Serenity: Gamma Radiation in Low Earth Orbit

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***Abstract*— The CubeSat mission entitled Serenity has a central focus of assessing components of gamma radiation in Low Earth Orbit. The components of gamma radiation to be studied are solar flares and gamma ray bursts. The methodology used to study the aspects will be to compare any gathered data showing a change in gamma ray flux to data gathered by NASA. Data showing a change in gamma ray flux will only be considered if there is a known solar flare or gamma ray burst occurrence. Comparing data collected by the mission's CubeSat with that gathered by NASA will provide validity that the instrumentation on Serenity is fully functional. It is the desire of the mission and those involved that the efficacy of the data gathered will provide validity to the concept of extraterrestrial sources of gamma radiation.**

Keywords*— *Compton scattering, CubeSat, gamma radiation, gamma ray burst, low Earth orbit, photodetector, scintillator, solar flare

I. Introduction

The key question to be answered through the proposed science mission is: "Is it possible for a CubeSat to assess the sources of gamma radiation in Low Earth Orbit (LEO)." With increased interest in manned missions to Mars, gamma radiation poses a potential threat to astronauts due to the lack of a protective atmosphere. Chem.libretexts.org discusses radiation and the effects of it on matter: "Radiation either ionizes or excites atoms or molecules in living cells, leading to the dissociation of molecules within an organism." The most dangerous effect is the way that ionized radiation interacts with DNA, leading to damaging genetic changes, birth defects, and cancer. Gamma rays are referred to as indirectly ionizing radiation because they have no charge but are forms of energy. Nondestructive Testing Resource Center discusses gamma rays passing through materials: "A given gamma ray has a definite probability of passing through any medium of any depth." Their high penetration range is another attribute that can cause damage to living cells. While Beta particles are used in radiation therapy to kill cancer cells, gamma rays are often used for irradiation, which is the process to kill living organisms.

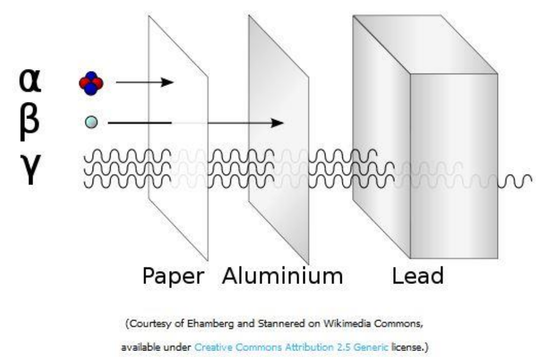

Fig. 1. Radiation passing through different mediums

Serenity is a CubeSat mission that hopes to assess the components of gamma radiation in Low Earth Orbit (LEO). CubeSats are compact, inexpensive satellites that may be used for multiple purposes. This allows experiments to be performed with ease in comparison to using a full satellite. LEO is a portion of the Earth's atmosphere ranging from 160 to 2,000 km altitude. Gamma rays pass through LEO and are no longer present around 10 to 50 km altitude, which is shown in Figure 2. This is due to a process known as Compton Scattering, which will be discussed in detail in the following section.

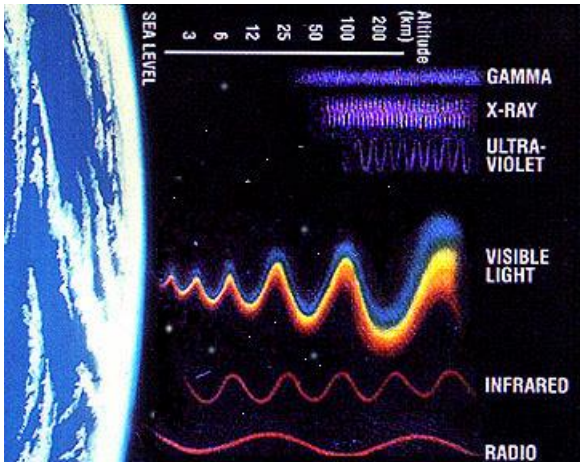

Fig. 2. Radiation's presence in Earth's atmosphere

The presence of gamma rays in the Earth's atmosphere validates that we will be able to collect data showing gamma rays in LEO. We propose that measuring the flux of gamma rays in LEO and comparing it to positional data along with known occurrences of solar flares and gamma ray bursts will allow for us to assess the components of gamma radiation in LEO.

II. Background

A. Gamma Radiation

Gamma radiation is the highest energy form that light can take with energy levels up to 200MeV [1]. At these energy levels the wavelength of gamma rays is often less than 10 picometers, which makes them small enough to pass through most materials [2]. Despite this, gamma radiation from extraterrestrial sources fails to reach the Earth's surface [3]. Gamma radiation is usually stopped in the stratosphere, which is an altitude of about 10 to 50 km. The process that keeps gamma radiation from reaching the Earth's surface is known as Compton Scattering. Figure 3 shows a gamma ray photon colliding with an electron to produce a lower energy gamma ray photon and recoil electron. Compton Scattering does not depend on the composition of the environment to occur; only the density of the environment.

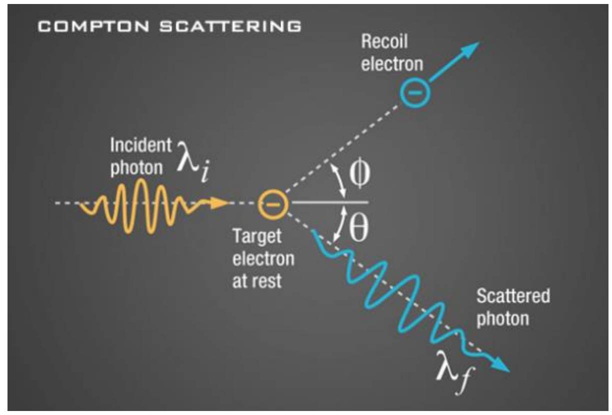

Fig. 3. Process of Compton Scattering

Gamma radiation has extraterrestrial sources such as supernova explosions, black hole accretion disks, neutron stars, and many others [4]. It is produced on Earth as well in the form of cosmic showers and terrestrial gamma ray flashes (TGFs). Cosmic showers are a process where high energy cosmic rays enter the Earth's atmosphere and break up, causing many byproducts to be created, one of those being gamma rays [3]. TGFs are created when certain types of lightning yield gamma rays. TGFs were the main study of the CubeSat known as Firefly from the NASA Goddard Space Flight Center [5].

B. Gamma Ray Bursts

Gamma ray bursts are eruptions of gamma ray light and although they are short-lived, they are the most powerful explosions in the universe, releasing more energy in a second than the Sun will in its 10-billion-year lifetime. Gamma ray light is the most energetic form of light, and thus the bursts shine hundreds of times brighter than a typical supernova and a million trillion times brighter than the Sun. These bursts can last for a few milliseconds, spanning to several minutes. Long gamma ray bursts are those that last from two seconds to a few minutes and are associated with supernovas. Short gamma ray bursts last less than two seconds and are most commonly associated with the merging of two neutron stars to form a black hole [6].

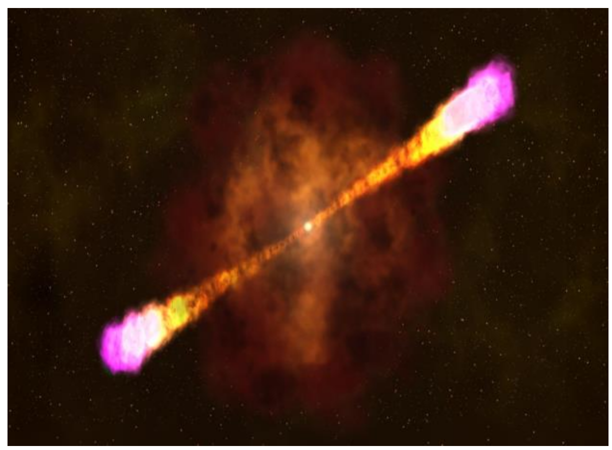

Fig. 4. Gamma ray burst

NASA's Swift and Fermi satellites measure gamma ray bursts. About one brief but intense flash per day is detected. Swift orbits in LEO and can relay the position of the burst within a few seconds of detection to Earth within 3 arcminutes of precision. It would just take a nearby burst to cause turmoil on Earth, although all bursts detected so far have been outside of the Milky Way. As the light travels, its window of impact expands, meaning that if it is pointed toward Earth then by the time it reaches Earth we could be in the window. A burst could be fatal, causing the ozone layer to be stripped away, leaving us susceptible to the Sun's radiation. This is one of many reasons why it is important and pertinent for scientists to study gamma ray bursts [7].

C. *Solar Flares*

Solar flares are intense bursts of light that occur when magnetic energy that has built up in the Sun is suddenly released. Created when complicated magnetic fields explosively rearrange themselves, they usually erupt from sunspots, which are temporary dark, cooler patches on the Sun's surface where the magnetic field is especially strong. The flares generate a burst of radiation that ranges a wide part of the electromagnetic spectrum, and are often associated with a coronal mass ejection (CME). These CMEs release plasma into space and can cause direct effects to Earth.

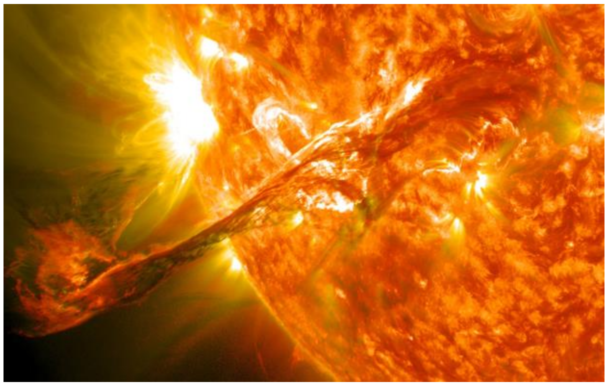

Fig. 5. Solar flare

Solar flares are classified into five different categories: A, B, C, M, or X. Classes A, B, and C are weaker eruptions that don't affect the Earth in a meaningful way. M class eruptions can cause brief radio blackouts at the poles, as well as radiation storms in the upper atmosphere that could endanger astronauts in orbit. Class X flares are detrimental, causing planet-wide radio blackouts and long lasting radiation storms. However, CMEs are by far the worst type of solar flare. With their own category, these ejections interact with Earth's magnetic field and can cause geomagnetic storms that have powerful impacts on GPS and radio communications. The most destructive CME in our recent history was in 1989, and it caused significant radio blackouts in the north hemisphere (specifically Canada and the northern United States). As CMEs and solar flares are occurrences that can potentially impact our day to day life, they are something that we owe our time and research to. NASA's Solar Dynamics Observatory (SDO) and Solar Terrestrial Relations Observatory (STEREO) both monitor them. The Sun runs on an 11-year cycle, with the last active maximum in 2011. This will be considered when our CubeSat is launched, as we will want to detect as many solar flares as possible [8] [9].

D. *Firefly*

Project Firefly was a study conducted by the NASA Goddard Space Flight Center. The study was sponsored by the National Science Foundation and took place from October 1st, 2008 to September 30th, 2011. The purpose of the study was to "study the most powerful natural particle accelerator on earth…lightning". Before Firefly, it was thought that gamma ray flashes were caused solely by events in space such as black hole mergers or other high-energy cosmic phenomena. These flashes were linked to lightning, "In addition to the tremendous head, light, and noise generated near the Earth's surface, lightning can also generate powerful beams of electrons and gamma-rays, which can only be observed by satellites, are known as Terrestrial Gamma-Ray Flashes". Firefly explored the link between lightning and terrestrial gamma ray flashes, in addition to furthering knowledge of sources of gamma radiation on a terrestrial level.

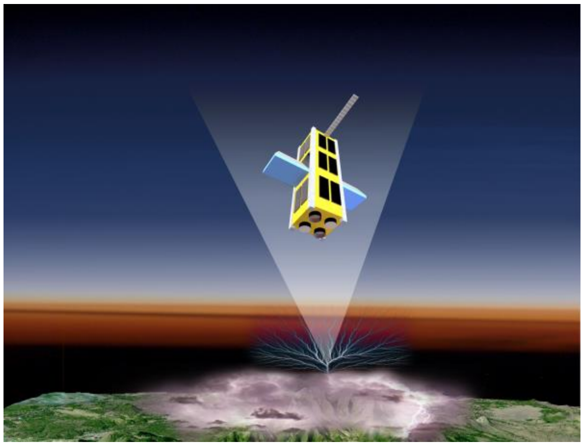

Fig. 6. Depiction of Firefly CubeSat

To accomplish this, the study had a threshold of detecting 50 TGFs with a baseline to detect 200 TGFs. The result was a successful count of 137 TFGs. Once detected, the TGF information was stored and then retrospectively analyzed to determine which type of lightning produced the most gamma radiation. Firefly's focus was on terrestrial sources of gamma radiation, while our project Serenity proposes to analyze the sources of gamma radiation coming from space. Firefly serves as an inspiration for our project because of the similarities in goals and instrumentation, but they are entirely different studies [5][10].

III. Threshold Science Goals

For our threshold science goal, we aim to see if it is possible for a CubeSat to assess the sources of gamma radiation in LEO. To accomplish this goal, we will use captured flux of gamma rays to verify our objectives that follow.

A. Solar Radiation

The threshold objective within the goal of assessing the components of gamma radiation in LEO is to validate that there are no changes in gamma radiation as the CubeSat orbits the Earth passing into its shadow. It is known that gamma rays leaving the Sun are typically scattered into lower energy [11]. We hope that looking at the difference in gamma ray flux when the CubeSat moves in and out of the shadow of the Earth will support the idea that gamma radiation in LEO is not originating from the Sun, except in the case of solar flares. This will also function as a control for our baseline objectives below, helping to limit the sources to gamma ray bursts and solar flares.

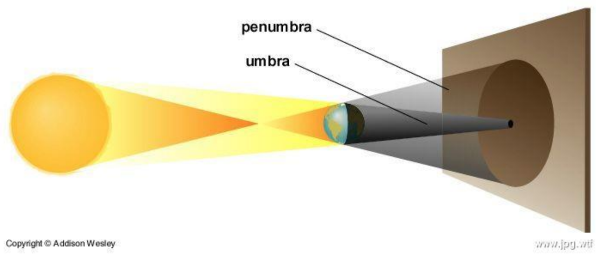

Fig. 7. Image showing the shadow of Earth

B. Gamma Ray Bursts

A baseline objective within the goal of assessing the components of gamma radiation in LEO is to compare the measurement of flux of gamma rays to known occurrences of gamma ray bursts. To accomplish this objective, we will first analyze our data to see if our instrumentation detected any drastic changes in gamma ray flux and attempt to isolate possible GRB occurrences. Afterwards, we will compare our data to that of NASA's Fermi satellite, which looks at GRBs. We will compare any known occurrences of gamma ray bursts with our measurement of flux of gamma rays in LEO. This comparison will aim to link certain increases in gamma rays in LEO to the occurrence of a gamma ray burst.

C. Solar Flares

A baseline objective within the goal of assessing the components of gamma radiation in LEO is to compare the measurement of flux of gamma rays to known occurrences of solar flares. To accomplish this objective, we will first analyze our data to see if our instrumentation detected any drastic changes in gamma ray flux and attempt to isolate possible solar flare occurrences. Afterwards, we will compare our data to that of NASA's RHESSI satellite, which looks at solar flares. We will compare any known occurrences of solar flares with our measurement of flux of gamma rays in LEO. This comparison will aim to link certain increases in gamma rays in LEO to the occurrence of a solar flares.

IV. BASELINE SCIENCE GOAL

For our baseline science goal we aim to see if it is possible for a CubeSat to detect the direction of sources of gamma radiation in LEO. In order to accomplish this goal we will use captured gamma ray flux to verify our objectives that follow.

A. Directionality of Solar Flares

The threshold objective within the goal of detecting the direction of the gamma radiation sources is to calculate the direction of solar flares. We will know the CubeSat's position in space as it moves in orbit and also the position of the Sun at a given time due to timestamps on the data collected from Serenity. This data combined with our science objective that aims to detect when solar flares occur will allow for us to calculate the direction that the Sun is in relation to our CubeSat. The direction of the Sun will function as a control for our baseline objective within the baseline science goal since we will know the position of both the Sun and the CubeSat.

B. Directionaly of Gamma Ray Bursts

The baseline objective within the goal of detecting the direction of the gamma radiation sources is to calculate the direction of GRBs. We will know the CubeSat's position in space as it moves in orbit and will use the same method of calculating the direction that was derived from the threshold objective used to calculate the direction of the Sun from captured solar flares. To calculate the direction of GRBs we will use the data collected from our threshold science goal involving the detection of known GRB occurrences. We will use the gamma ray flux detected from the three gamma ray detectors on the XYZ axis at a given timestamp matching the occurrence of a known GRB to calculate the direction of the GRB.

V. INSTRUMENTATION

A. Gamma Ray Detector

The gamma ray detector will be the main instrumentation to achieve our science goal and objectives. Without it, our mission would be unsuccessful since we would not be able to collect any data about gamma radiation. The gamma ray detector will be made of two main components: a photodetector and a scintillator. We chose to go with the mini-Planacon™ photodetector and BGO crystal scintillator. Our reasons for choosing these two are because they pair well together, meet our size requirements, and a similar setup was used on the Firefly CubeSat. These two components are compatible because the BGO crystal scintillator has a maximum emission at a wavelength of 480 nm (range 300-600nm) and the min-Planacon™ photodetector has maximum sensitivity at a wavelength of 380 nm (range 200-650nm).

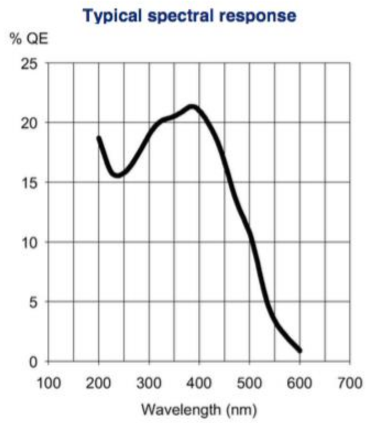

Fig. 8. Emission spectrum of a mini-Planacon™ photodetector

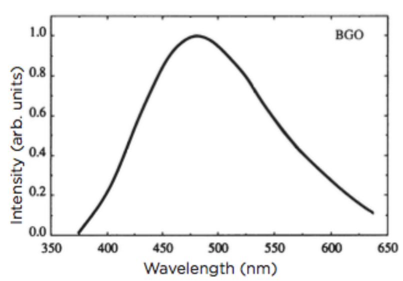

Fig. 9. Emission spectrum of BGO crystal scintillator

The size of the mini-Planacon™ photodetector is 32 by 32 by 24 mm and has a mass of approximately 50-100g [12]. The scintillator will be custom made to fit our photodetector and has a density of 7.13 g/cm^3 and our crystal will need to be 3.93mm thick to scintillate at least 90% of the gamma radiation up to 200keV [13][14]. A thicker crystal would allow us to assess higher energy level sources, but over 95% of all solar flares only have energy levels below the 200keV threshold [15]. This means each scintillator will have an approximate mass 16.14g.

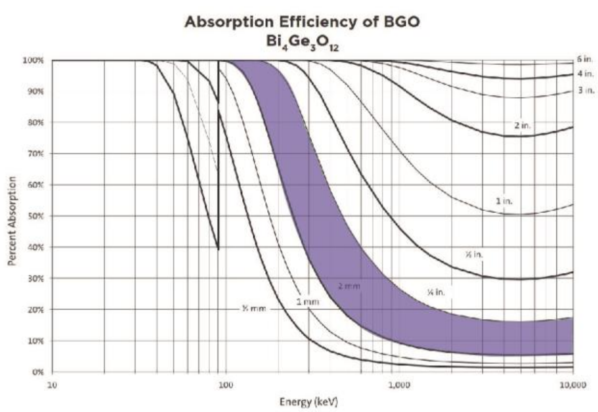

Fig. 10. Absorption efficiencyt of BGO with expected range highlighted

We plan to have 3 different gamma ray detectors placed with different orthogonal directions along the XYZ axis so that we may have a field of view that covers all directions. This will also allow us to find the direction of the source of gamma radiation. This will bring the maximum mass of gamma radiation detector to 348.42g that is well below the 1kg requirement given by the engineers.

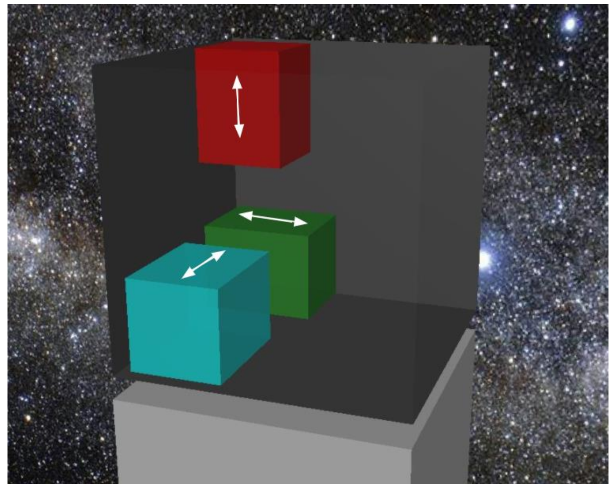

Fig. 11. A 3 dimmensional representation of our CubeSat layout

The process that which the gamma detector senses the gamma radiation is the following (see Figure 12):

1. Incident gamma photon strikes the scintillator to release a lower energy photon.
2. The lower energy photon enters the photocathode of the photodetector to produce a photoelectron.
3. The photoelectron strikes the photocathode to produce a photoelectron.
4. The photoelectron will pass through a photomultiplier to multiply the number of electrons.
5. These electrons will collide with anodes, generating a drop-in voltage.
6. This drop-in voltage will be recorded by and on-board computer and will be proportional to the amount of gamma radiation detected.

B. GPS

The GPS-702-GG-HV Antenna is the engineer's chosen GPS antenna. The rotation of the antenna or satellite elevation do not affect signal reception. It is enclosed in a durable housing which gives increased robustness for use under high vibration conditions. It is reliable within typical ranges and can operate at -40°C to 85°C.

VI. Mission Design

This mission will be implemented through the use of a CubeSat, which is a miniature satellite used for space research. They are built to a standard specification of 10 x 10 x 10 cm which is 1 unit, or U. One U weighs about 3 pounds, and they are launched with rockets as auxiliary payloads to reduce the costs. They can be assembled in different sizes such as 1U, 2U, 3U, or 6U. The Poly Picosatellite Orbital Deployer, or P-POD, is the CubeSat deployment system. It is a rectangular box with a hinge door and torsion springs used to eject the CubeSat into orbit by pushing the CubeSat along a series of rails.

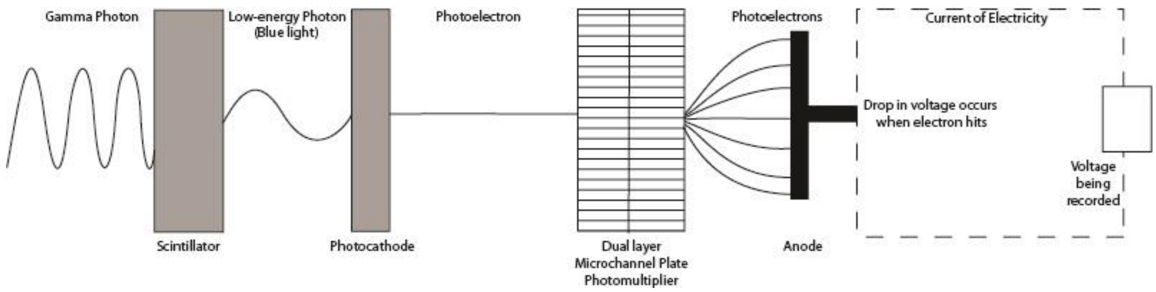

Fig. 12. Process of a gamma photon interacting with the components of a gamma ray detector

A. *Army System Requirements*

For the mission design, the Army has a list of system requirements that they require to be measured. For the CubeSat, they want to measure lift, drag, magnetic field, radiation, and the GPS performance in Low Earth Orbit. The CubeSat will be 3U CubeSat with a 10kg mass maximum. The proposed orbit will be at an altitude of 350km, and it will be designed to be in orbit for 6 to 9 months. The orbits the engineers gave us could potentially be circular or elliptical, but either will work for our science goal. With these system requirements, our team decided to focus on the radiation and GPS performance requirements. With radiation, our focus was on gamma radiation because “[g]amma rays can cause ionisation (sic) of other materials when present at high enough energies and this can cause serious and permanent damage to human tissue” [16]. For GPS, our plan is to verify the coordinates of GPS by matching that data with the gamma radiation data we receive.

B. *Data Acquisition*

While Serenity is in LEO, data will be downloaded once per orbit. The data will be cleared on the onboard computer after it is downloaded each time in the interest of storage capacity. This is due to us capturing as much data as possible to have a large sample size to compare to currently existing satellites. All data collected will be accompanied by a timestamp so that it easily be compared to the data collected by NASA’s other satellites.

C. *Data Products*

Figure 13 is a data spread obtained from the FERMI satellite tracking gamma ray burst counts from 2013. Along the x-axis is the time, in seconds, and the y-axis has the count, divided into three energy ranges. This is an example of what the data we collect may look like.

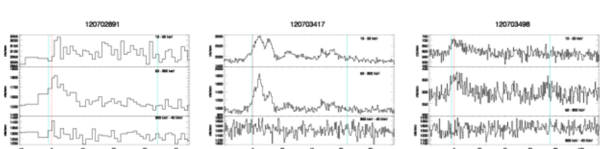

Fig. 13. Sample data from FERMI satellite

Figure 14 is data from the RHESSI satellite tracking solar flares from 2001. The data measures the count rates and energy levels, as well as flux versus energy and produces a reconstructed image of the data based on the gathered readings.

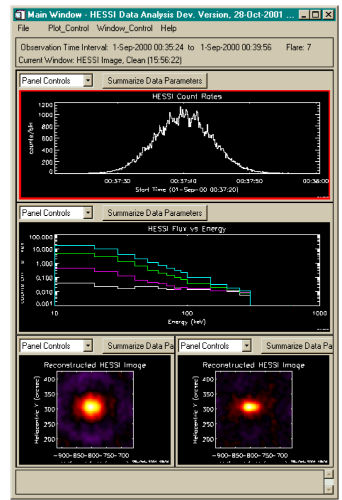

Fig. 14. Sample data from RHESSI satellite

We can estimate the number of solar flares and GRBs to be detected based on the frequency of solar flares and GRBs, the length of the mission, and the field of view of our CubeSat's gamma ray detectors. We estimate to measure a minimum of 85 solar flares and 85 GRBs under the worst conditions of launching at the minimum of the Solar cycle and only operating for 6 months. If launched under ideal conditions such as at the maximum of the Solar cycle and operating for 9 months, we could see as many as 2600 solar flares and 1700 GRBs.

VII. Conclusion

Our project measures gamma ray flux in LEO to assess the sources of gamma radiation. The flux measurements will be compared to satellites already in orbit to confirm readings and attempt to validate that gamma radiation can be detected in LEO. Three gamma ray detectors covering an XYZ axis will be utilized to investigate if it is possible to discern the location of these sources. If this mission is a success it will prove the ability of a CubeSat to perform tasks previously only done by much larger satellites. With increased interest in Mars this will allow for CubeSats to cheaply and readily be used to study the atmospheric environment of the planet.

Acknowledgment

Our team would like to acknowledge our instructors, Dr. Cassandra Runyon and Dr. Jon Hakkila, for all of their help in shaping our experiment and running the NASA Space Mission Design course. This course has greatly enhanced our teamwork skills, particularly those relating to working as part of a large team split between two locations.

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Science Goals	Objectives	Measurements / Data Collection	Instrumentation	Expected Measurement
Assess the sources of gamma radiation in Low Earth Orbit (LEO)	Validate that gamma radiation in LEO is not from the Sun except in the case of a solar flare	Measure flux of gamma radiation	Planacon Photodetector with BGO crystal scintillator	Gamma radiation flux should change little in orbit in the absence of a GRB or solar flare
		Examine the position of the CubeSat to determine location in orbit	GPS-702-GG-HV Antenna	Location of CubeSat in orbit
	Compare any changes in gamma ray flux with known gamma ray burst occurrences	Measure flux of gamma radiation	Planacon Photodetector with BGO crystal scintillator	Gamma ray flux should increase in the presence of a GRB
		Analyze the data captured by NASA's FERMI Gamma Ray Burst Mission	NASA's FERMI Gamma Ray Burst Mission	Capture an estimate of 85 to 1737 GRBs over 6-9 months
	Compare any changes in gamma ray flux with known solar flare occurrences	Measure flux of gamma radiation	Planacon Photodetector with BGO crystal scintillator	Gamma ray flux should increase in the presence of a solar flare
		Analyze the data captured by NASA's Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)	Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)	Capture an estimate of 85 to 2600 solar flares over 6-9 months
Demonstrate the capabilities of calculating relative direction of gamma radiation sources on a CubeSat in LEO	Validate ability to match location of solar flares to the location of the sun	Analyze the location and orientation of the CubeSat to determine the relative location of the Sun	GPS-702-GG-HV Antenna	Direction of the Sun relative to the CubeSat
		Combine data collected by the three gamma ray detectors to determine location relative to the CubeSat on XYZ axis	3 Planacon Photodetectors with BGO crystal scintillator on XYZ axis	Direction of solar flares relative to the CubeSat
	Calculate location of gamma ray burst occurrences	Combine data collected by the three gamma ray detectors to determine location relative to the CubeSat on XYZ axis	3 Planacon Photodetectors with BGO crystal scintillator on XYZ axis	Direction of GRBs relative to the CubeSat