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ABSTRACT

We describe the design and fabrication of a prototype Global Light System (GLS) laser station for the JEM-EUSO project. The GLS will consist of a network of ground-based Ultraviolet (UV) light-emitting diodes (LEDs) and steered lasers to monitor and calibrate the cosmic ray detector planned for install on the International Space Station (ISS). The GLS units will generate optical signatures in the atmosphere that are comparable to tracks from cosmic ray extensive air showers (EASs). Unlike an EAS, the number, time, energy, location and direction (for lasers) of GLS events can be specified as JEM-EUSO passes 400 km overhead.

Laser tracks from the GLS prototype will be recorded by prototype detectors in ground-to-ground tests. Distant tracks with low angular speed are of particular interest because these are the types of EAS tracks that will be measured by JEM-EUSO. To do these ground-to-ground tests, the prototype detectors will need to measure the laser through the atmosphere at low elevation viewing angles. The beam energy can be adjusted from 1 to 90 mJ to compensate for this additional atmospheric attenuation. The frequency-tripled Nd:YAG laser produces 355 nm (7 ns pulse) light. This wavelength is near the center of the UV EAS fluorescence spectrum. The system is housed in a utility trailer that can be transported by a small truck for domestic campaigns or shipped in an industry standard 20 foot container for global deployment. In operation mode, the laser platform inside the trailer is isolated mechanically to maintain beam pointing accuracy. A retractable two stage steering head can point in any direction above the horizon. A slip ring eliminates cable wrap problems. The GLS prototype will be used to test the EUSO-TA detector and will also be used in preflight tests of the EUSO-balloon payload planned for a super pressure balloon mission.
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LIST OF SYMBOLS

Angle between target plate and distant target ........................................... $\beta$

Angle between target plate and true north .............................................. $\alpha$

Bearing angle with respect to true north (clockwise is positive) .............. $\gamma$

Latitude of GLS prototype ........................................................................ $\phi_1$

Longitude of GLS prototype ....................................................................... $\lambda_1$

Latitude of distant target/EUSO-TA ..................................................... $\phi_2$

Longitude of distant target/EUSO-TA ..................................................... $\lambda_2$

Distance between EUSO-TA and GLS prototype .................................. $\Delta d$

Time between time 1 and time 2 ............................................................. $\Delta t$

Length between EUSO-TA and light pulse at time 1 .............................. $L_1$

Length between EUSO-TA and light pulse at time 2 .............................. $L_2$

Elevation angle of light track at time 1 ............................................... $\theta_{t1}$

Elevation angle of light track at time 2 ............................................... $\theta_{t2}$
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AMT</td>
<td>Atmospheric Monitoring Telescope</td>
</tr>
<tr>
<td>ARCADE</td>
<td>Atmospheric Research for Climate and Astroparticle DEtection</td>
</tr>
<tr>
<td>CLF</td>
<td>Central Laser Facility</td>
</tr>
<tr>
<td>CFR</td>
<td>Compact Folded Resonator</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>CMB</td>
<td>Cosmic Microwave Background</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EASs</td>
<td>Extensive Air Showers</td>
</tr>
<tr>
<td>EECR</td>
<td>Extreme Energy Cosmic Ray</td>
</tr>
<tr>
<td>EUSO</td>
<td>Extreme Universe Space Observatory</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>FD</td>
<td>Fluorescence Detector</td>
</tr>
<tr>
<td>GTU</td>
<td>Gate Time Unit</td>
</tr>
<tr>
<td>GLS</td>
<td>Global Light System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GZK</td>
<td>Greisen, Zatsepin, and Kuzmin</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>JEM</td>
<td>Japanese Experiment Module</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
</tr>
</tbody>
</table>
Multi-Anode Photomultiplier .......................................................... MAPMT
National Institute of Standards................................................. NIST
Off the Shelf ............................................................................. OTS
Photo-Detector Module............................................................... PDM
Root Mean Square ................................................................. RMS
Single-Board Computer ......................................................... SBC
Super Pressure Balloon ......................................................... SPB
Surface Detector ................................................................. SD
Telescope Array ................................................................. TA
Third Harmonic Generation .................................................. THG
Ultra-High Energy Cosmic Ray ........................................... UHECR
Ultraviolet ............................................................................ UV
Wavelength Purity Separation ............................................... WSP
Yttrium Aluminum Garnet ......................................................... YAG
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This work would not be possible without the dedication of many people. First and foremost, I would like to thank my advisor, Dr. Lawrence Wiencke for his insight, guidance, and giving me the opportunity to work with him. I would also like to thank the physics department Machine Shop and all of the members of the Astroparticle Physics group at the Colorado School of Mines. All of your input and efforts have been paramount to the success of this project. A special thanks to the EUSO-TA group who operated the detector for our field campaigns. Finally, a big thank you to my family and wife, whose support helped me get through this.
CHAPTER 1
INTRODUCTION, BACKGROUND AND MOTIVATION

The purpose of this thesis is to describe the design, operation, and performance of the Global Light System (GLS) Laser Station prototype as well as provide some of the light track plots of the scattered ultraviolet (UV) light detected by the EUSO-TA prototype detector. Chapter 1 begins with a brief introduction and motivation for cosmic rays and detection. Chapter 2 provides a justification for the GLS prototype and its application to the JEM-EUSO collaboration. The design and performance of the GLS prototype are provided in Chapter 3, followed by test locations and plots of the light tracks in Chapter 4. Finally, a summary and future outlook of the system is provided in Chapter 5.

1.1 Sources of Cosmic Rays

Cosmic rays are highly-energetic particles, mainly protons, alpha particles, a few heavy nuclei, and trace amounts of particles such as electrons, positrons and antiprotons that travel at relativistic speeds. The most energetic of these particles are designated into two categories: Ultra-High Energy Cosmic rays (UHECRs) and Extreme Energy Cosmic Rays (EECRs). UHECRs have an energy above $10^{18}$ eV and EECRs have an energy above $10^{19}$ eV.

Their physical source, acceleration mechanism, and composition elude us to this day. Plausible sources range from active galactic nuclei to radio galaxies to gamma ray bursts and neutron stars [1]. A. M. Hillas constructed a simple plot (Figure 1.1) of possible cosmic ray accelerator sites by their known magnetic field strengths and size. Objects below the solid diagonal line are not expected to accelerate protons above $10^{20}$ eV (the dashed diagonal line corresponds to iron of energy above $10^{20}$ eV). From the Hillas plot, it is suggested that the the sources of UHECRs are either extremely magnetic, but condensed, or very large and weakly magnetic. Additionally, the arrival direction of the particles with energies above
$3 \times 10^{19}$ eV suggest that if the particles originate within our galaxy, their trajectories have been deflected by an implausible magnetic field and they would be mainly heavy nuclei. Protons, on the other hand, would originate outside of our galaxy [2].

Figure 1.1: Hillas plot of plausible cosmic ray acceleration sites [3].

Shortly after the discovery of cosmic microwave background (CMB) by Wilson and Penzias [4], Greisen, Zatsepin, and Kuzmin (GZK) proposed a theoretical upper limit for energetic protons detected. Greisen, Zatsepin and Kuzmin theorized protons with energy greater than $6 \times 10^{19}$ eV, known as the GZK cutoff, could interact with CMB photons. The energetically favored processes are:

\begin{align*}
\gamma_{\text{CMB}} + p &\rightarrow \Delta^+ \rightarrow p + \pi^0 \\
\gamma_{\text{CMB}} + p &\rightarrow \Delta^+ \rightarrow n + \pi^0
\end{align*}
From these interactions, the proton typically loses $\sim 20\%$ of its energy. Additionally, for the protons to interact with CMB photons, they must originate farther than the mean interaction length (greater than $\sim 100$ Mpc) which is dependent on photon density and cross-sectional area. Heavy nuclei also interact with CMB photons via photonuclear disintegration to create smaller nuclei via the emission of nucleons. This process is repeated until the energy of the particle has fallen below the threshold energy [1, 5]. The lack of a correlation with the galactic plane in data observed to date [6] and the observation of a suppression in the energy spectrum suggest that the high energy sources are outside our galaxy, but within 100 Mpc which is small compared to the size of the universe (roughly 5,000 Mpc radius).

### 1.2 Extensive Air Showers and UHECR Detection

When protons and heavy nuclei of UHECRs strike the atmosphere, they interact with particles in the atmosphere which generates a nuclear cascade, as shown in Figure 1.2.

![Figure 1.2: Diagram of extensive air shower generated by primaries of cosmic rays [7].](image_url)
There are three main results of a nucleonic cascade: The muonic, hadronic, and electromagnetic components. The muonic components decay from charged pions and typically reach the ground, but only when they’re highly relativistic. The hadronic component of the shower decays into pions and other fragments. The electromagnetic component of the shower is a cascade event where a highly-energetic photon or muon generates an electron-positron pair, each of which generate a photon. The process is repeated until the energy of the shower has fallen below the critical energy, the energy threshold for pair production.

The flux of EECRs is less than $1 \text{ particle} \frac{\text{per km}^2 \times \text{century}}{}$. The world’s largest detector, Pierre Auger Observatory, has a detection area of $\sim 3,000 \text{ km}^2$ but detects just 30 EECRs per year. Discovering the sources of EECRs will require significantly more events. The area of detection or duration of detection must increase by 50-300 times to increase the number of EECRs detected to a few thousand events per year. Since it is not plausible to create detectors with areas of 3,000 km$^2$ and fly them above the atmosphere for years at a time, the characteristics of the primary particles are inferred from measurements of the generation of secondary particles, extensive air showers (EASs). These secondary particles are measured with ground detectors that encompass large areas. A common type of detector used to measure the emitted UV light from the interactions of the charged particles with atmospheric nitrogen is a fluorescence detector (FD). FDs record the UV light reflected from a grid of mirrors focused onto a camera. Surface detectors (SD), which are installed in an array, measure the energy of the particles generated in the EAS either by scintillation of acrylic strips [8], or by Cherenkov light generated by particles passing through tanks of ultra-pure water [9]. When FDs and SDs are used together as complimentary detectors, they create a ”hybrid detector”. Hybrid detectors can provide measurement redundancy and a more accurate geometrical reconstruction. The FDs, which are positioned to overlook the surface array, provides a longitudinal profile as the nitrogen fluorescence propagates through the atmosphere. From the measured UV light, it is possible to measure the total energy deposited in the atmosphere by the EAS which is approximately equal to the energy of the cosmic ray. The array of
SDs detect the amount of Cherenkov light emitted from the charged particles which allows scientist to provide a redundant energy calculation of the cosmic ray. Additionally, the trajectory of the cosmic ray can be calculated by use of the difference in detection times at different tanks [10]. Even though local hybrid detectors are improving the statistical uncertainty of EECRs, a detector with a larger detection area is required to identify the sources of EECRs.
The Extreme Universe Space Observatory on board the Japanese Experimental Module (JEM-EUSO) is an experiment planned for the International Space Station (ISS) to discover the source(s) of EECRs. Additional goals include measuring different spectra, better understand ultra-high energy neutrinos and photons, as well as fundamental physics studies. JEM-EUSO will look down at Earth and record the flashes of UV light that are emitted by EASs as they propagate through the atmosphere. A prototype ground-based detector, EUSO-TA, is operating at the Telescope Array (TA) site at Black Rock Mesa west of Delta, Utah. Just as the GLS is envisioned to direct scattered UV light across the field of view (FOV) of JEM-EUSO to validate it, the GLS prototype will do the same to test the performance of EUSO-TA. The characteristics of the light track such as number, time, energy, and pointing angle are known and used to calibrate the detectors.

### 2.1 JEM-EUSO Detector

The JEM-EUSO detector will orbit the earth every 90 minutes at an altitude of $\sim 400$ km. The moving footprint of the detector FOV will be $\sim 140,000$ km$^2$ when pointed straight down and $\sim 750,000$ km$^2$ when titled at $\sim 30^\circ$ with respect to vertical (Figure 2.1).

The JEM-EUSO detector features a telescope that houses three Fresnel lenses that focus UV light from a $\pm 30^\circ$ FOV onto a focal surface (Figure 2.2). The focal surface consists of 137 photo-detector modules (PDMs). These PDMs are pixelized UV cameras that detect the individual photons from the fluorescence of the EAS. Each PDM is composed of 36 multi-anode photomultipliers (MAPMTs). Each MAPMT comprises of 64 pixels (grid of $8 \times 8$) which results in 2,304 pixels per PDM or $\sim 300,000$ pixels for the entire focal surface. Signals are accumulated in 2.5 $\mu$s time units (Gate Time Unit - GTU). When the pattern of
Figure 2.1: Artist rendition of the observation of UV light from an EAS by JEM-EUSO (left) [11]. Comparison of detection areas between JEM-EUSO and Pierre Auger (right) [12].

When an EAS candidate is recognized, a trigger condition is satisfied and the data for that event is written to a disk for download to earth for analysis.

Figure 2.2: Main components of the JEM-EUSO telescope [13].

2.2 EUSO-TA prototype Detector

EUSO-TA is a ground-based prototype detector of JEM-EUSO. The prototype features two Fresnel lenses that focus UV light from a $\pm5.25^\circ$ FOV onto a single PDM. EUSO-TA
shares its location with the FD for the TA experiment located at Black Rock Mesa, near Delta, Utah. The orientation of the prototype is such that its FOV lies inside the FOV of the FD-TA and covers a few SDs (Figure 2.3). EUSO-TA can utilize the existing Central Laser Facility (CLF), Light Detection and Ranging (LIDAR) instrument and electron beam source for absolute calibration and minimizing systematic uncertainties. EUSO-TA can compare detections with the FD-TA as a cross calibration. With the addition of EUSO-TA, shower coincidence can be measured and compared when events cross both FOVs of the FD and EUSO-TA (Figure 2.4).

Figure 2.3: EUSO-TA (front) and FD-TA station (back) [14].

2.3 Motivation for the GLS prototype

To validate and support the operation of EUSO-TA, a laser station that can steer a pulsed UV laser in any direction at various energies to simulate atmospheric attenuations is required. Directing the scattered light from a pulsed UV laser beam across the FOV of a cosmic ray fluorescence detector is an established technique first used at Fly’s Eye [15] and continued at HiRes [16], Telescope Array [17], and the Pierre Auger Observatory [18].
Figure 2.4: SD array at Black Rock Mesa. The EUSO-TA FOV (green) lies within the FD-TA FOV (red) [14].
Data from these experiments [19, 20, 21, 22] have demonstrated that the intensity of the light produced from EASs are comparable to that of the scattered light from lasers propagating through the atmosphere (Figure 2.5).

![Figure 2.5: Laser tracks compared to EASs measured by Pierre Auger Observatory [23].](image)

Extensive air showers superimposed on laser light profiles have shown that near vertical 50 EeV showers that are 16 km from the detector are optically equivalent to a 5 mJ laser fired vertically 27 km from the detector [23]. The calibration lasers at the Pierre Auger CLF emit 7 mJ at full power which is optically equivalent to an air shower of roughly $10^{19}$ eV [24]. These energies are not sufficient to test the upper limit of EUSO-TA. The beam energy of the GLS prototype laser can be varied from $<1$ to 90 mJ, via an internal attenuator. With an energy range of scattered UV light that is comparable from well below the GZK cutoff to beyond the edge of energy spectrum (Figure 2.6 and Figure 2.7), the detection range of EUSO-TA can be tested.

The GLS prototype laser emits a wavelength of 355 nm UV light. This specific wavelength was chosen because it is near the middle of the air fluorescence spectrum that is emitted by EASs in the atmosphere (Figure 2.8). At this wavelength, the scattering mechanism is described by molecular (Rayleigh) scattering since the wavelength (nm range) of the UV
Figure 2.6: Overview of cosmic ray spectrum [1].
Figure 2.7: Cosmic ray spectrum zoomed in at UHECR energy range [25].
light is much larger than the size of nitrogen and oxygen molecules (pm range). Additionally, Rayleigh scattering is a dominantly elastic collision and therefore the wavelength of the scattered light is not altered by collisions with the air molecules.

Figure 2.8: The wavelength of the GLS prototype laser indicated on the Fluorescence Spectrum of electrons in air [26].
CHAPTER 3
THE GLS LASER STATION PROTOTYPE

The GLS prototype (Figure 3.1) is a portable steered laser system that generates light tracks with an optical equivalence to EASs of energy $10^{19} - 10^{21}$ eV. The beam can be pointed in any direction above the horizon. The prototype is housed in a utility trailer that can be hauled by a truck for national campaigns or shipped in a standard 20 foot shipping container for international campaigns. Outrigger jacks level the optics table and steering assembly and mechanically isolate these components from the trailer. The trailer can be shaken by wind or by people walking inside without affecting the beam direction.

3.1 Laser System

The system features a frequency-tripled, pulsed, Nd:Yttrium Aluminum Garnet (YAG), 90 mJ laser [27]. A portable power supply circulates coolant (distilled water) through the laser head to prevent overheating and damage during operation (Figure 3.2). The laser can be controlled from a handheld remote or from the command prompt of a computer.

The laser head utilizes a doubler and tripler oven, located in the third harmonic generation (THG) module, that generates 532 nm light from the incident 1064 nm light. The output light is then mixed with residual 1064 nm light to generate 355 nm light. To ensure that pure 355 nm light exits the laser head, a wavelength purity separation module (WSP) containing four dichroic mirrors is used to remove and dump existing 1064 nm and 532 nm light (Figure 3.3). The vertically polarized light beam that exits the laser head is approximately 5.07 mm in diameter and diverges at 2.61 mrad (See Figure A.1 in Appendix A). An internal attenuator provides a range of beam energy of two orders of magnitude. The laser pulses at a maximum repetition rate of 20 Hz.
Figure 3.1: 3D model of the GLS prototype (top) and the fabricated GLS prototype (bottom). The system is shown in Operation Mode with the outrigger jacks in position.
Figure 3.2: Laser head (left), handheld remote (center) and integrated cooling and power/control unit (right).

Figure 3.3: Components of the laser head.
3.2 Optics

Optics are located inside the optics enclosure and inside the steering head (Figure 3.4 and Figure 3.5).

![Figure 3.4: Propagation of the laser beam inside the optics enclosure.](image)

### 3.2.1 Optics Enclosure

The emitted beam from the laser head is reflected by two dichroic mirrors that reflect the 355 nm light and transmit 1064 and 532 nm light. Next, a UV window reflects approximately 5% of the beam into an energy probe ("Energy Probe 1" in Figure 3.4). A radiometer wired to the energy probe, converts detected analog signals from the probe into a corresponding energy that is used to monitor the shot-to-shot output of the laser and to determine the energy calibration of the system (See Section 3.5.1). The remaining portion of the beam is sent through a depolarizer and reflected up into the steering mechanism and aimed into the
Figure 3.5: Laser propagation traveling through and out of the steering head to the sky.
The pickoff probe is a large area (4.9 cm$^2$) pyroelectric detector. The cavity of the detector is constructed with an angled surface that directs unabsorbed photons deeper into the cavity. The photon must reflect three times before it is reflected away from the probe which maximizes the absorption of the beam (Figure 3.6).

![Figure 3.6: Diagram of the pyroelectric energy probe. Dimensions are in inches (millimeters) [28].](image)

The incident photons heat up the sensor material which alters the polarization of the atoms in the sensor. This change in polarization causes the resistivity of the sensor material to change which causes a voltage to develop across the sensor that is amplified and sent to the radiometer. The sensor can detect a large range of pulsed energies but cannot record large energy densities (maximum intensity of 0.4 J/cm$^2$) without damaging the sensor [28].

### 3.2.2 Steering Head Optics

A dual band (355 nm and 633 nm) mirror installed on a 3D axis mount below the steering head directs the laser beam from the optics enclosure up into the steering head. In the steering head, a dual band mirror mounted in each rotation stage (azimuth and elevation...
angles) directs the beam through the center of the rotation axis and out into the sky. The mirrors are installed on a 3D axis mount to provide a constant reflection angle of 45°. The second wavelength (633 nm) corresponds to a 633 nm self-leveling laser that is used to align the optics of the steering head. The self-leveling laser is a safer option than the UV laser for beam alignment. At the exit of the second stage of the steering head, a window passes UV light and minimizes the amount of dust or other debris that can contaminate or damage the system and mirrors in the steering head.

For absolute energy calibration, a second energy probe is mounted temporarily to the steering head to measure the energy of the entire beam after it has passed through all of the optics of the system (Refer to Section 3.5.1). This energy probe is also a pyroelectric detector but contains a diffuser (Figure 3.7).

Figure 3.7: Diagram of the pyroelectric energy probe. Dimensions are in millimeters [29].
3.3 Steering Head

The beam steering system features a periscope-style design with two orthogonal rotary stages for independent control of the azimuth and elevation pointing angles (Figure 3.8 and Figure 3.11). Three stepper motors control the motion of this subsystem. Two motors are mounted on rotary stages that turn the steering assemblies (Figure 3.8). The third motor raises the steering head above the trailer roof during operation (Figure 3.12). Each stepper motor is accurate to approximately two steps which corresponds to $0.0278^\circ$ for beam steering. Although the rotary stages are supplied with a magnetic switch that indicates the "home" position of the rotary stages, the accuracy of this switch is not adequate for our application (Figure 3.9). To evade this problem, custom mechanical proximity switches with pointed metallic levers have been installed on the housing of each motor. A rounded bolt has been installed on the rotator of each rotary table. When the stage rotates to home position, the bolt will press the metallic lever and activate the proximity switch (Figure 3.10). The new proximity switches for the azimuth and elevation rotary stages are activated for approximately 250 motor steps ($3.125^\circ$) and 225 steps ($2.8125^\circ$), $\pm$ 1 step ($0.0278^\circ$). The angle of activation can be decreased or increased by increasing or decreasing the inclination of the point on the lever.

Figure 3.8: Rotary stage used to rotate each stage of the steering head assembly [30].

The platform on which the steering head is mounted can be raised and lowered by a stepper motor that drives a ball screw assembly (Figure 3.11).
Figure 3.9: Integrated home switch.

Figure 3.10: Image of the steering head with focus on the stepper motors (left). Details of the custom home switch in the activated position (right).
Figure 3.11: Assembly of steering head and cage in down position.
Figure 3.12: Assembly of steering head and cage elevated through the roof of the trailer for operation. The output of the steering assembly now protrudes above the trailer roof and hatch.
The stepper motors can be controlled with strings of ASCII commands through a serial port on the motor controller or by pushing buttons on the controller. Commands are sent to the motor controller which are interpreted and sent in the form of pulses to the respective motor for the desired duration, velocity, and acceleration. Upon completion of the command from the controller, power supplied to the electromagnets of the motor is interrupted and the rotor is not held in place anymore and allowed to rotate freely. For example, if the previous command from the controller was to raise the steering head above the roof of the trailer, the platform would lower back into the trailer after the command is completed due to the weight of the steering head. This acts as a safety precaution in the event that power to the system should fail. The steering head will lower back inside the trailer automatically. To keep the steering head lifted during operation, a control system is needed. A possible design could use a mechanical brake on a disc rotor (See Figure B.3 of Appendix B).

To prevent the cabling from the elevation (second) stage stepper motor from wrapping around the steering head and potentially causing damage, a slip ring has been integrated into the steering head assembly (Figure 3.11). The slip ring uses interior rotating conducting brushes and rings. A brush and ring connect external stationary wiring to external wiring that can be rotated (Figure 3.13).

3.4 Operation of System

The off the shelf (OTS) single-board computer (SBC) is the central component to the GLS prototype laser station. It communicates and acquires data during operation. The operator can access the single-board via a wireless or wired network connection to the router that is connected to the computer (Figure 3.14). The laser, radiometers, and motor controllers communicate with the SBC, which can set the laser attenuation and frequency, specify and record absolute time the laser is fired, and direct the steering head to any pointing direction desired. To accurately determine a standard global time during operation, a global positioning system (GPS) antenna is mounted on top of the trailer and plugged into the SBC. An internal custom GPS receiver module (GPSY) [32] in the SBC provides the location.
based on the data acquired from the antenna. Pulses that trigger the laser are programmed and generated from this GPS module. Timing of the pulses are specified in a coordinated universal time (UTC) with an accuracy of 20 ns. Each shot of the laser can now be accurately timed and synchronized with the timing of the detector to ensure that each shot of the laser is accurately measured and not mistaken for a cosmic or unknown event. The custom GPS clock is a proven device that has been also tested with the National Institute of Standards (NIST) [32]. Modules of this design are used to synchronize the laser stations with the detectors at Pierre Auger for calibration.

The SBC records the energy of every laser pulse from the radiometer that is connected to the pickoff probe. The energy and statistics of the laser shots are recorded in a log file which is located on a removable flash disk. The code used to control the system is a modified version of existing code used by the CLF currently in operation at Pierre Auger.

The number of steps between the azimuth internal zero position and the direction of north must be specified in a configuration file that is read by the program. The system uses true north as a reference point for rotation of the azimuth stage. To point the steering head in a specific direction, the program requires the input of two angles, in units of degrees.
Figure 3.14: Top-level view of the GLS prototype.

The first angle corresponds to the azimuth angle of the steering head. The second angle corresponds to the elevation, angle relative to horizontal, of the UV window located on the second stage of the steering head. Input angles of $0^\circ$ and $0^\circ$ rotates the azimuth (first) stage until the second stage is perpendicular to true north. The second stage is rotated until the UV window is pointing horizontal as shown in Figure 3.15. Rotation of the first stage, when looking down at the steering head, is positive when the stage rotates counter-clockwise and vice versa. Rotation of the second stage, when looking perpendicular to the pointing direction, is positive when the stage rotates counter-clockwise and vice versa (Figure 3.15).

When the main program is started, a log file is opened. The system writes a record of all operations to this file. The user may enter comments that are recorded to this file. Initializing the radiometers is required to establish the serial communication links to them, and to set their recording parameters. Additionally, the steering head must be initialized and zeroed as well. This process is done by sending both stages of the steering head to their limit switches for reference and then to the pointing angle of $(0^\circ,0^\circ)$. The system also automatically detects and initializes the GPSY module when the GPS antenna is connected.
to the SBC. With the system initialized, the laser is now ready to be fired.

When a firing command is sent from the user to the SBC, a digital trigger signal is sent to the pickoff radiometer and to the flashlamp input of the laser. The flashlamp is the laser pumping portion of the system that excites the atoms of the Nd:YAG rod through energy transfer of a flashlamp. The trigger pulse from the pickoff radiometer is sent to the Q-switch input of the laser which causes the Q-switch to trigger. When the Q-switch is triggered, the photons generated by stimulated emission of excited atoms are released from the laser as a vertically polarized 7 ns pulse (Figure 3.16). The Q-switch is a voltage-controlled waveplate, known as a Pockel cell. When a voltage is applied to the waveplate, it allows light to pass through of a specific polarization. Both the flashlamp and Q-switch are pulsed and can be set at a user-specified frequency. Refer to Appendix B (Figure B.2) for the block diagram of the laser system. While the laser is firing, the energy and percent error of every shot is recorded and displayed. Every 25 shots, the average and root mean square (RMS) are recorded and displayed.
3.5 Calibration of System

Prior to embarking on a field campaign, all of the optics are aligned, calibration of both energy and polarization are measured, and total system checks are performed in the lab where environmental conditions can be controlled and optimized. After the completion of lab calibration, the optics which are not considered delicate (dichroic mirrors and dual band mirrors) are secured in place with hardware and mounts. The delicate items (energy probes, depolarizer, and laser head) are removed from the system and packed in pelican cases. Their opto-mechanical supports are left in place with hardware and mounts. Additionally, neoprene blocks mounted between the table and frame (Refer to Section 3.6.2) dampen vibrations and maintain internal alignment. In the field, the delicate optics are unpacked and mounted to their stands and the internal alignment is checked. Both the energy calibration and polarization are remeasured. Finally, the direction of true north is determined using a theodolite (Figure 3.26) and entered into the configuration file on the SBC.

3.5.1 Energy Calibration

The energy that exits the steering head must be known accurately to test reconstructions of the scattered UV light as measured by the detector. A ratio of the beam energy exiting the system...
steering head and the energy measured by the pickoff probe must be determined for reference during operation. The ratio of the measured energies from the two probes is expressed as:

$$\text{Calibration Factor} = \frac{\text{Energy Probe 2}}{\text{Energy Probe 1}}$$  \hspace{1cm} (3.1)

During operation, the measurements of the pickoff probe are multiplied by the calibration factor to yield the beam energy sent to the sky. The exit energy can be measured in two configurations. The exit of the steering head can be pointed down on to the support platform where an energy probe is placed (Energy Probe 2, see dashed black line in Figure 3.14). For a more robust energy calibration, Energy Probe 2 is mounted to an apparatus that attaches to the second stage of the steering head (Figure 3.17). The steering head can be pointed in any direction with the probe in place to measure the beam energy. A diffuser incorporated in Energy Probe 2 disperses the beam to permit measurement up to full energy without damaging the detector.

The energy calibration sequence (SBC program is reading commands from a list in a file to perform these steps) automatically runs through the full attenuation range of the laser energy in 5% attenuation steps and fires (and measures) 100 shots of the laser, where every 25th shot is averaged.

Figure 3.18 - Figure 3.20 are plots of the calibration measurements, with a repetition rate of 4 Hz, prior to the September 2015 campaign. Each data point represents the average of 25 shots. Using Equation 3.1, the energy calibration factor is calculated (Figure 3.19). To determine the stability of the energy calibration over the energy range of the laser, the calibration factor is normalized over the full range of laser energy (Figure 3.20). Over an energy range of 0.4 mJ to 90 mJ, the calibration factor is stable to within 5%. In both Figure 3.19 and Figure 3.20, there are noticeable curves to the data (red) which had filters placed in front of the pickoff probe. This can be accounted for by the fact that the energy transmitted through the filters was near the low limit of the detection range of the probe. This is confirmed by the stability of the data (green), without filters placed in front of the pickoff probe, at the same energies.
Figure 3.17: Apparatus that supports the energy probe in front of the UV window on the steering head assembly. The propagation of the beam is shown in blue.
Figure 3.18: Measurement of the pickoff probe (Energy Probe 1) versus the sky energy (Energy Probe 2) both without (green) and with (red) filters place in front of the pickoff probe.
Figure 3.19: Calibration factor both without (green) and with (red) filters place in front of the pickoff probe.

Figure 3.20: Normalized Calibration Factor.
After the energy calibration is measured and analyzed in the lab, a similar procedure is carried out in the field. Once at the test site and after the delicate items have been installed in their supports, the energy calibration is measured. Energy Probe 2 is placed in the apparatus and positioned at the exit of the steering head assembly. The calibration sequence is executed from the SBC and the 25 shot average is used to calculate the calibration factor. The calibration factor is compared to the one performed in the lab to check for similarity.

3.5.2 Polarization Calibration

A depolarizer is an optic that is used to randomize the polarization of incident light. A depolarizer is favorable in our application because the randomly polarized light can be modeled as isotropic about the beam direction for a given scattering angle in the atmosphere. The depolarizer used in this system is a wedge quartz-quartz depolarizer. Two quartz wedged discs, one twice as thick as the other, are bonded together with a metallic ring spaced between them. Quartz is a birefringent material that has a refractive index dependent upon the polarization and direction of incident light. Additionally, each wedge has a fast axis that is separated by 45°. The angular difference of the two axis causes a phase shift of the light and retards a component of the polarization. The resultant polarization from the features of the depolarizer is a spatially dependent polarized beam, or a pseudo-random polarized beam [33].

To measure the randomized polarization, a polarizing beam splitting cube is placed between the exit of the steering head and the sky energy (Energy Probe 2). The apparatus that mounts Energy Probe 2 to the steering head contains provisions for installing the cube (Figure 3.21).

The beam splitting cube transmits one component of polarization onto Energy Probe 2 and reflects the other. The cube is rotated a full revolution while the energy variation is measured from the radiometer that is wired to Energy Probe 2. The depolarizer is then rotated in small, 0.1°, increments until the changes in measured calibration factor are minimized over a full rotation of the cube. If the beam is randomly polarized, the cube will
Figure 3.21: Apparatus that supports the energy probe and polarizing cube in front of the UV window on the steering head assembly. The propagation of the beam is shown in blue.
split the beam 50/50 and the energy measured by the probe will be constant as the cube is rotated. Figure 3.22(a) is a plot from a recent polarization test during the September 2015 campaign. As the polarization cube is rotated, the calibration factor varies. Figure 3.22(b) is a plot of the normalized polarization which should approach 1 when the beam is completely randomly polarized. In this example, a depolarization factor of $\pm 4^\circ$ was achieved. Once the fluctuation of energy is minimized over a rotation of the polarizing cube, the angle of the depolarizer is noted and a set screw is tightened to lock the orientation of the depolarizer.

A quarter waveplate can be used (and was used during the March and May 2015 campaigns) in place of a depolarizer. It circularly polarizes the light equally in the plane perpendicular to the propagation path but is less favorable because the polarization changes more with changes in steered beam direction.

When the laser system is in the field, the orientation of the depolarizer is not adjusted. The level of randomized polarization cannot be achieved in the field because the depolarization changes with minute adjustments of the depolarizer. This is difficult with sometimes harsh and unpredictable conditions of the field. Instead, the polarization of the beam is verified and recorded. The same apparatus is used to mount both the Energy Probe 2 and rotating polarizing cube at the exit of the steering head. The polarizing cube is rotated one full revolution and the deviation of energy measured from Energy Probe 2 is recorded and plotted to determine the amount that the beam is randomly polarized.

3.5.3 Mirror Alignment

In the lab, the optics from both the optics enclosure and the steering head must be aligned to ensure accurate beam point directions. The optics table and steering head are leveled prior to alignment. Additionally, the assumption is made that the steering head assembly has been created with machine precision quality. The optics in the enclosure are aligned first, followed by the optics of the steering head. Finally, the alignment of the entire system is tested.
(a) Polarization Calibration.

(b) Normalized Polarization Calibration.

Figure 3.22: Polarization of Laser System
In the optics enclosure, at the first dichroic mirror (Figure 3.4), a lens cap with a paper target is placed on the optic and the UV laser is fired onto the target. The optic is adjusted until the beam strikes the center of the target. For repeatability, an indexer is placed on the stem of the optic to reference the height of the optic should it ever be removed. The lens cap is moved to the next optic downstream of the laser and the process of adjusting the optic until the beam strikes the center of the target is repeated until all optics of the enclosure have been aligned and indexed.

Next, the dual band mirrors of the steering head and the dual band mirror under the steering head must be aligned such that they are reflecting the beam through the center of the steering head and out to the sky perpendicular to the UV window of the second stage. When the self-leveling laser is required, it is placed on a lazy susan apparatus that elevates the laser above the first dual band mirror (Figure 3.23). The apparatus that supports the lazy susan fixture contains indexers which allow the laser and fixture to be removed and installed in the same position. The lazy susan is used to center the beam of the self-leveling laser onto the center of the axis of rotation of the steering head.

The following is a procedure to align the self-leveling laser, the dual band mirror under the steering head and the dual band mirror located in the first (azimuth) stage of the steering head.

1. Aligning the self-leveling laser

   (a) Place self-leveling laser on lazy susan apparatus.

   (b) Place paper target centered on the dual band mirror located in the first stage.

   (c) Shift the lazy susan assembly until beam is centered on target.

      i. Spin the lazy susan to ensure center of the beam spots is centered on target.

      ii. Slide the lazy susan assembly as need and repeat previous step.

   (d) Lock indexers on the support that elevates the lazy susan apparatus.

   (e) The self-leveling laser is now centered under the steering head axis of rotation.
Figure 3.23: Self-leveling laser attached to lazy susan rotary table that is supported above the dual band mirror. Vertical laser propagation shown in blue.
2. First dual band mirror (located on optics table under steering head)

(a) Place paper target centered on first dual band mirror.

(b) Adjust the fixture until self-leveling laser spot is centered on the target.

(c) Verify that the UV laser beam hits center of the target as well.

   i. Adjust the optics in the enclosure until UV beam hits center of the target.

(d) Direct the self-leveling laser through the steering head to a target 10 m away and rotate the laser. Generally, a circle is created.

(e) Using the UV laser, adjust the dual band mirror on the table until the UV spot is centered on the circle created by the self-leveling laser.

(f) The first dual band mirror is now aligned.

(g) Tighten the set screws to each axis of the 3D mount.

(h) Recheck the alignment of the mirror to ensure tightening of the set screws did not alter the alignment.

3. Second dual band mirror (located in first stage of steering head)

(a) Remove second stage steering head cap and third dual band mirror.

(b) Place machined laser (pointed out) in opening of second stage rotary table.

(c) Rotate machined laser and mark trajectory on target placed at least 10 m away (this ensures a long lever arm for the laser to increase accuracy).

(d) If the trajectory of the rotated laser forms a circle, the center of the circle is the center of axis of rotation for the second stage rotary table. If not, there will be one spot on the target as the laser is rotated.

(e) Remove machined laser and install self-leveling laser.
(f) With the self-leveling laser, adjust the mirror until the beam is centered on the mark made from the machined laser (or the center of the circle formed from the rotated machined laser).

(g) Remove the self-leveling laser and verify that the UV laser is centered on the mark made from the self-leveling laser.

(h) The second dual band mirror is now aligned.

(i) Tighten the set screws to each axis of the 2D mount (only 2 of the 3 set screws are accessible in the fixture).

(j) Recheck the alignment of the mirror to ensure tightening of the set screws did not alter the alignment.

(k) Install third dual band mirror.

To align the final optic (third dual band mirror located in the elevation stage of the steering head), a test is performed on the steering head with the self-leveling laser installed. The test rotates each stage by 180°. If the third dual band mirror is aligned at a constant reflection angle of 45°, the beam spots before and after the rotations are spaced specifically apart on a horizontal line. The horizontal distance between the two spots must be equal to horizontal distance that the UV window traverses during the two rotations (Dimension ‘d’ in Figure 3.24).

If the mirror is not aligned, adjustments are made to the mirror and the 180-180 test is performed. This process is repeated until the third dual band mirror is aligned. After tightening the set screws, the self-leveling laser is removed and the UV laser is used with the 180-180 test. For repeatability, the 180-180 test is performed at multiple azimuth angles. On average, 0.2° beam pointing accuracy can be achieved.

In the field, the final 180-180 alignment of the mirrors is performed. A quick check of the alignment is performed with the laser in the trailer and pointed horizontal and forward. A 180-180 test is performed and the beam spots are marked and measured on sheets of paper.
Figure 3.24: (Top view) Diagram of 180-180 test used for steering head mirror alignment.

supported by clipboards. This provides a rough estimate as to if the mirrors are still aligned or if they must be realigned. After nightfall, the trailer doors are opened and another 180-180 test is performed with the steering head pointed out the back of the trailer. The test is performed with the self-leveling laser and a target (Figure 3.25) located at least 30 m away from the trailer. The longer distance allows the system to be aligned to within $\sim 0.1^\circ$-$0.2^\circ$.

Figure 3.25: Custom alignment plate used to check alignment of the steering head in the field.
3.5.4 Determining Azimuth Direction

Since the GLS prototype uses true north as its zero azimuth angle, the angle between true north and the detector (azimuth direction) must be determined at each test site. With determining the azimuth angle, the geometry between the GLS prototype and detector is known. A measurement from a compass is not precise enough to fulfill the requirement of a pointing accuracy of 0.1°. Refer to Figure 3.26.

The procedure of determining true north is performed with the use of a theodolite and portable GPS antenna. The theodolite is positioned above the elevated steering head and centered on the azimuth rotational axis. The theodolite is pointed in the same direction as the steering head using a target and the self-leveling laser. The correction of the offset between beam exit and azimuth rotation axis is accounted for. This azimuth direction is set...
to 0°. Next, measure the angle to a distant target (e.g. mountain tops) of which the GPS coordinates are known (β in Figure 3.26). Using the known coordinates of the distant target and the GLS prototype, the bearing angle is calculated with the following equation [34],

\[
\gamma = \tan^{-1}\left(\frac{\sin(\Delta \lambda) \cdot \cos(\phi_2)}{\cos(\phi_1) \cdot \sin(\phi_2) - \sin(\phi_1) \cdot \cos(\phi_2) \cdot \cos(\Delta \lambda)}\right)
\]

Where \( \gamma \) is the bearing angle measured clockwise from true north, \( \Delta \lambda = \lambda_2 - \lambda_1 \) is the longitudinal difference of the distant target and the laser, and \( \phi_1 \) and \( \phi_2 \) are the latitudes of the laser and distant target, respectively. The measured angle of the target plate and distant target, \( \beta \), is subtracted from the bearing angle, \( \gamma \). This angle, (\( \alpha \) in Figure 3.26), is used to point the steering head to true north. A second distant target can be added to the procedure as a redundant measurement for true north. This data is used to set true north in the configuration file of the SBC. Using the known GPS coordinates of the GLS prototype and EUSO-TA, the bearing angle is calculated and the geometry is fully understood.

3.6 Housing Infrastructure

The laser system is housed in a utility trailer that has been modified with a sliding hatch to allow the elevated steering head to be steered in any direction above the horizon. The system can be transformed between two modes. Transport mode is used to move the system into the field and between field locations (Figure 3.27). At a field site, the system is unhooked from the truck and transformed into Operation Mode (Figure 3.28). The GLS prototype features an internal power distribution system that is powered from internal batteries or an external source.

3.6.1 Power Distribution System

The GLS prototype is powered from two 12 volt 256 amp-hour batteries, or a 120 volt single phase alternating current (AC) source such as a gasoline-driven generator or a 15 amp wall outlet. Each power source is input into and monitored by a small power distribution and inverter system (Figure B.1 in Appendix B for Power Block Diagram). The distribution
Figure 3.27: 3D model of the GLS prototype (left) and the fabricated GLS prototype (right) in Transport mode.

Figure 3.28: 3D model of the GLS prototype (left) and the fabricated GLS prototype (right) in Operation mode. The steering head is protruding above the roof and hatch.
system supplies both AC and direct current (DC) power to the system. AC power is supplied to a 15 amp outlet that powers the laser components and DC power is supplied to actuators for the motorized hatch and ventilation fan (Figure 3.29). There are multiple powering scenarios with this distribution system. The inverter can be bypassed and AC power from the generator (or outside power) is sent directly to the lights and laser components. The system can invert AC to DC to charge batteries and/or power the DC components, such as the actuators for the hatch or ventilation fan, while providing AC power to the laser system components. If the generator fails, DC power from the batteries is inverted to provide AC power to the laser components and lighting. The inverter monitors the charge of the battery as well as temperature of the lug terminals on the batteries to apply the appropriate charge method (trickle, floating, full charge, etc.) to charge the batteries efficiently and safely. Additionally, the maximum amount of charge current can be set to prevent the system from drawing excess current and tripping the input circuit breakers. Both DC and AC circuit breakers are installed in the distribution system to protect the components, and the inverter from power surges and other anomalies from the input power.

3.6.2 Transport Mode

In Transport Mode, the optical table frame is secured to the trailer frame by a redundant arrangement of bolts and supports. Neoprene blocks are secured between the optics table and the table frame to dampen vibration (Figure 3.30).

With the optics table secured to the table frame via cushioning, the table frame is also coupled to the trailer frame via custom u-channels (Figure 3.31). Additionally, guide tabs are attached to the outside of the trailer frame to ensure that the table frame remains aligned when the laser system is decoupled in Operation Mode.

3.6.3 Operation Mode

When the trailer reaches its destination, the system is transformed into Operation Mode (Figure 3.28). Four outrigger jack assemblies are installed at the rear corners and both sides
Figure 3.29: Power distribution panel and inverter system for GLS prototype.
Figure 3.30: Provisions used to secure table to table frame while dampening out vibration during transport.

Figure 3.31: U-channel used to support the perpendicular supports of table frame in 4 places.
of the tongue of the trailer to level and stabilize the trailer (Figure 3.32 and Figure 3.33). These trailer jacks are equipped with a telescoping support for additional stability. Four outrigger jacks are then attached to the frame assembly that supports the optical table. These jacks are lowered to take the weight off the trailer. Then the fixtures that attach the frame to the trailer are removed (Figure 3.31). The jacks can now be adjusted to mechanically decouple the table frame from the trailer (Figure 3.34).

Figure 3.32: GLS prototype in Operation Mode. The jack assemblies (highlighted in blue) support the trailer.

To secure the jack assemblies, a bolt threaded into the corner of each assembly pushes the vertically telescoping jack portion into the corner of the jack. To prevent the table frame jacks from moving and causing the table to move, five-bolt attachment points per jack secure the jacks to a corner of the perpendicular tubing that spans the width of the trailer.
Figure 3.33: Outrigger jack used to stabilize the trailer (left) and table (right).

Figure 3.34: GLS prototype in Operation Mode. The jack assemblies (highlighted in blue) support the optics table assembly (also highlighted in blue).
Since a tilt of the optical table also tilts the steering head, the optical table must be level for alignment and beam operations. The optical table is leveled using the outrigger jacks. The jack cranks have been replaced by bolt heads that fit a standard 15/16 inch socket. One complete rotation of the socket raises the jack by 0.109 inches. The jacks are separated by 80.5 inches front to back and 120 inches side to side. This corresponds to a tilt of the table of 0.078° and 0.052° per rotation, respectively. Rotating the lifting mechanism by approximately a quarter turn levels the optics table within 0.019° and 0.013°. However, currently the optics table can only be measured to 0.024° in both directions due to the resolution of the leveling device used in the leveling process.

An automated sliding hatch has been installed to allow the steering head assembly to raise above the trailer roof (Figure 3.35).

The hatch is a sliding cover that slides on two rods. Two 12 VDC linear actuators slide the hatch open and closed. A control box mounted below the distribution panel contains a switch that powers the circuit and a three-way switch that opens, closes, or halts the linear actuators. To open the hatch, a switch provides 12 VDC power to the actuators when in the ”Open” position. The hatch is closed by reversing the polarity of the voltage applied to the actuators via the ”Closed” position of the switch. If the hatch needs to be opened partially, the hatch is opened or closed to the desired position and the switch is put into the ”Neutral” position which interrupts power to the actuators. Internal limit switches in the actuator assembly prevent the hatch assembly from exceeding the stopping points and pushing against the framing of the hatch when the toggle switch is left in the ”Open” or ”Closed” positions.
Figure 3.35: 3D model of hatch assembly during design (top) and final assembly of the hatch (bottom).
CHAPTER 4

TEST LOCATIONS AND FIRST LIGHT TRACKS

The GLS laser station prototype has provided many laser tracks to test the EUSO-TA detector at the Telescope Array near Delta, Utah. Light tracks from the GLS prototype have been detected from 24 km to 100 km from EUSO-TA during campaigns in March, May, September, and October of 2015. Prior to the termination of the Atmospheric Research for Climate and Astroparticle DEtection (ARCADE) [35], the GLS prototype provided light tracks (80 km from the detector) for the Atmospheric Monitoring Telescope (AMT) in July of 2015. This was a research and development campaign.

4.1 Test Locations

The test sites for the Telescope Array site in Utah are chosen so that they are within the $\pm 5.25^\circ$ FOV of the EUSO-TA detector. For convenience, all but one site have been in line with the CLF, which is used as a reference. An added constraint in determining a test site for the GLS prototype is that the site must be on or near a marked road because of the difficult terrain encountered. Figure 4.1 is a map of the test sites that have been used thus far. Each location lies on the intersection between dirt roads and a straight line projected from EUSO-TA through the CLF, except for the 40 km site.

Light tracks from the GLS prototype have been observed by the AMT which is located south of Lamar in southeast Colorado. Land is owned by private farmers, therefore, possible test sites must lie on the intersection of roads and a straight line projected from the AMT through the Raman LIDAR facility. Figure 4.2 is a zoomed in map of the test site used for the AMT campaign.
Figure 4.1: Locations of test sites and EUSO-TA/CLF near Delta, UT.
4.2 Light Tracks

Light tracks from the GLS prototype were recorded for the March, May, September, and October 2015 campaigns. For each location, the goal was to record a series of optical tracks at variable laser energies and elevation angles at various distances to simulate different atmospheric conditions. Figure 4.3 is a diagram that represents the detection process.

The GLS prototype is typically pointed towards EUSO-TA at elevation angles between $75^\circ - 90^\circ$. As the laser exits the steering head and propagates through the atmosphere, EUSO-
TA detects the UV light that is scattered from the beam through scattering of aerosols and molecular components in the atmosphere.

The following, Table 4.1, represents the testing conditions during each campaign. Specific data is lacking from the October campaign due the timing of the campaign and composition of this thesis.

The first campaign, March 2015, was an initial test of both EUSO-TA and the GLS prototype. Proper alignment procedures of the GLS prototype were still being determined during this campaign. EUSO-TA was still being initialized, focused, and debugged. Figure 4.4 is a plot of approximately 150 laser shots from the 40 km site. Notice that the light track propagates towards the bottom corner of the FOV of the detector. This can be explained by the fact that the 40 km site is not in line with the CLF and EUSO-TA from Figure 4.1. Therefore, EUSO-TA was not detecting the GLS prototype when it was shooting vertically into the sky. With the use of the steering head, the GLS prototype was able to alter the pointing direction required to cross the FOV of EUSO-TA instead of having to physically
Table 4.1: Parameters of testing of the 2015 EUSO-TA campaigns.

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<td>Zenith angle of 70, parallel sweep, pointed towards EUSO-TA</td>
</tr>
<tr>
<td>20150920</td>
<td>34</td>
<td>1-30</td>
<td>Zenith angle of 80, parallel sweep, pointed towards EUSO-TA</td>
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<tr>
<td>20151011 - 20151021</td>
<td>24, 34, 100</td>
<td>1-90</td>
<td>Dynamic vertical energies, perpendicular and parallel sweeps, pointed towards/away/tilted with respect to EUSO-TA. Tested self-trigger of EUSO-TA</td>
</tr>
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</table>
move the laser station until it was in line with the CLF and EUSO-TA.

During the September campaign, the laser was stationed at the 34 km site. The 34 km site was a correction from the previous campaign in March (Figure 4.1). The new site was better lined up with the CLF and EUSO-TA, which is evident with the near vertical superposition of light tracks shown in Figure 4.5. The tracks are more centered in the FOV than the previous campaign. Background noise has been removed from the data to make the light track more visible. The leftover noise in the upper right corner of the detector was due to an unknown issue with the cells of the detector. The plot was generated using etos.py provided by the EUSO-TA collaboration.

Figure 4.6 is a sequence of two images separated by 3 GTUs in time which illustrates the light track as it propagates across the FOV of the detector.

A quick calculation can be performed from the propagation of the light track in Figure 4.6 to test the geometry of the set up. Figure 4.7 represents the set up of the system. The two
Figure 4.5: Superposition of light tracks from September 19, 2015 at 34 km from EUSO-TA with a laser energy of $\sim$ 20 mJ. The color scheme represents the propagation of time during the recording. Blue dots indicate the first shots detected and red indicate the most recent shots.

Figure 4.6: Propagation of light track from September 19, 2015 at 34 km from EUSO-TA with a laser energy of $\sim$ 20 mJ. The images are separated by 3 GTUs (7.5 $\mu$s).
shapes on the right represent the light track as it propagates through the atmosphere.

Figure 4.7: Diagram of the set up between the propagating light track and EUSO-TA.

Assuming the laser beam is traveling vertically at $c$, and also assuming that the time between images is $7.5 \, \mu s$, the difference in height between the two images results as,

$$ v = \frac{\Delta h}{\Delta t} \hspace{1cm} (4.1) $$

$$ \Delta h = v \times \Delta t = c \times (7.5 \, \mu s) = 2.25 \, km \hspace{1cm} (4.2) $$

This is confirmed by using the geometry of the set up. Using the following equation, we can determine the change in height of the light pulse during the change in time.

$$ v = c = \frac{L_2 - L_1 + \Delta h}{\Delta t} \hspace{1cm} (4.3) $$

Where $L_1$ and $L_2$ are the distances that the light must travel to reach the detector at each time, $\Delta h$ is the change in between the two times, $\Delta t = 7.5 \, \mu s$, and $c$ is the speed of light.

Knowing the horizontal distance from the detector to the GLS prototype and calculating the angle of the light pulse at each time, $L_1$ and $L_2$ can be determined from the following equation:

$$ \cos(\theta_{t_1}) = \frac{34 \, km}{L_1} \hspace{1cm} (4.4) $$
The center of the FOV of EUSO-TA was angled at a $10^\circ$ elevation angle. Given that the detector surface is comprised of a grid of 48 by 48 pixels and the FOV is approximately $10.5^\circ$, each pixel FOV is $0.22^\circ$. At time 1, the bottom of the light pulse is at the 10th pixel. At time 2, the bottom of the light pulse is at the 26th pixel. From these conditions, we can calculate the elevation angles of the light pulse at each time with,

$$\theta_{t1} = 5.25^\circ + 10 \text{ pixels}(0.22 \text{ deg/pixel}) = 7.45^\circ$$ (4.6)

$$\theta_{t2} = 5.25^\circ + 26 \text{ pixels}(0.22 \text{ deg/pixel}) = 10.97^\circ$$ (4.7)

Knowing both of the elevation angles and the distance between EUSO-TA and the light pulse, we can compute the length at each time by,

$$L_1 = \frac{34 \text{ km}}{\cos(\theta_{t1})} = \frac{34 \text{ km}}{\cos(7.45^\circ)} = 34.29 \text{ km}$$ (4.8)

and

$$L_2 = \frac{34 \text{ km}}{\cos(\theta_{t2})} = \frac{34 \text{ km}}{\cos(10.97^\circ)} = 34.63 \text{ km}$$ (4.9)

Solving equation 4.3 for $\Delta h$, the change in height can be determined.

$$\Delta h = c \times \Delta t + L_1 - L_2 = c \times (7.5 \mu s) + (34.29 \text{ km}) - (34.63 \text{ km}) = 1.91 \text{ km}$$ (4.10)

Given that the two methods differ by $\sim 15.1\%$ and the assumption that the speed of light in atmosphere is $c$, proves the functionality of both prototypes and they appear to functioning as intended. A detailed reconstruction of the light tracks detected with EUSO-TA would be required to determine the accuracy of the system.

From the campaign in September, Figure 4.8 represents light tracks recorded over a sweep of pointing angles parallel to the FOV of the detector from the 34 km test site. A few pixels on the EUSO-TA detector were defective and were not able to record data.
Figure 4.8: Parallel sweep of light tracks from September 19, 2015 at 34 km from EUSO-TA with varying laser energies and azimuth pointing angles. (Plot courtesy of Lech W. Piotrowski.)

Additional data is located on the EUSO-TA website of the light tracks detected by EUSO-TA for each of the campaigns listed above. Detailed analysis of the laser data is beyond the scope of this thesis. The plots and calculations above are some example data shown.
CHAPTER 5
SUMMARY

The goal of this research was to design and build a functioning prototype of the JEM-EUSO Global Light System laser station. Building on experience from ground based cosmic ray experiments including HiRes, Fly’s Eye, and Pierre Auger, we developed a laser station capable of producing steered beam energies that exceed the maximum beam energy used at Pierre Auger by more than ten times. The system is transported in a modified utility trailer that is not found in the fixed systems at Pierre Auger and TA.

The retractable two stage steering head is elevated through the roof of the trailer allowing any pointing direction above the horizon to within a pointing accuracy less than $\pm 0.2^\circ$. The adjustable absolute beam energies of $<1 \text{ mJ}$ to $90 \text{ mJ}$ allows the user to compensate for atmospheric attenuation during different pointing directions. The laser station is housed in a utility trailer that can be hauled by a truck for local campaigns or shipped in a standard container for international campaigns. With its own dedicated power system, the GLS prototype can operate for an entire night through a 120 VAC inverter powered by two large 12 V batteries. Alternatively, the system can be powered by solar panels. For future modifications, the GLS prototype contains provisions to remotely lift the steering head through the open hatch of the trailer. Finally, with a dedicated internet link, the GLS prototype could be remotely operated.

The GLS prototype has completed four campaigns by providing the first light tracks for the EUSO-TA prototype ground detector. The campaigns include various pointing angles, parallel and perpendicular angular sweeps of the steering head, and energies at distances ranging from 24 km to a record-setting 100 km from the detector. Prior to the termination of ARCADE, the GLS prototype travelled to Lamar, Colorado and was observed at a distance of 80 km. The completion of these campaigns demonstrate the versatility of this laser station
to the JEM-EUSO and EUSO-TA collaborations.

The goal of this research has been achieved and even exceeded. This project has seen full-life cycle, from design and assembly to operation in the field. In fact, the GLS prototype is at the point to where it is testing features of the EUSO-TA detector rather than the opposite as was the case during the first two campaigns.

Future plans for the GLS prototype consists of providing continued support for EUSO-TA as well as ground test support for the detector of the EUSO-SPB (Super Pressure Balloon - SPB) project. EUSO-SPB consists of a prototype PDM, similar to EUSO-TA, mounted inside a gondola that will be flown via high altitude balloons. The gondola is planned to float over the southern hemisphere and look down at Earth while recording cosmic ray events. Finally, the GLS prototype could be utilized over the next two years to test the Mini-EUSO prototype, a scaled-down version of JEM-EUSO, recently approved for the ISS [36].
REFERENCES CITED


<table>
<thead>
<tr>
<th>Beam Parameters</th>
<th>Principal</th>
<th>Residual</th>
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<tr>
<td>Energy (mJ)</td>
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<td></td>
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<tr>
<td>Near Field Beam Diameter (mm)</td>
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<td>Pulse Width - FWHM (nsec)</td>
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<td>Divergence at 65.5% (mrad)</td>
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| Hold-off (steady state) | 26.08 J |
| Hold-off (turn-on)      | N/A J   |
| Threshold               | 8.19 J  |

| Pulse Rate Limit (Hz) | 0.01 Hz |
| High Voltage Limit (Cap) | 810 µF |

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<th>Power Supply Setting</th>
<th>Pulse Rate</th>
<th>Energy Input (Joules)</th>
<th>Duty Fire-every (µsec)</th>
<th>Duty Delay (µsec)</th>
<th>Duty Turn-On Delay (µsec)</th>
<th>CW Ramp (%)</th>
<th>Q-Switch (CFP)</th>
<th>Shutter (CFP)</th>
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<td>17.41 J</td>
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<td>172</td>
<td>40</td>
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<td>X</td>
<td>X</td>
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<td>172</td>
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<td>172</td>
<td>40</td>
<td>0</td>
<td>X</td>
<td>X</td>
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Notes, Special Features, Precautions, etc.:

IMPORTANT: CUSTOMER PLEASE READ!

☐ Be sure to fill cooler with distilled water.
☐ Cooler filled with 50-50 Ethylene Glycol and Distilled Water mix.
### MVAT Data Summary

SYSTEM PN: **CFR372F01D2-1**  
SYSTEM SN: **1412130101**

<table>
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<tr>
<th>Attenuator</th>
<th>E_{OUT}(mJ)</th>
<th>E_{OUT}(mJ)</th>
<th>E_{OUT}(mJ)</th>
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<tr>
<td>0%</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>30%</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>53.1</td>
<td></td>
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<td>80%</td>
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<td></td>
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</tr>
<tr>
<td>90%</td>
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<td></td>
</tr>
<tr>
<td>100%</td>
<td>94.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Stability Data taken at spec energy
- Record calibration factor minimum **12CC**
- Record attenuator software revision **1.5_V**
- Record backlash compensation factor **D**
- MVAT lifetest completed and results copied to DHR
Figure B.1: Block diagram of the power distribution portion of the GLS Prototype.
Figure B.2: Block diagram of the signal distribution portion of the GLS Prototype.
The block diagrams represent the concept for the mechanical brake that could be used to hold the elevating platform in its elevated position. A mechanical brake acts on a disc rotor that is attached to the top of the gear drive of the stepper motor. Once the elevating platform raises to a specified height and engages a proximity switch, a signal is sent to a relay which energizes it and provides power to a solenoid that applies the mechanical brake. This will hold the steering head elevated until the power is turned off or fails. The relay is integrated into the circuit such that if power is removed, the solenoid relaxes and the mechanical brake releases the rotor, allowing the platform to lower into the trailer.

Figure B.3: Block diagram of the possible mechanical brake design in its relaxed state (top) and energized state (bottom).
The following steps transform the GLS Prototype from Transport to Operation mode and back again.

The following steps transform the GLS Prototype from Transport to Operation Mode.

1. Install front trailer outriggers
   
   (a) Install lower two bolts of plate first and extend jack until the tongue of the trailer touches the lower bolts and foot of jack reaches the ground.
   
   (b) Install upper two bolts
   
   (c) Tighten all four bolts until plate is secured to tongue of trailer and jack assembly.
   
   (d) Keep angled support elevated until final leveling.

2. Install rear trailer outriggers

   (a) Unthread hex bolts on ‘J’ portion of jack assembly support enough that the frame of the trailer sits completely in the U-channel.

   (b) Extend jack until it reaches the ground and is fully seated on the trailer frame.

   (c) Tighten hex bolts on inside of U-channel with 8 mm hex key.

   (d) Keep angled support elevated until final leveling of the trailer.

3. Trailer Leveling/Unhitching

   (a) Release the ball of the hitch from the trailer.

   (b) Elevate the trailer with the front outriggers until hitch is cleared and truck can drive away.

   (c) Begin leveling the trailer via the outriggers.
Once the trailer is leveled:
- Tighten 3/4 inch bolts that are located on the corners of the outrigger assemblies.
- Extend angled supports on each outrigger and tighten the securing bolt.

4. Install Table Outriggers

(a) Insert all four table outriggers into 4 x 4 tubing using the names labelled on the top of each outrigger cap.

(b) There is a marking on each outrigger indicating the proper depth.

(c) For each outrigger, begin threading 3/4 inch bolts into the 4 x 4 tubing with three underneath and two on the side of the tubing. This secures the jack assemblies to the tubing and prevents any movement of the outriggers.

Note: You will not be able to thread the outside most bolt because the U-channel is blocking it. Four bolts are sufficient, however, the fifth can be installed after the removal of the U-channel.

(d) Once the bolts are started, tighten all five bolts per table jack.

(e) Extend each jack until the foot of the jack is pushing against the ground and some weight is taken off the U-channel.

(f) Remove the red floor jack from the table inside the trailer.

(g) Remove the four 14 mm bolts from each U-channel at the edge of the 4 x 4 tubing.

(h) Using the long screwdriver and dead blow hammer (Orange tool box), knock the U-channels out of their wedge locations.

(i) You can now safely lower and level the table using the outriggers.

(j) Once the table is leveled, tighten the 3/4 inch bolt on each corner of the jacks.

5. The table and trailer are now mechanically isolated and leveled in Operation Mode.
The following steps transform the GLS Prototype from Operation to Transport Mode.

1. Remove Table Outriggers
   
   (a) Elevate the four table jacks until the 4 x 4 tubing is seated against the trailer frame.
   
   (b) Unthread the center 3/4 inch bolt of each U-channel.
   
   (c) Install and elevate the red floor jack in the trailer until the jack is snug between the floor and table frame.
   
   (d) Using the long screwdriver and dead blow hammer, hammer the U-channels into their wedged locations.
   
   (e) Begin threading all four 14 mm bolts per U-channel.
   
   (f) Hammer the U-channel down with the screwdriver and hammer until the bolts are sitting at the bottom of the slots.
   
   (g) Tighten the four 14 mm bolts and tighten the center 3/4 inch bolt which is under the U-channel.
   
   (h) Retract the jacks until the foot of the outrigger is elevated.
   
   (i) Remove the 3/4 inch bolts (five per jack) that secure the outrigger assembly to the 4 x 4 tubing and store in a bag.
   
   (j) Keep the outriggers installed in the 4 x 4 tubing until the trailer is safely hitched as a safety precaution.

2. Trailer Outriggers/Hitching

   (a) Elevate the trailer with the front outriggers until the hitch is cleared and back the truck up to the tongue of the trailer.
   
   (b) Lower the trailer onto the hitch and secure the ball of the hitch via the nut and bolt that keeps the locking mechanism in place.
3. Remove Rear Trailer Outriggers

(a) Loosen the 8 mm hex bolts on the inside of the U-channel of the trailer outrigger.

(b) Retract the angled support enough that it won’t get in the way when you remove the outrigger.

(c) Lower the outrigger until it is freed from the trailer.

4. Remove Front Trailer Outriggers

(a) Retract the angled supports such that they will not get in the way of removing the outriggers.

(b) Retract the outrigger until it is barely touching the ground.

(c) Remove the four bolts and plates for each outrigger and store in a bag.

5. The table and trailer are now mechanically coupled and the system is in Transport Mode.
The following steps are a general guide for powering the system in multiple scenarios, and operating the laser system. Refer to the manuals listed at the end of this appendix for further detail.

1. Powering the Laser System

(a) Configuration 1 - External AC Power with DC Back-up (Recommended Operation)

i. Connect external extension cable to exterior 3-prong male connector (located on lower left back corner of trailer).

ii. Power for external extension cable is provided by the following sources:
   A. 120 VAC wall outlet
   B. 120 VAC outlet of gas-driven generator

iii. Turn ON circuit breakers labeled ‘Inverter AC Input’, ‘Inverter AC Output’, ‘Inverter DC Disconnect’ (all other breakers are OFF).

iv. Plug in cable from electrical strip (located on electronics shelf) to lower outlet (located below subpanel).

v. Turn ON electrical strip.

vi. Power is provided to the following components (if they’re plugged into the electrical strip):
   A. SBC
   B. Router
   C. Motor Controllers
   D. Laser
E. Radiometers

F. Lighting

vii. Hatch and Fan can be operated in this configuration.

viii. Inverter will detect and charge the batteries as needed.

ix. If external AC power fails, the inverter will detect and use DC power from batteries to maintain loads (as long as batteries are charged).

(b) Configuration 2 - External AC Power only

i. Connect external extension cable to exterior 3-prong male connector (located on lower left back corner of trailer).

ii. Power for external extension cable is provided by the following sources:

A. 120 VAC wall outlet

B. 120 VAC outlet of gas-driven generator

iii. Turn ON circuit breaker labeled 'Inverter AC Bypass' (all other breakers are OFF).

iv. Plug in cable from electrical strip (located on electronics shelf) to lower outlet (located below subpanel).

v. Turn ON electrical strip.

vi. Power is provided to the following components (if they’re plugged into the electrical strip):

A. SBC

B. Router

C. Motor Controllers

D. Laser

E. Radiometers

F. Lighting
vii. Hatch and Fan cannot be operated in this configuration.

viii. **CAUTION:** If external AC power fails, the system will not be powered.

(c) **Configuration 3 - DC Power only**

i. Turn ON circuit breakers labeled ‘Inverter AC Input’, ‘Inverter AC Output’, ‘Inverter DC Disconnect’ (all other breakers are OFF).

ii. Plug in cable from electrical strip (located on electronics shelf) to lower outlet (located below subpanel).

iii. Turn ON electrical strip.

iv. Power is provided to the following components (if they’re plugged into the electrical strip):

   A. SBC
   B. Router
   C. Motor Controllers
   D. Laser
   E. Radiometers
   F. Lighting

v. Hatch and Fan can be operated in this configuration.

vi. **CAUTION:** If DC batteries are completely discharged, the system will not be powered.

2. **Operating the Hatch and Fan**

   (Note: The power system must be in configurations 1 or 3.)

   (a) **Hatch Operation**

   (Note: All switches utilized are on the hatch control box, located under the subpanel.)

   i. Open the Hatch
A. Toggle power switch to ON.
B. Toggle position switch to OPEN.
C. Hatch will open until internal limit switches are activated.
D. Toggle power switch to OFF.

ii. Close the Hatch
A. Toggle power switch to ON.
B. Toggle position switch to CLOSE.
C. Hatch will close until internal limit switches are activated.
D. Toggle power switch to OFF.

iii. Open/Close the Hatch to desired position
A. Toggle power switch to ON.
B. Toggle position switch to OPEN/CLOSE.
C. When hatch is at desired position, toggle position switch to NEUTRAL.
D. Toggle power switch to OFF.

(b) Fan Operation

i. To power the fan, press red button located on fan control box (located under subpanel).

ii. To turn fan OFF, rotate red button until it automatically depresses.

3. Operating the Laser System
(Note: It is assumed that the components required to operate the laser system are powered.)

(a) Connecting to SBC

i. Connect personal computer to wireless network named ‘AugerNails’.

ii. In a command prompt, ssh into the SBC with the following code:

   ssh root@192.168.10.50
(b) Running the Laser Program

i. To run the laser program, type the following command: `./GLS.run`
   (Note: A log file is automatically started.)

ii. Enter initials of users present during operation and purpose of operation.

iii. To insert a comment into the log file, type the following command: `comment`
    A. Enter the comment (limited to one line of text).

iv. Initializing the components of the laser system (excluding steering motors).
    A. Type the following command: `init`
    B. A list of components that pass the initialization are displayed.
    C. During diagnostics, the sky energy probe must be reinitialized if the probe is moved between measurements.
    D. To initialize the radiometer wired to the sky energy probe, type the following command: `rad3init`

v. Operating the Steering Motors
    A. To initialize the motors, type the following command: `sinit`
    B. To send the motors to the zero position (pointed north), type the following command: `szero`
    C. To change the azimuth direction of the steering head, type the following command: `xgoto x.xxx`
       Where `x.xxx` is the desired angle in degrees (with positive angles measured counter-clockwise).
    D. To change the elevation direction of the steering head, type the following command: `ygoto y.yyy`
       Where `y.yyy` is the desired angle in degrees (with positive angles measured counter-clockwise).
E. To change both directions with one command, type the following command: goto x.xxx y.yyy

F. Currently the motor used to elevate the steering platform is raised and lowered with a cordless drill attached to the gear shaft of the motor. Preliminary designs are included in Appendix B (Figure B.3) to operate the motor via the command prompt.

vi. Setting laser parameters and firing

A. To set the firing frequency, type the following command: \texttt{lfreq x}
   Where 'x' is the desired frequency in Hz.

B. To set the firing energy, type the following command: \texttt{CFR400Att x}
   Where 'x' is the desired percent of transmitted energy. Refer to Figure A.2 of Appendix A for percent transmission and corresponding laser energy.

C. To fire the laser during calibration, type the following command: \texttt{cfire xxx 3}
   Where 'xxx' is the number of desired shots. Energies are recorded and displayed from the radiometers.

D. To fire the laser during optics alignment and operation, type the following command: \texttt{fire xxx}
   Where 'xxx' is the number of desired shots.

(c) To close the laser program, hold down 'ctrl' and press 'c'.

(d) The SBC must be shutdown via command prior to removing power to the SBC.
   i. Type the following command: \texttt{shutdown -h now}

(e) Power can now be removed from the system.

The following documents are reference manuals for the components of the laser system:

- Power Distribution (Subpanel): 64-0029-Rev-D-Mini-Magnum-Panel
• Power Distribution (Inverter): 64-0007-Rev-D-MS-Series

• Laser: CFR-400-Manual-DOC00013

• Motor Controller: VXM Stepper Motor Controller User’s Manual (VXM-UM-E5)