Proceedings of the National Conference
On Undergraduate Research (NCUR) 2013
University of Wisconsin Lacrosse, WI
April 11-13, 2013

Atmospheric Stratification of Terrestrial Gamma-ray Flashes (TGFs) and Capture of Electromagnetic Phenomena in the Southern Appalachian Region

Michele K. Coker
Department of Chemistry and Physics
Western Carolina University
Cullowhee, NC. 28723

Faculty Adviser: Dr. Enrique Gomez

Abstract

Verso l'alto is a multi-disciplinary undergraduate research and development project whose goal is to gain insight into the upper atmospheric electromagnetic environment above the Southern Appalachian Mountains. Using high altitude weather balloons, Verso l'altos' payload carries scientific and amateur radio equipment in order to record cosmic radiation fluctuations and locate gamma rays that produce terrestrial gamma-ray flashes (TGFs). TGF's commonly form in high electrical fields within and above thunderstorms and snowstorms in the troposphere and tropopause; where they produce a shot of intense gamma radiation that is hurled into space. A high-speed camera is also included within the payload to capture images of the region and of the lightning in the upper atmosphere. Live tracking and telemetry of the flight is performed by amateur radio, and coordinates are uploaded to aprs.fi for real-time access online. The chase team consists of three licensed mobile amateur radio vehicles and licensed undergraduate amateur radio operators who track and retrieve the payload. This project encourages cooperation between local communities, scientific organizations and academic institutions, in order to better understand the impact of cosmic radiation fluctuations from the ground into the mid-stratosphere, where direct observation is extremely limited. A launch of Verso l'alto was conducted in October 2012 and a second launch is scheduled for December 2012. In the October flight, radio and tracking equipment indicated the balloon rose to an altitude over 76,271 feet, covering 43.25 direct miles in a southeasterly flight path. Throughout the journey, a radiation dosimeter recorded cosmic radiation, which generally increased with altitude. The onboard camera captured 476 pictures during the 117 minutes of the operation. In December 2012, it is anticipated that a new digital radiation monitor will more precisely record the variations in radiation counts in each atmospheric layer during the flight. This project brings together interdisciplinary scientists, engineers, and students, which further enhances multiple STEM fields.

Keywords: Atmospheric radiation, thunderstorms, cosmic rays.

1. Introduction:

Cosmic rays that bombard our planet interact with the terrestrial atmosphere; the troposphere, tropopause, and stratosphere. These cosmic particle showers are modulated by solar wind and the terrestrial weather, which influence the amount of charged particles entering our atmosphere. During thunderstorms, the electric field fluctuates dependent upon lightning activity and storm cloud production. Muons are the most penetrating part of the showers and their large energy provide information on how primary cosmic ray fluxes interact with the atmosphere.

Terrestrial Gamma ray Flashes, (TGFs), are brief pulses of gamma radiation that are generated within the lower troposphere and emit photons out into space.[1] Discovered in 1994 by RHESSI and Fermi satellite detectors, TGFs usually form during a thunderstorm or in intense electrical activity. Typically lasting a millisecond or less, TGFs can have photon energies exceeding 20 MeV.[2] Since gamma-rays are absorbed by the atmosphere; the scarcity of TGFs seen by satellites might have an obstructed view of their production in the lower troposphere. The distribution of TGFs at intensities below those seen from space does not follow a power law distribution and determining their mechanism of production has posed a challenge to scientists. It is still unclear if these photon energies follow a geomagnetic field line upon escape, or if the moment of origination occurs at the peak of intracloud (IC) lightning as a lag in its tail leading to cloud to ground (CG) peaks.[3] Storm cloud production and height during a thunderstorm, along with atmospheric pressure also pose questions if a single storm system produces multiple TGFs, or how to localize them.[4] See section 3.6, Supplementary data analysis for further details.

The Southern Appalachian region is geographically located in the south east of the US, with WCU nestled in the Great Smoky Mountains of Western North Carolina. The climate in this region varies from sub-tropical in the summer to harsh and sub-alpine winters in the higher elevations. Weather patterns that traverse the region are diverse, and as a system moves across the mountains, their energy is displaced which creates pockets of intense thunderstorm cells throughout the area. Could these displaced cells harbor a source for gamma radiation? If TGFs occur and generate at low intensities in the troposphere, can Verso l'alto detect them?

2. Methodology:

Using high altitude weather balloons equipped with small payloads, each balloon experiment is launched from Jackson County Airport in Cullowhee, NC. (See figure 1) Verso l'alto's cargo consists of a scientific payload to record atmospheric radiation, a Cannon A495 camera programmed to take pictures every 10 seconds, and a payload equipped with amateur radio equipment for tracking. (See figure 2) For Catamounts 4-5, a Vernier digital radiation monitor to record counts of beta and gamma radiation is connected to a Labquest 2 (LQ) data acquisition device. The LQ is programmed to receive the counts of radiation every minute, and records all of its counts for the time programmed. Figure 2 shows all of the balloon's payload equipment. All balloons are chased after its launch from the Jackson County Airport to its impact site, via APRS (Figure 3) which shows its trajectory online. A 6 foot parachute safely allows the balloon to coast to its landing destination. Locating the balloon after landing requires the operators to use directional antennae and Radio Directional Finding (RDF). Each operator uses the antenna to tune in the balloon's beacon by sound and direction to locate the payload. (See figure 4).

Figure 1: Cat 5 liftoff. There is 10 feet between the balloon and parachute, and both payloads.

Catamount 1 was launched in October 2011 from Landrum, SC. Using a cell phone for gps, Cat-1 was not retrieved. Catamount 2 was also launched from WCU campus in May 2012. Also using a cell phone for gps, Cat-2 was not recovered. It was then decided to purchase the amateur radio equipment and construction of Cat-3 began.

2.1 Flight equipment:

Amateur radio frequencies and equipment used to track and communicate with the balloon are licensed and experienced amateur radio operators who have volunteered to engineer and operate the communications systems in accordance with Federal Communications Commission (FCC) rules. The call sign for Verso l'alto is K4WCU-11.

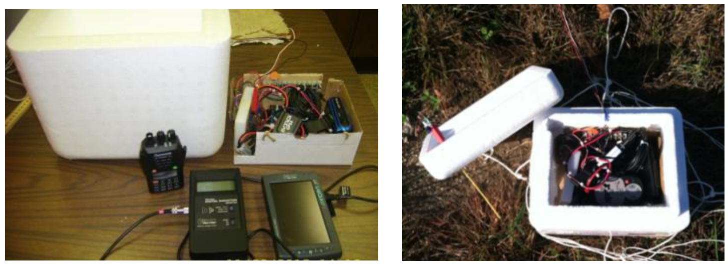

Figure 2: Verso l'alto's flight equipment. Vernier digital radiation monitor is connected to a Labquest2 to record atmospheric radiation counts. Amateur radio equipment is used for tracking of the balloon.

To determine and transmit the balloons' latitude, longitude, and altitude, a very lightweight GPS receiver, APRS encoder and VHF/UHF transceiver is included in the payload. The APRS encoder is a device which receives GPS coordinates from orbiting satellites and reformats them into an open digital packet radio protocol called Automatic Position Reporting System. (See figure 3) The encoder then converts these packets into audio tones that are rapidly transmitted by a standard FM voice transmitter operating in the 2 meter amateur radio band. If a frequency of 144.39 MHz is used, and automated APRS stations all over the world can listen for packets transmitted on this frequency. Packets are automatically uploaded to the internet and are instantaneously available at http://aprs.fi/.

Figure 3: APRS flight path of Cat-4 from December 15, 2012. The beacon packets are transmitted every 60 seconds and show the balloon's flight path, altitude, heading, time, and mph it is horizontally traveling.

2.2 Chase equipment:

All amateur radio chase vehicles are equipped with a laptop running APRSICE software, a 2 meter mobile radio and a Byonics Tiny Trak 4 for optimal coverage during flight. APRSICE software is an amateur radio real time tactical display program written for Windows mobile operating systems. For tracking in real time, the program interfaces with a network of servers that are gathered from stations operating on the internet and/or the radio network. Users on the radio network (RF) can operate completely detached from the internet. This is a very useful tool to have during a chase, since most of the area covered is within a dead zone of phone/internet reception. (Figure 4 shows the laptop and mobile unit). All operators participating in the chase keep in radio contact, and report thoroughly each time a packet is received.

Radio Direction Finding, (RDF) is used to locate the balloon once it has landed by tracking the 100mW beacon signal. The antennae tune in on the beacon signal from the payload; the stronger and more frequent the signal is, the closer the payload is to being recovered. Catamounts 3-5 have all safely landed in tree tops and were retrieved undamaged.

Figure 4: Cat 4 impact location. Chase equipment in each mobile vehicle. Directional antennae used to locate after its impact.

3. Data:

3.1 Catamount 3:

On October 13, 2012 Cat-3 was launched from the Jackson County Airport at 11:29 am. This was the first flight using the radio equipment for tracking. The balloon rose to 76,271 feet, covering 43.25 direct miles in a southeasterly path, with its impact in Dacusville, SC. The camera captured 476 pictures in flight, including Figure 5 of WCU campus. A small radiation dosimeter recorded cosmic radiation, which generally increased with altitude.

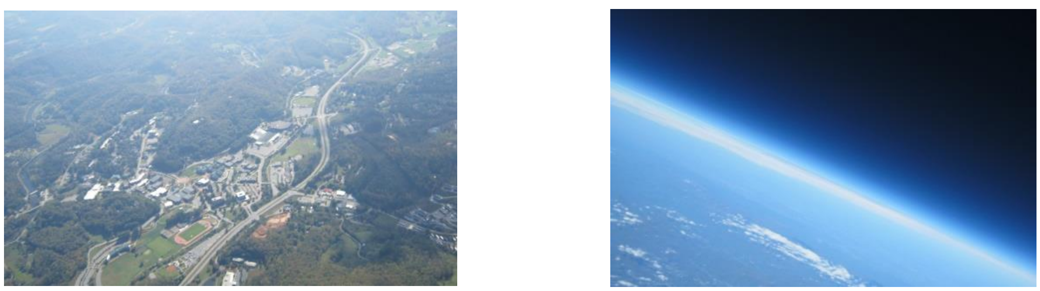

Figure 5: WCU campus at 6,541 feet and NC/SC border at 64,353 feet taken from Cat-3.

3.2 Catamount 4:

Catamount 4 launched from the Jackson County Airport at 10:06 am on December 15, 2012. The balloon rose to 88,656 feet, covered 216 miles, with its impact in Wingate, east of Monroe, NC. The onboard camera captured 750 pictures during its three hour flight. (Figure 6) An overnight stay was required for two team members as the property owners were located. Cat 4 suffered no damage and was successfully collected.

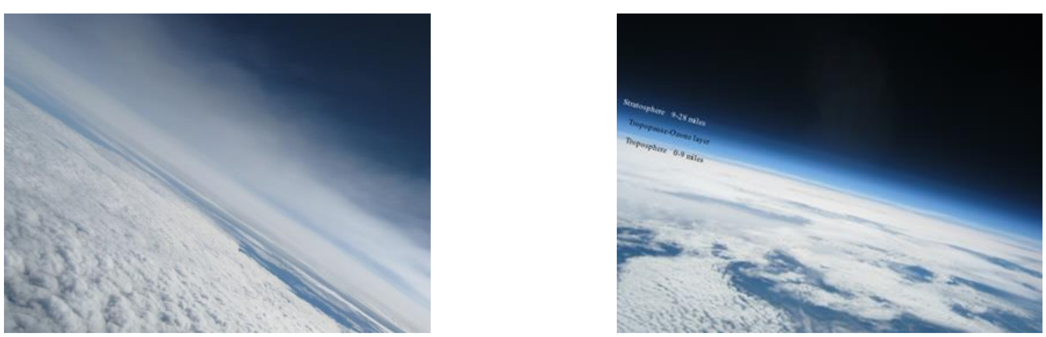

Figure 6: Cat-4 transition of the cloud layers at 41,624 feet and at its highest altitude of 88,656 feet. The layers of the atmosphere are clearly seen at 12:16 pm flying near Lake Wylie, SC.

Cat-4 data analysis showed that the programming of the LQ was set to run for only an hour, with the connection from the radiation monitor to the LQ2 needing additional security during flight. 24 minutes of flight data were recorded. No radiation counts were collected. Beacon packets were void to aprs.fi for over an hour. Verso l'alto was located three hours after impact.

3.3 Catamount 5:

Catamount 5 was scheduled for February 16, 2013 to be launched from WCU campus. Equipment malfunction and inclement weather prevented the flight, and was rescheduled. On April 27, 2013, Catamount 5 was launched successfully from the Jackson County Airport at 10:52 am. The balloon rose to an altitude of 97,928 feet with flight time of 2 hours and 35 minutes, impacting in Tigerville, SC. Weather conditions for that day was dense fog and rain, with periods of moderate rain within the region. This was the first rain launch for Verso l'alto. The payload was separated in two boxes, the bottom payload housed the radio equipment and the top payload housed the science equipment. Figure 1 shows Cat-5 lift off and assemblage.

The digital radiation monitor collected 1977 counts of atmospheric radiation during 141 minutes of flight. The onboard camera captured 524 pictures. The onboard data logger recorded clean coordinates during ascent, but stopped recording until 1 second before bursting altitude for 11 minutes during descent, with gaps in data coordinates thereafter. Figure 10 shows the data logger kml file on Google earth. Highest counts of radiation were detected at 12:55 pm over (35.06 N, -82.64 W) near the northwest corner of Pickens County, SC. with 24 counts within the troposphere between altitudes 48,074-45,273 feet upon descent. (See figure 7)

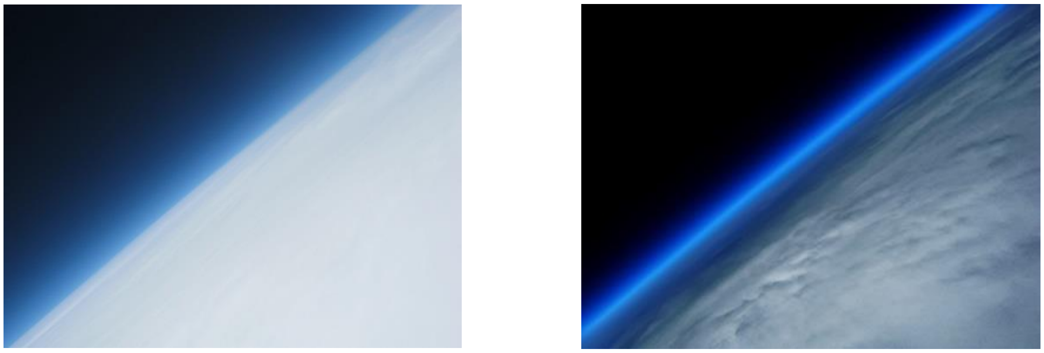

Figure 7: Cat-5 snapshot during its maximum counts of radiation at 12:55 pm. The picture on the left is the original, and the picture on the right was enhanced to see the depth of the clouds over the region.

Figure 8: Storm cloud production at 11:44 am at 50,827 feet. Picture is enhanced to show cloud height.

3.4 Raw Data:

All data collected was thoroughly analyzed, both in flight trajectories and in radiation observance.(See figure 9 and 10) Cat 5 lost APRS signal during mid-flight, and was located 4 hours after impact by the SpotII GPS tracker; a small satellite messaging system, also inside the communications payload, as an extra locater instrument.

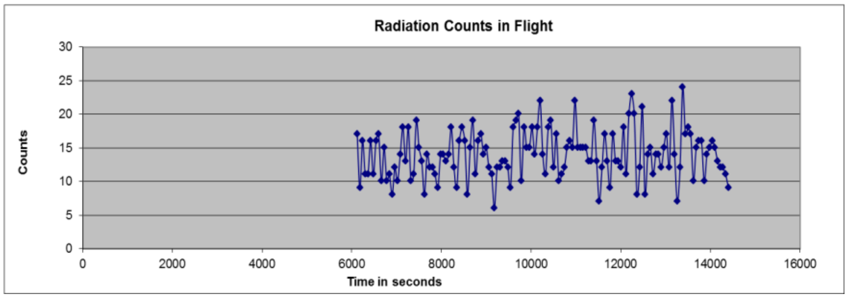

Figure 9: Cat-5 collection of radiation counts during flight.

A Sparkfun APRS data logger was added for additional GPS data. It captures locally the data from the GPS receiver to the APRS tracker. Much of this same data is transmitted, via radio, by the APRS equipment on the balloon; however, since the terrestrial APRS network can cause some packets to be delayed, marking them with incorrect timestamps, the local data logger gives an accurate time and position. It was programed to record coordinates every second, however, it did have some gaps within its data locations. (See figure 10) The purpose of an additional data logger was to enhance the APRS encoder, and to have a solid collection of coordinates throughout flight.

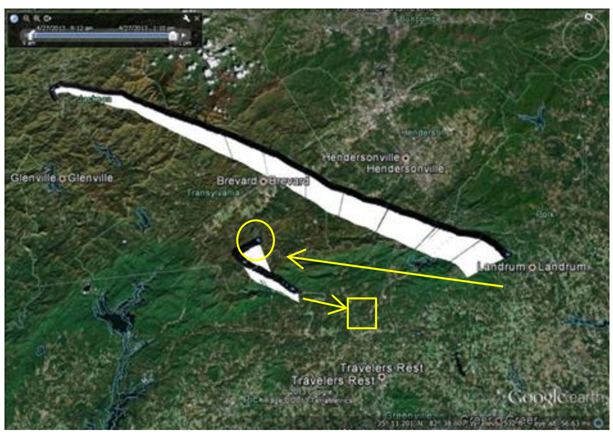

Figure 10: The Sparkfun data logger kml file of flight. The circle is Cat-5 maximum altitude. The arrows represent the direction the balloon was traveling during those gaps. The square represents the impact zone.

3.5 Simulated Data:

The altitude versus radiation counts were modeled using CORSIKA (Cosmic Ray Simulations for KASCADE), which is a program that simulates cosmic ray shower interactions in the atmosphere via Monte Carlo algorithms. CORSIKA initializes air shower simulations from an input file that specifies the number of particles impinging upon the atmosphere, the particle identities, their energy range and their power law spectral index. It then outputs a file specifying all the observation height particle types, energies, locations and arrival times. We used the Dual Parton Model for high energy hadronic interactions (DPMJET) and the Gamma Hadron Electron Interaction Shower code (GHEISHA) options for CORSIKA version 6.900. We assume Fe nuclei as primary particle in the energy range $2x10^4$ to $4x10^4$ GeV energy ranges. The need to simulate data is important because it gives a visual understanding about how the particles are behaving in the atmosphere. The raw data (Figure 9) can then be imported into a simulation which would show the outcome of particles expected at given altitudes.

To simulate the cosmic ray showers we considered the gamma, electron, positron, muon and anti-muon components as these would be the particles that would penetrate the detector shielding. We considered also the population of each species at the altitudes corresponding to the flight path as well as the average energy of each. Since the particle detector would be more sensitive for higher energy particles even when their population is smaller, we modeled the detector sensitivity by multiplying the number of particles in the flight path by a weighting factor equal to the logarithm of their kinetic energy. Figure 11 shows the simulated cosmic ray showers with the raw data (Figure 9) as an output to altitude within the tropopause and the stratosphere.

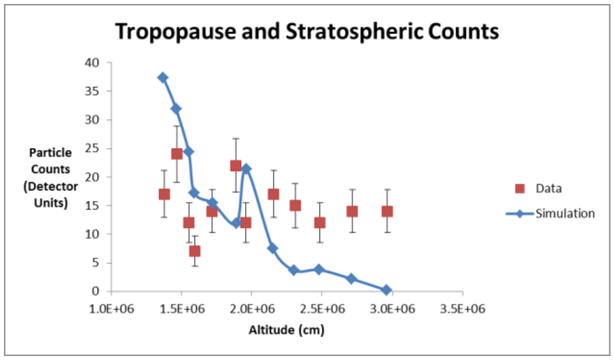

Figure 11: Cat-5 tropopause and stratospheric data for of the simulation and actual flight data. The error bars are given as the standard deviation for each particle count.

Both the flight data and the simulation capture a peak in at $1.8x10^6$ cm in altitude corresponding to the region just before the charged particles enter the tropopause. Further down the increase of density absorbs much of the core, low energy gamma, electron and muon components. Then the cosmic ray particle shower begins to spread out giving many more particles at lower energies. In the troposphere the detector is undercounting the number of particles. We understand this as a lower sensitivity because these particles would be less energetic. The detector also seems to be overcounting the number of particles in the stratosphere. We understand this as an increased sensitivity to fewer, but more energetic particles.

3.6 Supplementary Data:

Pisgah Astronomical Research Institute (PARI) has several Earth Science detectors that are used throughout the flight analysis. Several instruments including the Geomagnetometer, Lightning Detector and Cosmic Ray Detector provide ground measurements that accurately collect data over a 24 hour period. The archived files are accessed for extent analysis and understanding of the additional variables occurring during flight.

The geomagnetometer data records every minute the magnetic field, inclination and declination. The archived file for the cosmic ray detector was not available for Cat-5's analysis. Figure 12 shows the magnetic field recorded by PARI's geomagnetometer and Cat-5's radiation counts.

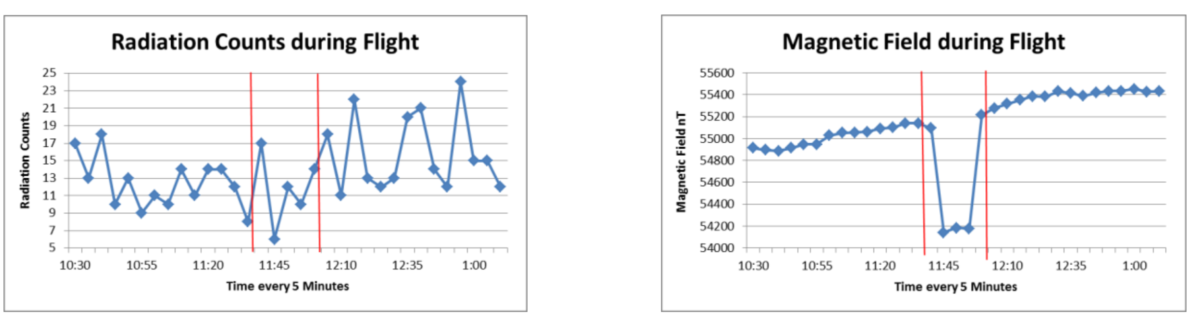

Figure 12: Cat-5 radiation counts during flight from 10:30 am-1:10 pm. The drop in counts coincides with the drop in the magnetic field from 11:40 am-12:05 pm. During this time Verso l'alto was in the tropopause.

The lightning detector archived data is uploaded into the Lightning 2000 software program, which plays the detector file in animation relative to the map of the 200 mile radius detector area. During the storm analysis, the type of lightning; Intracloud, (±IC), and Cloud to Ground, (±CG) is counted, and how many flashes and strokes are present during a 24 hour period. Figure 13 shows a screen capture of the archived file, beginning at 12:00 am of the morning of April 27th, Cat-5's flight. Most of the electrical activity occurred well before the flight, but at 12:03pm, a severe thunderstorm watch took place, noted by the red box around the mapped area.

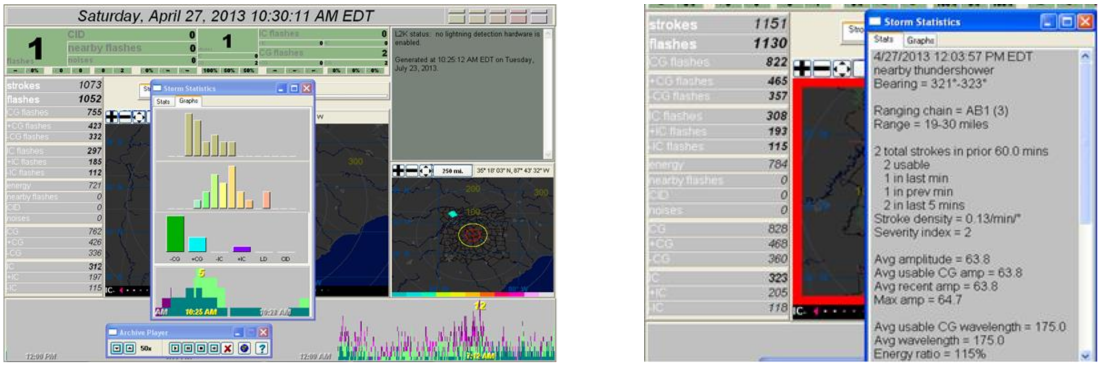

Figure 13: Lightning 2000 software program for PARI lightning detector archived files.

3.7 The future of Verso l'alto:

In the summer of 2012, Dr. Gomez entered the design for the small cosmic ray detector that would be engineered to fly in the payload of Verso l'alto in Discovery and Astronomy magazine's 30 day challenge for the ArduSat satellite program through NanoSatisfi and Kickstarter. The grand prize was $1500. in equipment and a weeks' worth of data onboard the ArduSat nanosatellite. A few of these components include a gamma ray detector, EM wave and 3-axis magnetometer sensors. Not only would this provide an accurate collection of data, a larger variety of data could be collected. Figure 14 shows the Ardunio equipment that will be included in the July launch.

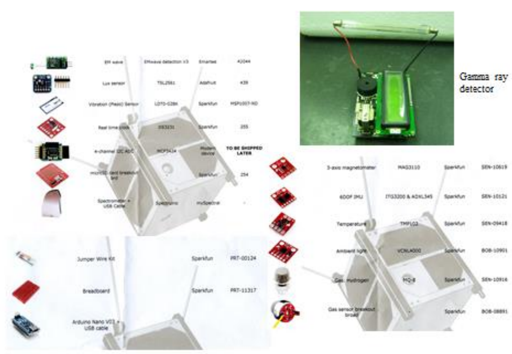

Figure 14: Ardunio components that are currently engineered for Cat-6 flight. Most of this equipment can be converted from digital to analog into the radio equipment for live data packets via aprs.fi

The July flight of Catamount 6 has been rescheduled for October. The gamma detector that Dr. Gomez designed for the ArduSat launched August 3, 2013 from the Yoshinobu Launch Complex in Japan. The H-IIB Launch Vehicle No. 4 carried the nanosatellites to the International Space Station (ISS), where it is docked. In October, the nanosatellite is scheduled to launch into low earth orbit for a week. Catamount 6 will fly during the week that the ArduSat is in orbit, and all data collected will be thoroughly analyzed using PARI ground detectors, Cat-6 flight detectors and the ArduSat detectors for gamma radiation.

4. Conclusion:

Three successful launches of Verso l'alto have been completed. The first launches have been on a clear/cloudy day, mainly for practice purposes in the entire flight process. Collecting the counts of radiation during a clear day will also give a baseline control of atmospheric radiation. Cat-5 was the first rain flight, and Cat-6 could be in a thunderstorm. Counts collected during a thunderstorm could then be compared to the baseline and evaluated. Coordinating launches on a specific day between the volunteering organizations are arranged months in advance. The safety of the payload upon landing for the past three flights have been secluded within a rural location, and fortunately have impacted amongst the trees.

Several variables including magnetic field, electric activity and forecast for the day of the flight strengthen the evidence of variability within the atmospheric layers. Each flight has been different in flight duration, distance traveled, altitude and data collection. Using PARI's ground detectors also serves as a strong baseline for gathering a broad statistical cadence of various measurements in flight also magnifies the outcome of the search for TGFs in the Southern Appalachian Region.

The importance of such a project is to engage education in a multidisciplinary field of study and enhance the STEM fields in the region. The science of TGFs is data starved, with only satellite and/or ground based detectors strategically geographically correlated and analyzed after months of data has been collected. Verso l'alto provides new data to be examined and interpreted in real time and provides a geophysical application of statistical collection in an unfamiliar environment within thunderstorms.

5. Acknowledgements:

Dr. Enrique Gomez for introducing me to TGFs and for purchasing the equipment. Thank you for allowing me to take charge of this project, and the freedom to make this project a reality at WCU. Al Sanders for designing the radio payload, sticking with this project over the years, purchasing the radio equipment, and numerous testing of all the equipment. Chuck deCourt for contacting various (NC/SC/VA) state organizations, local law enforcement and amateur radio repeater stations per impact location. CARGO (Catamount Amateur Radio Group) and HCARC (Haywood County Amateur Radio Club) for their amazing hunting skills, time, and dedication. We would truly be lost without you. PARI (Pisgah Astronomical Research Institute) for their numerous use of archived data; lightning detector, cosmic ray detector, and geomagnetometer. Mike Schoonover at Jackson County Airport for allowing us access to the airport anytime for launches. WCU Honor's College for the Undergrad Project Grants and WCU Dept. of Geosciences for the Student Enrichment Funds. My family, friends, colleagues; Thank you for keeping hope alive that I would get off our planet one way or another during the four years that I have worked on this project. You have been by far my largest motivation.

6. References:

[1] B. Carlson. et al. Terrestrial Gamma-ray Flash Electron Beam Geometry, Fluence, and Detection Frequency. 2011. Journal of Geophysical Research, 116:A11217, 2011.

[2] Gaopeng L. et al. Lightning Mapping Observation of a Terrestrial Gamma-ray Flash. Journal of Geophysical Research, 37:L11806, 2010.

[3] D.M. Smith. et al. Terrestrial Gamma-ray Flashes Correlated to Storm Phase and Tropopause Height. Journal of Geophysical Research, 115:A00E49, 2010.

[4] D.M. Smith. et al. The Rarity of Terrestrial Gamma-ray Flashes. Geophysical Research Letters, 38:L08807, 2011.

[5] APRS http://aprs.fi/#!mt=roadmap&z=12&ts=1367020800&te=1367107200&call=a%2FK4WCU-11

[6] Google Earth images