HASP Student Payload Application for 2011

Payload Title:

Directional Cherenkov Detector

Payload Class: (check one)	Institution:	Submit Date:
☐ Small ☐ Large	Louisiana State University	December 17, 2010

Project Abstract

The purpose of this project is to create a prototype cosmic ray charge detector for the use in the Calorimetric Electron Telescope (CALET) project. The proposed detector system design utilizes Cherenkov radiation emissions to measure the charge, up to 6 charge units, of primary cosmic ray particles. Essentially, the primary goal for the directional Cherenkov detector project is to effectively identify incoming cosmic ray particles as hydrogen, helium, lithium, beryllium, boron, carbon, or heavier cosmic ray nuclei.

Team Name:	Team or Project Website:
Team Electron Volt (TeV)	

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Mission Goal

Investigate the primary cosmic ray spectrum in the stratosphere by prototyping a directional Cerenkov detector for use by the Calorimetric Electron Telescope (CALET) project.

Objectives

1. Develop a directional Cerenkov detector for flight on HASP (High Altitude Student Platform)
2. Resolve the charge (Z) of primary cosmic ray events for ions of Z≤6, for the purposes of identifying the cosmic ray ions
3. Determine a flux measurement for each of the identified cosmic ray ions
4. Construct a detector system which is verified to function in simulated flight conditions
5. Integrate with flight vehicle

Requirements

Functional Requirements

- Payload shall exceed an altitude where secondary particles are at a negligible flux (above 80,000 feet)
- Payload should not measure back-scatter particles
- Payload shall record altitude data within 5000 feet to ensure that the device detects primary cosmic rays with negligible secondary cosmic ray events
- Data acquisition system should continue to acquire interpretable data after power restart

Performance Requirements

- Primary cosmic rays with a charge Z≤6 shall be separated by charge
- Detector shall have a high enough charge resolution (.3 e) to distinguish particles having a charge of Z≤6
- Detector shall record at least 100 counts of each primary particle (Z≤6) in order to ensure statistical reliability of data

Environmental Requirements

- The payload shall be able to operate within temperatures of -70 C and 35 C
- The payload shall be able to operate within pressures of 5 and 1000 millibars

Deployment Requirements

- Payload power system will be activated remotely, before launch

Operability Requirements

- The entire payload system shall be assembled and tested as a system before flight
- PMTs should be coated and verified not to arc before flight
- Payload shall be thermally tested in simulated flight conditions before flight
- Payload shall be pressure tested in simulated flight conditions before flight

Management Requirements

- A risk assessment and mitigation plan shall be established
- A Gantt chart should be made and adhered to

Design Requirements

- The payload shall be powered with voltages of 29V to 33V and under .5 amps
- The payload shall remain secured to the HASP mounting plate under a 10 g vertical and 5 g horizontal shock
- Payload shall weigh less than 3 kg
- The payload shall have a footprint under 15 cm by 15 cm and a height under 30 cm
- Payload shall have a serial downlink of data under 1200 bps

Science Background and Justification

Cosmic Rays

Cosmic rays are highly energetic charged particles, which are generated by certain stellar phenomena. Aside from the particles generated from solar flares, cosmic rays originate outside the solar system. Since the trajectory of the cosmic ray is affected by various complex stellar magnetic fields, the exact origin of each cosmic ray cannot be determined. However, the composition and energy spectrum of cosmic rays can be observed, and these properties point toward possible galactic sources of cosmic rays. A variety of detector systems are designed and utilized to test the validity of these theories of origin. Some detectors, like those found at the Pierre Auger Observatory, exist as part of an array of devices on the earth's surface. An alternative, to placing detectors at ground level, is measuring cosmic rays at high altitudes. High-altitude balloons are ideal vehicles for carrying and supporting detector systems in upper-atmosphere environments. In addition to high-altitude balloons, many detector systems, such as the Calorimetric Electron Telescope (CALET), utilize space vehicles to run experiments above the earth's atmosphere.

CALET project

The purpose of our mission is to develop a prototype device for use in the Calorimetric Electron Telescope experiment. Set to launch in 2013, CALET is designed by Waseda University to search for the sources of primary cosmic rays, details of their transportation, and signatures of dark matter. Their research involves making detailed measurements of the electrons entering the atmosphere. Collecting data on these high-energy electrons will provide the CALET mission with the information they need to learn more about high-energy astrophysical phenomenon. CALET intends to investigate the natural acceleration processes experienced by cosmic ray electrons. Theoretically, the highest energy electrons should have relatively identical origins compared to the other electrons, making it possible to identify specific sources such as supernova explosions, black hole accretions, and Active Galactic Nuclei (AGN) jets. By the end of their mission, CALET will obtain information on high-energy electron production and transportation. The energy range being detected will be from 1 GeV to 20 TeV. Similar in concept to our own project, the CALET mission will also be to distinguish charges and measure cosmic ray nuclei fluxes up to 1,000TeV. CALET's high-energy capability is what makes it possible to detect signatures of dark matter particle interactions. Some of these dark matter candidates, such as Kaluza-Klein particles, have relatively high kinetic energies up into the TeV range.

Interaction with the Earth's Atmosphere

A cosmic ray particle is typically classified as either a primary or secondary particle. Primary particles are comprised of naturally occurring atomic nuclei and beta particles. A primary particle originates at a source and travels through the vacuum of space until it interacts with matter. The interaction between the primary particle and matter, such as the air molecules in the earth's atmosphere, results in the fragmentation of the primary particle into one or more secondary particles as seen in Figure 1. Depending on the total relativistic energy of the originating primary particle, the secondary particle(s) produced can be composed of differing amounts of kaons, pions, mesons, muons, and a myriad of other subatomic particles with charges of either 1 or -1 elementary charge units. These secondary particles can proceed to either decay or interact with other air molecules, producing more secondary particles. In some cases, one highly energetic primary particle can result in a cascade of numerous secondary particles. Since the probability that a cosmic ray will interact with air molecules increases as the atmospheric density increases, the intensity of primary cosmic rays tends to decrease rapidly as altitude decreases from 80,000 feet to the earth's surface. Therefore, an essential requirement, to observing exclusively primary cosmic rays, is to exceed 80,000 feet. This is where a sufficient primary cosmic ray flux exists and the secondary cosmic ray flux is kept to a minimum.

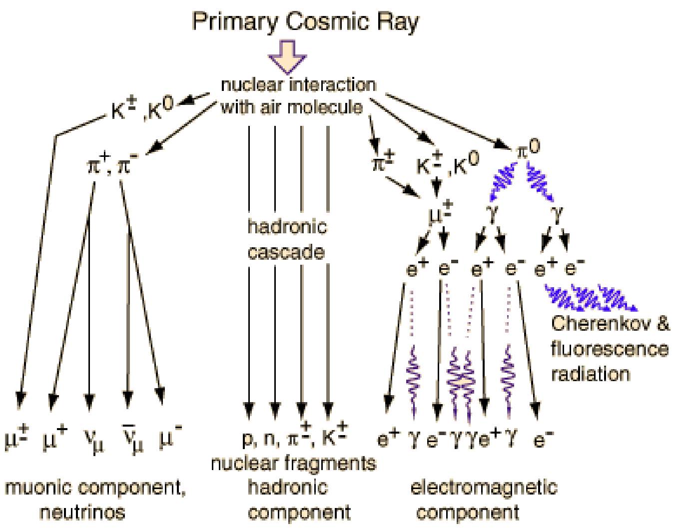

Figure 1 - Interaction with the Earth's Atmosphere (Nave)

Geomagnetic Cutoff

Before a cosmic ray particle enters the earth's atmosphere, it must first travel through the earth's magnetic field. Cosmic rays are moving charged particles and are, thus, susceptible to magnetic forces. The geomagnetic cutoff is a minimum rigidity required for a cosmic ray to overcome the earth's magnetic field and reach the atmosphere at a specific location (Friedlander). Assuming the earth's magnetic field is approximately a magnetic dipole, the geomagnetic cutoff rigidity is a function, shown in Equation 1 (Fermi), of the location of the cosmic ray relative to the magnetic poles, otherwise known as the geomagnetic latitude (λ).

$$rigidity = 14.9 \cos^4 \lambda \qquad [1]$$

Table 1 - Cutoff Rigidity for Fort Sumner

Cosmic ray nuclei	Cut-off Rigidity (GeV)
Hydrogen	4.97
Helium	9.46
Lithium	14.19
Beryllium	18.92
Boron	23.65
Carbon	28.38

Setting λ to Fort Sumner's geomagnetic latitude, -41.36°, the cutoff rigidity is calculated as 4.73 GV. Table 1 shows the geomagnetic cutoff in terms of kinetic energy for hydrogen, helium, lithium, beryllium, boron, and carbon cosmic ray nuclei.

Cosmic Ray Flux

Table 2 – Primary Cosmic Ray Fluxes

Cosmic Ray Nuclei	Total Flux (counts/m^2 s sr)
Hydrogen	354.7
Helium	103.1
Lithium	0.97
Beryllium	0.28
Boron	0.68
Carbon	2.36

Data on primary cosmic rays is provided by previous research experiments and models in the form of a plot of differential fluxes verses kinetic energy per nucleon. The data must be integrated over kinetic energies ranging from the geomagnetic cutoff to infinity in order to obtain a total flux for each cosmic ray nuclei, shown in Table 2.

The Cherenkov Effect

Cherenkov radiation occurs when a charged particle, such as a cosmic ray, transverses through an insulator at a velocity exceeding the speed of light in the material. The Cherenkov light has specific properties that are related to the speed and charge of the incoming particle (Fernow). The intensity of Cherenkov radiation can be measured using photomultiplier tubes (PMTs). The equation for the intensity of the Cherenkov radiation, shown in Equation 2, is a function of two variables, the relativistic speed of the incoming particle (β) and the charge of incoming particle (z).

$$\int_0^N \mathrm{dN} = \int_{x_1}^{x_2} 2\pi\alpha z^2 \left(1 - \frac{1}{n^2\beta^2}\right)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\mathrm{d}x \qquad [2]$$

Since there are two unknown variables, two radiators, Lucite and lead glass with different indexes of refraction, n_{lucite}=1.49 and $n_{lead\ glass}$=1.70, are needed in order to deduce the charge of the cosmic ray particle.

Overall System Design

A high-level system design, illustrated in Figure 2, includes a power system, detector system, and control system. The system is designed within the constraints of a small payload configuration.

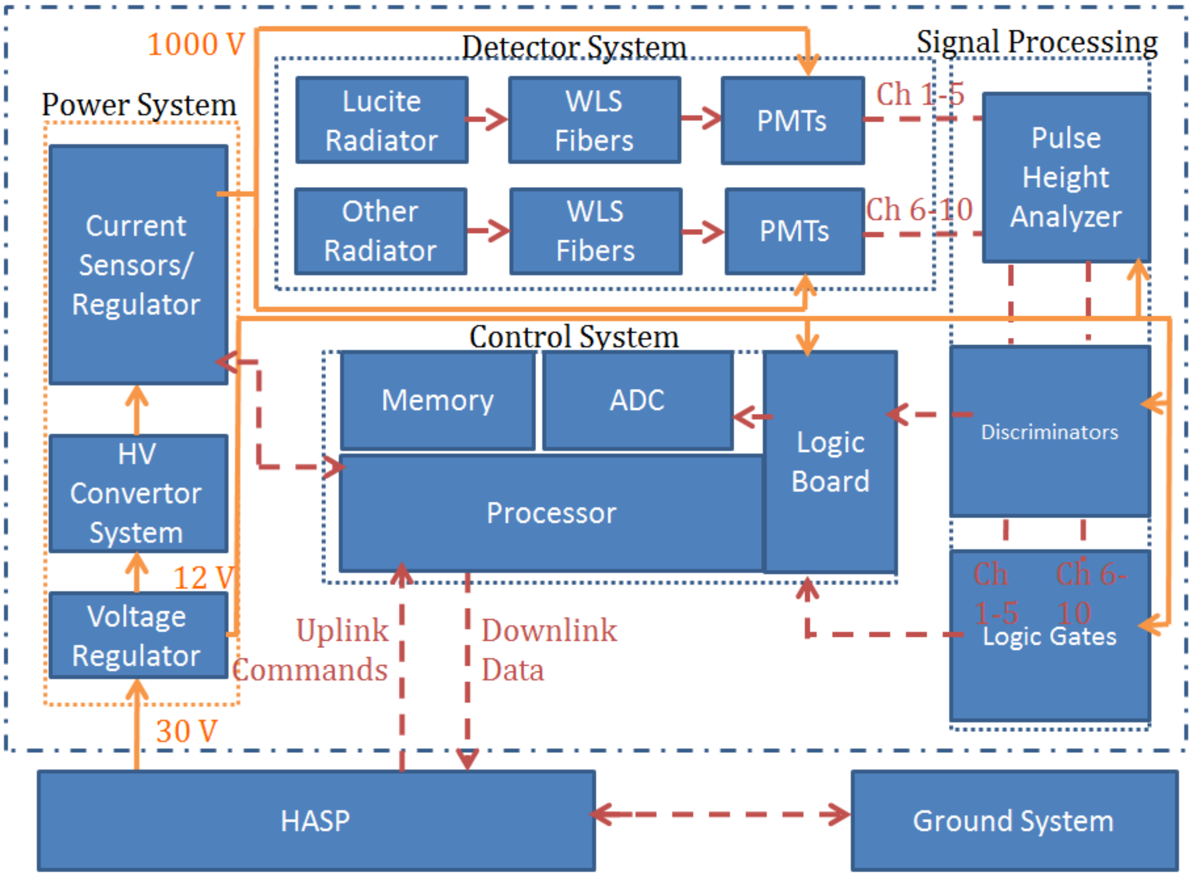

Figure 2 - System Diagram

Power System

The power system includes a voltage regulator which, in addition to attenuating the nominal 30 V input to 12 V, reduces electronic noise throughout the payload system. PMTs are extremely sensitive to minor fluctuations in voltage, so it is crucial that voltage regulation be used to keep a steady voltage level. High voltage converters are also included in the power system as the PMTs will require 1000 V. Multiple high voltage converters are required in order to mitigate the effects of high voltage arcing across the electronic components. Current sensors and a power regulator are included in order to provide a means to reduce power or completely turn off PMT systems that are arcing due to low pressure.

Detector System

The detector system consists of two radiators. The top radiator will consist of ultraviolet transmitting Lucite, and the other radiator will consist of lead glass. Each radiator will have its top surface painted with black paint so the detector will not detect back-scattered particles. On each radiator, one hundred BC-480 wavelength-shifting fibers (WLS fibers) will shift the UV Cherenkov radiation into the blue spectrum, which increases the detector efficiency.

Additionally, the WLS fibers internally refract the Cherenkov radiation into the PMT attached to each of the fibers. Five R5611 PMTs will be used per radiator and will be attached along the edge of the radiator as to collect all of the Cherenkov radiation collected by the 100 WLS fibers. The bases of the PMTs shall be coated with conformal coating or a potted to prevent arcing.

Signal Processing System

The signal processing system contains two important subsystems, the pulse-height analyzer and the logic gates. The pulse-height analyzer reduces electronic noise by utilizing discriminators, samples the PMT output current pulse, produces an analog signal proportional to the pulse-height, and holds that analog signal long enough for the analog to digital converter (ADC) to read that signal. These functions are essential in order to convert the quick PMT current pulse into digital value that can be analyzed and utilized in the determination of the charge of the incoming cosmic ray particle. The logic gates are needed to assess if the PMT pulses are in coincidence with each other. The particle must travel through both radiators in order to be registered as an event.

Control System

The control system consists of a logic board, processor, memory chip, and ADC. Each PMT signal output must be routed into the ADC in a logical fashion so that separate pulse-heights originating from each PMT system can be distinguished and analyzed in data analysis. The ADC is needed to convert the analog signals from the pulse-height analyzer and convert each of them into a digital value that can be processed into a digital format. The memory chip is needed to store a pulse-height value and a time-stamp. In addition to storing the pulse-height values, the data will be sent via serial telemetry to ground in a data format specified in the telemetry specification section. Additionally, the processor shall receive uplink commands, which will be sent to the current regulator in the event of PMT arcing. Thermal control will be taken care of by the walls insulating the payload. The payload should not need a feedback control system for this purpose.

Payload Specifications

Power Specifications

The power on HASP for small payloads is limited to 0.5 A at 30 V, which is 15W. The power budget for the payload is located in Table 3.

Table 3 – Power Specifications

Component	Power (W)
Photomultiplier Tube System	2.5
Pulse Height Analyzer System	8.8
Control System	1.1
Total	12.4

The photomultiplier tube system was estimated to be powered by 2.5 W. This estimate was based on the utilization of ten R5611 PMTs with a current of 100mA at 1000V. The power conversion efficiency was estimated to be 50% across the high voltage convertor and the regulator. The ten PMTs alone used 1W, the DC converter uses 0.5 W, and the regulator uses 0.75 W. The pulse height analyzer system power usage was estimated using pulse height analyzers used in a previous Cherenkov detector payload. The power for a four-channel pulse height analyzer board coupled with a regulator was measured to be 2.94 W. Since ten channels will be needed, a total of 8.82 W will be required for the pulse height analyzer system. The control system power usage was estimated to be 1.1 W with regulation voltage conversion from 30 V. Therefore, the total power needed for the payload is 12.4 W, which is under the 15W limit for small payloads on HASP.

Weight Specifications

Table 4 - Payload weight decomposition

Component	Measurement Method	Weight (g)
PMTs with coated bases	Measured	450 ± 0.1
Pulse Height Analyzer System	Measured	615 ± 0.1
Control System	Estimated	205 ± 5
Power system and wiring	Measured	175 ± 0.1
Lucite radiator	Estimated	354 ± 1
Lead glass radiator	Estimated	872 ± 1
Mechanical structure	Estimated	160 ± 5
Total		2831 ± 12.3

The maximum weight for small HASP payloads is 3kg. The weight budget for the payload is located in Table 4. The mass of a R5611-01 PMT and a PMT circuit base used for a previously flown cosmic radiation payload was measured to be 45 grams. Since there will be 10 PMTs and bases, the total amount of mass of the PMT system is estimated to be about 450 g. A coating on the PMTs to prevent arcing is estimated to be 100g. The weight of a four-channel pulse height analyzer used on a previous payload was 205 g. Since ten channels will be needed, three boards with a total mass of 615 g, must be used. The control system is estimated to have a similar weight to one pulse height analyzer board, 205g. A regulator and high voltage convertor from a previous payload along with the wiring was measured to be 175g. This amount is used to estimate the power system weight for this payload. The weight of the Lucite radiator is estimated using the volume of the needed 10x10x3 cm^3 detector and a density of 1.18 g/cm^3. The weight of the Lucite radiator is calculated to be approximately 354 g. The weight of the lead glass radiator is estimated using a volume of 10x10x2 cm^3, with a density of 4.36 g/cm^3. This yields a mass estimate of 872 g for the lead glass. The mechanical structure was estimated using the volume of foam used to create the structure. This foam estimate yielded 110 grams and it is estimated that the structure will need 50 grams of wood for increased support. The total weight comes out to be 2831±12.3 grams. This is less than 3000 grams and leaves a 5% margin of safety.

Telemetry Specifications

Table 5 - Data Record Format

Bytes	Bits	Description
1	0-7	Type
2-5	0-31	Timestamp (UNIX time)
6	0-7	Least significant 8 bits of checksum
7-26	0-159	Pulse height PMTs 1-10

The format for the data record for the payload is in Table 5. The first byte is used to read out the type of record. There are two types of records that the payload will send: a data record and a status record. Each type of record will have a unique first byte. The second through fifth bytes of the data record include a timestamp in UNIX time. The sixth byte is the least significant 8 bits of the current data record so the data record can be checked for transmission errors. Bytes 7 through 26 are used for the pulse heights of each photomultiplier tube for each coincidence. 2 bytes have been allocated for each PMT pulse height. The total byte usage for each data record is 26 corresponding to a total number of bits of 208. The data record will downlink every time there is a coincidence event, which is approximately 96 times a minute.

Table 6 - PMT Status Format Record

Bytes	Bits	Description
1	0-7	Type
2-5	0-31	Timestamp (UNIX time)
6	0-7	Least significant 8 bits of checksum
7-8	0-15	Status for PMTs 1-10
8-10	0-23	Coincidence tally

The format for each status record is shown in Table 6. The first byte signifies that the record is of a status type. Bytes two through six are the same as in the data record. Bytes seven through eight show the status of each PMT. Each PMT's status will be shown using one bit. A high bit signifies that that PMT is arcing and a 0 signifies no arcing has taken place. Bytes eight through ten show how many coincidences there have been on the flight since launch. Three bytes will allow for 16,777,215 counts, which is comfortably higher than expected. The total number of bytes calculated for each status record is 10, which corresponds to a total of 80 bits. The status record is designed to downlink every 20 seconds.

The expected coincidence rate of the detector at HASP float altitude is 96 events per minute. Allowing for a 20% uncertainty in the expected coincidence rate of the detector, the bit rate of the data record is estimated to be 23,920 bits/min. The bit rate of the status record is estimated to be 240bits/min. The total data rate is 24,160 bits/min or 403 bits/s. This bit rate is within the limits of the HASP small payload telemetry rate constraint, which is not to exceed 1200 baud.

The payload will also utilize an uplink command that will either turn off or lower the power going to the PMTs if the PMT status downlink data shows that the PMTs are arcing. Ideally, this command would not be used during the flight and if it is used, it will not be more than ten times since there are ten PMTs.

Structural Specifications

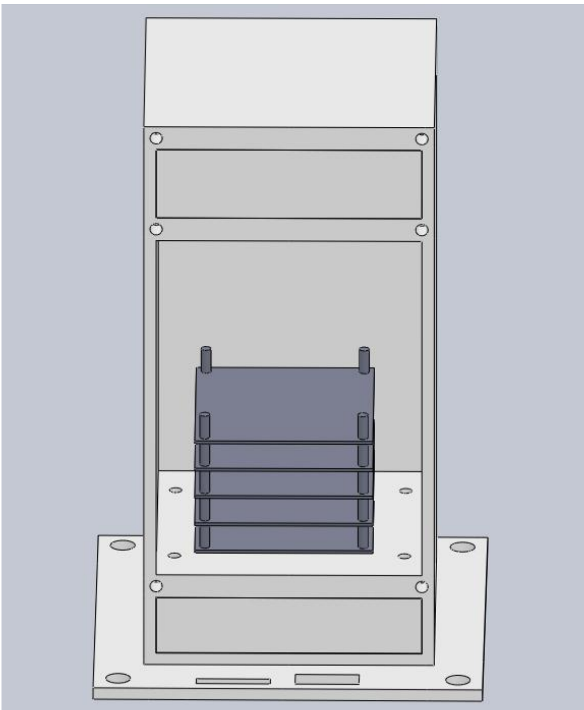

Figure 3 – Payload Interior

The outside structure of the payload will be a 10x10x30 cm box. The payload will open on the side using a removable door that is fastened to the structure using six screws. As shown in Figure 3, the inside of the payload has three shelves. The top and bottom shelves will house the Lucite radiator system and the lead glass radiator system, respectfully. The middle shelf will house the electronics and wiring. The radiator system shelves each contain a 10x10 cm radiator and five housing areas for PMTs. The shelves are shown out of the structure in Figure 4. The radiators are inset in the box so that they do not move around when being placed in the shelf or during the payload flight. The lead glass radiator, on the bottom shelf, will rest on the bottom of the payload structure. The shelves ensure that there are 27 cm between the top of the Lucite radiator and the bottom of the lead glass radiator in order to minimize the uncertainty in the path length of the cosmic ray particle. Next to the PC 104 stack on the middle shelf is four holes

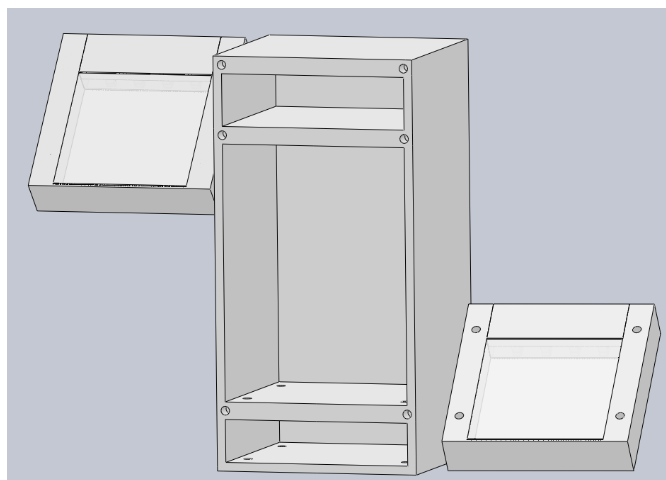

Figure 4 - Payload Shelves Out

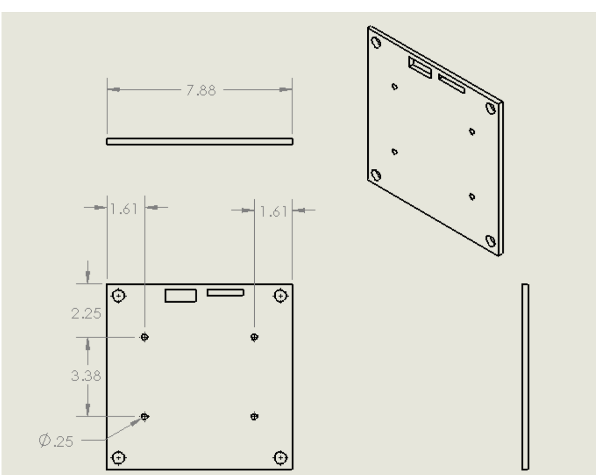

Figure 5 - Payload Mounting Plate Modifications (inches)

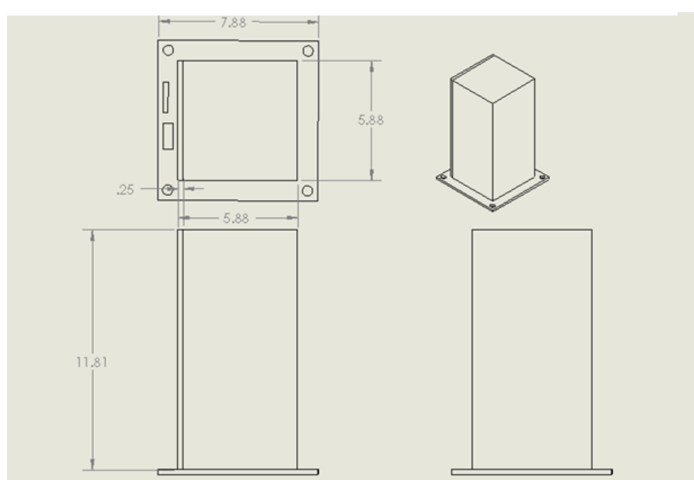

Figure 6 – Fully Assembled Payload Mounted (inches)

that extend to the end of the mounting plate. This is where four bolts will be placed to mount the payload to the mounting plate. The positions of the four holes that need to be drilled into the mounting plate are shown in the middle of the dimensioned front view in Figure 5. The holes are within the specified mounting area on the mounting plate. Figure 6 shows the fully assembled payload on the mounting plate. It shows that the payload will be within the dimension limits of small payloads and fit into the mounting area of the mounting plate. All of the payload structure will be made out of foam. All drawings made using SolidWorks software from Dassault Systèmes SolidWorks Corp. headquartered in Concord, Massachusetts.

The payload should be oriented on HASP as in Figure 3 so that the top of the payload points towards the sky. Otherwise, the payload will not be able to measure cosmic rays and instead will exclusively measure back-scattered particles. This payload requires no special position on HASP.

Team Management Structure

Team Electron Volt is comprised of Jace Boudreaux and Sean McNeil. Contact information and individual roles are shown in Table 7. Both team members will participate in HASP integration and it is not anticipated that a member will need to be on location in Fort Sumner during flight operations.

Table 7 – Team Management Structure

Name	Sean McNeil	Jace Boudreaux	Dr. Gregory T. Guzik
Roles	• Software • Testing • Calibrations • Data Analysis	• Project Management • Electrical • Mechanical	• Faculty Advisor
Department	LSU Physics and Astronomy	LSU Mechanical Engineering	LSU Physics and Astronomy
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Timeline and Milestones

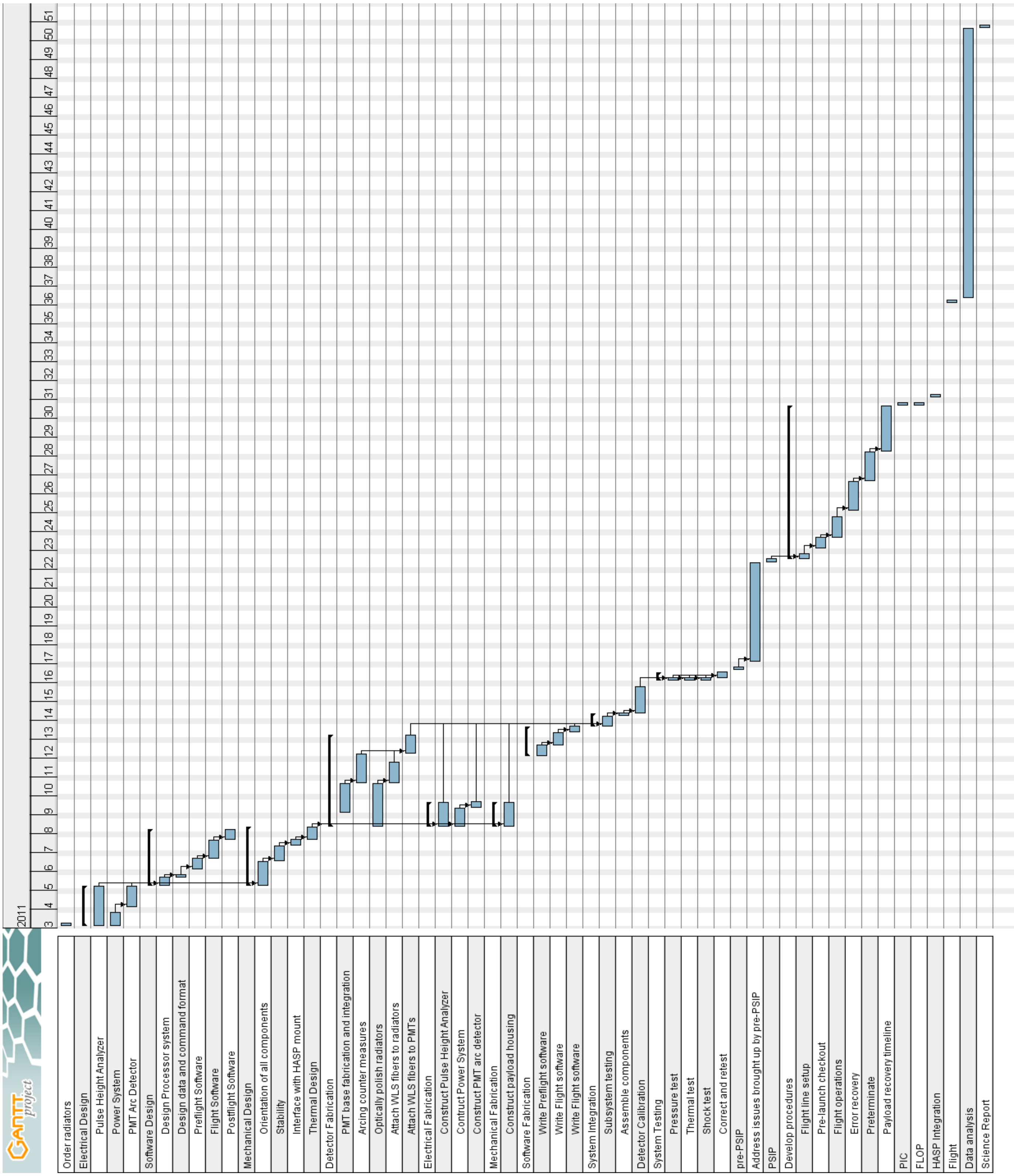

Figure 7 – Projected HASP schedule

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