Final Science Report

University of Minnesota High Altitude X-ray Detector Testbed Payload
High Altitude Student Platform - 2016

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Abstract

This document describes the results and lessons learned from the 2016 HASP flight from the University of Minnesota High Altitude X-ray Testbed (HAXDT) payload. The flight of HAXDT had two objectives. The first objective was to characterize the sensitivity of the Avalanche Photo Diodes (APDs) used on a University of Minnesota designed X-ray spectrometer known as the Gamma Ray Incidence Detector (GRID). GRID is being developed as a payload for CubeSats. The second objective was to perform an engineering system test of GRID and the radio communication sub-system that will be integrated within a CubeSat. The detector system (GRID) is being developed as part of a program to explore the possibility of developing a dual-use CubeSat[1] sensor. As a science instrument, it measures X-ray and gamma-ray photon arrival times and energies. As an engineering sensor, it will use high-energy photons emitted by astrophysical sources to perform ranging, enabling autonomous deep-space navigation capabilities for future spacecrafts. Other lessons learned in the design process are described and documented so that the design of future payload iterations (and eventually, CubeSat nanosatellites) can be improved.

[1] The University of Minnesota is currently building two 3U CubeSats: EXACT (Experiment for X-ray Characterization and Timing) and SOCRATES (Signal of Opportunity CubeSat Ranging and Timing Experiments). Components for these CubeSats are being tested on HAXDT.

Introduction

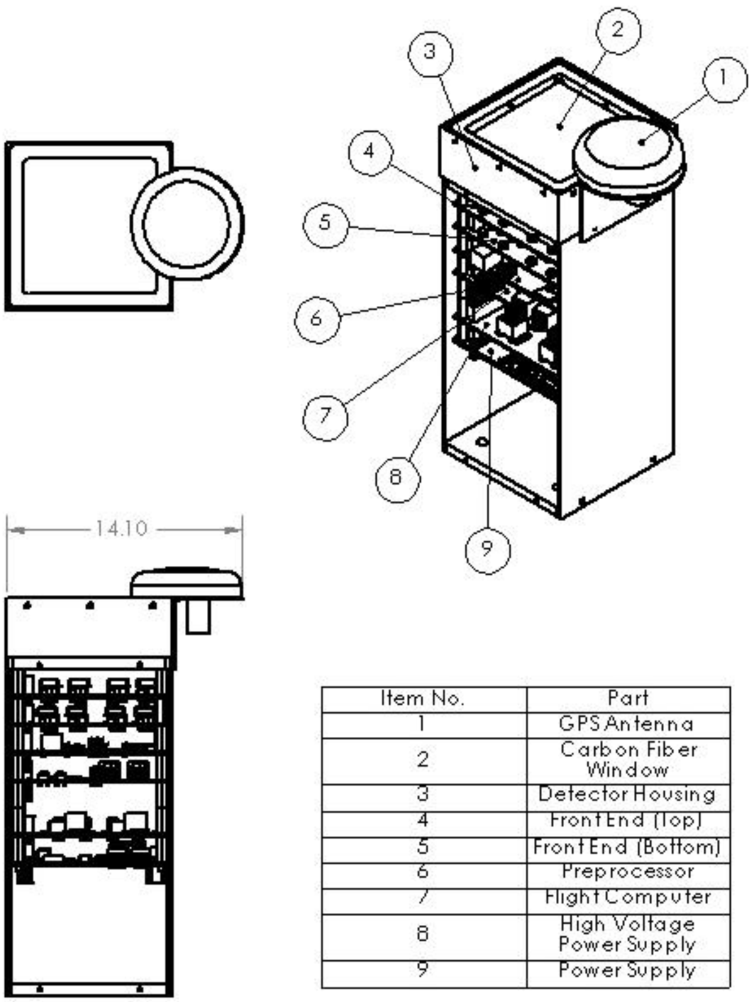
The purpose of the University of Minnesota High Altitude Student Platform (HASP) experiment was to investigate the performance of a gamma-ray detector designed to detect X-ray and gamma-ray emissions from astrophysical sources such as the sun, pulsars, or Gamma Ray Bursts (GRB).

Collecting and analyzing X-ray and gamma-ray emissions is useful in understanding the mechanics of astrophysical phenomena. A detector that measures gamma-ray photons from GRB can also be used for navigation purposes. GRBs occur at a rate of approximately one a day, and emit a burst of radiation with most energy concentrated in the gamma-ray band of the electromagnetic spectrum. Photons from a GRB observed at two spatially separated detectors- at times that are offset by a delay- can be used to determine a relative position solution using the time difference of arrival (TDOA).

The HASP payload serves as a test bed for the compact detector subsystem designed to record the X-ray and GRB data. The University of Minnesota HASP payload is known as the High Altitude X-ray Detector Testbed (HAXDT) and provides an interface for a compact X-ray/gamma-ray spectrometer in development known as the Gamma Ray Incidence Detector or GRID. When installed on a CubeSat it can be used as a relative range sensor or a science instrument. As a science instrument, it is primarily used to measure X-ray photon energies and arrival times, enabling the study of electron acceleration in solar flares, which are the drivers of space weather events (e.g. coronal mass ejections). This objective is mostly focused on our sun, and would reveal more information about these large-scale space weather events, which can pose threats to space satellites, astronauts, and even power grids on Earth. Since measuring this energy band of X-rays in solar flares coincides with the goals for GRID, this research will also benefit from the HASP payload testing and results.

As a result of the 2016 flight test, the UMN team has uncovered some design issues with the current GRID design. Specifically, the avalanche photodiodes used in the sensors are temperature-sensitive. In addition, the detector was affected by the electromagnetic noise generated by other electronics in its proximity. The APDs used in the GRID payload are very sensitive to temperature change and the gain provided by the high bias voltage applied. As the temperature changes, the gain of the APD changes with a logarithmic relationship to temperature. To accurately calibrate the detector, its gain must remain fixed throughout temperature fluctuations during flight. Further data will be needed on this behavior in order to model an effective algorithm for a feedback current loop to adjust the bias voltage based on temperature readings.

HAXDT Description



Item No.	Part
1	GPS Antenna
2	Carbon Fiber Window
3	Detector Housing
4	Front End (Top)
5	Front End (Bottom)
6	Preprocessor
7	Flight Computer
8	High Voltage Power Supply
9	Power Supply

Figure 1: A 3D SolidWorks model of the 2016 payload; dimensions shown are in centimeters.

The experiment described in this report was designed to conform to the power and interface requirements of Louisiana State University's (LSU) High Altitude Student Platform (HASP). The detector itself is a 4x4 grid of CsI(Tl) scintillation crystals with optical readout devices and associated electronics. The detectors were selected to produce a peak sensitivity in the range of 90 keV–1330 MeV, corresponding to hard X-rays and gamma-rays which can be easily observed in the Earth's atmosphere. The rest of the payload, implemented as a PC/104 stack, contains a GNSS receiver, an IMU, a flight computer, and several additional boards for power regulation. The ultimate goal of GRID is to prove that an alternative navigation solution can be obtained by combining information received from sensors measuring fluxes of charged particles. Provided the time arrival of these particles can be precisely characterized in a way that can be represented as a distinctly binned rate (i.e., a signal that consists of detected event rates), the concept of relative positioning can be applied. This is all based on the assumption that cooperating spacecrafts are equipped with similar detectors capable of picking up the same information that is being observed. With this information, one detector's observed rates can be correlated with another's to obtain an estimate of the amount of time the detected radiation took to propagate from one detector to the other.

In previous years, the HAXDT payload was designed to conform to CubeSat generic structure standards. Using an internal PC/104 stack was also an effort to emulate the interface requirements of a real CubeSat. GRID is situated on top, as seen in Figure 1, with the PC/104 stack extending below. These boards all share common power rails and use the same computer bus, although the only use for the PC/104 bus was photon data. The stack itself consists of commercially available components and OEM components. The detector's front end is based on a thermalized nuclear particle detection board circuit designed by Lockheed engineers. Originally designed for a two-channel instrument, this circuit was duplicated and spread onto a four-channel (two-board) PC/104 version. The detector's front end is monitored by one AVR microprocessor; another is in charge of PC/104 bus handshaking. Timestamps are based on a clock derived from the GPS pulse-per-second output (PPS, accurate to 20 ns). The initial time at power-up is obtained from a real-time clock (RTC), but after this the PPS signal increments a counter. Thus, photon timestamps have microsecond precision (from the ATmega2560's oscillator) and are accurate to 20 nanoseconds. Detector data is packetized and sent to a first-in-first-out (FIFO) buffer that is periodically dumped to non-volatile memory (via the PC/104 bus). Currently, these packets contain an ADC temperature, event timestamp, ADC bin, and channel ID. Important details of this setup are:

1. From all combined channels, only one event can be digitally stored at a time. The GRID peak detector is a track-and-hold circuit that must be reset to the initial state when the event has been logged.
2. The minimum time to completely process an event is 10 milliseconds, which still may result in data loss. The cumulative count rate from all channels is hard-limited at 10 counts per second for flight data, because a safety factor of 10 was implemented in firmware (100 milliseconds dead time).
3. With the information contained in a set of packets, the photons can be sorted by energy, channel, and timestamps to examine various parameters (flux in different bands, for each individual channel).

The central processing unit is an ATmega 2560 chip, chosen mostly for its versatility and performance specifications. The ATmega handles sensor logs for both a GNSS receiver (a NovAtel OEM615) and an IMU (a VectorNav VN-100). The mounting board for these two sensors is connected to the ATmega via printed circuit board (PCB) traces. The GPS is sampled at 1 Hz and the IMU is sampled at 40 Hz, and all data are stored on an SD card located on a different PC/104 board. Additionally, the ATmega waits for an IRQ to initiate a byte-by-byte transfer of the contents of the FIFO buffer. As was mentioned above, this occurs whenever a front-end buffer exceeds half of its capacity (42 photons).

A downlink method independent of telemetry was used to transmit the on-board data to a ground station via a 915 MHz radio link. The FreeWave MM2-T radio received data from the flight computer to be sent to the ground station. Figure 4 shows the connection history of the payload to ground station. Intentionally, none of the data was compressed prior to downlink. All data was also stored in the on-board SD card to check packet quality upon retrieval of the payload. Ideally, the SD card data should match downlinked data. The ground station consisted of an omni-directional antenna, a parabolic antenna, a tri-pod, and a computer. Via the LED readout on the MM2 radio, the ground station team had knowledge of when the link was established and broken. Prior to launch, the omni-directional antenna was "on" and receiving data. Once that link was broken, the team switched to the parabolic antenna. Pointing the antenna was done using line-of-sight tracking as well as HASP's downlink telemetry GPS and elevation data. Using a program for ease of calculation, the crew determined bearing and elevation angle based on this data to determine where to point the antenna. The computer was connected to the ground-based MM2 and recorded the received data in real-time.

Payload Performance

The payload met all performance expectations in ground testing (specifically during Student Payload Integration) leading up to the HASP flight. The payload properly recorded data to the SD card, the ground station received data from the onboard transmitters, and that data that was sent was as expected, as well as the "noise" the detector was seeing. One issue was encountered during integration: the SD card failed to write when the temperature of the chamber reached 50 degrees Celsius. This issue was initially detected during the first thermal vacuum test done at integration. To mitigate this issue, a new SD card was used for the second test and results came back as expected with no data loss at high temperatures.

This was the first year the UMN team used an independent downlink with a separate frequency. With multiple payloads on the HASP gondola, it was necessary to consider any interference the radios might have on other payloads or the gondola system itself. To mitigate any issues that may occur as a result of the radio, a relay switch was installed providing power to the radio independent of the system's power. This relay was triggered via a discrete line in the HASP telemetry and purpose was to have the ability to turn the radio off independent of the payload. Our science mission would be uninterrupted if our radio was causing interference and needed to be turned off since the system's power would still be on and would be able to still write the data to the SD card. This hardware was implemented before the second thermal vacuum chamber testing, and was successful at high and low temperatures and pressures.

During flight, the performance of the communications system can be seen in Figure 4. The team set up the ground station and tracked the gondola for approximately five hours. At this time, the ground station was unable to maintain a connection. The team packed up the ground station and continued monitoring telemetry after this point. Overall, considering manual pointing, the communication testing was successful. The data received allowed for experience with checksum protocols, maintaining link, and future ideas to improve gondola tracking.

Soon after launch, SD card writing errors appeared in the telemetry. The payload was power-cycled; yet the problem persisted. Data was sporadically written to the SD card according to telemetry data. Upon retrieval of the SD card post-flight, all data on the card was corrupt and there was nothing for the team to compare radio data.

Based upon the functionality of the payload prior to the HASP flight, GRID performed as expected. It was hoped that GRID would either have increased functionality, in that it would overcome some of its issues in a near-space environment, or that it would function the same as it did in lab. Knowing that the components maintained operation will allow the teams working with the payload to redesign GRID using the current components.

Problems Encountered and Lessons Learned

The HASP flight has shown the importance of knowing the APDs temperature. The underlying issue of the noise floor was exacerbated by the increased gain of the APD at lower temperatures. From this, the necessity of accounting for APD temperature during flight was determined. This can be accomplished either by controlling the environment around the APDs, or through adjusting the reverse bias voltage to maintain gain levels throughout temperature variations.

After diagnosing the SD card issues, the investigation revealed problems in the way the SD card was mounted to the stack. As a last-minute fix before integration, an old breakout board was attached and wired into the stack's electronics. In lab testing, the SD card was writing properly and worked throughout the thermal vacuum testing. The team believes this breakout board was not intended for frequent use in such rough environments. No documentation could be found about this particular board. To mitigate this issue in the future, PCB mounted memory will be used in place of an SD card. These future components are rated for the environment and will be rigorously tested prior to any future flight.

Results Summary

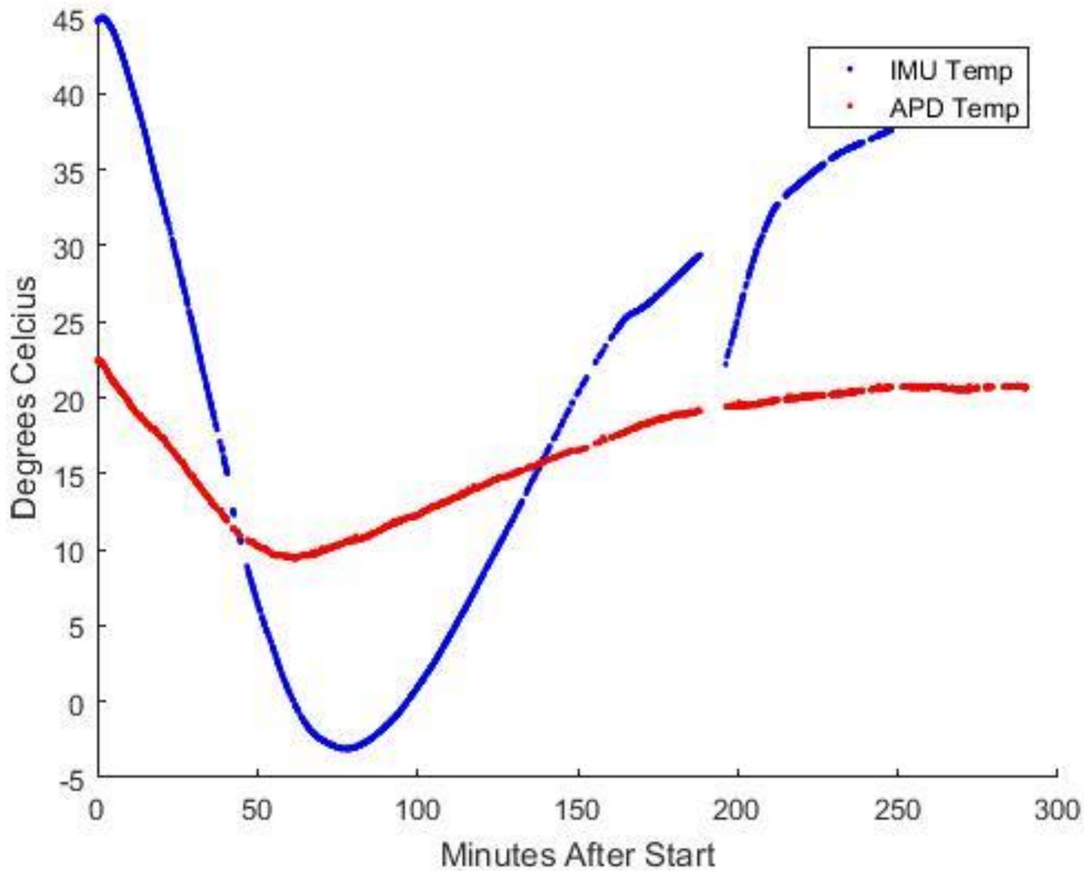


Figure 2: This plot depicts the temperature of the IMU and APD during the flight. As can be seen, the temperature of the APDs fluctuated approximately 12 degrees Celsius, which corresponds to a change in gain of approximately 40x. It is suspected that this level of gain increase would result in an increase in shot noise that far outweighs the possible decrease in thermal noise from cooler temperatures.

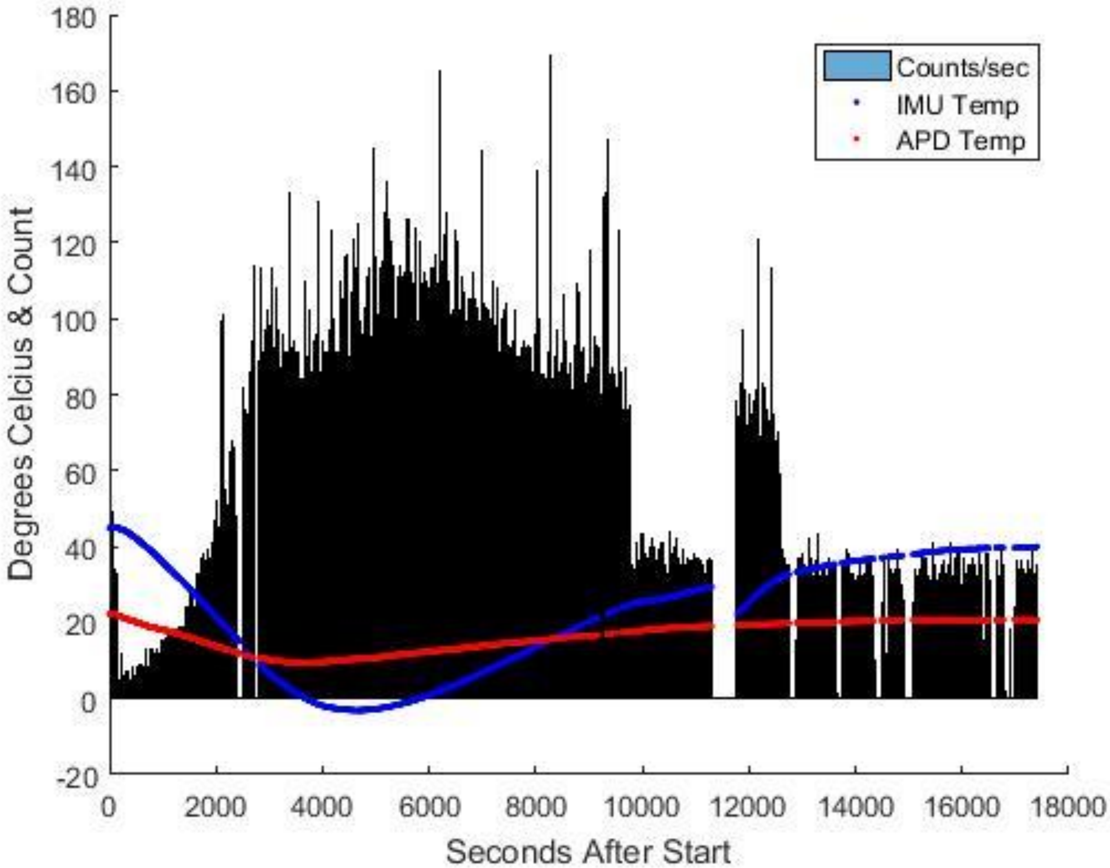


Figure 3: This plot depicts the temperature versus time again, but with the number of counts superimposed on the plot. This demonstrates the suspected behavior. The initial values for total counts are relatively low; however, as the temperature of the APDs cool, the number of counts increases dramatically as a result of increased APD shot noise. As time progresses, the APD's temperature rises back to the initial temperature and the number of counts returns to lower values.

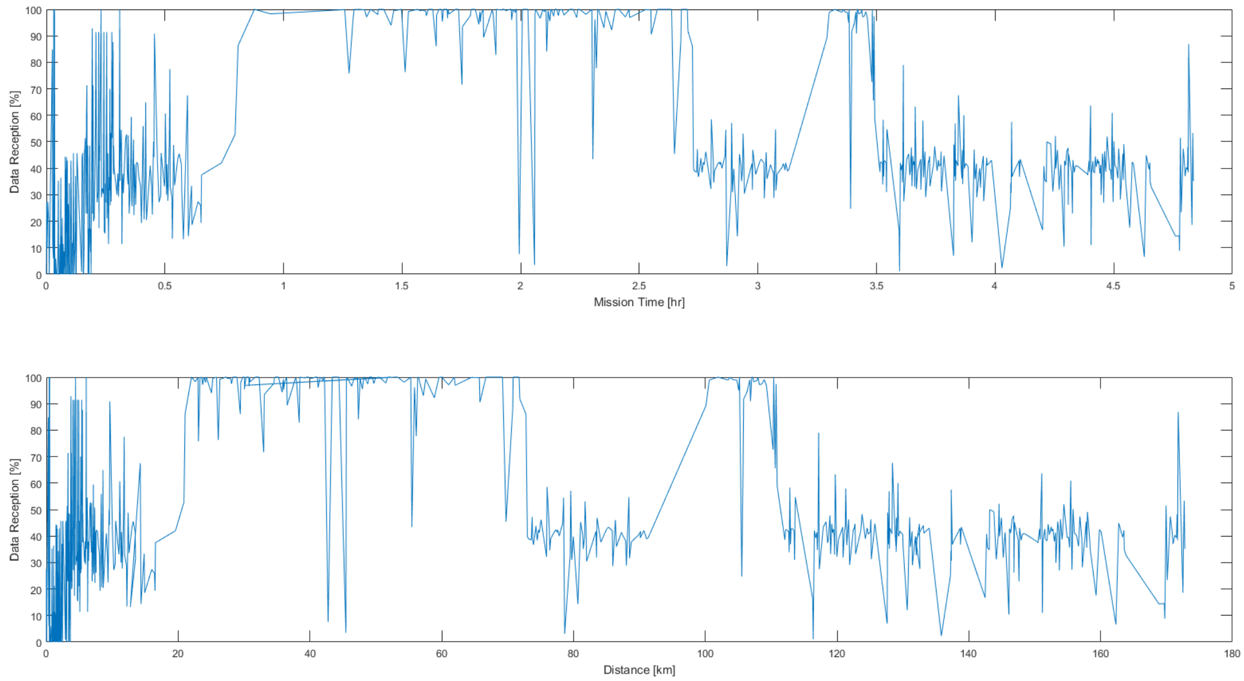


Figure 4: These plots depict data reception throughout the flight. In the beginning of the flight, the omni-antenna was used until 13 km of range. The reception due to that antenna was hit and miss. Around 20km, the directional antenna provided better aim, and reception was maintained nearly 100% of the time until 75km. Dips in the graph resulted from having to manually point the antenna. After 75km, partial connectivity was maintained until 175km. Data reception was measured by comparing the number of photon event packets (full packets with a valid checksum) received over the radio versus the expected number of photon events as specified by the telemetry through the HASP gondola. Since the photon event packets made up over 99.5% of the data sent down, comparing all positions and statuses of other packets was not necessary.

Conclusions and Future Work

The GRID detector system is currently under redesign. To determine how to improve the current design, a laboratory-testing version of the detector was built as a single channel system within a controlled environment. The goal is to determine the best methods for improving the functionality of the payload. Eventually, these methods will be implemented in the redesign to create a fully functional detector. The physics team will investigate how to best increase the signal-to-noise ratio, how to maintain an appropriate gain for the APD's (to minimize both thermal and shot noise), and how to shield the detector from the extraneous noise sources of the other systems.

The University of Minnesota plans to submit a proposal to fly HAXDT again next year to test the new redesigns due to items discovered during this 2016 flight.

Student Involvement

Below is the table of all students associated with the 2016 HASP mission and their demographic information.

Name	**Gender**	**Ethnicity**	**Race**	**Student Status**	**Disability**	**Responsibilities**
Hannah Weiher	F	Non-Hispanic	Caucasian	Graduate Student	None	Team lead
Tim Kukowski	M	Non-Hispanic	Caucasian	Undergraduate Senior	None	Chief Engineer
Joel Runnels	M	Non-Hispanic	Caucasian	Graduate Student	None	Technical Consultant (Detector engineering and physics)/Payload Lead
Ryan Vogt	M	Non-Hispanic	Caucasian	Undergraduate Sophomore	None	Detector Systems Physicist (Calibration and testing)
Kendra Bergstedt	F	Non-Hispanic	Caucasian	Undergraduate Sophomore	None	Detector Systems Physicist (Calibration and testing)
Maxwell Yurs	M	Non-Hispanic	Caucasian	Undergraduate Junior	None	Detector Systems Lead (Calibration and testing)
Jeffrey Chaffin	M	Non-Hispanic	Caucasian	Undergraduate Senior	None	Detector Systems Physicist (Design, Calibration and testing)
Ilya Zubarev	M	Non-Hispanic	Caucasian	Undergraduate Senior	None	Detector Systems Physicist (Calibration and testing)
Gaurav Manda	M	Non-Hispanic	Asian	Undergraduate Sophomore	None	Detector Board Redesigns
Luke Granlund	M	Non-Hispanic	Caucasian	Undergraduate Senior	None	Payload Systems Software
Aaron Nightingale	M	Non-Hispanic	Caucasian	Undergraduate Junior	None	Payload Systems Hardware
Seth Willing	M	Non-Hispanic	Caucasian	Undergraduate Junior	None	Flight Structures Engineer

Below is the table of all past students associated with the 2015 HASP mission and their current information.

Name	**Degree Obtained**	**Graduation Date**	**Current Activity**
Seth Frick	Master of Aerospace Engineering	May 2015	Current employer: Honeywell Aerospace Title: Radar Systems Engineer
Josiah Delange	Bachelor of Aerospace Engineering	December 2015	Current employer: Digi International Title: Cellular Firmware Engineer
Charles Denis	Bachelor of Aerospace Engineering	May 2016	Current employer: Quality Bicycle Products Title: Design Engineer
Justin Seifert	Bachelor of Aerospace Engineering	May 2016	Current employer: Carl Zeiss Industrial Metrology Title: Applications Engineer
Jacob Gustafson	Bachelor of Aerospace Engineering	May 2016	Current employer: UTC Aerospace Title: Software Engineer
Nick Janak	B.S Physics Bachelor of Aerospace Engineering	December 2015 May 2016	Current employer: Carl Zeiss Industrial Metrology Title: Applications Engineer M.S Mechanical Engineering (In Progress)
Nicholas Sloan	Bachelor of Aerospace Engineering	May 2016	Current employer: Generation Orbit Title: Structures Engineer
Ethan Arendt	Bachelor of Aerospace Engineering	May 2016	Unknown
Brian Hanson	Bachelor of Aerospace Engineering	May 2016	Unknown
Benjamin Setterholm	Bachelor of Aerospace Engineering	May 2016	Graduate School: University of Michigan, Ph.D. in Astrophysics

Papers and Presentations

Conference/ Location of Publication	Title of Article or Poster	Authors and/or Presenters	Date Published or Presented
Solar Physics Division Conference of the American Astronomical Society/Boulder, Colorado	EXACT - The Experiment for X-Ray Characterization and Timing	Trevor Knuth	June 2, 2016
Asteroid Day at UMN (public outreach)/Minneapolis, MN	EXACT CubeSat	Jeff Chaffin, Joel Runnels, Kale Hedstrom	June 25, 2016
SmallSat Conference/ Logan, Utah	EXACT CubeSat	Ryan Vogt	August 7, 2016

Acknowledgements

The University of Minnesota HASP/HAXDT team gratefully acknowledges the technical advice and support from the staff of ASTER Labs, Inc. We also thank the Louisiana Space Consortium and NASA's Balloon Program Office for the continued support of the HASP flight. We would like to thank Kale Hedstrom and Dr. James Flaten for their technical advice and encouragement. Finally, we acknowledge the NASA/Minnesota Space Grant Consortium for providing funding to the HASP payload development and the University of Minnesota. The generous resources we've received for this project encourage us to continue working and innovating.

While the authors gratefully acknowledge the aforementioned individuals, the views and conclusions expressed in this report are those of the authors alone, and should not be interpreted as necessarily representing the official policies, either expressed or implied, of any organization.