The High Altitude X-Ray Detector Testbed Payload
for the 2012 High Altitude Student Platform

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Introduction

The University of Minnesota's (UMN) High Altitude X-ray Detector Testbed (HAXDT) is a high altitude balloon payload developed to test and validate the performance of a compact, low power, low cost X-ray detector and its associated flight hardware on Louisiana State University's (LSU) High Altitude Student Platform (HASP). The HAXDT payload consists of a flight computer and daughter board, onboard flash storage, attitude and navigation sensors (IMU and GPS), a power regulation and protection circuit, and a small detector capable of capturing high-energy photon events and its associated hardware.

The impetus for developing a small detector system is that many envisioned deep space missions, such as long-range sample return or interplanetary reconnaissance, will require space vehicles to have autonomous navigation capabilities so that such vehicles will not have to remain in constant contact with Earth. Such autonomy could relieve reliance upon Earth-based monitoring systems such as NASA's Deep Space Network (DSN). Recent work has shown that celestial X-ray sources such as pulsars can be used as navigation beacons for determining the absolute position of space vehicles [1-13]. Pulsars occur naturally over immense astronomical distances and do not rely on Earth-based operations for their utilization in a navigation solution.

Pulsars are excellent candidates for navigation beacons because their unique, identifying signals can be used to provide time, range, and range-rate measurements, which are key parameters in obtaining an accurate navigation solution [13]. However, because pulsars occur many parsecs from Earth, the signal-to-noise ratio (SNR) of the received X-ray signals is small [13]. Further, the performance of a small detector receiving such signals is relatively unknown. Such small detectors could easily and affordably be placed on a fleet of autonomous spacecraft, thus providing analysis and flight heritage for such detectors is crucial to the development of an autonomous, low-cost deep space X-ray navigation system.

The payload is designed to conform to CubeSat generic structure standards, based on one or more cubes with internal dimensions of 10 cm x 10 cm x 10 cm. A single cube is known as a 1-U, or unit volume, configuration. HAXDT is a 2.5-U payload as shown in the 3-D rendering in Figure 1 below. The CubeSat infrastructure allows the payload to be easily reconfigured to accommodate additional hardware components and future upgrades to X-ray detector hardware. The payload is ultimately being designed to test the system in space, thus the CubeSat model provides a flexible platform that can be modified for future HASP missions as well as space flight opportunities. Such modifications could include solar panels for onboard power and a shielded detector capable of being pointed at various X-ray sources.

The Uninhabited Aerial Vehicle (UAV) Research Group at UMN developed the flight computer and attitude determination package used on HAXDT [14]. The flight computer is a 32-bit PowerPC Phytec MPC5200B-tiny SoM, which uses a real-time operating system written in C language. A custom-designed daughter board handles the hardware interface to the flight computer. The flight code is open source code courtesy of the UAV Research Group at UMN [14], and has been custom edited to perform attitude determination while collecting data from an X-ray detector. The GPS signal is provided using a NovAtel OEMV-3G receiver modified for operation above 60,000 feet. The IMU is an Analog Devices ADIS16405 that provides angular rates, accelerations, magnetic field, and temperature readings. An attitude solution is obtained by combining the IMU data with the GPS navigation solution.

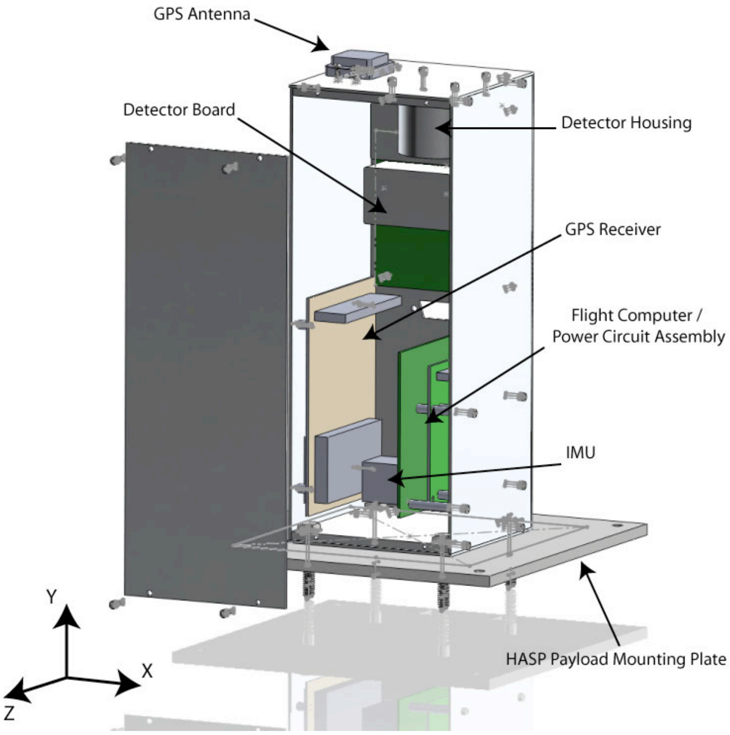

Figure 1. A 3-D rendering of the HAXDT structure. The base is 10 cm x 10 cm, while the wall is 25 cm high. All interior hardware is custom mounted as indicated. The detector sits in the cylindrical mount as shown attached to the interior of the upper plate. The dimensions conform to a 2.5-U CubeSat design and allows for easy reconfiguration of the interior components.

The detector assembly is seated in an aluminum housing as shown in Figure 2 below and consists of an avalanche photodiode (APD) affixed to an inorganic plastic scintillator with optical grease, which is then wrapped in polytetraflouroethylene (PTFE) tape. Light flashes generated by high-energy particle interactions with the scintillator are shaped into pulses by a two-channel nuclear pulse-shaping circuit (detector board) provided by Lockheed Martin’s Advanced Technology Center in Palo Alto, CA, and are thus detected as photon strikes that are time-tagged by the flight computer. The detector board also provides the high-voltage supply required to power the APD.

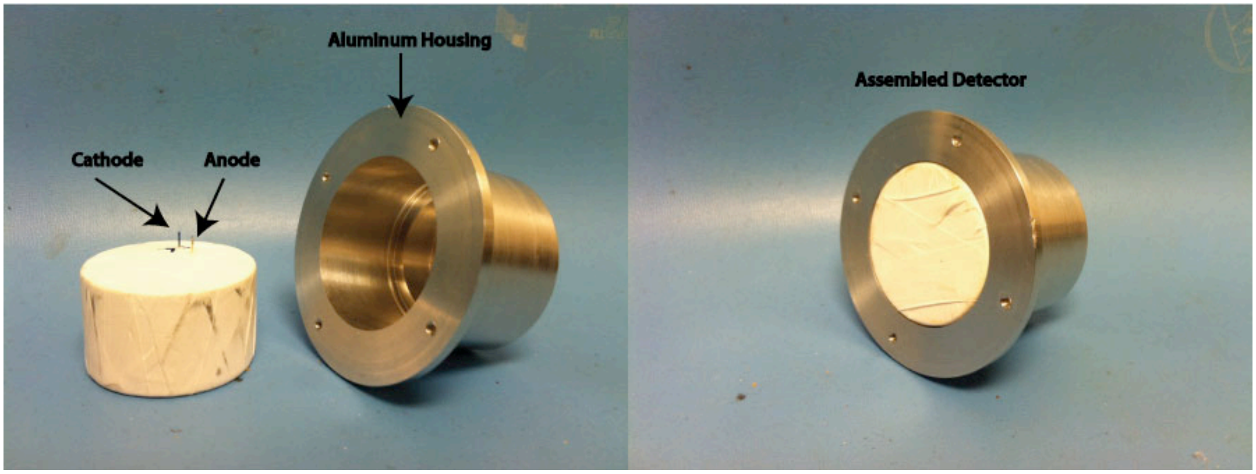

Figure 2. The HAXDT detector is comprised of an APD attached to a plastic scintillator and then wrapped in PTFE tape. Shown are the cathode and anode of the APD protruding from the PTFE tape (left). The wrapped assembly is then seated in the aluminum housing to complete the assembled detector (right).

Payload Performance

The HAXDT payload performed to expectations. There were not any payload operation shortcomings during the flight that led to test results being unusable or inconclusive. HASP program participant requirements as well as the team's advisor's requirements were satisfied. Some of the specific performance benchmarks were that the payload's average current draw from the 30V supply was 220mA and never exceeded 270mA. The structure of the payload stayed intact throughout transportation to the launch site, during the flight and after retrieval at the landing site. There was also successful data logging to the onboard storage device as well as consistent downlink transmissions throughout the flight. These milestones indicate that the payload met minimum performance standards.

However, more specific functional performance was not as high as it could have been due to several issues. The GPS receiver experienced four unexplained outages where no new satellite information was processed for a length of time. One of the outages lasted an hour and another lasted 20 minutes. Otherwise, the GPS subsystem performed as expected. There was also a sensor or related system failure associated with one of the analog voltage lines that was connected to the payload. Analog Line K was intended to monitor the temperature of the flight computer's CPU core. The interpreted data does not seem to be valid.

The last negative performance mark was that the photon detector was designed to save the time stamp of a photon strike to a data structure and then once the structure filled, it would be written to the onboard storage unit. This process worked well for the detector subsystem during float, but during the ascent phase of the flight the detector was exposed to activity in the Pfotzer Maximum where there was an abundance of secondary high-energy particle activity that overwhelmed the storage schema. An implementation change needs to happen to account for detection event bursts in the future. The IMU logged data at 35Hz and monitored the ambient temperature inside the payload's walls as expected.

Problems Encountered and Lessons Learned

The overall HASP project came together with minimal setbacks and was considered a success. But, as with most engineering projects, there were several challenges worth noting which will be corrected in future iterations of the project.

1. During the design phase, the student team brainstormed and researched the needs that would have to be filled by the X-Ray detector hardware. This was a time consuming task and the source of much frustration due to the fact that none of the team had any extensive experience with high-energy particle detection. These shortcomings cost the team a lot of planning time, but also, after committing to a detector hardware set, there was still a lack of knowledge on how to get the most information out of the detector that was chosen. In the future, it is clear that there needs to be a team member not only familiar with photon detection prior to joining the team, but also dedicated to the detection subsystem's development.
2. The efforts on chassis design were focused in the wrong direction from the start. The charge of the project is to design a low-cost and reliable navigation node; this means that having an overly efficient and thereby expensive structure is less important in the overall rank of components. Many hours were spent designing walls and mounting plates that were overly strong and aesthetic while minimizing material use to reduce weight. This resulted in a design that required a lot of machining and fabrication time. In the end, the team ended up scrapping the well-laid structure design and fabricating one out of sheet aluminum. This meant that time was wasted on the design of the initial structure (which would have been sent to a shop for fabrication) and extra time was needed to fabricate the structure in-house that was not planned for.
3. During the integration process, the ribbon cable for the IMU data lines cracked. The cable is of fine pitch and physically connected inside of the IMU housing (factory sealed). A faulty IMU would eliminate the ability to calculate a navigation solution and render the project essentially useless. In addition, this hardware failure was standing in the way of the team achieving flight readiness certification. Fortunately, there was still another day of preparation, so the team was able to ship a replacement IMU to the integration facility overnight and get the payload re-assembled in time for the final integration tests.
4. As expected, the most unfortunate and difficult to accept problems arose during flight. The team is still unclear as to what the cause was, but periodically throughout the flight, the GPS receiver lost track of the PVT solution and sent unchanging data to the flight computer for logging. There were reports of other student teams that also experienced this, what is assumed to be, interference at intermittent and sometimes extended intervals. The loss of GPS solution makes an accurate strap-down, integrated navigation solution near impossible to compute with the grade of inertial sensors used.
5. Inclement thermal conditions for the detection hardware resulted in a period of time during balloon ascent where the detector was exposed to very cold temperatures. This was expected, but the effect was surprising. As the detector was cooled, either the increase in high-voltage source efficiency, the sensitivity of the scintillator/APD interaction resulted in huge particle strike counts, or the system went through an extremely active layer of the atmosphere. The team did not expect to use the ascent or descent data since the detection circuit was optimized for the temperature at float, but

knowing how much more sensitive the device can be raised questions of how the effectiveness of the detector can be better harnessed in future hardware builds.

6. A minor problem that occurred was that since the flight code was initially designed for storing the flight data in volatile system memory, it was keyed to only fill a finite buffer. This feature was not adequately disabled and caused the peripheral data logging to hang every time the in-system data structure over-flowed. The glitch resulted in a half of a data entry being lost in approximately 70-second intervals. This does not seem to be a critical failure since the sensors were being sampled and logs were being stored at a rate of approximately 35 Hz. This issue will be resolved for future flight opportunities.
7. There seemed to a problem with the analog voltage line that was measuring the core processor temperature. The temperature readings are within the range of valid sensor readings, but the data are very intermittent and change rapidly. A faulty connection or improper sampling seems to be at fault. Regardless of the quality of the data, no value exceeded or fell below the safe operating temperature range of the processor.

Results Summary

The payload was operational for about 11.3 hours once it was powered on at Fort Sumner, NM. The flight system successfully collected all expected data throughout the flight, which includes GPS, IMU, temperature, and scintillation event times. From the GPS and IMU data, a semi-complete flight trajectory and attitude solution has been generated as seen in Figures 3 – 7 where the red data are direct measurements from the GPS, while the blue data are the integrated INS/GPS navigation solution.

The gaps in valid GPS measurements have encouraged the team to look into other methods of attitude determination which will hopefully increase the accuracy of the “known” sections and allow for less error propagation through the GPS-unaided navigation segments. There has been effort to compare IMU drift to the visual data available from the onboard camera logs, and a more detailed future investigation will use the magnetometer readings to aid the navigation system. The attitude solution in Figure 7 shows that the payload stayed mostly level throughout the flight but rotated about its vertical axis. Video of the flight verified that the gondola was indeed rotating throughout the duration of the flight.

The detector successfully counted high-energy particle scintillation events, or photon events, for the entire time the HAXDT payload was operating as seen in Figure 8 below. Throughout the entire flight, the average photon count rate was 27.4 photons/sec, while the average flux was 0.54 photons/cm^{2}sec. Once the HASP gondola reached float altitude after about 2.9 hours from when the payload powered on, the average photon count rate was 12.7 photons/sec, while the average flux was 0.25 photons/cm^{2}sec. As seen in Figures 8 and 9, there is a period of heightened activity during ascent, especially around 25km in altitude. This activity corresponds to an area in the atmosphere where cosmic rays initiate nuclear-electromagnetic cascades in the atmosphere, causing a maximum in secondary particle intensity. This area is called the Pfotzer Maximum and occurs at altitudes of 15-26 km depending on location and solar activity [15]. In comparing the altitude data to the recorded flux in Figure 9, there is indeed a detected maximum level of particle intensity at 25km, and thus the drop in count rate and flux for the duration of operations at float altitude is expected.

However, the peak of this maximum is not resolved in the data due to poor budgeting of photon event storage in the HAXDT software. Therefore, the total average count rate and flux as reported above do not entirely account for the intensity encountered in the Pfotzer maximum region. Also of note in Figure 9 is the expected temperature profile as the payload ascends and reaches float altitude.

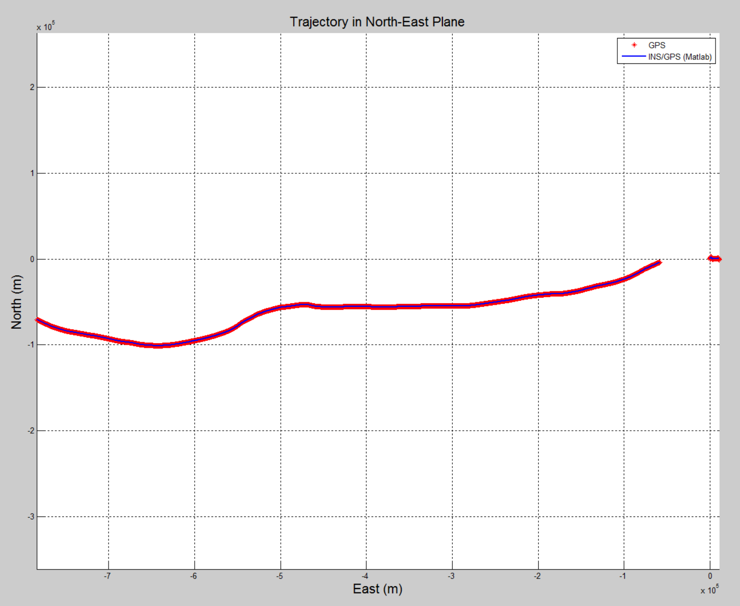

Figure 3: Overall trajectory of the flight in meters relative to starting location (Fort Sumner, NM). The plot clearly shows the westward progress towards flight termination West of Phoenix, AZ. Discontinuities correspond to GPS outages.

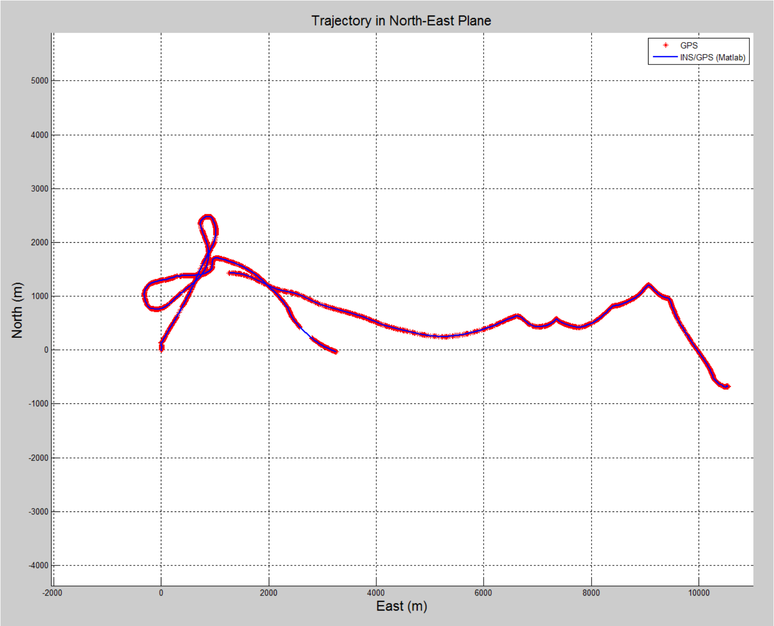

Figure 4: Recognizable flight trajectory near launch site, discontinuities on the plot correspond to GPS outages.

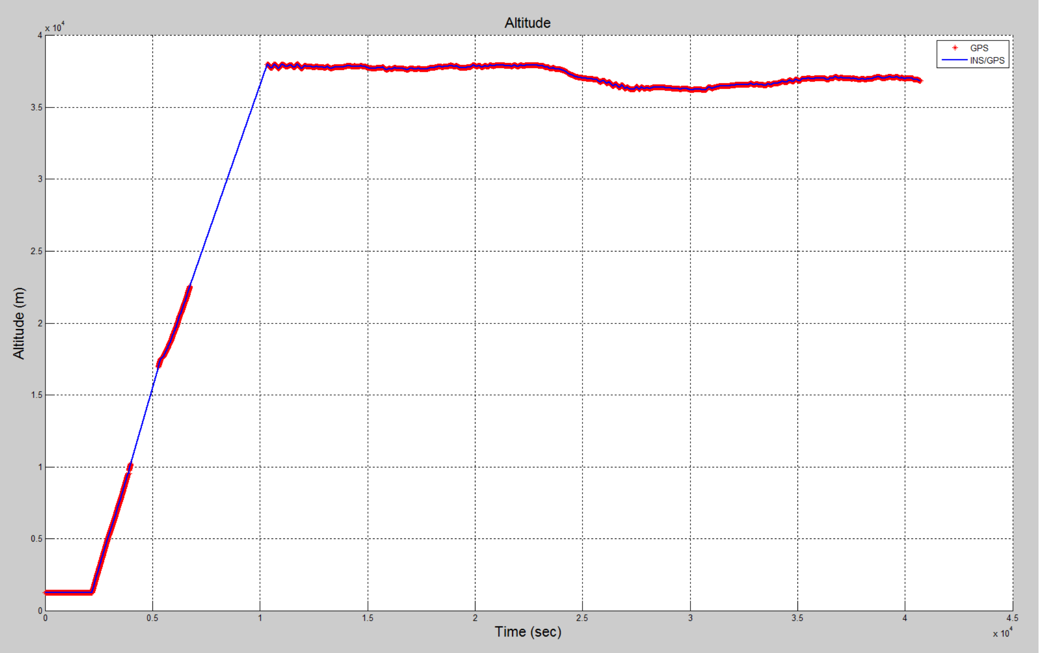

Figure 5: Altitude of payload throughout flight. Areas where the red line appears absent correspond to GPS outages.

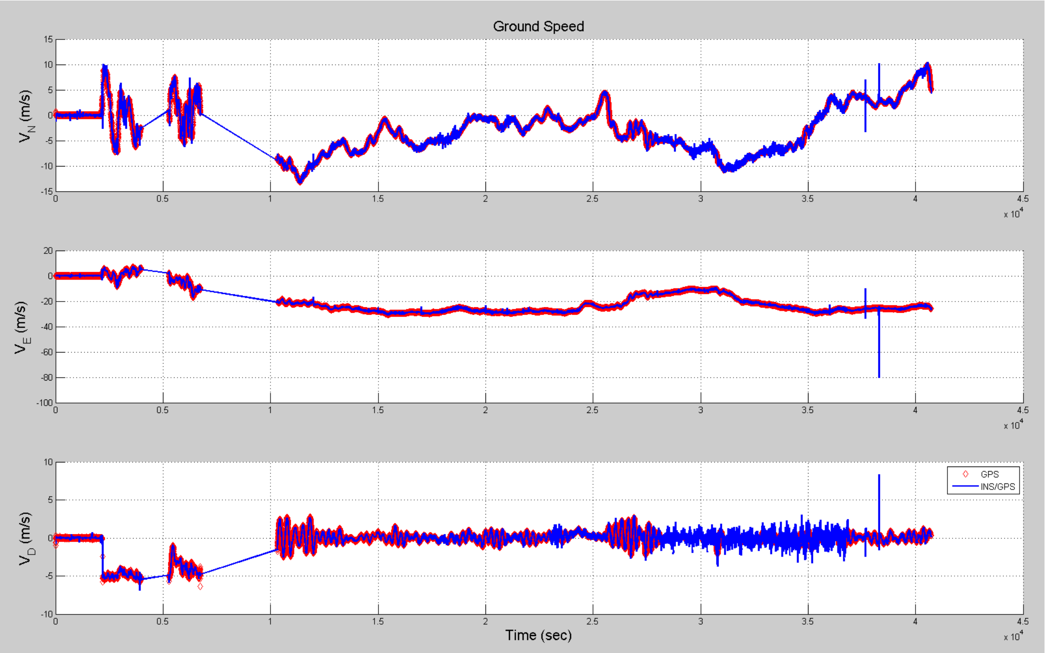

Figure 6: Velocity of payload in the North-East-Down navigation reference frame throughout the flight. Areas where there is only a solid blue line correspond to GPS outages.

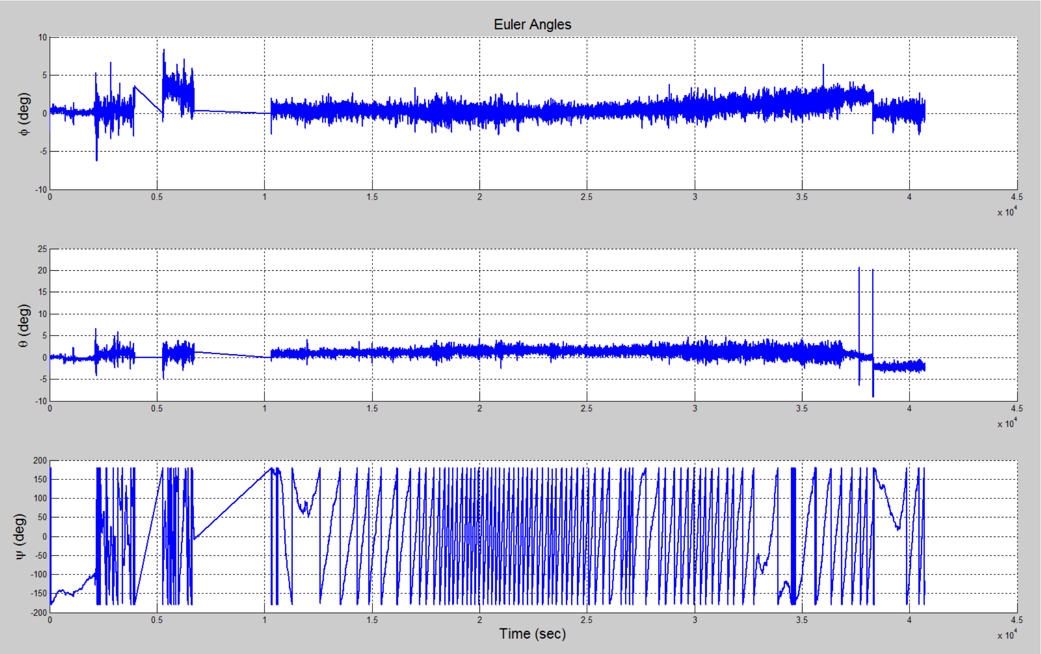

Figure 7: Euler angles of payload throughout flight. Roll and pitch (top and middle figures respectively) action was minimal, while the yawing motion (bottom figure) indicates that the HASP gondola was rotating during flight.

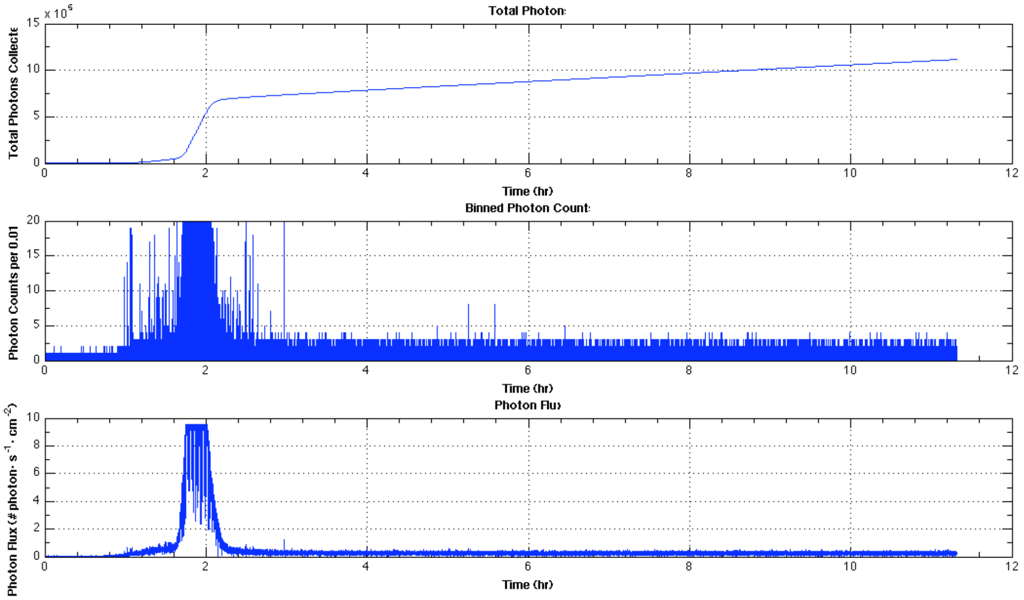

Figure 8. Time histories of the total accumulated photons (top), the number of photons counted in 0.01 second intervals (middle), and the flux of the high-energy scintillation events as seen by the detector (bottom) throughout the flight.

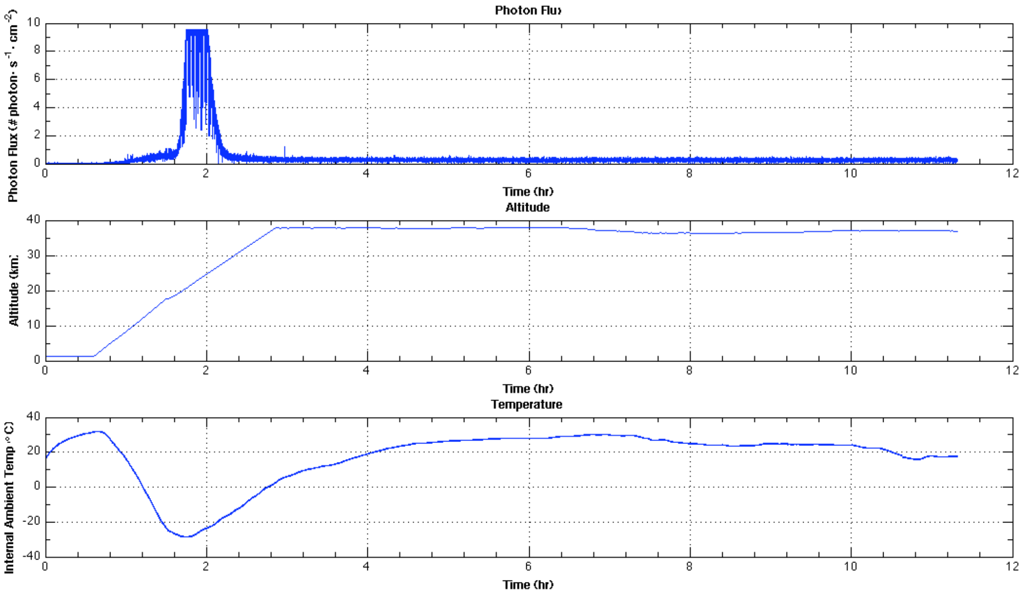

Figure 9. Time histories of the flux of the high-energy events as seen by the detector (top), payload altitude (middle), and internal payload temperature (bottom).

Conclusions and Future Work

The University of Minnesota's High Altitude X-ray Detector Testbed performed as expected during its inaugural flight on HASP. The primary objective of building a functional payload that is able to detect high-energy photon events while collecting navigation and attitude data was met. However, the detector was unable to record energy levels of these events, and the software scheme for recording periods of very high activity was inadequate as the data structure size was too small. In order for the detector to effectively identify high-energy celestial sources, the energy information encoded in these particles must be recorded. Identification of high-energy celestial sources is paramount to the X-ray navigation concept as well as other scientific objectives such as attitude determination. Therefore, both hardware and software upgrades to the current detector system must be implemented in order to increase the detector's scientific capabilities and its readiness for the ultimate goal of flying in space.

Student Involvement

Below is a table displaying all students involved in the 2012 HASP mission and their demographic information.

Name	Gender	Ethnicity	Race	Student Status	Disability
Patrick Doyle	M	Non-hispanic	Caucasian	Graduate	No
Curtis Albrecht	M	Non-hispanic	Caucasian	Graduate	No
Mark Abotossaway	M	Non-hispanic	Native American	Undergraduate	No
Steven Haviland	M	Non-hispanic	Caucasian	Undergraduate	No
John Fraatz	M	Non-hispanic	Caucasian	Undergraduate	No
Sean Grogan	M	Non-hispanic	Caucasian	Undergraduate	No
Ryan Carlson	M	Non-hispanic	Caucasian	Undergraduate	No
Zach Fadness	M	Non-hispanic	Caucasian	Undergraduate	No
Brian Erickson	M	Non-hispanic	Caucasian	Undergraduate	No

Two of the students above graduated during development of the 2012 HASP payload. Steven Haviland is attending graduate school at Georgia Tech, and John Fraatz is employed at the University of Minnesota's Saint Anthony Falls Laboratory as a research and data analyst in supercavitation.

Papers and Presentations

1. Mr. Doyle presented his research and the then-current progress of the development of the HAXDT payload to the AEM 8400 Aerospace Systems Seminar at the University of Minnesota on March 28, 2012.
2. Mr. Doyle and Dr. James Flaten (Assistant Director of the Minnesota Space Grant) spent a day presenting at Eden Prairie Middle School in Eden Prairie, MN on June 1, 2012. Throughout the day, they spoke to 7th and 8th grade geometry classes about the challenges and rewards of scientific ballooning.
3. Dr. Gebre-Egziabher presented a paper [13] he co-authored with Mr. Doyle and Dr. Suneel Sheikh of Aster Labs, Inc. at the SPIE Nanophotonics and Macrophotonics for Space Environments IV conference on August 12, 2012 in San Diego, CA.
4. Dr. Gebre-Egziabher presented his and Mr. Doyle's research and the HAXDT payload to the AEM 8000 Aerospace Engineering and Mechanics Seminar on September 28, 2012.
5. Mr. Doyle presented a poster displaying preliminary HAXDT results at the Midwest Space Grant Regional Meeting in Milwaukee, WI on October 12, 2012.

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