1. Payload Description

The University of Minnesota's High Altitude X-ray Detector Testbed (HAXDT) was developed to test and validate the performance of a compact X-ray detector and its associated flight hardware for the recently completed 2012 HASP mission. Such compact x-ray detectors are being developed for use as navigation sensors for future deep space missions.

The payload flown on the 2012 HASP mission collected a time history of photon events counted by an X-ray detector (a scintillation detector). However, the detector system was incapable of detecting the energies of the cosmic rays that created the scintillation events. Thus, the engineering objective of the experiment being proposed is to upgrade the compact X-ray detector along with associated hardware, electronics, and software that flew on the 2012 HASP mission to allow recording the time and energy of the photon events. These upgrades include the following: The addition of a second scintillation detector to the two-channel nuclear pulse-shaping circuit (detector board) provided by Lockheed Martin's Advanced Technology Center in Palo Alto, CA; the addition of a multi-channel analyzer to detect the energy level of the detected cosmic rays, and finally, the addition of shielding to the detector so as to provide it with a field of view.

The scientific objectives of the experiment are to separate individual cosmic ray events into different energy bands, and to examine periods of higher photon flux in these bands along the flight trajectory. This will allow correlation of photon flux with celestial bodies capable of emitting such high-energy cosmic rays. Another scientific goal is to characterize the cosmic ray background, and thus the signal-to-noise ratio (SNR) as seen by such small detectors in these separate energy bands.

1.1 Background

The work described in this proposal is motivated by the idea of using celestial X-ray sources such as pulsars as beacons for deep space navigation. The impetus for this is that many envisioned future space missions will require spacecraft to have autonomous navigation capabilities. For missions close to Earth, Global Navigation Satellite Systems (GNSS) such as GPS are readily available for use. For missions far from Earth, however, other alternatives must be provided. While existing systems such as the Deep Space Network (DSN) can be used, latencies associated with servicing a fleet of vehicles may not be compatible with some autonomous operations requiring fast updates of the navigation solution.

Recent work has shown that variable celestial X-ray sources such as pulsars can be used as navigation beacons for determining the absolute position of space vehicles [1-9]. This approach is called X-ray navigation (XNAV). Current XNAV techniques are applicable to many deep space operations where GPS or other GNSS signals are unavailable or DSN tracking is not possible. While the current demonstrated accuracy of XNAV is not at the level of GNSS, XNAV is a nascent technology and it is reasonable to expect future increases in its accuracy. This increased performance will be the result of future improvements in sensors and navigation algorithms. The work described in this proposal is an effort in that direction. It deals with characterizing the performance of small and compact cosmic ray detectors. Such detectors placed on envisioned future deep space vehicles could be used to generate an accurate navigation solution at low power levels while taking up little space.

1.2 Technical Challenge

Pulsars are excellent candidates for use as XNAV beacons. This is because their signals can be used to provide time, range, and phase measurements — key parameters for navigation. It has been demonstrated that the stability of pulsar spin rates compares well to atomic clocks [4]. Furthermore, X-ray signals from pulsars have identifying profiles [5]. However, because the distance to even the closest pulsar is on the order of parsecs, the signal-to-noise ratio (SNR) of the received X-ray signals is small. The low SNR is due to, in part, the background X-ray noise in space. One current method for detection of these low SNR signals relies on counting a bin number of photons in some known time interval and measuring the energy released by the photons upon striking a detector. In this manner, specific peaks are recorded according to the pulsar's wavelength, thus allowing the source pulsar to be identified. This implies that accurate range or phase measurements require large X-ray detector areas, long signal collection times, or both. For example, it has been demonstrated that detectors with areas larger than 1 m^2 provide position accuracies that are acceptable for many space-based applications [4]. While detectors of this size can be used on larger space vehicles, they are impractical for smaller ones. The work described in this proposal attempts to characterize the background noise at different energy levels as seen a by small photon detector at altitudes above 30 km, and add to the detector's flight heritage.

1.3 Hypothesis

Pulsars that have been investigated for X-ray navigation fall in the 2-10 keV range [1-9], whereas at ballooning altitudes only X-rays above 20 keV are available for detection due to atmospheric absorption [10]. Such energies may be unsuitable for navigation algorithms, but detection of photons at these energy levels still allows analysis of the SNR for small detectors to be performed. The ability of a small detector system to associate an energy level with a detected cosmic ray event will allow characterization of the SNR over multiple energy bands while also allowing the data to be examined for possible high-energy celestial sources.

1.2 Payload Systems and Principle of Operation

A high-level diagram of the payload's systems is shown in Figure 1 below. The interior components consist of a two-channel detector board, two detector assemblies and their housings, a NovAtel OEMV-3 GPS receiver, a power circuit with an attached Analog Devices inertial measurement unit (IMU), and a flight computer affixed to a daughterboard. These components are shown in Figures 2-8. Power is provided by HASP and is regulated to +12 VDC to power all payload systems as seen in Figure 9. The power circuit also provides protection from reverse polarity and limits the current draw to 495mA to prevent inrush current spikes. The schematic for this circuit is shown in Figure 10.

1.2.1 Sensor Payload

The detector assembly is seated in an aluminum housing (Figure 2) and consists of an avalanche photodiode (APD) affixed to an inorganic plastic scintillator with optical grease. The assembly is then wrapped in polytetraflouroethylene (PTFE) tape (Figure 3). Light flashes generated by high-energy particle interactions with the scintillator are shaped into pulses by the two-channel detector board and are, thus, detected as photon strikes that are time-tagged by the flight computer. The pulses will also pass through a multichannel analyzer in order to detect the pulse height, and thus the energy of each photon strike. This information will be stored along with the time-tagged photon strikes in onboard flash memory in order to perform analysis on multiple detected energy bands. Two detector assemblies will be constructed in order to utilize both channels on the detector board.

1.2.2 Structure

The structure is composed of 6061-T6 aluminum with one side polished to assist in thermal protection as outlined below. Four wall panels are attached to top and bottom plates (see Figures 11-17) with size #4-40 self-locking 18-8 stainless steel socket head cap screws while the bottom plate is attached to the HASP Payload Mounting Plate with 1.25" long ATSM A307 1/4" – 20 bolts. The interior walls of the payload will be composed of mirrored 6061-T6 aluminum, while the exterior walls will be coated with a white spray-on epoxy. The white exterior coating will inhibit energy absorption, thus protecting the payload from overheating at float altitudes, while the reflective interior will assist in keeping the payload warm as it passes through the extreme cold environment encountered in the tropopause. In addition, an electrical resistance heater is part of the detector board. It is powered on when temperatures drop below 25°C.

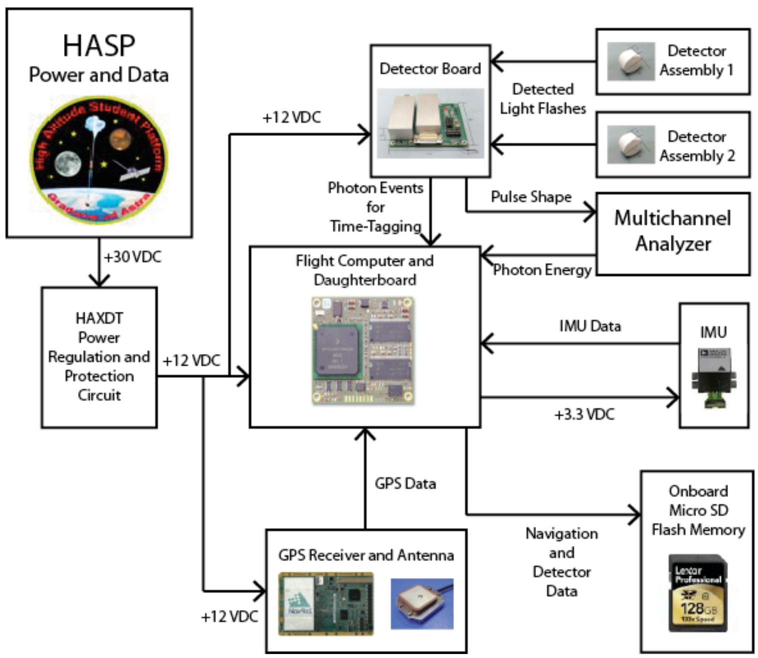

Figure 1. High-level HAXDT payload system diagram.

1.2.3 Computer and Data Logger

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 the University of Minnesota, and has been custom edited to perform attitude determination while collecting data from an X-ray detector. The GPS signal will be 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 and accelerations as well as magnetic field and temperature data. An accurate navigation and attitude solution is obtained by combining the IMU data with the GPS position estimate. The data generated by the attitude determination system is placed in onboard storage throughout the flight for post processing. This package successfully flew on the 2012 HASP mission, thus, it has a proven flight history in the extreme environments encountered during HASP flight operations.

1.2.4 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. Therefore, a single power up command will be sufficient for payload operation. All data will be stored onboard 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 off and on the payload will be made.

The temperature of the Detector Board will be monitored during flight, and once the temperature drops below 25°C, an electrical resistance heater will activate to attempt to keep the Detector Board near its nominal temperature of 25°C. Internal ambient temperature data collected during the 2012 HASP mission indicates that the payload interior remains at or near this nominal temperature at float altitude, thus the heater will deactivate once the temperature rises to 25°C. The Flight Computer processor core will also be monitored for overheating. If the core temperature reaches 125 °C, a request to turn the payload off will be submitted to allow the payload to cool. The analog lines will allow this thermal monitoring and control to take place and is described further in Section 3 below.

2. Team Structure and Management

HAXDT will be constructed by a student team led by Patrick Doyle as part of his Masters of Science thesis work on X-ray navigation. Mr. Doyle will be responsible for team management, monthly report submission and teleconferences, and hardware and material procurement. Mr. Doyle's engineering responsibilities will focus on the development of the energy detection portion of the X-ray detector system and the operation of the attitude and navigation sensors. One graduate student, Curtis Albrecht, will assist Mr. Doyle with the energy detection portion of the X-ray detector system as well as lead operations of the power management system and flight computer. One undergraduate student, Mark Abotossaway, will focus on research and development of the X-ray detector's shielding and pointing capabilities. Mr. Abotossaway will also lead undergraduate recruits in structure development and construction and detector testing and calibration.

Additional undergraduate participants will be recruited through the Minnesota Space Grant Consortium High-Altitude (Weather) Ballooning Team to assist the team leads in payload operation and development. As the two graduate students mentioned above anticipate graduation in May 2013, two to three students will be specifically recruited and trained to assume the responsibilities of the two graduating students during the University of Minnesota's spring semester (January – May, 2013). These students will be meticulously trained to assume all operations of the HAXDT payload in order to provide a seamless transition. The graduating students will remain as advisors, but will not participate directly in daily program operations.

Current student participants and their responsibilities are listed in Table 1 below along with faculty advisors and industry partners.

Dr. Flaten is supervisor for the University of Minnesota ballooning team and provides expert advice in balloon flight operations. Dr. Sheikh is an expert in X-ray navigation and provides ongoing consultation in the development of this payload system. Dr. Chenette's laboratory provided the nuclear pulse detection circuit vital to the design of the X-ray detector system and provides ongoing technical advice and expertise. Dr. Gendreau developed an X-ray detector package similar to the system on HAXDT, and also provides technical expertise in the integration of the X-ray detectors into the system. Funding is provided by the Minnesota Space Grant Consortium.

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Industry Partner	Dr. Keith Gendreau Research Astrophysicist	NASA GSFC X-ray Astrophysics Lab Mail Code 662.1 Greenbelt, MD 20771	keith.c.gendreau@nasa.gov 301-286-6188

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

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

Month of 2013	**Description of Work**
January	Additional hardware acquisition. Undergraduate recruitment and training. **Structure development.**
February-March	Testing and calibration of upgraded detector design. Continuation of training.
March-April	**Design of flight configuration. Final dimensioned mechanical drawings.** Continuation of training.
April 19	**Preliminary PSIP document deadline.**
April-May	Full systems integration and software testing. **Transition to new team leads. Fabrication of payload structure.**
June	**Final assembly and testing of payload.**
June 21	**Final PSIP document deadline.**
July	Finalize flight operations plan. Verify all systems go for launch.
July 26	**Final FLOP document deadline.**
July 29 – Aug. 2	**Student payload integration.**
August	Correct unforeseen issues found during payload integration if needed.
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 2014 application.**

Table 2. Preliminary 2013 HASP timeline.

3. Payload Specifications

The payload is designed to conform to a CubeSat generic structure, based on one or more cubes with internal dimensions of 10 cm x 10 cm x 10 cm, thus having a 100 cm^2 footprint on the HASP mounting plate as shown in Figure 18. A single cube is known as a 1-U, or unit volume, configuration. The 2013 HAXDT payload is anticipated to be in a 3-U configuration. This implies that the payload height will be 30 cm, thus assuring that the payload falls within the HASP height guidelines for the **small payload** classification. The CubeSat infrastructure supports several future envisioned XNAV/HASP missions as well, including onboard X-ray attitude control for detector pointing and X-ray communications (X-COM). It is possible that the footprint may expand to include the entire area available on the HASP mounting plate if upgrades to the detector system require a larger footprint, but the need for such an increased footprint is uncertain at this time.

At this time there are 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 1200 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 440 bps (the 44 byte packet outlined in Table 3 below plus serial framing bits) sent over the 1200 baud connection. This implies we will initiate data transfer at a frequency of 1 Hz. 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.

Byte	Title	Description
1-2	Header	Indicates beginning of data record
3-10	GPSec	Milliseconds since beginning of GPS week
11-18	X_Pos	Earth-centered Earth-fixed, x coordinate
19-26	Y_Pos	Earth-centered Earth-fixed, y coordinate
27-34	Z_Pos	Earth-centered Earth-fixed, z coordinate
35-42	Ambient_Temp	Temperature of internal chamber of payload
43-44	Footer	Indicates end of complete data record

Table 3. Anticipated downlink data record

Both analog channels are expected to be utilized for internal temperature monitoring and control. The detector board has been configured to operate nominally at HASP float altitudes, thus it is preferable to heat the board during ascent. One analog line will be used to monitor the temperature of the detector board, and if it indicates that temperature has dropped below 25°C then heaters will be activated to keep the board warm. The other analog line will be used to monitor the flight computer's processor core temperature. If the processor core temperature exceeds 125 °C, then a power off command will be requested to let the processor cool for 15 minutes.

Procedures at integration are anticipated to 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, transmits, 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.

3.1 Payload Mass and Power Budget

The payload will use the EDAC 516 connector to provide power to all systems as indicated in Figure 9. Voltage will be regulated and distributed according to each system's power requirements as shown in Figures 9 and 10.

Payload components and their mass and power budgets are given in Table 4 below. The flight computer, daughterboard, and power circuit are bundled together as shown in Figures 7 and 8, so their combined mass and power requirements are reported as such. The X-ray detector system consists of two detector housings, two scintillators, two APDs, and the two-channel detector board, so their combined mass and power requirements are reported together as well. Mass and power for the additions to the detector system (shielding, collimating, and energy detection) are unknown at this time, thus the reported mass and power are estimates only. Structural components include payload walls, mounting hardware, and the GPS antenna embedded in the top plate (assuring height does not exceed 30 cm). The large uncertainty in structural mass accounts for the possibility of expanding the footprint to utilize the entire available mounting plate area. Thermal components such as heaters, temperature sensors, and logic circuits are unknown at this time and are thus allowed a large amount of uncertainty compared to other known hardware components. Both power and mass uncertainties meet the specifications of +30 VDC at 0.5 amps (15 Watts) and 3 kg respectively for the small payload classification.

	Mass (g)	**Mass Uncertainty (g)**	**Power (W)**	**Power Uncertainty (W)**
Flight Computer, Daughterboard, and Power Circuit Bundle	170	10	2.0	0.2
X-ray Detector System	380	20	0.5	0.1
X-ray Detector Shielding and Energy Detection	700	100	1.0	1.0
IMU	20	5	0.5	0.2
GPS Receiver	90	5	2.5	0.5
Thermal Protection	100	25	5.0	1.0
Structural Components	875	500	-	-
TOTAL	2335	665	11.5	3.0

Table 4. Mass and power budget.

3.2 Payload Location and Orientation

The experimental goals are independent of physical location on the HASP gondola, thus any small payload location is suitable. HAXDT successfully flew on the 2012 HASP mission in payload position 3, thus, that position is suitable for the 2013 flight as well (see Figure 19). Payload mounting does not depend on orientation as the detectors will be vertically mounted. Modifications to the HASP mounting plate are shown in Figure 20.

4. Preliminary Drawings

The figures below include the following: mechanical drawing of the detector housing (Figure 2); APD/scintillator detector assembly (Figure 3); two-channel detector board (Figure 4); GPS receiver (Figure 5); GPS antenna (Figure 6); power circuit and IMU (Figure 7); flight computer and daughterboard (Figure 8); schematic of HAXDT power system and HASP interface (Figure 9); circuit diagram of the power circuit (Figure 10); 3-D rendering of the 2.5-U HAXDT configuration (Figure 11); mechanical drawings of the 2.5-U HAXDT configuration (Figures 12 – 17); payload mounting plate footprint (Figure 18); desired payload location and orientation (Figure 19), and lastly, anticipated modifications to the payload mounting plate (Figure 20).

Please note that the 3-U HAXDT payload walls will be 5cm (about 2in) taller than depicted in Figures 13-16.

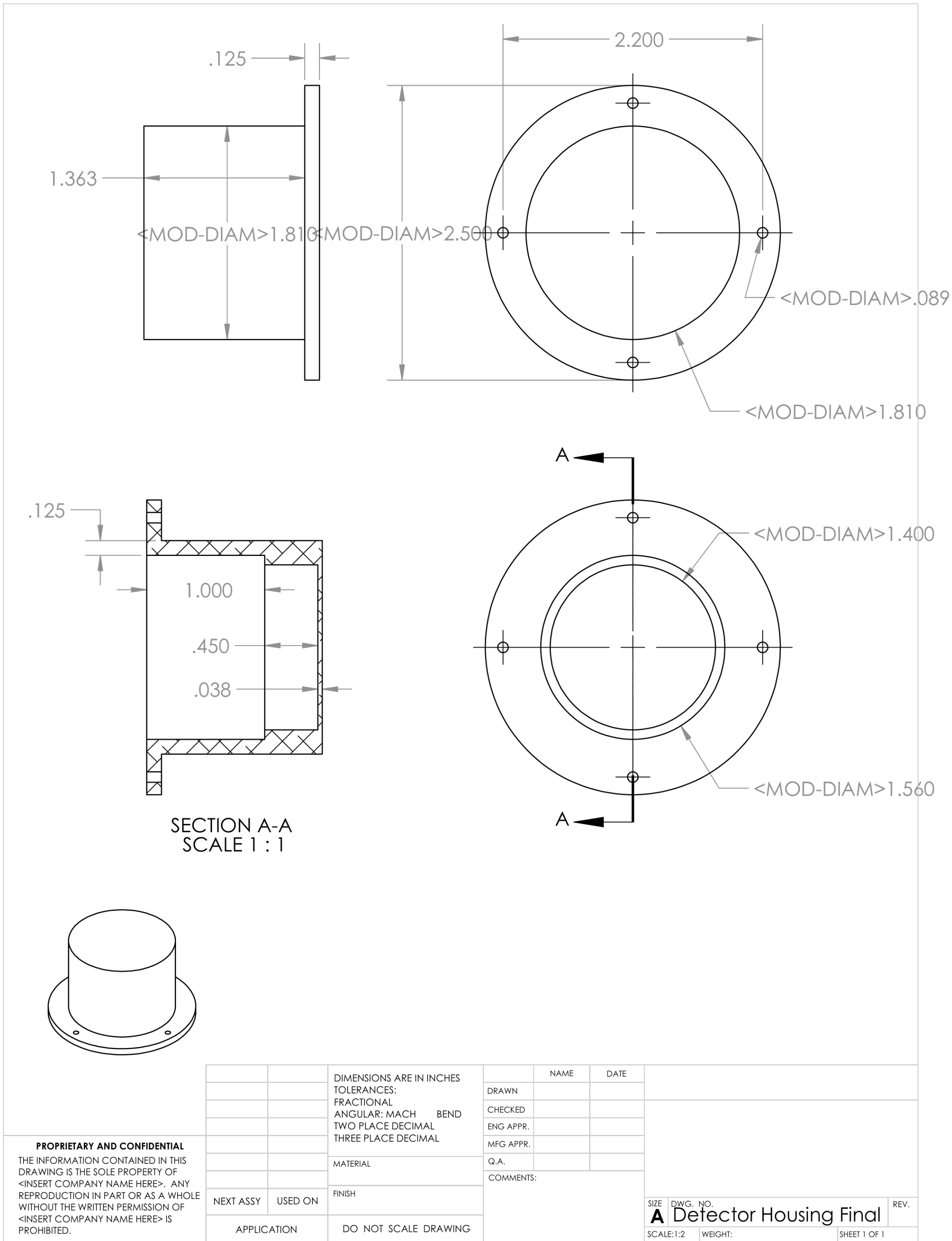

Figure 2. Mechanical drawing of detector housing with dimensions in inches. This housing attaches to the top plate of the HAXDT structure (Figure 17).

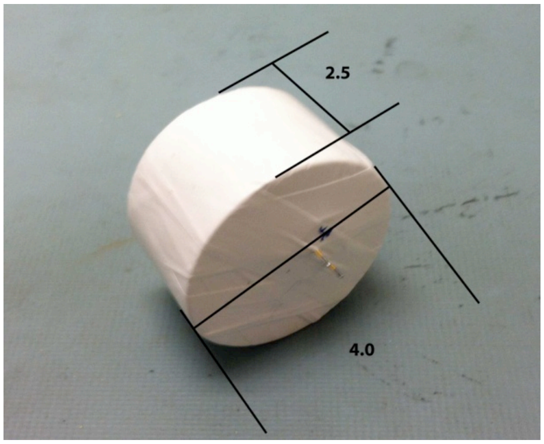

Figure 3. Detector assembly (Si APD affixed to scintillator and wrapped with PTFE tape) with dimensions in centimeters.

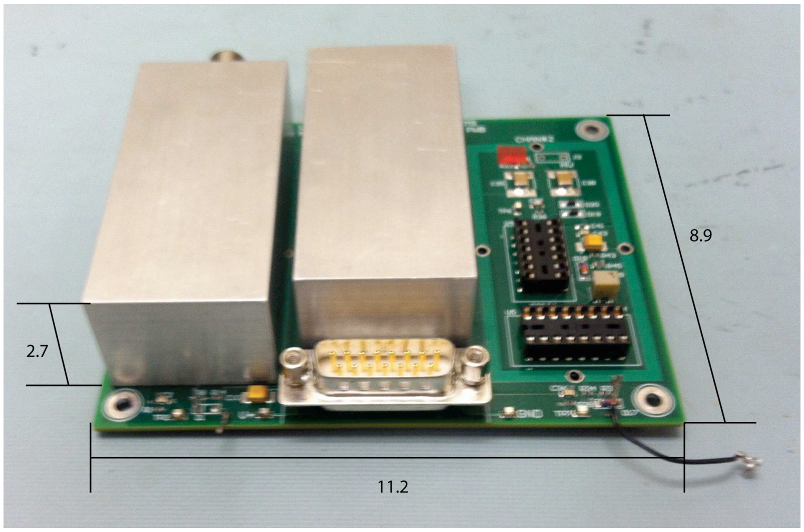

Figure 4. Picture of detector board with dimensions in centimeters. Note that the second channel (right side) will be used and shielded in the same manner as the channel on the left side.

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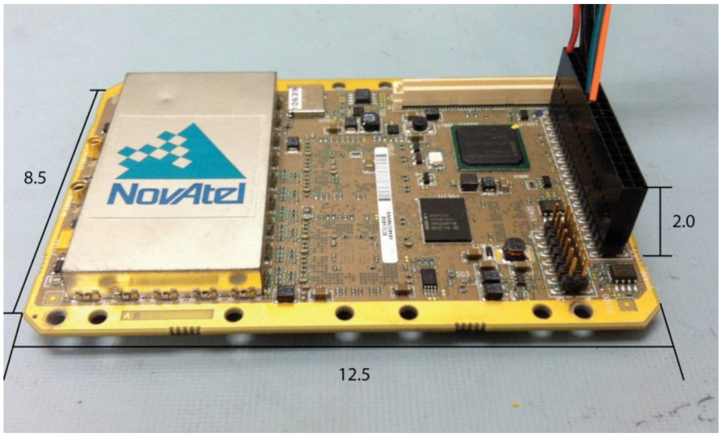

Figure 5. Picture of Novatel OEMV-3 GPS receiver and wiring harness with dimensions in centimeters.

Figure 6. Picture of San Jose Technology, Inc. SA60 GPS antenna, which attaches to the outside of the top plate as seen in Figure 11.

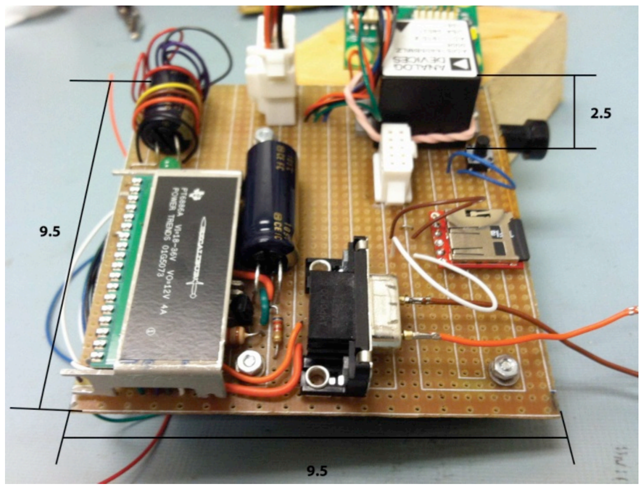

Figure 7. Picture of power circuit and Analog Devices IMU with dimensions in centimeters. This board is bundled with the daughterboard and flight computer as seen in Figure 8.

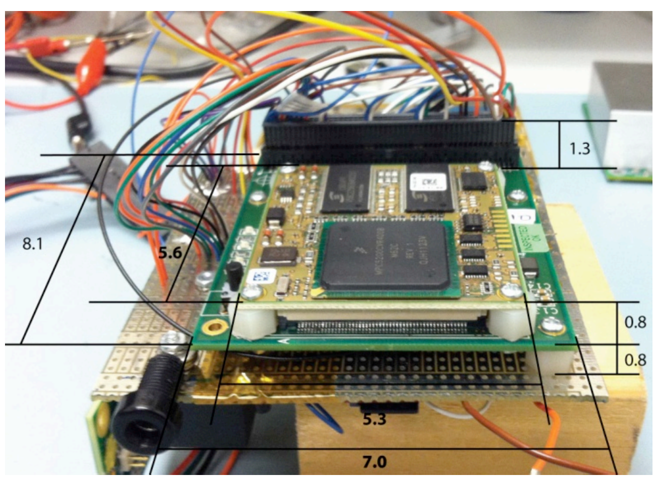

Figure 8. Picture of daughterboard (green board) and flight computer (tan board) bundled with the power circuit with dimensions in centimeters.

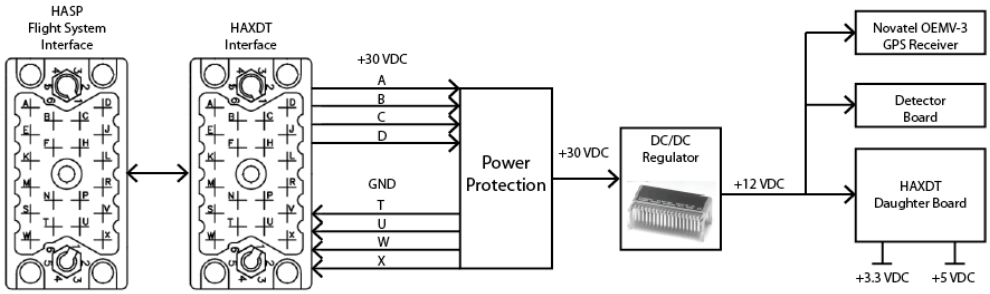

Figure 9. Schematic of HASP EDAC516 connector interface with the HAXDT payload power system.

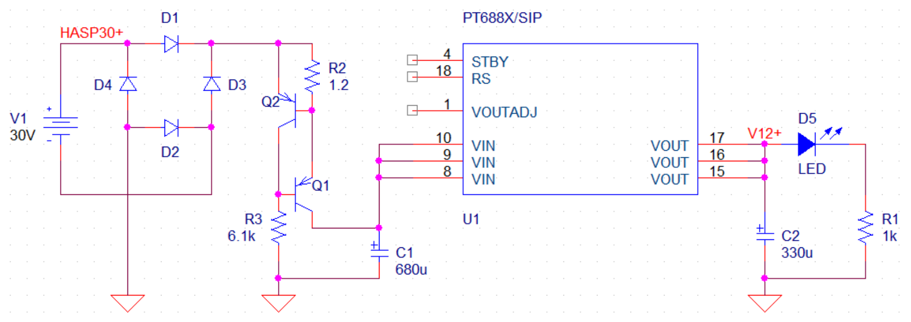

Figure 10. Power regulation and protection circuit diagram.

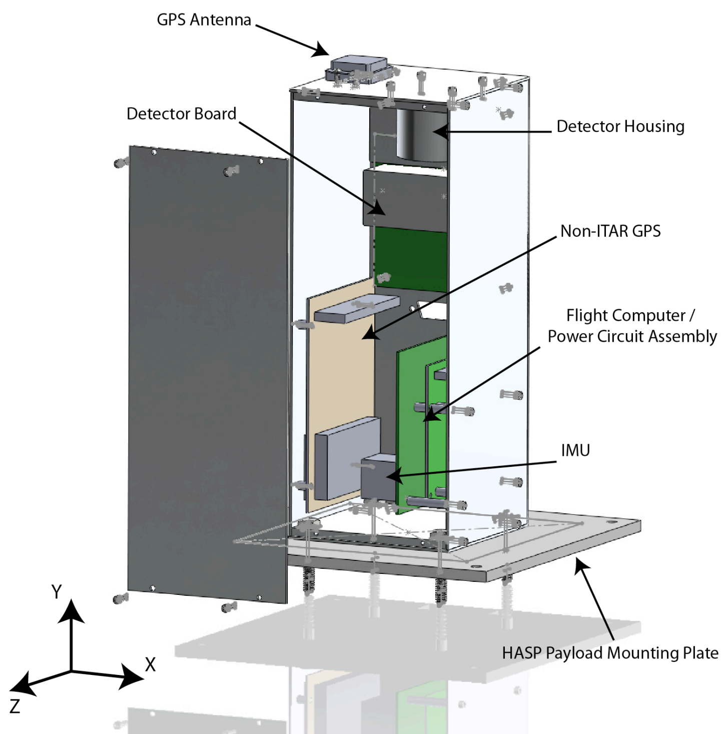

Figure 11. 3-D rendering of a 2.5-U HAXDT configuration. This configuration successfully flew on the 2012 HASP mission.

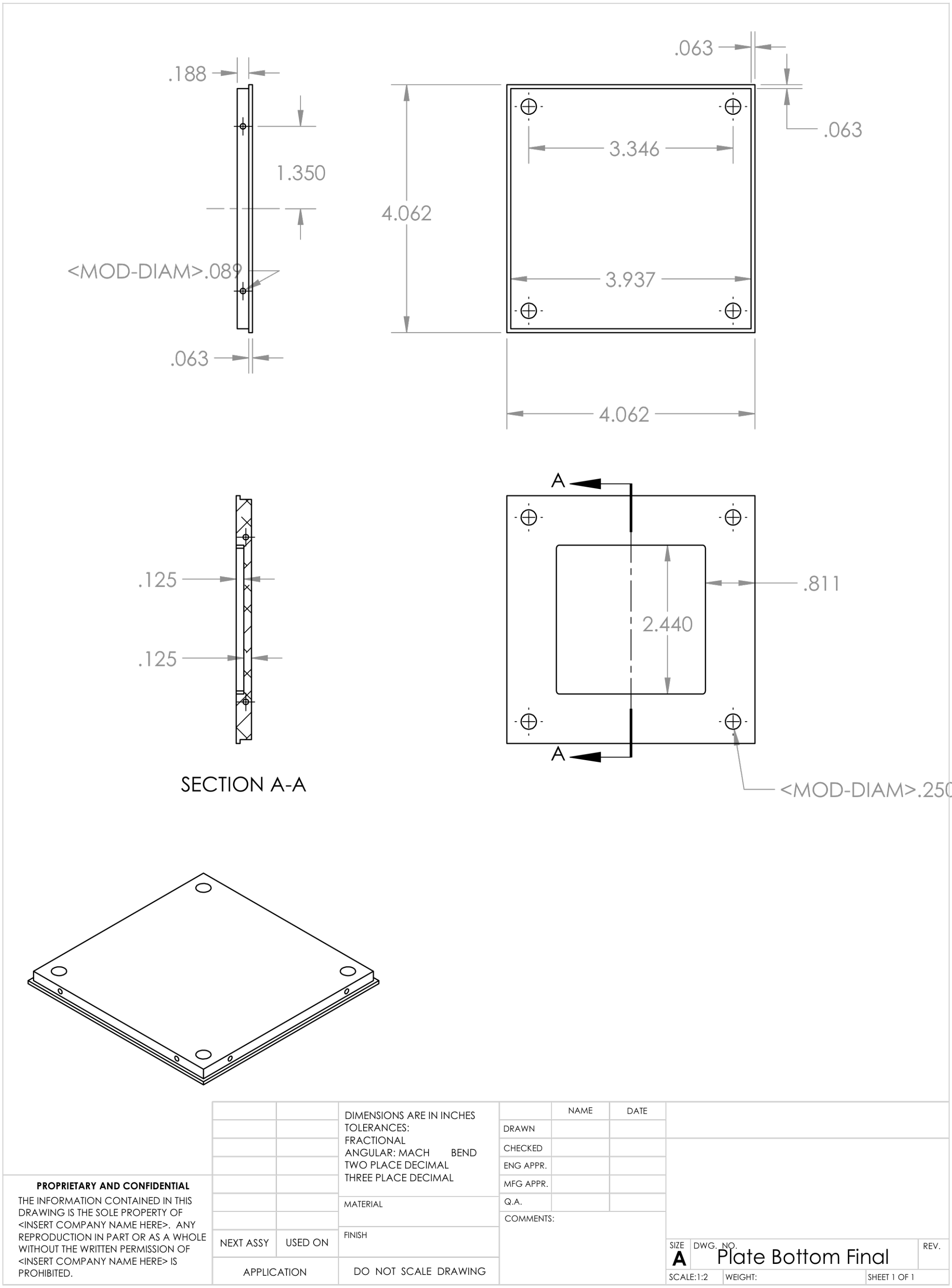

Figure 12. Mechanical drawing of bottom plate of 2.5-U and 3-U HAXDT structure with dimensions in inches.

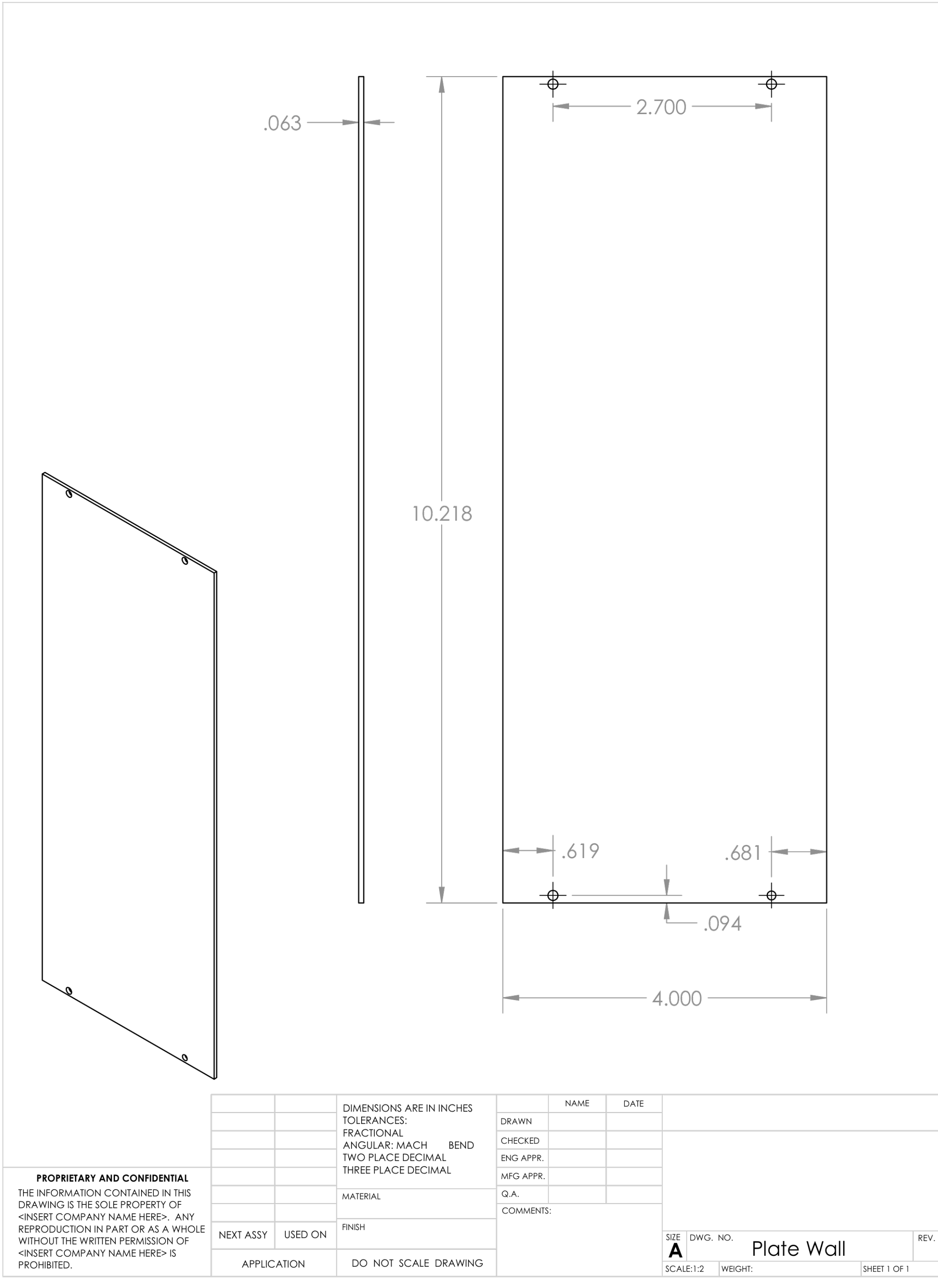

Figure 13. Mechanical drawing of 2.5-U HAXDT structure enclosing wall with dimensions in inches.

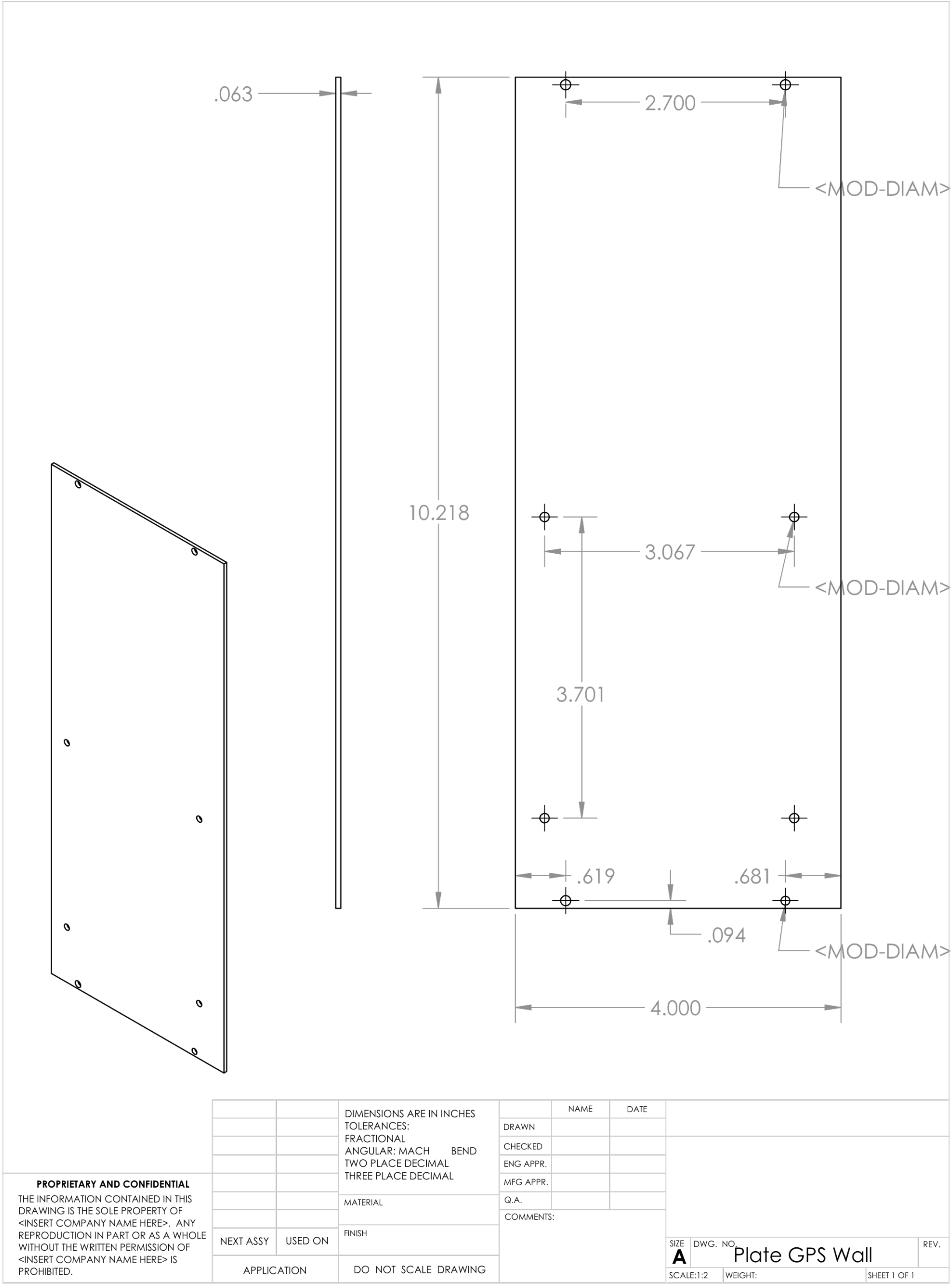

Figure 14. Mechanical drawing of 2.5-U HAXDT GPS mounting wall with dimensions in inches.

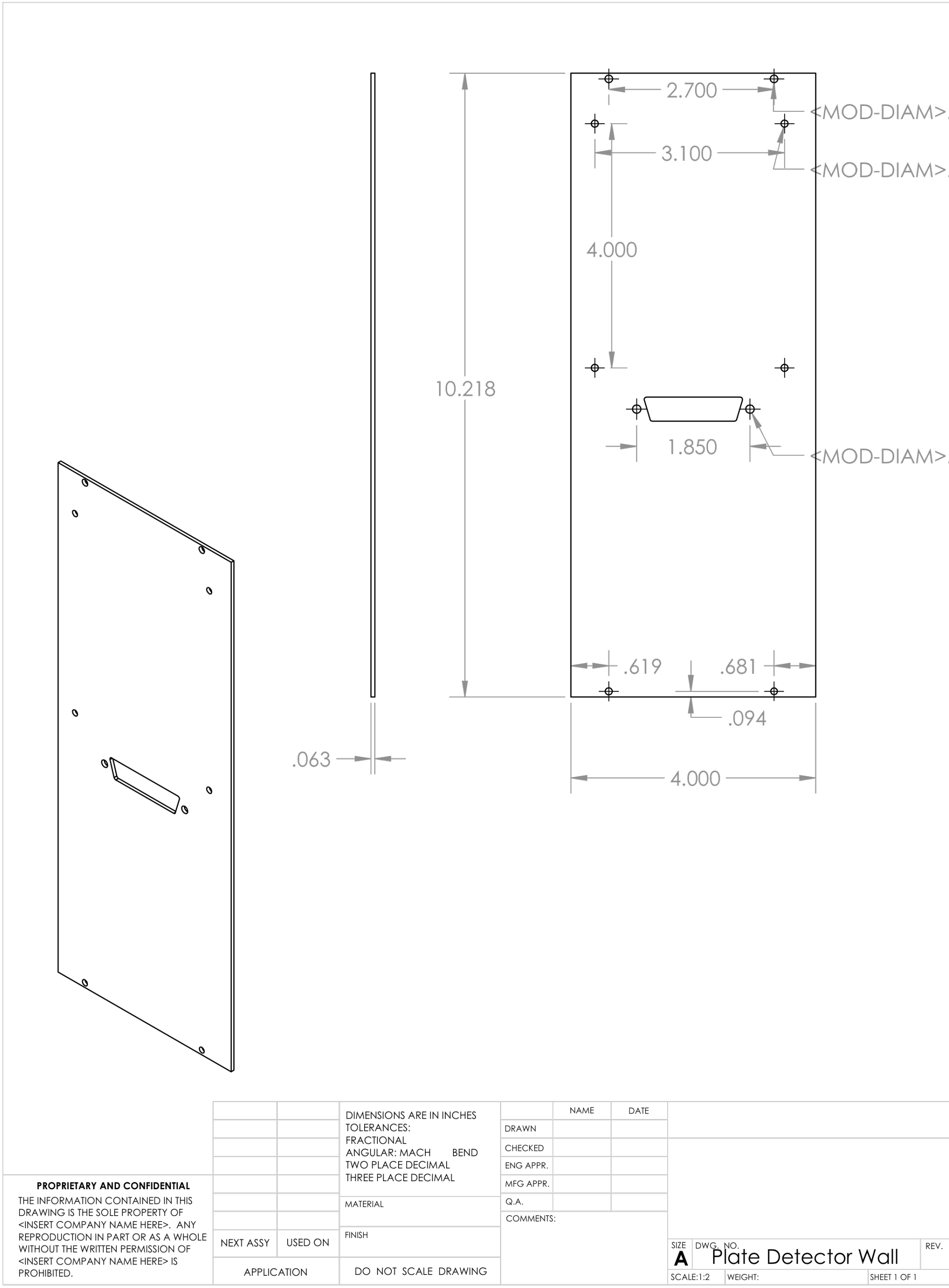

Figure 15. Mechanical drawing of 2.5-U HAXDT detector board mounting wall with dimensions in inches. The hole depicted is for a DB-25 connector for the HASP power, serial, and analog lines.

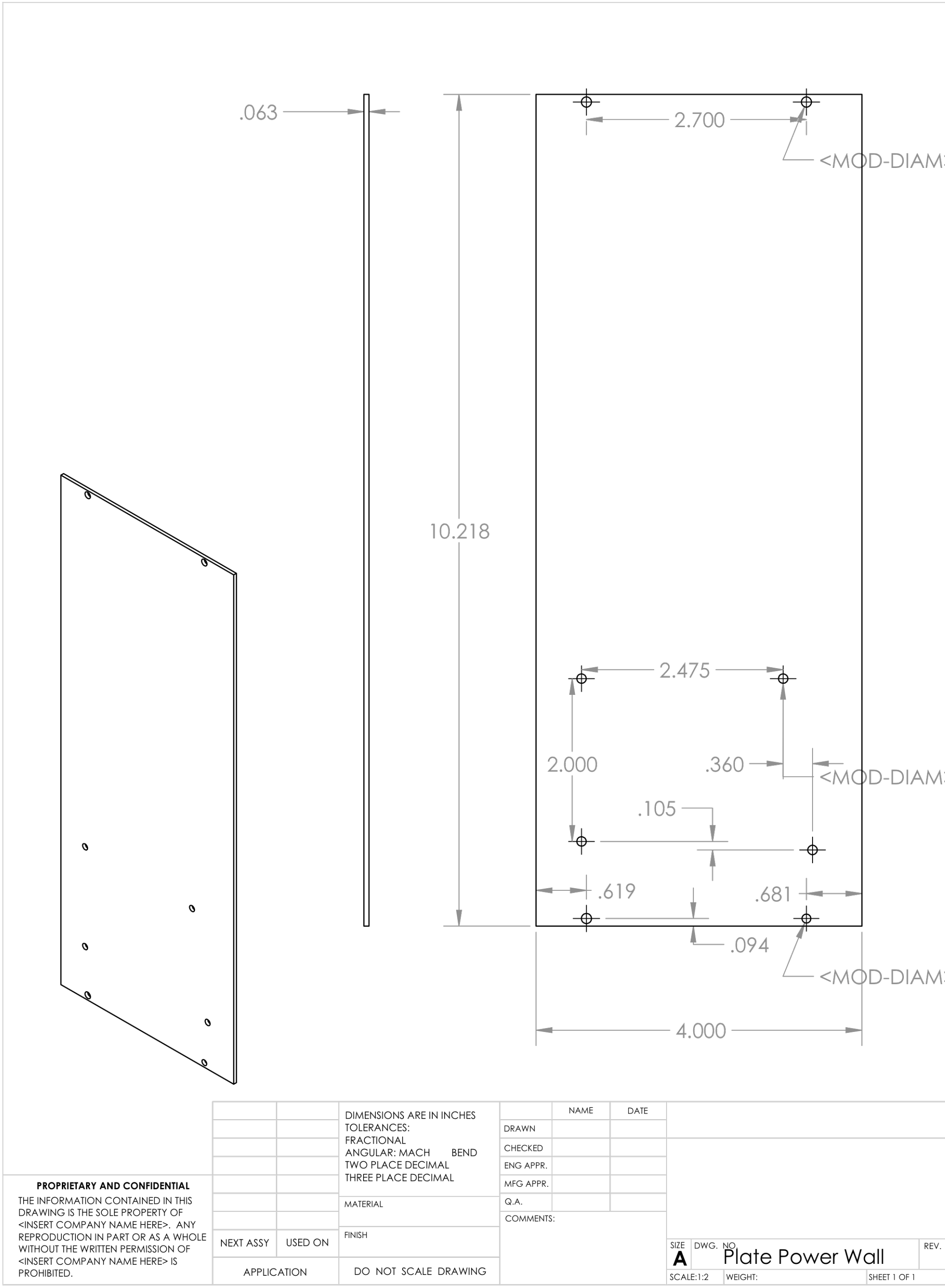

Figure 16. Mechanical drawing of 2.5-U HAXDT flight computer/IMU/power circuit bundle mounting wall with dimensions in inches.

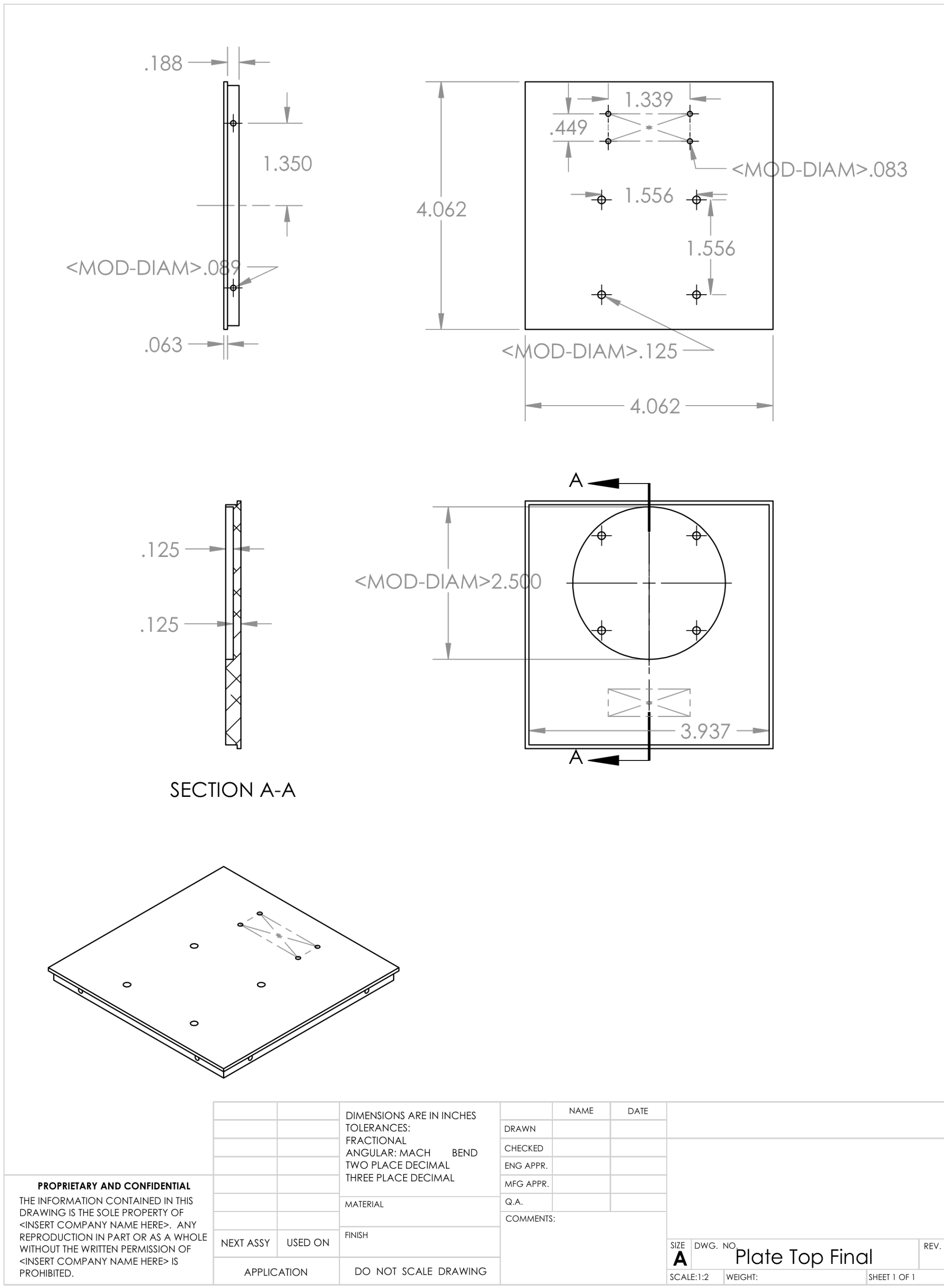

Figure 17. Mechanical drawing of top plate of 2.5-U HAXDT structure with dimensions in inches. This plate will be altered to accommodate two detector assemblies.

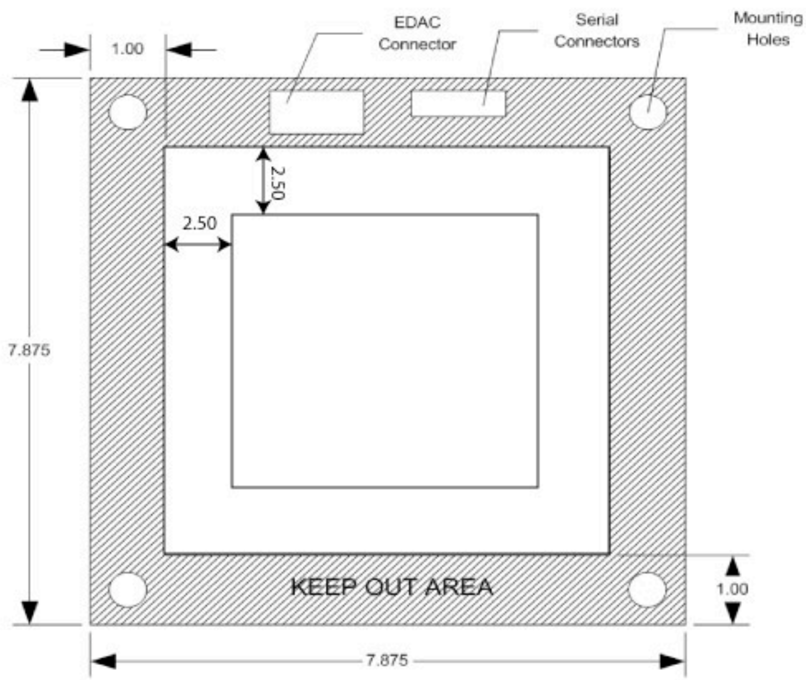

Figure 18. Anticipated 3-U HAXDT footprint on the HASP mounting plate. Note that the dimensions of the footprint are 2.50cm (not inches) from the Keep Out Area.

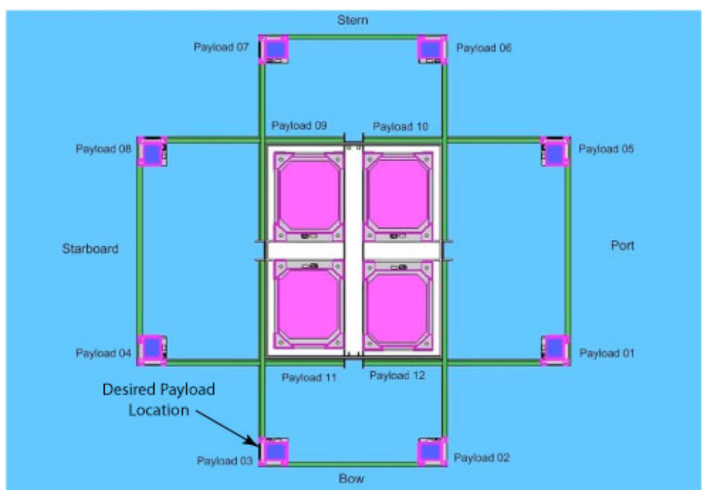

Figure 19. Desired payload location on the HASP gondola. Payload orientation does not depend on payload location.

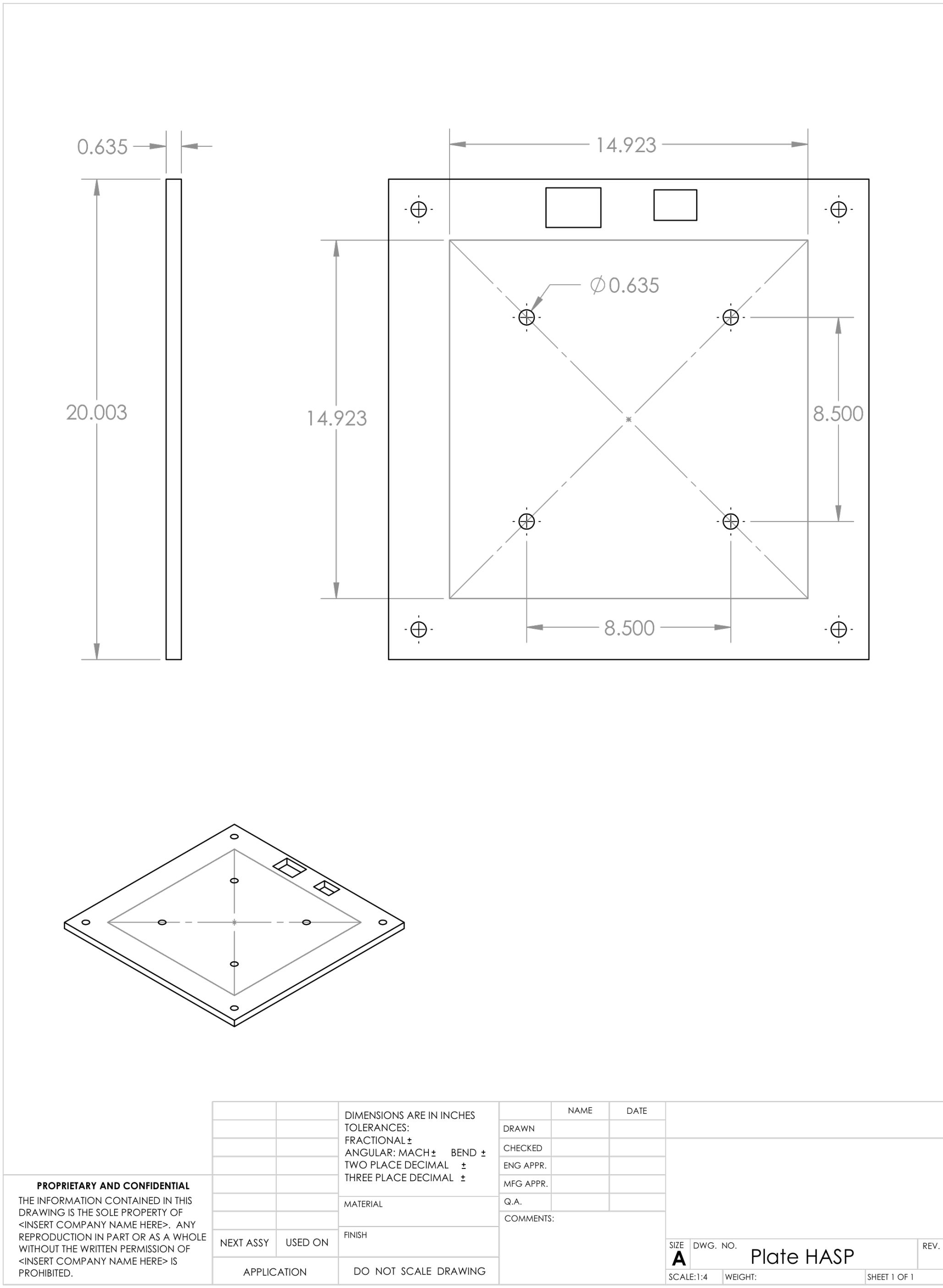

Figure 20. Anticipated modifications to the HASP mounting plate with dimensions in centimeters.

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