HASP Student Payload Application for 2016

Payload Title:
Flight Test of a GRID on the High Altitude X-Ray/Gamma-Ray Detector Testbed (HAXDT)

Payload Class: (check one)	Institution:	Submit Date:
☑ Small ☐ Large	University of Minnesota, Twin Cities Campus	December 18, 2015

Project Abstract

The High Altitude X-Ray/Gamma-Ray Detector Testbed (HAXDT) is platform used for flight testing prototype sensors and sensing concepts for CubeSats. HAXDT has a 3 U CubeSat form factor and is designed to interface with High Altitude Student Payload (HASP) adapter plate. It hosts a flight computer and which is used to log data from the prototype sensor. The logged data is saved to solid state hard drive that is analyzed after flight to assess the performance of the prototype sensor. On the 2016 HASP flight, HAXDT will host the 3rd generation prototype of the Gamma Ray Incidence Detector (GRID) developed at the University of Minnesota. GRID is essentially a gamma-ray (and hard x-ray) detector optimized for making accurate positioning, navigation and timing (PNT) measurements. In operation, it will use signals of opportunity (e.g., naturally occurring gamma-ray emissions for sources such as Gamma-Ray Bursts or GRBs) as navigation and timing beacons akin to GPS satellites. Currently, GRID is at a Technology Readiness Level (TRL) of 5. The HASP 2016 flight test is "stepping stone" in preparation for an eventual CubeSat flight whose goal is to elevate the TRL to 7.

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University of Minnesota	https://wiki.umn.edu/HASP/WebHome

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A. INTRODUCTION

The University of Minnesota (UMN) high-altitude balloon project is a student-run, independent research project started and sponsored by the Minnesota Space Grant. Its activities take place in the small satellite laboratory at the UMN and since 2010, it has been designing and testing x-ray and gamma-ray detectors on the High Altitude Student Platform (HASP) opportunities made available by NASA/Louisiana Space Grant [1, 2]. The technical goal of these flight test has been to test x-ray/gamma-ray sensors that are being developed into novel ranging and timing sensors for small satellites.

To support these efforts the team developed the High Altitude X-ray Detector Testbed (HAXDT). HAXDT is a platform used for flight testing prototype sensors and sensing concepts for CubeSats. HAXDT has a 3 U CubeSat form factor and is designed to interface with the HASP adapter plate. It hosts a flight computer and which is used to log data from the prototype sensor. In addition, it has a GPS receiver and an inertial measurement unit (IMU) which provide a time history of the kinematic states of the HAXDT. The logged data is saved to solid state hard drive that is analyzed after flight to assess the performance of the prototype sensor.

1. Flight Objectives for 2016 Flights

On the 2016 HASP flight, HAXDT will host the 3rd generation prototype of the Gamma Ray Incidence Detector (GRID) developed by University of Minnesota high-altitude balloon project. GRID is essentially a gamma-ray (and hard x-ray) detector optimized for making accurate positioning, navigation and timing (PNT) measurements [3]. In operation, it will use signals of opportunity (e.g., naturally occurring gamma-ray emissions for sources such as Gamma-Ray Bursts or GRBs) as navigation and timing beacons akin to GPS satellites. GRID is being developed in support envisioned future space missions (e.g., [5, 6]) and NASA technology needs identified by NASA in [4]. As will be discussed below, currently, GRID is at a Technology Readiness Level (TRL) of 5. The HASP 2016 flight test will be a “stepping stone” in preparation for an eventual CubeSat flight whose goal is to elevate the TRL of GRID.[1]

In preparation for a future CubeSat flight, two major changes to GRID have been made: (1) A change to the readout electronics and (2) The method for powering the sensor. The readout electronics are circuits which time-tag each photon event observed by GRID and log it to a data file. Changes to the readout electronics are being made in response to anomalies observed during the 2015 HASP flight and subsequent laboratory testing. These modification will eliminate saturation of the sensor when it is in an environment with high photon flux. The second change will allow powering GRID from a typical CubeSat power bus. To this end, the power made available from the HASP gondola will be used simulate the charging current being supplied available from the solar cell panels on a CubeSat. This will be used to charge the batteries which, in turn, will be supplying current to the power bus from which GRID will be energized.

[1] The University of Minnesota has submitted a CubeSat proposal to the 2015 Undergraduate Student Instrument Project (USIP). The CubeSat built as part of USIP will be used to elevate GRID to TRL 7.

2. Experiment Description

Once at altitude, HAXDT will be used as a passive observatory platform. Data collected during the flight will be used for characterizing the noise figures of the new GRID readout electronics. It will also provide a means for assessing whether the method for powering GRID using a typical CubeSat battery pack is operational.

In parallel, the team will be monitoring data from the SWIFT Burst Alert Telescope (BAT) [7] and the *Fermi* Gamma-ray Burst Monitor [8]. These spacecraft continuously monitor for GRB events and publicly, immediately issues alerts. If a fortuitous GRB even occurs during the float phase of the HASP flight, the event will be simultaneously recorded by SWIFT/Fermi and GRID. Since the positions of BAT/Fermi and GRID will be known, the timing and ranging performance of GRID can be assessed in post-process.

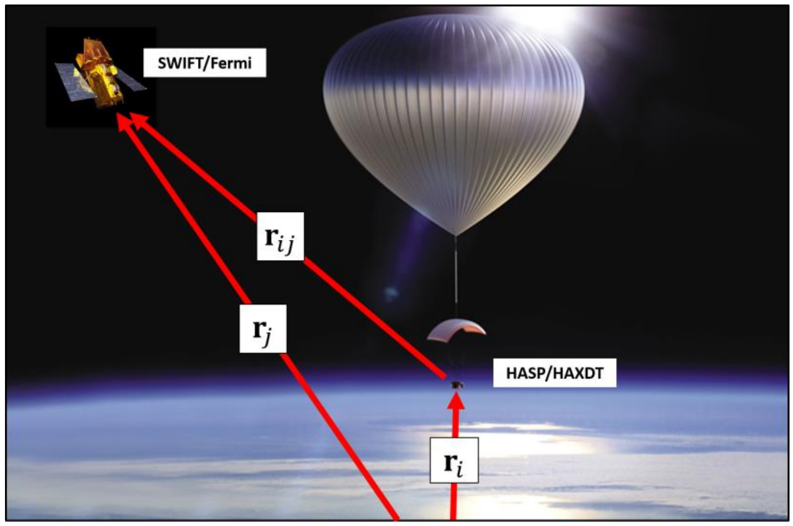

Figure 1. Concept of operation for testing the ranging and timing functions of GRID if a Gamma Ray Burst (GRB) even it observed during float.

To understand how this will be done, refer to the graphical depiction of the concept of operation for the 2016 HAXDT flight for shown in **Figure 1**. The figure shows the position of HAXDT, $\boldsymbol{r}_i$, at $t = t_i$ when the GRB is received. The same GRB is received by SWIFT (or Fermi) at $t = t_j$ when its position vector is $\boldsymbol{r}_j$. The position vector of HAXDT will be determined by the onboard GPS receiver. The positions and SWIFT/Fermi can be using their known orbital elements and time. The position vectors can now be used to calculate the magnitude of the difference between HAXDT and SWIFT's position $\rho_{ij} = \|\boldsymbol{r}_i - \boldsymbol{r}_j\|$. This difference is directly proportional to the measured time difference of arrival or $t_{ij} = t_i - t_j$ of a gamma-ray photons at HAXDT and SWIFT/Fermi. The time difference of arrival can be estimated from light curves of the GRB constructed using data from GRID and SWIFT/Fermi.

B. PAYLOAD DESCRIPTION

An engineering drawing of HAXDT is shown in **Figure 3**. It is effectively a data logging system packaged in a 3 U CubeSat structure. The interior components of the 3U CubeSat structure consist of the following: a four-channel detector board including preamplifiers for each channel and a high voltage power supply (HVPS) to provide the bias voltage for the detectors; four individual detector assemblies in a common housing; photon energy measurement hardware, either the previouslyused pulse height analysis circuitry or a multichannel analyzer (MCA); a NovAtel OEMStar GPS receiver and associated antenna; a VectorNav VN-100 inertial measurement unit (IMU); power regulation, protection, and distribution circuitry; and a flight computer with an SD card for data logging. Power is provided by HASP and is regulated to +12 VDC to power all payload systems. The power circuit also provides protection from reverse polarity and limits the current draw to just under 2.5A to prevent inrush current spikes.

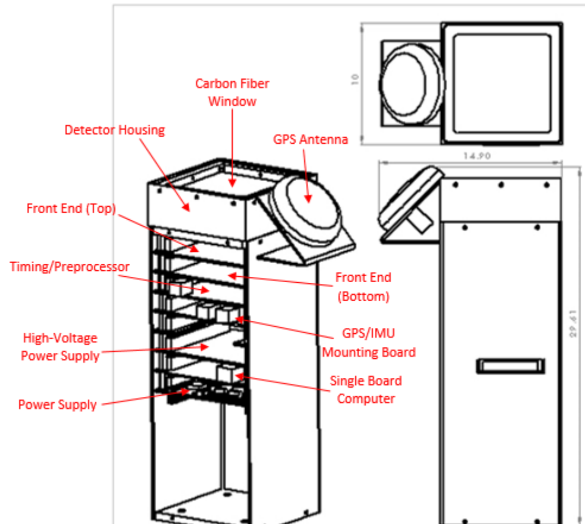

Figure 3. Engineering Drawing of HAXDT.

Figure 2 below shows a high level schematic of the test hardware that will be hosted by HAXDT on the 2016 HASP flight. This will allow testing the new data readout electronics and power system for GRID. As noted above, the power made available from the HASP gondola will be used simulate the charging current being made available from the solar cell panels on a CubeSat. This will be used to charge the batteries, which, in turn, will be supplying current to the power bus from which GRID will be energized.

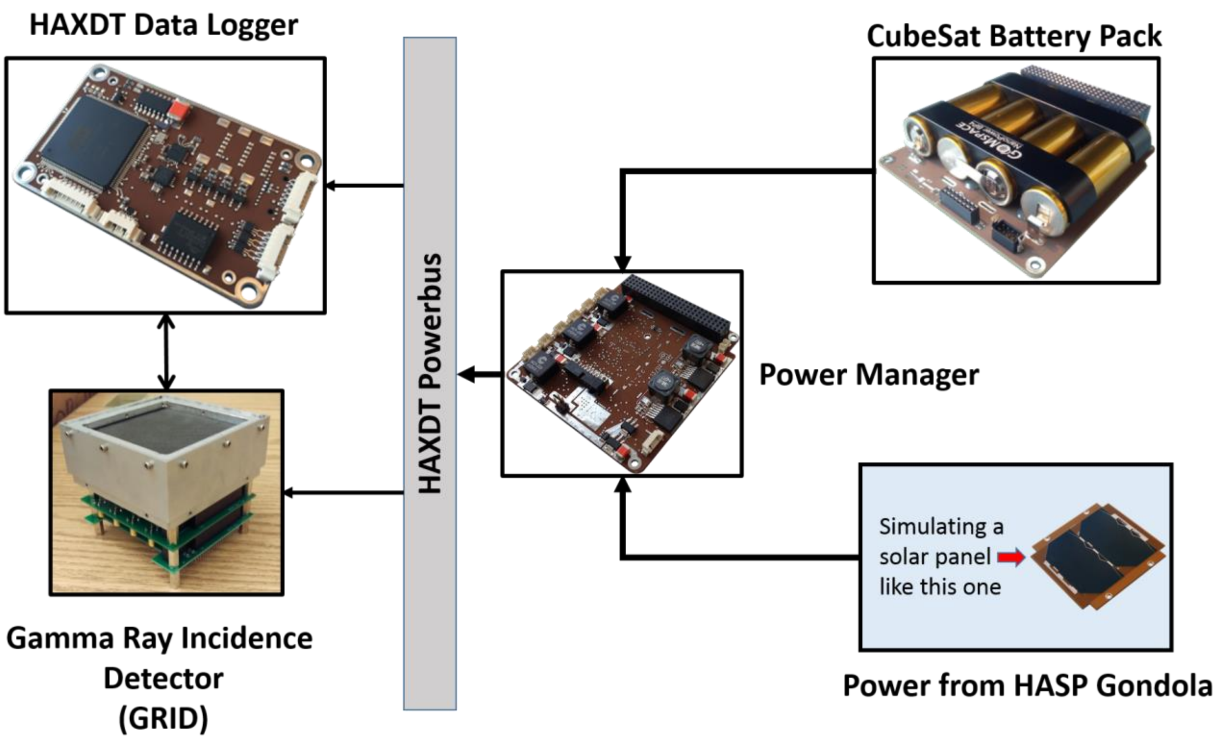

Figure 2. Schematic of hardware system that will be tested on HAXDT during the 2016 HASP flight.

1. Sensor Payload

The sensor payload flown on HAXDT will be GRID. GRID is a $10\ \text{cm} \times 10\ \text{cm}$ scintillator-based detection instrument, designed to be consistent with the form factor of a 1U CubeSat. The detection elements are four thallium-doped cesium iodide (CsI(Tl)) crystals which are sealed in a custom aluminum housing structure. Each crystal is optically decoupled from the others, and contained securely in its own cavity of the structure. Each of the CsI(Tl) crystals is a block that is approximately $4\ \text{cm} \times 4\ \text{cm} \times 2\ \text{cm}$ in dimension. Together they yield an effective detector area of $64\ cm^2$. A prototype of GRID with its black, zenith carbon fiber window covering the $64\ cm^2$ detector area is shown in **Figure 4**. The low density of carbon fiber is less susceptible to the effects of scattering and allows gamma photons to pass more easily than aluminum. The edges of the support structure result in a total sensor package with dimensions of $10\ \text{cm} \times 10\ \text{cm} \times 4.6\ \text{cm}$.

Attached to each CsI(Tl) crystal is an avalanche photodiode (APD). The APDs convert the light created from the interaction of gamma ray photons with the CsI(Tl) crystal to an electric charge. This charge is then integrated, amplified, and shaped by the readout system. In addition to a measure of the incident photon's energy (as a pulse height), the readout system also generates a TTL signal for each pulse height above an adjustable voltage threshold. A dedicated microprocessor time-tags the leading edge of this TTL signal to the closest second from the onboard clock (GPS-disciplined). This time-tag has a micro-second resolution and is used to form the complete time-of-signal-receipt tag that is applied to each individual photon observation.

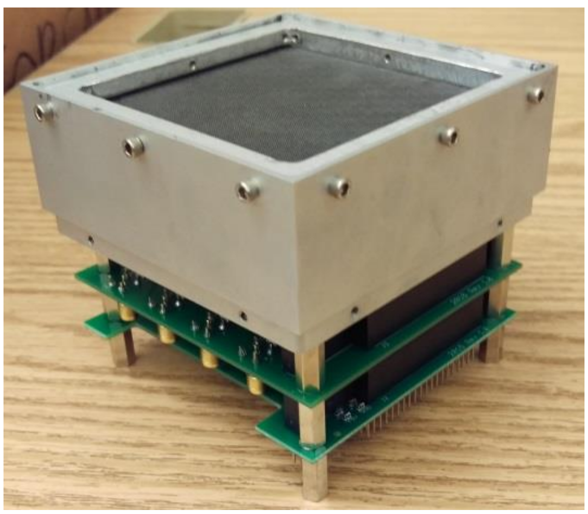

Figure 4. Gamma Ray Incidence Detector (GRID).

The $4\ \text{cm} \times 4\ \text{cm} \times 2\ \text{cm}$ dimensions were the result of a design optimization to maximize the sensitivity of the APDs. This means that each $4\ \text{cm} \times 4\ \text{cm} \times 2\ \text{cm}$ element is an independent channel for measuring gamma-ray photon count. The output of the four channels are summed to yield the total photon count seen by GRID. A time history of the total photon counts is then binned appropriately in time (or alternately, low pass filtered). The photon data thus processed forms a time history of gamma-ray flux which is the basic observable when GRID is used as ranging and timing sensor.

Currently, GRID is assessed to be at TRL 5. This is based on the fact that a working prototype shown in **Figure 5** exists and light curves collected from it show that relative timing measurements can be made. The plots in Figure 5 are example of light curves from a GRID calibration test in the laboratory. A GRB event was simulated using an artificial source (^{232}Th) that was placed in the vicinity of GRID. Initially, the source was in a shielded container and GRID was powered on. For approximately 10 minutes GRID was measuring background X-ray levels. At the $t = 10$ minutes (600 seconds) the cover of the shielded container is slowly opened to expose GRID to the artificial source. After a 10 second exposure the cover of the shielded container is closed. The procedure is repeated at $t = 1{,}620$ and $t = 2{,}020$ seconds. Figure 5 shows the flux response of two of the four GRID channels. In principle, similar light curves from another GRID detector can be cross correlated with these to yield a timing measurement. The lab simulations of GRBs are a way to measure GRID's ability to respond to photon fluxes in a given energy band (approximately 75keV – 900 keV for ^{232}Th).

An update to the GRID front end will be included in the 2015 HASP payload that enables the instrument to capture flux data that would occur during a gamma ray burst. Additional hardware will introduce a counting element (similar to the type of circuitry used in clock dividers). This will count the number of low-level discriminator (LLD) signals from the GRID front end for a specified accumulation period, and store/reset this value at the end of the period. It will thus record a count rate, in units of counts per time bin, with minimal overhead. If designed properly the counter will take near one microsecond to store and reset, which means that during a burst the effective dead time of the system is on the order of microseconds. This will significantly improve the issue seen during the 2015 HASP flight, where the count rate measured by GRID became saturated at float due to the amount of time required to process a photon event.

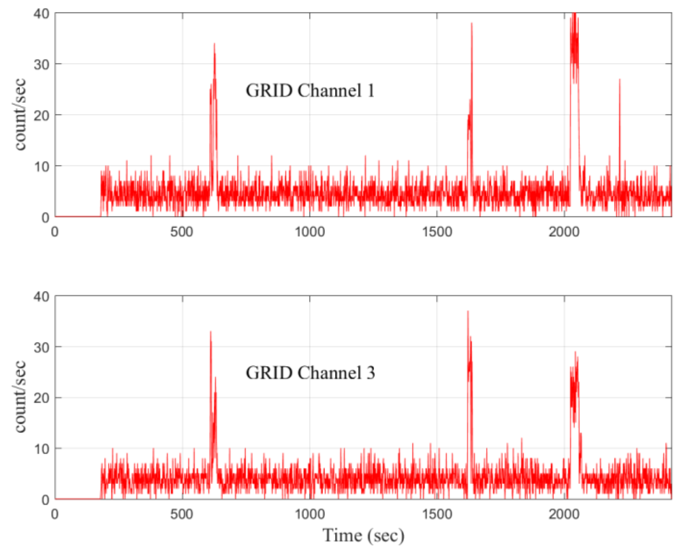

Figure 5. Light curves collected from GRID in laboratory tests.

Note that the GRID processing system's current operation is designed to utilize these LLDs to drive microprocessor interrupts. This enables the HAXDT data logger to stop what it was doing and immediately service a photon event, logging its energy, timestamp, channel, and a temperature reading from an analog-to-digital converter. This packet of information is unique to each photon, and when logged to memory is used later to accumulate a large dataset, which can be sorted to examine various parameters such as count rates in a specific amplitude (energy) band, for individual channels. This is one of the intended uses of the two Amptek op-amps (the A225 and A206) used in the circuitry; pulse-height analysis, as is done currently (with the addition of timestamp information) can be used to replicate the operation of a multi-channel analyzer (MCA). This is often done to examine spectral artifacts from known radioactive sources or elements, like in spectroscopy. The other intended use of the Amptek op-amps is in a high-speed counting application, in which the LLDs drive a counter to give the number of detected particles (without the overhead of obtaining pulse-height information). An example of this would be a Geiger counter, which responds to photon flux without knowledge of individual particles' energy.

The new GRID design proposes to incorporate both of these operational modes, counting LLDs with the fast counter, but also logging their pulse-height data from the front-end peak detector (like in the 2015 flight). This will enable the instrument to both respond to high flux, and gather spectral information about the flight environment. The second front-end board will be re-designed to accommodate this new addition, which has yet to be laid out; at this stage, a prototype of the fast counter has been verified with the GRID instrument in a laboratory setting.

2. Structure

The primary structure is composed of 6061-T6 aluminium in a 3U CubeSat configuration. The four side panels are 1/16" aluminium sheet. These panels are held together by four edge rails, which are joined by an aluminium plate at the bottom of the structure. The components are fastened together with size #4-40 self-locking 18-8 stainless steel socket head cap screws, and the bottom plate is affixed to the HASP Payload Mounting Plate with 1.25" long ATSM A307 ."-20 bolts. The exterior walls of the side panels will be coated with a white spray-on epoxy, while the inside walls will be polished to a mirror finish. The white exterior coating will inhibit energy absorption, thus protecting the payload from overheating at float altitudes. The reflective interior will assist in keeping the payload warm as it passes through the extreme cold environment encountered in the tropopause by. These structures, of course, do not need to conform to CubeSat standards.

3. Computer and Data Logger

The flight computer on the 2016 HAXDT payload has yet to be selected. It needs to be small, low power, and capable of handling the computational requirements from the HAXDT data processor, the OEMStar GNSS receiver, the VectorNav VN-100 IMU, and the power management board. For improved mission assurance, issues will be investigated for current generation microcontrollers and microprocessors that focus on all types of single-event effects (SEE) total-ionizing dose (TID) that may occur in a LEO environment.

Most likely, it will be based on a 32-bit ARM processor to resemble the technology currently used in high-end 3U CubeSats. However, the final design may include changes in the required form factor or the software development procedures that could lead to a different selection. The flight code, written in C, will be based off of code written for the previous HAXDT missions; it is a software state machine that samples the GPS and IMU at specified rates, as well as receives data from GRID. Therefore, an accurate timing reference is important. Since a GPS receiver is part of the HAXDT system, it will be used for disciplining the oscillator in the computer.

4. System Operation

Once HASP operations begin, power will be provided to HAXDT and the payload will remain on for the duration of the flight. There are no control capabilities included on the payload, thus, there are no commands to be sent to the payload during flight. The exception to this may be camera control commands for the video downlinking system, but these would be sent through radios directly associated with this system and not rely on the HASP systems for uplink. Therefore, a single power up command from the HASP systems will be sufficient for payload operation. All data will be stored on-board the payload for post processing. The downlink will be utilized to monitor payload health by sending a data packet every second as outlined in Section 3 below. If data collection is not proceeding as expected, then a request to power cycle the payload will be made.

C. TEAM STRUCTURE AND MANAGEMENT

HAXDT will be constructed by a student team led by **Hannah Weiher** as a part of her master's research. Ms Weiher will be responsible for team management, monthly report submission and teleconferences, and hardware and material procurement. Ms Weiher will also serve as the Principal Engineer for the project. Several undergraduate students who worked on the 2015 payload will continue their contributions for the 2015 project cycle. **Charles Denis** will lead the development of the new detector system and integration with the payload. **Jacob Gustafson** will assist the flight computer and software development. **Seth Willing** will lead the design and fabrication of the payload structure.

Ryan Vogt (Physics) will lead the team that will calibrate and characterize GRID (the sensor payload). He will lead a team of physics & astronomy students to run laboratory tests to ensure the sensor noise floor, sensitivity etc., are in the range that will be needed for making accurate PNT measurements.

Joel Runnels, a doctoral candidate whose research is looking at the design of algorithms for GRB-based ranging and timing, will be used as a consultant to help Mr. Vogt and his team. Additional undergraduate participants may be recruited through the Minnesota Space Grant Consortium High-Altitude (Sounding) Ballooning Team to assist the team leads in payload operation and development. One such student is the Ballooning Team Lead, **Christopher Gosch**, who will serve as the technical point of contact for the video downlinking system.

Dr. James Flaten is supervisor for the University of Minnesota ballooning team and provides expert advice in balloon flight operations. **Dr. Suneel Sheikh** is the CEO of ASTER Labs, Inc. and an expert in X-ray navigation. Dr. Sheikh provides ongoing consultation in the development of this payload system.

Students			
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Table 1. Mailing addresses, affiliations and contact information of key personnel.

It is anticipated that between three and six students will participate in integration at CSBF and possibly two students will participate in flight operations at Ft. Sumner. Table 2 below shows the anticipated timeline and milestones for this project (milestones in bold).

Month of 2015	Description of Work
January	Undergraduate recruitment and training. Design new power system. Acquire flight hardware. Finish new readout electronic design
February – March	Develop structure and finalize power system design.
March – April	Final flight system design and integration with new detectors. Fabrication of payload structure. Development of flight software.
April 24	**Preliminary PSIP document deadline.**
April – May	Full systems integration and testing.
June	Final assembly and testing including thermal vac test.
June 26	**Final PSIP document deadline.**
July	Finalize flight operations plan. Verify all systems go.
July 30	**Final FLOP document deadline.**
August 3-7	Student payload integration.
August	Correct unforeseen issues, if any.
September	Launch. Parse and extract flight data upon payload's return to UMN.
October	Analyze results and begin science report.
November	**Complete data analysis and final report.**
December	**Submit final report and prepare 2016 application.**

Table 2. Preliminary 2016 HASP timeline for the UMN team.

D. **PAYLOAD DATA, POWER AND MASS SPECIFICATIONS**

There are presently no serial uplink or additional discrete commands anticipated for the payload. However, some downlink bandwidth will be required for system health monitoring. The serial link will be connected at 4800 baud using 8 data bits, no parity, and 1 stop bit as described in the HASP Student Payload Interface Manual. The serial downlink traffic from HAXDT will be 540 bps (the 64 byte packet outlined in **Table 3** below plus serial framing bits) sent over the 4800 baud connection. This implies we will initiate data transfer at a frequency of 1 Hz.

The data rate and/or packet structure may change during the development of the payload to include metrics which will be used to determine proper operation of all payload components in real time. Any such changes will be detailed in future documentation. If the data received via the downlink indicates that data collection is not proceeding as planned, then a power on/power off command will be requested. Thus, the only discrete line required is the default line that powers the payload on and off.

No analog downlink channels are expected to be utilized for the 2016 HAXDT payload.

Byte	Title	Description
1-2	Header	Indicates beginning of message.
3-10	GPS second	Seconds from beginning of GPS week.
11-18	X_Pos	ECEF x-coordinate, from OEMStar.
19-26	Y_Pos	ECEF y-coordinate, from OEMStar.
27-34	Z_Pos	ECEF z-coordinate, from OEMStar.
35-42	Ampient_Temp	Ambient internal temperature of the 3U CubeSat payload.
43-46	Detector 1 photons	Cumulative number of photon events recorded by Detector 1.
47-50	Detector 2 photons	Cumulative number of photon events recorded by Detector 2.
51-54	Detector 3 photons	Cumulative number of photon events recorded by Detector 3.
55-58	Detector 4 photons	Cumulative number of photon events recorded by Detector 4.
59-62	Power System	Status of power manager and power bus
63-64	Footer	Indicates end of complete data record.

Table 3. Preliminary HAXDT downlink packet structure.

Anticipated procedures at the Student Payload Integration include testing that the HAXDT interface with the HASP gondola is configured properly via the EDAC 516 connector; that power is being delivered and does not exceed the allowed current draw; and that the payload collects, downlinks, and stores data without issue. If the payload passes these tests, then it will be subjected to the planned thermal/vacuum testing. Assuming success at integration, procedures at flight operations are anticipated to consist solely of making sure the payload is connected properly and powers up without issue. It should be noted that HAXDT will undergo thorough integration testing as well as thermal/vacuum testing at the University of Minnesota before integration.

1. **Payload Mass and Power Budget**

The payload will use the EDAC 516 connector to provide power to all systems as indicated in **Figure 3**. Voltage will be regulated and distributed according to each system's power requirements as shown in **Figure 6**. In addition, **Table 4** below outlines the power and mass budgets for the payload components. Regardless of the design changes which may yet be made (modifying the payload auxiliary structures, adding further secondary experiments, etc.), the mass and power specifications of the payload will remain well within the limits of 20 kg and 75 W, respectively, for the large payload classification.

In **Table 4**, GRID detectors and front end includes the carbon fiber window, detector window clamp, four CsI(Tl) crystals, four avalanche photodiodes, silicone, anti-static foam, eight PC/104 standoffs, and both of the two populated front end circuit boards. GRID's data logger will be an updated design for 2015, however the estimates for this component shown above are based on the 2014 payload's timing/pre-processing board. The high voltage power supply circuit was measured and weighed separately, but this is required for proper operation of GRID. Specifications for power management mass and power consumption (row four) was estimated using the gs-ds-nanopower-p31u-9.0 datasheet from GOMSpace and assumes the power management device is connected to 2600mAh batteries.

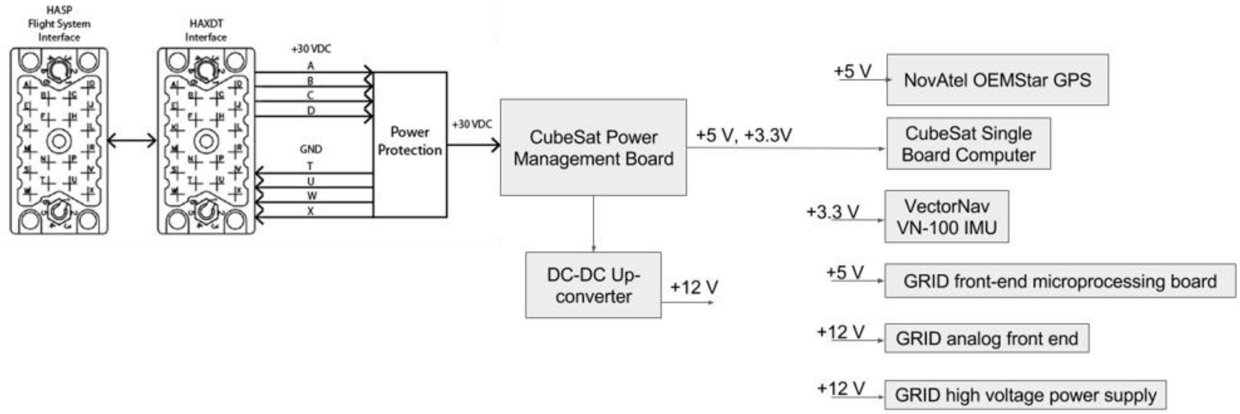

Figure 6. Shown is a high-level block diagram of the payload power distribution system. The power management board features two regulated power buses: 3.3V@5A and 5V@4A. Additionally, a +12V rail will be derived via a DC-DC converter.

Component	**Mass [g]**	**Mass Uncertainty [g]**	**Power [W]**	**Power Uncertainty [W]**
GRID detectors and front end	1161	5	3.89	0.02
GRID high voltage bias supply	150	5	0.5	0.02
HAXDT data processor	100	5	0.3	0.02
Microsemi Quantum CSAC	35	2	0.12	0.05
Power management board and battery pack	200	80	0.16	0.16
Novatel OEM615 GPS receiver and antenna	158	2	0.65	0.05
VectorNav IMU	20	5	0.35	0.03
CubeSat single board computer.	100	5	0.7	0.5
Structure and mounting hardware	1000	500	-	-
Total	**2924**	**604**	**6.67**	**0.85**

Table 4. Preliminary mass and power budget for the 2016 HAXDT payload.

2. Payload Location and Orientation

The HAXDT payload contains a GPS receiver and an IMU. Thus, in post process it will be possible to reconstruct the position, velocity and orientation states of the payload. There are no pointing requirements for the evaluation of the GRID sensor.

E. **MECHANICAL DRAWING OF HAXDT STRUCTURE**

The figures below show mechanical drawings of the bottom plate, side panels, and edge rails of the 3U CubeSat structure. They are provided here to give a sense on how HAXDT will mate to the HASP interface plate.

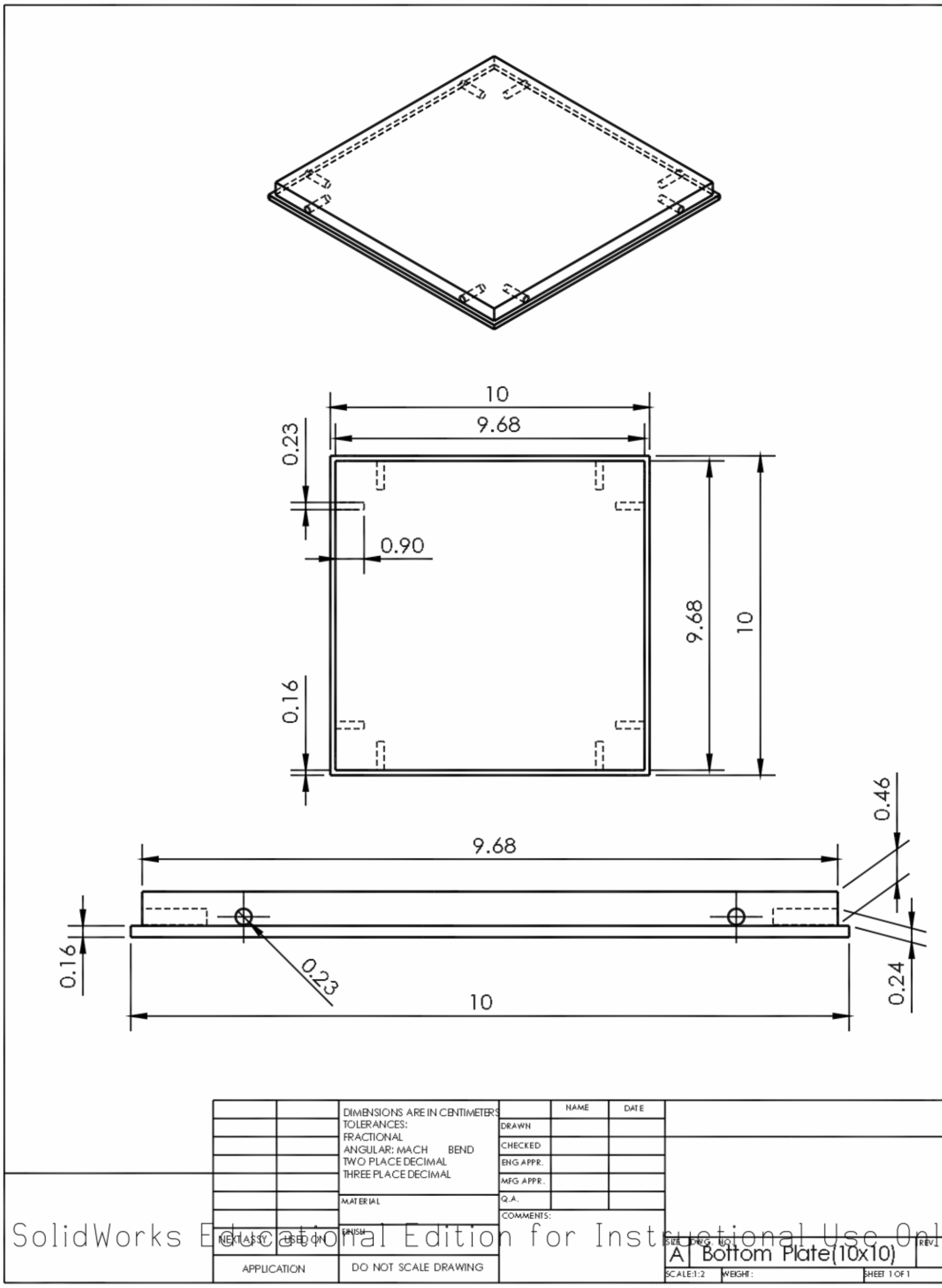

Figure 7. A mechanical drawing of the aluminum bottom plate of the 3U CubeSat structure, with dimensions shown in centimeters. This plate will be securely fastened to the HASP payload plate.

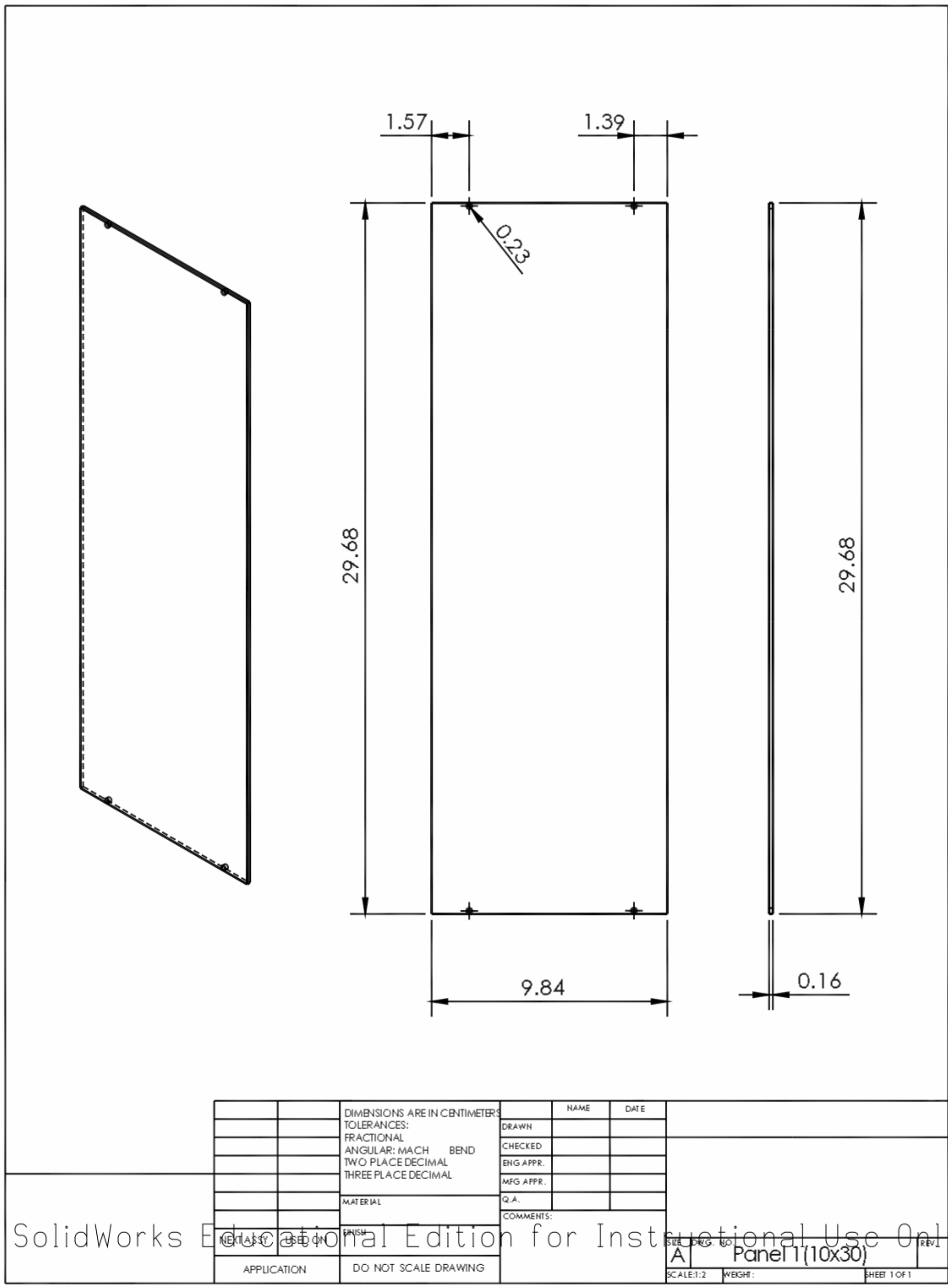

Figure 8. A mechanical drawing of the aluminum side panels of the 3U CubeSat structure, with dimensions in centimeters.

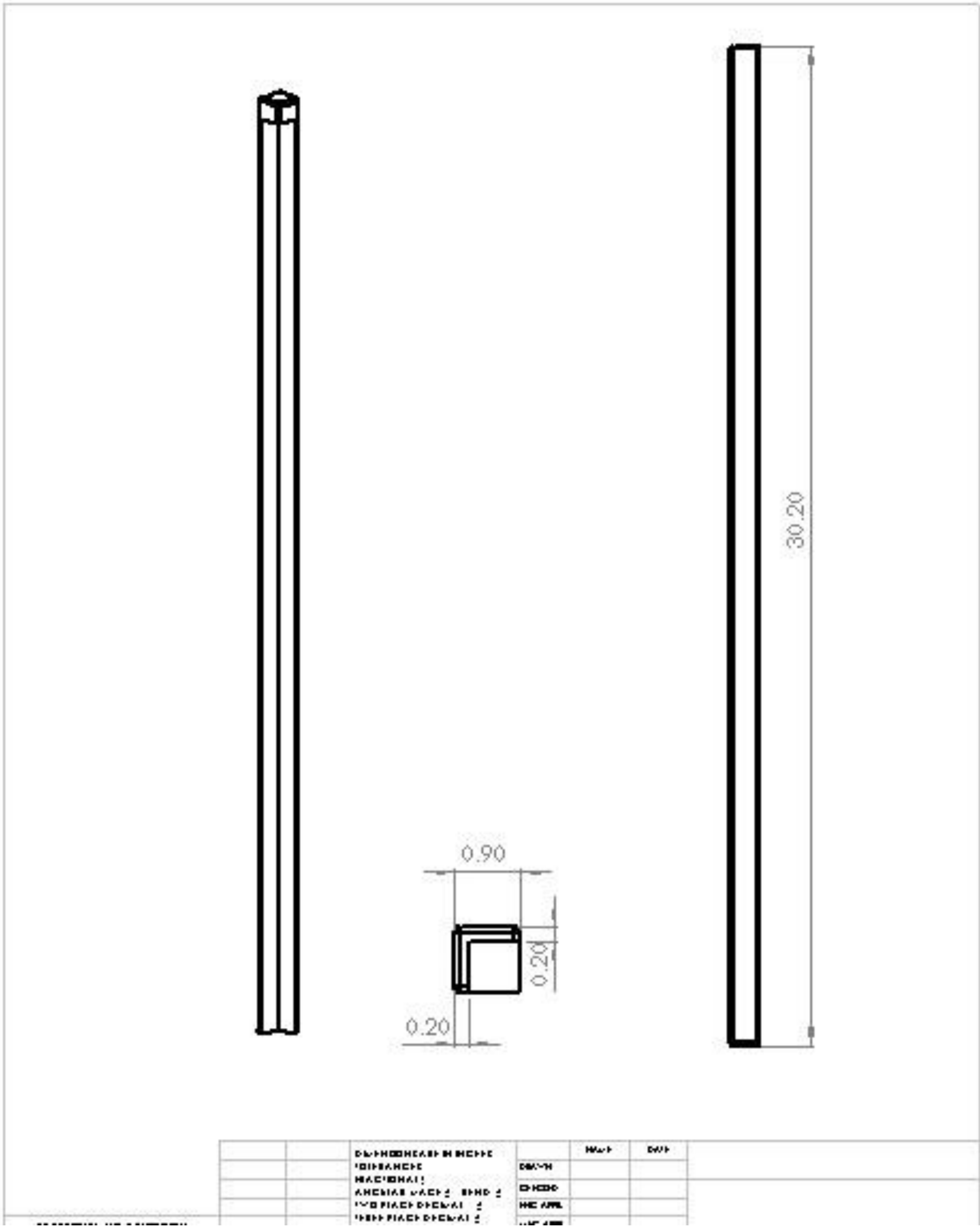

Figure 9. A mechanical drawing of the edge rails used in the 3U CubeSat structure, with dimensions in centimeters.

F. **REFERENCES**

[1] P. T. Doyle, The Development of a Simulator System and Hardware Test Bed for Deep Space X-ray Navigation, vol. Master of Science Thesis, Minneapolis, MN: Departmetn of Aerospace Engineering and Mechanics, University of Minnesota, Twin Cities Campus, 2012.

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