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Performance of the EUSO-Balloon optics

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EUSO-Balloon is a prototype of the JEM-EUSO detector to perform an end-to-end test of the subsystems and components, to prove the entire detection chain and measure the atmospheric and terrestrial UV background. In August 2014, the instrument was launched in collaboration with the French Space Agency CNES for its maiden flight. This article describes the optics of EUSO-Balloon, which consists of two large (1 m^2) Fresnel lenses made from PMMA. We also present the methods used for the alignment and characterization of the optics. The alignment of the optics was obtained with the use of a laser tracker and the tests were performed using a one-meter collimator and UV light sources. We present the performance of the optical system, the point spread function and the global efficiency, as a function of UV wavelength and incidence angle.

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1. Introduction

EUSO-Balloon is a balloon board pathfinder for the Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO). JEM-EUSO will be attached on the International Space Station and its mission is to observe the UV fluorescence light (between 290 and 430nm) produced by UHECR air shower in the atmosphere with a very large field of view (±30°)[1]. The EUSO-Balloon prototype tests the principle of the JEM-EUSO experiment by performing an end-to-end test of all the subsystems and components, and measuring the atmospheric and terrestrial UV light in real conditions[2]. For this purpose, all subsystems have been conceived based on the JEM-EUSO design. As for the space mission, the optics of EUSO-Balloon is composed of large Fresnel lenses. The two 1mx1m convergent lenses are made of UV transmittance grade PMMA and are designed to produce a focal spot size close to the size of a pixel (2.9mm) of the detector with a quite large field of view (12°). The baseline of the optical system used during the first flight in august 2015 was the optical design named "TA-EUSO" with two lenses and it is described in this article [3].

In order to characterize the optics, a 1m collimator was used with UV LEDs at different wavelengths. The optical system was aligned with the collimated beam using a laser tracker and two theodolites. A photo-sensor, called "NIST", with absolute calibration was implemented at the focal plane to measure the light flux. A second test campaign took place in a long corridor. Using a Xe lamp and a Hg lamp as light sources placed at long distance, the optical system was characterized at selected wavelengths between 300 and 400nm. The global efficiency and the point spread function were measured at IRAP Toulouse with the equipment and test configurations.

In this article, we present the characteristics of the optics measured so far by the two methods: the point spread function, efficiency and field of view. The size of the spot is characterized by the full width at half maximum (FWHM) of the point spread function (PSF) and the efficiency is the amount of light received by the focal surface in a certain area centered on the centroid of the PSF. The efficiencies measured are of two kinds : one computed from the focal spot relevant for the study of imaged events and one computed from the entire detector relevant for the study of the background measurement. The second efficiency is called throughput in the rest of the article.

2. The EUSO-Balloon optics design

The EUSO-Balloon optics design is composed of two large PMMA Fresnel lenses. Each lens has a collective area of 0.95m^2 and a thickness of 8mm. They are made with grooves on only one side: the back side for the front lens and the front side for the rear lens. The optics have been designed to resemble the JEM-EUSO optics and their performances have been calculated to reproduce a background rate close to the one predicted for the space telescope JEM-EUSO. Together with the detector efficiency, the optics have to produce a background light level of roughly 2 ±1 photoelectrons TBC per pixel in a 2.5μs frame.

The front lens and the rear lens are convergent with focal lengths equal to 2586 and 600 mm respectively. These two characteristics are given as ideal reference values only, due to the non-stigmatic images produced by one lens alone. The figure 1 presents pictures of the lenses and a ray

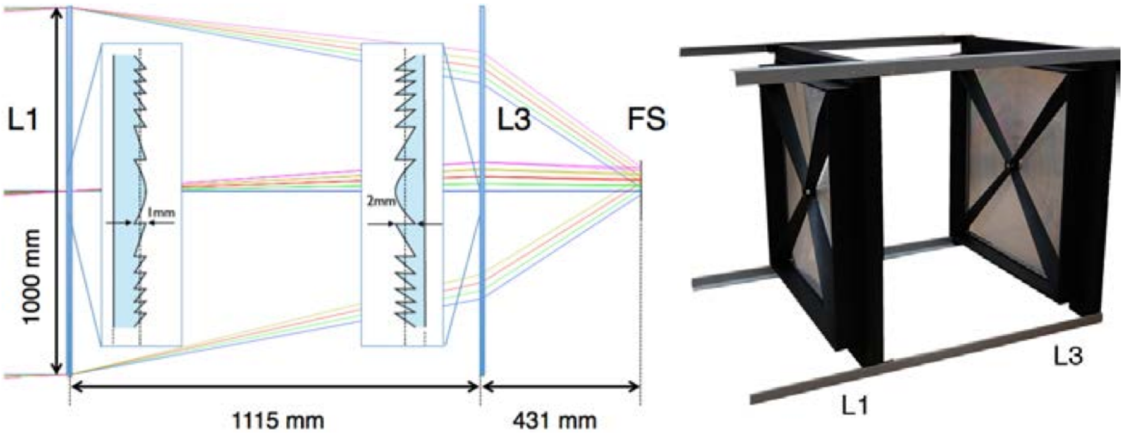

Figure 1: *left*: raytracing diagram for the EUSO-Balloon optics with the two Fresnel lenses (front lens L1 and rear lens L3) and the position of the focal surface. The incident rays are at off-axis angles for 0° (blue), 1° (green), 2° (red), 3° (yellow) and 4° (purple). The raytracing diagram shows partial sectional views of each lens. *left*: the two lenses mounted onto their fiberglass frames and spiders. Positions are adjustable.

tracing diagram showing positions of the two lenses and ray traces of light for different angles of incidence.

The positioning of the lenses has been made using a laser tracker. This device enables us to know the position of objects in space with a precision of few μm. The lenses are positioned with an error smaller than 1 mm (TBC) and are parallel within an error of TBC.

3. Collimator first test campaign

3.1 Description of the test setup

For this test campaign, a 1m collimator was used with a 390nm LED in order to create a 390nm collimated light beam. Sent through the optical system, the collimated light beam acts as a point source at infinity. An absolute calibrated NIST photodiode was used to measure the light at the focal plane of the telescope as well as in the collimated beam. This led to the first measurement of the focal spot, specifically the encircled energy. The size of the focal spot and the efficiency of the optics has been computed from this measurement.

The test was performed at a wavelength of 390nm from the LED with an angle of incidence of 3.5 +/- TBC, approximately corresponding to the centre of the field of view. The test setup is illustrated in figure 2.

3.2 Performances measured

3.2.1 Beam absolute measurement

In order to compute an absolute calibration of the optics, the collimated beam was measured utilising the NIST photodiode. More than 150 measurement points were taken over the beam section on a regular grid described in figure 3. From this, the light power in the beam was determined to be $80500nW\,(\pm 4400nW \simeq 5\%)$.

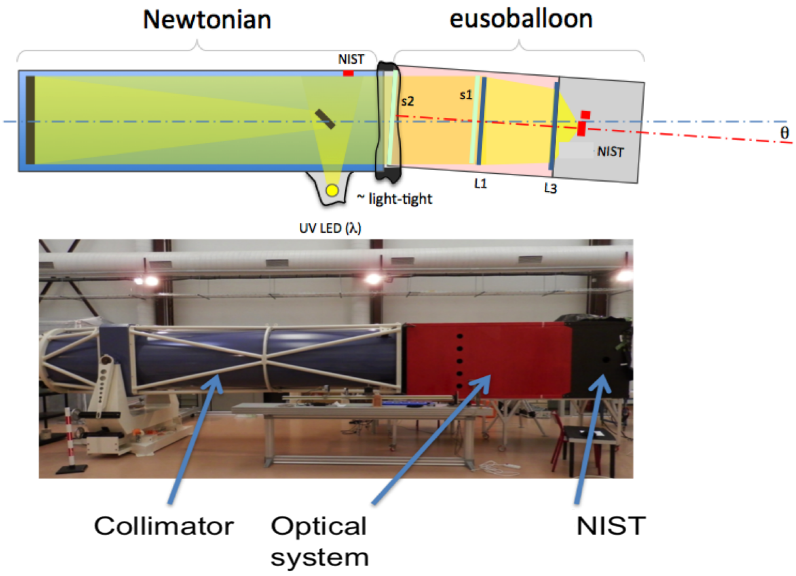

Figure 2: Diagram and picture of the setup using the collimator to test the optics. A 1m collimated UV light beam was sent through the optical system. A NIST photodiode was used at the focal plane to measure the focal spot.

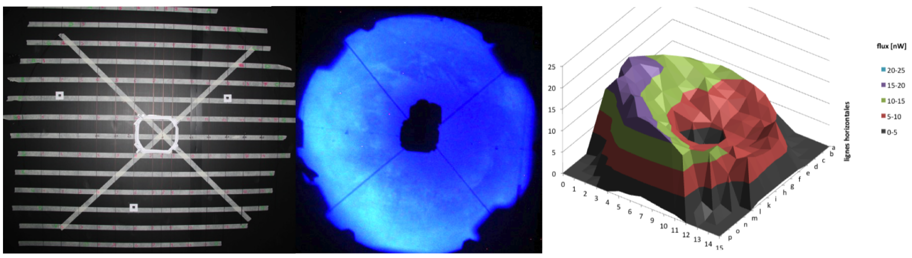

Figure 3: Measurements of the beam. From left to right: grid of NIST measurements, image of the UV beam and absolute final measurement of the light power distribution of the beam.

3.2.2 Encircled energy

The best way to measured the efficiency is to look at the encircled energy. The encircled energy is the amount of light contained in a certain circle centered on the center of the optical spot. Knowing the light power collected on the aperture of the instrument, the encircled energy can be absolute calibrated. Computing the encircled energy for different radius enables us to measure the shape of the spot and to calculate the efficiency and the throughput.

Due to the size of the focal spot, the NIST photodiode needed to be moved across the focal plane. After finding the best position along the optical axis ($\simeq$ position measuring the maximum light), the focal plane was scanned with the NIST along an axis perpendicular to the optical axis. This measurement was used to compute the encircled energy at different distances from the centroid of the spot, i.e the light flux measured at the focal plane in a circle of a certain radius. For that, and knowing that the NIST active area as a surface of $1cm^2$, the focal plane was split up into 1cm-thick rings. Measurements along the perpendicular axis enable the light power within each ring to be approximated. The encircled energy was then computed by summing the energy contained within

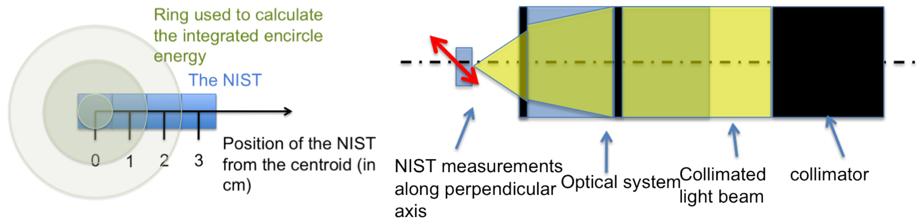

Figure 4: *Left* : diagram describing the way to compute the encircled energy using the rings integration method. *Right* : experimental setup. The collimated beam is sent through the optical system while the NIST measures light along a perpendicular axis to the optical axis.

each ring at varying distances from the centroid. This method is depicted by the figure 4.

The measured encircled energy is shown in figure 5. It increases quickly due to the central spot but never reaches a plateau, even when it is far from the centroid. this is due to the presence of an intense diffuse light that reaches all the focal plane. We defined the efficiency of the optics as the absolute encircled flux, calibrated with the light power sent through the optics from the collimated beam. Thus, the efficiency is equal to **30.5%±3 for the central area of 1cm^2 and 22%±2.2 for an area of 0.75cm^2**, equivalent to 3x3 pixels of the real instrument detector (PDM).

Using the measurements made with the instrument detector PDM, we produced an image of the focal spot in order to fit a 2-dimensional Gaussian distribution. This led to a full width at half maximum of **9mm±0.2** as shown in figure 6.

So, according to this measurement, the efficiency of the optics to use in a study of an imaged object would be the one provided by a 3x3 pixels spot : **22%±2.2**.

Since the encircled energy has been measured on a large radius, it can be used to compute the throughput, i.e. the total amount of light power received on the entire focal surface. The real detector, PDM, is a square of 165mm by 165mm. Knowing the encircled flux is equal to 48% for a radius of $82.5mm$ and 51% for a radius of $82.5 * \sqrt{2}mm$, we can compute a first rough idea of the throughput of the optics. It should be **around 50%** for a PDM focal surface size.

4. Long corridor test campaign

4.1 Description of the test setup

For the long corridor test campaign, 'collimated light' was achieved by placing the light source at a position approaching infinity from the EUSO-Balloon optical system.

A 100W mercury lamp light source was positioned 73m from the EUSO-Balloon optical system. The setup is detailed in figure 7. Band-pass filters for 313nm, 365nm and 405nm were positioned to transmit a specific UV wavelength to the optical system. Apertures and baffles were placed in front of the light source to eliminate any stray light emitted by the mercury lamp. The angle of incidence of the light source was determined by shining a laser from the mercury lamp to a small mirror at the centre of the L1 lens manifold. The angle was determined by observing the location of the laser's reflection, depicted in figure 8.

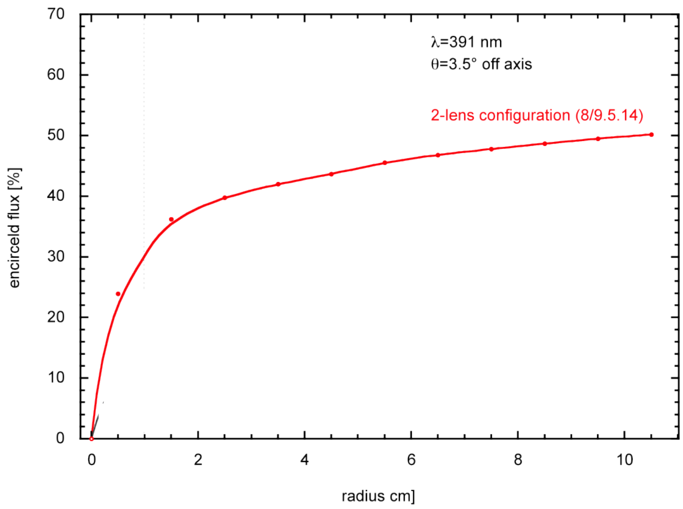

Figure 5: Encircled light energy measured with the collimated beam.

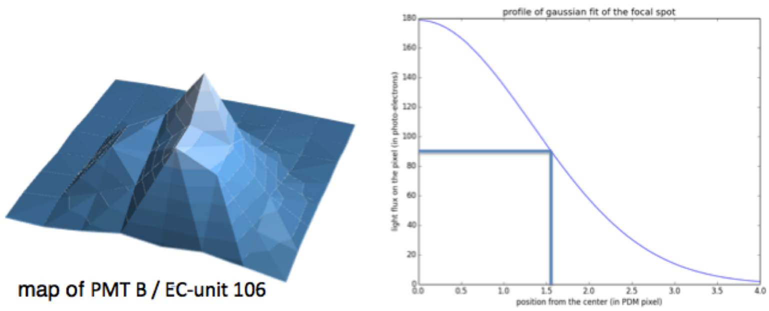

Figure 6: *left* : Focal spot taken by the PDM. *right* : 2-D gaussian fit of the focal spot. FWHM = 9mm

To map the focal spot, the light flux received through lenses L1 and L3 was recorded by the NIST, which was fixed to a 3-dimensional translation stage behind L3. The translation stage can measure through a 300mm x 100mm x 100mm range in the x, y and z directions respectively and is capable of taking flux measurements at increments of less than 1mm. This configuration allows for the accurate mapping of the focal spot and the shape of focused beam. A second NIST was placed at the front of the EUSO-Balloon optical system to record the ambient light flux. This was so that any fluctuations from the light source could be monitored and used to adjust the received light values accordingly. Using the same methodology as per the collimator test campaign, the encircled energy and optical efficiency were able to be determined.

4.2 Performances measured

Helped by the 3-axis translation stage of the NIST, the focal plane can be scanned in 3D, the NIST regularly taking measurements along the 3 axis. This entire 3D scan of the focal plane was used to find the best distance between L3 and the NIST, it is the one where the focal spot is the most peaked and the most intense. At this distance, the measurements of the focal plane provided us the shape of the focal spot and the encircled energy. An image of the focal spot as shown by

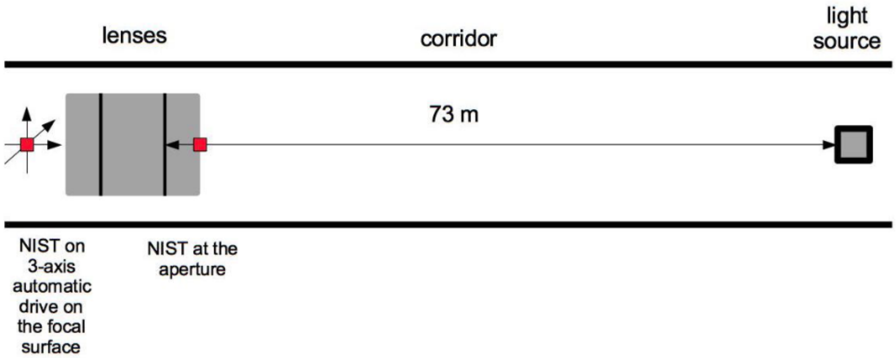

Figure 7: Description of the experimental setup. A light source is placed far from the optical system (73m) in order to produce a roughly parallel light beam at the instrument. The focal plane is measured by the NIST photodiode along the 3 axis.

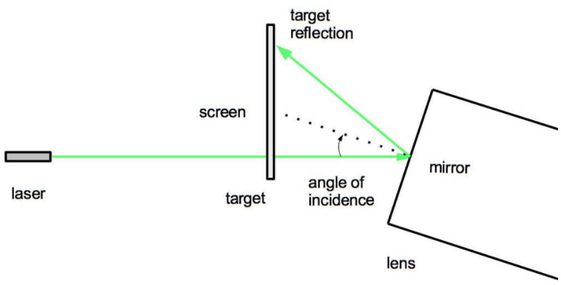

Figure 8: The angle of incidence of the incoming beam is measured firing a laser from the light source to the instrument. The position of the reflection of the laser on the first lens of the instrument is used to measure the angle of incidence.

figure 9 can be obtained from those measurements.

The encircled energy was computed with a method close to the one used with the collimator test setup. Indeed, the focal plane was split up into 1mm-thick rings. Measurements on the focal plane were used to calculate the average light power contained in each rings. The encircled energy was then computed by summing the energy contained within each rings at different distances from the centroid. To get a more precise measure, small steps were used on the translation stages and a 1.4mm diameter diaphragm was placed on the NIST to reduce its collective area.

So far, we measured the encircled energy for three wavelengths at one incident angle as shown by the figure 10. The angle of incidence was **2.3 degrees** $\pm$ **0.1** and the three wavelength were **313nm, 365nm and 405nm**. Assuming that the focal spot size is the same as the one measured by the first test campaign, i.e. 3x3 pixels size, we computed the efficiency at 2.3 degrees for each wavelengths. These efficiencies are presented table 1.

5. Conclusion

In this article, we have presented few measurements of the characteristics of the optical system.

wavelength	efficiency
313nm	16%
365nm	21%
405nm	26%

Table 1: Efficiencies computed for a 3x3 pixels spot size at an angle of incidence of 2.3 degrees

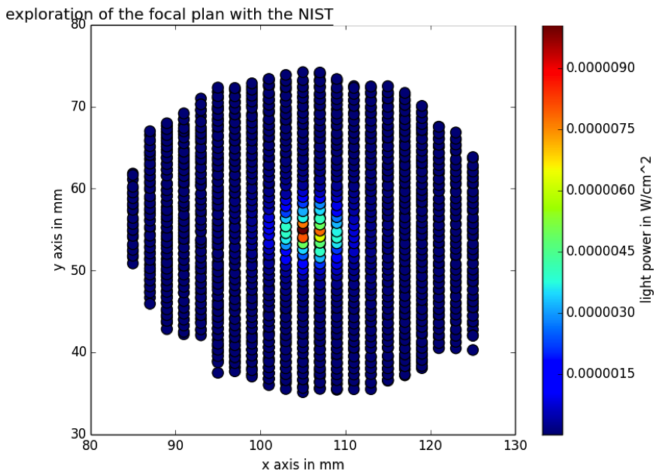

Figure 9: Image of the focal spot at 405nm and 2.3 degree and at the best position along the optical axis. Horizontal and vertical axis origins are arbitrary.

The measurements were made during two test campaigns described in the article and characterization is still going on. The first campaign used a collimator and a 390nm UV LED. The second campaign used a different setup with a polychromatic light source placed far away of the instrument. Different passband filters provided monochromatic lights. An absolute calibrated NIST photodiode was used to scan the entire the focal plane in order to measure the size of the spot and the encircled energy. From the encircled energy, the efficiency was computed.

The spot size has been measured at one wavelength and one degree of incidence and is equal to 3x3pixels size, approximately 9mm. Since the angle of incidence is at the middle of the field of view, this measurement could be used as a first approximation of the focal spot size.

The efficiency of the spot was measured at 3.5 degrees of incidence and 390nm wavelength during the first campaign and is equal to 22%. During the second campaign, we measured the efficiency at 2.3 degrees of incidence and for three wavelengths (313nm, 365nm and 405nm) and it is equal to respectively 16%, 21% and 26%. Those numbers and any combination of them should be used carefully as first measurements of the characteristics of the optics. Indeed, despite we are confident on the results, the measurements are not complete and the characterization need to be done at other wavelengths and other angles.

This efficiency must be used only for imaged objects study or point sources study, as for example the optics efficiency used to image air shower. It is not due to be used in background light study.

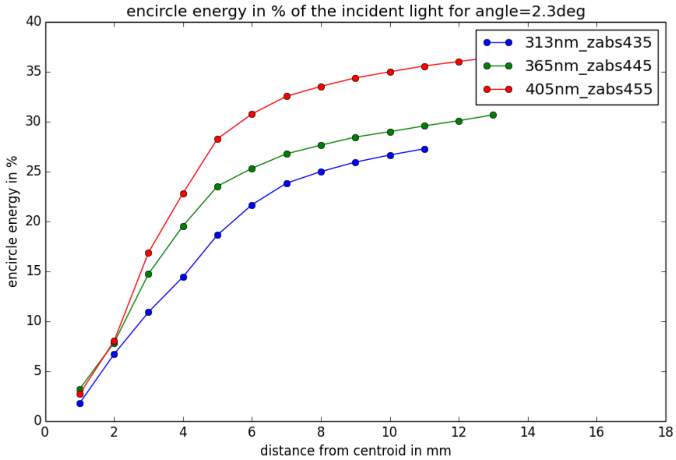

Figure 10: Encircled energy measured at 2.3 degree and at three wavelengths. For each wavelength, the measurement was taken at the best distance between L3 and the NIST, called "zabs". The encircled energy is normalized with the light power collected by the instrument.

Because of the first campaign measurement, we have a first idea of the throughput of the optical system. The measurement has been made at 3.5 degrees and 390nm and is roughly around 50%. This is a first idea and should not be taken as a precise measurement of the throughput.

This throughput is the kind of efficiency that should be used to study the background measured by EUSO-Balloon provided using future measurements at different wavelengths and different angles of incidence.

In a conclusion, we presented in this article first measurements of the characteristics of the optics : focal spot size, efficiency and throughput, for few angles of incidence and few wavelengths. Those numbers should be used as first approximations. Measurements are still going on and full characteristics (at many wavelengths and many angles of incidence) will be available soon as well as combined computation.

References

[1] J.H. Adams Jr. et al. - JEM-EUSO Collaboration, *Astroparticle Physics* **44** (2013) 76

[2] P. von Ballmoos et al. 34nd ICRC, Rio de Janeiro, 2015

[3] Y. Takizawa et al. 33nd ICRC, Rio de Janeiro, 2013