Front	Back	Front	Back
	Plane	Fresnel	Fresnel	Plane

Table 2: Specifications of the TA-EUSO optics.

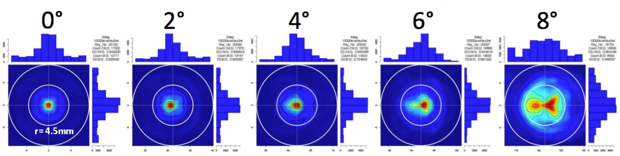

Figure 4: Spot diagrams of the TA-EUSO between FOV 0° and 8°. Inner circle radius is 4.5 mm. Outer circle radius is 9 mm.

3.3 The EUSO-Balloon optics design and its performance

The requirements and the designed values of the EUSO-Balloon optics are shown in Table 5. The RMS spot size must be smaller than the PMT pixel size (= 2.8 mm). The EUSO-Balloon optics consists of two TA-EUSO lenses and an additional flat diffractive lens. The diffractive lens is placed between the front lens and the rear lens to correct for chromatic aberration and to obtain a small RMS spot size (< 2.8mm pixel size). The specifications of the EUSO-Balloon optics design are shown in Table 6. The design was done for operating temperatures of the front lens equal to −40°C, for the middle lens and the rear lens equal to 10°C. The optics design takes into account only changing the temperature of the rear lens, since the focusing power of the first lens is weak and the diffractive lens is not sensitive to changes of temperature. The rear lens is connected with the PDM electronics components by thermal radiation heating. We should study the thermal condition between the rear lens and the PDM components, and then, adjust the focusing point moving the PDM. The Full FOV of EUSO-Balloon is ±6° for the PDM. The spot diagrams of the EUSO-Balloon, between FOV 0° and 6°, are shown in Fig 6. The loss factor of the optics system is

Item	Loss factor (%)
Suface roughness	2
Diffractive structure depth error	0
Fresnel facet back-cuts error	4
Support structure obscuration	1
Total	7

Table 3: Loss factors of the TA-EUSO.

Field angle	Efficiency
0°	40%
2°	41%
4°	46%
6°	43%
8°	30%

Table 4: The photon collection efficiency of the TA-EUSO for three wavelengths (337, 357 391nm). These efficiencies are taken into account of the surface reflection, the material absorption and the loss factors of Table 3, except for the support structure obscuration.

shown in Table 7. PCE of the EUSO-Balloon is shown in Table 8.

	Requirements	Design result
Optical system	3 lenses sys.	3 lenses sys.
Focal length	-	1620.717mm
FOV for a PDM	$> \pm 6°$	±6°
RMS spot size	$<$ pixel size	1.6 mm @ 0°
Entrance pupile	$> 0.785\ m^2$	$0.95\ m^2$
Base shape of lens	Flat type	Flat type
Lens material	PMMA-000	PMMA-000
Lens thickness	< 10 mm	8mm
FS curvature	2505 mm	2505 mm

Table 5: The EUSO-Balloon optics design requirement parameters and designed values.

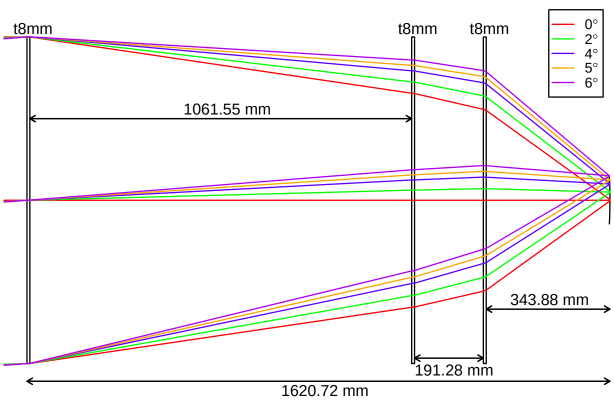

Figure 5: The optics design of the EUSO-Balloon.

	Front lens		Middle lens		Rear lens	
Material	PMMA-000		PMMA-000		PMMA-000	
Lens shape	1m square		1m square		1m square	
Thickness	8 mm		8 mm		8 mm	
Weight [kg]	9.6		9.6		9.6	
Surface type	Front	Back	Front	Back	Front	Back
	Plane	Fresnel	Plane	Diffractive	Fresnel	Plane

Table 6: Specifications of the EUSO-Balloon optics

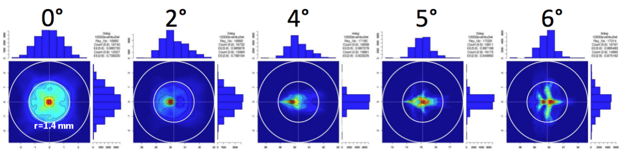

Figure 6: Spot diagrams of the EUSO-Balloon between FOV 0° and 6°. Inner circle radius is 1.4 mm. Outer circle radius is 2.8 mm.

Items	Loss factor (%)
Suface roughness	3
Diffractive structure depth error	7
Fresnel facet back-cuts error	4
Support structure obscuration	4
Total	18

Table 7: Loss factors of the EUSO-Balloon.

Field angle	Efficiency
0°	35%
2°	39%
4°	46%
5°	47%
6°	43%

Table 8: The photon collection efficiency of the EUSO-Balloon for three wavelengths (337, 357 391nm). These efficiencies are taken into account of the surface reflection, the material absorption and the loss factors of Table 7, .except for the support structure obscuration.

4 Conclusions

We have developed feasible optics designs for the TA-EUSO and EUSO-Balloon projects based on the JEM-EUSO optics development. These designs are simplified version of the JEM-EUSO baseline optics design, and are very similar to the central portion of the JEM-EUSO lenses. These designs are taking into account the manufacturability of the lenses under strong time constraint. The TA-EUSO and the EUSO-Balloon shared the design of the front lens and the rear lens. The EUSO-Balloon optics is a suitable design to demonstrate and to test a representative of the whole JEM-EUSO instrument. If we manufacture the middle lens (the diffractive lens) for TA-EUSO, TA-EUSO will acquire the same focusing power of EUSO-Balloon. Its optical system is able to observe the lateral distribution image of the inside of a TA-FD pixel with high resolution.

The optics design parameters for the main JEM-EUSO missions will be improved based on the real production of the optics of these two pathfinder experiments.

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