ESTIMATING THE COSMIC RAY EXTENSIVE AIR SHOWER DETECTION RATE FOR THE EUSO - SUPER PRESSURE BALLOON MISSION

by

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ABSTRACT

Ultra-high energy cosmic rays (UHECRs) are the most energetic particles ever recorded. However, their sources and acceleration mechanisms are unknown. The JEM-EUSO mission is a UHECR detector planned for the International Space Station (ISS). Its main scientific objective is to identify the sources of UHECRs and measure their energy spectra. It will do so by recording the fluorescence light emitted by cosmic ray interactions in the atmosphere from outer space. Above $10^{20}$ eV, the flux of UHECR is less than one particle per square kilometer per century, making it difficult to record a significant number of UHECR events. The unique approach of JEM-EUSO is expected to yield a dramatic increase in detection rate relative to the largest ground based observatories in the world.

The EUSO - Super Pressure Balloon (EUSO-SPB) mission is a pathfinder mission for JEM-EUSO. It uses a prototype version of the JEM-EUSO detector to look down on the atmosphere from a stratospheric balloon at an altitude of approximately 40 km. EUSO-SPB is planned to launch for a long duration flight in 2017 from Wanaka, New Zealand. In this thesis we use extensive air shower simulations and the cosmic ray flux to estimate the expected rate of UHECR detection for EUSO-SPB as a function of energy and detector optical efficiency. We find that in a seven night mission with eight hours of observation time per night EUSO-SPB would record approximately ten UHECR events, all with energies above $10^{18}$ eV.
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LIST OF SYMBOLS

depth of shower maximum .............................................................. $X_{\text{max}}$
zenith angle ................................................................................. $\theta$
azimuth angle ............................................................................... $\phi$
**LIST OF ABBREVIATIONS**

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<tr>
<td>ultra-high energy cosmic ray</td>
<td>UHECR</td>
</tr>
<tr>
<td>extensive air shower</td>
<td>EAS</td>
</tr>
<tr>
<td>cosmic microwave background radiation</td>
<td>CMBR</td>
</tr>
<tr>
<td>Greisen, Zatsepin and Kuzmin</td>
<td>GZK</td>
</tr>
<tr>
<td>surface detector</td>
<td>SD</td>
</tr>
<tr>
<td>fluorescence detector</td>
<td>FD</td>
</tr>
<tr>
<td>Pierre Auger Observatory</td>
<td>Auger</td>
</tr>
<tr>
<td>International Space Station</td>
<td>ISS</td>
</tr>
<tr>
<td>field of view</td>
<td>FOV</td>
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<tr>
<td>Japanese Experiment Module</td>
<td>JEM</td>
</tr>
<tr>
<td>Extreme Universe Space Observatory</td>
<td>EUSO</td>
</tr>
<tr>
<td>focal surface</td>
<td>FS</td>
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<tr>
<td>multi-anode photomultiplier tube</td>
<td>MAPMT</td>
</tr>
<tr>
<td>photo-detector module</td>
<td>PDM</td>
</tr>
<tr>
<td>elementary cell</td>
<td>EC</td>
</tr>
<tr>
<td>atmospheric monitoring system</td>
<td>AM</td>
</tr>
<tr>
<td>light detection and ranging device</td>
<td>LIDAR</td>
</tr>
<tr>
<td>EUSO - Super Pressure Balloon</td>
<td>EUSO-SPB</td>
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CHAPTER 1
INTRODUCTION, BACKGROUND AND MOTIVATION

The EUSO-Balloon is a prototype detector for JEM-EUSO, an ultra-high energy cosmic ray
detector planned for the International Space Station. The prototype is attached to a stratospheric
balloon and flown at an altitude of approximately 40 km and pointed down to observe the at-
mosphere from above. EUSO-Balloon’s first flight in August, 2014 in Timmins, Ontario did not
record any extensive air showers. This was primarily due to the short flight time of approximately
four hours at float altitude. The purpose of this thesis is to estimate the cosmic ray extensive air
shower detection rate for the super pressure EUSO-Balloon flight (EUSO-SPB).

Chapter 1 begins with a brief background on cosmic rays. Next, JEM-EUSO and EUSO-
Balloon are described in Chapter 2, followed by an overview of the software packages used to
simulate extensive air showers in Chapter 3. The analysis methods used to estimate the extensive
air shower events EUSO-SPB would record are then described in Chapter 4. Finally, we estimate
detection rates of EUSO-SPB for various possible detector efficiencies.

1.1 What are Ultra-High-Energy Cosmic Rays?

Cosmic rays are subatomic particles traveling at high velocities through space. Their observed
energies span 12 orders of magnitude, from $10^8 - 10^{21}$ eV [1], and are the highest energy particles
known to exist. The sources, acceleration mechanisms, and compositions of ultra-high energy
cosmic rays (UHECRs), or cosmic rays of energies above $10^{18}$ eV, are unknown. Possible sources
include active galactic nuclei (AGN), neutron stars, and gamma ray bursts. However the Hillas
plot (Figure 1.1) shows that none of these potential sources can accelerate particles to the energies
we have recorded [2].
1.2 The Cosmic Ray Spectrum

The cosmic ray flux spectrum, ranging from $10^8 – 10^{21}$ eV (Figure 1.2), follows an approximate power law determined empirically to be about $E^{-2.7}$. The spectrum shows a slight steepening at the “knee” at $3 \times 10^{15}$ eV, and levels out slightly at the “ankle“ at $3 \times 10^{18}$ eV. The ankle may represent the transition to cosmic rays of extragalactic origin. The knee represents the upper energy limit of particles caused by supernovae [1].

A third important feature of the cosmic ray spectrum is the sudden steep drop in flux above $5 \times 10^{19}$ eV [1]. This was predicted independently by Greisen, and Zatsepin and Kuzmin and is known as the GZK effect. The GZK effect is due to the interactions between high energy protons and thermal photons from the cosmic microwave background radiation (CMBR). When a proton above an energy threshold of approximately $5 \times 10^{19}$ eV interacts with a CMBR photon, some of
the proton’s energy is lost and converted to mass to create a pion in the following process:

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi$$  \hspace{1cm} (1.1)

This process is repeated for cosmic rays with energy above the interaction threshold until the nucleon falls below the threshold energy, or collides with an object such as the Earth’s atmosphere. The GZK effect implies that any cosmic rays of energy above $5 \times 10^{19} eV$ must originate from a source closer than 50 Mpc, since any non-local cosmic ray with energy above this threshold would fall below this energy by the time it was detected.
1.3 Extensive Air Showers

The flux of UHECR is less than one per square kilometer per century above $10^{20}$ eV. Consequently, direct detection methods are technically impossible. However it is possible to observe the extensive air showers (EAS) that occur in the Earth’s atmosphere. These EAS are cascades of ionized particles and electromagnetic radiation caused by a cosmic ray primary particle interacting with particles in the atmosphere. There are three main components of an EAS: electromagnetic, hadronic and muonic (Figure 1.3). These EAS continue to propagate through the atmosphere until they either reach the Earth’s surface or the energy of the primary particle is dissipated.

Figure 1.3: Illustration of EAS with the three major components [4].

1.4 Ground Based Observatories

Currently, UHECR detectors are all on the ground (Table 1.1). They consist of either surface detectors (SD), fluorescence detectors (FD), or a combination of the two known as a hybrid detector.

The Pierre Auger Observatory (Auger) (Figure 1.4) is currently the largest UHECR observatory in the world with a detection area of approximately 3000 km$^2$ [5]. The SD array of Auger consists of water tanks with photomultiplier tubes inside that record the Cherenkov radiation produced by
Table 1.1: Major cosmic ray experiments

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Detector Type</th>
<th>Detection Area</th>
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<tr>
<td>Pierre Auger Observatory (Argentina)</td>
<td>Hybrid</td>
<td>3000 km²</td>
</tr>
<tr>
<td>Telescope Array Project (Utah, USA)</td>
<td>Hybrid</td>
<td>776 km²</td>
</tr>
<tr>
<td>High Resolution Fly’s Eye (Utah, USA)</td>
<td>FD</td>
<td>100 km² sr</td>
</tr>
<tr>
<td>Akeno Giant Air Shower Array (Japan)</td>
<td>SD</td>
<td>100 km²</td>
</tr>
</tbody>
</table>

EAS secondary particles passing through the tanks at ground level. Although this type of detector can reconstruct the geometry of EAS, values such as energy of the primary particle and \( X_{\text{max}} \), the atmospheric depth of shower maximum, require calibration. A FD setup consists of telescopes that detect ultraviolet (UV) light emitted by cosmic ray interactions with nitrogen molecules, the primary component of the atmosphere. They observe the EAS develop through the atmosphere, not just at ground level and are able to reconstruct the energy and \( X_{\text{max}} \) more directly.

Figure 1.4: The Pierre Auger Observatory, Argentina [5].

A hybrid detector has several advantages by combining the two methods: improving accuracy of geometrical reconstructions by adding the third dimension from the FD, allowing for an improved reconstruction of energy, and providing calibration for the SD array. Although hybrid observatories like Auger are a significant improvement over only SD or FD observatories, ground-based detection systems still have several major limitations. The FD can only operate on clear,
dark nights and is dependent on atmospheric conditions. This results in a FD duty cycle of approximately 14% [5], compared to the near 100% duty cycle of the SD, meaning less frequent hybrid reconstructed events. However the primary limitation of a ground-based observatory lies in the detection area. Even with an extremely large observation area like that of Auger, we only record a few dozen events above $5 \times 10^{19}$ eV per year.

### 1.5 Space Based UHECR Detection

A significant increase in detection aperture may be realized by observing EAS from space. Such a detector would be similar to the FD of the Pierre Auger Observatory, calibrated to detect UV fluorescence light emitted by EAS. A spaced based detector would sacrifice some resolution as well as sensitivity to lower energy cosmic rays due to its distance from the atmosphere. However, a wide FOV would allow for a significant increase in statistics of cosmic rays with energies above $10^{20}$ eV, allowing us to more effectively search for UHECR origins.
The Extreme Universe Space Observatory (EUSO) aboard the Japanese Experiment Module (JEM) is a detector planned for the International Space Station (ISS). Its primary scientific objective is to identify the sources of UHECR and measure their energy spectrum. The secondary objectives include the detection of high energy gamma rays and neutrinos, and studying the galactic magnetic field [6].

The detector principle is similar to a ground-based FD. It is essentially a wide-view large-lens telescope that records the UV fluorescent light emitted by EAS in the atmosphere. JEM-EUSO will record these events looking down on the atmosphere from an altitude of 400 km as opposed to looking up from the ground. This unique approach dramatically increases the detection area. The instrument can either be pointed perpendicular to the Earth’s surface (nadir mode), or tilted to view a greater portion of the atmosphere, resulting in a detection area of 50 to 250 times that of the Pierre Auger Observatory (Figure 2.1) [6]. To obtain a wide FOV, lenses rather than mirrors are used.

2.0.1 JEM-EUSO Detector

JEM-EUSO instrument consists of four major components: optics, focal surface, electronics and physical structure. The optical system, composed of three Fresnel lenses, focus the UV fluorescent light emitted by an EAS onto the focal surface (Figure 2.2). Fresnel lenses were chosen because of their ability to allow for high UV photon transmission and a wide field of view (FOV) while keeping mass to a minimum. The result is a FOV of $\pm 30^\circ$ in each direction for a total of $60^\circ$, with an angular resolution of $0.1^\circ$ [6].

The focal surface of JEM-EUSO is a spherically curved surface 2.3 m in diameter, consisting of approximately 5,000 multi-anode photomultiplier tubes (MAPMTs), each with an 8x8 pixel array. The FS is grouped into 137 photo-detector modules (PDMs), each of which are made up
Figure 2.1: The exposure area of JEM-EUSO in nadir and tilted modes, with detection areas of current ground-based observatories for scale [6].

Figure 2.2: The optical system and focal surface of JEM-EUSO [6].
of nine elementary cells (ECs), consisting of four MAPMTs, for a total of 137 PDMs on the FS (Figure 2.3). The FS electronics then record the signals of the UV-fluorescent photons that pass through the optics in 2.5 $\mu$s bins, or gate time units (GTUs). This signal is then recorded if it matches pre-programmed trigger sequence designed to recognize EAS.

![Focal Surface Structure of JEM-EUSO](image)

Figure 2.3: Focal surface structure of JEM-EUSO [6].

JEM-EUSO also includes an atmospheric monitoring system (AM), consisting of an infrared camera and light detection and ranging device (LIDAR). The AM is responsible for recording atmospheric information such as cloud cover and distribution of aerosol layers in the FOV of the detector. Since the light recorded from EAS propagates through the atmosphere, it is crucial for accurate reconstruction of the primary particle’s energy and arrival direction to understand how the light is attenuated. The entire telescope would then be mounted on the ISS as illustrated in Figure 2.4.
2.1 EUSO-Balloon

The EUSO-Balloon is a pathfinder mission for JEM-EUSO. It is designed to demonstrate the technologies and techniques used on the JEM-EUSO or any other future space-based detection system. Its scientific objectives are threefold:

- to perform a full test of key JEM-EUSO technologies,
- to measure atmospheric and terrestrial UV background components,
- to detect the first EAS while looking down on the atmosphere.

EUSO-Balloon is designed as a smaller version of the JEM-EUSO detector, consisting of one PDM. This prototype detector is attached to a stratospheric balloon and flown at a near space altitude, approximately 40 km. Its two main components are the optical bench and instrument booth (Figure 2.5). The optical bench is composed of two Fresnel lenses resembling the optics of JEM-EUSO. Only two lenses were chosen for the EUSO-Balloon in order to increase UV photon transmittance. The two lenses are both adjustable along the optical axis, providing a total FOV of $\pm 6^\circ$, or $12^\circ$ in total.
Figure 2.5: EUSO-Balloon instrumentation overview [8].

The instrumentation booth is a watertight capsule which contains one of the PDMs used in JEM-EUSO, or 36 MAPMTs organized into nine ECs in a 3x3 grid array. A UV filter is attached to the PDM, which transmits light of wavelengths from 290 - 430 nm. There is also an infrared (IR) camera attached to the outside of the optical bench, similar to the one on JEM-EUSO, responsible for the monitoring of cloud cover and atmospheric properties in the FOV.

2.1.1 First Flight - August 2014

In August, 2014 the EUSO-Balloon flew for the first time in Timmins, Ontario. The main objectives of this flight were to both measure the UV background and test the detector performance. The UV background was measured with the PDM. The IR camera attached to the optical bench was used to detect clouds. In addition to these, a calibrated UV laser was fired across the field of view from a helicopter while the detector was at float altitude (Figure 2.6).

During the approximately four hours of flight time at float altitude the detector successfully recorded multiple laser shots, and measured the UV background radiation over several different
Figure 2.6: Flight diagram of the first EUSO-Balloon flight [9].

Figure 2.7: The EUSO-Balloon flown in Timmins, Ontario.
surfaces. This pioneering flight did not record any EAS because the flight time was too short and a trigger for EAS was not yet implemented.

2.1.2 EUSO-SPB Mission - Long Duration EUSO-Balloon Flight

The EUSO - Super Pressure Balloon (SPB) mission is a plan for a long duration flight of the EUSO-Balloon instrument. The primary objective is to record a cosmic ray EAS from space for the first time in history. It is currently tentatively scheduled for a 2017 launch from New Zealand. EUSO-SPB would include several modifications to EUSO-Balloon. These include the addition of an EAS trigger, and plans for an improved optical system. The focus of this thesis is to estimate the EAS detection rate of the EUSO-SPB for various detector efficiencies.
Simulating EAS for the EUSO-SPB is a two-step process. The first step is to generate the longitudinal profile of particles in the shower as a function of atmospheric depth. This is done using a Monte-Carlo shower generator called CONEX. The JEM-EUSO Offline simulation package uses these profiles to first generate the flux of light along the profiles. It then propagates the light generated along the shower through the atmosphere to the detector.

3.1 CONEX: Monte-Carlo Shower Generator

The CONEX software package applies Monte-Carlo methods and numerical solutions to the cascade equations to generate distributions of the secondary particles in an EAS. The energy deposit, charged particle, and muon longitudinal profiles are generated given a direction, energy, and type of a primary particle. Several different interaction models for these simulations exist. QGSJET-II will be used for the EUSO-SPB simulations in this thesis, as it has been used extensively in cosmic ray physics, with CONEX v4r37. The profiles are written to an output file in a ROOT format [10].

3.1.1 Isotropic Shower Generation

For the purpose of this thesis we assume that cosmic rays are emitted isotropically. In order to simulate an isotropic distribution of EAS, we use CONEX to generate 10,000 proton EAS at the following energy levels: \(10^{17.5}\) eV, \(10^{17.75}\) eV, \(10^{18}\) eV, ..., \(10^{19.25}\) eV, for a total of eight energy bins. This is a slightly wider range of energies than EUSO-SPB is expected to record. The EAS are generated with random zenith and azimuth angles at each energy level.

The CONEX default angle randomization gives a linearly randomized azimuth distribution, and a zenith distribution weighted as a function of \(sin(\theta)cos(\theta)\). The azimuth is randomized linearly because of the spherical symmetry of the sky. For zenith, the \(sin(\theta)\) term is necessary because the
solid angle for some range of zenith angles increases as the zenith increases. The $\cos(\theta)$ term is for a flat detector on the Earth’s surface. However this is not the case for EUSO-SPB, a volume detector viewing the atmosphere from above. The proper isotropic zenith distribution for a volume detector is weighted by $\sin(\theta)$ only.

The CONEX default randomization was modified to produce a distribution weighted by $\sin(\theta)$ (Figure 3.1, right panel). The CONEX source code “CxRoot.cc” was modified as seen in Appendix A. To illustrate this isotropic distribution, we use a spherical projection of 10,000 EAS generated by modified CONEX onto a unit sphere to produce a hemisphere (Figure 3.2).

![Figure 3.1](image.png)

Figure 3.1: Default (left) and modified (right) CONEX zenith distribution from $0^\circ - 80^\circ$.

### 3.2 JEM-EUSO Offline

The JEM-EUSO Offline framework was adapted from the Pierre Auger collaboration to provide the software infrastructure to support the variety of computational tasks required by the JEM-EUSO collaboration. Offline consists of three main parts. The first is a collection of modules used to process data. These modules are assembled and ordered through XML configuration files. The second is the event data model that allows the modules to pass reconstruction or simulation data to each other. The third is the detector description which provides a description of the JEM-EUSO detector, and the atmospheric conditions as a function of time [11]. This structure is illustrated in Figure 3.3.
Figure 3.2: Projection of an isotropic distribution of 10,000 EAS onto a unit sphere.

Figure 3.3: The three main components of the Offline framework [11].
The FSimulation package in Offline uses the charged particle and energy deposit profiles generated in CONEX to simulate the light arriving at the detector's optical aperture over time. The XML module sequence for these simulations is given below:

<!−−A Module sequence for an FD simulation −−>

<module> EventFileReaderOG </module>
<module> EventGeneratorOG </module>
<module> FdSimEventCheckerOG </module>
<module> ShowerLightSimulatorKG </module>
<module> LightAtDiaphragmSimulatorKG </module>
<module> ShowerPhotonGeneratorOG </module>
<module> GroundReflectionSimulatorJG </module>
<module> EventFileExporterOG </module>
<module> UserModule </module>

The EventFileReaderOG reads the simulated shower profiles from the CONEX output file to be used in the simulation. The EventGeneratorOG module then generates the location that the shower core hits the ground. This can be either predefined or random. The FdSimEventCheckerOG checks which fluorescence telescope is active during the simulation. It is a remainder of the Pierre Auger Detector framework that uses multiple telescopes in different locations. The ShowerLightSimulatorKG simulates the fluorescence and Cherenkov light along the shower track. The light is then propagated through the atmosphere to the optical diaphragm of the detector by the LightAtDiaphragmSimulatorKG. The ShowerPhotonGeneratorOG categorizes photons by type and simulates detector response. The detector response is not yet available for JEM-EUSO or EUSO-SPB. The reflected Cherenkov light from the ground is simulated by the GroundReflectionSimulatorJG and propagated to the detector aperture. Finally the EventFileExporterOG organizes the data into individual events.

The UserModule allows the user to run analysis on the event data. To save computation time the UserModule used in this thesis stores only raw event data in a ROOT output file, and can be found in Appendix B. Different analyses are then applied to the ROOT files without rerunning the entire Offline simulation.
3.2.1 EUSO-SPB Simulation Package

The simulations for EUSO-SPB use the same Offline configurations and module sequence as the simulations for JEM-EUSO. There are two differences. The detector altitude is lowered from 400 km to 40 km, and the size of the detector diaphragm is changed to 1 m$^2$. The ROOT files generated by the UserModule contain information regarding each photon at the detector’s optical aperture. Each photon has values for zenith and azimuth angles, type, weight, and time. The zenith and azimuth use the same coordinate system as the detector. From this information we construct the light profiles for the different photon types over time (Figure 3.4, left panel). This is done by multiplying the photon type by it’s weighted value for each time bin (µs), and scaled to GTUs (2.5µs). From these profiles we create a projection of these light profiles on the ground (Figure 3.4, right panel). The program used to generate the light profile and projection onto the ground was modified from the drawEvent.C file written by Brian Vleck.

![Image](image-url)

Figure 3.4: Example of light profile and projection of shower track on ground of raw Offline output for $E = 10^{18.5}$ eV, zenith = 62°, azimuth = 295°.
Figure 3.5: Example of light profile and projection of shower track on ground of raw Offline output for E = 10^{18.5} eV, zenith = 72°, azimuth = 358°.
CHAPTER 4
ESTIMATING EUSO-SPB EAS DETECTION RATE

To estimate the EAS detection rate of EUSO-SPB, we first define the field of view (FOV) of the detector. We then repeatedly use the 10,000 simulated EAS per energy bin in the Offline simulations with random core locations in a large area around the detector. The simulation area should be large enough that we have a chance of recording events with zenith angles up to 80°. In this thesis we use a 150 km radius. If this area is large enough we should observe the frequency of events producing at least one photon in one GTU be close to zero at the 150 km boundary.

Since the EUSO-SPB optics, electronics and trigger are not yet available in Offline, the showers recorded are selected with one of two simple methods. The first requires a minimum level of brightness of the EAS, defined by the total number of photons reaching the optical aperture from within the FOV. The second method invokes a pseudo trigger to the aperture from within the FOV. Five consecutive GTUs must have a minimum number of photons. The thresholds for both methods are determined for various detector efficiencies.

The UHECR differential flux data \([\text{m}^2 \text{sr eV s}^{-1}]\) from the Pierre Auger Observatory Infill Array is scaled by the simulation parameters \[\text{m}^2 \text{sr}\]. This is the flux of UHECR into the simulation area \[(\text{eV s})^{-1}\]. This is multiplied by the percentage of events recorded as a function of energy to get the flux of UHECR detected by EUSO-SPB for various detector efficiencies. The flux of UHECR into EUSO-SPB can be integrated over energy to get the estimated EAS detection rate of EUSO-SPB.

4.1 Constructing the EUSO-SPB Field of View

The FOV of EUSO-SPB is a 6° x 6° square. Projected from 40 km this yields a detection area of 8.4 km x 8.4 km on the ground. The light profile generated by Offline from the EASs simulated in CONEX is the amount of light per GTU reaching the front lens of the detector. There is no constraint on the photon arrival direction. This includes light from portions of the shower track.
inside and outside the FOV (Figure 4.1). Removing the photons that arrive with zenith angles greater than the FOV ($6^\circ$ in the case of EUSO-SPB), yields the light profile of photons that arrive at the detector from within the FOV.

![Diagram of EUSO Balloon and FOV cut](image)

Figure 4.1: Before (left) and after (right) FOV photon cut.

The FOV of EUSO-SPB is square because the PMT camera at the focal surface is square (Figure 4.2). We cannot simply remove all the photons with zenith angles above $6^\circ$. Instead, we define a square FOV by removing the photons with azimuth ($\phi$) and zenith ($\theta$) angles that do not satisfy the inequality in Equation 4.1.

$$\theta \leq 6 + 3(\sqrt{2} - 1) - 3(\sqrt{2} - 1)\cos(2\phi)$$ (4.1)

Equation 4.1 is a sinusoidal function oscillating between $6^\circ$ and $(6 \times \sqrt{2})^\circ$ as a function of $\phi$, with a period of $45^\circ$ that defines a square. The results of this FOV photon cut are demonstrated for the same EAS in Figure 3.4 and Figure 3.5, with the FOV implemented in Figure 4.3 and Figure 4.4.
Figure 4.2: FOV of a square detector at different azimuth angles compared to circular FOV.

Figure 4.3: Example of light profile (left panel) and shower track (right panel) inside detector FOV. $E = 10^{18.5}$ eV, zenith = $62^\circ$, azimuth = $295^\circ$. 
4.2 Core Randomization in Offline Simulations for EUSO-SPB

The 10,000 EAS generated with CONEX at each energy bin were used by Offline to generate light profiles. To increase statistics, the 10,000 event samples were reused with random core locations in a 150 km radius and azimuth angles from $0 \rightarrow 2\pi$. In order to ensure the chance of recording EAS with zenith angles up to $80^\circ$ we need to randomly assign core locations up to a large distance from the center of EUSO-SPB’s FOV. Simulating in too small an area would underestimate the EAS detection rate. Using too large an area would cost only small amounts of additional computational time because Offline skips simulations for events that have no photons arriving at the aperture.

The EAS that have a chance of being recorded have at least one photon in one GTU arrive at the aperture from within the FOV. Figure 4.5 to Figure 4.12 are plots of the core locations of the randomized EAS for all energy levels. The black points are the core locations of all the EAS. The red points highlight the events with at least one photon in one GTU arriving at the aperture from the FOV. These plots illustrate that the event rate of EAS possibly recorded drops to zero at 150 km.
Figure 4.5: 66,000 proton EAS, $10^{17.5}$ eV

Figure 4.6: 60,000 proton EAS, $10^{17.75}$ eV

Figure 4.7: 56,000 proton EAS, $10^{18}$ eV

Figure 4.8: 70,000 proton EAS, $10^{18.25}$ eV
Figure 4.9: 76,000 proton EAS, $10^{18.5} \text{ eV}$

Figure 4.10: 60,000 proton EAS, $10^{18.75} \text{ eV}$

Figure 4.11: 60,000 proton EAS, $10^{19} \text{ eV}$

Figure 4.12: 60,000 proton EAS, $10^{19.25} \text{ eV}$
4.3 EAS Selection Criteria

The Offline framework does not yet include the optics or electronics for EUSO-SPB. Instead we estimate which events would be recorded using two simple algorithms. The first requires a minimum number of total photons from the FOV light profile. The second applies a pseudo trigger. Both methods depend on the following detector specifications:

- quantum efficiency of MAPMTs
- optical point spread function (PSF)
- optical transmission efficiency

The nominal quantum efficiency of the MAPMTs is 25%, meaning one in four photons arriving at the focal surface generates a photoelectron count. The PSF of the Fresnel lenses spreads the incoming light over four pixels. The optical transmission efficiency of the Timmins lenses was approximately 20%. This means with the Timmins flight configuration, for one photoelectron to be recorded per GTU, a minimum of \(4 \times 4 \times 5 = 80\) photons must hit the front lens from inside the FOV per GTU. For EUSO-SPB there are plans to improve the optical transmission with a new set of lenses. The new transmission efficiency has yet to be determined, but is expected to be 40%.

To record at least one photoelectron over 10 GTUs with a 20% optical transmission efficiency we need \((4 \times 4 \times 5) \times 10 = 800\) total photons. At 60% we need \((4 \times 4 \times 1.6) \times 10 = 256\) total photons. We can select events with total number of photons above thresholds of 1000, 2000, 3000, 4000, and 5000. This range is chosen to mimic the requirements of several different optical transmission.

We can also select events recorded with a pseudo trigger. The real trigger is programmed to recognize EAS events based on photoelectron signals that match a specific criteria. We can mimic the complex nature of the trigger by requiring five consecutive GTUs with at least five photoelectrons per GTU. To simulate optical transmission efficiencies of 20%, 40%, 60% and 80% we can require photon thresholds of 100, 200, 300 and 400 photons per GTU, for five consecutive GTUs.
4.4 EUSO-SPB EAS Detection Rate from Overall Shower Brightness

To estimate the EUSO-SPB EAS detection rate we first select which simulated events are recorded. We require a minimum amount of photons at the aperture in the amounts of 1000, 2000, 3000, 4000, or 5000. Figure 4.13 through Figure 4.18 illustrate the core locations of all simulated EAS of $10^{18.5}$ eV. The black points are events below the photon threshold and the red are events above the photon threshold. As expected, the number of EAS above threshold decreases as photon threshold increases. The full set of results for energies of $10^{17.5}$ eV to $10^{19.25}$ eV are shown in Appendix C.

![Core Locations - 495 Recorded](image1)

![Core Locations - 138 Recorded](image2)

**Figure 4.13:** 76,000 EAS, $10^{18.5}$ eV, 1 photon threshold

**Figure 4.14:** 76,000 EAS, $10^{18.5}$ eV, 1000 photon threshold
Figure 4.15: 76,000 EAS, $10^{18.5}$ eV, 2000 photon threshold

Figure 4.16: 76,000 EAS, $10^{18.5}$ eV, 3000 photon threshold

Figure 4.17: 76,000 EAS, $10^{18.5}$ eV, 4000 photon threshold

Figure 4.18: 76,000 EAS, $10^{18.5}$ eV, 5000 photon threshold
From this data we calculate the percent of events recorded by dividing the number recorded by the total simulated in Offline for each energy bin (Figure 4.19). These points are fitted with a three parameter quadratic fit as a function of $log_{10}(E)$. Figure 4.19 also illustrates the energy threshold for the various photon thresholds. With the addition of the UV background these energy thresholds should increase. The EAS are simulated in a geometric aperture of $\pi \times (150\text{km})^2 \times 2\pi \int_0^{80^\circ} \sin(\theta)d\theta = 3.68 \times 10^5 \text{ km}^2 \text{ sr}$, with zenith angles range from $0^\circ \rightarrow 80^\circ$. We then scale the UHECR differential flux data taken by the Pierre Auger Observatory [12] (Figure 4.20) by the simulation geometric aperture (Figure 4.21). The scaled UHECR flux is then multiplied by fitted percent recorded functions evaluated at each energy bin. The result is the flux of UHECR detected by EUSO-SPB. The different curves in Figure 4.22 correspond to different photon thresholds. Figure 4.22 also illustrates the energy thresholds for the various photon thresholds.

![Image of graph showing percent events recorded from 1 to 5000 photon thresholds with fits.](image)

Figure 4.19: Percent of EAS recorded in simulation area as a function of energy.
Figure 4.20: Pierre Auger infill UHECR flux [12].

Figure 4.21: UHECR flux from Figure 4.20 in a 150 km$^2$ radius circle with zenith up to 80°.
Figure 4.22: UHECR differential flux recorded by EUSO-SPB for various detector sensitivities.

<table>
<thead>
<tr>
<th>Photon Threshold</th>
<th>Events/hr</th>
<th>Events/night</th>
<th>Events/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.9 ± 0.4</td>
<td>567. ± 4.</td>
<td>3971. ± 25.</td>
</tr>
<tr>
<td>1000</td>
<td>4.5 ± 0.01</td>
<td>35.8 ± 0.1</td>
<td>250.7 ± 0.8</td>
</tr>
<tr>
<td>2000</td>
<td>1. ± 0.05</td>
<td>8.1 ± 0.4</td>
<td>56.8 ± 2.7</td>
</tr>
<tr>
<td>3000</td>
<td>0.27 ± 0.03</td>
<td>2.2 ± 0.2</td>
<td>15.3 ± 1.6</td>
</tr>
<tr>
<td>4000</td>
<td>0.14 ± 0.02</td>
<td>1.2 ± 0.2</td>
<td>8.1 ± 1.2</td>
</tr>
<tr>
<td>5000</td>
<td>0.085 ± 0.02</td>
<td>0.7 ± 0.1</td>
<td>4.8 ± 0.9</td>
</tr>
</tbody>
</table>

Figure 4.23: EUSO-SPB detection rate calculated with various EAS brightness thresholds, assuming 8 hour nights of continuous detection.
The UHECR flux recorded by EUSO-SPB is numerically integrated over energy for the various photon thresholds to get the estimated detection rates. Figure 4.23 shows the detection rate according to photon threshold. The highlighted rows are the thresholds thought to be realistic for the EUSO-SPB flight. With this event selection method we estimate between 8 and 15 events recorded per week, assuming seven eight hour nights of continuous detection in ideal conditions. Figure 4.24 and Figure 4.25 show the distribution of events recorded over energy for the 3000 and 4000 photon thresholds.

![Events/hr per Energy Bin @ 3000 photon Threshold](image)

Figure 4.24: Distribution of events over energy for 3000 photon threshold

4.5 EUSO-SPB EAS Detection Rate with Pseudo Trigger

The EUSO-SPB detection rate can also be calculated by applying the method outlined in Section 4.4, but by selecting EAS with a pseudo trigger. The pseudo trigger is described in Section 4.3. It requires recorded events to have five consecutive GTUs, each with greater than 100, 200, 300 and 400 photons. Figure 4.26 to Figure 4.29 show the core locations of the events recorded with the pseudo trigger for the same generated events used in Section 4.4. The same plots for all
energy levels can be found in Appendix C.

From this data we calculate the new percent of simulated events above each photon threshold for each energy level (Figure 4.30). These values are again fit to a 3 parameter quadratic function as a function of $\log_{10}(E)$. These new percentage functions can be multiplied by the scaled UHECR flux (Figure 4.21) to yield the flux of UHECR recorded by EUSO-SPB (Figure 4.31). This is again integrated over energy to give the EUSO-SPB detection rate for various detector efficiencies (Figure 4.32). The highlighted row represents a realistic 300 photons/GTU threshold which corresponds to a 40% optical transmission efficiency. With the pseudo trigger we estimate 10 events per week assuming seven eight hour nights of continuous detection in ideal conditions, for a 40%*25% = 10% overall detector efficiency. Figure 4.33 shows the distribution of events recorded per hour over energy with the pseudo trigger threshold of 300 photons/GTU.
Figure 4.26: 76,000 EAS, $10^{18.5}$ eV, 100 photon/GTU threshold

Figure 4.27: 76,000 EAS, $10^{18.5}$ eV, 200 photon/GTU threshold

Figure 4.28: 76,000 EAS, $10^{18.5}$ eV, 300 photon/GTU threshold

Figure 4.29: 76,000 EAS, $10^{18.5}$ eV, 400 photon/GTU threshold
Figure 4.30: Percent of EAS recorded in simulation area as a function of energy.

Figure 4.31: UHECR differential flux recorded by EUSO-SPB for various pseudo trigger thresholds.
<table>
<thead>
<tr>
<th>Photon Threshold</th>
<th>Events/hr</th>
<th>Events/night</th>
<th>Events/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.3 ± 0.005</td>
<td>18.1 ± 0.04</td>
<td>127. ± 0.3</td>
</tr>
<tr>
<td>200</td>
<td>0.43 ± 0.02</td>
<td>3.4 ± 0.1</td>
<td>24. ± 1.</td>
</tr>
<tr>
<td>300</td>
<td>0.18 ± 0.01</td>
<td>1.4 ± 0.08</td>
<td>10. ± 0.6</td>
</tr>
<tr>
<td>400</td>
<td>0.089 ± 0.008</td>
<td>0.71 ± 0.07</td>
<td>5. ± 0.5</td>
</tr>
</tbody>
</table>

Figure 4.32: EUSO-SPB detection rate calculated with pseudo trigger, assuming 8 hour nights of continuous detection.

Figure 4.33: Distribution of events over energy with pseudo trigger for 300 photons/GTU threshold.
4.6 Recorded EAS Events with $X_{\text{max}}$ in FOV

Sections 4.4 and 4.5 provide estimates for the number of EAS events EUSO-SPB will record. However not all of these events can be accurately reconstructed for energy. The energy deposited by the EAS as a function of atmospheric depth is directly proportional to the light emitted along the shower track, which is calculated from the light at the aperture of the detector. The energy deposit function is fit to the well known Gaisser-Hillas function:

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

(4.2)

The energy deposit function is integrated over atmospheric depth to yield the energy of the primary particle. Since $X_{\text{max}}$ is an important fit parameter in the Gaisser-Hillas fit, events without $X_{\text{max}}$ in FOV will have poor fits, and a poor energy reconstruction.

Due to the narrow FOV of the EUSO-SPB detector, many events will be recorded without $X_{\text{max}}$ in the FOV. $X_{\text{max}}$ is defined as the depth in the EAS with the greatest number of particles. It is also the depth of the shower producing the most light. We can estimate if $X_{\text{max}}$ is recorded by analyzing the light profile behavior around the brightest GTU. For an event to have $X_{\text{max}}$ in FOV, we require the number of photons in the three GTUs around the brightest GTU to decrease, and remain above a nontrivial threshold. The threshold is set to 20% of the brightest GTU. Several GTUs less than this threshold indicates the light profile is cut off by the FOV. Figure 4.34 through Figure 4.38 show the core locations of the same events recorded with the pseudo trigger with a threshold of 300 photons/GTU and events recorded with $X_{\text{max}}$ in FOV. Figure 4.39 illustrates these values as a percentage of events recorded with $X_{\text{max}}$ in FOV. Although the error is large due to low statistics, the percentage of events recorded with $X_{\text{max}}$ clearly decreases as energy increases. Since $X_{\text{max}}$ is the brightest depth in the EAS, events near the energy threshold are more likely to require $X_{\text{max}}$ in the FOV to be recorded. At higher energies, other parts of the event will be bright enough to be recorded without $X_{\text{max}}$ in FOV, meaning a lower percentage of events recorded with $X_{\text{max}}$.

The flux of events recorded by EUSO-SPB (Figure 4.31) multiplied by the percent of events recorded with $X_{\text{max}}$ is integrated over energy to yield the estimated detection rate of EAS with
$X_{max}$ in FOV by EUSO-SPB. This result for a pseudo trigger of 300 photons/GTU threshold is illustrated in Figure 4.40 to be approximately four events per week. Since recording $X_{max}$ would be an excellent indicator that an EAS was recorded, this rate is an important factor in determining flight time of the EUSO-SPB mission.

Figure 4.34: 70,000 EAS, $10^{18.25}$ eV, events with $X_{max}$ in FOV

Figure 4.35: 76,000 EAS, $10^{18.5}$ eV, events with $X_{max}$ in FOV
Figure 4.36: 60,000 EAS, $10^{18.75}$ eV, events with $X_{\text{max}}$ in FOV

Figure 4.37: 60,000 EAS, $10^{19}$ eV, events with $X_{\text{max}}$ in FOV

Figure 4.38: 60,000 EAS, $10^{19.25}$ eV, events with $X_{\text{max}}$ in FOV
Figure 4.39: Percent of events recorded with pseudo trigger of 300 photons/GTU threshold with $X_{\text{max}}$ in FOV.

<table>
<thead>
<tr>
<th>Photon Threshold</th>
<th>Events/hr</th>
<th>Events/night</th>
<th>Events/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 photons/GTU</td>
<td>0.07</td>
<td>0.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Figure 4.40: EUSO-SPB detection rate of EAS with $X_{\text{max}}$ in FOV calculated with pseudo trigger.
Figure 4.41: Example of recorded EAS event with $X_{\text{max}}$ inside FOV. $E = 10^{18.75}$, zenith = 44°, azimuth = 46°.

Figure 4.42: Example of recorded EAS event with $X_{\text{max}}$ inside FOV. $E = 10^{18.75}$, zenith = 27°, azimuth = 336°.
CHAPTER 5
CONCLUSION

The EUSO - Super Pressure Balloon mission is a plan for a long duration flight of the EUSO - Balloon instrument. It’s primary scientific objective is to record several UHECR EAS from above for the first time in history. A successful mission would be an excellent indicator to the possible success of the JEM-EUSO mission.

The number of cosmic ray EASs recorded by EUSO-SPB depends on two main factors: overall detector efficiency, and the duration of the flight. The overall detector efficiency depends on both the quantum efficiency of the MAPMTs, and the optical efficiency, or transmission rate of photons through the lens system. Although the detector optics for EUSO-SPB have not been finalized, the new optical transmission efficiency is expected to be 40%. The EAS detection rate of EUSO-SPB has been estimated for various possible detector efficiencies. This was calculated by simulating a large number of EAS in a geometrical aperture around the FOV. Events recorded were selected with either a threshold on the total number of photons at the aperture from within the FOV, or with a pseudo trigger. The detection rate is calculated by integrating over energy the percent of events recorded at each energy level multiplied by the UHECR differential flux in the simulation’s geometrical aperture.

In one week of detection, assuming seven nights of eight hours of detection time per night, and an optical transmission efficiency of 40%, EUSO-SPB should record ten events with five consecutive GTUs above 300 photons per GTU. Of the 10 events recorded in one week, approximately four of them would include $X_{\text{max}}$ in the FOV. It is important to consider the events with $X_{\text{max}}$ recorded for several reasons. A recorded event with $X_{\text{max}}$ will allow for an approximate energy reconstruction of the cosmic ray. It would also be an excellent indicator that the recorded event is indeed a cosmic ray EAS.
Although the simulations in this thesis do not include the UV background or trigger, and uses ideal atmospheric and detector conditions, it does provide a baseline estimate for EUSO-SPB’s EAS detection rate. However, many factors including the UV background, adverse weather, and non-ideal detector response will lower this detection rate. The combination of these factors with the requirement of recording $X_{\text{max}}$ to both confirm EAS detection and allow energy reconstruction, suggests that a one week flight time is not sufficient to guarantee the recording of multiple cosmic ray EAS. This thesis also illustrates that small improvements in the optical transmission efficiency yield significant increases in EUSO-SPB’s EAS detection rate.

During the final edits of this thesis, NASA launched the first super pressure balloon from Wanaka, New Zealand. As of April 9, 2015 it had been at float altitude for 12 days and had nearly circumnavigated the southern ocean. The target length for this flight is 100 days. We note that a period of 18 days during the March dark moon period contains about 120 hours of potential observing time. This corresponds to a possible measurement of 8 EAS with the 300 photons/GTU trigger and $X_{\text{max}}$. 
REFERENCES CITED


APPENDIX A - CONEX - CXROOT.CC MODIFICATIONS

Modifications to GetTheta() function of CxRoot.cc CONEX source file:

```cpp
/******************************************************************************
 * GetTheta() : dice a zenith angle from isotropic flux
 * *
 * returns theta [deg.]
 ********************************************************************************/

double CxRoot::GetTheta(double i)
{ const

  if (fTheta1 == fTheta2)
    return fTheta1;
  else {
    double tmp, fT1, fT2;
    if (fTheta1 > fTheta2)
    {
      tmp=fTheta1;
      fT1= fTheta2;
      fT2= tmp;
    }
    else
    {
      fT1 = fTheta1;
      fT2 = fTheta2;
    }
  const double degrad = 180./TMath::Pi();
  const double c1 = cos(fT1/degrad);
  const double c2 = cos(fT2/degrad);
  const double u = fConeInterface->ConexRandom(i)*(c2-c1)+c1;
  return acos(u)*degrad;
}
```
# include "UserModule.h"
# include <util/ErrorLogger.h>
# include <evt/Event.h>
# include <fevt/FEvent.h>
# include <fevt/Eye.h>
# include <fevt/TelescopeSimData.h>
# include <fevt/Telescope.h>
# include <evt/ShowerSimData.h>
# include <det/Detector.h>
# include <fdet/FDetector.h>
# include <fdet/Eye.h>

// Allows local definitions of coordinates
#include <fwk/LocalCoordinateSystem.h>

// Commonly used points are hardcoded into a registry to avoid
// having to repeatedly create the locations
#include <fwk/CoordinateSystemRegistry.h>

// Tools
#include <utl/JemEusoUnits.h>
#include <utl/TimeStamp.h>
#include <utl/UTCDateTime.h>

// Geometry Related Headers
#include <utl/ReferenceEllipsoid.h>
#include <utl/CoordinateSystemPtr.h>
#include <utl/UTMPoint.h>
#include <utl/Point.h>
#include <utl/AxialVector.h>
#include <utl/Vector.h>
#include <utl/TransformationMatrix.h>

// Use of the boost c++ package to extract
// coordinates from vectors
#include <boost/tuple/tuple.hpp>
#include <boost/tuple/tuple_comparison.hpp>
#include <boost/tuple/tuple_io.hpp>

#include <det/Detector.h>
#include <fdet/FDetector.h>
#include <fdet/Eye.h>
#include <fdet/Telescope.h>
#include <fdet/Camera.h>

#include <TTTree.h>
#include <TFFile.h>

#include <iostream>

using namespace fwk;
using namespace utl;
using namespace fevt;
using namespace det;
using namespace std;
using namespace boost;

UserModule::UserModule() {
}

UserModule::~UserModule()
{
}

VModule::ResultFlag
UserModule::Init()
{
    // Create output TFile and TTrees
    fOutFile = new TFFile("fSimulation.root", "RECREATE");
    fTree = new TTTree("Photons","">
    fTree->Branch("nPhoton", &fNPhotons, "nPhoton/i");
    fTree->Branch("theta", fTheta, "theta[nPhoton]/D");
    fTree->Branch("phi", fPhi, "phi[nPhoton]/D");
    fTree->Branch("type", fType, "type[nPhoton]/I");
    fTree->Branch("weight", fWeight, "weight[nPhoton]/D");
    fTree->Branch("time", fTime, "time[nPhoton]/D");

    // Branches with general shower info
    fTree->Branch("energy", &fEnergy, "energy/D");
    fTree->Branch("zenith", &fZenith, "zenith/D");
    fTree->Branch("azimuth", &fAzimuth, "azimuth/D");

    fTree->Branch("xcore", &x, "x/D");
    fTree->Branch("ycore", &y, "y/D");
    fTree->Branch("zcore", &z, "z/D");
}
return eSuccess;
}

VModule::ResultFlag
UserModule::Run(evt::Event& event)
{

// Begin additions to UserModule.cc added by J. Fenn, 05/2015

Detector& detector = Detector::GetInstance();
const fdet::FDetector& detFD = detector.GetFDetector();

// Get event data
FEvent& fEvent = event.GetFEvent();

// Get event parameters from FEvent class
INFO( "UserModule->Passing on shower info: ENERGY, ZENITH, AZIMUTH, CORE LOCATION" );
const evt::ShowerSimData& SimDat = event.GetSimShower();
fEnergy = log10( SimDat.GetEnergy() );
fAzimuth = SimDat.GetAzimuth();
fZenith = SimDat.GetZenith();

// From the fDetector class setup a coordinate system (CS) at Eye-center
CoordinateSystemPtr jemeusoCS = detFD.GetEye("BALLOON EUSO").GetEyeCoordinateSystem();
// Acquire core location in eye-centric CS
Point detectorPOSITION = detFD.GetEye("BALLOON EUSO").GetPosition();
cout << "Detector Position = " << detectorPOSITION.GetCoordinates( jemeusoCS ) << endl;

// Create a point with the shower position
Point showerPOSITION = SimDat.GetPosition();
Triple showercore = showerPOSITION.GetCoordinates();
cout << "Shower Position = " << showercore << endl;
boost::tie(x, y, z) = showercore;
cout << "x = " << x << ", y = " << y << ", z = " << z << endl;
cout << "Shower core assigned = " << x << ", " << y << endl;

////// End code additions by J. Fenn

unsigned int currPhoton = 0;
for (FEvent::EyeIterator iEye = fEvent.EyesBegin(ComponentSelector::eInDAQ);
iEye != fEvent.EyesEnd(ComponentSelector::eInDAQ) ; ++iEye) 
{
for (Eye::TelescopeIterator iTel = iEye->TelescopesBegin(
    ComponentSelector::eInDAQ);
    iTel != iEye->TelescopesEnd<ComponentSelector::eInDAQ); ++iTel)
{

    const fdet::Telescope& detTel = detFD.GetTelescope(iTel);
    const CoordinateSystemPtr telCS = detTel.
    GetTelescopeCoordinateSystem();

    const TelescopeSimData& telSim = iTel->GetSimData();

    for (TelescopeSimData::ConstPhotonIterator iPhoton =
    telSim.PhotonsBegin(); iPhoton != telSim.PhotonsEnd(); ++
    iPhoton) {
        if (currPhoton < fMaxPhoton) {
            const Vector& direction = iPhoton->GetDirection();
            fTheta[currPhoton] = direction.GetTheta(telCS) / degree;
            fPhi[currPhoton] = direction.GetPhi(telCS) / degree;
            fType[currPhoton] = iPhoton->GetSource();
            fWeight[currPhoton] = iPhoton->GetWeight();
            fTime[currPhoton] = iPhoton->GetTime().GetNanoSecond();
            ++currPhoton;
        }
        else {
            WARNING("photons in TTree truncated!");
            break;
        }
    }
}

fNPhotons = currPhoton;
fTree->Fill();
return eSuccess;
}

VModule::ResultFlag
UserModule::Finish()
{

    fOutFile->Write();
    fOutFile->Close();

    return eSuccess;
}
C.1 Simulation results for total photon count thresholds for all energy bins

Figure C.1: 66,000 EAS, $10^{17.5}$ eV, 1 photon threshold

Figure C.2: 66,000 EAS, $10^{17.5}$ eV, 1000 photon threshold
Figure C.3: 66,000 EAS, $10^{17.75} \text{ eV}$, 1 photon threshold

Figure C.4: 66,000 EAS, $10^{17.75} \text{ eV}$, 1000 photon threshold

Figure C.5: 66,000 EAS, $10^{17.75} \text{ eV}$, 2000 photon threshold
Figure C.6: 56,000 EAS, $10^{18}$ eV, 1 photon

Figure C.7: 56,000 EAS, $10^{18}$ eV, 1000 photon threshold

Figure C.8: 56,000 EAS, $10^{18}$ eV, 2000 photon threshold

Figure C.9: 56,000 EAS, $10^{18}$ eV, 3000 photon threshold
Figure C.10: 70,000 EAS, $10^{18.25}$ eV, 1 photon

Figure C.11: 70,000 EAS, $10^{18.25}$ eV, 1000 photon threshold

Figure C.12: 70,000 EAS, $10^{18.25}$ eV, 2000 photon threshold

Figure C.13: 70,000 EAS, $10^{18.25}$ eV, 3000 photon threshold
Figure C.14: 76,000 EAS, $10^{18.5}$ eV, 1 photon threshold

Figure C.15: 76,000 EAS, $10^{18.5}$ eV, 1000 photon threshold

Figure C.16: 76,000 EAS, $10^{18.5}$ eV, 2000 photon threshold

Figure C.17: 76,000 EAS, $10^{18.5}$ eV, 3000 photon threshold
Figure C.18: 76,000 EAS, $10^{18.5}$ eV, 4000 photon threshold

Figure C.19: 76,000 EAS, $10^{18.5}$ eV, 5000 photon threshold

Figure C.20: 60,000 EAS, $10^{18.75}$ eV, 1 photon threshold

Figure C.21: 60,000 EAS, $10^{18.75}$ eV, 1000 photon threshold
Figure C.22: 60,000 EAS, $10^{18.75}$ eV, 2000 photon threshold

Figure C.23: 60,000 EAS, $10^{18.75}$ eV, 3000 photon threshold

Figure C.24: 60,000 EAS, $10^{18.75}$ eV, 4000 photon threshold

Figure C.25: 60,000 EAS, $10^{18.75}$ eV, 5000 photon threshold
Figure C.26: 60,000 EAS, $10^{19}$ eV, 1 photon threshold

Figure C.27: 60,000 EAS, $10^{19}$ eV, 1000 photon threshold

Figure C.28: 60,000 EAS, $10^{19}$ eV, 2000 photon threshold

Figure C.29: 60,000 EAS, $10^{19}$ eV, 3000 photon threshold
Figure C.30: 60,000 EAS, $10^{19}$ eV, 4000 photon threshold

Figure C.31: 60,000 EAS, $10^{19}$ eV, 5000 photon threshold

Figure C.32: 60,000 EAS, $10^{19.25}$ eV, 1 photon threshold

Figure C.33: 60,000 EAS, $10^{19.25}$ eV, 1000 photon threshold
Figure C.34: 60,000 EAS, $10^{19.25} \text{ eV}$, 2000 photon threshold

Figure C.35: 60,000 EAS, $10^{19.25} \text{ eV}$, 3000 photon threshold
Figure C.36: 60,000 EAS, $10^{19.25}$ eV, 2000 photon threshold

Figure C.37: 60,000 EAS, $10^{19.25}$ eV, 3000 photon threshold
C.2 Simulation results with pseudo trigger for all energy bins

Figure C.38: 60,000 EAS, $10^{17.5}$ eV, 100 photon/GTU threshold

Figure C.39: 60,000 EAS, $10^{17.5}$ eV, 200 photon/GTU threshold
Figure C.40: 60,000 EAS, $10^{17.75}$ eV, 100 photon/GTU threshold

Figure C.41: 60,000 EAS, $10^{17.75}$ eV, 200 photon/GTU threshold

Figure C.42: 60,000 EAS, $10^{18}$ eV, 100 photon/GTU threshold

Figure C.43: 60,000 EAS, $10^{18}$ eV, 200 photon/GTU threshold
Figure C.44: 60,000 EAS, $10^{18.25}$ eV, 100 photon/GTU threshold

Figure C.45: 60,000 EAS, $10^{18.25}$ eV, 200 photon/GTU threshold

Figure C.46: 60,000 EAS, $10^{18.25}$ eV, 300 photon/GTU threshold

Figure C.47: 60,000 EAS, $10^{18.25}$ eV, 400 photon/GTU threshold
Figure C.48: 60,000 EAS, $10^{18.5}$ eV, 100 photon/GTU threshold

Figure C.49: 60,000 EAS, $10^{18.5}$ eV, 200 photon/GTU threshold

Figure C.50: 60,000 EAS, $10^{18.5}$ eV, 300 photon/GTU threshold

Figure C.51: 60,000 EAS, $10^{18.5}$ eV, 400 photon/GTU threshold
Figure C.52: 60,000 EAS, $10^{18.75}$ eV, 100 photon/GTU threshold

Figure C.53: 60,000 EAS, $10^{18.75}$ eV, 200 photon/GTU threshold

Figure C.54: 60,000 EAS, $10^{18.75}$ eV, 300 photon/GTU threshold

Figure C.55: 60,000 EAS, $10^{18.75}$ eV, 400 photon/GTU threshold
Figure C.56: 60,000 EAS, $10^{19}$ eV, 100 photon/GTU threshold

Figure C.57: 60,000 EAS, $10^{19}$ eV, 200 photon/GTU threshold

Figure C.58: 60,000 EAS, $10^{19}$ eV, 300 photon/GTU threshold

Figure C.59: 60,000 EAS, $10^{19}$ eV, 400 photon/GTU threshold
Figure C.60: 60,000 EAS, $10^{19.25}$ eV, 100 photont/GTU threshold

Figure C.61: 60,000 EAS, $10^{19.25}$ eV, 200 photon/GTU threshold

Figure C.62: 60,000 EAS, $10^{19.25}$ eV, 300 photon/GTU threshold

Figure C.63: 60,000 EAS, $10^{19.25}$ eV, 400 photon/GTU threshold