Evaluation Analysis of the UV-detector on the Mini-EUSO Space Telescope

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Abstract

Extragalactic charged particles, each with energies rising up to and beyond 1 Joule, have been studied for almost a century. Yet, no precise evidence have proven to show where they might originate from as their energy levels rise above the current familiar acceleration sources in outer space. The highly energetic particles have been given the name Ultra-High Energy Cosmic Rays (UHECR) and investigations of particle properties such as primary energy, mass composition and direction can be made through indirect measurements of the interaction between the UHECR and Earth’s atmosphere. The considered interaction induces an Extensive Air Shower (EAS) which emits fluorescent light in the Ultraviolet (UV) range. The probability of detecting such events is, however, as low as a few particles per km$^2$ per century. Making observations more sufficient therefore requires larger detection volumes.

By introducing the Mini-EUSO instrument, a telescope of which the main purpose is to measure the UV-light radiated from the Earth in the wavelength range of 300-400 nm, allows just for this. To be accommodating the International Space Station and targeting Earth in the nadir direction, the Mini-EUSO instrument will allow for a higher exposure to the interactions than what is currently available. The use of two Fresnel lenses provides the instrument with a large field of view ($\pm 22^\circ$) and the detections are made through multiple photomultiplier tubes.

The scope of this thesis is to evaluate the main detector of the Mini-EUSO instrument (i.e. the UV-detector) through ground-based tests. The procedures involved in the evaluation have consisted of; validating the statistical distributions of the signals, implementing dark field and flat field calibrations, and radiations measurements with three kinds of radiation sources. The data from the tests were provided during two periods and the visualization was made by adapting an already existing piece of code, using Python and ROOT Cern, to perform step by step procedures such that all operations are overlooked properly.

The analysis showed that the implementation of the dark field and flat field procedures improved the original image significantly. It also showed that both the lower and higher photon count values in a pixel indeed gave the expected statistical behaviours, with a Poissonian distribution for low values and a Gaussian distribution for higher values. The flat fielding screen did however show unknown fluctuations in the emitted light and further tests have to be implemented to assure its functionality. Under proper covering, almost no dark current was found, however, observation tests showed that the borders of the Multi-Anode Photomultiplier Tubes (MAPMTs) gave higher photon count values than the center part even when they were emitted with Lambertian light.
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Abbreviations

UV : Ultraviolet
FoS : Field of View
EUSO : Extreme Universe Space Observatory
CR : Cosmic Ray
UHECR : Ultra High Energy Cosmic Ray
EAS : Extensive Air Showers
SR : Supernova Remnant
JEM-EUSO : Japanese Experiment Module - Extreme Universe Space Observatory
PDM : Photo Detection Module
EC : Elementary Cell
MAPMT : Multi Anode Photomultiplier Tube
PMT : Photomultiplier Tube
SNR : Signal to noise Ratio
FFF : Flat Field Frame
DFF : Dark Field Frame
CMBR : Cosmic Microwave Background Radiation
AGN : Active Galactic Nuclei
PAO : Pierre Auger Observatory
TA : Telescope Array
SD : Surface Detector
FD : Fluorescence Detector
ASIC : Application Specific Integrated Circuit
FPGA : Field-Programmable Gate Array
CCB : Cluster Control Board
PDM-DP : Photo Detection Module-Data Processing
CPU : Central Processing Unit
HV : High Voltage
1 Introduction

1.1 Cosmic Rays

Between 1911 and 1912 multiple balloon experiments were conducted by a physicist named Victor Hess, the aim of the experiments were to measure at which rate the air ionization changed with respect to the distance of the radiative sources. At that time it was thought to be the $\alpha$, $\beta$ and $\gamma$ -radiation coming from the surface of the Earth due to radioactive decay. A decrease in air ionization was expected at elevated heights as a result of the high absorption rates of $\alpha$ and $\beta$ particles in air. The experiments, however, showed an increase in air ionization with elevated height, this suggested that the radiation causing the increase in ionization must have been coming from space. The unknown radiation was first given the name “high altitude radiation” but was later to be known as Cosmic Rays (CR). It was at this point that CRs were first acknowledged and approximately 30 years after the discovery scientists concluded that CRs were in fact mainly positively charged particles and not dominated by $\gamma$ - rays, but by high energy protons [1].

![Figure 1.1: The cosmic ray spectra starting from $10^{13} eV$. Contributors of the data are given in the lower left corner. The flux $F(E)$ is multiplied by $E^{2.7}$ to make features more distinguishable. Credit: [2].](image)

The high energy CR spectra ranges between a few GeV to approximately $10^{18} eV$ whilst for the Ultra High Energy Cosmic Rays (UHECR) it extends up to approximately $10^{21} eV$. CRs with energies between $10^{15} eV$ and $10^{21} eV$ can only be observed indirectly through interactions with Earth’s atmosphere in so-called extensive air showers [3], which will be explained in more detail in section 1.3. The origin of the CRs is still not fully understood but it is however known that CRs of energies extending beyond...
10^{18}\text{eV} \text{ originate from outside the Milky Way, as for CRs with energies below the limit most likely originate within the galaxy [4]. This theory is strengthened by numerous investigations, one being the comparison between the Larmor radius for different proton energies in the galactic magnetic field with the galaxy diameter. Calculations show that a 10^{20}\text{eV} \text{ proton have the Larmor radius } R_L \approx 36\text{kpc} \text{ which is a close approximate of the galaxy diameter, this concludes that the origin most likely is extra-galactic as the magnetic field would not be able to withhold the CR. The CR flux spectrum is shown in Figure 1.1, starting at CR energies of } 10^{15}\text{eV}, \text{ the spectrum follows an approximate power-law function } dN/dE \propto E^\gamma \text{ [5] and has four features of importance, the } \text{Knee}, \text{ the } \text{2nd Knee}, \text{ the } \text{Ankle} \text{ and the cut-off, at approximately } 4 \times 10^{15}\text{eV}, 4 \times 10^{17}, 3 \times 10^{18}\text{eV} \text{ and } 5 \times 10^{19}\text{eV} \text{ respectively [6, 5, 7]. The features are of importance because of the transitions in the spectral index } \gamma \text{ at the different points. Looking at Figure 1.1 one can see that before the } \text{Knee} \text{ and after the } \text{Ankle} \text{ the power law function seems to have about the same spectral index, } \gamma \approx -2.7 \text{ [5]. Between the } \text{Knee} \text{ and the } \text{2nd Knee} \text{ } \gamma \text{ is } \approx -3.1 \text{ and lastly between the } \text{2nd Knee} \text{ and the } \text{Ankle} \text{ } \gamma \text{ is } \approx -3.3 \text{ [5]. }

The \text{Knee} \text{ feature of the CR spectrum have been discussed frequently among scientists and the two most accepted explanations of the change in the spectral index is, (a) Supernova Remnants (SRs) accelerates galactic CR particles in strong fronts by first-order Fermi acceleration where the maximum energy achieved by a charged particle is } E_{\text{SNR,Z}} \propto ZBR, Z \text{ being the particle charge, } B \text{ is the magnetic field strength and } R \text{ the size of the acceleration area. And (b) the escape of CRs from the galaxy, the galactic magnetic field faces greater challenges keeping the CRs within the galaxy as their energy increase. The Larmor radius can be further simplified to } R_L \approx 1/Z \text{ which shows that the light nuclei preferably escapes prior the heavier, meaning that the protons leaks first, followed by heavier elements. Hence the } \text{Knee} \text{ most likely represents the cut-off/escape of protons, investigations have also shown that the } \text{2nd Knee} \text{ probably rises from the cut-off of heavier primaries, i.e. up to the iron nuclei [5, 6].}

This assumption is further strengthen by observing the maximum achieved energy from the SRs (E_{\text{SNR,Z}}) for an iron nuclei with respect to the proton cut-off energy, the particle energy is proportional to } Z \times E_{\text{Knee}} \text{ (scales with } Z) \text{ which for an iron nuclei leads to } 26 \times 4 \times 10^{15} \approx 10^{17}\text{eV} \text{ [7]. The approximated iron nuclei energy agree with the energy of the } 2nd \text{ Knee} \text{ in the CR flux spectra, implying once more that the change most likely represents the cut-off of the iron nuclei [6]. The conclusion from these assumptions should then be that all particles eventually escape above some energy point and that the CRs are to be heavier with increased energy. However, the transition between galactic and extra-galactic produced CRs cause deviation in the expected CR spectra which can most easily be observed at the } \text{Ankle} \text{ feature in Figure 1.1 [5].}

CRs of extra-galactic origin are dominated by protons which leads to a mixed composition of high energy protons and heavier nuclei at the end of the CR spectra [6]. Studies have shown that at approximately } 5 \times 10^{19}\text{eV} \text{ the flux should decrease rapidly because of the Greisen-Zatsepin-Kuzmin (GZK) -effect, i.e. the loss of CR energy from the pion production that occurs due to the interactions between high energy CRs and the Cosmic Microwave Background Radiation (CMBR) [7]. Excluding data from the Agasa detector, the GZK-effect indeed seems to be the correct interpretation when comparing to the cut-off feature in Figure 1.1 as the flux drops rapidly at around } 5 \times 10^{19}\text{eV}.
A comparison between the flux around the Knee and the Ankle will give an impression of the detector dimensions necessary to retrieve sufficient data for a given CR energy, two approximate points are taken in those areas from Figure 1.1. The rewritten point fluxes at the given CR energies then become:

$$F_{\text{knee}} = \frac{F(E)_{\text{Knee}}}{(E_{\text{knee}}/10^9)^{1.7}}$$  \hspace{1cm} (1.1)$$

$$F_{\text{ankle}} = \frac{F(E)_{\text{Ankle}}}{(E_{\text{ankle}}/10^9)^{1.7}}$$  \hspace{1cm} (1.2)$$

$$F_{\text{knee}} \approx 4 \text{ particles/m}^2/\text{year}/\text{sr}$$

$$F_{\text{ankle}} \approx 3 \text{ particles/km}^2/\text{year}/\text{sr}$$  \hspace{1cm} (1.3)$$

The resulting fluxes from Equation 1.3 show that to retrieve data for CRs at energies around $6 \times 10^{15}$ eV the area of the detector must have a size of square meters while for CRs with energies around $4 \times 10^{18}$ eV the detector area must exceed square kilometers. As the CR energy increases further (around $4 \times 10^{19}$ eV and beyond) the flux decreases to some detections per km$^2$ per century per steradian, which means that it will require even larger detection area and longer exposure times to get statistically sustainable data.

### 1.2 Ultra-High Energy Cosmic Rays

Studies of the different behaviours at the far end of the spectra has lead to a better understanding of the UHECR acceleration processes and thus given the opportunity to identify their origin more thoroughly. At this point, SNRs no longer have enough energy to fuel the UHECRs, other more powerful sources need to be investigated that could rise to the demands required for the acceleration processes [8, 7].

![Figure 1.2: Comparison between data from Auger and HiRes measurements at the far end of the CR spectra, fitted power law functions are also shown. The two measurements show the same behaviour as the systematic error is taken in to account. Credit: [8].](image-url)
Narrowing the search down to the most extreme events in the extra-galactic space lets us find such extremely high energy sources (see Figure 1.5), taking in account that the UHECRs lose energy due to their propagation in space. Reasonable conclusions have been that UHECRs are accelerated by diffusive shocks from Active Galactic Nuclei (AGN) jets, which represents flux values as seen from Equation 1.4. Further investigations have also shown that the transition point between the galactic and extra-galactic component is dependent on the composition of the extra-galactic sources, as can be seen in Figure 1.3 [7].

\[ J_{\text{source}} = kE^\gamma \ast e^{-E/E_{\text{max}}} \quad (1.4) \]

Here \( kE^\gamma \) (also known as \( Q(E) \)) represents the injection function that is expected from the acceleration process, revealing that it depends on the spectral exponent [9]. Different fitted models in Figure 1.3, named \( \text{EGAL p, EGAL H+He and EGAL mixed} \) represent changes in source composition properties which will be further explained below. The retrieved \( \gamma \) values from the fits, however, resulted in \(-2.4\) for \( \text{EGAL p} \), \(-2.2\) for \( \text{EGAL H+He} \) and \(-2.3\) for \( \text{EGAL mixed} \). \( E_{\text{max}} \) further represents the CR maximum energy found at the source [7].

![Figure 1.3: Data from Auger and Yakutsk has been rescaled to align with the fluxes of the HiRes measurements, the scale values are shown in the top right corner (E*)](image)

Illustration of the presumed total galactic component is represented by the horizontal lines. Credit: [7].

The calculated models that were discussed above have been made to determine the composition of the extra-galactic component, the thin solid and dotted lines in Figure 1.3 represents behaviours from three different types of source compositions, comparison with the observed data are then made to conclude the most preferable composition. The three investigated models of extra-galactic composition were, (a) a source containing only protons (\( \text{EGAL p} \)), (b) a mixed hydrogen and helium source (\( \text{EGAL H+He} \)) and (c) a normal abundance mixture source (\( \text{EGAL mixed} \)) [7]. Two different maximum source energies were used during the calculations of the \( \text{EGAL p} \) fluxes, however, they only seem to deviate between approximately \( 2 \ast 10^{19} \) and \( 10^{20} \text{eV} \) as can be seen in Figure...
1.3. Here the upper line represents $E_{\text{max}} = 10^{22}\text{eV}$ and the lower line $E_{\text{max}} = 5 \times 10^{20}\text{eV}$, $E_{\text{max}}$ for $\text{EGAL H + He}$ and $\text{EGAL mixed}$ remains at $5 \times 10^{20}\text{eV}$. The more accepted model is, however, the pure proton source composition as it is more substantially possible. The transition point between the galactic and extra-galactic component for the proton composition model was shown to happen already around $5 \times 10^{17}\text{eV}$ (from Figure 1.3), where escape of heavier nuclei still occurs from the galactic component. The early transition point was contradicting with the originally expected value as it was thought to be at much higher energies (around the Ankle feature). The mean value of observed data points below $10^{17}\text{eV}$ are represented by the thick line in Figure 1.3, subtraction of the extra-galactic component (proton source, $\text{Total} - E = \text{egalP}$) from the observed CR flux falls perfectly within the horizontal lines, proving further that the galactic component eventually becomes negligible as CR energy increases [7].

![Figure 1.4: Showing the transition between the galactic and extra-galactic components of a source composition of only protons. The left dotted line represents the galactic component and the right dotted line represents the extra-galactic component. The thin solid lines show the behaviour of the spectra if the extra-galactic component is lowered or raised by a factor of $\sqrt{10}$ (bottom thin line) or 10 (top thin line). The thick line shows the total observed CR spectrum at which the circles and triangles represents 50% and 80% respectively of the total flux that has extra-galactic origin. Credit: [7].](image)

From Figure 1.4 it becomes even more clear that only low degrees of the extra-galactic component will result in a transition point close to the Ankle. This shows that the extra-galactic component must have a greater significance to influence the total observed CR spectra, thus automatically induce an earlier transition point between the galactic and extra-galactic component. However, the CR composition of the observed data at energies above $10^{18}\text{eV}$ showed large variations as measurements from HiRes revealed a significant increase of protons while measurements from Stereo Fly’s Eye and Yakutsk showed no proof of the increase in protons around the 80% significance level and beyond [7]. Further measurements from the Auger observatory showed a lighter composition, to begin with, but turned heavier with increased energy, as can be seen in Figure 1.6 [10]. This uncertainty naturally effects the determination of the UHECR sources and the outcome is simply that more data needs to be taken to establish the origin.
Figure 1.5: Different acceleration sources presented in a Hillas diagram, $B$ is magnetic field strength and $R$ is the size. Uncertainties are shown as colored areas around the sources. Production of iron -and proton nuclei with maximum energies of $E_{\text{max}} = 10^{20}\text{eV}$ and $E_{\text{max}} = 10^{21}\text{eV}$ is possible if the sources are above the limits of the red and blue lines respectively. Credit: [11].

Figure 1.6: Observed data from the Pierre Auger Observatory with simulated EAS penetration depth (presented in the lower right corner) for a proton and iron nuclei around maximum CR energies. Credit: [10].
1.3 Extensive Air Showers

By now it is known that the total CR flux decreases with increased CR energy (seen from Equation 1.3 and the CR spectra in Figure 1.1). The low likelihood of detecting high energy CRs, as a result of the low fluxes, is the reason why direct detection is extremely insufficient. Nevertheless, it is possible to detect, the pathway for sufficient observations of CRs with higher energies than approximately $10^{18}\text{eV}$ lays within the Extensive Air Showers (EAS). The EAS is the product of the interaction between high energy CRs and Earth’s atmosphere, more accurately, a vast number of secondary particles (in form of cascades) are produced due to a large amount of released energy from the collision between the primary CR and air atoms [11].

![Figure 1.7: Illustration of the Extensive Air Shower, consisting of the hadronic -and electromagnetic component. The electromagnetic cascade is fed by approximately 1/3 of the energy at each collision of the hadronic cascade due to the decay of neutral pions. Credit: [3].](image)

The main focus of early research in this field considered only the electromagnetic component of the EAS and one of the most notable studies was made by Walter Heitler. His work clarified the development of the electromagnetic cascade using simplified numerical models, which later became known as the Heitler model [12]. Heitler’s model prove to be a more accurate representation of the electromagnetic cascade than was earlier expected due to its simplicity, further investigation, however, showed that a second component needed to be taken in account for a more complete picture of the EAS. Similar to the Heitler model, an extension of the electromagnetic cascade was made by James Matthew, this semi-empirical model explained the evolution of the second component which is the hadronic cascade of the EAS [13]. The EAS is thus divided into two sub-components, (a) an electromagnetic cascade and (b) a hadronic cascade (as can be seen in Figure 1.7), and it is the hadronic cascade that induces the electromagnetic
cascade subsequently after primary collision. The electromagnetic component, however, is much more dominant than the hadronic component in terms of the amount of particles produced and observations of the fluorescent light emitted (in the UV-range) from the electromagnetic cascade allows for the determination of specific properties of the primary particle [3, 11]. Characterization of properties such as, maximum amount of particles in the shower ($N_{\text{max}}$), maximum penetration depth of the shower ($X_{\text{max}}$) and elongation rate of the shower ($\Lambda$), from the EAS observations are specifically crucial to enable any information regarding the primary particle.

1.3.1 Electromagnetic Showers

Heitler’s model of the electromagnetic cascade considers only the undergoing interactions between photons ($\gamma$), electrons ($e^-$) and positrons ($e^+$) as they propagate through the atmosphere. The energy loss, as a result of particle propagation through matter, for electrons and positrons is somehow different in comparison to the heavier nuclei due to their small masses. Nearly all energy losses from heavier nuclei regards inelastic collisional transitions (both soft and hard). Further applying of the small masses of the electrons and positrons, however, leads to a two-component dependency, i.e. loss of energy through radiation ($\text{Bremsstrahlung}$), and the expected loss of energy due to collisions (leading to ionization or excitation). The two components result in the total loss of energy [14]:

$$\left(\frac{dE}{dx}\right)_{\text{tot}} = \left(\frac{dE}{dx}\right)_{\text{rad}} + \left(\frac{dE}{dx}\right)_{\text{coll}}.$$  \hspace{1cm} (1.5)

Figure 1.8: Illustrating the evolution of Heitler’s electromagnetic cascade model, the distance between the dotted horizontal lines represents the interaction length $d$. If the energy of the primary photon is $E_\gamma$, then it will results in an individual energy of $E_\gamma/2$ after the first interaction length for the electron and positron pair. Credit: [13].

The evolution of the cascade can be seen as a symmetrical tree that increases in size after every interaction length $d$ by splitting the original component into two
sub-components of which each is carrying half of the energy from its original component. The interactions are accomplished either by an electron or positron undergoing Bremsstrahlung (i.e. emissions from when $e^-/e^+$, in some way, are tempered by the electric field of a nucleus), or by the induced electron-positron pair production from the photon [14]. A conceptual visualization of the growing tree and the interaction length are shown in Figure 1.8 where each jump represents the length

$$d = \lambda_r \ln(2).$$  \hspace{1cm} (1.6)

As can be seen from Equation 1.6, the interaction length also shows dependency on the radiation length ($\lambda_r$) of the considered material (in this case, $\lambda_r^{air} \sim 37 g/cm^2$). [15, 13]. The amount of particles (due to the splittings) after $n$ interactions lengths then become

$$N_n = 2^n,$$  \hspace{1cm} (1.7)

with respective energies of

$$E_n = \frac{E_0}{N_n}.$$  \hspace{1cm} (1.8)

Consequently, the depth distance of the tree can be determined by multiplying the interaction length $d$ with the amount of steps $n$, thus resulting in

$$X_n = n \times \lambda_r^{air} \ln(2).$$  \hspace{1cm} (1.9)

The evolution of the cascade is only sustained for as long as there is enough energy for the components to undergo the processes of Bremsstrahlung or electron-positron pair production. The critical energy of where the components no longer are able to produce secondary particles is defined such that the energy loss of the Bremsstrahlung equals the collisional loss [14], i.e.

$$\left(\frac{dE}{dx}\right)_{rad} = \left(\frac{dE}{dx}\right)_{coll}. \hspace{1cm} (1.10)$$

Due to this, the critical energy value can be determined by knowing the characteristics of the absorbing material. An approximated value of the critical energy has been defined by

$$E_{c,\gamma,e} \simeq \frac{800 MeV}{Z + 1.2}, \hspace{1cm} (1.11)$$

where $Z$ is the atomic number (for air $E_{c,\gamma,e} \sim 85 MeV$) [14, 13]. The collisional energy loss component dominates for particle energies below the critical level and Bremsstrahlung dominates at energies above, meaning that the highest energy deposition will be due to Bremsstrahlung while the cascade is still developing [14]. Naturally, the tree stops growing when all the components reach the critical energy, thus resulting in a maximum number of particles in the cascade. From these assumptions and equation 1.8 one gets that the maximum amount of particles is given by

$$N_{max} = \frac{E_0}{E_{c,\gamma,e}}, \hspace{1cm} (1.12)$$

and since $N_{max} = 2^{n_c}$ ($n_c$ being the total amount of interaction lengths after which all components reached the critical energy) one gets

$$n_c = \frac{\ln(N_{max})}{\ln(2)}. \hspace{1cm} (1.13)$$
The expected maximum penetration depth of the shower (in $g/cm^2$) is thus obtained by using Equation 1.9 and 1.13, resulting in

$$X_{\gamma,e}^{\max} = n_c \lambda_r \ln(2) = \lambda_r \ln\left(\frac{E_0}{E_{\gamma,e}}\right).$$  (1.14)

Additionally, the progression rate of which the maximum penetration depth $X_{\max}$ changes with primary energy $E_0$ (also known as the elongation rate) is given by

$$\Lambda_{\gamma,e} = \frac{dX_{\gamma,e}^{\max}}{d\log_{10} E_0}.$$  (1.15)

The elongation rate in air can then be determined by using the maximum penetration depth in Equation 1.14 with the radiation length in air $\lambda_{\gamma,e}^r$, thus resulting in $\Lambda = 2.3 \lambda_{\gamma,e}^r = 85 g/cm^2/\text{decade}$. It now becomes clear that the crucial properties of Heitler’s electromagnetic cascade show a direct link to the primary particle; the conclusions made from his calculations have resulted in (a) the maximum amount of particles in the shower ($N_{\max}$) is proportional to the energy of the primary particle ($E_0$) as shown in Equation 1.12 and (b) the maximum penetration depth ($X_{\max}$) is logarithmically proportional to the primary particle as shown in Equation 1.14. These are well evaluated as extensive simulations and experiments have shown to confirm the hypothesis [3, 13]. The transverse density profile of the shower can most easily be explained by the Moliere radius

$$R_M = \lambda_{\gamma,e}^r \frac{E_s}{E_{\gamma,e}},$$  (1.16)

where $E_s = m_e c^2 \sqrt{4\pi/\alpha} = 21.2 MeV$. This distance can be visualized as the radius of a cylinder where the energy deposition probability is distributed. More than 90% of the energy deposition for the electromagnetic cascade is within $2R_M$ [14], deeper evaluated models, however, show more detailed features. One of the first accurate numerical models of the shower profile (around the incident axis) was made by Gaisser and Hillas in 1977 [16], the model enables parameterization of specific variables linked to the shape of the shower. This is done by fitting the model function

$$N(X) = N_{\max} \left(1 - \frac{X}{X_{\max}}\right)^{X_{\max} - X_0} \frac{X_0}{X_{\max} - X_0} e^{\frac{X - X_{\max}}{X_{\max} - X_0}}$$  (1.17)

to already observed data where $X_0$ and $\lambda$ are the parameters related to the shape of the shower profile [11, 17]. Although the proportion between photons and electrons/positrons in Heitler’s model showed to be inaccurate, the anticipated ratio observed from the tree eventually leads to an electron/positron component having double the value of the photon component. Actual measurements, however, show the ratio to be approximately 6 to 1 in favour of the photon, the dissimilarities originates both from Heitler’s model, as a result of his assumptions (Bremsstrahlung radiates more than one photon) and due to technical aspects of the detectors (stronger signals arises from electrons/positrons compared to photons in scintillators). These limitations do, however, not affect the assumptions made earlier for the crucial properties of $N_{\max}$ and $X_{\gamma,e}^{\max}$ as correlations were implemented to improve the true number of electrons in the shower (see Equation below, $g = 10$) [3, 13].

$$N_e = \frac{N_{\max}}{g}$$  (1.18)
1.3.2 Hadronic Showers

Matthew’s hadronic extension of Heitler’s electromagnetic model contributed to further improvements in the total view of the EAS. His study explained the interactions of hadrons, in this case, both charged pions ($\pi^+\pi^+$) and neutral pions ($\pi^0$), after primary particle collision with the same means as of the Heitler model. Consequently, the hadronic cascade shows the same development behaviour as the electromagnetic shower. However, the interaction length $\lambda_I$ and the number of particles created are different. The jumps in the tree are now observed as fixed layers in the atmosphere and are given by the distance $d_h = \lambda_I \ast \ln(2)$. $\lambda_I$ in air, for interaction energies between $10^{-1000}$ GeV, showed to give a relatively stable value for pions ($\lambda_I^m \approx 120 \text{ g/cm}^2$) [13].

![Figure 1.9: Illustrating the evolution of the Heitler-Matthews hadronic cascade model, $N_{ch}$ amount of charged ($\pi^+/\pi^-$) pions and $N_{ne}$ amount of neutral ($\pi^0$) pions are created, adding up to a total of $N$ particles after the first collision. Each jump represent the layer distance $d_h$. Credit: [15].](image)

The original component is again divided into two sub-components (one charged and one neutral) however with $N$ amount of particles and not two. The assumption is that the same amount of particles is created for all three pions, thus leading to a relation

$$N_{ch} = \frac{2}{3} N$$

$$N_{ne} = \frac{1}{3} N$$  \hspace{1cm} (1.19)

where $N_{ch}$ and $N_{ne}$ represent the amount of positively/negatively charged -and neutral pions respectively. The electromagnetic shower is then triggered through the instant decay of neutral pions described by

$$\pi^0 \rightarrow \gamma\gamma,$$  \hspace{1cm} (1.20)

while the charged pions continue the evolution of the hadronic cascade by traveling to the next layer and interact as can be seen in Figure 1.9 [15, 13]. As the hadronic
cascade is an extension of Heitler’s model, the same assumptions are made regarding
the hadronic evolution and respective energies. The number of charged pions after $n$
interaction lengths is thus given by

$$N_\pi^n = \left(\frac{3}{2} N_{ch}\right)^n$$

(1.21)

with respective energies resulting in

$$E_\pi^n = \frac{E_0 N_\pi^n}{N_n}.$$  

(1.22)

The critical energy of charged pions ($E_\pi^c$) is presented as the energy where the prob-
ability of pion decay is more likely to happen than the transition to another layer and
re-interact. Again, when the critical energy is reached, the evolution of the hadronic
cascade stops as the charged pions rather decay to muons. What should be acknowl-
ledged is that the critical energy is not constant in the hadronic case but decreases with
increased primary particle energy, the decrease is however much smaller then the growth
of primary particle energy and measurements have provided a tolerated critical energy
for pions in air to be $E_\pi^c \sim 20\text{GeV}$ [15]. The maximum amount of charged pions in the
shower is thus given by

$$N_\pi^{\text{max}} = \frac{E_0}{E_\pi^c}.$$  

(1.23)

The number of layer transitions needed for the individual charged pion to reach the
critical energy results in

$$n_\pi^c = \frac{\ln(N_\pi^{\text{max}})}{\ln(\frac{3}{2} N_{ch})} = 0.85 \log_{10} \left(\frac{E_0}{E_\pi^c}\right).$$

(1.24)

The total energy of the primary particle can now be described by combining the
hadronic -and electromagnetic critical energy levels, i.e. Equation 1.12 and Equation
1.23, which join up to give

$$E^\text{tot}_0 = E^{\gamma,e}_c N_{\text{max}} + E^{\pi}_c N_\pi^{\text{max}}.$$  

(1.25)

This energy is furthered simplified by taking into account the corresponding number
of electrons from the correlation expression in Equation 1.18 and by introducing the
muon number $N_\mu = N_\pi^{\text{max}}$, assuming that all the charged pions decay to muons at the
critical energy, thus resulting in

$$E^\text{tot}_0 = g E^{\gamma,e}_c \left(N_e + \frac{E^{\pi}_c}{g E^{\pi}_c} N_\mu\right) \rightarrow$$

$$E^\text{tot}_0 = 0.85 \times 10^9 (N_e + 24 N_\mu) \text{eV}.$$  

(1.26)

The accurate determination of the maximum penetration depth of the hadronic
cascade can only be explained properly if all subshowers are taken into account in-
dependently such that their origin and attenuation points are contemplated. These
calculations, however, can not be conducted entirely in our case due to the assumptions
that followed as Heitler’s model was implemented. Nevertheless, evaluations made after
only one interaction showed good promise for the elongation rate of the hadronic cascade, but as expected, undervalued the maximum penetration depth. The increase in primary particle energy leads to both a greater interaction cross-section and an increase in the abundance of generated pions, this then results in an earlier EAS development and an earlier disperse of the electromagnetic cascade. The first interaction occurs after a distance $d_h$ as mentioned before, however, now $\lambda_I$ represents the primary particle interaction length for a proton ($\lambda_I^{pr}$). 1/3 of the primary energy goes to the electromagnetic component and from Equation 1.19 we get the relation $N_{ne} = (1/2)N_{ch}$, which gives $N_{ch}$ photons after the first interaction, thus resulting in photon energies of $E_0/(3N_{ch})$. Taking into account the starting point of the shower ($d_h = X_0$) and the instant presence of the first electromagnetic component leads to a maximum penetration depth of

$$X_{max}^p = X_0 + \lambda_I^{air} ln \left( \frac{E_0}{3N_{ch}E_c^{\gamma,e}} \right) \rightarrow$$

$$X_{max}^p = \lambda_I^{pr} ln(2) + \lambda_I^{air} ln \left( \frac{E_0}{3N_{ch}E_c^{\gamma,e}} \right).$$

(1.27)

Recall that this maximum depth is not agreeing with simulations, probably because only the first interaction has been taken into account. The followed elongation rate of the proton, given by

$$\Lambda^p = \frac{d}{dlog_{10}E_0} \left( \lambda_I^{air} ln \left( \frac{E_0}{E_c^{\gamma,e}} \right) \right) + \frac{d}{dlog_{10}E_0} \left( \lambda_I^{pr} ln(2) - \lambda_I^{air} ln(3N_{ch}) \right)$$

(1.28)

is however in good agreement with simulations [13, 11, 18]. Shown in Figure 1.10 are simulations of the elongation rates of the proton and iron nuclei together with measured data, here it becomes clear that lower energies are dominated by heavier nuclei and that when given the same energies, the iron shower cannot penetrate as deep as the proton-induced shower.

Figure 1.10: Observed CR data (presented by the observatories in the top left corner) with simulated EAS maximum penetration depths (presented in the lower right corner) for a proton and iron induced EAS. Credit: [2].
1.4 Ground-based Experiments

The success in detecting UHECR is born from the very first conclusions made about the CR particle probability. These conclusions are known to be associated with exposure time, coverage area and energy resolution. Consequently, a larger area means a higher probability of detection, however, the increase in coverage area comes with other technical issues and finding geographical sites for these observatories is not an easy task, yet it still exists. The two most considerable sites for the detection of UHECR are currently the Pierre Auger Observatory (PAO) [19] in Argentina and the Telescope Array (TA) [20] in the USA.

![Image of footprint area comparison between the Telescope Array site (left image) and the Pierre Auger Observatory (right image), the surface area is approximately 700 km$^2$ for the Telescope Array and $\sim 3000$ km$^2$ for the Pierre Auger Observatory. The black and red dots symbolize the surface detector units and the green marks symbolize the fluorescence detectors. Credit: [21].]

1.4.1 Detection Methods

The operating principles of the observatories include two different detection methods, direct measurements of secondary particles at the ground with Surface Detector (SD) units, and Fluorescence Detectors (FD) which measures the fluorescent light (in the UV-range) that arises due to the re-excitation of air molecules by the EAS. The emitted UV-light expands isotropically after re-excitation, and the number of emitted photons is proportional to the energy dissipated by the EAS (as mentioned in Section 1.3.1), hence the energy of the primary UHECR with regard to the fluorescence yield (i.e. the proportionality factor) [11].

The FDs specifically allow for studies of the longitudinal profiles of the EAS, naturally, this leads to a more complete characterization of the maximum penetration depth $X_{\text{max}}$ which is known to be the key component in the search of primary particle mass composition, as has been discussed in section 1.3. The FDs are pointing towards the sky and the air molecule that has the highest contribution to the UV-light has been recognized as nitrogen. The FDs capture the events by focusing the emitted light, using large spherical mirrors or lenses, to multiple Photomultiplier Tubes (PMTs). UV-filters
are further used to reduce the background noise and to restrain the detections such that they are within the desired wavelengths. The duty cycle of the FDs is bound to be about 10% as the measurements must be performed during the night with a low illumination of moonlight and good environmental conditions such as dry air and cloudless skies [21, 19].

Two different types of approaches are implemented when it comes to the SD units of the observatories. The PAO uses enclosed tanks which are filled with purified water and the intention of the water tanks is to capture induced Cherenkov light. The water is contained inside a cylindrical liner where the interior is coated with a reflective surface. The Cherenkov light is created and reflected diffusively inside as higher energy secondary particles pass through the tank. Several PMTs, looking downwards from inside the top of the tanks allows for the measurement of the Cherenkov light event [19].

The TA, on the other hand, uses plastic scintillators. The scintillating material is placed as two layers inside a metal housing, each scintillating layer is connected to several fiber optic cables which in turn come together and connect to one PMT at the other end. The directed re-exited photons that the PMT reads is created from when high energy secondary particles hits the scintillating material. The SDs will especially allow for the determination of arrival direction of the EAS as well as primary particle energy. The SD units do not require any specific atmospheric conditions as they only depends on direct secondary particles, hence an operational duty cycle of 100% can be implemented. [21, 20, 19].

Figure 1.12: Illustration of atmospheric UHECR interaction and the Hybrid detection method as used by the Pierre Auger Observatory, the cylinders and the sphere symbolize the Surface -and Fluorescence Detectors respectively. Credit: [22].

Having the two detection methods at the same location leads to the possibility of exploring the Hybrid design, a design which combines the FD and the SD measurements during the same observation period. The simultaneous measurement of an EAS event leads to a more accurate determination of the properties of the primary particle. The
methods complement each other and permits cross-checking of corresponding properties as well as added featured properties that only a specific method gives. The combination of the observed data therefor leads to lower uncertainty values. Furthermore, both the detectors have their own GPS timing which is logged to the instant of the detected data, this is what eventually allows the determination of the arrival direction and trajectory of the EAS. Having errors in mind, the backtracking of the trajectory path gives a restricted area of where the source of the UHECR should be as the path of the particles does not change significantly due to the high energies contained within them [19].

1.4.2 Pierre Auger Observatory

The building of the PAO was put into motion in the beginning of the 21st century, it took approximately six years and a supporting collaboration of 18 countries to successfully finish the 3000 km$^2$ detection site. The observatory consists of 1660 Cherenkov water tanks which are placed in a 1.5 km triangular spacing pattern, and 24 FDs which are equally divided and spread over four sites (see Figure 1.14 for an illustration of the SD unit and FDs). Each FD has a FoV of ±15° and a 1.5° minimum elevation, together, the FDs at each site covers a 180° azimuth angle and are placed such that they are targeting events that occur over the Cherenkov water tanks, as can be seen in Figure 1.11. The placement of the FDs and the SDs have enabled the use of the Hybrid design at the PAO, the massive amount of detectors and coverage area has further made it the worlds largest high-energy cosmic ray detector, and it is above four times larger (in coverage area) than the second largest observatory, which is the TA [22, 19].

Figure 1.13: An illustration of the method used for detection with surface arrays from the Pierre Auger Observatory. The dots represent the SDs and the footprint area of the EAS is shown as colored dots in the top right corner (the zoomed in view of the footprint area shows a more detailed image of the particle densities in the lower left corner). The red points are observed densities and the blue line is the fitted lateral distribution function of the data, showing that there is a higher signal closer to the center of the shower axis. Credit: [3].
1.4.3 Telescope Array

The building of the TA site occurred almost in parallel with the construction of the PAO. Starting in 2005 and lasting approximately over three years, the finalization of the 700 km² detection site became a fact in 2008. The TA consists of three FD sites, two of the sites accommodates 12 FDs each and the third accommodates 14. The FDs are stacked two and two as can be seen in Figure 1.15, and depending on the site, has different FoV (all sites, however, have a set elevation at 3°). The configuration of the two sites which accommodates 12 FD results in a vertical FoV of ±15° and a horizontal FoV of ±9° (thus an azimuth view of 108°). The configuration of the third site results in a vertical FoV of ±14° and a horizontal FoV of ±8° (leading to a total azimuth view of 112°). The TA site also consists of 507 SD units which are placed in a 1.2 km squared spacing pattern, like the PAO, the FDs at the TA are targeting events occurring over the SDs such that the Hybrid design also can be implemented here [21, 24].

Figure 1.15: The Telescope Array surface detector unit with descriptions (left image) and an illustrated view of the fluorescence detector (right image). Credit: [21].
2 The Extreme Universe Space Observatory

In the end of the 1970s a scientist named John Lindsley first suggested a new concept regarding observations of UHECRs [25], his idea was to move observations from the ground into space by proposing the Satellite Observatory of Cosmic Ray Showers (SOCRAS). The observation techniques of SOCRAS included a 38 m in diameter mirror that pointed down on Earth such that it could capture the fluorescent light induced by the EAS. The concept of space-borne instruments would allow for a much larger coverage area as well as a greater uniformity response (see Figure 2.5) compared to the ground-based instruments. The uniformity especially reduces systematical errors in the statistical analysis regarding the direction of the UHECRs, which is also directly linked to the anisotropy. NASA included the proposal in their final Field Committee Report but in 1981 the experiment was doomed to be non-feasible as the technology of that time was not yet developed to sustain the requirements of SOCRAS.

It took another 15 years after Lindsley’s first proposal for the idea of space-borne UHECR observatories to reborn, this through the Maximum-energy Auger (Air)-Shower Satellite (MASS) proposed by Yoshiyuki Takahashi. His change in the imaging concept, using double Fresnel lens optics, allowed for a larger FoV as well as reduced focal point length which naturally lead to a smaller telescope size and by that making it more attractive for space applications. The European Space Agency (ESA) selected the MASS mission in 2000, renewing the name to Extreme Universe Space Observatory (EUSO). The instrument was planned to be mounted on the Columbus module of the International Space Station. Unfortunately four years after the selection it was canceled due to financial difficulties.

A redefinition of the mission took place once more in 2006, the instrument was now to be mounted on the Japanese Experiment Module (JEM) of the International Space Station while overseen by the Japanese space agency JAXA. The redefinition of the mission also lead to a change of name, the space-borne observatory was from now on known as JEM-EUSO [26].

2.1 JEM-EUSO

The main purpose of the JEM-EUSO program is to investigate the nature of UHECRs, featuring the JEM-EUSO instrument [27]. JEM-EUSO will make it possible to observe CRs with energies exceeding $10^{20}$eV. Using Earth’s atmosphere as a detector while observing from the International Space Station allows for a tremendous amount of detection area which is crucial for observations of UHECR due to the low fluxes. Specifically, the main scientific objectives of the JEM-EUSO instrument is to identify the UHECR sources, measure the energy spectra of the UHECRs and also the GZK spectra [26, 28]. Further objectives are to measure atmospheric phenomena such as TLE’s, nightglow, meteors, and meteoroids. Additionally, investigation of extreme energy neutrinos, photons, and other exotic particles will also be possible.

The telescope is designed to measure UV light emission, in the range of 290-430nm, arising from the EAS and the Cherenkov radiation as a result of UHECR interactions in Earth’s atmosphere. The observations will be made as the telescope passes through the dark side of the Earth such that it observes the fluorescent light created in the night atmosphere. The resulting observation time will approximately be 40 minutes per orbit, during the rest of the time it will be covered by its lid to prevent any potential damage
to the PMTs. The considered carrier which will take JEM-EUSO to the International Space Station is currently the Dragon launcher developed by Space-X [26, 27].

The UV light will pass through three circular Fresnel lenses before hitting the Photo-Detection Modules (PDMs) at the focal surface of the instrument, see Figure 2.1. Each PDM is assembled with a set of $3 \times 3$ Elementary Cells (ECs), subsequently, each EC consists of a $2 \times 2$ set of Multi-Anode Photomultiplier Tubes (MAPMTs), see figure 2.3. Lastly, one set of MAPMTs consist of 64 PMTs (pixels), thus one PDM adds up to a total of 2304 pixels. The focal surface of JEM-EUSO have a spherical shape and is made up of 137 PDMs, thus 315648 pixels with a time resolution of 2.5$\mu$s and a pixel resolution of 0.51 km [27].

<table>
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<th>Mass</th>
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<tr>
<td>Power consumption</td>
<td>516.7 W</td>
</tr>
</tbody>
</table>

Table 1: Main parameters of the JEM-EUSO instrument. Credit: [27].

The instrument covers a circular like area of about $1.4 \times 10^5 km^2$ when pointed in nadir direction, tilting of the instrument is possible to a maximum of $30^\circ$ which allows for a greater footprint area, as can be seen in Figure 2.2. The main technical aspects of the instrument are given in Table 1 and a more detailed explanation of how the technical system works will be given in section 3. What should be acknowledged is that due to JEM-EUSOs large Field of View (FoV) and the fact that it will be placed on
the International Space Station, its statistical probability of seeing UHECRs increases ∼ 10-folded with respect to the observations that are currently being taken on ground (the exposure times for different observatories can be found in Figure 2.4). This also shows that the telescope will have great promise for Earth observation in the UV-band [27].

Figure 2.4: Past exposure levels of UHECRs from Fly’s Eye, AGASA, HiRes, PAO and the TA as well as expected exposure levels in the future for the PAO, TA and JEM-EUSO. Credit: [29].

Figure 2.5: Left image: Shows the expected exposure of JEM-EUSO at different latitudes, the highly uniform behaviour arise due to the position of the International Space Station in the sky. Right image: Shows the expected exposure map of JEM-EUSO [26]

2.2 JEM-EUSO Program

The JEM-EUSO collaboration currently consists of 16 countries and has involved over 300 researchers all over the world. The program has produced several missions which in turn have established projects that have helped to optimize the next generation instruments and allowed for a higher technology readiness level as well as investigations of the operational performance of the instruments. These missions can be seen as pathfinders for the final instrument to make sure that when the time comes, the JEM-EUSO instrument will perform according to the highest standards. Figure 2.6 shows all instruments included in the JEM-EUSO program except the Tracking Ultraviolet Setup (TUS), which was not included in the JEM-EUSO program until 2016 [30, 31].
Figure 2.6: View of all instruments included in the JEM-EUSO program (except TUS) and an illustration of the cosmic ray interaction in the atmosphere (red lines represent the EAS). Credit: JEM-EUSO Collaboration.

Not all instruments created for the different missions in the JEM-EUSO program are space-borne and some have extra scientific and technical goals which in turn will produce additional data. The fundamental observation techniques are however the same for all instruments and listed below are three of the most recent instruments that has risen from these missions, EUSO-Telescope Array (TA), EUSO-Super Pressure Balloon (SPB) and the featured instrument of this study, mini-EUSO.

2.2.1 EUSO-TA

The EUSO-TA detector is the first and currently the only permanently stationed ground-based instrument produced by the JEM-EUSO program. The telescope (seen in Figure 2.7) uses the same fluorescence detection method as JEM-EUSO. The central goal of the EUSO-TA mission is to validate the optical and detector systems of JEM-EUSO through UHECR detections from the ground. Additionally, it gives the possibility to further develop and improve the self-trigger algorithms for the data acquisition, resulting in a more efficient and reliable data extraction.

The telescope became operational in the beginning of 2015 and is stationed in Utah (USA) at the Black Rock Mesa Telescope Array site. The location of the instrument gives the opportunity to make simultaneous measurements with the TA-FD and the surface detectors within its FoV. The location also allows for on-site equipment usage besides the UHECR detectors, most importantly the calibration facility (Central Laser Facility [32]). The utilities provided by the Telescope Array site makes a great beneficial impact for the purposes of EUSO-TA and the combined parallel measurements will additionally give a more accurate determination of the observed events as systematic uncertainties diminish [33, 34].
The optical setup of EUSO-TA (see Figure 2.8) accommodates two square Fresnel lenses, each with an area of 1 m$^2$. The light is guided onto the focal surface which consists of one PDM, resulting in a $48 \times 48$ pixels image over $17 \times 17$ centimeters. The two lenses yield a FoV of approximately $\pm 6^\circ$ and the maximum photon detection efficiency is about 35%. The small housing covers the telescope from environmental changes that could potentially cause damage to the instrument, furthermore, it can only be alternated in elevation and to a maximum of $25^\circ$ with respect to the horizontal plane. The limited FoV of EUSO-TA (see Figure 2.8) will only allow for regionally measurements of the EAS, investigations of the transversal profile of the observed region will, however, give a better spatial resolution in comparison to the TA-FD [33, 34].
2.2.2 EUSO-SPB

The second telescope from the JEM-EUSO program to observe EAS from elevated heights is the EUSO-SPB, see Figure 2.9. The optical- and detector setup of EUSO-SPB is virtually the same as in EUSO-TA, the lenses have the same size of 1 m², covers the same FoV of approximately ±6° and has one PDM that collects the signals. The first concept of the optical setup was, however, to use a third lens (see Figure 2.9), a diffractive Fresnel lens, which was meant to reduce the chromatic aberration effect. Nevertheless, it was decided that the optical setup should remain the same as EUSO-TAs because the lens simply absorbed too much light and by that decreased the detection efficiency. The telescope also carried ancillary equipment such as telecommunication systems, trackers, visual cameras and an IR camera. The cameras were used to monitor environmental conditions while measurements with the main detector were made. The “Health Led” in Figure 2.9 was used to examine the functionality of the PDM.

EUSO-SPB was designed to conduct its measurements while pointing in the nadir direction such that it captures any event occurring in the atmosphere between the balloon and the ground, naturally, within the FoV. The SPB was launched from New Zealand on the 24th of April 2017, it was expected to provide a long time duration flight (between 30-40 days) since the cold easterlies winds from the south pole allowed for a whole polar revolution. Unfortunately, it was compromised and approximately 12 days after the launch they announced an early termination due to a leakage in the balloon. Luckily 30 hours of data was managed to be downloaded while the balloon was still hovering in the stratosphere at an altitude of approximately 33 km [35, 36].

Figure 2.9: Upper left image: The conceptual optical setup of EUSO-SPB consisted of three Fresnel lenses. Lower left image: View of the PDM and the rear Fresnel lens inside the instrument, circled with red is the “Health LED”. Right image: EUSO-SPB on launch pad just before lift off. Credit: [36] and the JEM-EUSO Collaboration
3 Mini-EUSO

3.1 Overview

Mini-EUSO is planned to be the first instrument, produced by the JEM-EUSO program, to travel into space. It will carry out its measurements through a UV transparent window in the Russian Zvezda Service Module on board the International Space Station. Targeting Earth, its main objective is to measure the emitted UV-light that is created due to the UHECR interactions in the atmosphere. It will however also allow for measurements of other atmospheric phenomenas such as transient luminous events, meteors and meteoroids, as well as studies in strange quark matter and bioluminescence [37].

Additionally, the instrument will carry a near infrared (1500-1600 nm) camera and a visible (400-780 nm) light camera which will work alongside the main detector. The auxiliary cameras will allow for further information regarding the atmospheric conditions of the UV event. Overall, the observations that are made with Mini-EUSO will eventually lead to a complete picture of the UV-background of Earth, this will, in turn, allow for future instruments to faster distinguish between the background and interested UV events [38].

![Illustration of the Mini-EUSO instrument in an exploded view. Credit: JEM-EUSO Collaboration.](image)

The working principles of the main detector can be explained in three steps, the UV-light travels through the optical setup and is focused onto the focal surface, the focal surface consists of several MAPMTs which collect the light, and lastly the data processing unit which saves the values of the collected data. The optical design provides the instrument with a large FoV despite its compact size, this has allowed the engineers to cut down on mass- and volume budgets which in turn have made Mini-EUSO more favorable for space-related missions.
Furthermore, the intent of the Mini-EUSO mission is to raise the technology readiness level for the JEM-EUSO instrument. The expected launch date is at the end of 2018 and the team is currently working on operations, testing and validation of data on the Mini-EUSO engineering model, see Figure 3.9 [37].

3.2 Instrument Description

<table>
<thead>
<tr>
<th>Mini-EUSO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>30 kg</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>$37 \times 37 \times 62 \text{ cm}^3$</td>
</tr>
<tr>
<td><strong>Spot size</strong></td>
<td>$3.6 - 3.8 \text{ mm}$</td>
</tr>
<tr>
<td><strong>Focal surface</strong></td>
<td>$17 \times 17 \text{ cm}^2$</td>
</tr>
<tr>
<td><strong>PDM</strong></td>
<td>1 p</td>
</tr>
<tr>
<td><strong>MAPMT</strong></td>
<td>36 p</td>
</tr>
<tr>
<td><strong>Lens diameter</strong></td>
<td>250 mm</td>
</tr>
<tr>
<td><strong>FoV</strong></td>
<td>$\pm 22^\circ$</td>
</tr>
<tr>
<td><strong>Pixel resolution</strong></td>
<td>$48 \times 48$</td>
</tr>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>$6.11 \times 10^3 \text{ m}$</td>
</tr>
<tr>
<td><strong>Temporal resolution</strong></td>
<td>$2.5 \times 10^{-6} \text{ s}$</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>60 W</td>
</tr>
</tbody>
</table>

Table 2: Main parameters of the Mini-EUSO instrument. Credit: [37, 38].

Figure 3.2: The different functionalities and subsystems of Mini-EUSO shown in blockchain view. Credit: JEM-EUSO Collaboration.
3.2.1 Optical Setup

The two double-sided Fresnel lenses (see Figure 3.3) of the Mini-EUSO instrument yield a focal length of approximately 300 mm, the optical configuration of the system can be seen in Figure 3.4. Each lens weighs approximately 0.8 kg and is made out of a plastic material. The maximum thickness of the lenses are 11 mm and the lens area diameter is 250 mm (total diameter of 300 mm). The difference in the shape of the lenses and the focal surface gives a maximum allowed angle of where the light fully projects an image over the PDM. Figure 3.5 shows the relation between the change in angle and the projected light [37].

Figure 3.3: The Fresnel lenses of the Mini-EUSO instrument, protective boxes are used for transportation and storing. Credit: JEM-EUSO Collaboration.

Figure 3.4: The optical configuration of the Mini-EUSO instrument including a code-V simulation with light traces and FoV. Credit: JEM-EUSO Collaboration.

Figure 3.5: Showing the position of the projected light onto the focal surface with angle dependence. Credit: JEM-EUSO Collaboration.
3.2.2 Detection Chain

The focal surface of Mini-EUSO consists of one PDM, this PDM has the same development construction as the JEM-EUSO instrument in Section 2.1, i.e. a PDM of $3 \times 3$ ECs which lead to a total of $6 \times 6$ MAPMTs (2304 pixels). Each MAPMT also has a 2 mm thick BG3 UV-glass filter mounted onto it, as can be seen in Figure 3.6. The implementation of the UV-filters function as a regulator where the radiation becomes more within a suitable wavelength range in regard to the purposes of the Mini-EUSO scientific objectives (i.e. in the range of 300-400 nm) [37, 27, 39].

![Figure 3.6: Construction steps of the PDM of Mini-EUSO. Credit: JEM-EUSO Collaboration](image)

(a) MAPMT  (b) EC  (c) PDM

The light that has been focused by the Fresnel lenses and passed through the UV-filters eventually hits the MAPMTs, there the photons are converted into electrons through photo-cathodes before being pre-amplified and read by the Application Specific Integrated Circuit (ASIC) boards (seen in Figure 3.7). There are a total of six ASICs boards mounted on Mini-EUSO and each board further consists of six ASICs chips, one for each MAPMT [37].

![Figure 3.7: Mini-EUSO ASIC boards (a) and the PDM-DP unit (b) which consists of one power board (right), one Zynq board (middle) and the cross board (left). Credit: JEM-EUSO Collaboration.](image)

(a) ASIC  (b) PDM-DP
The digitalized data from the ASIC boards is received by the Zynq Field-Programmable Gate Array (FPGA) board which evaluates the data using multiple trigger levels. The Photo Detection Module-Data Processing (PDM-DP) unit (seen in Figure 3.7) consists of a cross board (which purpose is to connect the ASICs to the Zynq), a power board and the Zynq FPGA board mentioned above. If data meets the requirements given by the triggers in the Zynq FPGA board, it is sent to the Central Processing Unit (CPU), seen in Figure 3.8. The CPU then saves the data to USB Solid State Disks (SSDs) which are physically removed and transported back and forth from the International Space Station and the Earth [38, 37].

Figure 3.8: Mini-EUSO CPU (top board) with heat sink, under is the storage board. Credit: JEM-EUSO Collaboration.

Figure 3.9 shows the assembled Mini-EUSO engineering model without side panels where all the systems that have been discussed above can be seen.

Figure 3.9: Mini-EUSO engineering model with removed side panels, the two circular Fresnel lenses can be seen as well as the PDM with belonging electronics. Credit: JEM-EUSO Collaboration.

### 3.2.3 Power

The instrument is connected to the International Space Station through a +27 Voltage cable and has an allowed power consumption of 60 W. A primary voltage filter is implemented to restrain the inrush current and to reduce noise before distributing out to
the rest of the system. The low voltage power supply accommodates all six DC/DC converters which are used to produce the different voltage levels after the filter, as can be seen in Figure 3.10 [37].

![Mini-EUSO power distribution scheme](image)

Figure 3.10: Mini-EUSO power distribution scheme. Credit: JEM-EUSO Collaboration.

Each EC is powered through a Cockcroft-Walton circuit which uses voltage multipliers to amplify the power output (the MAPMTs utilize high power sources to properly function). The resulting effect of the Cockcroft-Walton circuits has lead to the use of only one high voltage power supply, which in turn has lead to a lower power dissipation by the instrument (currently $< 15 \text{ W}$) [37, 27, 38].

### 3.3 Data Acquisition

The ASIC boards read single photon count values which are detected by the PMTs every $2.5 \mu s$. Almost simultaneously, the Zynq FPGA board receives the data counts from the ASICs and stores it into buffers of $128 \times 2.5 \mu s$. Every buffer goes through a trigger which has an acceptance level, if the data value is below the acceptance level nothing happens and the Zynq board continues to read the next buffer in order. Data values which are above the acceptance level are sent to the CPU where it is saved in several SSDs (total space of approximately 1000 Gb).

The triggering levels are implemented to reduce the transmitted data such that the saving becomes more sufficient and the result is a data transmission of approximately 324 KB per event (instead of about 0.96 GB/second at full transmission) [37].
The data which is taken from the CPU of mini-EUSO is saved in the raw format, these files are then converted into ROOT TTree files which enables the analysis of the data through the ROOT framework. The basic architecture of the ROOT TTree format can be explained, as its name suggests, like a tree with branches. Each branch further represents some type of data which is pre-defined by the programmer, the conversion, in this case, is already defined and this study will only focus on the evaluation of one branch that has 3200 entries (each entry represents a frame of the focal surface). The branch specifically represents the obtained photon counts in a four-dimensional array. Information regarding the obtained photon count at a specific position of the PDMs and PMTs can thus be extracted from the array for visualization of the data. The four-dimensional array has the configuration

- Photon Value = array[CCB number][PDM number][x pixel][y pixel],

where the CCB (Cluster Control Board) and PDM number are put to zero for all instruments that hold a single PDM (the array is standardized according to JEM-EUSO data acquisition). Furthermore, there are three trees that are considered in the extraction of the photon counts, information regarding their content is shown below.

- TTree: tevent
  - Each entry in the photon count branch represents one single frame with the value of the obtained photon counts for each PMT. Each frame has an exposure time of approximately 2.5\(\mu s\) and is the fastest shutter speed used in the measurements.

- TTree: tevent_1st_integral
  - Each entry shows the average of 128 single frames, the interpreted timescale thus represents an exposure time of approximately 0.32\(ms\).
• TTree: `tevent_2nd_integral`
  △ Each entry represents the average of 128 frames as taken from the `tevent_1st_integral`, resulting in an exposure time of approximately 40ms. This is the longest exposure time used during the measurements.

The time to fill all 3200 entries for one file in the `tevent_2nd_integral` therefore results in $52.4288 \times 10^6 \times 2.5 \times 10^{-6} \approx 2$ minutes and 11 seconds. When all the entries are fully filled a new file is created which further saves the data taken. Each conducted measurement run with the telescope is given a specific file name depending on the time of the recording, this allows for an easier extraction, verification, and determination of events occurring at specific point. Runs taken under this analysis were given two names depending on which cycle they belonged to, listed below is a description of the file names for both of them.

• Cycle One:
  △ CPU_RUN_year_month_day_hour_minutes_seconds

• Cycle Two:
  △ CPU_RUN_MAIN_year_month_day_hour_minutes_seconds

The run names concerning involved figures under a section in the analysis below will be given in the beginning of each section such that identification can easily be made.
4 Analysis and Results

4.1 Cycle One

Mini-EUSO data from cycle one was taken at the Tor Vergata University in Rome, Italy, in between the 31st of July and the 5th of August 2017. The team made multiple tests during this period where the goal was to check flat field data, dark field data, radioactive data and data from the auxiliary cameras. The analysis that is done under cycle one only regards data taken on the 4th of August 2017, specifically flat fielding data and radioactive data. An external screen (electroluminescent) was used for the purpose of flat fielding while a tritium source was used for the radiation measurements. The investigated data in cycle one particularly concerns information from the *tevent* tree.

4.1.1 Statistical Distribution of Signal

CPU_RUN_2017_08_04_08_57_00:

Figure 4.1: Pixels extracted during measurements of the tritium source for the statistical analysis are shown in purple color where the low valued photon count is given in pixel x:19, y:12 and the high valued photon count in pixel x:34, y:30. This specific frame represents the photon count values from one frame in the *tevent* data package.

Visualization of the distribution from the obtained photon count value is an important step in understanding if the signal is manipulated or not. The statistical distribution of any signal, under the conditions that they are independent of each other and arriving at a fixed rate, will present a Poissonian distribution. Moreover, if the signal was manipulated or dependent it would have shown as the expected distribution would not take shape. The first analysis of the distribution was made on two pixels during the radiation source run, one for a low photon count value and one for a high photon count value (see Figure 4.1).

Figure 4.2-4.3 shows the low and high valued distributions respectively over 3200 frames in the *tevent* package, the visualization was completed by filling a histogram.
with the photon count value for each frame at that specific pixels such that one could see the photon count values with respect to how many times they occurred during the 3200 frames, i.e. under 8 ms.

![Histogram showing the photon counts for pixel (x:19,y:12) over 3200 frames with a Poisson step distribution fitted to the data giving $\mu \approx 0.68, \sigma \approx 0.82$ for a low value pixel.](image)

Figure 4.2: Histogram showing the photon counts (blue) for pixel (x:19,y:12) over 3200 frames, a Poisson step distribution (red) has then been fitted to the data which gives $\mu \approx 0.68, \sigma \approx 0.82$ for a low value pixel.

The distribution of the specific pixels clearly shows the expected behaviour and it is further confirmed by fitting an already defined Poissonian curve to the data. The fitted curve is represented by the red line and results in an almost perfect fit, hence allowing for an easy extraction of the mean and sigma values of the distribution. Figure 4.3 also shows that the signal progresses more towards a Gaussian distribution as the number of counts increases, confirming once more that the events are natural.

![Histogram showing the photon counts for pixel (x:34,y:30) over 3200 frames with a Poisson step distribution fitted to the data giving $\mu \approx 55.5, \sigma \approx 7.45$ for a high valued pixel.](image)

Figure 4.3: Histogram showing the photon counts (blue) for pixel (x:34,y:30) over 3200 frames, a Poisson step distribution (red) has then been fitted to the data which gives $\mu \approx 55.5, \sigma \approx 7.45$ for a high valued pixel.
4.1.2 Corrupted Pixels

During the analysis of the distributions we by chance noticed that data from higher valued pixels appeared to be corrupted (as can be seen in Figure 4.4, 4.5 and 4.6). It further seemed that the corrupted pixels only occurred for some of the highly obtained photon count values, the effect was however identical for all of them. The corruption appeared at every 16th value in the photon count detection and it showed that the values in between were mirrored or misplaced. Investigations of the corrupted data concluded that it was caused by an error in the saving processes of the Zynq FPGA board where the least significant bit was compromised. By manually correcting the mirroring and misplacements, further analysis of the high photon count valued pixels could be made.

Figure 4.4: Histogram showing the photon counts in tevent for pixel x:27, y:37 over 3200 frames

Figure 4.5: Histogram showing the photon counts in tevent for pixel x:30, y:37 over 3200 frames, the red line represents the fitted Poisson distribution
The manually corrected data was made in three steps, the first step regarded only the correction of the data (Figure 4.4), the second step regarded the correction and a Poissonian fit (Figure 4.5), and the third step regarded the correction and a Gaussian fit (Figure 4.6). The results after the corrections showed the expected distributions as discussed above, confirming that it indeed was a coding problem.

Figure 4.6: Histogram showing the photon counts in `tevent` for one pixel (x:33,y:30) over 3200 frames, the red line represent the fitted Gaussian distribution.

4.1.3 Flat Fielding

To get a better representation of an observed object one must begin with conducting flat fielding calibrations of the camera system. The calibrations are done by illuminating the telescope with a Lambertian surface and an electroluminescent screen was used for this purpose. The PMTs on the instrument may not have the same characteristics which could give rise to different pixel values even if the emitted light is the same in all directions. The purpose of the flat fielding is to examine the difference in pixel sensitivity as light passes through. By averaging over the frames taken with the electroluminescent screen, one eventually gets the Flat Field Frame (FFF). The actual observation frames are then divided by this FFF which naturally leads to the removal of instrument (PMT effect) induced light. The results of the flat fielding procedures thus lead to a better representation of the image.

4.1.4 Stable Flat Field Frame

CPU_RUN_2017_08_04__09_55_27:

The Signal to Noise Ratio (SNR) is known to increase when averaging over a higher amount of frames, the more frames the better SNR. This however become insufficient at some point as averaging over more frames automatically generate a longer simulation time which in the end may not necessarily give a better interpretation of the image. A test was conducted where the photon count values were averaged with an increased number of frames, the resulting image eventually show where the average photon count starts to stabilize in regard to amount of frames used. One point in Figure 4.7 represent
the average of all photon counts over the amount of frames that are given at that point, after some time the fluctuations stop and practically become constant. This point imply the number of frames that should be used before it becomes insufficient. Recognizing how many frames that are needed for stabilization is a central point in the extraction of the FFF, if the FFF were to be taken before this point it would most likely not represent the actual FFF. Figure 4.7 show the fluctuations in the tevent data package, strong fluctuations are seen during the first 1200 frames, however, the average photon count value starts to stabilize to a certain degree after the 1200 frame limit. This limit thus provides a good opportunity of where the FFF, at least, should be averaged over.

![Figure 4.7: Illustration of the stabilized FFF for the average photon count over the first 3200 frames in the tevent data package.](image)

The FFFs seen in Figure 4.8 and Figure 4.9 are normalized through their respective median, the color bar thus represent the photon count ratio with respect to the median and not to the actual photon count that was measured from the electroluminescent screen. The normalization keeps the ratio changes correct but does not impact the change in photon count values, the implementation of the normalization of the FFFs are therefore made to better keep the real representation of the observed data after flat fielding procedures.

The FFFs seen below, Figure 4.8-4.9, have been visualized in logarithmic scales to easier distinguish features appearing on the focal surface. A visual comparison between the extracted FFF at an average of 1200 frames and at an average of 3200 frames show that they indeed have many similarities, thus it conclude that the FFF at the 1200 frames average can be used as the correct representative of the FFF.

The FFFs from cycle one, did, however, clearly show that the mapping of the PMTs was out of sync. The mapping seem to have been swirling the PMTs which can be seen as the borders of the MAPMTs are not following the square shape of the $8 \times 8$ MAPMTs but are tilted.
It is further seen in the FFFs that most of the detected data from the electroluminescent screen has the same photon count values as the frame is mostly green, however, the red and yellow features show higher values while the aqua and blue features show lower values. Looking closer, and having in mind that the data is swirled due to false mapping, the higher photon count values seem to appear at the borders of each MAPMT. It also show that the difference in the photon count values between most center parts and the borders rise up to 10 folded. This number however needs to be further investigated due to the uncertainties in the PMT mapping. Furthermore, the FFFs show that the pixels which give no values, i.e. in white, are nonfunctional and need to be checked.

Figure 4.9: Calculated FFF at an average of 3200 frames, HV 3900.
4.1.5 Flat Fielding Tritium Source

During tests in the laboratory, a tritium source was put in front of the telescope. The original data is shown as the non flatten figures while flat fielded data is shown as the flatten figures. Figure 4.10 shows when the tritium sample is slightly to the right of the center line of the focal surface and Figure 4.11 shows when it is slightly to the left. What can be directly noticed is that the three center MAPMTs are not functioning properly, it can also be seen that the mapping of the PMTs has still not been corrected. However, the implementation of the flat fielding procedures were conducted as both the data from the FFFs and the radiation tests were under the same swirl condition. The color bars in Figure 4.10 and Figure 4.11 show the actual averaged photon count which was detected with the Mini-EUSO instrument.

CPU_RUN_2017_08_04_08_57_00:

![Figure 4.10: Showing the non flatten tritium and the flatten tritium source using the FFF in Figure 4.8, i.e. after an average of 1200 frames. HVdac 3900](image)

The non flatten images in Figure 4.10 and Figure 4.11 show higher averages of the photon count values at the upper half of the focal surface. Furthermore, as the mapping of the PMTs is swirled, the distinguishing of the radiated source and the background become harder. As the flat field procedures are implemented it, however, becomes easier to distinguish as can be seen in the flatten images of Figure 4.10 and Figure 4.11. The flatten images further show that the tritium source approximately covers three MAPMTs, which seemed possible with the movements included and as the size of the radiation source, when put directly in front of the focal surface, resulted in approximately one MAPMTs.

The total exposure time of the images is known from before to be 8 ms, which from the flatten images lead to an average activity of approximately 1250 detections per second. Unfortunately, it was not possible to confirm the counts as no external instruments were used alongside the tests. The results from the flat field images must, however, be taken with caution as the PMT mapping was wrong.
4 ANALYSIS AND RESULTS

Matej Lukanovic

CPU_RUN_2017_08_04_09_06_50:

![Figure 4.11: Showing the non flatten tritium and the flatten tritium source using the FFF in Figure 4.8. HVdac 3900.](image)

4.2 Cycle Two

Mini-EUSO data from cycle two was also taken at the Tor Vergata University in Rome, Italy. The data was collected during the 21st and 23rd of October 2017 and at this point the team managed to fix the bugs in the data acquisition code and to map the PMTs correctly. New flat field data and dark field data was tested using different high voltage power outputs, the radioactive data, however, had the same high voltage output. The investigated data in cycle two particularly concerns information from the \textit{tevent\_2nd\_integral} tree.

4.2.1 Dark Field Frame

The Dark Field Frame (DFF) is also an important step in the calibration phase of the camera system as it is used to properly remove the background noise that is produced by the system through thermal leakage. These signals depend on the properties of the camera system, especially the exposure time and temperature. The conventional way of extracting these dark frames are by covering the screen such that its surroundings become dark, then only the instrument background noise is taken into account.

An even better representation of the actually observed objects than only using the FFF is to implement both the DFF and the FFF through two procedures. Firstly one needs to subtract the DFF with the actually observed frame, the resulting image is then divided by the FFF to finally give the correct representation. As the data is taken from \textit{tevent\_2nd\_integral} tree, the exposure time of the images in Figure 4.12 and Figure 4.10b results in approximately 2 minutes and 11 seconds. The changes in the SNR from \textit{tevent} data to the \textit{tevent\_2nd\_integral} data results in an increased ratio of $\sqrt{128 \times 128}$ for the images that are visualized from the \textit{tevent\_2nd\_integral}.
4 ANALYSIS AND RESULTS

CPU_RUN_MAIN__2017_10_21_18_37_24:

Figure 4.12: Calculated Dark Field Frame at an average of 3200 frames, HV 3500.

Figure 4.12 and Figure 4.13 represent the average DFF over 3200 frames in the `tevent_2nd_integral` of two different runs, now the color bar represents the actual average photon count of the 3200 frames. Two different methods were used to cover the focal surface for the DFF measurements which is why the DFF varies. The screen was covered with a black cloth in Figure 4.12 while for Figure 4.13 it was covered with cardboard. It can clearly be seen that the DFF which was taken with the black cloth represents a better DFF as the photon count values are significantly less, and from this, we also see that there is almost no dark current. However, questions were raised regarding its correctness as it was not fully known if light penetrated the black cloth.

CPU_RUN_MAIN__2017_10_23_18_53_17:

Figure 4.13: Calculated Dark Field Frame at an average of 3200 frames, HV 3700.
It can be seen from the DFF in Figure 4.13 that a higher number of photons managed to pass the cardboard, however, it is not known if the rise is due to the cardboard or due to changes in the high voltage power output. The DFF further shows that the correction of the mapping of the PMT was successfully implemented. Each MAPMT can easily be seen and now it also becomes even clearer that the borders of the MAPMTs have higher photon count values. Besides the increase in photon counts at the borders of the MAPMT, it also seems that the photon count value increases when further from the center of the focal surface.

The impact of the subtraction of the DFF to the actual footage will, however, not be considered as the average values of the DFF are so low. A statistical analysis was performed on the obtained data for a random pixel from the DFF in Figure 4.13. The results of the analysis are displayed in Figure 4.14 and it can be seen that the data from both trees, \textit{tevent\_1st\_integral} and \textit{tevent\_2nd\_integral}, gives the expected Gaussian distribution.

![Figure 4.14: Showing the total amount of photon counts for the sum of the 1st and 2nd integrals of pixel $x = 31; y = 42$ in the DFF (Figure 4.13), the fitted Gaussian distributions is represented by the red line.](image)

A second crosscheck was performed to further confirm that the signals were correctly detected by the Mini-EUSO instrument, this included the comparison between the SNR for the two trees. The SNR was investigated through the use of the mean and sigma values that were extracted from the Gaussian distributions in Figure 4.14. The resulting SNRs are thus given by:

\[
SNR_{1st} = \frac{48.4}{7.115} \approx 6.80 
\]

\[
SNR_{2nd} = \frac{6149}{88.89} \approx 69.2
\]

From equation 4.1-4.2, it can be concluded that the signals have been detected correctly by the instrument. It is known that the SNR increases with $\sqrt{N}$ where $N$ is the number of combined frames and the equations show that the SNR increases by approximately a factor of 10, this is about the same as $\sqrt{128}$ which further is the number of more frames that are averaged between the \textit{tevent\_1st\_integral} and \textit{tevent\_2nd\_integral}.
4.2.2 Flat Field Frame

Stabilization tests of the FFF were performed for cycle two data as well. The obtained photon count data was taken from the *tevent* tree and the result is shown in Figure 4.15. Once again it can be seen that the stabilization appears almost instantaneously.

![Figure 4.15: Showing the stabilization of the FFF for the averaged photon count over the first 3200 frames in the *tevent* data package.](image)

As mentioned earlier, the tests from cycle two provided both flat fielding data and dark fielding data using two different settings in the high voltage power output of the PMTs. Figure 4.16 show the FFF at a high voltage level of 3500 V and Figure 4.17 show the FFF at a high voltage level of 3600 V from the *tevent* 2nd_integral data package.

![Figure 4.16: Calculated FFF at an average of 3200 frames, HV 3500.](image)
The clear difference between the FFFs in Figure 4.16 and Figure 4.17 immediately show that the change in the high voltage output result in changes of the photon count values. A comparison further show that the difference in the read photon count values is up to a factor of ten higher for the lower high voltage power output. It can also be seen that Figure 4.16, i.e. the lower valued high voltage supply, represents a worse FFF than expected as the image shows only little similarities with previous tests. Some of the borders of the MAPMTs have higher values which is known but the increase in photon counts for a whole MAPMTs have not been seen before and this FFF has three MAPMTs which show much higher values than the surroundings. It is also seen that some of the MAPMTs are not working as they show no detected pixels at all, i.e. white pixels.

Figure 4.17: Calculated FFF at an average of 3200 frames, HV 3600.

The FFF which was powered through a higher voltage output, Figure 4.17, show a better representation of the FFF. The recognized pattern of the higher values at the borders of the MAPMTs are seen and the rest of the focal surface shows a symmetrical pattern. When further comparing the DFF in Figure 4.12-4.13 to the FFFs in Figure 4.16-4.17 it can be seen that when a higher voltage is applied, a better representation is given. The increase in the high voltage power output should, however, give higher photon count values than when the high voltage power output is lower. This does not seem to occur for the FFFs as the FFF which has a lower voltage gives higher photon counts.

Nevertheless, more tests should be performed to make sure that the increase in photon count values, for the FFF with the lower voltage source, was not caused by something else than just the change in voltage (as the resulted image did not show any pattern correspondence to previous flat fielding data). As there was some uncertainties regarding the electroluminescent screen, statistical tests were also performed for the FFF in Figure 4.17 and the result can be seen in Figure 4.18.
4 ANALYSIS AND RESULTS

4.1 ANALYSIS

Figure 4.18: Showing the total amount of photon counts for the sum of the 1st and 2nd integrals for pixel x:31, y:42 of the FFF in Figure 4.17, the fitted Gaussian distribution is represented by the red line.

It can be seen from Figure 4.18 that the data from the \textit{tevent\_1st\_integral} in Figure 4.18 has an unexpected behaviour, it should show a Gaussian distribution due to the increased number of data points but however seems to show three averages instead. The different behaviour lead to further investigations of other pixels for the \textit{tevent\_1st\_integral} and it became clear that most of them show the same features, two other pixels are shown in the Figure 4.20. The three peak feature was further confirmed by checking the photon count values with regard to the temporal dimension as can be seen in Figure 4.19. The cause of the three averages is still unknown but due to the increase in averages in the \textit{tevent\_2nd\_integral}, an extraction of a proper Gaussian distribution was possible. However, it can not be strengthen that the data is correct as the three averaged behaviour is seen.

Figure 4.19: The three peak behavior is also clearly shown when plotting the photon counts in the 1\textit{st integral} against time for pixel x:31, y:42. The photon counts are more concentrated around a value of approximately 100, 160 and 220, which naturally is represented as the peaks in Figure 4.18.
Furthermore, a correlation analysis was made to check that the different three peak behaviours are caused by the same phenomenon. The check was performed by plotting the number of photons for one pixel in the `tevent_1st_integral`, in this case, x:8, y:13 against the number of photons in another pixel x:32, y:42. The result can be seen in Figure 4.21 and the diagonal pattern show that the data is correlated. It can thus be concluded that the three peak behaviour rises from the same cause and is not induced by the PMTs of the instrument. Data from the `tevent` tree was also investigated due to the unexpected behaviour of the `tevet_1st_integral` data. Figure 4.22 show the `tevent` data and it can be clearly seen that the illumination fluctuates in an otherwise expected constant behavior.
Each point in Figure 4.22-4.23 show the sum of photons in the specific frame. Information of the unknown fluctuations can be extracted by investigating possible repeated behaviours in the data, i.e. by finding a periodic feature. In this case such behaviour was established within the blue lines in Figure 4.22. Following the extraction of the periodic data, it was shown that it had a sinusoidal pattern, this allowed for the extraction of its frequency by fitting the data to a sine curve. The resulting fit, in Figure 4.23 gave an approximated angular frequency of 0.049 rad/frame.

Figure 4.22: Fluctuations in the flat field data are shown over 3200 frames in $tevent$, the blue lines represent the limits over which a sine curve have been fitted.

Figure 4.23: Results from the fit (blue line) shows an amplitude $p_0$, an angular frequency $p_1$ and a starting point $p_2$.

It is seen from Figure 4.23 that the angular frequency value is $p_1 = 0.0494$, however, this angular frequency is known to be dependent on frames. The angular frequency, given in SI units, is thus calculated by dividing the found angular frequency with the exposure time of one frame, i.e. $2.5 \times 10^{-6} \text{ s}$.
The resulting angular frequency is thus
\[ \omega_s = \frac{0.0494}{2.5 \times 10^{-6}} = 19760 \, \text{rad/s}, \] (4.3)
which leads to the actual frequency of
\[ f_s = \frac{\omega_s}{2\pi} \approx 3150 \, \text{Hz}. \] (4.4)

The conclusion is thus that electroluminescent screen fluctuates between approximately 1000 and 2400 photon counts, with a frequency of 3 kHz. Investigations regarding the change in the high voltage output for tevent data also showed that an increase in the voltage supply leads to higher photon count values as shown in Figure 4.24-4.25. The voltage difference between the two runs is about 55 V, finding an appropriate dependency between the photon count values and the change in the high voltage supply is, however, not applicable as there is too much fluctuation in this data.

Figure 4.24: Measured photon count after supplying a HV of 3.7kV.

Figure 4.25: Measured photon count after supplying a HV of 3.755kV.
4.2.3 Processed Tritium Source

Even though there have been many uncertainties in the functionality of the electroluminescent screen, the implementation of the DFF and the FFF have still been made possible. This is due to the fact that the data has been taken from the `event_2nd_integral` tree where it is known that the photon count values have been averaged several times. The result of the different radiation tests and the implementation of the DFF and the FFF can be seen from Section 4.2.3-4.2.5. All tests have the same high voltage power output which is set to 3500 V.

![Original and Processed Tritium Source](image)

Figure 4.26: Showing the original tritium source and the processed tritium source after implementing the DFF and the FFF from Figure 4.13 and 4.17 respectively. The Tritium source was put in front of the PMTs, HV 3500.

One of the most visually significant changes from an original image to a processed image can be seen in Figure 4.26, the tritium source has been put in front of the PMTs but can barely be seen in the original image as it basically drowns in the rest of the data. However, as the DFF and the FFF are implemented, the separation of the source and the background becomes unmistakable. The processed image in Figure 4.26 clearly show the location of the tritium source on the focal surface, i.e. the little mark which is slightly to the left and that show a considerable higher photon count value than the rest of the focal surface.

Figure 4.27 further show that the dark field and flat field procedures improved the original image, the radiation source for this test was put alongside the UV-filter of the PMTs. We again see that without the implementation of the DFF and the FFF it would not be possible to determine where the source was located. The processed image also show that the detected UV-light from the tritium source scatters across several MAPMTs as a distinct mark is no longer seen. It can, however, be established that the source was put to the right of the focal surface as we see an increase in photon counts there with regard to the rest of the focal surface.
4 ANALYSIS AND RESULTS

4.2.4 Processed Thorium Source

Figure 4.28: Showing the original thorium source and the processed thorium source after implementing the DFF and the FFF from Figure 4.13 and 4.17 respectively. The Thorium source was put in front of the PMTs, HVdac 3500.
Figure 4.29: Showing the original thorium source and the processed thorium source after implementing the DFF and the FFF from Figure 4.13 and 4.17 respectively. The Tritium source was put on the PMT side, HVdac 3500.

4.2.5 Processed Americium Source

Figure 4.30: Showing the original americium source and the processed americium source after implementing the DFF and the FFF from Figure 4.13 and 4.17 respectively. The Americium source was put in front of the PMTs, HVdac 3500.
The radiation tests from the thorium and americium source, however, showed very little activity in comparison to the tritium source. This could be due to the different decay processes of the sources, the tritium source emits through beta decay while the thorium and americium emit through alpha decay. Nonetheless, the thorium and americium tests show that the implementation of the dark field and flat field procedures remove photon counts which rise from dark current and flat fielding light (as is clearly seen in the processed images of Figure 4.29 and Figure 4.31).

4.3 Sky Observations

The calibration steps above have visually shown us that the procedures regarding the subtraction of the DFF and the division by the FFF of the actually observed image indeed gives a better representation of the observed object. Knowing that the physical procedures meet the theoretical assumption is a first step in the evaluation process of the true data and a pathway in moving observations from the laboratory to actual sky measurements outside.

The change in environmental properties naturally leads to a new reference frame and in our case new flat field data needed to be taken when the instrument was moved outside and aiming towards the sky. The new flat fielding data is only necessary due to the uncertainties in the electroluminescent screen, otherwise, the same FFF that is used in the laboratory should be implemented. The analysis of the observations made outside will be given below and the data was taken on October 14th, 2017 at the roof of the University of Vergata in Rome, Italy.
Figure 4.32: Showing the FFF of the sky, the image represents one frame in the 
tevent\_2nd\_integral data package.

The FFF of the sky can be seen in Figure 4.32, moreover, the use of a frame from the 
tevent\_2nd\_integral for the flat fielding purposes was suggested as it had been averaged 
enough for the SNR to be sufficient for removal of background but not for removal of 
interesting events.

![Sky Data (Average:3200frames) vs DFF and FFF Sky (Average:3200frames)](image)

(a) original sky  
(b) processed

Figure 4.33: Image (a) show the average of the original sky for 3200 frames in the 2nd 
integral, image (b) show the processed sky after implementing the DFF and the FFF 
from Figure 4.13 and 4.32 respectively.

During the observations, an airplane flew through the FoV of the instrument, the 
time of the pass by was noted by the team such that it could later be compared with 
the frames taken. If the instrument managed to capture the event it would have shown 
around the time stamp and fortunately, it did. The signal is however so short that it
drowns and disappears when averaging over all frames in the t\textsubscript{event 2nd_integral}, this is why it does not show up in the processed image of Figure 4.33. Some of the individual images from the t\textsubscript{event 2nd_integral} around the time of fly by is, however, shown in Figure 4.34.

![Figure 4.34](image-url)

Figure 4.34: Individual footage of sky observations as the plane pass through the FoV of the instrument, the implemented DFF and FFF is taken from Figure 4.13 and 4.32 respectively. The numbers below the images show at which frame the data was taken.

The images in Figure 4.34 are not placed in chronological order, they however show the most interesting features of the passage of the plane. It can be seen that the plane passes through the lower left corner of the focal surface and that the plane covers one pixel approximately, the direction of the plane is also shown in Figure 4.34d. The interesting features of the plane data are the changes of intensity as the plane travels across the focal surface. The jump between Figure 4.34a and Figure 4.34b show where the plane enters the FoV and is first detected by the instrument. As we go to Figure 4.34c, it can be seen that the intensity of the plane data rises as well as an increase in activity for pixels around the main plane pixel before it eventually goes back to its standard intensity as in Figure 4.34d.

Investigations around the increased intensity in Figure 4.34c resulted in that it might be due to the reflection of sun light from the ocean onto the plane which then scatters the light back to Earth again. This can, however, not be strengthened by external measures. Further tests of the collected photon count values can be seen in Figure 4.35, this image represents the sum of all pixel values in one frame in a chronological timeline. Figure 4.36 show a zoomed view of the same event and it can be seen that
the plane event occurs around the 94-second line and that the whole passage lasts for approximately 6 seconds. The intensity change from the presumed scattered sun light can also be seen as the photon count spike between the 97 and 98-second line.

![Sky Fluctuations](image)

Figure 4.35: Showing the sum of photon counts from the `tevent_2nd_integral` data package for the bottom left MAPMT, i.e. the data which contains the plane data.

The intensity raise that is seen in Figure 4.35 seem to have a periodic behavior as the two spikes are identical to each other. The cause of this is unknown but it was thought to be related to the data acquisition problems which lead to corrupted files for high photon count valued pixels. Further tests, however, needs to be implemented to reconstruct the periodic behavior such that the data acquisition code can be properly checked and debugged if necessary. Nevertheless, the final conclusion is that it indeed was possible to observe events in the sky through the implementation of the DFF and the temporary FFF.

![Sky Fluctuations](image)

Figure 4.36: Zoomed view of the sum of photon counts from the `tevent_2nd_integral` data package for the bottom left MAPMT, i.e. the data which contains the plane data.
5 Conclusions

5.1 Cycle One

Data from cycle one showed that pixels with low photon count values gave the expected statistical distribution, i.e. a Poissonian distribution. Most of the pixels with high photon count values were, however, corrupted. The corrupted data visually resulted in both mirroring and misplacement of the photon count values at every 16th step in the statistical analysis and it was later established that the corrupted values did not come from hardware failure but of a data acquisition software problems. By manually changing the mirrored and misplaced data, it was possible to extract the statistical distribution of the high valued pixels as well, and the resulting outcome lead to the expected Gaussian distribution.

Stabilization of the flat field frame occurred almost instantaneously, furthermore, the implementation of the flat fielding procedures in cycle one only showed small improvements in the visualization of the radiation source. The assumed reason to this was that the mapping of the PMTs, during the flat fielding tests, were out of sync. This resulted in a distorted flat field frame, as can be seen in Figure 4.9.

5.2 Cycle Two

Corrections in the data acquisition code lead to improved high valued pixel data, however, sky observations revealed that a periodic behaviour now occurred instead. Nonetheless, the statistical distributions of the data for the low and high valued pixels gave the expected Poissonian and Gaussian distribution respectively. Crosschecking and confirming the statistical behaviours with the SNR further showed that the statistics agreed as the SNR approximately increased with the $\sqrt{N}$.

The dark field tests showed that the dark current indeed had little impact when the PDM was properly covered. The analysis further showed that the electroluminescent screen behaved unexpected and an unknown photon fluctuation, with a frequency of 3000 Hz, was found. It was also shown that the photon count values increased with increased high voltage power, the specific parameter of increased photon count with voltage change could not be found due to the fluctuations and further crosscheck has to be implemented to confirm the effect. The fluctuations did however not effect the final result as the flat field frame was average over $128 \times 128 \times 3200$ frames. The implementation of both the dark field and flat field procedures in cycle two, therefore, resulted in a significantly improved image in comparison to the original footage (see Figure 4.26).

Data from cycle two also showed that the mapping of the PMTs was correctly made, it also became clear that the pixels which are at the border of the MAPMTs gave higher photon count values than what was detected in the center part of the MAPMTs. The reason for this was not established, however, the dark field and the flat field procedures removed this as its data have the same feature. Sky observations further proved the successfulness of the implementation of the dark field and the flat field procedures, the implementation lead to the visual observation of a plane passing by.
5.3 Further Work

Future investigations should include the following:

- New dark field and flat field tests should be performed in a more controlled environment, especially for the flat fielding screen as uncertainties in its full functionality were found.

- Performing new radiation tests together with external instruments such as Geiger counters to confirm the detection rates.

- Deeper investigations of why the MAPMTs show an increased photon count value at the borders.

- Further tests with proper timing of high voltage changes should be performed to see the actual photon count value dependency.

- Further tests of the data acquisition code should be performed using a high radiance source such that debugging procedures of high valued photon count pixels can be made, i.e. to check the periodic behaviour.

- Performing new sky observation tests using a known source such that the observations can be confirmed properly.
References


REFERENCES


