Proposal for the EUSO Instrument Calibration System

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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 pre-flight ground calibration and in-flight calibration are essential topics 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. These uncertainties must therefore 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 plane. This proposal will address the main requirements to design the EUSO calibration system and the crucial items for further analyses and discussions. The target is to accomplish a reliable system that can be used for ground and in-flight calibrations. This way, a relative measurement of the post-launch instrumentation status can be easily achieved.

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 propose a possible extension of the in-flight calibration to simulate tracks and to probe the atmosphere, but it will not discuss the problems and the calibration procedure concerning the atmospheric contribution. This is an important item that 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.

![Nitrogen Fluorescence Spectrum](image)

*Figure 1. Fluorescence spectrum of the atmospheric nitrogen.*

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. Fig.1 shows a measured spectrum of this emission. The main contribution to the fluorescence photon flux is due to four peaks in the emission spectrum, at 312 nm, 337 nm, 357 nm, and 391 nm, plus some
minor line peaks. The estimated integrated flux from each kilometer of the shower track is greater than \(10^{14}\) photons. However, it must be reminded that the fluorescence emission is isotropic over a \(4\pi\) solid angle, while the EUSO telescope can collect only a small fraction of it proportional to the size of its entrance pupil and inversely proportional to the square of the distance. This reduces the expected flux on the EUSO focal plane to \(\sim 30\text{-}40\) 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 focal plane 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. THE EUSO INSTRUMENT PAYLOAD

The EUSO instrument payload can be divided in three main sub-systems (see Fig.1):

- The telescope or optical system
- The focal plane detector
- The front-end and trigger electronics
The EUSO telescope is an unconventional optical solution based on a couple of curved double-sided plastic Fresnel lenses. The use of plastic Fresnel lenses matches the wide aperture and weight specifications, but they represent an unknown factor in terms of UV transmissivity, cleanliness of the instrument, and degradation of the performance during the long period of operation in orbit.

Another crucial component of the optical system is the UV filter, selecting the wavelength bandwidth. Several solutions are under evaluation, such as filter glasses or interference filters, filters at the entrance pupil of the telescope or filters on each detector on the focal plane. Whatever is the final solution, possible changes of the filter transmissivity and degradation of their optical quality must be considered.

The focal plane detector is a concave surface having a diameter of 2.3 m. This surface is completely filled by more than 4500 Multi-Anode PhotoMultiplier Tubes (MAPMT). Actually, two different type of MAPMT from Hamamatsu Corp. are under consideration: the first is a 64-channel photomultiplier having a 2-mm pixel size and a total sensitive area of 18 mm over a detector cross-section of 25.7 mm, while the other is a 25- or 36-channel photomultiplier with electrostatic focusing of the photogenerated electrons increasing the total sensitive area up to 24 mm over a detector cross-section of 26.2 mm. The increase of the sensitive area produces an increase of collection efficiency of the focal plane detector, thus improving the total effective area of the telescope.

The front-end and trigger electronics is devoted to the acquisition of the signal maximizing the signal-to-noise ratio. This task is obtained using a three-level trigger that helps the signal detection rejecting the spurious signals. The trigger efficiency is a crucial parameter to avoid the rejection of true signals and it must be calibrated using a signal very similar to the EECR track, in order to activate all the trigger levels. The trigger efficiency does not contribute to the effective area of the telescope, it acts on the entire track rather than on every single photon: it can be activated if the total signal from the track is higher than a fixed threshold; therefore trigger inefficiency means that some track is lost, while the parameters contributing to the effective area cause a decrease of the signal level, but the signal may be still detected.
The EUSO telescope is not very complex and its effective area depends on a small number of parameter, i.e., the transmissivity of the two Fresnel lenses $\tau_l$, the transmissivity of the filter $\tau_f$, the collection efficiency of the detector $\eta$ and the quantum efficiency $Q$ of the detector. Therefore the photon flux $F$, producing a number $S$ of photo-electrons in each pixel, can be expressed as

$$S = \kappa \tau_f \tau_l \tau_a Q F$$

where $\tau_a$ is the transmittance of the atmosphere and $\kappa$ is a factor included to account 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.

The aim of this report is to discuss the calibration of the EUSO telescope and detector in order to find the proper way to monitor the parameters influencing the total effective area of the instrument. The trigger efficiency will be discussed in a following report, because it requires a specific technique to be implemented that must be studied and designed carefully. The possibility of producing a line-shaped source simulating an EECR track is under study. It should be based on the same optical system used for the EUSO calibration, but a particular optical arrangement can be inserted to produce the line source.

3. THE CALIBRATION SYSTEM AND ITS TRANSFER TO ORBIT

Any radiometric measurements that are performed on a space instrument with the aim of deriving physical properties must be traceable to (ultimately based on a comparison with) primary laboratory standards. Such standards are absolute radiation sources or detectors that can be realized in the laboratory. Then, the laboratory standards must be transferred to satellite instruments, considering the way of applying them to a space telescope and the calibration changes during an instrument’s orbital lifetime.

A primary or secondary standard that is operated in orbit as part of the EUSO scientific payload must be used to determine the values of the optical parameters influencing the measurement of the UV fluorescence light as a function of wavelength. Such a standard must assure a calibration “end-to-end”, i.e., from entrance aperture to detector output, of the instrument system. The needs for an “end-to-end” calibration will be briefly discussed hereafter in this paragraph.

The EUSO instrument calibration could be accomplished in laboratory with a primary standard light source, such as synchrotron radiation, monitored at the telescope entrance and on the focal plane by secondary standard detectors. This procedure should reduce the uncertainties on the measurements and provide a cross-check of the responsivity of the standard detectors. Then, a second pre-launch calibration of the EUSO apparatus should be planned using the calibration system that will be used in orbit. Using the same apparatus for pre-launch and in-flight calibration allows a direct comparison between the data from the two measurements, providing reliable
information about even small changes in the responsivity of the EUSO telescope-detector combination.

Unless extreme care is exercised, environmental influences, such as contamination on the ground of optical surfaces and the influence of radiation in space, may cause the spectral responsivity of the EUSO instrument to change dramatically between laboratory calibration and initial operation in space and during the subsequent long period of orbital operations. Surface layers that originate from exposure to pre-launch environments or from “outgassing” from the spacecraft bus and payload itself cause changes in performance when exposed to the harsh electromagnetic and particle emission from the Sun. In-orbit monitoring and validation of the optical properties of each component and of the responsivity of the detectors is, therefore, necessary. Unless on-board radiometric standards that calibrate the overall system from “end-to-end” are available, it is particularly difficult to detect whether a change in the spectroradiometric responsivity has occurred between laboratory calibrations and measurements in orbit.

The calibration of the EUSO instrument can be achieved considering it as a whole, i.e., arranging a radiation source in front of the telescope and measuring any variation of the responsivity at the focal plane, using the same MAPMTs as detectors. The radiation source can be monitored by a secondary standard detector to monitor the stability of its emission. The advantage of this solution is a simple and a light-weight system providing basic information about variations of the effective area of the instrument. Another possibility is to implement some detectors on the focal plane, different from the MAPMTs, in order to separate the contribution of the telescope transmittance to the effective area from the contribution due to the MAPMTs quantum efficiency. Unfortunately, it is very difficult to check the transmittance of the filters independently. This “end-to-end” solution provides advanced information about the instrument’s components and their specific contribution to the effective area of the telescope. For example, it is possible to monitor occurred non-uniformities of the instrument responsivity that could be corrected if they depend on the MAPMTs. It is possible to improve the measurement of non-uniformities or local damages of the Fresnel lenses by combining measurements that use the reference detector or the MAPMTs.

Another item to consider in the calibration concept study is the availability of spectral measurements. It is possible to illuminate the EUSO instrument with a narrow- or large-band source without any spectral resolution, monitoring variations of the integrated flux. The advantage is again a simple and light-weight system; the drawback is greater uncertainties on the calibration data, because of probable non-uniform degradation of the performance over the spectral range of interest. Illuminating the instrument in orbit with a radiation source having a spectrum similar to the atmospheric nitrogen fluorescence is not trivial, therefore a viable solution is to use a source having a large emission spectrum, covering the 300-400 nm region, selecting portion of this spectrum through narrow-band filters or a grism (or grating). Spectroradiometry may assure a more reliable calibration, checking the effective area of the instrument as a function of wavelength and minimizing uncertainties related to the spectral distribution of the signal.
4. REQUIREMENTS FOR ABSOLUTE CALIBRATION OF EUSO

The requirements for the calibration of EUSO instrument are

- Assessing the performance of individual components and sub-systems using a primary standard radiation source and to verify if they match the instrument specifications
- Achieving a pre-flight ground-based “end-to-end” spectroradiometric calibration of the instrument as a whole, using the same calibration system for the in-flight calibration
- Performing in-flight “end-to-end” frequent spectroradiometric calibration to provide updated data about the effective area of the telescope-detector combination as a function of wavelength
- Determining values of the effective area with uncertainty below 10%. This level must be compared with the expected uncertainty on the EECR energy measured values, which is around 20% and depends on many factors such as atmospheric transparency, background level, signal-to-noise ratio, etc.
- Optionally, combining the measurement of the instrument spectral responsivity with the atmospheric corrections accomplished with a LIDAR using only one calibration arrangement

Pre-flight and in-flight calibrations will address the following targets:

- Measuring the transmittance and the optical quality of the Fresnel lenses and of the UV filters as a function of wavelength as well as their possible variations during the instrument lifetime;
- Measuring the spectral responsivity and the collection efficiency of the photo-detectors (optical adapters + MAPMT) and to monitor possible variations during their operation in orbit
- Measuring the response of the instrument to flat-fielding to evaluate ageing effects or to identify failure of the detectors
- Monitor trigger efficiency and track recognition above the signal background
- Measure the scattered light level by the optical system

Testing the focal plane performances requires a photon counting regime. Therefore the radiation intensity from an on-board source must be strongly reduced. The availability of on-axis and off-axis simulated tracks and point-like images is desirable to provide better information about the performance of the optical system. In fact, they allow monitoring of the point spread function, the trigger efficiency, and the scattered light level during the EUSO lifetime.

Generally, in-flight measurement of uniformity of the spectral responsivity is performed using a flat field that is achieved by looking at sky regions free of stars. However, EUSO will look downward at the Earth surface from the ISS and it cannot be rotated; therefore, sky regions are not accessible. In this case, see and deserts could be useful regions. The UV radiation scattered or reflected by these dark regions should form a uniform planar wave front over small field of view. Unfortunately, the wide field of view of EUSO will image large desert or see regions on the focal plane and the uniformity of the wave front cannot be assured. As an example, the reflectivity and
the amount of scattered radiation can change from different see or desert regions inside the same field of view. This means that an on-board UV source must be used and the emitted radiation diffused. This measurement does not require a primary or secondary standard source, because relative measurements can be carried out. However, the other measurements need a stable calibrated radiation source or a calibrated detector to measure the emitted radiation; therefore a viable solution could be to use a non-calibrated source and secondary standard detectors arranged on the focal plane.

Pre-flight calibration in laboratory must be performed taking great care of cleanliness conditions; this is in order to minimize changes of spectral responsivity of the instrument between pre- and after-launch calibration.

The calibration system must satisfy the requirement of a small (negligible) impact on the mass budget of the instrument payload.

5. SETUP AND INSTRUMENTATION
The calibration system can be composed of a few components. These are

1. A radiation source with a monitoring detector added
2. An optical system to focus/diffuse the radiation on the focal plane
3. Some photon counting UV detectors on the focal plane

Selecting a calibrated source of radiation or a calibrated detector to measure the photon flux on the focal plane MAPMTs depends on the design of the system and on the availability of calibrated sources. Having a primary or secondary standard source should be the optimal solution because this choice avoids the use of a detector and reduces the uncertainties on the calibration measurements. Unfortunately, available primary or secondary radiation sources are generally large or complex and they are inconvenient for arrangement in a space-borne experiment. It is therefore more practical to use simpler and stable calibrated detectors.

5.1 The radiation source
The radiation emitted from a reference source must have wavelengths included in the 300-400 nm range. Some possible choices can be considered, depending on the calibration scheme that is preferred. A monochromatic light source, having wavelength in the spectral region of interest, can be used for basic calibration of the instrument. Spectroradiometric calibration requires a UV lamp with a wide wavelength bandwidth, including the EUSO range, while the combination of calibration and LIDAR technique needs an infrared laser with a medium-high power. Hereafter some possible candidates are briefly described.

**Nitrogen UV laser**
This is typically a monochromatic source, emitting radiation with wavelengths ranging in a narrow band centered at 337 nm. The advantages of this source are its emission line coinciding with one of the atmospheric fluorescence spectrum and the 4 ns pulse width allowing time resolution and track simulation. The drawback is that no spectral
information can be obtained. The Laser Science Inc. produces an OEM version of its nitrogen laser (model 337SI, see Fig.4) already spatialized. The main features of this source are hereafter summarized, while some specifications are reported in Table 1.

- Highly directional and very low divergence (quasi-collimated)
- Point or diffused source
- Stable over 20 millions of pulses
- Limited impact on the mass budget
- Too many photons for the photon counting
- A sweep or tilting movement is required
- Require a calibrated power meter or photodetector
- Power consuming

![Figure 4. Nitrogen laser from Laser Science Inc.](image)

### Table 1. Specifications of a nitrogen laser.

<table>
<thead>
<tr>
<th>UV Laser Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>Spectral Bandwidth</td>
</tr>
<tr>
<td>Repetition Rate</td>
</tr>
<tr>
<td>Pulse Width, FWHM</td>
</tr>
<tr>
<td>Pulse Energy</td>
</tr>
<tr>
<td>Pulse to Pulse Energy Stability</td>
</tr>
<tr>
<td>Peak Power</td>
</tr>
<tr>
<td>Average Power</td>
</tr>
<tr>
<td>Beam Area</td>
</tr>
<tr>
<td>Beam Divergence, Full Angle</td>
</tr>
<tr>
<td>Optical Pulse to Optosync Delay</td>
</tr>
<tr>
<td>External Trigger Input</td>
</tr>
<tr>
<td>Trigger In to Optical Pulse Out</td>
</tr>
<tr>
<td>Power Requirements</td>
</tr>
<tr>
<td>Power Consumption</td>
</tr>
<tr>
<td>Dimensions, l x w x h</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>

**Ytterbium laser**

The opportunity to combine the design efforts in order to produce one instrument performing optical calibration and atmosphere measurements (LIDAR) is very appealing because of the possibility of reducing weight and system complexity. The
A basic element for this kind of project is the laser. Hereafter, a possible candidate requiring further development for the specific application is described, while a possible scheme of application to EUSO instrument will be explained in a following paragraph.

The Ytterbium laser modules produced by IPG Photonics Corp. (YLP series) can be a candidate. Its features are listed below and its main specifications are reported in Tab.2:

- pulsed output beam
- average output power up to 20 Watts
- pulse duration from 30 to 200 ns
- Center emission wavelength is in the range of 1060 to 1080 nm
- acceptable impact on the mass budget and small size
- require frequency doubler and triplicating crystal for VIS-UV light
- require further developments
- not yet been spatialized

The laser output is provided by a 5 meter metal sheathed optical fiber cable terminated by a beam collimator, providing a near diffraction limited \((M^2 < 1.8)\) beam with a diameter from 8 to 12 mm. Specifications and operating parameters, such as pulse repetition rate, delivery cable length, output beam parameters, and operating voltage, can be matched to the application requirements.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>YLP-0.5/40/20</th>
<th>YLP-0.5/200/20, YLP-1/200/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode of operation</td>
<td>pulsed</td>
<td>pulsed</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Central emission wavelength</td>
<td>nm</td>
<td>1060 - 1080</td>
<td>1060 - 1080</td>
</tr>
<tr>
<td>Emission bandwidth (FWHM)</td>
<td>nm</td>
<td>&lt; 6</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Pulse tail shape</td>
<td>exponential decay</td>
<td>Gaussian</td>
<td></td>
</tr>
<tr>
<td>Nominal average output power</td>
<td>W</td>
<td>10</td>
<td>10, 20</td>
</tr>
<tr>
<td>Output power tunability to full power</td>
<td>%</td>
<td>10 - 100</td>
<td>10 - 100</td>
</tr>
<tr>
<td>Pulse repetition rate, PRR</td>
<td>kHz</td>
<td>20 - 100</td>
<td>10 - 100</td>
</tr>
<tr>
<td>Pulse width, (FWHM), PRR = 20 kHz</td>
<td>ns</td>
<td>30 - 40</td>
<td>60 - 200</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>mJ</td>
<td>0.5</td>
<td>0.1 - 1</td>
</tr>
<tr>
<td>Fiber output length</td>
<td>m</td>
<td>1 - 5</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Operating voltage, (DC)</td>
<td>V</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Maximum power consumption (@ 20ºC)</td>
<td>W</td>
<td>110</td>
<td>100, 200</td>
</tr>
<tr>
<td>Dimensions</td>
<td>mm</td>
<td>290 x 230 x 90</td>
<td>290 x 230 x 90</td>
</tr>
<tr>
<td>Weight</td>
<td>kg</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

**UV diodes**

Recently, UV LEDs have become available based on nitride materials such as GaN, InGaN and AlGaN. Their features are very interesting as they emit a very directional continuous radiation at 350-400 nm. Again, this is a quasi-monochromatic light source
Figure 5. Schematic drawing of a possible arrangement of the multiple-LED radiation source for the EUSO calibration system. In this example 3 LEDs emitting at different wavelengths (say 350 nm, 380 nm and 395 nm) can be mounted with circular symmetry. An aperture wheel (green in the drawing) rotates to select the quasi-monochromatic light emitted by each LED.

and therefore cannot be used for spectral radiometry. Owing to their reduced size, however, it is possible to design a multiple-LED source (see Fig.5) giving radiation at 3 or more wavelength in the 350-400 nm range. Unfortunately, the region at wavelengths shorter than 350 nm is not presently accessible for LEDs.

UV LEDs are commercially available by many companies, such as Nichia Corp., Marubeni Sunnyvale Corp., Nitride Semiconductor Co., Roithner Lasertechnik, and so on. Typical characteristics of such sources are listed and reported in Fig.6 and in the Tables 3, 4 hereafter.

- UV radiation in the instrument wavelength bandpass
- Stable emission
- High photon fluxes for the photon counting
- Continuous emission
- Ultra-fast pulsed LEDs available
- A sweep or tilting movement is required
- Require a calibrated power meter or photo-detector
- Very limited impact on the mass budget
- Low power consumption

Figure 6. Optical characteristics of the emitted radiation by nitrides UV LEDs.
A calibration system based on these LEDs requires a careful design to provide a calibration of the trigger efficiency, owing to their continuous emission. On the other hand, ultra fast pulsed UV LED could solve this problem. This pulsed LED is available from IBH (model NanoLED-03). It has a pulse width of 4 ns and a narrow waveband centered at 370 nm (see Fig.7). This LED does not allow spectral calibration, but a combination of multi-LED including a pulsed LED can be studied and implemented (as shown in Fig.8).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Dissipation</td>
<td>120</td>
<td>mW</td>
</tr>
<tr>
<td>Continuous Forward Current</td>
<td>25</td>
<td>mA</td>
</tr>
<tr>
<td>Peak Forward Current #1</td>
<td>100</td>
<td>mA</td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td>5</td>
<td>V</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-30 to +80</td>
<td>°C</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>-40 to + 100</td>
<td>°C</td>
</tr>
</tbody>
</table>

Table 4. Electro-optical characteristics of a typical UV LED.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Voltage I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>-</td>
<td>3.6</td>
<td>4</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Reverse Current V&lt;sub&gt;r&lt;/sub&gt; = 5V</td>
<td></td>
<td>10</td>
<td>µA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant Flux I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>0.8</td>
<td>0</td>
<td>1</td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Viewing Angle I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>15</td>
<td>-</td>
<td>deg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Wavelength I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>370</td>
<td>373</td>
<td>380</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Spectrum Radiation Bandwidth I&lt;sub&gt;f&lt;/sub&gt;= 20mA</td>
<td>15</td>
<td></td>
<td></td>
<td>nm</td>
<td></td>
</tr>
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Table 3. Electrical characteristics of a typical UV LED.

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<th>Unit</th>
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<tbody>
<tr>
<td>Forward Voltage I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>-</td>
<td>3.6</td>
<td>4</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Reverse Current V&lt;sub&gt;r&lt;/sub&gt; = 5V</td>
<td></td>
<td>10</td>
<td>µA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant Flux I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>0.8</td>
<td>0</td>
<td>1</td>
<td>mW</td>
<td></td>
</tr>
<tr>
<td>Viewing Angle I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>15</td>
<td>-</td>
<td>deg.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Wavelength I&lt;sub&gt;f&lt;/sub&gt; = 20mA</td>
<td>370</td>
<td>373</td>
<td>380</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Spectrum Radiation Bandwidth I&lt;sub&gt;f&lt;/sub&gt;= 20mA</td>
<td>15</td>
<td></td>
<td></td>
<td>nm</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 8. Schematic drawing of a possible arrangement of the multiple-LED source configuration with the pulsed LED (violet) added.

UV flash or continuous lamps (Xe or Hg-Xe lamps)

These lamps are very versatile and allow any possible configuration of the calibration system. Calibrated lamps are also available from Hamamatsu Corp. However, matching between the pulse width of the flash lamps and the requirements to measure the trigger efficiency must be studied carefully.

Figure 9. Spectra of the Xe and Hg-Xe lamps. The lower spectra, comparing the emission spectra from different UV radiation sources or using different glass envelopes, are from the Hamamatsu Corp.
The drawback of this solution is the power consumption (limited for flash lamps) and a more complex optical and electrical arrangement. The typical features of these lamps are listed hereafter and shown in Fig.9.

- Emit a spectral continuum in the instrument bandwidth
- Hg-Xe lamp emits some spectral lines in the 300-400 nm range that are very close to those of interest for the EUSO experiment
- Flash and continuous lamps
- Flash lamps are low power (1-10 microsec pulses)
- Calibrated lamps are available from Hamamatsu
- Continuous lamps require cooling systems
- Impact on the mass budget
- Power consuming
- 1% to 3% stability
- 1000-2000 hours average lifetime for continuous lamps
- Up to $10^9$ flashes for flash lamps

**Figure 10. Schematic drawing of a possible arrangement of the Xe or Hg-Xe lamp.**

Fig.10 shows a sketch of a possible solution to arrange the Xe or Hg-Xe lamps in the calibration setup. The lamp is mounted in a box with a mirror on the rear side to increase the outgoing radiation intensity. Since a very low photon flux is needed on the focal plane detector, this mirror could be avoided. The lamp box aperture is closed by a filter wheel supporting the four filters that determine four narrow wavebands (for example 330-340 nm, 350-360 nm, 370-385 nm, 390-400 nm) in the EUSO wavelength range. These filters can be interference filters.

### 5.2 The telescope calibration setup

The scheme of the instrumentation arrangement for the EUSO calibration is based on simple assumptions and constraints, such as

- The calibration is performed during the off time in the measurement duty cycle. During that time, the main shutter of the telescope is closed and it could support optics and/or light sources
The beam light on the focal plane needed for calibration are a large uniform wave front, achieved diffusing the entrance beam, and a point-like (or a track) image. This last is accomplished using a collimated beam illuminating the Fresnel lenses.

Light sources, such as diodes, not collimated and arranged on the shutter or on the spider provide only diffused light and cannot be used to have point-like or track images on the focal plane, because the EUSO Fresnel lenses focalize only collimated beams.

The accommodation of the light source and the related optics on the telescope shutter could be difficult; therefore a lateral accommodation is preferred and a back reflecting optics and/or a diffuser can be put on the telescope shutter.

The light source and the optical system must be simple and light-weight as much as possible, reducing the number of moving components to limit the chance of failures.

The reference detectors on the focal plane can be placed in the free space between the MAPMTs due to their arrangement on a curved surface.

Some types of radiation sources has a limited lifetime and therefore special calibration procedures and the need for a backup radiation source have to be investigated.

Fig.11 sketched the idea proposed in this report. The basic concept is to put a radiation source aside the EUSO telescope and to arrange a back reflecting optical system on the telescope shutter in order to collimate/diffuse the light. Then, the

![Figure 11. Schematic drawing of a possible calibration system for EUSO (not in scale). The left panel (a) shows the setup to calibrate the optical system and the focal plane detectors; the right panel (b) shows a possible way to combine the optical system calibration with the LIDAR technique by opening the telescope shutter.](image-url)
Fresnel lenses focus the radiation on the focal surface or diffuse it further. Finally, an array of secondary standard detectors monitors the light intensity on the focal surface. A couple of additional options can be proposed, such as a solid state detector to monitor the beam intensity variations of the light source and the combination of calibration and LIDAR measurement using the same laser beam (see the right panel in Fig.11).

The light source can be located outside the telescope and the collimated UV beam can enter in the optical system through a small aperture (for example 10 x 10 mm²) in the main telescope baffle. To avoid any external light entering the optical system through this aperture, a tubular feed-through or a connecting baffle can join the “source box” to the baffle. The beam is then reflected back to the telescope by a mirror that is situated in the center of the telescope shutter. If necessary, this mirror could have a very low-reflecting coating (10%) in order to reduce the number of photons on the focal plane. The mirror is on the telescope optical axis and is tilted, so that the reflected beam is parallel to the optical axis.

Optionally, this mirror can be partially coated in order to diffuse back the radiation towards the lenses (see the left panel in Fig.12). This allows two alternative ways: having a back reflected collimated beam that is focalized on the focal surface by the lenses or having a diffused beam that illuminates the lenses and all the detectors. The Fresnel lenses are designed to focus a collimated beam; if the beam is pre-diffused, they should contribute to light diffusion and the wave front should be more flattened. Another viable scheme to be investigated is that the back reflected UV beam can go straight to the lenses or can pass through a Teflon diffuser, which produces a very wide wave front and weakens the beam intensity (right sketch in Fig.12).

Both these ideas are based on a moveable light beam. This is preferable because it is better to fix the optics on the shutter and to move the beam with an additional mirror nearby the radiation source; otherwise, some mechanism arranged on the shutter close to the mirror must be introduced to remove the diffuser.
The focused spotlight is useful for example to check locally transmissivity variations of the lenses or to test if any changes of the PSF of a point-like image on the focal plane have occurred. The diffused wave front is essential to test the efficiency of all the MAPMT and to identify variations of the optical system transmissivity. Unfortunately, the schemes described above produce a focused spotlight testing only a lens region and some MAPMT close to the optical axis and do not provide a spatially resolved mapping of the response uniformity.

A possible alternative avoiding these problems is to arrange an array of collimated sources on the telescope shutter (see Fig.13 showing one of these light sources). In this case, useful sources are only the UV LED, or the multiple-LED if spectroradiometric calibration is desired, and the UV lamps. The immediate advantages of distributed sources are for example that the MAPMT can be fully tested as a whole in orbit and that optical transmissivity, detector responsivity, and local damages can be spatially resolved and mapped. The drawback is in term of complexity and weight. In addition, a careful design has to be studied because the LEDs and related electronics must be powered, or movements such as the filter wheel or to remove the diffuser must be arranged on the shutter and powered too.

![Figure 13. Schematic arrangement of one of the multiple-LED sources forming an array on the shutter. At the source exit, the beam light has to pass through a collimating optics and then it goes straight to the Fresnel lenses (with the diffuser in the upper position) or through the diffuser. The aim of this picture is to illustrate the idea and not to show the real scheme, because the collimating optics must be achromatic and it has to collimate the beam from every LED.](image)

The pre-flight calibration will determine the uniformity of the response, the MAPMT gain and responsivity, and the power consumption when the entire focal surface is fully illuminated. Relative or absolute calibration can be performed frequently in orbit and the data compared to the pre-flight calibration. However, absolute calibration can be achieved if the UV beam intensity arriving on the focal plane is known.
There are several possibilities to measure the flux intensity on the EUSO focal surface. The first is to put one or more calibrated detectors on the focal surface, as shown in Fig.14. These detectors must have photon counting capabilities and a very fast time response, if pulsed sources are selected. Having more than one detector is desirable, because multiple and distributed measurements of the beam intensity improve the accuracy of the measurement and provide a more spatially resolved distribution of non-uniformities. If adding other detectors to the focal plane arrangement is not convenient, a viable solution may be to calibrate one or more MAPMT and to produce a reference curve for their time stability and responsivity.

![Image of detectors on focal surface](image)

*Figure 14. Suggested location for the detectors monitoring possible variations of the beam intensity on the focal plane. The drawing shows four PMTs added to the focal plane, but a greater number of distributed PMTs can be envisaged, depending on the trade off between the needs for spatially resolved data and weight and complexity of the electronics.*

It must be reminded that a small number of reference detectors distributed on the focal surface allows the radiometric calibration of the MAPMTs with insufficient spatial resolution of the wave front non-uniformities; therefore, the calibration accuracy is low. A greater number of distributed detectors should be better, but the weight and the system complexity could increase, exceeding acceptable limits.

Using calibrated MAPMT should improve the spatial resolution and therefore the calibration accuracy, because a certain number of MAPMTs can be calibrated in laboratory and placed in specific position so that an acceptable spatial resolution can be achieved without influencing the weight budget. In addition, each MAPMT is composed of 16 or 64 independent channels. The great number of channels per MAPMT allows also the calibration of only a few channels (or one channel) for each MAPMT, reducing the number of detectors that must be calibrated.

In case the calibrated MAPMT is the preferred solution, it is crucial to monitor the reproducibility of the beam intensity of the radiation source and to characterize its time behavior.
5.3 Calibrated detectors

The reference detectors arranged on the focal plane have to operate in a photon counting regime and they should be very fast, as the MAPMTs are. These two requirements focus the selection of the appropriate detector on photomultipliers. Other requirements are

- UV sensitive
- Small sensitive area
- Small cross-section
- Calibrated against a primary standard source

A candidate satisfying these requirements is the R1635P head-on type photomultiplier tube from Hamamatsu Corp. The main specifications of this PMT are reported in Tab.5. The calibration of such a tube can be assured by Hamamatsu, but it can be performed also at Synchrotron Radiation facilities such as ELETTRA in Trieste (Italy), BESSY in Berlin (Germany) or in Grenoble (France).

Table 5. Main specification for the R1635P Hamamatsu PMT.

<table>
<thead>
<tr>
<th>R1635P Specifications</th>
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<tbody>
<tr>
<td>Spectral response</td>
<td>300-650 nm</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>420</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>&gt; 25% @ peak wavelength</td>
</tr>
<tr>
<td>Window material</td>
<td>Borosilicate</td>
</tr>
<tr>
<td>Anode to cathode voltage</td>
<td>1250 V</td>
</tr>
<tr>
<td>Average Anode current</td>
<td>0.03 mA maximum</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.8 ns typical</td>
</tr>
<tr>
<td>Transit time</td>
<td>9 ns typical</td>
</tr>
<tr>
<td>Size</td>
<td>Ø 9.7 mm; L = 45 mm</td>
</tr>
</tbody>
</table>

This photomultiplier is also available with a UV glass window (R3878) in case a high efficiency is required even at shorter wavelengths.

The large spectral range covered by this PMT should require a bandpass filter similar to that for the MAPMT. However, it must be reminded that several sources among those being considered emit at UV wavelengths with no visible emission. Therefore, the filter should be useless. If the Xe or Hg-Xe are used, they produce also a lot of visible light and thus a filter should be required on top of the PMT or at the lamp aperture.

5.4 The Ytterbium laser optical arrangement

A possible combination of the calibration and LIDAR measurement has been suggested for evaluation in order to have a more compact, simple and lightweight instrumentation. The Ytterbium laser described above can be a possible candidate as radiation source for such an application, probably other laser are available. This is a matter of further investigation, while the aim of this paragraph is to propose an
optical scheme to explain a concept that requires a deeper study and a substantial contribution from the groups involved in the LIDAR Working Group.

The optical layout of the laser system must be configured to have a laser beam inside the EUSO telescope or alternatively outside, downwards the Earth’s atmosphere. This can be achieved introducing a moveable mirror, deflecting the laser beam to the mirror placed on the telescope shutter.

Referring to Fig.15 (upper panel), the laser position is tilted with respect to the enclosure box by a specific angle, in order to have an outgoing beam that is used for the LIDAR measurements. A translating support is placed in front of the laser output. This support can be moved in three different positions. The central position allows the laser beam to go out without any deviation or intensity attenuation. Pushing the support, a deflecting mirror can be placed on the optical path; thus, the beam is reflected toward the second mirror on the telescope shutter. This mirror can be coated with the Mg\(_2\)F-aluminum thin layers, or it can be coated with a different coating to reduce the beam intensity. The translated support can be also pulled in a third position to insert a power meter on the optical path, in order to monitor the laser beam intensity and to check its stability. This is an important aspect, because this allows testing the intensity before the beam enters in the optical system. Consequently, it will be possible to correlate correctly any intensity variations to the optics or to the focal plane detectors. The power meter can be a silicon-based solid state detector requiring a low-voltage bias and a simple voltmeter circuit.

*Figure 15. Schematic view of the two possible laser system arrangements.*
After the mirror-detector support, the outgoing beams pass through non-linear crystal to have the emerging radiation at the desired wavelengths. For LIDAR purposes, a doubler crystal shift the wavelength at 530-540 nm, while for the calibration purposes a triplicating crystal can be used and the final wavelength is 353-360 nm. The intensity values must be carefully estimated, because the non-linear crystals greatly reduce the beam intensity and this can be a problem for the LIDAR technique. On the other hand, for the calibration setup, it is possible to insert a set of neutral filters (one or more) along the optical path to have a further reduction of the photon flux. These filters can be placed in a fixed position at the exit hole or on a filter wheel where they can put in different numbers to have increasing attenuation factors.

Another possible arrangement of this system is shown in the lower panel of Fig.15. The main difference with respect to the previous setup is a beam splitter placed at the exit hole sending the beam inside the telescope. In this way, part of the laser beam is back reflected to a power meter that can monitor continuously the stability of the beam intensity. Another advantage of this solution is that the translation movement has only two positions: push to insert the mirror on the optical path or pull to remove it from the path. The drawback is that the radiation intensity is not monitored during the LIDAR measurements.

The electronics and power supply box is located on the back of the laser system enclosure. There is the controller electronics of the movements, the laser and the power meter supplies and finally the signal acquisition from the power meter, the data storage and the interface with the main EUSO system.

It must be noticed that the same optical scheme, based on a beam light emitted from a source and a moveable flat mirror deflecting the beam, can be used with the other mentioned sources (lamp, LED or multi-LED, UV laser) to illuminate the mirror or the diffuser arranged on the telescope shutter. The added element is a collimating optics for the lamp or the LEDs.

6. CALIBRATION OF THE SUB-SYSTEMS

The calibration of each sub-system and the assessment of its performance will be one of the tasks of the teams responsible for the sub-system itself. These have been indicated during the EUSO kick-off meeting at Annecy, November 2001:

- **Focal Plane**
  - Detectors
  - Micro-cells
  - Macro-cells
  - Optical Adapters
- **LV/HV power supply**
- **Optical Module**
  - Fresnel Lenses
  - Filter
- **Analog Front End Electronics**
- **Digital Front End Electronics**
- **Trigger Electronics and On Board Readout**
7. PRE-FLIGHT CALIBRATION
A pre-flight ground-based calibration of the entire EUSO telescope must be carried out in a clean room. Special care have to be compelled for cleanliness and negligible humidity content of the environment, for selecting materials that minimize outgassing, for eliminating source of dust particles, molecular deposition and UV radiation. Cleanliness hazards control avoids the great risks due to change of the optical properties and contamination of the optical surfaces, degrading the performance of the whole instrument during the time lapse between pre-flight calibration and measurements in orbit.

Calibration before launch has to assess the

- Absolute efficiency of the optical system (Fresnel lenses and UV filter)
- Uniformity of the wave front after the optical system in response to a flat field illumination
- Absolute responsivity and time response of the photo-detectors (optical adapters + MAPMT)
- Collection efficiency of the photo-detectors (optical adapters + MAPMT) in response to simulated tracks
- Background signal level due to the dark counts
- Non-uniformities of the response of the focal plane detectors
- Track recognition and triggering capabilities
- Scattered light level by the optical system
- Power consumption of a fully illuminated MAPMTs

8. IN-FLIGHT CALIBRATION
The in-flight calibration is a very important task of the experimental procedure during the entire operational lifetime of EUSO. A correct calibration of all the instrument components will ensure the reduction of uncertainties on the acquired data and it will provide the scientists with real information about the performance of the optical system and of the detector.

The pre-flight calibration will provide a reference for the in-flight calibrations that will follow the EUSO switching on. A first calibration set of measurements will be mandatory after the experiment starting procedure: this is to assess the instrument status after the launch, deployment and installation on the ISS.

During the mission, calibration measurements will be periodically carried out taking advantage of the experiment dead time (for example when the telescope shutter is closed). The target is to check the performance of the instrumentation making relative and absolute re-calibrations, comparing the results with the pre-flight data and with the data from the previous measurements. Possible variations are expected and among them the following can be cited:

- Reduction of the transmissivity of, and induced non-uniformities on, the two plastic Fresnel lenses
- Solarization and wavelength bandpass shifting of the UV filter glasses
- Reduction of the transmissivity or reflectivity of each optical adapter (they can be transmissive lenses or light guides or reflective light collectors) and variations in the relative optical transfer function
- Modification of the collection efficiency of the optical adapters – detector system due to the effects of vibrations, possible damage, cropped up misalignments, increased scattering power, etc.
- Variations of the detector gain and photocathode quantum efficiency
- Failure of some photo-detectors
- Increase of the scattered light level from the optical system and of the background level