The JEM-EUSO optics design

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FOR THE JEM-EUSO COLLABORATION

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Abstract: The Extreme Universe Space Observatory onboard the Japanese Experiment Module is an international mission devoted to the detection of ultra high-energy cosmic particles with energies $E > 7\times10^{19}$ eV. They are revealed through emission in the atmosphere of Cherenkov and fluorescence light in the near-UV region, by using an optical system with 60° field of view and a 2.3m entrance pupil. One of the challenges consists in developing an unusual combination of large and lightweight refractive optics: two double-sided curved Fresnel lenses and a central curved Fresnel + diffractive lens, whose maximum dimensions are 2.65m. This paper describes the development of such an optical system and its performances of the latest configurations.

Keywords: Refractive optics, Diffractive optics, Ultra high-energy cosmic rays, Extensive air shower.

1 INTRODUCTION

Accommodated on the Japanese Experiment Module (JEM) of the International Space Station (ISS), the Extreme Universe Space Observatory JEM-EUSO is the first planned space mission devoted to the exploration of the outermost bounds of the Universe through the detection of the Ultra High Energy ($E > 7\times10^{19}$eV) Cosmic Rays (UHECRs), the most energetic particles coming from the Universe, by using the Earth atmosphere as a giant detector [1]. Looking downward the Earth, JEM-EUSO will detect such particles observing the fluorescence signal produced during their pass in the atmosphere. In particular, an UHECR collides with a nucleus in the Earth atmosphere, mainly Nitrogen, and produces an Extensive Air Shower (EAS made of electrons, positrons and photons. JEM-EUSO will capture the moving track of the fluorescent and Cherenkov ultraviolet (UV) photons, reproducing the calorimetric development of the EAS. At these energies the probability of detection is very low (~1 Km^{-2} $\mathrm{century}^{-1}$). Since the volume of Earth atmosphere targeted from the ISS orbit is huge (~1 Teraton or more, observing on ground a circle of ~250 km radius or more), this observatory will increase the UHECR detection statistics with respect to the existing ground- based experiments, allowing to detect at least 500 UHECRs in three-year operation. Besides, its threshold energy is about 10^{19} eV, thus yielding cross calibration with the other experiments [2].

The instrument concept is a fast, high-pixelized, large-aperture and large Field-of-View (FoV) digital camera, working in the near-UV wavelength range with single photon counting capability. The telescope will record the track of an EAS with a time resolution of 2.5 μs and a spatial resolution of about 0.75 km (corresponding to ~0.1°), thus allowing the determination of energy and direction of the primary particles.

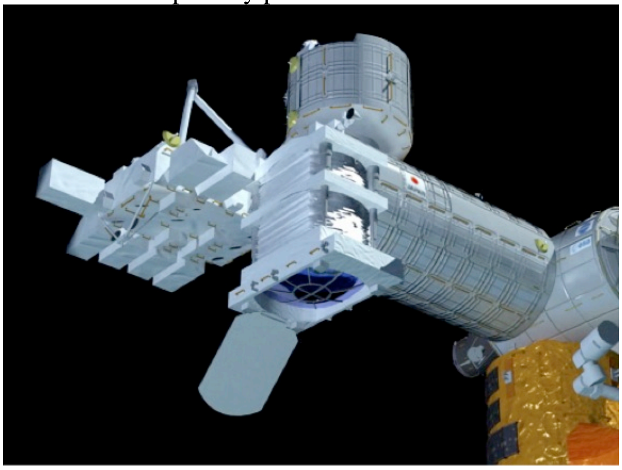

Figure 1. The telescope on the ISS.

Optics		**Focal surface**	
FOV	±30°	Focal surface area	~4.5 m^2 (curved)
Optical bandwidth	330 ÷ 400 nm	Number of pixels	~2.0×10^5
Entrance Pupil Diameter (EPD)	≥ 2.3 m	Pixel size	2.8 mm for “M64” MAPMT
F/number (F/#)	≤1		

Table 1. JEM-EUSO instrument parameters

2 THE JEM-EUSO TELESCOPE

In order to collect enough signals at the requested energies, the optical system must have a large aperture, wide FoV (Tab. 1). Besides, the system must be necessarily lightweight since the overall dimensions of the instrument, related to the maximum allowable stowing room on the launcher, let optical elements to be as big as 2.65m in diameter. Also for this reason reflective optics, in the form of a properly designed Schmidt camera, does not have yet a technological readiness, since the optical requirements would need a large, deployable, primary mirror, with some sort of active control on the shape [3], and with all the constraints of movable parts onboard the ISS. The main components of the telescope are: collecting optics, focal surface detector, electronics and structure (shown schematically in Fig. 2). The proposed optics system is essentially based on refractive elements: two Fresnel lenses and another one with a diffractive surface. The focal surface detector is covered by a grid of ~6000 multi-anode photomultipliers (MAPMTs), which convert the energy of the incoming photons into electric pulses with duration of 10 ns. The electronics counts-up the number of the electric pulses in time periods of 2.5 μs and records them to the memory; when a signal pattern coming from extreme energy particle events is found, the electronics issues a trigger signal and transmits all the useful data to the ground operation center, tracking back the image information stored in the memory.

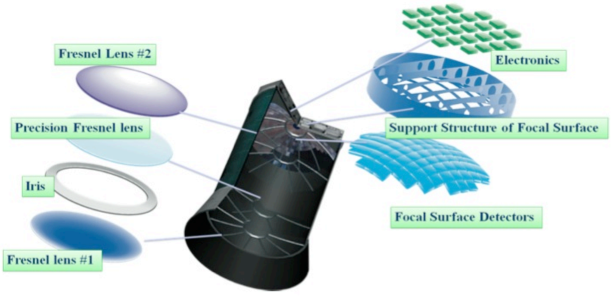

Figure 2. The main components of JEM-EUSO telescope concept.

3 THE OPTICS MODULE

The Optics Module (OM) is formed by two curved double-sided Fresnel lenses and a central lens with a Fresnel surface and a diffractive one for chromatic aberration reduction. Indeed, because of the scientific requirements, a large aperture, wide FoV system is needed. Besides, a small F/number condition helps controlling the focal surface dimensions. A Fresnel optical system is the challenging solution adopted for this mission: the Fresnel lens basically works as its prescription lens, with the advantage of being lighter and consequently less radiation absorbing, which is a critical feature especially in the UV. A lightweight design is really compulsory, since for the considered operative conditions a normal (i.e. prescription) lens system would be too expensive, not adequate and also difficult to carry into space. However, a combination of lenses cannot avoid the chromatic aberrations in the waveband of interest, for which the refractive index shows a steep behavior with respect to longer wavelengths; therefore a diffractive lens was added, with the purpose to reduce those aberrations. Being in the vicinity of the Aperture Stop, this optical element serves also as a sort of field lens, which helps gaining signal in particular on the wide fields.

3.1 Lens Materials

Two materials have been chosen to prove the feasibility of the optics: CYTOP and PMMA (000 grade). CYTOP is an amorphous, soluble perfluoro polymer (by Asahi Glass Co. LTD, Japan). It combines the excellent properties of highly fluorinated polymers with solubility in selected perfluorinated solvents to provide outstanding coatings for optical, electronic and other applications. CYTOP has a 95% transmittance between UV and near-IR. PMMA-000 is a special Grade UV-transmitting polymetyl methacrylate (by Mitsubishi Rayon Co. LTD, Japan). Fig. 3 shows the refractive index and transmittance (for a 15-mm sample measured by RIKEN) of CYTOP and of PMMA-000. CYTOP provides less dispersion and more transmittance, and its refractive index is generally lower than PMMA-000.

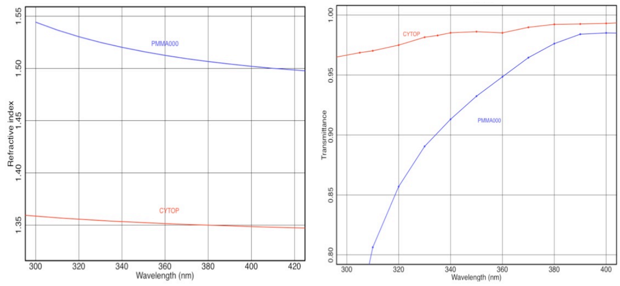

Figure 3. Left: refractive index for CYTOP and PMMA-000. Right: transmittance for CYTOP and PMMA-000 for 15-mm thickness.

3.2 Optics design

After many efforts both in optimization and in searching for optimal materials, only in the last few years the option on CYTOP and PMMA UV grade has been decided. Recently, only two designs have been adopted and analyzed: the so-called “Baseline” optics and the “Advanced” optics (see their cross sections in Fig. 4). Both are F/1 on-axis, with 2.3 m EPD and 60° overall FoV. Both use two curved double-sided and rotationally symmetric Fresnel lenses and one curved diffractive + Fresnel lens, the former design being all in PMMA-000, the latter having the front lens in CYTOP and the two others in PMMA-000. As previously stated, the optical advantages of CYTOP are evident; however, it is heavier and more expensive, therefore a system all made in CYTOP has not been considered as a valuable option. In both designs an intermediate lens is positioned, with a rotationally symmetric diffractive surface from one side and Fresnel one on the other side. Since a diffractive surface introduces dispersion with opposite sign with respect to a refractive one, this element helps taming the chromatic aberration. This lens acts also as a field lens, which assures the minimum possible loss due to vignetting. Indeed, the available room on the HTV transfer vehicle stowing area necessarily limits the lenses’ diameter dimensions, while the wide-angle and large EPD conditions would require even bigger diameters to avoid vignetting (Fig. 4). In both designs, all the three lenses are 10-mm thick, with 2.65 m maximum diameter. As for all the parameters, also the base curvature is a result of the optimization, which is also related on the considered material. The corresponding prescription lenses are all convex- concave positives, therefore for each curved Fresnel lens there is one prescription surface curvature that does not follow the bending direction of the Fresnel, thus resulting in an increased number of back-cuts, typical of Fresnel designs. At this stage, base curvature is spherical, while all the surface curvatures are slightly aspheric.

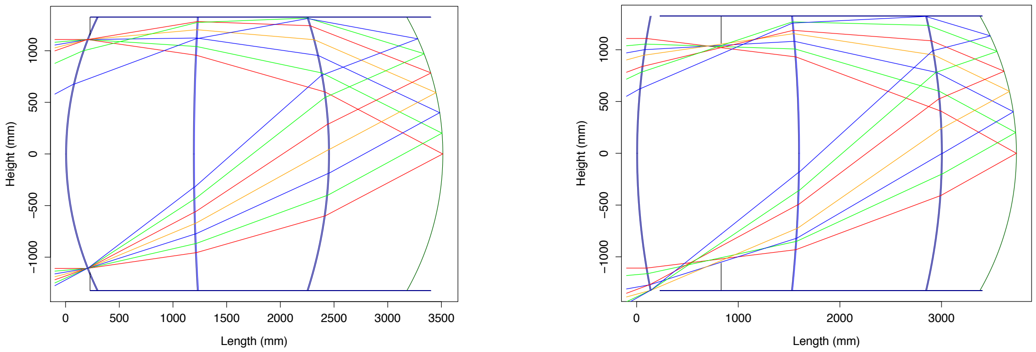

Figure 4. Baseline (left) and Advanced (right) designs.

3.3 Optics performance

The scientific goals do not need diffraction-limited conditions for the optics: with the described requirements, geometrical aberrations and back-cuts losses and scatterings are the main drivers. The performance of the optics designs is given in terms of geometrical Encircled Energy (EE) and Throughput (Fig. 5). The EE is defined as the ratio between the number of photons in the spot area and the those reaching the whole focal surface for a given field, while the Throughput is the ratio between the number of photons in the spot area and those passing through the Aperture Stop (i.e. the iris of Fig. 2). EE and Throughput are estimated using a ray-tracing code that takes into account the different material absorptions, Fresnel structures and surface reflections. Besides, the considered losses due to the surface roughness and the depth error of the diffractive + Fresnel structure were previously estimated by formulas and then verified via simulations. Manufacturing trials on plastic samples have also helped defining some of these maximum tolerable conditions. Fig. 5 shows how better the Advanced design performs with respect to the Baseline. This behavior depends on several issues, as well as on the fact that the advanced optics average RMS spot size is smaller than the one of Baseline optics, since CYTOP presents smaller refractive index dispersion than PMMA-000. Throughput necessarily drops with bigger angles, since the back-cuts’ geometrical obscuration tends to increase, as well as scattering losses.

3.4 Performance of the HTV stowing type

So far, two designs with 2.65 m diameter have been presented. However, more realistic considerations on the true available volume lead to edit both the designs and the corresponding performance. Indeed, the HTV unpressurised stowage area constrains the layouts to a maximum 2.65 x 1.9 m^2 (Fig. 1). After a re-optimization, the so-called “side- cut” optics has ~82% aperture of the original 2.65 m design. It keeps the performance up to 15°, while the FoV on the side-cut direction is limited to ~24°, since beyond that angle there is no more focal surface.

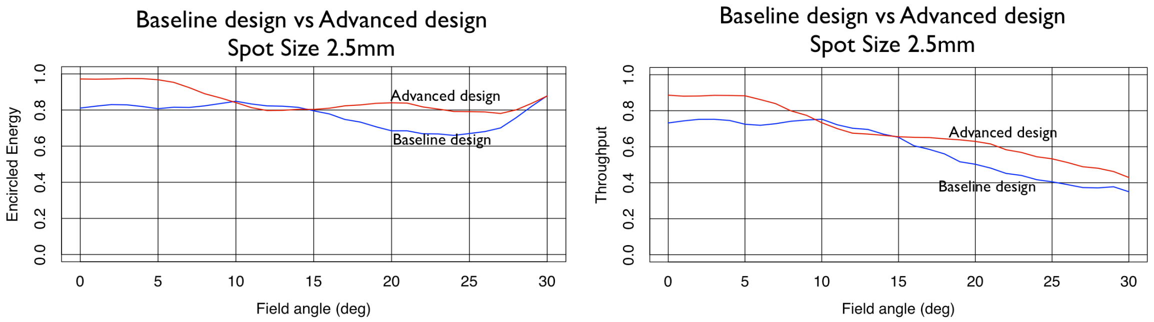

Figure 5. Performance of Baseline and Advanced optics designs. Left: EE, right: Throughput.

3.5 Tolerance analysis

The angular resolution tolerance can be roughly 300 thousand times larger than the diffraction limit. Consequently, tolerance of the optics is much lower than for astronomical telescopes. Preliminary tolerances with 2.5-mm spot sizes have been verified via ray- tracing code. For each lens and for the focal surface the axial displacement, the lateral displacement and the tilt have been considered. Another source of error comes from thermal issues. Since JEM-EUSO orbits around the Earth in ~90 minutes, each lens has a thermal cycle synchronized with the orbit. Refractive index is shifted by temperature changes, causing de- focusing effect. Thermal analyses predict that the front lens shifts ±2°C from the equilibrium temperature, vs. a requirement of max ±10°C. On the other hand, tolerance analysis (with numerical ray-tracing method) allows the refractive index to vary no more than 0.0013/10°C. The measurement results of temperature dependence of refractive index state that the temperature shift amount is 0.0007/10°C (CYTOP) and 0.0009/10°C (PMMA-000), which are below the requirement. A further study on simulations regarding the temperature difference between lenses, due to the environment, is under way.

3.6 Manufacturing

Manufacturing procedures give a feedback on the design and tolerances of the Fresnel lenses. Since June 2008, a large diamond turning machine is being used in Japan to manufacture lenses up to 3.4 m in diameter. This machine has already successfully cut three 1.5-m diameter PMMA-000 Fresnel lenses, being the central portion of a 1:1 scale JEM-EUSO prototype [4]. These lenses will be shipped to NASA - MSFC to undergo complete optical tests. These tests will be used as a feedback for detailing the optical design as well as for improving manufacturing of future lenses.

4 CONCLUSIONS

The construction of an all-refractive space-based telescope for detection of Ultra High Energy Cosmic Rays is on its way. Intensive simulations of the optics are being conducted for the last years, in connection with the development of the other subsystems, and two possible designs are presented: a Baseline (with all PMMA-000 lenses), and an Advanced one (with two PMMA-000 and one CYTOP lens). Their performances show that Science with such a challenging optical system is not only possible but almost a reality. Once the prototype will be tested, more information and a stronger feedback for simulations and opto-mechanical issues will be provided, thus reinforcing the reliability of the ray- trace and stray light simulations in view of building the final telescope.

[1] Y. Takahashi et al. "The JEM-EUSO mission", New Journal of Physics 11 (2009) 065009.
[2] http://www.auger.org/index.html.
[3] A. Zuccaro Marchi et al. "A Technology demonstrator for development of ultra-lightweight, large aperture, deployable telescope for space applications", Proceedings of the 7th International Conference on Space Optics, Toulouse, France, 14-17 October 2008.
[4] Y. Hachisu et al., "JEM-EUSO lens manufacturing", 32nd ICRC conference, Beijing, China, 2011