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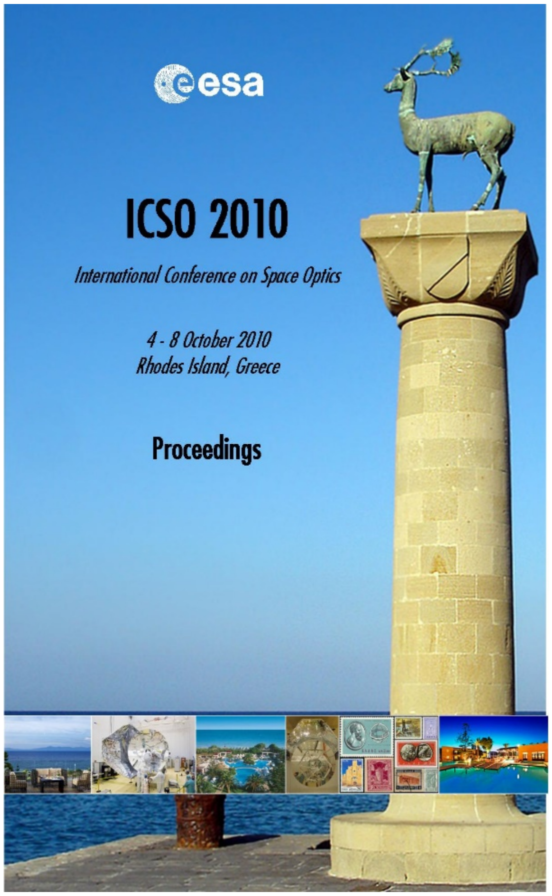

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THE JEM-EUSO MISSION AND ITS CHALLENGING OPTICS SYSTEM

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ABSTRACT

The Extreme Universe Space Observatory (EUSO), onboard the Japanese Experiment Module (JEM) of the International Space Station (ISS), is a project led by Japan, with contributions from the United States, Italy, Germany, France, Spain, Switzerland, Russia, South Korea and Mexico. It is devoted to the detection of ultra high-energy cosmic particles with energies $E>7x10^{19}$eV, which are revealed through emission in the atmosphere of Cherenkov and fluorescence light in the near-UV region. Current experiments are all ground-based. A big enhancement would rise from space, since a bigger atmospheric target could be monitored. However, since at these high energies the signal is faint and the probability of detection is very low (~1 Km^{-2} $century^{-1}$), the optical system must have a large aperture, wide Field of View (FoV) and be necessarily lightweight. This project is the continuation of the EUSO mission, led by ESA, stopped some years ago at the end of phase A, and JEM-EUSO is currently at the end of phase A. For both experiments, a ~2.3 m Entrance Pupil (EP) diameter and a 60° FoV were required to achieve the science goals. However, for the present configuration, the constraint of the maximum stowable dimensions of the JAXA's H-II Transfer Vehicle (HTV) unpressurized cargo area forces the instrument to have maximum transverse dimensions of 2.65 x 1.9 m^2. Reflective optics, in the form of a properly designed Schmidt camera, are not yet suitable for this purpose, since these optical requirements would need a large, deployable, primary mirror. The main challenge for designing the current configuration 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, in UV-grade PMMA and/or CYTOP, have been considered. This paper describes the development of such a system, focusing on the possible choices of materials and overall optical design, which is responsibility of the authors. Performances of the latest configurations are also presented.

I. INTRODUCTION:

Accommodated on the Japanese Experiment Module (JEM) of the International Space Station (ISS), the Extreme Universe Space Observatory JEM-EUSO is the first space mission devoted to the exploration of the outermost bounds of the Universe through the detection of the Ultra High Energy ($E > 10^{20}$ eV) Cosmic Rays (UHECRs) and neutrinos, 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 and produces an Extensive Air Shower (EAS) that consists of numerous electrons, positrons, and photons. JEM-EUSO will capture the moving track of the fluorescent and Cherenkov Ultra Violet (UV) photons, reproducing the calorimetric development of the EAS.

The main objective of JEM-EUSO is the possibility of doing astronomy and astrophysics through the particle channel with extreme energies above 10^{20} eV, so extending, with significant statistical evidence, the measurement of the energy spectrum of the cosmic radiation beyond the Greisen-Zatsepin-Kuzmin (GZK) cut-off. Moreover, using the atmosphere as a giant detector, JEM-EUSO could observe extremely high energy neutrinos, so opening the field of high energy neutrino astronomy. Furthermore, JEM-EUSO will contribute to the investigation of phenomena intrinsic to the Earth's atmosphere (such as nightglows, plasma discharges and lightning) or induced by the flux of meteoroids coming from space. JEM-EUSO will have a threshold energy ~10^{19} eV, which is useful to cross the information acquired with the existing ground experiments [2].

Firstly proposed as a free-flyer, the observatory was selected by the European Space Agency (ESA) as a mission attached to the Columbus module of the ISS. The phase-A study was successfully completed in July 2004. Nevertheless, it was stopped because of financial problems. In 2006, Japanese and U.S. teams redefined the mission as an observatory attached to the Japanese Experiment Module/Exposure Facility (JEM/EF) of the International Space Station, renaming it as JEM-EUSO. Nowadays, JEM-EUSO is a worldwide collaborating effort of 62 research groups from 12 countries. JEM-EUSO, planned to be attached to JEM/EF of ISS, will be launched in 2015 by H2B rocket and conveyed to ISS by HTV.

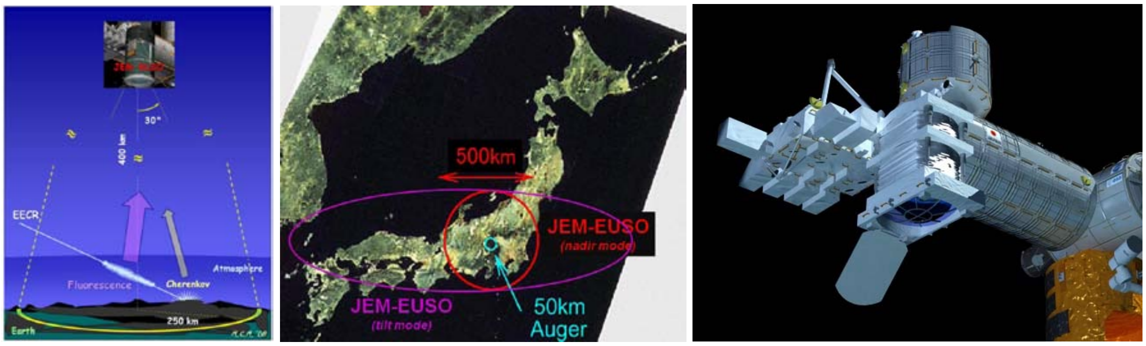

Fig. 1. The observational principle (left); nadir or tilted mode (centre); the telescope on the ISS (right).

II. THE JEM-EUSO TELESCOPE:

This remote-sensing instrument will orbit around the Earth every ~90 minutes on board of the ISS at the altitude of ~400 km for more than 3 years.

The JEM-EUSO telescope 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 (Tab. 1). 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°). These time-segmented images allow determining energy and direction of the primary particles. Its observational aperture of the ground area will be a circle with 250 km radius, and its atmospheric volume above it, with a 60° FoV, will be ~1 Tera-ton or more. The target volume for upward neutrino events will exceed 10 Tera-tons. Since the effective area can be increased by inclining the telescope from nadir, in a so-called “tilted mode” (Fig. 1), the instantaneous aperture of JEM-EUSO will become far larger than the Pierre Auger Southern Observatory [2], depending on its observation mode (nadir or tilted). One of the main advantages is the increased statistics, allowing to detect at least 1000 UHECRs in three-years operation.

The main components of the telescope are: collecting optics, focal surface detector, electronics and structure, as shown in Fig. 2. The optics system is basically composed of two Fresnel lenses and one diffractive + Fresnel lens. The focal surface detector is covered by a grid of ~6000 multi-anode photomultipliers (MAPMT) 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 centre, tracking back the image information stored in the memory.

Tab. 1. JEM-EUSO instrument parameters

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/#)	< 1.25		

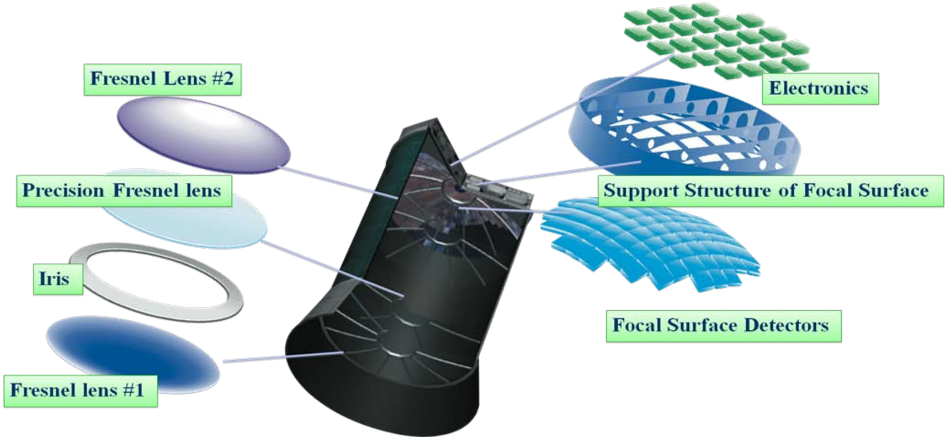

Fig. 2. The main components of JEM-EUSO telescope concept.

II. THE OPTICS MODULE:

JEM-EUSO uses a wide-angle refractive telescope operating in the near-ultraviolet wavelength region to observe the time-and-space-resolved atmospheric fluorescence images of extensive air showers. The large FoV is needed to retrieve enough statistics, while the pupil aperture must be as big as possible in order to detect the faint fluorescence and Cherenkov photons with enough signal.

The Optics Module (OM) is formed by two curved double Fresnel lenses and a diffractive lens for chromatic aberration correction. Indeed, the scientific requirements demand a challenging optical system which is necessarily shaped by the need of large aperture, wide FoV and small F/# (to reduce the focal surface dimensions). A Fresnel system is the solution adopted for this mission (although other conceptual designs may be possible, with other kinds of constraints and criticalities [3]): a Fresnel lens basically works as its prescription lens, with the advantage of being far lighter and consequently more transparent on the UV. A lightweight design is really compulsory, since for the considered conditions a normal 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; therefore a diffractive field lens, positioned close to the Aperture Stop, was added, with the purpose to tame those aberrations.

The design of the OM is therefore constrained also on the availability of suitable materials that are enough transparent in the UV.

A. Lens Materials

Two materials have been chosen to prove the feasibility of the optics: CYTOP and PMMA (000 grade).

CYTOP is an amorphous, soluble perfluoropolymer (by AGC Corporation, 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 metacrylate (by Mitsubishi Rayon Corp., Japan).

Tab. 2 shows the characteristics of CYTOP and of PMMA-000, while refractive index and transmittance (for a 15-mm sample) are presented in Fig. 3. CYTOP provides less dispersion and more transmittance. However, it is heavier than PMMA-000.

Tab. 2. Characteristics of CYTOP and PMMA-000.

	CYTOP	**PMMA-000**
Density (25 ℃)	2.03 g/cm^3	1.19 ~ 1.20 g/cm^3
Glass transition temperature	108 ℃	105 ~ 120 ℃
Water absorption	< 0.01	0.3
Coefficient of linear expansion	7.4 ×10^{-5} cm/℃	8.0 ×10^{-5} cm/℃
Rupture strength	40 MPa	65 ~ 73 MPa
Break elongation	150%	3 ~ 5%
Yield strength	40 MPa	(65) MPa
Tensile strength	1200 MPa	3000 MPa

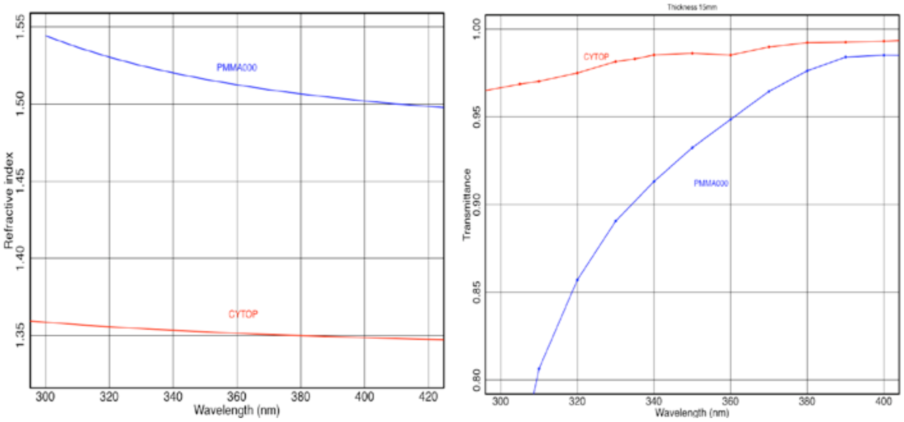

Fig. 3. Left: refractive index for CYTOP and PMMA-000.
Right: transmittance for CYTOP and PMMA-000 for 15-mm thickness.

B. Optics design

In the past years, different configurations using these two materials were designed, first with Code V™ and now with another suitable ray-tracing code. Recently, only two were adopted: the so-called "Baseline" optics and the "Advanced" optics. Both have an 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 partially compensates the big vignetting due to the wide FoV and EPD and the limited size of the lenses, due to the maximum dimension of the HTV transfer vehicle stowing area (see also *D*).

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 optimisation. For reasons of structural integrity and survivability during launch, the lenses cannot be designed flat. Furthermore, since the corresponding prescription lenses are all positive, for each Fresnel lens there is one prescription surface curvature that does not follow the Fresnel base curvature, 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.

Cross-section views of Baseline and Advanced optics designs are shown in Fig. 4.

The atmospheric fluorescence emission of interest for JEM-EUSO resides in the three Nitrogen lines (337 nm, 357 nm, 391 nm). A BG3 baseline filter, however, transmits photons between 250 nm and 500 nm. Therefore, the signal-to-noise (S/N) ration of detector is not well optimised since JEM-EUSO will collect Nitrogen lines and also background photons. An interference filter, able to pass through only around the three lines, has been considered: it is a multilayer filter, with 25 pair layers of Ta_2O_5/SiO_2. A test on its transmittance performance makes the S/N ration to improve by a factor of 1.4.

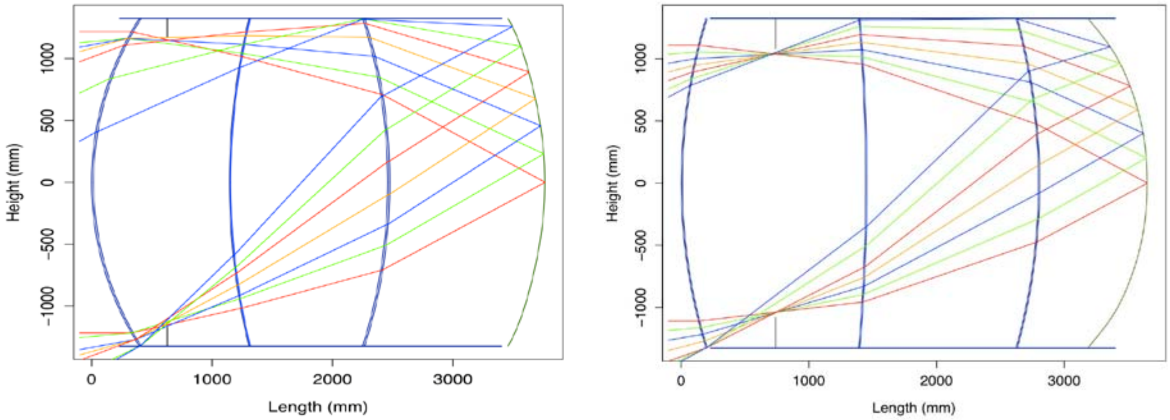

Fig. 4. Baseline (left) and Advanced (right) designs.

C. Optics performance

The performance of the optics designs are given in terms of Encircled Energy (EE) and Throughput (Fig. 5).

The EE is defined as the ration between the number of photons in the spot area and the photons which reached the focal surface, while the Throughput is the ration between the number of photons in the spot area and those which passed through the Aperture Stop (i.e. the iris of Fig. 2).

EE and throughput were estimated using a ray-tracing code that takes into account the material absorption, the Fresnel structure and the surface reflections. The losses due to the surface roughness and to the depth error of the diffractive + Fresnel structure were previously estimated by formulas, and then verified via simulations.

The difference between the performances depends on the surface reflection and material absorbance. Advanced optics has better performance than Baseline optics also because CYTOP has better transmittance than PMMA-000.

Tab. 3 lists the main loss factors which have been considered for these two designs.

Tab. 3. Summary of loss factors.

Item	**Loss factor**
Surface roughness	3% (15 nm RMS)
Diffractive structure depth error	1%
Fresnel facet back-cuts Root & Peak tool error	10%
Support structure obscuration	12% @ 0° field angle

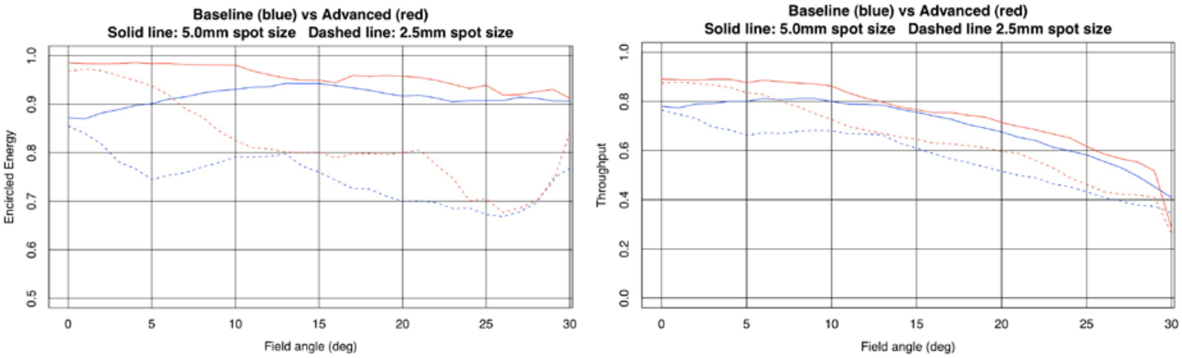

Fig. 5. Left: EE performance of Baseline (blue) and Advanced (red) optics designs.
Right: Throughput performance of Baseline (blue) and Advanced (red) optics designs. Each curve is normalized to the throughput of the Advanced optics value with 0° incident angle.

Fig. 5 shows how much higher is the performance of the Advanced design with respect to the Baseline. The level of performance depends on several elements, such as surface roughness, surface reflection and corresponding scatter loss, and material transmittance. Furthermore, the Advanced optics average RMS spot size is smaller than Baseline optics, since CYTOP presents a smaller dispersion of refractive index than PMMA-000.

D. 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, right). After a re-optimisation, the so-called "side-cut" optics has ~90% aperture of the original 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 (Fig. 6).

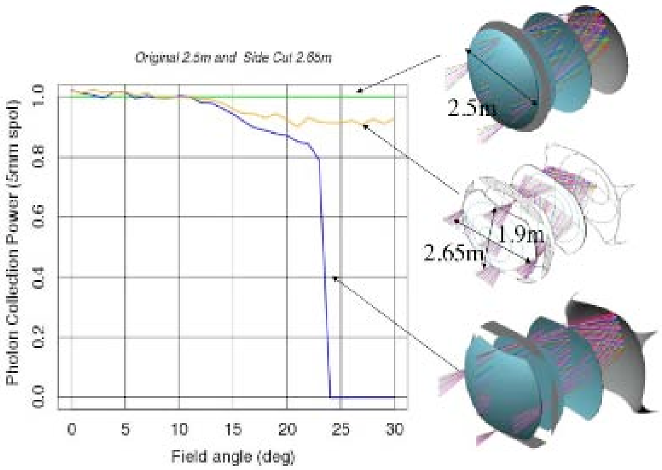

Fig. 6. Performance of the HTV stowing type optics, normalised with respect to the 2.5 m diameter case (green line). Blue curve corresponds to FoV on the 1.9 m direction, yellow curve to FoV on the 2.65 m direction.

E. Tolerance analysis

Because of its scientific goals, JEM-EUSO optics does not need diffraction limit resolution like usual astronomical telescopes: its angular resolution tolerance can be roughly 300 thousand times larger than the diffraction limit. Consequently, tolerance of the optics is much lower than astronomical telescopes. JEM-EUSO optics tolerates an error of less than the spot size, because the focal number is small and the rays impinge on the focal surface in a cone whose half angle is less than 30°. Preliminary tolerances with 2.5 mm spot sizes were verified via ray-tracing code. For each lens and for the focal surface the axial displacement, the lateral displacement and the tilt were 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 synchronised with the orbit. Refractive index is shifted by temperature changes, causing de-focusing effect. Thermal analyses predicted 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. Anyways, a focusing adjust mechanism is foreseen on the focal surface to account for the longitudinal thermal expansion of the structure and other effects.

F. Manufacturing

Since June 2008, a large diamond turning machine is being used to manufacture lenses up to 3.4 m in diameter. This machine has already successfully cut two (out of three) PMMA-000 Fresnel lenses, which belong to a subscale 1.5-m diameter JEM-EUSO prototype. These lenses will be transported to NASA – MSFC and they will undergo optical tests by using NASA facilities.

CONCLUSIONS

The construction of an all-refractive space-based telescope for detection of Ultra High Energy Cosmic Rays and neutrinos is on its way. Intensive simulations of the optics (as well as for the other subsystems) are being conducted for the last years, 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.

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