Calibration of the Extreme Universe Space Observatory

Malek Mastafa

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CALIBRATION OF THE EXTREME UNIVERSE SPACE OBSERVATORY

by

MALEK MASTAFA

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in The Department of Physics and Astronomy to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2021
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Malek Mastafa

Malek Mastafa

06/20/21

(date)
DISSEASON APPROVAL FORM

Submitted by Malek Mastafa in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics and Astronomy and accepted on behalf of the Faculty of the School of Graduate Studies by the dissertation committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics and Astronomy.

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ABSTRACT

School of Graduate Studies
The University of Alabama in Huntsville

Degree Doctor of Philosophy College/Dept. Science/Physics and Astronomy

Name of Candidate Malek Mastafa

Title Calibration of the Extreme Universe Space Observatory

The most energetic particles in the universe are ultra high energy cosmic rays UHECRs with energies up to $3 \times 10^{20}$ eV. However, their flux is strongly suppressed at the highest energies ($\sim 1$ particles/km$^2$/century for $E = 10^{19.75}$ eV), leaving the sources and the acceleration mechanisms unknown. The detection of UHECRs from space via fluorescence method is very compelling because of the large area that can be observed. The Extreme Universe Space Observatory on a Super Pressure Balloon (EUSO-SPB) collaboration is developing and flying balloon-brone prototypes of a satellite instrument to make such observations. The EUSO-SPB1 instrument is the first of these to be flown on a super-pressure balloon. It was launched in Wanaka, New Zealand in April, 2017 as a mission of opportunity payload. The detector was developed as part of the Joint Experimental Missions for the Extreme Universe Space Observatory (JEM-EUSO) program. The main objective of EUSO-SPB1 is to test an instrument designed to observe UHECRs and to make the first observation of UHECRs using the fluorescence technique from suborbital space. The instrument is a refractive telescope that consists of two 1 m$^2$ Fresnel lenses and a high speed UV focal surface. The focal surface has $48 \times 48$ individual pixels capable of single photoelectron counting with temporal resolution of 2.5 $\mu$s. An end-to-end test of the
instrument was performed during a field campaign in the Utah desert on the Telescope Array (TA) site near Delta, Utah, USA in September 2016. In this thesis the results of the flat-field and the photometric calibration measurements are presented. Based on these measurements, it was determined that EUSO-SPB1 has a calibration factor of 12.04 photo/photoelectron.
ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my advisor, Prof. James Adams, for the continuous support of my Ph.D study and research, for his patience, motivation and immense knowledge. His guidance helped me through all research and writing of this thesis. Besides my advisor, I would like to thank the rest of my thesis committee: Prof. James Miller, Prof. Max Bonamente, Prof. Richard Lieu and Prof. John Matthews, for their encouragement and insightful comments. My sincere thanks also goes to Prof. Don Gregory for his advice and suggestions for the reflectivity measurements in optics lab. I would like to thank all JEM-EUSO members since this work not have been possible without the support and collaboration of a large number of colleagues around the world. I would like to thank my lovely wife Marwa Bakri for all her support, love and helping me to push aside the stress of preparing a Ph.D dissertation. Last but not least, I would like to thank my family and my friends for their continues support and encouragement throughout this long journey.
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<tr>
<td>$E$</td>
<td>Total energy of a cosmic ray</td>
</tr>
<tr>
<td>$\Phi(E)$</td>
<td>Differential flux of cosmic rays</td>
</tr>
<tr>
<td>$K$</td>
<td>Normalization factor</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Differential spectral index of cosmic ray flux</td>
</tr>
<tr>
<td>$R$</td>
<td>Magnetic rigidity</td>
</tr>
<tr>
<td>$e$</td>
<td>Charge of the electron</td>
</tr>
<tr>
<td>$Z$</td>
<td>The atomic number of the nucleus</td>
</tr>
<tr>
<td>$p$</td>
<td>Particle’s momentum</td>
</tr>
<tr>
<td>$c$</td>
<td>The speed of light</td>
</tr>
<tr>
<td>$\tau_{esc}$</td>
<td>The mean lifetime of cosmic ray in the galaxy</td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic flux density</td>
</tr>
<tr>
<td>$R_L$</td>
<td>Larmor radius</td>
</tr>
<tr>
<td>$d$</td>
<td>The distance traveled by a cosmic ray</td>
</tr>
<tr>
<td>$\theta$</td>
<td>The angle through which the cosmic ray was deflected</td>
</tr>
<tr>
<td>$E_{GZK}$</td>
<td>Greisen-Zatsepin-Kuzmin cutoff</td>
</tr>
<tr>
<td>$\Delta^+$</td>
<td>Delta baryon</td>
</tr>
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</table>
\[ p^+ \quad \text{Proton} \]
\[ \gamma_{\text{cmb}} \quad \text{The cosmic microwave background photons} \]
\[ \pi \quad \text{Pion} \]
\[ \mu \quad \text{Muon} \]
\[ \nu \quad \text{Neutrino} \]
\[ l_{p\gamma} \quad \text{The energy loss length of a proton in the CMB} \]
\[ y \quad \text{The fraction of energy loss per interaction} \]
\[ \sigma_{p\gamma} \quad \text{The cross section of the process } \gamma p \rightarrow \pi^0 p \]
\[ n_{\gamma_{\text{cmb}}} \quad \text{The CMB photons number density} \]
\[ A \quad \text{The mass number} \]
\[ E_p \quad \text{The threshold energy for electron-positron pair production} \]
\[ E_\gamma \quad \text{The average energy for CMB photon} \]
\[ l_{\text{adia}} \quad \text{The adiabatic energy loss length of a cosmic ray} \]
\[ H_0 \quad \text{Hubble constant} \]
\[ \Delta E \quad \text{Energy gain of cosmic ray particles} \]
\[ U \quad \text{The speed of intersteller cloud} \]
\[ \rho_{\text{CR}} \quad \text{The energy density of the cosmic ray} \]
\[ V_G \quad \text{The galactic volume} \]
\[ P_{\text{SN}} \quad \text{The power delivered by supernova} \]
<table>
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<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$P_{CR}$</td>
<td>The energy loss rate of cosmic rays due to escape out of the galactic volume</td>
</tr>
<tr>
<td>$E^{max}$</td>
<td>The maximum energy of cosmic rays attained by diffuse shock mechanism</td>
</tr>
<tr>
<td>$X$</td>
<td>The depth in the material</td>
</tr>
<tr>
<td>$\rho$</td>
<td>The atmospheric density</td>
</tr>
<tr>
<td>$X_0$</td>
<td>The radiation length</td>
</tr>
<tr>
<td>$\alpha(E)$</td>
<td>The excitation-ionization energy loss term</td>
</tr>
<tr>
<td>$E^c_e$</td>
<td>The critical energy for the electrons</td>
</tr>
<tr>
<td>$E(X)$</td>
<td>The energy as a function of depth</td>
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<tr>
<td>$N_{max}$</td>
<td>The shower maximum</td>
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<tr>
<td>$X_{\gamma max}$</td>
<td>The depth where the maximum of EM occurs</td>
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<tr>
<td>$N^\gamma_e(X)$</td>
<td>The mean number of electrons as a function of atmospheric depth for $\gamma$ ray induced shower</td>
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<tr>
<td>$s$</td>
<td>The shower age</td>
</tr>
<tr>
<td>$N^\gamma_{e max}$</td>
<td>The number of electrons at shower maximum for EM induced shower</td>
</tr>
<tr>
<td>$r$</td>
<td>Shower core distance</td>
</tr>
<tr>
<td>$r_1$</td>
<td>Moliere unit</td>
</tr>
<tr>
<td>$C(s)$</td>
<td>Normalization constant</td>
</tr>
<tr>
<td>$r_M$</td>
<td>Moliere radius</td>
</tr>
<tr>
<td>$\lambda_I$</td>
<td>The interaction length of the primary cosmic ray particles</td>
</tr>
</tbody>
</table>
\( N_{ch} \) The multiplicity of the charged particles produced in the hadronic component of the shower

\( \tau_{\pi^0} \) Neutral pions lifetime

\( d'_{\pi^0} \) Neutral pions decay length

\( \tau_{\pi^\pm} \) Charged pions lifetime

\( d'_{\pi^\pm} \) Charged pions decay length

\( \lambda_I^\pi \) Pions’ interaction length

\( E_{dec}^\pi \) Charged pions’ threshold energy

\( m_{\pi} \) Pion’s rest mass

\( E_h \) The energy of the hadronic component of the shower

\( N_h \) The total number of hadronic particles in the shower

\( E_0 \) The initial energy of the cosmic ray particle

\( N^p_{\mu} \) The number of muons at shower maximum for proton-initiated air showers

\( N^p_{\text{max}} \) The number of electrons/photons at shower maximum for proton-initiated air showers

\( N_0 \) The multiplicity of the neutral particles produced in the hadronic component of the shower

\( N^p_{e_{\text{max}}} \) Number of electrons at shower maximum for proton-initiated air showers

\( N^A_{e_{\text{max}}} \) Number of electron at shower maximum for nucleus-initiated showers
I write to interpret, to approximate, to estimate, not to create.

—Unknown
CHAPTER 1

INTRODUCTION TO COSMIC RAYS PHYSICS

The discovery of cosmic rays CRs started in the beginning of 20th century when it found that an electroscope discharged even if it kept away from sources of natural radioactivity. It was believed that this radiation is due to natural radiation of the Earth. To investigate this problem, the physicist Victor F. Hess made manned balloon ascents to altitudes of 5 km in order to investigate the ionisation of the atmosphere with increasing altitude. Hess found that as the balloon ascended, at first the ionization rate decreased but then at higher altitudes the average ionisation rate increased with respect of the ionisation at sea level. His conclusion was that a source of ionizing radiation must be located above the Earth’s atmosphere [19].

Later on, Millikan and Cameron suggested that cosmic rays were a product of the formation of complex nuclei. It was thought that these nuclei were created by the binding of electrons to protons. In this process, energy will be released in the form of gamma rays [20] \(^1\). This suggestion was proven to be wrong by Compton while he was measuring the intensity of cosmic rays at 69 stations distributed over the Earth. From his measurements he found that cosmic rays are affected by the

\(^1\)The term cosmic rays came from here
Earth’s magnetic field proving that cosmic rays are charged particles and not neutral gamma rays [21].

At present, we understand that cosmic rays are ionized particles. Ninety-nine percent are protons and alpha particles. The rest are heavier nuclei. These abundance estimates are valid for lower end of the spectrum. Above energies ($E > 10^{15} eV$) their composition is still under debate. A low fraction have ultra-relativistic energies, above $10^{20} eV$. Until today, the following questions are still remain answered in this field:

1. What are they?

2. Where are they coming from?

3. What mechanism accelerate them to these high energies?

1.1 The Cosmic Ray Spectrum

The range of energies encompassed by cosmic rays is enormous. Their energies extend from $10^6 eV$ range to $10^{20} eV$. The primary particles arriving on the top of the atmosphere include all stable charged particles and nuclei. Also some unstable nuclei are found. At energies larger than few GeV (where the contribution of particles coming from the sun is negligible) the energy spectrum can be described by a power law with differential spectral index $\alpha$.

$$\Phi(E) = K \left( \frac{E}{1 GeV} \right)^{-\alpha} \frac{particles}{cm^2 s sr GeV}$$ (1.1)
The parameter $\alpha$ is the differential spectral index of cosmic ray flux (or the slope of the CR spectrum on a log-log plot) and $K$ is a normalization factor.

Figure 1.1: Energy spectra of cosmic rays as measured by various experiments [1].
From Figure 1.1, we note that the spectrum can be divided to four regions. From $10^9 eV$ to $10^{15} eV$, the differential spectral index $\alpha \approx 2.9$ [22], from $10^{16} eV$ to $10^{18} eV$ it is $\alpha \approx 3.3$ [23]. Above $10^{18} eV$ the spectrum flattens again with a spectral index of $\alpha \approx 2.5$ [23] and then it cuts off around $10^{20} eV$. The transition regions are known as the knee at $3 \times 10^{15} eV$ and the ankle at around $3 \times 10^{18} eV$ where the spectrum becomes flatter again. Cosmic rays above the ankle (denoted as Ultra High Energy Cosmic Rays UHECRs) are thought to have an extragalactic origin.

![Spectrum Diagram](image)

**Figure 1.2:** CR flux is scaled by $E^{2.6}$. The structures of the knee and the ankle are more evident as well as point-to-point differences between different experiments [2].

The knee and ankle structures are more visible in Figure 1.2. It shows the spectrum with the flux scaled by $E^{2.6}$, this enhances the visibility for structures in the spectrum. The steepening in the knee region has different possible explanations: 1) the galactic accelerators are running out of energy and cannot accelerate particles to higher energy; 2) alternatively the galactic magnetic field are no longer
strong enough to confine particles leading to a depletion which steepens the spectral flux. For both explanations the spectral change should be characterized by magnetic rigidity which is defined as \( R \equiv \frac{pc}{Ze} \simeq \frac{E}{Ze} \) where \( p \) is the particle momentum and \( Ze \) is its charge, assuming it is fully-ionized. That means the starting energy of the steepening should depend on the charge (\( Z \)) of the nuclei. Higher \( Z \) particles will still be confined at higher energies, so they do not escape and deplete the number observed. Measurements of the KASCADE-Grande air shower detector supports this result [24]

1.2 Abundances of Elements in the Solar System and in CRs

The mass composition of cosmic rays is an essential piece of information to understand the origin and history of accelerated particles, especially when compared with the nuclear composition of the solar system. The chemical composition of cosmic rays is well known at low energies. Figure 1.3 shows the relative abundances of elements in cosmic rays as a function of nuclear charge \( Z \) and compared with solar system abundances. A similarity between the measured cosmic ray abundances of nuclear species and the abundances found in solar system can be seen.

However, There are some two noticeable differences between them. First, the abundance of nuclei with \( Z > 1 \) is more in cosmic rays. This is not understood, but it could be a clue for different composition of the source or preferential acceleration. The second one is corresponding to the overabundance of Li, Be, B (lithium, beryllium and boron) elements in cosmic rays with respect to the cosmic chemical composition. The cosmic rays abundance ratio \((\text{Li+Be+B})/(\text{C+N+O})\) exceed the value found in the
solar system by order of $\sim 10^5$, see Table 1.1. This is due to the fragmentation of the heavier C, N and O elements (primarily) during the propagation of cosmic rays in the interstellar medium (ISM). Therefore, lithium, beryllium and boron are considered secondary products produced by spallation process of primary cosmic rays elements principally (carbon, nitrogen and oxygen). Since the cross section for these nuclei is known at GeV energies, the secondary-to-primary ratio can be used to calculate the average escape time $\tau_{esc} \sim 6 \times 10^6 yr$ [25]. This quantity corresponds to the average time needed for a cosmic rays, trapped by the galactic magnetic field, to reach the galactic boundary.

**Figure 1.3:** The relative chemical composition of cosmic rays at 1 TeV, general abundance of elements in the solar System (normalized at silicon), as a function of nuclear charge $Z$ [3]. Solar system: filled circles, cosmic rays: open circles.
<table>
<thead>
<tr>
<th>Element (Z)</th>
<th>Number of particles per 100 Si</th>
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<tbody>
<tr>
<td></td>
<td>Cosmic Rays</td>
</tr>
<tr>
<td>H (1)</td>
<td>$1.9 \times 10^5$</td>
</tr>
<tr>
<td>He (2)</td>
<td>$2.63 \times 10^4$</td>
</tr>
<tr>
<td>Li (3)</td>
<td>130</td>
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<tr>
<td>Be (4)</td>
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<td>B (5)</td>
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<td>C (6)</td>
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<td>N (7)</td>
<td>180</td>
</tr>
<tr>
<td>O (8)</td>
<td>655</td>
</tr>
</tbody>
</table>

**Table 1.1:** The relative cosmic rays abundances up to Oxygen compared with that of the solar system [17] [18]. Both of them are normalized to 100 for Si.

1.3 Cosmic Ray Origin and Acceleration Mechanisms

Energetic particles with energy ranging from few tens of keV to few GeV can occasionally come from the Sun. Solar activity affects the probability that solar energetic particles reach the earth. There is a continuous flux of galactic cosmic rays nuclei reaching Earth. Cosmic rays with energy below $\sim 1\text{GeV/nuclon}$ is modulated by their interaction with the magnetic field carried by the expanding solar wind. Thus, the low energy cosmic ray intensity varies over the solar cycle. This phenomenon is known as solar modulation. The solar modulation and the magnetic activity of the sun are correlated with the number of sunspots, which varies on an 11 year cycle. Their is inverse correlation between the intensity of low energy cosmic rays and the number of sunspots, i.e., when the solar activity is high many sunspots are visible, the cosmic rays intensity at Earth is low, and vice versa.
The galaxy is filled with magnetic fields whose average intensity is \( B \sim 4\mu G \) [26]. Milky Way consists of two main components: a spheroidal and a disk. The spheroidal component has a very massive nucleus with mass \( 2 \times 10^6 M_\odot \), with radius less than 3 pc, a bulge with radius about 3 kpc and halo of about 30 kpc. The thin disk is made up of dust, gas, and stars with thickness about 200-300 pc and radius of about 15 kpc. The galactic field is oriented parallel to the galactic plane, with a small component perpendicular to the galactic plane. The propagation of cosmic rays is affected by the presence of this magnetic field since charged particles are deflected by it. The Larmor radius of particle with energy \( E \) and charge \( Ze \) in a magnetic field \( B \) can be expressed as

\[
R_L = 110(kpc)Z^{-1} \left( \frac{\mu G}{B} \right) \left( \frac{E}{10^{20}eV} \right)
\]  

(1.2)

Larmor radius for a proton with energy \( 10^{18}eV \) is 300 pc. Cosmic rays particles below \( 10^{18}eV \) are strongly confined in the galactic volume by the galactic magnetic field. Cosmic rays with energies above \( 10^{18}eV \) are denoted as Ultra high Energy Cosmic Rays (UHECRs). The Larmor radius of UHECRs is extremely large and can be larger than the thickness of the magnetic galactic disk. This allows UHECRs to enter and leave the galaxy.

Connecting the arrival direction of UHECRs to the coordinates of the extra-galactic object is still an open question since the magnitude of extra-galactic magnetic field is still unknown. A particle with energy \( E \) moving in a direction perpendicular to a uniform magnetic field after traveling a distance \( d \) will deflect
Figure 1.4: Simulated 20 trajectories of proton primaries with energies from 1eV up to 100EeV [4]. Protons with low energy is bent by the magnetic field, while those with energy above 100EeV travel almost straight trajectories.

with an angle as

$$\theta \sim \frac{d}{R_L} \sim 0.5^\circ Z \left( \frac{E}{10^{20} \text{eV}} \right)^{-1} \left( \frac{d}{kpc} \right) \left( \frac{B}{\mu G} \right)$$

(1.3)

Figure 1.4 shows the simulated 20 trajectories for proton originating in a fixed position in the galactic plane with different energies. A proton of energy $5 \times 10^{19} eV$ will be deflected by $1^\circ$-$5^\circ$ in the galactic magnetic field depending upon the direction and length of the trajectory. The influence of galactic magnetic field on protons at energies $> 10^{19} eV$ is not large, and so a dominate galactic source of cosmic rays with that energy would produce clear anisotropy in the flux arriving at Earth, which is not observed.
The propagation of UHECRs in the cosmic microwave background (CMB) was independently studied in 1966 by K.Greisen, V. Kuzman and G.Zatsepin [27] [28]. They predicted that the flux of cosmic rays from sources at cosmological distances would greatly be attenuated above a threshold energy $E_{GZK} \simeq 5 \times 10^{20} eV$ which is called GZK cut-off. Proton would interact with 2.7K cosmic microwave background photons if its energy is high enough to reach the center of mass system the resonant production of the $\Delta^+$ hadron, which is immediately decays to the following products

\begin{align*}
p^+ + \gamma_{cmb} & \rightarrow \Delta^+ \rightarrow \pi^+ + n \quad \text{(1.4)} \\
\quad & \rightarrow \pi^0 + p \quad \text{(1.5)}
\end{align*}

The proton will always be in the final products since the neutron decays into $pe^- \bar{\nu}_e$, so the overall effect of the interaction is that the energy of cosmic ray proton above the threshold is reduced and high energy photons and neutrino are produced ($\pi^0 \rightarrow \gamma \gamma, \pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$). This process limits the energy loss length ($l^{-1} = \frac{1}{E} \frac{dE}{dx}$) of proton with energy higher than the threshold energy for pion-production to few tens Mpc. The energy loss length $l_{p\gamma}$ of a proton in the CMB for this process is

\begin{equation}
l_{p\gamma} = \frac{1}{y \cdot \sigma_{p\gamma} \cdot n_{\gamma_{cmb}}} = \frac{1}{0.1 \cdot 250 \times 10^{-30} \cdot 400} = 10^{26} \text{ cm} = 30 \text{ Mpc} \quad \text{(1.6)}
\end{equation}

Where
- \( y = \frac{\Delta E_p}{E_p} \sim \frac{m_e}{m_p} \simeq 0.1 \) is the fraction of energy loss per interaction. 10% of the proton energy is lost in each process. This means that within few successive interaction, proton energy decreases to a value below the threshold energy.

- \( \sigma_{p\gamma} \simeq 250 \mu b \) is the cross section for the processes \( \gamma p \rightarrow \pi^0 p \) and \( \gamma p \rightarrow \pi^+ n \) found in laboratory, as a function of the photon energy in the laboratory frame [29].

- \( n_{\gamma\text{cmb}} \simeq 400 \text{ cm}^{-3} \) is the CMB photons number density.

Therefore all protons coming to the Earth from distances larger than \( \sim 30 \text{ Mpc} \) should have energies below \( \sim 10^{20} \text{eV} \). This distance is small compares to the dimensions of the universe and the detection of cosmic rays protons with energy exceeding the threshold energy corresponds to protons produced in local sources. For a heavier nucleus with mass \( A \) and energy \( E \), the resonant reaction occurs through the interaction of one of the nucleons, which has energy \( E/A \). The threshold energy \( E_{GZK} \) for heavier nuclei is higher by factor \( A \).

Another energy loss process for protons (or heavier nuclei) propagating over cosmological distances is electron-positron pair production. During the propagation in the CMB, electron-positron pairs can be produced in the process

\[
p + \gamma \rightarrow p + e^+ e^-
\]  

(1.7)

with threshold energy \( E_p \geq \frac{m_e m_p}{E_{\gamma}} \simeq 2 \times 10^{18} \text{ eV} \) where \( E_{\gamma} \) is the average energy of the CMB photon. The cross section of this process is a factor \( \sim 10^{-4} \sigma_T \sim 0.1 \text{ mb} \), which is comparable with the production of \( \Delta^+ \) resonance. The fraction of energy loss
y has a value about two order of magnitude smaller than pion-production which gives rise to an average energy loss length about two order of magnitude larger ($\sim 10^3\ Mpc$). Finally, an adiabatic energy loss process is due to the expansion of the universe. The corresponding energy loss length is $l_{\text{adia}} = \frac{c}{H_0} \sim 4\ Gpc$.

A model to provide cosmic rays with energies up to the knee is the relativistic shock acceleration (first order Fermi acceleration [30]). In this process, particles gain energy $\Delta E/E \propto U/c$ when they are moving between two plasma clouds of stellar material mutually approaching, driving shocks. Fermi acceleration mechanism produces a power law spectrum $N(E) \propto E^{-\alpha_s}$ with $\alpha_s = 1 + \frac{\tau_F}{\tau_{\text{esc}}}$. A suitable candidate for galactic cosmic rays is diffusive shock acceleration resulted from supernova. The amount of the energy released from supernova explosion is about $(2-3) \times 10^{53}\ erg$ with 99% of this energy is emitted as neutrinos, and only 1% is converted to kinetic energy of expelled material, which drives the shock wave [31]. The acceleration mechanism due to supernova explosions is consistent with following points:

- The energy balance (hypothesized by Baade and Zwicky [32]) between the loss of cosmic rays due to their escape of the galactic volume and the energy provided by supernova shock wave. Type II supernova with mass $\sim 10M_\odot$ are ejected with bulk velocity $U \sim 5 \times 10^8\ cm/s$ (corresponding to total kinetic energy $\sim 10^{51}\ erg$), which means that the power delivered by supernova is $P_{SN} \sim 3 \times 10^{42}\ erg/s$ assuming that three supernovas per century in the galaxy. The
energy loss rate of cosmic rays due to escape out the galactic volume is

\[ P_{CR} \simeq \frac{\rho_{CR} \times V_G}{\tau_{esc}} = 5 \times 10^{40} \text{ erg/s} \]  

(1.8)

where \( \rho_{CR} \) and \( V_G \) are the density of cosmic ray and the volume of the galaxy receptively. By equating \( P_{CR} \) and \( P_{SN} \) we notice that the shock waves from supernova are able to inject into the galaxy new accelerated particles at the rate needed to maintain the stationary energy content of cosmic rays.

• The efficiency of the acceleration process requires that the acceleration mechanism should convert part of the kinetic energy in the ejected material from the supernova to energetic particles, with efficiency 0.01-0.1. The particle gain for each iterative acceleration process in the first order Fermi acceleration is proportional \( \eta = \frac{4U}{3c} \simeq 10^{-2} - 10^{-1} \). Therefore \( \eta \) is the required efficiency to explain the cosmic ray acceleration by supernova.

• The maximum energy that a charged particle can attain in the acceleration process due to the diffusive shock mechanism from supernova is [33]

\[ E^{max} \simeq 300 \cdot Z \text{ TeV} \]  

(1.9)

This model explains the spectrum of cosmic ray particles up to few hundreds of TeV, corresponding to the knee region.

A good candidate as cosmic rays accelerator for both galactic and extragalactic source must provide enough energy to reach the highest observed energy. The
maximum energy of cosmic rays nucleus of charge $Ze$ accelerated in a region where the magnetic field $B$ changes in spatial region of size $L$ is expressed as [34]

$$E_{\text{max}} \simeq Z \beta \cdot \left(\frac{B}{\mu G}\right) \cdot \left(\frac{L}{\text{kpc}}\right) \ EeV$$  \hspace{1cm} (1.10)$$

where $\beta = U/c$ is the velocity of magnetic scattering centers. The above equation is known as the Hillas criterion. The maximum energy that a given nuclear charge $Ze$ can attain is approximately equal to the product of the magnetic field $B$ and the size $L$ of the acceleration region. Hillas plot is shown in the figure 1.5 where several kinds of astrophysical sources are shown by their potential to accelerate cosmic rays particles.

![Figure 1.5](image)

**Figure 1.5:** Hillas diagram: The characteristic size $L$ and magnetic field $B$ are plotted for various candidate of accelerated particles [5].
CHAPTER 2

EXTENSIVE AIR SHOWERS

Cosmic rays flux above $10^{15}$ eV drops below few tens of particles per $\text{meter}^2$ per year. Such a low flux makes no longer possible to detect them directly above the atmosphere before they interact. Therefore, the direct method must be replaced with indirect method which detects the shower of particles produced when the primary cosmic ray particle interacts in the atmosphere. While the initial interaction is with one nucleus in the atmosphere, the shower is the result of a cascade of interactions. These showers are called Extensive Air Showers (EASs). The showers are divided into three main parts: electromagnetic, hadronic and muonic component and they contain a large number of particles extending over several kilometers. By measuring the shower contents, one will be able to extract information about the primaries, in particular their energy and the arrival direction.

2.1 The Electromagnetic Cascade (EM)

The EM showers consists of electrons, positrons and photons. They grow by the interactions of electrons and photons with the atmosphere, which occur after they traverse, on average, one radiation length. The main two process that govern the
development of an EM cascade are the bremsstrahlung of electrons and pair production by photons. In addition to bremsstrahlung, electrons are subject to energy loss by excitation and ionization of the atmosphere. The total energy lost by the electrons can be described as

\[- \frac{dE}{dX} \simeq \alpha(E) + \frac{E}{X_0} \quad (2.1)\]

Where

- \( X \) is depth in the material. For the atmosphere, it is the integral of the atmospheric density \( \rho \) along the path of the electron \( h ( \int_h^{\infty} \rho(h')dh') \).
- \( \alpha(E) \) is the excitation-ionization energy loss term.
- \( X_0 \) is the radiation length which is the distance over which the energy \( E_0 \) of the particle is reduced by \( E_0/e \) due to bremsstrahlung.

The EM cascade development continues until the energy of the electron falls below the critical energy \( E_{e}^c \). This is defined as the energy at which the energy loss by bremsstrahlung equals to the energy loss by ionization-excitation. Below the critical energy, energy loss by excitation-ionization is dominant. The critical energy and the radiation length depend on the material. Their values for electrons in air are \( X_0 \simeq 37 \ g/cm^2 \) and \( E_{e}^c \simeq 86 \ MeV \) respectively.

2.1.1 Heitler’s Model

The properties of EM showers can be understood by a model due to Heitler [35]. According to this model, the development of EM cascades is described by a
binary tree. When an incoming electron interacts in the atmosphere, it produces two particles, each with half energy of the initial electron. In the same way, a photon converts into an electron/positron pair if its energy $> 2m_e$. In these two processes it is assumed that the cross-section are equal and independent of energy. Moreover, any additional energy lose mechanism are ignored. Using eq(2.1) with $\alpha = 0$, one can find the energy as a function of the depth.

$$E(X) = E_0 e^{-X/X_0}$$ \hspace{1cm} (2.2)

The depth at which the electrons halve their energy by emitting a single photon via bremsstrahlung and the photons produce an electron/positron pair is $d = \ln 2 \cdot X_0$. Thus, at each step, $d$, the energy is reduced by factor of two and the number of particles increases by factor of two. Therefore, the number of particles is $N_n = 2^n$ and their individual energy is $E_0/2^n$ after $n$ generations. The number of secondary particles reaches its maximum (shower maximum) when the energy of individual particles falls below the critical energy at step $n^*$ at that step the shower maximum is

$$N_{max} = 2^{n^*} \simeq \frac{E_0}{E_c}$$ \hspace{1cm} (2.3)

The depth where the maximum of EM cascade occurs $X_{\gamma max}^\gamma$ is given by

$$X_{\gamma max}^\gamma = X_i + n^* \cdot d = X_i + X_0 \cdot \ln \left( \frac{E_0}{E_c} \right)$$ \hspace{1cm} (2.4)
The dependence of the shower maximum on the energy $E_0$ is through the quantity called the elongation rate. It corresponds to the slope of the curves representing the depth of the EM maximum as a function of the primary energy $E_0$

\[
D_{10} = \frac{dX_{\gamma_{\max}}}{d(log_{10}E_0)} = 2.3 \cdot \frac{dX_{\gamma_{\max}}}{d(lnE_0)} \tag{2.5}
\]

2.1.2 Analytic Solutions

The general solutions for purely EM showers were studied by coupled differential equations that describe the evolution of the number of electrons $N_e$ and the number of photons $N_\gamma$ as a function of the atmospheric depth $X$ [36]. From the solu-
tion of the cascade equations, the mean number of charged particles as a function of atmospheric depth $X$ for a $\gamma$ ray induced shower is [37]

$$N_\gamma^e(X) = \frac{0.31}{\sqrt{\ln(E_0/E_c^e)}} \exp \left[ \left( 1 - \frac{3}{2} \ln s \right) \frac{X}{X_0} \right]$$  \hspace{1cm} (2.6)$$

The parameter $s$ is called the shower age $s \simeq \frac{3X}{X+2X_{max}}$, it is derived from the observation that all showers at the maximum have similar characteristics. Showers have age $s=1$ at maximum, age $s < 1$ before the maximum and age $s > 1$ after the maximum. The number of electron $N_{e\max}^\gamma$ at shower maximum is

$$N_{e\max}^\gamma = \frac{0.31}{\sqrt{\ln(E_0/E_c^e)}} \left( \frac{E_0}{E_c^e} \right) = \frac{1}{g} \left( \frac{E_0}{E_c^e} \right)$$ \hspace{1cm} (2.7)$$

The value of $g = \frac{\sqrt{\ln(E_0/E_c^e)}}{0.31}$ is weakly dependent on the primary energy. In energy range $(E_0 \simeq 10^{15} - 10^{18} \text{ eV})$, the approximate value of $g \sim 10$. Thus, the EM size at maximum is about 10% of the total size obtained from Heitler’s model.

The particle’s lateral distribution (called Nishimura-Kamata-Greisenor NKG distribution) as a function of the distance $r$ to the shower core is a measured quantity. It is mainly determined by multiple Coulomb scattering of electrons and parametrized by Greisen as

$$\frac{dN_e}{rdrd\phi} = N_e(X) \cdot \frac{C(s)}{2\pi r_1^2} \left( \frac{r}{r_1} \right)^{s-2} \left( 1 + \frac{r}{r_1} \right)^{s-4.5} \frac{\text{particles}}{m^2}$$  \hspace{1cm} (2.8)$$
C(s) is normalization constant obtained by \( \frac{2\pi}{N_e(X_0)} \int_0^{\infty} r^2 dN_e(r) dr \) and the quantity \( r_1 \) is Moliere unit \( r_1 = X_0 \left( \frac{E}{E_c} \right) \simeq 9.2 \ g \ cm^{-2} \). The Moliere radius can be obtained by dividing \( r_1 \) on the density of the medium \( r_M = \frac{r_1}{\rho} \). At the sea level \( r_M \sim 80 \ m \) and at the position of the shower maximum \( r_M \sim 200 \ m \).

### 2.2 The Hadronic Component

The hadronic shower is initiated when cosmic rays primary particles (proton or heavier nuclei) interact with atmosphere nuclei after traversing on average one interaction length, \( \lambda_I \). The number of charged particles resulting from the interaction depends on the multiplicity which increases with the center of mass energy. Most of the products in the hadronic component are pions \( (\pi^\pm, \pi^0) \). The multiplicity, \( N_{ch} \), of \( \pi +^{14}N \) interactions increases with energy and one finds: \( N_{ch} \simeq 5, 11, \) and \( 27 \) at \( 10, 100, \) and \( 10^4 \) GeV, respectively [38]. \( \frac{1}{e} \) of the hadrons interact after traversing one interaction length on average, and producing \( N_{ch} \) charged pions and \( \frac{1}{2}N_{ch} \) neutral pions on average. The process continues until the hadron energy drops below an interaction threshold. Neutral pions decay quickly (lifetime \( \tau_{\pi^0} = 8.4 \times 10^{-17} \) s) to photons, initiating the EM cascade. The neutral pion decay length is

\[
\pi^0 \rightarrow \gamma \gamma \quad \text{with} \quad d'_{\pi^0} = \gamma_{\pi^0} c \tau_{\pi^0} = \gamma_{\pi^0} \cdot 2.5 \times 10^{-6} \ cm
\]  

(2.9)
Charged pions decay through weak interactions with longer life time ($\tau_{\pi^\pm} \approx 2.6 \times 10^{-8}$ s):

$$\pi^+ \to \mu^+ \nu_\mu; \quad \pi^- \to \mu^- \bar{\nu}_\mu$$

with

$$d'_{\pi^\pm} = \gamma_{\pi^\pm} \cdot c \tau_{\pi^\pm} = \gamma_{\pi^\pm} \cdot 780 \text{ cm} \quad (2.10)$$

The interaction length for charged pions is $\lambda_{\pi I} \simeq 120$ g cm$^{-2}$. Whether decay or interaction dominates depends on which of the two, $d_{\pi^\pm}$ or $\lambda_{\pi I}^\pi$, is smaller. High energy pions interact because their Lorentz factor is large, while low energy pions decay. To first order model [39], $\pi^\pm$ always interact if their energy is above threshold energy $E_{\pi \text{dec} \pi}$, and decay if the energy is below this threshold. We can estimate $E_{\pi \text{dec} \pi}$ as the energy at which the decay length of the charged pions equals to their interaction length. By using $\rho \simeq 10^{-3}$ g cm$^{-3}$, one can find:

$$\lambda_{\pi I}^\pi = d_{\pi^\pm} \cdot \rho = \left( \frac{E_{\pi \text{dec} \pi}}{m_{\pi} c^2} \right) c \tau_{\pi^\pm} \cdot \rho$$

$$\Rightarrow E_{\pi \text{dec} \pi} \simeq 160 \cdot m_{\pi} c^2 \simeq 20 \text{ GeV}$$

Neglecting the correction factor due to inelasticity, the amount of energy transferred to the EM component can be estimated. In each hadronic interaction, 2/3 of the initial energy is transferred to the hadronic component and the rest is for the EM component. Therefore, the energies of the hadronic, $E_h$, and electromagnetic components, EM,
after n generations is:

\[ E_h = \left(\frac{2}{3}\right)^n E_0 \ ; \ E_{EM} = E_0 - E_h \]  \hspace{1cm} (2.11)

Thus, after n interactions the energy for each pion is 

\[ E = \frac{E_0}{(N_h)_{\pi}} \]  

where \( N_h \) is the total number of hadronic particles in the shower, we assume that all \( N_h \) are pions. The value \( n^* \) When \( E \) becomes less than \( E_{\pi \text{dec}}^{\pi} \) can be estimated by

\[ n^* = \frac{\ln(E_0/E_{\pi \text{dec}}^{\pi})}{\ln N_h} \]  \hspace{1cm} (2.12)

From the above discussion, the properties of the cascade induced by a primary hadron with energy \( E_0 \) can be understood assuming the decay channels for neutral and charged pions. At the shower maximum of proton-initiated air showers, the primary energy \( E_0 \) is shared between \( N_{\mu} \) muons and \( N_{\text{max}}^{p} \) electron/photons. The total energy can be written as 

\[ E_0 = E_{e\text{c}}^{\max} N_{\text{max}}^{p} + E_{\pi \text{dec}}^{\pi} N_{\mu}^{p} \]  \hspace{1cm} (2.13)

The number of muons in the cascade depends on the primary energy \( E_0 \). Muons are produced in the decay of the \( n^* \) generation of charged pions, when \( \pi^{\pm} \) reach an energy below the threshold \( E_{\pi \text{dec}}^{\pi} \) and all decay into muon-neutrino pair. Thus \( N_{\mu}^{p} = N_{\pi}^{p} = (N_{ch})^{n^*} \). By using eq(2.12), the number of muons in the cascade is:

\[ N_{\mu}^{p} = \left( \frac{E_0}{E_{\pi \text{dec}}^{\pi}} \right)^{\beta} \hspace{0.5cm} \text{Where} \hspace{0.5cm} \beta = \frac{\ln N_{ch}}{\ln N_h} \]  \hspace{1cm} (2.14)
The value of $\beta \sim 0.85$ is obtained for $N_{ch} = 10$. When the inelasticity is taken into account, $\beta \sim 0.9$. The numerical values of $\beta$ and $E_{\text{dec}}$ for different particles and hadronic interaction models are given in [40].
The number of electrons can be estimated by the relation $E_0 = E_{EM} + E_h$.

The EM component carries an energy fraction equals to:

$$\frac{E_{EM}}{E_0} = \frac{E_0 - N_p E_{\pi dec}^\pi}{E_0} = 1 - \left( \frac{E_0}{E_{\pi dec}^\pi} \right)^{\beta - 1}$$  (2.15)

There are $N_0$ independent showers initiated by the EM decay of each neutral pions. Each pion carries $E_0/N_h$ of the primary energy. By using eq(2.7) we can convert it to proton-induced shower as:

$$N_{p_{\text{max}}}^p = N_0 \cdot \frac{1}{g} \left( \frac{E_0/N_h}{E_c^e} \right) = \left( \frac{E_0}{3gE_c^e} \right) = 4 \times 10^5 \left( \frac{E_0}{P\text{eV}} \right)$$  (2.16)

Where $N_0/N_h = 1/3$. This relation underestimates by $\sim 30\%$ the electron size due to additional contribution of successive interactions of the leading particles and of charged pions, producing more neutral pions. A better estimate can be derived by approximating eq(2.15) as a power law $\frac{E_{EM}}{E_0} \approx a \cdot \left( \frac{E_0}{E_{\pi dec}^\pi} \right)^b$ and expand both equations around $x_0 = E_0/E_{\pi dec}^\pi = 10^5$ gives the electrons size at the shower maximum as a function of energy

$$N_{p_{\text{max}}}^p = E_{EM} \cdot \frac{gE_c^e}{gE_c^e} = \frac{a}{gE_c^e}(E_{\pi dec}^\pi)^{-b}E_0^{1+b}$$  (2.17)

with $b = (1 - \beta)/(x_0^{1-\beta} - 1) \approx 0.046$ and $a = (1 - x_0^{\beta-1}/x_0^b) \approx 0.4$. Then this yields:

$$N_{p_{\text{max}}}^p = 6 \times 10^5 \left( \frac{E_0}{P\text{eV}} \right)^{1.046}$$  (2.18)
The number of electrons at the maximum grows as a function of energy slightly faster than exactly linear.

### 2.2.1 Depth of the Shower Maximum

The cascade consists of the superposition of many individual showers. The number of neutral pions \( N_0 = 1/2N_h \) are produced in the first interaction. They generate \( 2N_0 \) \( \gamma \)-rays inducing the EM cascade with each \( \gamma \)-ray carries \( E_0/2N_h \) of the primary energy. An estimate of \( X_{\text{max}}^p \) can be obtained using eq(2.4) for a shower initiated by a \( \gamma \)-ray with \( X_i \to \lambda_I \) and \( E_0 \to E_0/2N_h \):

\[
X_{\text{max}}^p = \lambda_I + X_0 \cdot \ln \left( \frac{E_0}{2N_hE_e^c} \right) \tag{2.19}
\]

The difference between the position of the maximum for a proton and a \( \gamma \)-ray initiated showers with the same energy \( E_0 \) (\( X_{\text{max}}^\gamma - X_{\text{max}}^p \)) is approximately 1.4\( X_0 \), corresponding to about 50 g cm\(^{-2} \). The maximum of the EM shower induced by a proton occurs higher in the atmosphere than that induced by a photon of the same energy.

For a shower induced by nuclei, the superposition model is used. A nucleus with atomic mass number \( A \) and energy \( E_0 \) is equivalent to \( A \) individual single nucleons, each having an energy \( E_0/A \), and acting independently. Therefore, the EAS is treated as the sum of \( A \) individual proton induced shower, all starting at the same position. The number of electrons at the shower maximum induced by a primary nucleus is
derived by using eq(2.16) with $E_0 \rightarrow E_0/A$:

$$N_{\text{emax}}^A = A \cdot \left(\frac{E_0/A}{3gE_c^e}\right) = N_{\text{emax}}^p$$  \hspace{1cm} (2.20)

From the above equation, it is clear the EM size is equal for a cascade initiated by a proton with energy $E_0$ and by nucleus A of total energy $E_0$. The corresponding number of muons in nucleus induced shower can be obtained from eq(2.14):

$$N_{\mu}^A = A \cdot \left(\frac{E_0/A}{E_{\text{dec}}^\pi}\right)^\beta = A^{1-\beta} \cdot N_{\mu}^A$$  \hspace{1cm} (2.21)

The number of muons generated from nucleus-initiated shower, $N_{\mu}^A$, increases slowly as a function of the mass number, A, of the primary particle $N_{\mu} \propto A^{0.1}$. The heavier the shower initiating particle is more muons are expected for a given primary energy.

To obtain the depth of the shower maximum from a nucleus of mass A, we use eq(2.19) assuming that the shower is originated from a nucleon in the nucleus with energy $E_0/A$ and $\lambda_I \rightarrow \lambda_I^A$:

$$X_{\text{max}}^A = \lambda_I^A + X_0 \cdot ln \left(\frac{E_0}{2AN_hE_c^e}\right)$$  \hspace{1cm} (2.22)

The depth of maximum of the EM component of a nucleus induced shower differs from that of proton induced shower as $X_{\text{max}}^p - X_{\text{max}}^A = X_0 l n A$. 

Figure 2.3: Full MC simulation based on the CORSIKA code for two showers with energy $E_0 = 10^{14}\text{eV}$. Left: shower initiated by a proton. Right: shower initiated by an iron nucleus.

2.3 Light Production

Accompanying propagation of the particles of air shower in the atmosphere, light is produced along the shower track. This light is important for the reconstruction the longitudinal shower profile. It is also used to measure the mass and the energy of the primary cosmic ray. The light produced in the particle cascade comes from two different channels, fluorescence and Cherenkov light.
Fluorescence photons are emitted when energetic EAS particles, mostly electrons and positrons, pass through the atmosphere and collide, mainly nitrogen molecules and nitrogen ions, resulting in ionization and excitation of the air. This produces fluorescence photons. The fluorescence produced in the ultraviolet range between 300-440nm [41] is used for EAS measurements because there is less background light in this wavelength range. The emission of fluorescence photons, so fluorescence detectors can observe air showers from any direction. The fluorescence yield, $Y$, at wavelength, $\lambda$, is defined as the number of photons produced per ionizing particle per 1 meter of the path length. This quantity depends on the atmospheric pressure, the temperature, the humidity and the energy deposited. The absolute fluorescence yield as measured in dry air for an electron energy of 0.85 MeV is about $4.23 \pm 0.2$ photons per meter at 760 mmHg at 15° C [42]. In EASs, most of the ionizing particles are electrons and positrons with energies below 1 GeV with the most probable energy being about 30 MeV. This is confirmed by simulation studies [7], therefore most of the fluorescence is produced by relativistic electrons where fluorescence yield is independent of their energy. Figure 2.4 shows the results reported in [7].

The fluorescence detector uses the fluorescence yield to reconstruct the profile of the shower in the atmosphere. The number of fluorescence photons produced per unit of path length and detected at the fluorescence detector is given by

$$\frac{dN_\lambda}{dX} = \int \frac{dN_\lambda^0}{dX d\lambda} \cdot \tau_{atm}(X, \lambda) \cdot \epsilon_{FD}(\lambda) \cdot d\lambda$$

(2.23)
Where $\tau_{atm}$ and $\epsilon_{FD}$ are the transmission of the atmosphere and the efficiency of the detector respectively. The atmospheric transmission accounts for all transmission losses. The loss mechanisms are optical absorption, Rayleigh scattering and Mie scattering. Losses due to these mechanisms must be taken into account from the point where the photons emitted until they reach the detector. The number of fluorescence photons $dN^0_\lambda$ emitted per wavelength interval $d\lambda$ and pathlength interval $dX$ can be obtained by

$$\frac{dN^0_\lambda}{dXd\lambda} = \int Y(\lambda, T, p, E) \cdot \frac{dN_e(X)}{dE} \cdot \frac{dE_{dep}}{dX} dE \quad (2.24)$$

In this relation, $\frac{dN_e(X)}{dE}$ refers to the energy spectrum of the electrons and positrons at the atmospheric depth $X$ and $\frac{dE_{dep}}{dX}$ is the rate of energy deposition per unit pathlength, $dX$. The fluorescence yield $Y$ in the last expression has unit of photons.
per unit of deposited energy\(^1\). Since almost all the ionizing particles in the EAS are relativistic electrons, the fluorescence yield \(Y\) maybe assumed to be independent of the energy, the last expression becomes

\[
\frac{dN_\lambda^0}{dX d\lambda} = Y(\lambda, T, p) \cdot \frac{dE_{\text{dep}}^{\text{tot}}}{dX} \quad (2.25)
\]

Where \(\frac{dE_{\text{dep}}^{\text{tot}}}{dX}\) is the remaining integral from equation (2.24) corresponding to the differential deposited energy per traversed thickness, \(dX\). Therefore, the number of detected fluorescence photons becomes proportional to the total deposited energy per traversed matter.

\[
\frac{dN_\lambda}{dX} = \frac{dE_{\text{dep}}^{\text{tot}}}{dX} \cdot \int Y(\lambda, T, p) \cdot \tau_{\text{atm}}(X, \lambda) \cdot \epsilon_{FD}(\lambda) \cdot d\lambda \quad (2.26)
\]

Thus, the fluorescence light produced by EAS is directly related to the energy deposited along its shower axis. However, part of primary energy is not detected since it taken away by neutrinos and muons that are not stopped or interact. This missing energy is roughly about 10% of the total shower energy [43]. The correction for the missing energy depends slightly on the mass of the primary particle and the hadronic interaction model used to describe the shower development in the atmosphere. The Auger collaboration estimated that the correction factor varies between 1.07 and 1.17 [44].

The light profile of the EAS can be determined by constructing the shower geometry. This can be done by determining the Shower-Detector-Plane (SPD) which

\[
1Y \left[ \frac{\text{photons}}{m} \right] = Y \left[ \frac{\text{photons}}{MeV} \right] \cdot \frac{dE}{dX} \rho
\]
Figure 2.5: Geometry of the detection of air shower by fluorescence telescope [8]

is defined as the plane spanned by the viewing directions of the trigger detector pixels. The geometry of the shower within this SPD is reconstructed by measuring the arrival time of the signals at the detector and viewing angle of the pixels projected in the SPD (see Figure 2.5). To derive the time-angle correlation assuming the fluorescence light to be emitted by a point-like object advancing with speed \( c \) along the shower axis, the shower propagation time \( \tau_{\text{shower},i} \) from point \( S_i \) to the point at reference time \( t_0 \) on the shower axis is given by

\[
\tau_{\text{shower},i} = \frac{R_p}{c \cdot \tan(\chi_0 - \chi_i)}
\]

\( t_0 \) is the time at which the shower axis passes the closest point to the telescope at distance \( R_p \).
Where $\chi_0$ is the angle of incidence of the shower axis within the SPD and $\chi_i$ is the viewing angle of the pixel $i$ within the SPD. Next, the light propagation time $\tau_{\text{light},i}$ from $S_i$ to the telescope is

$$
\tau_{\text{light},i} = \frac{R_p}{c \cdot sin(\chi_0 - \chi_i)} \quad (2.28)
$$

Using the last two equations and assuming instantaneous emission of the fluorescence light at $S_i$, the arrival time, $t_i$, of fluorescence light at a pixel viewing at an angle $\chi_i$ can be calculated by noticing that $t_i = t_0 - \tau_{\text{shower},i} + \tau_{\text{light},i}$. Finally the time-angle correlation is

$$
t_i = t_0 + \frac{R_p}{c} \cdot tan\left(\frac{\chi_0 - \chi_i}{2}\right) \quad (2.29)
$$

Therefore, comparing the measured quantities $t_i$ and $\chi_i$ with the expected ones, the best fit parameters $R_p$, $\chi_0$ and $t_0$ can be found by $\chi^2$-minimization. This will provide the desired geometrical values of the shower parameters. However, it could happen sometimes that the fit fails. To overcome this problem, more than one telescope is used since each telescope has its own SPD and the combined use of these planes gives the solution and constrains the geometry of the shower axis. This technique, used first by the HiRes experiment [45] and Pierre Auger Observatory [46], is known as stereo reconstruction. Another solution to overcome this problem is to complement the measurements of the fluorescence telescope with measurements made by surface detectors. This gives, independently, the position of the impact point in
the ground and the reference time $t_0$. This is called the hybrid technique and used by both Pierre Auger and Telescope Array [47] experiments.
CHAPTER 3

DETECTION OF EXTENSIVE AIR SHOWERS FROM BALLOONS

3.1 Introduction

The vertical thickness of the Earth’s atmosphere corresponds to about 27 radiation lengths. For this reason, the detection of particles interacting in the atmosphere electromagnetically can be performed by viewing the atmosphere from space or from a balloon flying near the top of the atmosphere. John Linsely in 1979 was the first one who proposed using a fluorescence telescope from the space. Linsely’s idea resulted in a design of the Satellite Observatory of Cosmic Ray Showers (SOCRAS). However, due to the technical challenges involved, it was difficult to get the idea accepted. In 1995 Yoshiyuki Takahashi proposed a mission called MASS (Maximum energy Auger Shower Satellite). The MASS mission was designed for an orbit between 500 and 2000 km and a focal surface consisting of a fast CCD or a cluster of Multi Anode PMTs. These early efforts laid the groundwork for EUSO (Extreme Universe Space Observatory) project which was proposed by the European Space Agency (ESA) as a free flyer mission in 2000. It was selected by ESA to fly on board the Columbus module of the International Space Station (ISS). After a successful study in 2004, programmatic uncertainties in the ISS program and financial constrains with ESA lead to the
mission being abandoned by ESA. The mission was then re-proposed as a payload for Japanese Experimental Module (JEM), leading to the birth of the JEM-EUSO Collaboration in 2006. Unfortunately, the mission was again not canceled by JAXA for further funding issues.

3.2 Motivation

The multi-messenger astronomy is based on the study of astronomical sources using four different type of messenger particles: photons, neutrinos, cosmic rays and gravitational waves. To date, neutrino and charged particle astronomy are still elusive.

Neutrino are weakly interacting and electrically neutral so they are point back directly to their source. But this features raise challenges in the detection. A huge detector is needed to achieve a neutrino interaction within the detector. An example of this is the ICECUBE detector [48].

The galactic and extragalactic magnetic fields deflect the charged particles. The deflection angle increases with the mass to charge ratio and decreases with increasing energy. The path of a cosmic ray proton with energy $10^{19}$ eV is deflected strongly within 1 Mpc as shown in Figure 3.1, while cosmic rays proton with energy $10^{20}$ eV points straight back to the source over this distance. The energy at which cosmic ray astronomy is possible should be between $10^{19}$ eV and $10^{20}$ eV. The main problem of this energy range is the strong flux suppression. Figure 3.2 shows the spectrum at the highest energies together with the number of detected events at each energy bin. It can be seen from Figure 3.2 that even the largest cosmic ray observatory (Auger) only 119 cosmic ray with an energy above $10^{19.8}$ eV were detected over

35
about 8 years of operation. Therefore, it is crucial to greatly increase the statistics in the highest energy bin to include cosmic rays in multi-messenger astronomy. However, increasing the statistics is not a guarantee for charged particle astronomy if the composition becomes heavier at the highest energies. In this case only source cluster or over dense areas can be identified.

To overcome this issue, building a much larger air shower arrays on the ground is an option. But ground arrays have limitations regarding their size and costs. Another requirement is regarding the location. The location should be with low light pollution and clear atmosphere. In the late 70s, John Linsley proposed another option which is to observe EAS developing in the atmosphere beneath a fluorescence detector in space. This option will increase the observed area of about order of mag-
Figure 3.2: Cosmic rays energy spectrum as measured by Auger observatory with the number of measured events overlaid [10]

magnitude larger than possible with ground-based observatories. Moreover, the exposure of the space-based detector would be nearly uniform over the whole celestial sphere and with the same systematics uncertainties for both hemispheres. Systematics has been a problem when trying to compare ground-based observations of the Northern and Southern hemispheres, the Auger and TA experiments. Another advantage is the possibility to observe even under cloudy conditions since in many casses the shower maximum occurs above low clouds (a typical height for shower maximum of a cosmic ray with $10^{19}$ eV is above 4 km). Besides studing cosmic rays and high energetic neutrinos, space detector can be used to investigate atmospheric phenomena such as airglow, Transient Luminos Events (TLEs),lightning or meteors. TLEs occur in the upper atmosphere and are related to lightning. Figure 3.3 shows an overview of
The most common TLE’s include red sprites, blue jets and elves [49].

these atmospheric events. Observing these events from above the clouds provide new insights into the mechanism causing them.

Despite the above mentioned advantages, space-based detector is still faced with many engineering challenges regarding strict limitations on the mass and power as well as radiation hardness requirements for the electronics that ground-based detectors do not encounter. The designs must also fit inside the farings of existing launch vehicles and be able to endure the strong vibrations during launch.
3.3 JEM-EUSO Program

The JEM-EUSO collaboration, the Extreme Universe Space Observatory on board of the Japanese Experiment Module, is a detector concept for the study of UHECRs with energies above $5 \times 10^{19}$ eV where the flux is very low and required detector areas are extremely large [50]. It was initiated in 2006 under the leadership of the Japanese and US teams. Later on, in 2010 JEM-EUSO was added to the ESA program. In 2013 JAXA (Japan Aerospace Exploration Agency) withdrew the offer to launch and mount JEM-EUSO, which officially canceled the mission. However, an extensive supporting Research and Development R&D effort has led other missions listed in Table 3.1 together with their key parameters. A brief description of these individual mission is presented in this chapter.

<table>
<thead>
<tr>
<th>mission</th>
<th>date/status</th>
<th>FOV</th>
<th>number of pixels</th>
<th>optics</th>
<th>height (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEM-EUSO</td>
<td>canceled</td>
<td>60°</td>
<td>315648</td>
<td>Fresnel lenses</td>
<td>400</td>
</tr>
<tr>
<td>EUSO-Balloon</td>
<td>25/08/2014</td>
<td>11°</td>
<td>2304</td>
<td>Fresnel lenses</td>
<td>40</td>
</tr>
<tr>
<td>EUSO-TA</td>
<td>03/2005 -</td>
<td>10.6°</td>
<td>2304</td>
<td>Fresnel lenses</td>
<td>ground</td>
</tr>
<tr>
<td>EUSO-SPB1</td>
<td>24/04-06/05/2017</td>
<td>11.2°</td>
<td>2304</td>
<td>Fresnel lenses</td>
<td>17 - 33</td>
</tr>
<tr>
<td>EUSO-SPB2</td>
<td>2023</td>
<td>36° × 12°</td>
<td>6912</td>
<td>Schmidt optics</td>
<td>33</td>
</tr>
<tr>
<td>Mini-EUSO</td>
<td>22/08/2019</td>
<td>44°</td>
<td>2304</td>
<td>Fresnel lenses</td>
<td>400</td>
</tr>
<tr>
<td>TUS</td>
<td>04/2016 -</td>
<td>9°</td>
<td>256</td>
<td>mirror</td>
<td>~ 475</td>
</tr>
<tr>
<td>K-EUSO</td>
<td>2022</td>
<td>44°</td>
<td>119808</td>
<td>Schmidt optics</td>
<td>400</td>
</tr>
<tr>
<td>POEMMA</td>
<td>design study</td>
<td>45°</td>
<td>126720</td>
<td>Schmidt optics</td>
<td>525</td>
</tr>
</tbody>
</table>

Table 3.1: List of different missions carried out by JEM-EUSO collaboration.
Figure 3.4 shows an overview of JEM-EUSO mission. The instrument and ISS orbit the earth every about 90 minutes at an altitude of 330 km to 400 km. The energy and the direction of the cosmic ray is determined by the spatial and temporal profile of the event. Simulations carried out by the EUSO Simulation and Analysis (ESAF) shows the time profile as seen by JEM-EUSO of a shower initiated by a proton with energy $10^{20}$ eV and zenith angle of 60° is shown in Figure 3.5.
Figure 3.5: Time profile of photons generated by EAS initiated by a $10^{20}$ eV proton with zenith angle of 60° arriving at the aperture of JEM-EUSO. Fluorescence light: blue, scattered Cherenkov light: green, Cherenkove bounce: red [11].

3.3.1 JEM-EUSO Instrument

The instrument design features Fresnel optics, refractive UV-telescope (Figure 3.6) and two modes of observation. The observation modes are the nadir mode resulting in a footprint on the ground of 380 km in diameter and the tilted mode by 30° which increases the observation area to $7 \times 10^5 \, km^2$. JEM-EUSO payload also includes an Atmospheric Monitoring system that contains a LIDAR and an Infrared Camera. In addition, there will be support and calibration systems on the ground called the Global Light System as well as at the ISS. In the following we will briefly describe the designed instrument.
Figure 3.6: JEM-EUSO design, three Fresnel lenses, $≈ 300000$ pixels UV camera [11].

**Optics** The instrument’s optics consists of three Fresnel lenses made of Poly-MethylMethAcrylate (PMMA). The lens diameter was designed to be 2650 mm with a FoV of $±30^\circ$. The first lens is coated with Cytop to protect it against the atomic oxygen in the orbit of the ISS. The second lens is diffractive lens to reduce the vignetting factor and correct chromatic aberration. the last lens focuses the light onto the camera. The camera would have include SCHOTT BG3 filters flued onto the MultiAnodePhotomultipliers (MAPMTs) to select light in the wavelength range 290 nm to 430 nm.

**Focal Surface:** The focal surface (FS) is spherically curved and about 2.5 m in diameter. The FS modular structure is shown in Figure 3.7. The smallest unit is Multi-anode Photomultiplier Tube (MAPMT) which has 64 channels. Each $2×2$ MAPMT groups form an Elementary Cell (EC) with its own high volatge module. A
Photo-Detector Module (PDM) consists of a group of nine ECs. The JEM-EUSO FS design contains 137 PDMs for a total of 315648 pixels. Ultra-bialkali photo-cathodes are used to convert the incident photons into electric pulses, which are counted by the electronic with a 2.5 µs Gate Time Unit (GTU). The 12 stage dynode structure of the MAPMTs leads to a gain on the order of $10^6$. When a signal pattern of an EAS is detected, the trigger is issued and the intensity of the signal in the triggered and surrounding pixels is sent to the ground operation center.

### 3.3.2 The Pathfinders

As part of the JEM-EUSO development, several test or pathfinder experiments have been built. The first one is the ground-based EUSO-TA instrument, followed by EUSO-Balloon flown in 2014. The completed pathfinder is EUSO-SPB1 which was...
launched in 2017. EUSO-SPB1 are described in detail at a later point in this chapter. The JEM-EUSO collaboration is also working on space-based instrument: K-EUSO and Mini-EUSO. The later was launched in 2019.

**EUSO-TA** EUSO-TA is a ground based detector formed by one PDM [51]. It is located in front of the Telescope array Fluorescence detector in Black Rock Mesa, Utah, USA, see Figure 3.8. It consists of two 1 m² Fresnel lenses with a field of view of about 11° \( \times \) 11°. Moreover, it is considered the first detector to successfully use a Fresnel-lens-based optical system to detect UHECRs. The main objective of the instrument is detection of UHECRs through detection of ultraviolet light generated by cosmic ray air showers. Since its operation began in 2013, the detector has observed several UHECRs events and meteors.
EUSO-Balloon EUSO-Balloon is a prototype detector of the JEM-EUSO [12]. The objective of this pathfinder was to test the JEM-EUSO technology in the space environment and to test the response of the detector to several artificial cosmic ray events. The instrument’s focal surface consists of one full original JEM-EUSO PDM and with an optical system made of two Fresnel lenses, with a side of 1 m covering a field of view $11^\circ \times 11^\circ$. EUSO-balloon was launched as a balloon payload from Timmins Stratospheric Balloon Launch Facility in Ontario, Canada on 2014 August 24-25 at an altitude of 38 km. The flight lasted for more than 5 hours before descending to ground. To prove the capability of the instrument to detect UV fluorescence emitted from cosmic ray air showers, pulse form calibrated UV laser and a Xe flasher were fired in the instrument FoV for about 2 hours from a helicopter.

![EUSO-Balloon detector](image.jpg)

Figure 3.9: EUSO-Balloon detector [12].
Mini-EUSO

Mini-EUSO [52] was launched on August 22, 2019 from the Baikonur cosmodrome and consists of a system of circular two Fresnel lenses and one PDM with overall FoV $44^\circ$ accommodated inside the ISS. The instrument was placed in the Russian segment of the ISS behind a UV-transparent downward-looking window and to monitor the atmosphere from 400 km. The main purpose of Mini-EUSO is observing EASs generated by UHECRs with energy $10^{21}$ eV and detect artificial showers generated with lasers from the ground. Other objectives of the mission are studying the atmospheric phenomena such as TLEs, meteors and meteoroids and searching for Strange Quark Matter.

![Figure 3.10: Summary of Mini-EUSO mission [13].](image)
3.4 EUSO-SPB1

The extreme Universe Space Observatory on a Super Pressure Balloon (EUSO-SPB1) is considered a major step of the JEM-EUSO collaboration on the way to a space based cosmic detector. The instrument was the first mission intended to measure EAS from suborbital space. The main scientific goals of the mission were:

1. Measure the EAS signals by looking down on the Earth’s atmosphere from suborbital space with fluorescence detector.

2. Measure of the UV background over the ocean and clouds.

3. Search for faint and fast UV pulse-like signatures in the atmosphere from another phenomena.

EUSO-SPB1 was launched on the 24th of April 2017 at 23:51 UTC from Wanaka, New Zealand as a Mission of Opportunity on a NASA super pressure balloon. The flight duration was supposed to last for about 100 days, circulating the southern hemisphere. Unfortunately, The flight had to be terminated over the Pacific Ocean after 12 days and 4 hours, around 300 km SE of Easter Island. The payload was lost.

In this section I will give an overview of the EUSO-SPB1 mission, the instrument and the flight.

3.4.1 The Instrument

The EUSO-SPB1 instrument is an enhanced design similar to EUSO-Balloon, see Figure 3.12. The main core of the detector is a high-speed UV camera consisting
of one PDM with a total 2304 pixels to detect fast UV flashes. The instrument’s optics consists of two Fresnel lenses focusing the light in the FoV onto the camera. The readout electronics is mounted in the Data Processing (DP) crate and includes the subsystems that communicate between the different parts of the instrument, the power supplies, and the flight CPU that provides the interface between the instrument and the ground stations. The payload include the following:

- An IR camera monitoring the cloud during the flight.
- A differential GPS used as a compass for recording the instrument orientation.
- A pair of calibrated photodiodes to measure the background light for safe operation of the main camera.
Figure 3.12: The main components of EUSO-SPB instrument [14]

- A Photon Detector Module (PDM) composed of Silicon Photomultipliers (SiPMs).
- A UV health LED system illuminating the camera with UV flashes at present intervals.

The main features of the instrument are listed in Table 3.2.

3.4.1.1 Electronic

The PDM of the instrument is the modular design planned for the JEM-EUSO PDMs (see Figure 3.13). It consists of 36 (8 × 8) MAPMTs with 64 channels. These are arranged in nine elementry cells (ECs). Each EC contains four MAPMTs arranged in a 2 × 2 array of MAPMTs. The ECs are mounted in a 3×3 arrangement forming
the PDM. Each MAPMT is covered with a BG-3 optical filters to limit the sensitivity to a range of 290 nm to 430 nm with a tail up to 500 nm. This range spans the UV emission range of EAS.

Table 3.2: Specification of EUSO-SPB1 and 2017 mission [14].

<table>
<thead>
<tr>
<th>Specification</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Threshold</td>
<td>≈ 3 ( EeV )</td>
</tr>
<tr>
<td>Trigger Aperture</td>
<td>≈ 250 ( km^2 ) sr @ 3 ( EeV )</td>
</tr>
<tr>
<td></td>
<td>≈ 500 ( km^2 ) sr @ 10 ( EeV )</td>
</tr>
<tr>
<td>Telescope optics</td>
<td>two 1 ( m^2 ) Fresnel Lenses</td>
</tr>
<tr>
<td>Field of View</td>
<td>11.1° ( \times ) 11.1°</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>2304 (48 ( \times ) 48)</td>
</tr>
<tr>
<td>MAPMT</td>
<td>R11265-113-M64-MOD2</td>
</tr>
<tr>
<td>UV Filter</td>
<td>BG-3, 2 mm thick</td>
</tr>
<tr>
<td>Read Out</td>
<td>DC coupled</td>
</tr>
<tr>
<td>Time Bin Duration</td>
<td>2.5 ( \mu s ) integration</td>
</tr>
<tr>
<td>Flight CPU</td>
<td>CMA24GSD1000HR4096</td>
</tr>
<tr>
<td>Telemetry (Data)</td>
<td>( 2 \times \approx 75 ) ( kbits/s )</td>
</tr>
<tr>
<td>Telemetry (Coms)</td>
<td>( \approx 1.2 ) ( kbit/s ) (255 bit bursts)</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>40 W (day) 70 W (night)</td>
</tr>
<tr>
<td>Batteries</td>
<td>10 (12V, 42 Ah, lead acid)</td>
</tr>
<tr>
<td>Solar Panels</td>
<td>3×100 W on all 4 sides</td>
</tr>
<tr>
<td>Charger Controller</td>
<td>MorningStar Sunsaver</td>
</tr>
<tr>
<td>Detector Weight</td>
<td>2700 lbs (1227 kg)</td>
</tr>
<tr>
<td>Balloon</td>
<td>( 18 \times 10^6 ) ( ft^3 ) (0.5 × 10^6 m^3)</td>
</tr>
<tr>
<td>Nominal Float Height</td>
<td>110000 ft (33.5 km)</td>
</tr>
<tr>
<td>Releasable Ballast</td>
<td>1200 lbs (545 kg)</td>
</tr>
<tr>
<td>Flight Start</td>
<td>April 24 23:51 UTC 2017</td>
</tr>
<tr>
<td>Flight End</td>
<td>May 6 3:40 UTC 2017</td>
</tr>
<tr>
<td>Flight Duration</td>
<td>12 days 4 hours</td>
</tr>
</tbody>
</table>
The High Voltage (HV) system [53] has one HVPS (High Voltage Power Supply) board for each EC. The HVPS system consists of one HVPS board per EC that hosts the HV generator and a HVPS control board. The generator is a Cockcroft-Walton voltage multiplier which provide the voltage to the dynodes and anodes of each MAPMT. The HV control board is responsible for the communication with the HV generators and the rest of the instrument. The nominal voltage is 1100 V leading to a gain of $10^6$ electrons per photoelectron.

The readout electronic consists of two components, the EC-ASIC board and the PDM board. The EC-ASIC uses the SPACIROC-3 to digitize the analog signal at the output of each MAPMT. Each of EC-ASIC board is composed of 6 SPACIROC-3 ASICs developed by Omega (CNRS, France). The ASIC allows a double pulse
separation at 100 MHz which means only photons arriving separated by at least 10 ns will be counted separately. The PDM board receives the digital signals from ASICs, applied the first level trigger [54] and writes events to disk those that fulfill the trigger algorithm.

A FPGA (Field Programmable Gate Array) is implemented on the PDM board. Its main role is receiving the digital data from all the ASICs before sending the complete packets to the disk. Another role for the FPGA is to protect the MAPMTs from high light intensity that is too high. It switches down the voltage of the photo-cathode of each EC when the light intensity reaches a predefined threshold over an entire EC. The cathode voltage can be lowered to either the voltage of the first dynode or to 0 V to protect the MAPMT. The gain of the whole electro-multiplication chain remains the same since only the photo-cathode voltage changes, which allows the algorithm to switch within 1-2 GTUs.

The back-end electronics is composed of the CPU, the GPS, Control Cluster Board (CCB), Clock Board (ClkB) and the House Keeping (HK), all located in the same crate. Table 3.3 lists the different components and their primary role.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>acronym</th>
<th>main functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td></td>
<td>instrument control, data taking</td>
</tr>
<tr>
<td>Cluster Control Board</td>
<td>CCB</td>
<td>second level trigger, manage multiple PDMs</td>
</tr>
<tr>
<td>Clock Board</td>
<td>ClkB</td>
<td>internal clock for synchronization</td>
</tr>
<tr>
<td>House Keeping</td>
<td>HK</td>
<td>On/Off control, monitoring data</td>
</tr>
<tr>
<td>GPS</td>
<td></td>
<td>position and time stamping</td>
</tr>
</tbody>
</table>

**Table 3.3:** Subsystem of the Data Processing System of EUSO-SPB1.
The main role of the CCB is to manage multiple PDMs and to host the second level trigger. Both are not applicable to EUSO-SPB1, but to perform an end-to-end test of the full JEM-EUSO design, it is important to integrate the system including the CCB. The HK controls the ON/OFF of the subsystems and collects the monitoring data of all subsystems. The ClkB generates the internal clock for synchronizing the different subsystems and handles the communication with the GPS. The CPU is the brain of the instrument. It runs the program to collect data and saves the triggered events to a 1 TB raid disk. The main program running on the CPU is modular flight control software. This program communicates with all subsystems of the main instrument and with all auxiliary devices. The Instrument’s architecture is shown in Figure 3.14.

**Figure 3.14**: The diagram of the EUSO-SPB1 data readout system.
3.4.1.2 Optics

The **optics** of EUSO-SPB1 consists of two 1 $m^2$ PMMA Fresnel lenses manufactured at RIKEN (Japan). The front lens has an active area of 9378 $cm^2$. The distance between the two lenses is 1063.6 mm estimated by ray tracing simulations. The Performances of the optics were tested at Colorado School of mines with an optical bench set up to evaluate the Point Spread Function (PSF) and the optical efficiency of the system. The optical throughput was measured to be 30 % in the lab. The FoV was measured at the Telescope Array site in Utah with laser pulses and by observing the night sky and the inclination of bright stars. The measurement gave a FOV of $10.10^\circ \pm 0.15^\circ$. These measurements are described in [55].

3.4.1.3 Gondola and Power System

The instrument housing of EUSO-SPB1 was the fiberglass redbox gondola structure used in the recovered EUSO-Balloon experiment. The redbox design has three modules:

1. The electronic Chamber housing the electronics and the camera.

2. The optics.

3. A removable light baffle which was added to compensate for the fact that the redbox had to be shortened to fit under the hanger in Wanaka.

An access hatch with through connectors was also installed in the electronic chamber for a better access during integration and ground testing. Another usage
of the through connectors is to connect the instrument with the external auxiliary devices (GPS antenna, compass, IR camera) as well as with the NASA Support Instrumentation Package (SIP) system.

An exoskeleton structure (Figure 3.15) was designed to hold the payload: the redbox, SIP, the antenna boom, the ballast and the solar panel crinoline. The mechanical structure was to support ten times the weight of the payload applied vertically to the suspension point and five times the weight applied horizontally to the suspension points. Two rolling carts were used to move the instrument: detector cart and exoskeleton cart. The detector cart held the redbox structure and the exoskeleton cart was used to move the payload in and out of the Hanger during the final outside tests and launch attempts.

The Instrument was powered by a solar array of 12 panels (3 on each side) which charged the battery packs during the day time. The solar power system consists of $27\times31$ 100 W SunCat panels. The solar panels were mounted on a crinoline and tilted by 14° to maximize their power production during the day mode. Each panel produces a nominal power of 100 W when the sun is normally incident on the panels. The battery pack were five pairs of 12 V batteries connected in series to give nominal voltage of 24 V. The power system was connected to Morning stat Sunsaver MPPT controllers to manage the charging of the batteries. The maximum power consumption of the instrument during night was 150 W with an average 75 W.
Figure 3.15: (a): picture of the gonodola in the exoskeleton. (b): Schematic of the gonodola on the cart before integration in the exoskeleton.
3.4.1.4 Auxiliary Devices

In addition to the PDM, EUSO-SPB1 was equipped with several auxiliary devices. The most important one is the **Health LED**. It was used to monitor the health of the PDM. The LED system was mounted in the center of the rear lens facing the PDM (see Figure 3.16a). The LED system consists of three different LEDs at 340 nm (LED #3), 365 nm (LED #2) and a broad band LED ranges from 355 nm to 395 nm (LED #1). LED #3 gives a DC light to generate calibration curves recorded by the PDM. The other two LEDs are flashing LEDs. LED #1 flashes for 8.5 µs and LED #2 flashes for 11 µs. The LED system was powered from the batteries.

![LED System](image)

**Figure 3.16**: (a): The Health LED mounted in the center of the rear lens. (b): An example of the PDM response to the Health LED.

Silicon photomultiplier Elementary Cell Add-on (**SiECA**) was flown as an R&D test. It has the same low light sensitivity as the high voltage PMT with ad-
vantage that it operates at low voltage. In order to test this new technology in suborbital space, SiECA camera was developed and mounted next to the PDM (see Figure 3.17b). The focal surface consists of four SiPMs containing $8 \times 8$ pixels with totally 256 channels. BG3 filters was glued on the top of the photo sensors that provide the same bandwidth for detection as PDM’s EC. SiECA readout is triggered by the data acquisition of the main CPU, but not synchronized to the PDM trigger generated on the PDM board. For more detailed information of SiECA can be found in [15].

Monitoring the atmospheric conditions in the field of view of the instrument is critical to determine the exposure of EUSO-SPB1. Since cosmic rays air showers could partially develop under clouds, the exposure depends on their optical thickness and altitude. To determine cloud parameters, **UCIRC** (University of Chicago IR Camera) was developed and flown to take IR images underneath the balloon. UCIRC consists
of two FLIR Tau 2 IR cameras with 19 mm lenses. Both of them have different spectral response. One camera’s spectral response is in the range between 11.5-12.9 \( \mu \text{m} \) and the other is sensitive between 9.6-11.6 \( \mu \text{m} \). UCIRC has large field of view (32° × 24°), larger than the UV camera FoV by almost three times, gives the ability to measure the cloud coverage in the field of view of the PDM between pictures. UCIRC has its own power supply and it took pictures every 16 seconds. These pictures were stored in the main disk and downloaded in parallel to the PDM images. More details of UCIRC are presented in [56].

Figure 3.18: Picture of UCIRC.
CHAPTER 4

CALIBRATION OF EUSO-SPB1

4.1 Introduction

Prior to the launch of the EUSO-SPB1, flat-fielding measurements were made at the Colorado School of Mines. The flat fielding is used to obtain a correction matrix for the PDM in order to compensate for non-uniform sensitivity of the pixels across the PDM and for potential distortions in the optical path. This matrix will correct the response of the PDM so that the corrected signals from any pair of pixels will be identical when they are illuminated identically. After the flat field test was performed, the instrument transported from Golden, Colorado to the Telescope Array (TA) site in Delta, Utah. EUSO-SPB1 was set up next to another JEM-EUSO prototype system, EUSO-TA, on Black Rock Messa, one of the fluorescent detector installations in the TA.

One of the goal of this field test was to perform the photometric calibration of the detector. To do this a 365nm LED was mounted on a portable antenna mast at a distance of 47 m from the entrance aperture of EUSO-SPB1. The LED was operated in the pulse mode with each pulse have a duration of 50 $\mu$s (20 GTUs). The LED was temperature stabilized to guarantee that its calibration would not be affected by any
difference between its temperature when it was calibrated and when it was used as a calibration source on Black Rock Mesa. An example of the response of the PDM to an LED pulse during the calibration on Black Rock Mesa is shown in Figure 4.1.

4.2 Flat Field Measurement

The flat fielding was performed as follows. A 365 nm LED was mounted in the center of the front lens. This LED was equipped with an opal diffuser. It illuminated a 2.4 m by 3.7 m wide screen covered with Tyvek 1056. The diffuser insured that the screen was illuminated uniformly in azimuth. The screen was placed 4.65 m in front of the instrument aperture in a darkened room, see Figure 4.2.
The LED did not provide uniform illumination for the entrance aperture for two main reasons. First, the distance from the LED source to the center of the wall is slightly shorter than the distance to any other point in the wall. Second, the emission of light from the LED depends on the angle of emission relative to the optical axis of the LED. The LED was mounted in a metal cylinder whose axis was aligned with the optical axis of the LED. The emission therefore depended on the polar angle, \( \theta_p \). To measure the dependence of the LED’s illumination on distance and polar angle, a test was conducted in the optics lab at UAH. The setup is shown in the Figure 4.3. The power meter (Newport Power MeterModel 1918-R) was used to measure the illumination from the LED. This light power meter was set directly infront of the LED in the dark room and then the position of the light meter was changed while the
Figure 4.3: The setup used for the LED and the light power meter to measure the dependence of the LED illumination on distance.

LED is on. The reading of the light meter was recorded at different distances from the LED. The data are plotted and fitted to an inverse square law, see Figure 4.4.

Figure 4.4: plot of the LED luminosity in watts with distance in meters (blue dots). The fitted data (red line) follows inverse square law.
The fitted function from the data gives the luminosity of the LED with distance \( P(r) \):

\[
P(r) = \frac{p_0}{r^2}
\]  

(4.1)

Where \( p_0 = 1.0881 \times 10^{-8} \text{ Watt.m}^2 \) with error \( \Delta p_0 = 2.53 \times 10^{-12} \).

The second experiment setup was arranged to measure the dependence of the LED illumination on the polar angle \( \theta_p \). In this setup the power meter was at a fixed distance from. The LED was attached to a rotation stage in order to explore the dependence of the luminosity on the polar angle of the LED. Several measurements of the LED illumination were taken at different polar angles. The results of the test are shown in Figure 4.5. The data were fitted to a polynomial of degree two, i.e. \( p(\theta_p) = a_2\theta_p^2 + a_1\theta_p + a_0 \) with coefficients \( a_0, a_1 \) and \( a_2 \). The values of the coefficients and their errors are given in Table 4.1. The fit function \( p(\theta_p) \) are then normalized by dividing it by \( a_0 \), the illumination measured on the optical axis of the LED (where the polar angle is zero).

<table>
<thead>
<tr>
<th>Coefficient a</th>
<th>Value of a</th>
<th>Error ( \Delta a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_0 )</td>
<td>( 7.51 \times 10^{-9} )</td>
<td>( 2.65 \times 10^{-11} )</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>( 1.98 \times 10^{-12} )</td>
<td>( 1.5 \times 10^{-12} )</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>( -1.56 \times 10^{-12} )</td>
<td>( 9.29 \times 10^{-14} )</td>
</tr>
</tbody>
</table>

*Table 4.1: The values of the coefficients \((a_0, a_1 \text{ and } a_2)\) and their errors.*
Figure 4.5: The apparent luminosity of the LED versus polar angle. The data points and error bars on the measured luminosity are shown (in blue). The data were fitted to polynomial of degree two (red line).

4.2.1 Tyvek Reflectivity Measurements

Tyvek (DuPont registered trademark) is a white material used in many applications because of its high reflectivity over a wide spectral range. It is made of high density polyethylene microfibers that is randomly oriented. Because of its high opacity, Tyvek is considered as a diffuse reflection material. In fact, it has both diffuse and specular reflectivity. This section describes measurements the reflectivity profile of Tyvek 1056 bidirectional reflectance distribution function (BRDF), \( f_r \) according to Nicodemus et al. [16], is defined as \( dL_r / dE_i \), and it has a units of \( sr^{-1} \) where \( L_r \) is the reflected radianc and \( E_i \) is the incident irradiance. See Figure 4.6. So,

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i, \theta_r, \phi_r, E_i)}{dE_i(\theta_i, \phi_i)} \quad [sr^{-1}],
\]  

(4.2)

where:
• The subscripts $i$ and $r$ refer to the incident and reflected beams, respectively.

• The angle $\theta$ is measured from the surface normal and the azimuth angle $\phi$ is measured from an arbitrary reference in the surface plane.

• The irradiance $E$ is the areal density of the radiant flux $\Phi$, i.e., $E = \frac{d\Phi}{dA}$, and has the units of $Watt\cdot m^{-2}$.

• The radiance $L$ is the areal and solid angle density of the radiant flux, i.e. the radiant flux per unit projected area and per unit solid angle is $L = \frac{d\Phi}{d\omega dA cos \theta}$.

![Figure 4.6: Geometry of incident and reflected beams [16].](image-url)
Reflectivity is the ratio of reflected to incident radiant flux and it has value between 0 to 1. The BRDF $f_r$ defined in eq 4.2 can never be measured directly since infinitesimal elements of solid angle do not include measurable amounts of radiant flux. Actual measurements of reflectivity always involve non zero intervals of the governing parameters. A general relation for the reflectivity of a surface with an arbitrary configuration of beams can be obtained from the previous equations:

$$R(\omega_i; \omega_r; L_i) = \frac{d\Phi_r}{d\Phi_i} = \frac{\int_{\omega_r} \int_{\omega_i} f_r(\theta_i, \phi_i; \theta_r, \phi_r) \cdot L_i(\theta_i, \phi_i) \cdot \cos\theta_i \cdot \cos\theta_r \cdot d\omega_i \cdot d\omega_r}{\int_{\omega_i} L_i(\theta_i, \phi_i) \cdot \cos\theta_i \cdot d\omega_i} \quad (4.3)$$

If the incident radiance $L_i$ is uniform over a sufficiently large area, then it can be taken out of the integrals in the numerator and denominator of eq 4.3 and the it will cancel out, leaving the biconical reflectance.

$$R(\omega_i, \omega_r) = \frac{1}{\Omega_i} \cdot \int_{\omega_r} \int_{\omega_i} f_r(\theta_i, \phi_i; \theta_r, \phi_r) \cdot \cos\theta_i \cdot \cos\theta_r \cdot d\omega_i \cdot d\omega_r \quad (4.4)$$

where

$$\Omega_i = \int \cos\theta_i \cdot d\omega_i$$

The condition that $L_i$ is the same at all points and in all direction within the incident beam is a good approximation in any well designed reflectometer. Note that removing the integrals from numerator and denominator in eq 4.4 converts it to a definition of bidirectional reflectance. The bidirectional reflectance factor is just $\pi$ times the value of $f_r$, averaged over the designated solid angles.
The experimental set up to measure the Tyvek 1056 reflectivity is shown in Figure 4.7. In this experiment, a Tyvek sample with dimensions 9 cm by 7.5 cm was placed a distance 30 cm on an axis rotation stage in order to be able to change the incident angle $\theta_i$. A circle of radius 30 cm centered at position of the Tyvek sample was drawn and the light meter was able to move on the circle’s circumference measuring the reflected light $\Phi_r$. This allow us the ability to measure and vary the reflection angle $\theta_r$. With this arrangement, we measured the reflected radiant flux $\Phi_r$ at different incident and reflecting angles. To fit the measured reflected radiant flux, we proposed the following relation:

$$\Phi_r(\theta, \phi) = I_1 e^{-I_2(\theta-\phi)^2} + I_3 \cos(\phi - \frac{\theta}{2})$$ (4.5)

**Figure 4.7**: Experimental set up diagram.
Where $I_1$, $I_2$ and $I_3$ are the fitting parameters. The parameters’ values and their errors are given in Table 4.2. Figure 4.11 shows 2D plot of the reflected radiant flux by the Tyvek sample according to the fitting equation 4.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value of $I$</th>
<th>Error $\Delta I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1$</td>
<td>$2.34 \times 10^{-9}$</td>
<td>$3.17 \times 10^{-11}$</td>
</tr>
<tr>
<td>$I_2$</td>
<td>$3.1 \times 10^{-4}$</td>
<td>$9.65 \times 10^{-5}$</td>
</tr>
<tr>
<td>$I_3$</td>
<td>$1.435 \times 10^{-12}$</td>
<td>$3.41 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

**Table 4.2:** The values of the parameters ($I_1$, $I_2$, and $I_3$) and their errors.

**Figure 4.8:** Angular distribution of the light reflected by a sample of Tyvek 1056 according to the fitting equation 4.5.
The bidirectional reflectance distribution function, BRDF, can be computed by using equations 4.1, 4.5 and 4.2. The incident irradiance \( E_i \) is the incident radiant flux \( \Phi_i \) divided by the effective area of the light meter \( A_{eff} \), which equals to 1 \( cm^2 \). While the reflected radiance \( L_r \) is the reflected radiant flux \( \Phi_r \) divided over the projected area of the Tyvek sample and the solid angle, \( L_i = \frac{\Phi_r}{\omega \cos \theta_r A_{Tyvek}} \). The results of these measurements are plotted in Figure 4.9 for different incident and reflecting angles.

**Figure 4.9**: BRDF of Tyvek 1056 at four incident angles 0, 4, 8 and 12.
4.2.2 Flat Field calculations

As mentioned above, a Tyvek 1056 covered screen was located 4.65 m in front of the assembled detector in a darkened room in the Asstroparticle High Bay lab at the Colorado School of Mines. The detector was focused at infinity. The screen was illuminated by a 365 nm pulsed LED mounted in the center of the front lens, see Figure 4.10b. The first step for measuring the illumination of the PDM is to calculate the field of view angles of each pixels in the PDM. The layout of the MAPMTs within the PDM is shown below in Figure 4.10a.

![Figure 4.10: (a): The layout of the EUSO-SPB1 PDM. (b): Schematic of the flat field setup in the dark room.](image)

In Figure 4.10a, each blue square is occupied by 64 pixels. Each pixel has size of 2.9 mm $\times$ 2.9 mm. The yellow border is the glass envelope of each MAPMT. This yellow margin is 1.5 mm. The MAPMTs are grouped in Elementary Cells ECs. Each EC consists of 4 MAPMTs. These MAPMTs are separated by 1.2 mm from
their neighbors in the EC. The spacing between ECs within the PDM is 3 mm. The
dimension of the PDM is 16.68 cm × 16.68 cm. By using these data, one can find the
position of each pixel $ij$ relative to the center of the PDM ($x_{ij}, y_{ij}$). The field angle of
each pixel is given by the following equation:

$$r_{ij}(\theta_{ij}) = -0.623 + 15.912\theta_{ij} - 0.129\theta_{ij}^2 \quad (4.6)$$

Where $r_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2}$ is the position of the center of the pixel $ij$ relative to the center
of the PDM measured in mm and $\theta_{ij}$ is the field angle of the pixel $ij$. By using eq
4.6, the field angle of each pixel is calculated and is shown in Figure 4.11

![Figure 4.11](image.png)

**Figure 4.11**: 48 by 48 pixels of the PDM with the value of their field angles computed
using (4.6).
Since EUSO-SPB is focused at infinity, the entrance aperture collects light from 1 m by 1 m area of the Tyvek screen. As a result, the light reaching any pixel \(ij\) on the PDM is collected from such an area on the flat field screen. The radiant flux of the reflected light must be integrated over this observed area to determine the radiant flux focused on each pixels. To integrate the reflected light from the square meter that the pixel is viewing, the square meter is divided into smaller areas, i.e., 1 cm by 1 cm squares and the angle between the optical axis of the LED and the center of each 1 cm\(^2\) square is measured (the optical angle \(\Theta\)). To find this angle, the position vector \(c_{ij}\) of the center of the one meter square is calculated for the pixel \(ij\) as the following:

\[
c_{ij} = D \cdot tan(\theta_{ij})
\]

\[
\vec{c}_{ij} = c_{ij}cos(\phi_{ij})\hat{x} + c_{ij}sin(\phi_{ij})\hat{y}
\]

Where \(\phi_{ij} = tan^{-1}\left(\frac{y_{ij}}{x_{ij}}\right)\). Then the vector, \(\vec{l}_{nm}\), measured from the center of the square meteron the Tyvek wall to the center of each small square for the pixel \(ij\). See Figure 4.12b. This vector is given as:

\[
\vec{l}_{nm} = (0.5 - 5 \times 10^{-3} - n(1 \times 10^{-2})) \hat{X} + (0.5 - 5 \times 10^{-3} - m(1 \times 10^{-2})) \hat{Y}
\]

Where \((n,m)\) take integer values from 1 to 100 for the pixel \(ij\) and the coordinate \((X,Y)\) is taken from the center of the square meter. Finally, the incident light from the LED on the 1 cm by 1 cm square for the pixel \(ij\) comes from optical angle \(\Theta_{nm}\).
equals to:

$$\Theta_{nm} = tan^{-1} \left( \frac{R_{nm}}{D} \right)$$

(4.9)

Where $\vec{R}_{nm} = \vec{c}_{ij} + \vec{l}_{nm}$ for the pixel ij.

Figure 4.12: (a): Diagram shows the position vector $r_{ij}$ and the orientation angle $\phi_{ij}$ for the pixel ij on the PDM. (b): Diagram shows the square meter viewed by the pixel ij on the Tyvek screen.

The amount of the incident radiant flux from the LED on the small squares can be calculated from the dependence of the illumination of the LED on the polar angle and eq 4.1, where the distance from the LED to the small square is $L = \frac{D}{cos(\Theta_{nm})}$.

Finally, The Tyvek reflectivity measurements is then used to find out how much light is reflected back along the look-direction of the pixel ij (which is the field angle of that pixel). Since the telescope is focused at infinity, all the light coming to that pixel from any point in the square meter it views, is along the same field angle. Now a correction
is applied for the obliquity of the incident light from the LED. The projected area of
the small square is reduced by the cosine of the field angle of the light from the LED.
So the reflected light must be reduced by this cosine factor. These calculations for
each of the small squares in the square meter viewed by the pixel \( ij \) is summed up to
obtain the radiant flux reaching that pixel. This whole process is repeated for each
pixel to find the amount of light reaching the entrance aperture for each pixel. The
illumination of the PDM \( I[ij] \) is shown in Figure 4.13.

![Illumination of the PDM](image)

**Figure 4.13**: The illumination of each pixel on the PDM.

The number of photoelectrons measured by each pixel during the flat field
calibration is extracted from the root data file,

`allpackets-SPBEUSO-ACQUISITION-20160924-055817–650mV_opal_0.1_220mus_10Hz_t230-1.1.root`

The **ROOT CERN** software is a free, open source, object-oriented data analysis
frame work, written in C++. It is designed for large scale data analysis. It contains
many tools for statistical data exploration, fitting and reporting. For the research
described in this thesis, several C++ object-oriented scripts were written to open
and explore the EUSO-SPB1 root data files. Each EUSO-SPB1 root file consists of
200 packets and each packet has 128 GTUs (1 GTU = 2.5µs), so the total GTUs in
each file is 25600 GTUs. The first step in the analysis is to subtract the background
signal (when the LED is OFF). To do this, the mean count in the whole pixels for
each GTU is calculated, see Figure 4.14, and the number of GTUs when the LED is
on $N_{ON}$ and the number of GTUs when the LED is off $N_{OFF}$ are identified.

![PDM Mean Count Light Curve](image)

Figure 4.14: (a): The mean count of the PDM per GTU for the 200 packets (25600
GTUs). (b): The mean count of the PDM per GTU for the first 3 packets.

The background count of the PDM is then extracted by using the GTUs when
the LED is off $N_{off}$. The count is summed in for each pixel $ij$ in these GTUs and
divided by $N_{off}$ to find the average count for the pixel $ij$ $C_{back}^{[ij]}$

$$C_{back}^{[ij]} = \frac{\sum_{s=1}^{N_{off}} BC_s^{[ij]}}{N_{off}}$$  \hspace{1cm} (4.10)

Where $BC_s^{[ij]}$ is the background count for the pixels $ij$ in the PDM for the GTU number $s$. The same procedure is done to get the PDM count when the LED is on, but this time the mean count for each pixels is carried out for the $N_{on}$ GTUs and the average count for the pixel $ij$ $C_{LED}^{[ij]}$ is:

$$C_{LED}^{[ij]} = \frac{\sum_{s=1}^{N_{on}} LC_s^{[ij]}}{N_{on}}$$  \hspace{1cm} (4.11)

where $LC_s^{[ij]}$ is the count when the LED is on for the pixel $ij$ in the PDM for the GTU number $s$. The background substracted signal is then calculated, $C_{LED-back}^{[ij]} = C_{LED}^{[ij]} - C_{back}^{[ij]}$. Figure 4.15a shows the background substracted signal for the count of the PDM during the flat field measurements.

To find the realtive calibration map of the PDM $RC^{[ij]}$, The illumination of the PDM map $I^{[ij]}$ is then divided on the background substracted signal $C_{LED-back}^{[ij]}$ to get the illumination divided by the count $I^{1/C^{[ij]}}$, see Figure 4.16a. Then the value of the good pixels (any pixel with value less than $1.5 \times 10^{-6}$ is considered as a good pixel) in $I^{1/C^{[ij]}}$ were averaged and this average was divided on the value of each pixel of the $I^{1/C^{[ij]}}$ to get the relative calibration map $RC^{[ij]}$, see Figure 4.16b.
Figure 4.15: (a): The 48 × 48 pixels of the PDM with their photoelectron counts in each pixel after the background noise is substracted, the white pixels are dead pixels. (b): Histogram shows the frequency of different numbers of counts in the PDM.

Figure 4.16: (a): The illumination divided by the average count $I^{I/C}[ij]$, any pixel with value greater than $1.5 \times 10^{-6}$ $Watt/count$ is considered dead pixel. (b): The relative calibration map $RC[ij]$ of the PDM.
4.3 Absolute Calibration

The next step after the flat field test in Golden, CO was the field test. The field test is important to perform end-to-end test of the system in order to understand the instrument in the flight configuration before the launch. During these tests we performed the absolute calibration. In 26th of September 2016, the instrument was transported for 845 km from Golden CO to the Black Rock Mesa TA site in Delta Utah and set up next to EUSO-TA fluorescence camera located there, see Figure 4.17.

![Figure 4.17](image.png)

**Figure 4.17:** Picture of EUSO-SPB1 set up next to EUSO-TA in front of the TA telescope at Black Rock Mesa, Utah.

An absolute photometric calibration provides a relationship between the amount of photon flux arriving at the entrance aperture of the detector and the measured signal (photoelectrons) in the pixels of the PDM. The absolute calibration of EUSO-SPB1 was performed by illuminating the entrance aperture with 365 nm LED on a
Figure 4.18: Picture of absolute calibration setup, with the LED mounted on the antenna mast in front of EUSO-SPB1.

mast 46.04 m in front of the entrance aperture, see Figure 4.18. The mast was able to be raised and lowered to change the position of the LED within the FoV. To reduce the temperature effects on the LED output intensity, a temperature stabilizing circuit was installed with the LED. 20 LED runs were taken for the 2 lens system in two nights (09/28/2016 and 09/30/2016). The LED was operated in pulse mode with a pulse length of 50 µs (20 GTUs). The calibration factor $C_r$ is calculated as the ratio of the number of arriving photons at the aperture to the measured signal after applying the flat field correction $RC[i,j]$, and subtracting background noise. The number of photons were calculated based on the measured distance from the entrance aperture to the LED (taking into account the height of the LED on the mast and the height of the center of the entrance aperture) and the absolute calibration of the LED’s luminosity. The absolute calibration of the LED’s luminosity was performed at darkness by measuring the signal of the LED using a previously calibrated
Figure 4.19: Number of photons reaching the entrance aperture of EUSO-SPB1 during the the absolute calibration measurements.

PMT (Photo Multiplier Tube) with area 1 cm$^2$ a distance 84 cm. The LED is then mounted on the mast at height 7.88 m (which was within the FoV of the detector). The number of photons reaching the entrance aperture is calculated at different LED pulse voltages (Figure 4.19).

To analyze the data, we chose a root file when the LED operated at 1000 mV providing $2654.95 \pm 267.37$ total number of photons at the entrance aperture for each pulse. These data contained in the file: allpackets-SPBEUSO-ACQUISITION-20160930-051035-001.001–10Hz_50mus_1000mV.root.

As we did in the flat field, the average count per pixel per GTU was calculated and plotted to identify the GTUs when the LED was on and off, see Figure 4.20. The root file consists of 200 packets with each packet have 128 GTUs. The average signal from the detector was calculated during an average of LED pulses only using 20 GTUs.
when the LED was fully on. An average background for each pixel is calculated using the 10 GTUs before the LED was on and 10 GTUs after the LED was off. This was done for the whole packets. In this way we identified the GTUs that belong to the background and the GTUs that belong to the signal when the LED was fully on. The average counts per pixels for both background and when the LED was fully on is shown in Figure 4.21. Figure ?? shows the background substratced signal. The recorded signal of the LED is spread over almost the middle 8 by 8 pixels. The reasons for this is that our instrument was focused at infinity but the LED was only about 46 m away.

![Figure 4.20](image)

**Figure 4.20**: (a): The average count for a whole pixel in the PDM per GTU calculated for the 200 packets. (b): The count in a pixel per GTU, shown for the first 3 packets.

The total count in the whole PDM for the background subtracted signal is 555.57 photoelectrons and the sum of the recorded signal of the LED within a box of 2 by 3 pixels is 79.68 photoelectrons. This means that the ratio of the measured
Figure 4.21: (a): The average background count per pixel of the PDM. (b): The average count per pixel of the PDM when the LED is on. (c): The background subtracted signal of the PDM. (d): Histogram shows the frequency of the number of count for the background subtracted signal.

Signal to the total signal of the PDM is 0.143 and the number of photons from the LED signal reaching these six pixels is $379.65 \pm 38.23$. Finally, we apply the flat field correction matrix $R[i,j]$ to measured signal (within a box of 2 by 3 pixels). The
measured signal of the LED after applying the flat field correction is 31.52. From this we calculate the calibration factor $C_r = \frac{379.65}{31.52} = 12.0447$ photons/ photoelectrons with error value equals to 1.2. There are three contributions to the errors in the photon number: the dominant one is the uncertainty on the distance between the LED and the EUSO-SPB1 aperture during the field tests, the second and third are the uncertainties on the properties of the LED and the calibrated PMT in the lab.
EUSO-SPB1 was the first mission designed to detect EAS from suborbital space looking down on the atmosphere. Before the launch of EUSO-SPB1 in April 2017, the flat-field measurements and photometric calibration was performed. The flat-field measurements made at Colorado School of Mines in Golden, CO allowed us to equalize the pixels sensitivity of the PDM. An 365 nm LED and Tyvek 1056 were used in the flat-field measurements. The dependence of the apparent luminosity of the LED on the distance and the polar angle was measured and fitted to the best fit function. The bidirectional reflectance factor of the Tyvek 1056 was measured at different incident and reflecting angles in the dark room in the optic lab in University of Alabama in Huntsville. These measurements made it possible to calculate the BDRF of the Tyvek. The results of these laboratory measurements were used to calculate the flat-field correction map.

In the second step, an end-to-end test of the instrument was performed on the TA site in the Utah desert. The 365 nm LED was mounted on mast and operated at different setting while the EUSO-SPB1 instrument observed the LED a 46.04 m distance from the mast. The goal of this setup is to do a photometric calibration of
the instrument. The data was taken and analysed after subtracting the background noise to extract the LED signal and then the flat-field map was applied resulting a calibration factor $C_r = 12.0447 \pm 1.2$ photon/photoelectron.
REFERENCES


