The High Altitude X-Ray Detector Testbed Payload
for the 2013 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. The 2013 version of HAXDT is a 3-U payload as shown in the 3D drawing in Figure 1 below. This slight increase in size from the 2.5-U design of the 2012 payload is meant to accommodate the collimator-like elongated detector housing featured in the 2013 design. 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.

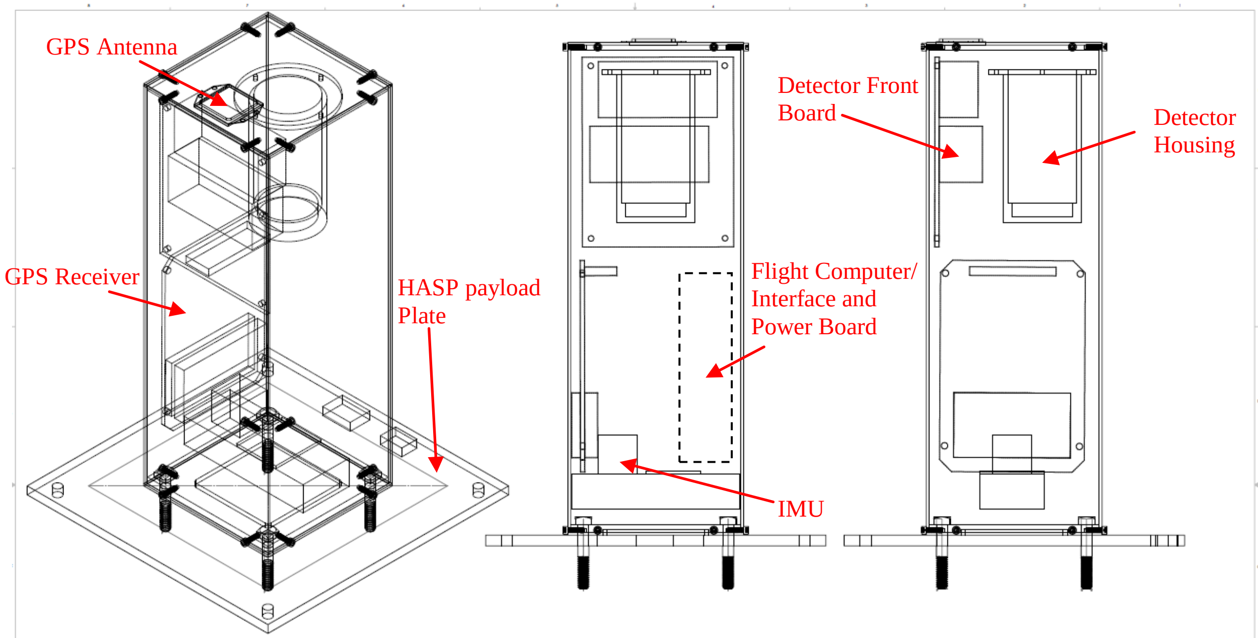

Figure 1. A 3D drawing of the HAXDT structure. The base is 10 cm x 10 cm, while the wall is 30 cm high. All interior hardware is custom mounted as indicated. The detector sits in the cylindrical mount as shown attached to the interior of the upper plate. The dimensions conform to a 3-U CubeSat design and allows for easy reconfiguration of the interior components.

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.

The detector assembly is seated in an aluminum housing as shown in Figure 2 below and consists of an avalanche photodiode (APD) affixed to plastic organic scintillator with optical grease, which is then wrapped in polytetraflouroethylene (PTFE) tape. In an attempt to limit the detection of high-energy photons and particles to those in a narrow field of view above the payload, the aluminum housing is elongated to act as a collimator, and the surface of the housing is covered with 8 mm of lead shielding. Light flashes generated by high-energy particle interactions with the scintillator are shaped into pulses by a nuclear pulse-shaping circuit (detector board) provided by Lockheed Martin's Advanced Technology Center in Palo Alto, CA. The detector board also provides the high-voltage supply required to power the APD (approximately 400V). Pulse height analysis is performed in real time by custom circuitry consisting of a high-speed op amp and an analog-to-digital converter. Photon strikes are time-tagged by the flight computer using the discriminator output of the detector board to drive an interrupt, and photon energy levels are recorded as voltage measurements from the pulse height analysis circuitry. The scintillator and APD were selected to produce a detector with a peak sensitivity in the range of 100 keV–5 MeV, corresponding to gamma rays which can be easily observed in the Earth's atmosphere. As mentioned earlier, the signal-to-noise ratio of X-rays in the Earth's atmosphere is very low, making the detection of actual X-rays exceptionally difficult, even at high altitudes. The detector is also sensitive to higher energy particles in the range of 5–20 MeV and above, such as fast neutrons.

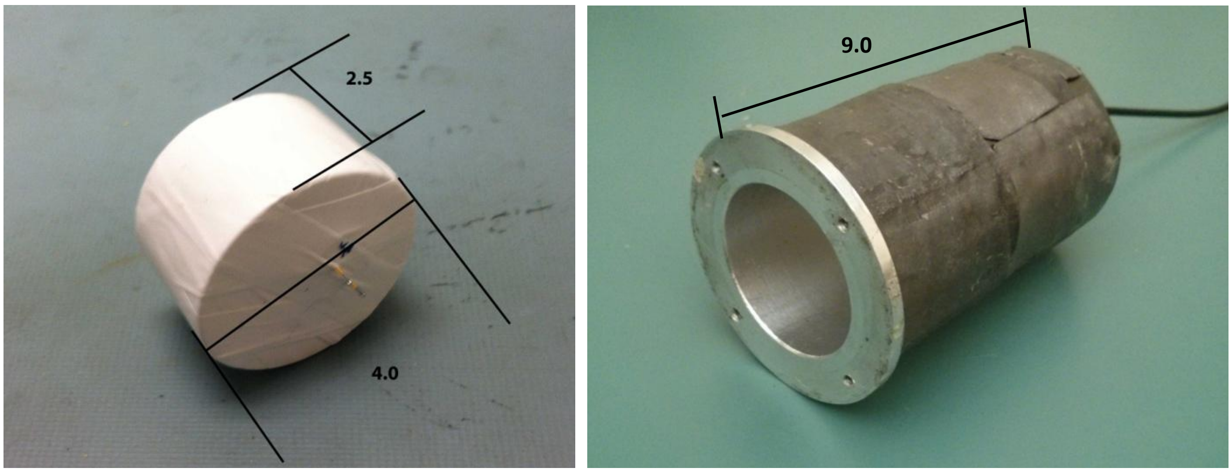

Figure 2. The HAXDT detector is comprised of an APD attached to a plastic scintillator and then wrapped in PTFE tape, shown on the left with dimensions in centimeters. The wrapped assembly is then seated in a lead-shielded aluminum housing to complete the assembled detector, shown on the right with the height indicated in centimeters. The coaxial cable coming out of the detector housing is used to connect the APD to the detector board.

Payload Performance

The 2013 HAXDT payload met all performance expectations in ground testing leading up to the HASP flight. The GPS receiver and IMU were able to provide stable and reliable navigation and attitude data for the payload, and the detector successfully recorded scintillation events at energy levels ranging from 100 keV–20 MeV, as measured by the pulse height analysis circuitry. Some tests even registered events as high as 100 MeV, likely from subatomic particles rather than extremely high-energy gamma radiation.

In addition to meeting the performance thresholds established by the UMN HASP team, the HAXDT payload stayed within the specified mechanical and electrical limits required for proper integration with the HASP flight equipment. The measured weight of the payload including the payload plate was 2.91 kg, within the 3 kg limit. Further, the measured current draw of the payload from the 30V supply was 220 mA, well below the 500 mA limit. The current draw remained relatively stable over the full range of temperature and pressure conditions tested, from −50 °C to 50 °C, and from sea-level pressure down to 9 mbar.

Problems Encountered and Lessons Learned

Unfortunately, a mishap during the 2013 HASP launch caused damage to the HAXDT payload. Upon release of the HASP gondola, the mobile launch vehicle did not reverse quickly enough, and the outrigger of the gondola on which the HAXDT payload was mounted struck the crane arm as the gondola ascended. This caused three of the four side panels of the payload, as well as the top plate, to be shed from the gondola and fall to the ground, shown in Figure 3 below. The flight computer, interface and power board, GPS receiver and antenna, pulse height analysis circuitry, and the detector assembly were mounted on these panels and all fell to the ground as well, causing permanent damage to the GPS receiver and the flight computer. The payload mounting plate and the bottom plate of the HAXDT payload remained attached to the HASP gondola for the duration of the flight, along with the fourth side panel, which remained attached by a single machine screw. The IMU, mounted to the bottom plate, and the detector board, mounted to the side panel, endured the full HASP flight with a limited mechanical connection to the gondola and no environmental protection. Luckily, both of these components were recovered safely and are continuing to function properly in ground tests. The damaged payload is shown in Figure 3 below.

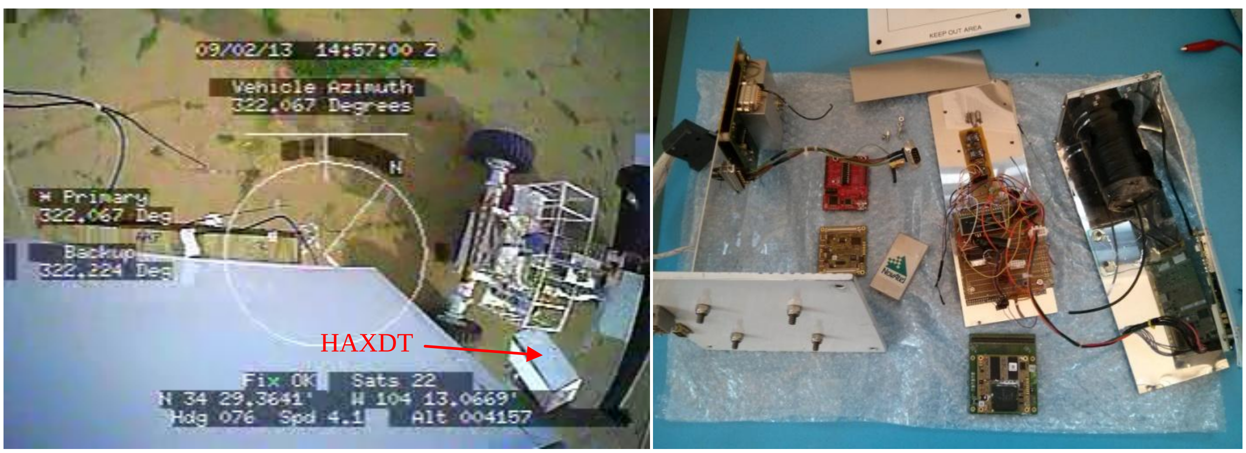

Figure 3. The HAXDT payload falling to the ground after striking the mobile launch vehicle's crane arm (left); the remains of the payload after recovery (right). Note the side panel still loosely attached to the payload plate, which remained attached to the gondola for the full flight.

With the exception of the lack of flight data and the damage experienced by the payload, the HASP project came together with minimal setbacks and the development of the payload was largely considered a success. However, like any other engineering project, there were several challenges and minor issues that arose during the design, build, and testing of the 2013 HAXDT. Dealing with these challenges produced many valuable lessons which will be applied to future iterations of the project in hopes of mitigating such issues.

1. Greater care needed to be taken in electrically insulating the detector housing and payload side panels from the coaxial connector used for the detector board input from

the APD. The payload enclosure was cramped and testing of the detector resulted in occasional short circuits between the detector housing and the coaxial connector, which caused the pulse height analysis circuitry to malfunction. The issue was corrected prior to payload integration using electrical tape for insulation, but polymide film will be used in the future. Also, design changes will be made to eliminate the close proximity of the coaxial connector and the detector housing.

2. To streamline our payload and allow for better cable management, the original design included a custom-printed power and interface circuit board to handle the power distribution and the connection of all components to the flight computer. Due to delays in both the design and manufacturing of the board, only one iteration was successfully produced, and very little time was available to test it. The testing seemed to be successful until only a week before payload integration, at which time an apparent short on the board damaged our flight computer beyond repair. We were able to borrow a new flight computer from the UAV lab at UMN and successfully revert to our former power and interface system, but the advantages of the custom circuit board were sorely missed.
3. The current payload design does not allow for easy accessibility of any major payload components. Future designs will allow for access to the SD card, status LEDs, and component reset switches without the complete removal of at least one side panel of the payload, as was the case with the 2013 HAXDT.
4. The current data logging scheme is slow and inefficient, which is a poor design when trying to measure random and frequent photon strikes. This portion of the flight code will be addressed in the future.
5. The serial downlink was utilized only to send GPS and temperature data from the payload. Therefore, the proper operation of the detector, the pulse height analysis circuitry, and the IMU cannot be confirmed remotely when the payload is powered up on the HASP gondola. Since only a small fraction of the available downlink bandwidth is currently being used, more data will be transmitted in the future to allow for complete analysis of payload health in real time throughout thermal/vacuum chamber testing and flight.

Results Summary

The data available on the serial downlink from the HASP gondola in the hours leading up to the flight confirmed that at least the basic functions of the payload were working properly on the launch day. However, the SD card was not recovered along with the damaged payload, so the proper operation of the IMU, detector, and pulse height analysis circuitry on the launch day cannot be confirmed. The only complete record of data available from the payload is the data collected during the thermal/vacuum chamber test during payload integration.

During the thermal/vacuum chamber test, the payload continued to operate successfully throughout the full range of temperature and pressure conditions. The GPS receiver maintained its position lock through the repeater mounted in the chamber, and the IMU maintained stable inertial readings, with some drift due to temperature bias. Further, the detector functioned as intended, logging an average photon count rate of 0.395 photons/second, consistent with the rates seen in previous ground testing. It is expected that this rate would be much greater at high altitudes, as was seen in the data from last year's payload. The pulse height analysis circuitry also performed as expected. The raw voltage peaks were converted into photon energy measurements by factoring in the light yield of the scintillator, the quantum efficiency and gain of the APD, and the input sensitivity and gain of the detector board circuitry. The photon energy measurements obtained using this theoretical approach may not be exact, and will be corrected in the future by calibrating the detector using known radioactive sources. The energy spectrum of approximately 2,800 photon events detected during a portion of the thermal-vacuum test is shown in Figure 4 below.

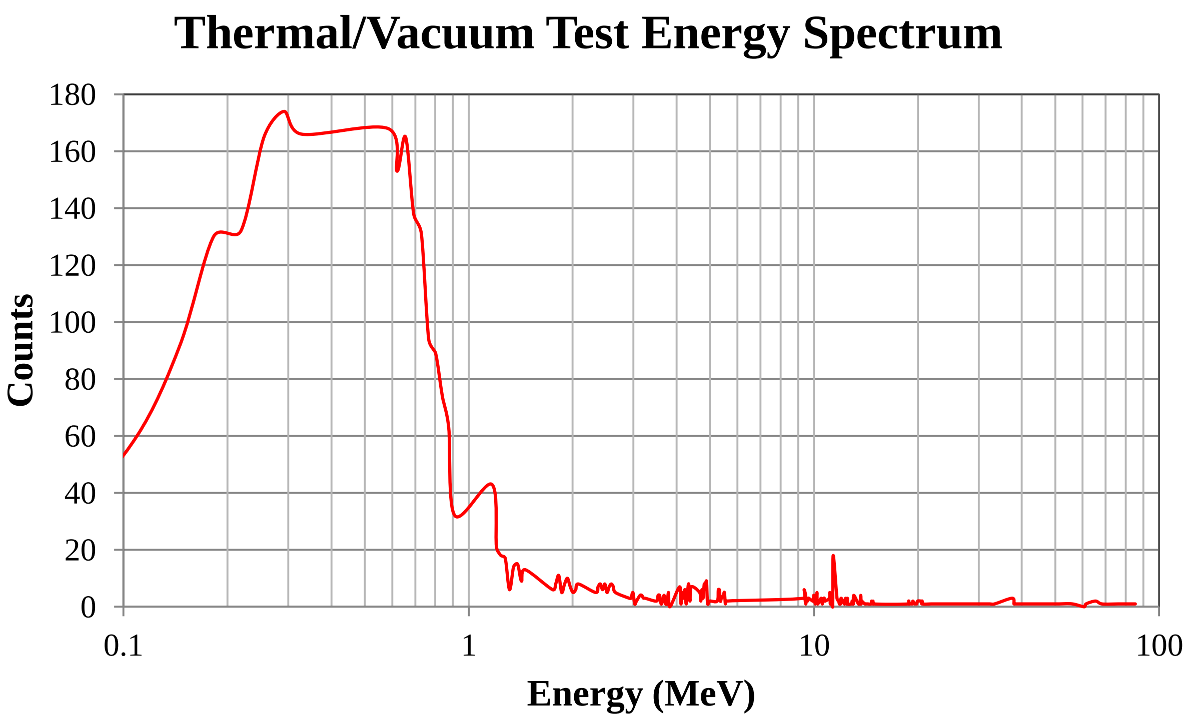

Figure 4. A plot of the photon energy spectrum from a portion of the thermal/vacuum test. Detected events ranged from just below 100 keV to 85 MeV.

The energy spectrum shows that the majority of scintillation events occurred in the range of 200–700 keV, which is consistent with typical gamma ray energy levels. Some higher-energy events were also recorded, which could be attributed to fast neutrons, alpha particles, or other sources. This is likely the case for the small peak just above 10 MeV, which would be consistent with either fast neutrons or alpha particles.

Conclusions and Future Work

The primary goal of the 2013 HAXDT payload was to maintain the same level of performance in counting photon events while simultaneously collecting navigation and attitude data that was realized in the 2012 payload, with the added functionality of measuring the energy levels of the photon events. Although no flight data was collected due to the unfortunate launch mishap, the data obtained from rigorous ground testing is sufficient enough to declare this goal to be successfully met. In addition to the minor design changes and improvements that will be made in future iterations of the project, a significant step towards the long-term goals of the project will be made by adding a second detector assembly in line with the first. This will allow for the development of a coincidence trigger, eliminating the need to record all photon events and instead focusing only on coincident ones. It will also give the detector a sense of direction, since any coincident events will be caused by photons traveling along the shared axis of the two detectors. Such directionality is a critical characteristic of a detector to be used in X-ray navigation; it allows for pinpointing of known celestial X-ray sources, each with a unique and known emission spectrum. A complete X-ray navigation system used on a small spacecraft would be required to both characterize X-ray sources by their energy spectra, and to determine the direction to each source. With each additional flight of HAXDT, these and other important capabilities can be implemented and tested one by one.

Student Involvement

Below is a table displaying all students involved in the 2013 HASP mission and their demographic information.

Name	**Gender**	**Ethnicity**	**Race**	**Student Status**	**Disability**
Seth Frick	M	Non-hispanic	Caucasian	Graduate	No
Patrick Doyle	M	Non-hispanic	Caucasian	Graduate	No
John Jackson	M	Non-hispanic	Caucasian	Undergraduate	No
Haley Rorvick	F	Non-hispanic	Caucasian	Undergraduate	No
Josiah DeLange	M	Non-hispanic	Caucasian	Undergraduate	No
Alec Forsman	M	Non-hispanic	Caucasian	Undergraduate	No
Seth Merrifield	M	Non-hispanic	Caucasian	Undergraduate	No
Mark Abotossaway	M	Non-hispanic	Native American	Undergraduate	No
Curtis Albrecht	M	Non-hispanic	Caucasian	Graduate	No
Michael Joseph	M	Non-hispanic	Caucasian	Undergraduate	No
Micael Menendez	M	Hispanic	White-Latino	Undergraduate	No
Andrew Mahon	M	Non-hispanic	Caucasian	Undergraduate	No

Curtis Albrecht completed his master's of science degree in May and is now employed at Honeywell Aerospace in Golden Valley, MN; Mark Abotossaway completed his bachelor's degree in May and is currently working as a research assistant with the Center for Compact and Efficient Fluid Power at the University of Minnesota; and Patrick Doyle completed his master's of science degree in September and is now employed at The Aerospace Corporation's Embedded Control Systems Department in El Segundo, CA. The focus of all three students' degrees was aerospace engineering and mechanics.

Papers and Presentations

1. Mr. Albrecht presented his Master's Plan B project concerning the development of the attitude and heading reference system on the HAXDT payload on May 15, 2013 at the University of Minnesota.
2. Mr. Doyle presented his Master's Plan A thesis concerning the development of the HAXDT payload and the use of HASP flight data alongside simulation results to determine the feasibility of using a compact X-ray detector for deep space navigation on September 6, 2013 at the University of Minnesota.

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