High Energy Lightning Emission Network

Mission Summary

Abstract

Terrestrial Gamma-ray Flashes (TGFs) are intense bursts of gamma-rays which are produced in the atmosphere and thought to be caused by intra-cloud and positive cloud-to-ground lightning. The leading theories suggest strong electric fields inside of thunderstorms can become momentarily destabilized by a stroke of lightning, which causes the acceleration of electrons in the opposite direction of the electric field. However, the specifics of these theories, including the direction of the electric field, the origin of the electric field, TGF propagation characteristics, and TGF source location, are still unknown. The High Energy Lightning Emission Network (HELEN) project at The University of Alabama in Huntsville will directly measure some of the unknown characteristics of TGFs including electric field strength and direction, bounds on the TGF cone of emission, the energy spectrum of a TGF, TGF source location, and the neutron fluence of a TGF. This project is set to have its first launch in late summer of 2019 and will work towards more launches in 2019 and 2020. The flights involve simultaneously launching four high altitude weather balloons, carrying two instrument payloads each, at different launch locations immediately after a strong storm has passed overhead. Once recovered, the payloads can be re-flown during the next strong storm. Once the data from the flights are retrieved, the evolving electric field structure of the thunderstorm and the radiation event spectra will be derived and correlated. Leading TGF models will then be compared to the gathered data. Results from the analysis of the first campaign of flights are to be published summer of 2020.

Background

Terrestrial Gamma-ray Flashes (TGFs) are intense bursts of gamma-rays and other particles such as electrons, positrons, and neutrons that are produced in the atmosphere during thunderstorms. TGFs are a relatively recent discovery, with the first detection made in 1994 by the Burst And Transient Source Experiment (BATSE), a spacecraft intended for detecting gamma-ray flashes from space. (Fishman 1994). TGFs have been correlated with lightning events and, more specifically, with intra-cloud and positive cloud-to-ground lightning (Stanley 2006, Shao 2010). The leading theory suggests strong electric fields inside of thunderstorms can become momentarily destabilized by a stroke of lightning, which causes the acceleration of electrons in the opposite direction of the electric field. The accelerated electrons liberate other electrons which are also accelerated by the electric field producing a runaway avalanche of electrons (Dwyer 2008). The electrons also interact with nuclei in air molecules creating high energy gamma-rays (bremsstrahlung) radiation. More recently, TGFs have been shown to produce neutrons although the exact energy and fluence of these neutrons is still largely undetermined (Köhn 2017). TGFs have been detected from orbiting satellites, from the ground, and once from an aircraft. These measurements have been enough for researchers to construct general models for TGFs but the specifics of these models including the direction of the electric field, origin of the electric field, TGF propagation characteristics, and TGF source location are still unknown. In addition, the geometry of emission is unknown, along with the exact physical mechanism used to begin the TGF. A TGF has also never been observed close to its source.

The High Energy Lightning Emission Network (HELEN) will directly measure the unknown characteristics of TGFs including electric field strength and direction, TGF propagation bounds, the energy spectrum of a TGF, its source location, and neutron energy and fluence. HELEN will accomplish this by flying a network of instruments on high altitude weather balloons above strong, lightning-producing thunderstorms.

The science objectives of the mission are that TGF source locations will be correlated with local cloud-to-ground and intracloud lightning strikes, bounds on the TGF cone of emission will be determined, the photon flux and energy spectrum of the TGF will be correlated with the measured electric field strength and structure of the thunderstorm, and the neutron energy spectrum and fluence of the TGF will be determined.

TGF source location, especially altitude, will help scientists develop exact models of TGF formation, narrow the current bounds on TGF altitude, and reconcile the various altitude prediction in certain models. For example, the DC field model cites a source altitude of 15 to 25 kilometers, the EMP model requires an altitude greater than 21-kilometers, and cosmic ray models require altitudes of around 35 kilometers (Dwyer 2005, 2008). HELEN will record TGF source locations within a kilometer altitude resolution, providing strong evidence for certain models over others. Different models provide different cones of emission, or “beam angles,” depending on the mechanism producing the TGF (Grefenstette 2008). HELEN will provide characteristics of the cone of emission by using multiple payloads to gather flux data over a rough angular distribution. Models also differ on the strength and duration of the electric field (Briggs 2010). HELEN will provide measurements of the time varying electric field around the thunderstorm. Neutrons have also been predicted to be produced by TGFs but have never been directly measured (Köhn 2017). HELEN would provide the first direct detection of high energy neutrons inside of thunderstorms. This provides implications beyond TGF research as it would be further confirmation of the predicted nuclear processes that occur in thunderstorms (Enoto 2017).

Other balloon-borne radiation detection instruments have launched single payloads around thunderstorms but did not detect TGFs (Ringuette 2014). Launching a network of reusable instruments will greatly increases the chances of the detection of a TGF as our setup will cover a wider area and can be launched more than once. A detection of a TGF by HELEN would be a first by a balloon borne instrument.

Design

HELEN will consist of a network of eight payloads flying on four separate high-altitude balloons. These balloons will be launched fifteen to thirty minutes after a strong, lightning-producing thunderstorm has passed overhead. For safety, balloons and payload trains will be prepared indoors, with only the balloon release occurring outdoors. The balloons will be prepared in three to four different locations, each staffed with their own flight team of 4 to 10 people. A launch coordinator will monitor the launches from a central location and will coordinate with all the stations.

Each balloon train will consist of two payloads (Figure 1): A Radiation Detection Payload (RDP) and an Electric Field Meter (EFM).

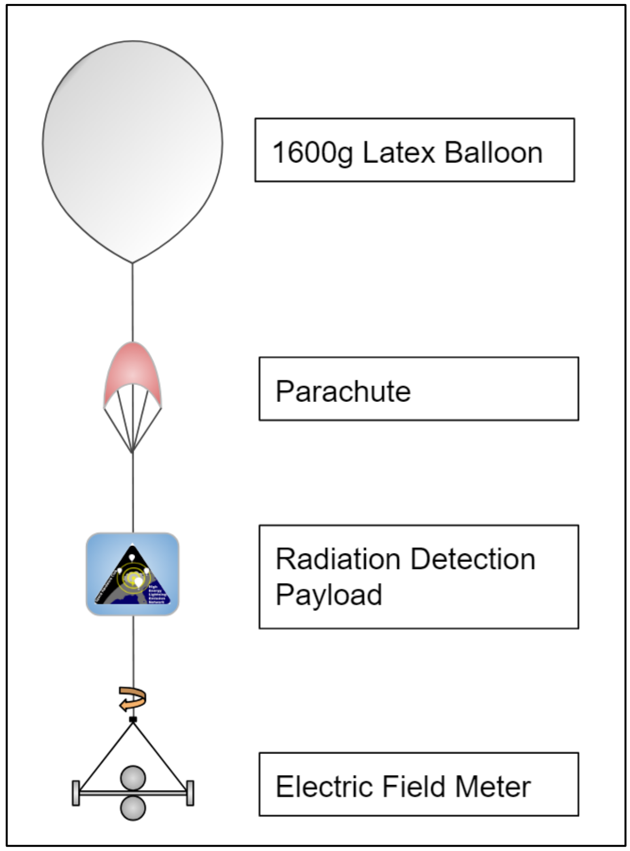

Figure 1: HELEN Balloon Train Consisting of Two Instruments, a Radiation Detection Payload (RDP) and an Electric Field Meter (EFM).

The RDP (Figure 2) will use a scintillator array mounted onto a PhotoMultiplier Tube (PMT) to measure the energy and type of radiation present in its environment. The chosen scintillation material, LSYO, has many desirable characteristics for this application including a fast decay time, high energy resolution, and a large neutron cross section. Radiation that hits the scintillator causes emission of light, which is captured by the PMT. This generates a current pulse in the photomultiplier tube. When passed through a preamplifier, the current is converted to a voltage and sent to a Field Programmable Gate Array (FPGA). The FPGA will use numerical integration on the processed pulse and linear correlation between the energy of particle and area under the curve to determine the particle energy. Different types of radiation have differently shaped voltage curves, so a technique known as Pulse Shape Discrimination (PSD) will be used to determine the radiation type. By measuring the difference between the total energy of the curve and the energy contained in the tail of the curve, PSD can distinguish between gamma rays, neutrons, and alpha particles. Each radiation pulse, or event, will be time tagged by the FPGA. An onboard GPS receiver will both read the location of each payload and maintain clock synchronization across the network. A Raspberry Pi camera mounted in the RDP will also record video throughout the flight. All the data collected by the radiation detection payload, including radiation events, environmental data, and video, will be saved to onboard micro SD cards.

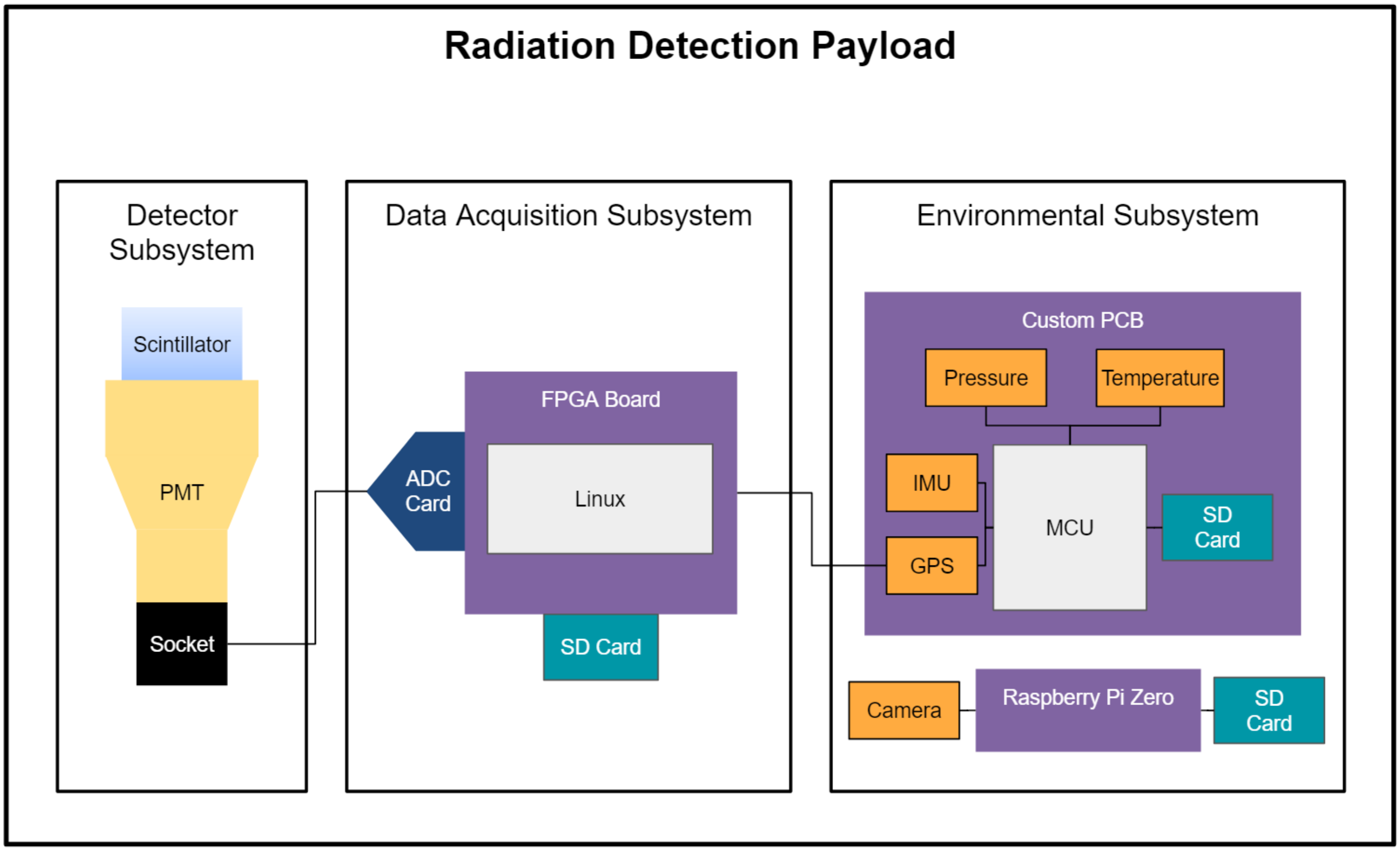

Figure 2: HELEN Radiation Detection Payload Comprising of Three Subsystems

Detector Subsystem: A LYSO crystal is mounted to the top of a PhotoMultiplier Tube (PMT) and the coupled to a socket that provides high voltage power to the PMT and converts the output current of the PMT into a voltage for the Data Acquisition Subsystem to read.

Data Acquisition Subsystem: A DE-10 Standard Field Programmable Gate Array (FPGA) Development Kit running Linux connected to an Analog to Digital Converter (ADC) Card will read, process, and save radiation data from the Detector Subsystem. The FPGA also keeps time via the GPS module on the Environmental Subsystem.

Environmental Subsystem: A custom Printed Circuit Board (PCB) containing environmental sensors such as pressure, temperature, Inertial Measurement Unit (IMU) data, and GPS position and speed will read and save data about the environment the payload is in. The subsystem will also have a raspberry pi camera to record video of the flight and any lightning events.

The EFM (Figure 3) has two aluminum spheres that rotate on a fiberglass rod connected to two wind vanes on either side. A custom Printed Circuit Board (PCB) equipped with a microcontroller, charge converting operational amplifiers, and an Inertial Measurement Unit (IMU) will be mounted inside one of the aluminum spheres. The charge difference between the spheres will be measured by the charge converting operational amplifiers. Using the charge measurement combined with directional measurements from the IMU, the electric field in the direction of the sphere can be determined. Since the spheres rotate about both the rod and the balloon line, electric field measurements can be swept out and the total electric field magnitude and direction can be determined.

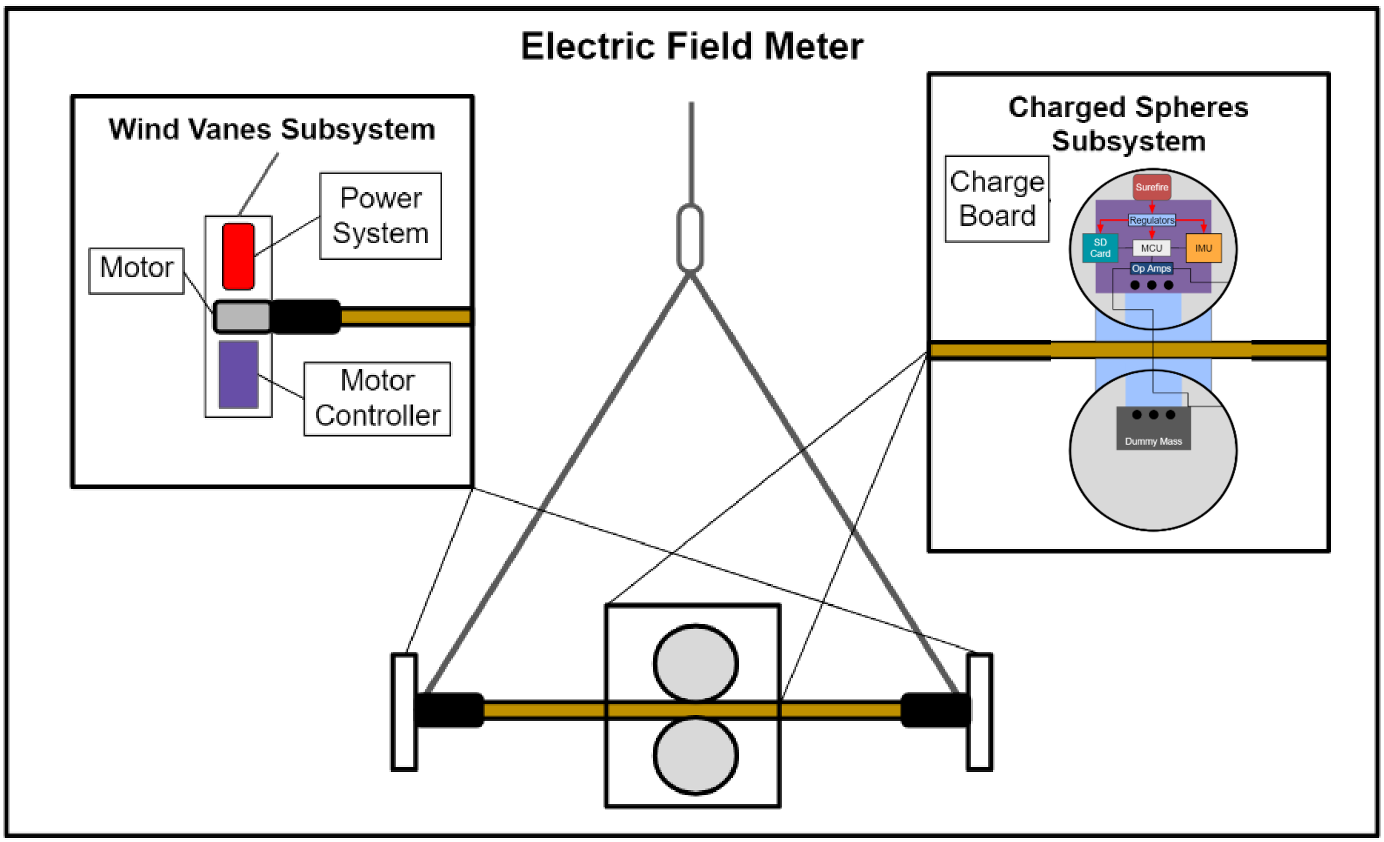

Figure 3: HELEN Electric Field Meter Comprising of Two Subsystems

Wind Vanes Subsystem: A motor, motor controller, and battery drive the rotation of the rod and spheres at 2 Hz.

Charged Spheres Subsystem: A small custom Printed Circuit Board (PCB) containing a battery, MicroController Unit (MCU), Inertial Measurement Unit (IMU), and charge amplifiers determines the electric field given the charges measured on the spheres and the direction as reported by the IMU.

Methodology

Once data from the flights have been gathered, they will be analyzed and compared with models of TGFs. The radiation data from one payload will include the energy and particle type of every event that interacts with the payload. Any period of elevated radiation levels will be cross checked with the other payloads' radiation data to see if they are correlated. Using the GPS data gathered by the payloads, a map can be made showing the position of the four payloads relative to the storm at any point during the flight. If a radiation event is shown to be correlated between payloads, then the timing of the event, the relative strength and spectrum of radiation, and the location of each payload will be used by a multilateration algorithm to pinpoint the source location of the radiation.

The voltage data and IMU data from each EFM payload will be processed by a custom script to determine electric field strength and direction for every 30 second interval through out the flight. Using the electric field data from each payload, a rough time varying 3-D structure of the large-scale electric field of the thunderstorm can be determined. Any sudden changes in electric field with be cross checked with radiation events to see how radiation events are corelated with the change electric field of the storm.

After the location, spectrum, and electric field correlation of an event is determined, radar data and radio lighting network data with be used to put the event in the context of the storm. Aspects such as where in the storm the event occurred, what phase the storm was in, and what lightning was correlated with the event will be derived.

Finally, models of TGF formation will be run and the expected results from each model will be simulated using GEANT4, a software tool for the passage of radiation through matter. The results of this comparison will be published in a paper that discusses the project and its findings.

Significance

The significance of this research would be to directly measure the unknown characteristics of TGFs, such as electric field strength and direction, propagation bounds, energy spectrum, source location, and neutron energy and fluence, and, ultimately, to identify the mechanism of Terrestrial Gamma Ray Flashes and provide more insight on the nuclear reactions possible in the atmosphere. Even if a TGF is not detected throughout campaign, HELEN will provide insight into neutron interactions within gamma ray glows, a lower energy phenomenon that occurs more commonly.

In addition to research significance, the project will provide a multidisciplinary challenge to a motivated groups of undergraduate students learning topics such as radiation measurement, pulse processing, FPGA programming, Linux development, high speed data management, embedded programming, PCB design, sensor interfacing, power management, 3D printing, computer aided design, environmental testing, laboratory research, management, event organization, and working in a team. The project will also provide STEM outreach to local middle schools, teaching topics like programming, electronics, and mechanical design. The outreach with culminate with a high-altitude balloon launch (not during a thunderstorm) which the students will participate in.

Personnel

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Jennifer Miller – Mechanical Assembly – Junior – Physics

References

Briggs, M. S., et al. “First Results on Terrestrial Gamma Ray Flashes from the Fermi Gamma-Ray Burst Monitor.” *Journal of Geophysical Research: Space Physics*, vol. 115, no. A7, 30 July 2010, doi:10.1029/2009ja015242. Wiley Online Library.

Dwyer, J. R., and D. M. Smith. “A Comparison between Monte Carlo Simulations of Runaway Breakdown and Terrestrial Gamma-Ray Flash Observations.” *Geophysical Research Letters*, vol. 32, no. 22, 28 Nov. 2005, doi:10.1029/2005gl023848. University of California.

Dwyer, J. R. “Source Mechanisms of Terrestrial Gamma-Ray Flashes.” *Journal of Geophysical Research*, vol. 113, no. D10, 20 May 2008, doi:10.1029/2007jd009248. Wiley Online Library.

Enoto, Teruaki, et al. “Photonuclear Reactions Triggered by Lightning Discharge.” *Nature*, vol. 551, no. 7681, 22 Nov. 2017, pp. 481–484., doi:10.1038/nature24630.

Fishman, G. J., et al. “Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin.” *Science* vol. 264, Issue 5163, pp. 1313-1316 May 27, 1994.

Grefenstette, B. W., et al. “Time Evolution of Terrestrial Gamma Ray Flashes.” *Geophysical Research Letters*, vol. 35, no. 6, 18 Mar. 2008, doi:10.1029/2007gl032922. Wiley Online Library.

Helmerich, Christopher, et al. “Radiation Detection in Various High Altitude Environments.” 2017. https://via.library.depaul.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1121&context=ahac

Köhn, Christoph, et al. “Production Mechanisms of Leptons, Photons, and Hadrons and Their Possible Feedback Close to Lightning Leaders.” *Journal of Geophysical Research: Atmospheres*, vol. 122, no. 2, 27 Jan. 2017, pp. 1365–1383., doi:10.1002/2016jd025445. Wiley Online Library.

Ringuette, Rebecca. https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=3933&context=gradschool_dissertations. 2014

Shao, Xuan-Min, et al. “A Closer Examination of Terrestrial Gamma-Ray Flash-Related Lightning Processes.” *Journal of Geophysical Research: Space Physics*, vol. 115, no. A6, 3 June 2010, doi:10.1029/2009ja014835. Wiley Online Library.

Stanley, Mark A., et al. “A Link between Terrestrial Gamma-Ray Flashes and Intracloud Lightning Discharges.” *Geophysical Research Letters*, vol. 33, no. 6, 17 Mar. 2006, doi:10.1029/2005gl025537. Wiley Online Library.