Study report on the in orbit calibration of the EUSO telescope

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ABSTRACT

The purpose of carrying out in-orbit calibration of the EUSO instrument requires a careful design of the optical setup to measure the performance of lenses and detectors during the EUSO lifetime. Several requirements drive the design, such as weight, power consumption and payload structure, as well as the need of decoupling the optical performance of the lenses from the responsivity of the focal surface detectors. This study report discusses some possible optical arrangements, their limits and impact on the mass and power budget. A possible UV source is also described to get spectroradiometric data on the instrument performance and the advantages or limitations of using independent detectors arranged on the focal surface is discussed.

1. INTRODUCTION

The Extreme Universe Space Observatory (EUSO) on the International Space Station (ISS) will detect the Extreme Energy Cosmic Rays (EECRs with $E > 4 \times 10^{19}$ eV) and the high-energy cosmic neutrino flux looking at the streak of fluorescence light produced when the particles interact with the Earth’s atmosphere. A reliable detection of this fluorescence light, in order to determine the energy scale and the energy resolution of the ultra-high energy cosmic rays, is the key issue for the success of this pioneering experiment. Consequently, accurate in-flight calibration is a crucial topic of the EUSO experiment. The major uncertainties come from the calibration of the absolute efficiency of the telescope and from the measurement of the absolute response of the detectors. Therefore, these uncertainties must be well figured out.

The aim of this report is to describe a first approach to, and some possible solutions for, the calibration system of the EUSO telescope and focal surface (FS). This proposal will discuss some possible designs of the EUSO calibration system. The correct estimation of the energy of the detected cosmic rays relies also on the atmospheric transmission, air Cherenkov subtraction, light multiple scattering, and cloud corrections to the fluorescence data. This document will not discuss the problems and the calibration procedure concerning the atmospheric contribution. This important item requires a separate and deep analysis related to the use of a LIDAR system. Some of the experimental groups involved in the EUSO collaboration are working on this subject and are dealing with these aspects.

When an EECR with energy $E > 4 \times 10^{19}$ eV interacts with the Earth’s atmosphere, produces a shower of $10^{10}$-$10^{11}$ particles that may excite the atmospheric nitrogen molecules generating a streak of fluorescence light. The expected flux on the EUSO FS is $\sim 30$-$40$ photons/pixel, which should produce a signal of $\sim 10$ photoelectrons/pixel. This number is strongly dependent on several parameters such as the atmospheric transparency, the transmittance and the optical quality of the telescope, the transmittance of the filters, and the quantum efficiency of the detectors. This implies determination of the spectral responsivity, i.e., the effective area of the telescope-detector combination as a function of wavelength, because of different contributions of spectral lines to the integrated photon flux on the FS detector.

The accurate detection of the fluorescence light, in order to determine the energy scale of the EECRs, relies on the knowledge of the values of these parameters and on their possible variations during the experiment lifetime. Therefore, frequent and thorough spectroradiometric calibration is a crucial task that must be included in the schedule of EUSO observations.

2. REQUIREMENTS AND TARGETS

The term calibration indicates the set of measurements that determine the absolute values or the relative variations of the parameters that form the transfer function in order to get the incident photon flux from the photo-electron signal.
The effective area of the EUSO telescope depends on a few parameters, i.e., the transmissivity of the two Fresnel lenses $\tau$, the transmissivity of the filter $\tau_f$, the collection efficiency of the detector $\eta$ and the quantum efficiency $Q$ of the detector. Therefore, the incident photon flux $F$ produces a number $S$ of photoelectrons in each pixel given by

$$S = \kappa \tau_f \tau_\alpha \eta Q F$$

where $\tau_\alpha$ is the transmittance of the atmosphere and $\kappa$ is a factor accounting for some fraction of the flux that may not fall on the given pixel owing to a larger point spread function or to dispersed photons. The role of an on-board calibration is to determine the contribution from each of these parameters in order to scale the measured signal to the incident photon flux that is to the energy of the EECR.

Therefore, calibration concerns the measurement of the performance of the following components:

- Fresnel lenses
- FS detectors
- Filters
- Optical adapters
- Trigger and Readout Electronics

The target is to measure the

- Transmissivity and uniformity changes of the two Fresnel lenses
- Variation of the UV filter properties
- Transmissivity or reflectivity reduction of optical adapter
- Efficiency degradation of the optical adapters + detector system due to vibrations, possible damage, misalignments, increased scattering, etc.
- Variations of the photomultiplier gain
- Failure of some photomultiplier
- Increase of the stray light level
- Performance of the trigger and readout electronics

The requirements for the calibration systems are:

- Spectroradiometry in the range 300-400 nm
- Photon counting regime:
  - Integration time: $\geq 200$ ns
  - Time resolution: 20 ns
  - Background: $< 5 \times 10^4$ ph/s/px ($< 10^{-2}$ ph/px)
- Uncertainty $< 10\%$
- Very low impact on the mass budget
- Low power consumption
- No movable components
- Monitor for the light source
- Fitting the EUSO structure

The major concern for the calibration system is to produce a stable illumination of the FS. This stability must be checked during the instrument lifetime. Non-uniform illumination of the FS is not a crucial aspect, but it must be limited to 20%. This is because the calibration system works in photon counting regime and the integration time is rather short. Strong non-uniformity can cause a reduced probability of monitoring specific regions of the lenses and FS.

Another point under discussion is to include analog and pulsed regime in order to calibrate the detectors and the trigger and readout electronics. This means to illuminate the telescope with higher fluxes ($2.5 \times 10^4$ ph/s/px) and with pulses having $< 10$ ns width. This will not be discussed in this report.

### 3. OPTICAL DESIGN

We have performed ray-tracing simulation of some optical arrangements to calibrate the EUSO telescope using the software code Zemax 9.0. We have analyzed the performance of such systems considering the main wavelengths of the atmospheric nitrogen fluorescence, i.e., 337 nm, 357 nm and 391 nm.

![Ray tracing of the EUSO telescope with a point-like Lambertian source placed on the optical system focus.](image)
The efficiency of this system is 71% and the photon flux is \(8 \times 10^7\) ph/s on the FS, starting from a source emitting \(10^{15}\) ph/s, i.e., 1600 photons on the FS collected during the integration time or 0.3 ph/detector, or \(~10^{-2}\) ph/px. These numbers are obtained taking into account the transmittance of a 1 mm Teflon film (~ 2.5 \(\times\) 10\(^3\) in the region 300÷400 nm) used to diffuse the radiation before collecting a radiation cone of 60° aperture, the total transmittance of lenses (90%), an integration time of 200 ns, and no scattered light.

The disadvantages of this optical scheme are a partial illumination of the first Fresnel lens that cannot be fully monitored and the source far from the entrance lens. Supposing an arrangement of the light source on the shutter, such a distance implies baffles exceeding the maximum allowed external dimension.

We have also analyzed the capability of this system to detect reduced performances of the Fresnel lenses. We have simulated a lack of transmittance as an obscuration on the first of the two Fresnel lenses having radius 200 mm. The result, reported in Fig.3, shows that the obscuration is detected with a good contrast. However, it must be reminded that the obscuration represents the worst case and that the analysis does not include the stray light.

A more compact design is obtained when the radiation source is placed in the center of the FS to illuminate the optical system. In this case, the radiation passes through the lenses and is reflected back into the telescope with an aperture of 60° by a spherical folding mirror arranged on the shutter. The size of this mirror is strongly dependent on the FS dimension and the beam fixed aperture. The shutter could be properly shaped and coated in order to get the mirror.

The optical scheme and the ray-tracing simulation of this optical arrangement are reported in Fig.4, while the distribution of radiation intensity on the FS is shown in Fig.5.

The efficiency of this system is about 48% because of the beam passing through the lenses twice. The photon flux is \(5 \times 10^7\) ph/s on the FS, using a source emitting \(10^{15}\) ph/s. This means that 950 photons can be detected during the integration time on the FS. This flux has been obtained by increasing the pinhole diameter up to 0.65 mm and reducing the output aperture angle (32°). The other parameter values remain unchanged.

The advantages of such configuration are a better illumination of both the lenses and a uniform illumination, as can be seen in Fig.5. The disadvantage is the mirror on the shutter reflecting the background radiation inside the telescope when the lid is open. This problem could be solved by taking into account that the telescope operates in the UV, the aperture angle of the lid can be fixed considering this problem and that the lenses focalize radiation on the FS with specific incidence angles.
This solution is compact, fits the payload structure and is able to monitor the entire optical system. Therefore, a deeper study can be faced in order to find out possible solutions. For example, the mirror could have a visible and UV low reflectance because of the need of reducing the photon flux to operate in photon counting. A trade off between baffles and aperture angle of the lid can be studied to avoid as much as possible reflected radiation inside the telescope.

An interesting result comes from the simulation of a partial obscuration of the first Fresnel lens having size 5 cm. The beam passes through the lenses twice and if the obscuration is located in the central region of the lens, the beam light sees it twice. Therefore, the intensity distribution on the FS shows two obscured regions, the outer having larger size (is a sort of optical magnification). This effect is useful to find out even small central regions where the transmissivity is worsened, but the region covered by the outer hole cannot be monitored directly. We are studying variations of the optical design to avoid this problem.

4. RADIATION SOURCE AND DETECTORS

The requirement is for a point-like UV light source, having a Lambertian emission profile, and providing multi-wavelength emission to enable spectro-radiometric capabilities of the calibration system. Among available UV sources, UV LEDs based on nitride technology are the most suitable. GaN, InGaN, and AlGaN UV LEDs emit in the spectral region ranging from 350 nm up to 450 nm and pulsed UV LEDs are also available with 4 ns pulse duration. They are commercially available by many companies, such as Nichia Corp., Marubeni Sunnyvale Corp., Nitride Semiconductor Co., Roithner Lasertechnik.

The features of interest for the EUSO application are:

- Emission wavelengths: 350 nm, 370 nm, and 393 nm
- Photon flux: $10^{15}$ ph/s in a narrow beam (15°-30°)
- Power consumption: ~120 mW
- Very lightweight: < 10 g

Fig. 7 shows a possible arrangement to produce a point-like Lambertian source, whose emission flux can be easily adjusted and monitored. A UV LED having a 15° aperture angle illuminates a 0.2 mm pinhole that is placed on a 0.5 mm thick Teflon film. The pinhole diameter and the LED-pinhole distance can be adjusted to fix the aperture angle and thus the photon flux arriving on the EUSO telescope. The Teflon film is a very good diffuser for UV radiation and the selected thickness allows for transmission values ranging from $2 \times 10^3$ to $3 \times 10^3$ in the spectral region of interest.

![Figure 7. Sketch of the source arrangement to get a point-like Lambertian UV source.](image)
After the Teflon film, a diaphragm can be placed at a certain distance. Again, the diaphragm diameter and the distance can be selected in order to fix the photon flux emitted from this source. The constraint is that the aperture of the outgoing beam light must be 60°. The stability of the emitted radiation can be monitored arranging a solid-state photodiode in the gap between the diffuser and the diaphragm. The radiation stopped by the diaphragm can be partially or totally collected and sent to the photodiode, placing a mirror nearby or around the diaphragm.

Spectroradiometry can be achieved using more than one LED, each emitting at a different wavelength. Fig.8 illustrates a possible arrangement of such a source, where 3 LEDs are used. The LEDs are alternatively switched on and the emitted radiation can be collected by an optical fiber, whose aperture angle fits perfectly with the LED emission angle. In this case, flux adjustment can be obtained acting on the fiber length. The optical fiber is connected to the pinhole so that the radiation emitted from each LED can pass through the pinhole.

The silicon-based components of the source (the electronics and the photodiode) pose a problem of radiation hardness; therefore, the box must be built using a 4 mm thick Al layer. This has a direct impact on the mass budget and thus a careful design will have to minimize radiation shielding.

Emitted radiation will enter the EUSO instrument providing information on the performance of the optical system and the FS detectors. This two-piece information must be decoupled in order to monitor the optical quality of the lenses independently from the detector responsivity.

Two different approaches can be envisaged:

1. to provide the FS with detectors devoted to calibration measurements
2. to arrange some UV sources on the spider around the internal Fresnel lens.

These solutions are almost equivalent in term of impact on the mass and power budget, depending on the number of sources or detectors. However, placing detectors on the FS can be a problem because of the need of holes (see Fig.9). In addition, monitoring the optical system requires many detectors spread on the FS. Photomultipliers operating in photon counting regime are presently the unique choice, but the option that will be studied shortly of having both the photon-counting regime and the integration regime will allow the use of solid-state photodiodes. This possibility is interesting because of the lack of durable calibrated response of photomultipliers. Possible choices for the photomultiplier are from Hamamatsu Photonics:

- R7400U-03 or R7400P (Ø = 12 mm and 5.3 g)
- R1635P (Ø = 10 mm and about 10 g)

Using UV sources around the internal Fresnel lens allows for monitoring the FS detectors independently from the EUSO optical system. The combination of data obtained illuminating the whole EUSO instrument and then the FS detectors provide information on the status of the lenses. The advantage of this solution is that the FS is fully illuminated and thus monitored. In addition, some of the sources around the lens can be pulsed in order to calibrate the electronics.

5. MASS AND POWER BUDGET

The mass and power budgets are reported in Table 1 and Table 2 respectively. They have been calculated considering only one source on the EUSO main shutter and 6 photomultipliers (mod. R7400U-03) on the FS. The number of photomultipliers could be larger, but both the total mass and power increase.
On the other hand, a possible number of UV-light sources around the internal Fresnel lens is 6. This means that the mass and power values for one source (1.18 kg and 1.36 W) increase by a factor of 7, i.e., they are 8.26 kg and 9.52 W. Work is in progress to find solutions in order to reduce these numbers, starting for example from the box that could be limited to radiation-soft electronic devices. No contingency has been added to this estimation.

Table 1. Mass budget of one source and detectors on the FS

<table>
<thead>
<tr>
<th>MASS BUDGET</th>
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<tbody>
<tr>
<td>Box</td>
<td>850 g</td>
</tr>
<tr>
<td>LEDs</td>
<td>60 g</td>
</tr>
<tr>
<td>Photodiode</td>
<td>20 g</td>
</tr>
<tr>
<td>Teflon, fibers, mirror</td>
<td>&lt; 50 g</td>
</tr>
<tr>
<td>Electronics</td>
<td>&lt; 200 g</td>
</tr>
<tr>
<td>FS detectors + readout electronics</td>
<td>&lt; 1000 g</td>
</tr>
<tr>
<td>TOTAL</td>
<td>&lt; 2180 g</td>
</tr>
</tbody>
</table>

Table 2. Power budget of one source and detectors on the FS

<table>
<thead>
<tr>
<th>POWER BUDGET</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LEDs</td>
<td>0.36 W</td>
</tr>
<tr>
<td>Photodiode</td>
<td>0 W</td>
</tr>
<tr>
<td>Electronics</td>
<td>&lt; 1 W</td>
</tr>
<tr>
<td>FS detectors + readout electronics</td>
<td>&lt; 1 W</td>
</tr>
<tr>
<td>TOTAL</td>
<td>&lt; 2.36 W</td>
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6. CONCLUSIONS

In orbit calibration of the EUSO telescope is one of the main task to ensure a correct estimation of the energy of the detected cosmic rays, figuring out the uncertainties on the parameter values that form the transfer function.

Work is in progress to design an optimized calibration system for EUSO, taking into account the requirements on weight, power consumption, and structure of the payload and of the FS.

We have analyzed a couple of preliminary optical designs based on a single point-like Lambertian source that illuminates the Fresnel lenses, producing a collimated beam on the FS. The collimated beam is not a requirement; the illumination can be non-uniform and obtained using multiple sources. The advantage of using a single source is in reducing system complexity, weight and power consumption.

Multiple sources can be placed on the EUSO lid, but this design has not been explored in this report; the single source has to be arranged on the center of the FS, but this configuration presents some aspects requiring a deeper investigation. Multiple sources can be also used to get independent data on the optical performance of the lenses and the responsivity of the detectors. We have also analyzed the possibility to have detectors on the FS devoted to calibration measurements.

The next step is to study improved optical designs taking into account also scattering from the Fresnel lenses and to include both the photon counting and the analog regime, using also pulsed UV sources to face the calibration of the trigger and readout electronics.

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References