HASP Student Payload Application for 2019

Payload Title: SHADOMS (Stratospheric Hypersonics Airborne Particulate Optical Measurement System)	
Institution: University of Minnesota - Twin Cities	
Payload Class (Enter SMALL, or LARGE): SMALL	Submit Date: 2/22/19

Project Abstract:

To make hypersonic vehicles more realizable in today's world, the complex multidisciplinary physics that are involved must be more understood. A current challenge involves accurately characterizing the particulate content at hypersonic cruise altitudes (stratosphere) and how they affect the performance of the vehicles. In this payload application, we propose to fly multiple optical particle detectors on the 2019 HASP mission to make multi-hour measurements of stratospheric particle concentrations at all altitudes up to and including float. The objective is to help compare/characterize low-cost, mid-cost, and high-cost optical particle detector performance in actual stratospheric conditions. This experiment will support an on-going research project to better characterize particulate content in the stratosphere above 80,000 feet for use in hypersonic flow computer simulations to assist in the design of future hypersonic vehicles.

Team Name: University of Minnesota Candler-MURI		Team or Project Website: n/a
Student Leader Contact Information:		Faculty Advisor Contact Information:
Name:	Garrett Ailts	Dr. James Flaten
Department:	Aerospace Engineering and Mechanics	Aerospace Engineering and Mechanics
Mailing Address:	University of Minnesota 107 Akerman Hall 110 Union Street SE	University of Minnesota 107 Akerman Hall 110 Union Street SE
City, State, Zip code:	Minneapolis, MN 55455	Minneapolis, MN 55455
e-mail:	ailts008@umn.edu	flate001@umn.edu
Office Telephone:	n/a	612-626-9295
Mobile Telephone:	612-804-2096	651-399-2423

1. Introduction

The University of Minnesota - Twin Cities (UMN-TC) is part of an Air Force Office of Scientific Research (AFOSR) funded Multidisciplinary University Research Initiative (MURI) project to study the role of stratospheric particulates (also known as "particles") and free-stream turbulence in hypersonic boundary layer transition. The University of Colorado is leading this effort, assisted by teams at the UMN-TC and Embry Riddle Aeronautical University in Florida. In particular, UMN-TC has been tasked with measuring the atmospheric particulate content at various altitudes in the stratosphere and using the resulting data as input to computational tools that simulate how particulates interact with the hypersonic flow field.

Over the past academic year, UMN-TC has been developing a preliminary, weather-balloon-based, particulate-measuring payload to perform such measurements. Great efforts have been made in perfecting weather ballooning techniques (flown locally) and calibrating particulate-measuring instruments such as optical particle detectors. Multiple weather balloon flights have been made in Minnesota with the goal of consistently reaching altitudes from 80,000 to 120,000 feet and floating for a short period of time (minutes, not hours) while collecting particulate data. In addition, UMN-TC included an optical particle detector as an add-on to our main payload on the 2018 HASP mission, which made measurements starting at an altitude of approximately 80,000 feet on ascent and throughout the duration of the flight until shortly before descent began. This HASP mission proved to be an excellent opportunity to evaluate these developing systems, as it consisted of a flight profile that is currently not possible in local stratospheric flights using weather balloons.

The UMN-TC's objectives for the 2019 HASP mission are to perform in-situ measurements of particle concentrations and size distributions in the stratosphere and directly compare multiple optical particle detector measurements in stratospheric conditions. The payload to be used will include particle detectors from multiple manufacturers, including low-cost, mid-cost, and high-cost detectors, along with support from a UMN-TC-developed sensor suite, which will be used for functions including data logging, active heating (when necessary), and GPS-tagging of data sets.

The results from the 2019 HASP mission will not only provide valuable particulate data at higher altitudes and for a much-longer duration than is practical with local weather balloon flights, but it will allow in-situ collection of particulate data at a wide range of altitudes by multiple optical particle detectors for direct comparison/cross-calibration purposes. This second aspect of the experiment will provide useful insight towards which particle detectors to use for future stratospheric flights in the MURI project and how to interpret their data (i.e. simultaneous calibration of multiple types of detectors at the extreme temperature and pressure conditions experienced during a stratospheric mission).

1.1 Scientific Background

1.1.1 Hypersonic flight

The regime of hypersonic speeds, which are generally defined as above Mach 5 (five times the speed of sound), is encountered during the reentry of space vehicles, such as the Space Shuttle or Apollo capsules, and is currently achievable by some emerging aircraft and missile technologies. Understanding the physics of such high-speed flight is critical in further developing safe and efficient vehicle designs. Further, this could open the door for numerous commercial applications (such as significantly reduced intercontinental travel time and routine "space-tourism") and would improve the safety of spacecraft during their descent into a planet's atmosphere.

However, flying at speeds exceeding five times the speed of sound poses complex multidisciplinary physics problems and risks immense practical failures. In particular, the fluid mechanics involved in the extreme aerothermodynamic environment associated with high-speed flight are still not completely understood. As a result, there has been extensive efforts made by researchers to develop tools, both experimental and computational, to aid in solving such problems.

A specific problem is measuring the small-scale atmospheric disturbances that are present in actual hypersonic flight conditions and how they affect the flow physics. Such disturbances include turbulence on small spatial scales (centimeter scales, or even smaller) and suspended particulates. This problem is of particular interest as it is currently not known if atmospheric turbulence or particulates are the source of the disturbances that ultimately cause the skin friction and aerodynamic heating rate to the vehicle to dramatically increase. If the heating load is too extreme, it could compromise the flight entirely. Thus, in obtaining accurate data on these disturbances, researchers could use them as inputs to computational fluid dynamics simulations to better understand how they interact with the flow physics.

1.1.2 Atmospheric particles versus hypersonic boundary layers

Near the body of a vehicle, viscous effects of the fluid dominate and promote steep gradients in fluid properties such as velocity and temperature. The result of this is a thin layer of fluid on the surface of the vehicle known in aerodynamics as the boundary layer. When a hypersonic boundary layer transitions from smooth laminar flow to chaotic turbulent flow, the skin friction and aerodynamic heating rate to the vehicle dramatically increase. Thus, the aerothermodynamic design of hypersonic vehicles relies on the ability to predict laminar-turbulent transition. Transition usually occurs when small disturbances in the atmosphere are amplified by the boundary layer until they reach a critical amplitude. Then, the flow breaks down to turbulent motion. As described above, it is currently not known if atmospheric turbulence or particulates in the flow are the source of the disturbances that cause observed transitions. Therefore, it is important to characterize the atmospheric state and study how disturbances interact with hypersonic boundary layers. From an applied perspective, this would consist of accurately and reliably characterizing the local particulate content of the atmosphere before a test flight of a hypersonic vehicle.

1.1.2 Optical particle detectors

Characterization of atmospheric particulate content can be done using optical particle detectors, which operate on the principle of light scattering. Air is drawn into the instrument by means of a small fan or pump; as the air passes through a designated region, it is illuminated by a laser beam. The beam strikes individual particles in the air flow and creates a scattering pattern. The corresponding intensity of the scattered light is then related to the particle size based on Mie scattering theory, where the intensity of the scattered light is typically measured by a sensor, such as a photodiode, at a particular deflection angle within the instrument. The resulting data is generally reported in terms of “particle count per second” and is categorized into “particle-size bins”. The concentration of particles can then be calculated in a post-processing routine (or some instruments calculate this internally) based on the particle counts and the recorded sample flow rate.

Optical particle detectors range in price from under one hundred dollars (“low-cost”) up to one thousand dollars (“mid-cost”) up to ten thousands of dollars or more (“high-cost”). For this reason, it is of particular interest to develop a payload using low-cost and/or mid-cost particle detectors and comparing their response to that of a well-characterized high-cost detector in an identical stratospheric environment. Ground calibration of optical particle detectors, though crucial, is expensive (and often cannot duplicate the extreme conditions encountered in the stratosphere). Therefore, it is important to fly multiple detectors on HASP to help determine the most suitable detector(s) for future weather-ballooning missions.

As an example, a depiction of the “LOAC” optical particle detector (more details described below) is shown in Figure 1 to illustrate the concept described above. This figure shows the orientation of the internal laser and photodiodes. The air flow inlet is on the bottom (not visible in image) and the air flow channel is perpendicular to the plane of the lasers and photodiodes. As the air crosses the laser beam it scatters the incident light, causing it to be sensed by the photodiodes at multiple deflection angles.

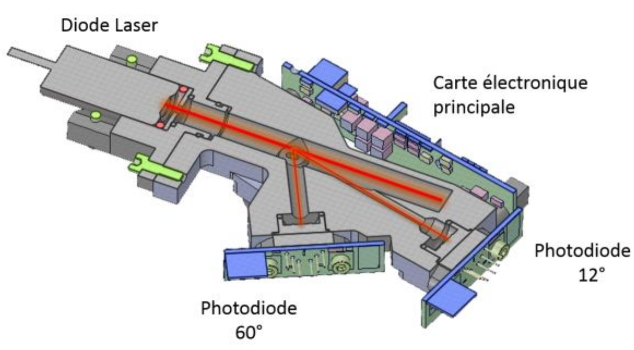

Figure 1. Depiction of the LOAC optical particle detector unit. Image from Renard et.al. [4].

1.1.3 Rarefied environment

A significant challenge that cannot be overlooked is the effect that the rarefied conditions of the upper atmosphere has on the optical particle detectors. Specifically, the effect of a low pressure and density environment on the performance of the detectors has not been quantified by low-cost and mid-cost instrument manufacturers. As the air becomes more vacuum-like, the drag force on the particles will decrease. If the drag becomes too small, the inertia of the particles will dominate and they may no longer follow the air flow streamlines through the detector. Thus it is speculated that they may not pass through the laser region of the instrument and be detected at all, or at least not as efficiently as anticipated, resulting in an inaccurate (low) particle count. Furthermore, as the air density decreases, there will be less mass influx per sample volume of air. Not all particle detectors account for the extreme variation in air density encountered in a stratospheric mission, resulting in an inaccurate sample flow rate and hence in an inaccurate particle concentration.

To deal with this challenge, UMN-TC is making an effort to calibrate multiple particle detectors in a low pressure, low density environment. Such a calibration will characterize the response of the detectors at high altitudes and quantify how their performance is affected.

1.2 Previous Work

A primary focus over the past academic year has been experimenting with one type of mid-cost optical particle detector, namely the Alphasense OPC-N2. This instrument uses a small fan to draw in air samples and is capable of sizing and categorizing particles into 16 separate size bins, ranging from 0.35 μm to 17 μm. It has been flown on six local weather-balloon flights in Minnesota to date, as well as the 2018 HASP mission. Efforts have been made to rigorously calibrate our Alphasense OPC-N2 detectors using NIST traceable monodisperse PSL spheres [1]. The calibration consisted of evaluating and comparing the response of four OPC-N2s with a previously calibrated TSI Optical Particle Sizer Model 3330, as a reference standard, at 1 atmosphere and room temperature conditions (i.e. NOT extreme conditions) using four different sizes of monodisperse PSL spheres: 400 nm (0.400 μm), 702 nm (0.702 μm), 1030 nm (1.030 μm), and 5027 nm (5.027 μm).

The 2018 HASP mission was ultimately successful in terms of payload functionality. The flight resulted in approximately 9 hours of data that was obtained between approximately 75,000 and 122,000 feet and it was the first flight using an OPC-N2 detector that had been calibrated beforehand. Figures 2 and 3 in Appendix A show data collected by the OPC-N2 during the 2018 HASP mission.

Figure 2 shows the average concentration (number of particles per cubic centimeter) of 0.35-0.54 μm size particles versus altitude (kilo-feet). The vertical error bars represent the altitude range over which the average concentration was taken. The horizontal error bars represent the uncertainty in concentration, which was determined based off calibration and the standard deviation of the averaged values. All other size bins (greater than 0.54 μm) measured zero and thus were not included in the figures.

Figure 3 shows the average concentration (number of particles per cubic centimeter) of 0.35-0.54 μm size particles versus time (orange) and altitude (kilo-feet) versus time (blue). The vertical error bars represent the uncertainty in concentration, which was determined based off calibration and the standard deviation of the averaged values. The horizontal error bars represent the time period over which the average concentration was taken. The origin ($t = 0$ min) is relative to the time at which particle sampling began, at approximately 80,000 feet during the ascent. From $t = 0$ to $t \cong 60$ min, the balloon is in ascent; from $t \cong 60$ to $t \cong 560$ min, the balloon is in float, or slow descent; after $t \cong 560$ min, the electronics of the payload are powered "off" before descent begins.

From an altitude of 80,000 to 120,000 ft., the OPC-N2 only detected particles in the size range of 0.35-0.54 μm. Figure 2 shows that from an altitude of approximately 80,000 to 120,000 ft., the particle concentration appears to have a relatively constant order-of-magnitude, near 10^{-1} particles/cc. Over an altitude of 110,000 feet, the concentration appears to decrease by approximately one order-of-magnitude, approaching 10^{-2} particles/cc. These magnitudes are fairly consistent with Renard et. al. [2] shown in Figure 4, which consist of measurements made up to slightly-lower altitudes (33 km, 108 kilo-feet) using weather balloons, but at a different location (France), time, and a better-characterized but high-cost "LOAC" optical particle detector..

Of significance importance to note is that the OPC-N2 did not detect any particles in size bins larger than 0.35-0.54 μm. Despite the measurements being made at different locations and time, this is inconsistent with measurements made by Renard et al. [2], who showed the presence of larger particles (up to 0.9 μm) in concentrations of similar magnitude to the smaller particles described above. They also show the existence of much larger particles (3-7.5 μm) in concentrations of the order less than 10^{-2} particles/cc at altitudes up to 108 kilo-feet.

For 2019 HASP, UMN-TC plans to fly the same high-cost LOAC optical particle detector as Renard et. al., as well as both mid-cost and low-cost detectors, in hopes of explaining this discrepancy.

Finally, Figure 5 shows a collage of pictures from the work outlined above: the top left shows the OPC-N2 (wrapped in gold-Mylar blanket) attached to the 2018 HASP payload; the bottom left shows a preliminary sensor suite inside a payload that supports the OPC-N2 on local weather balloon flights; the top right shows two weather balloons at apogee on a local flight, where the upward-facing camera captured the instant when the first balloon burst (right) initiates the burst of the second (left); and the bottom right shows the launch of the OPC-N2 payload on a local weather balloon flight.

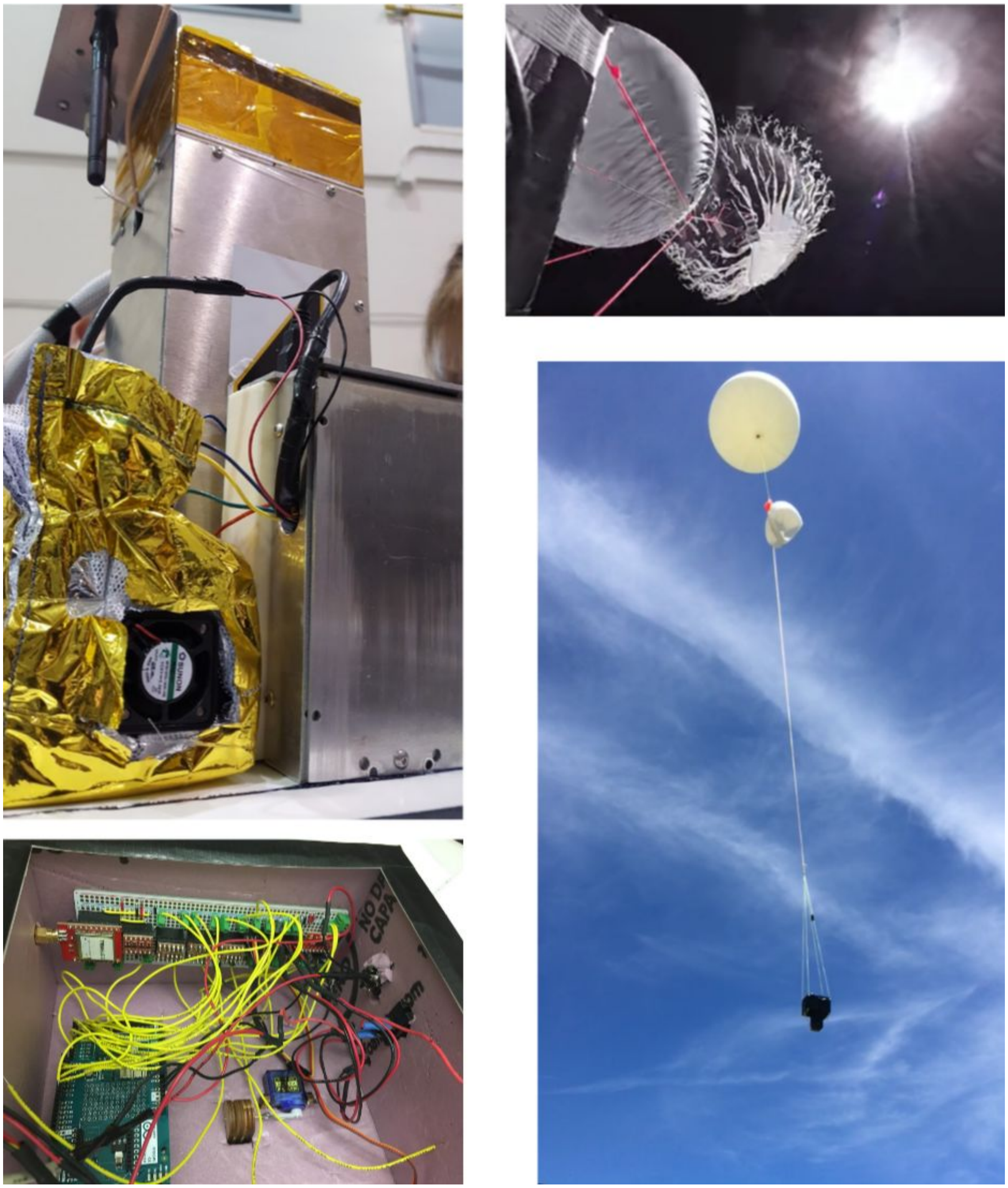

Figure 5. Collage of pictures taken over the past academic year from MURI project.

1.3 Flight Objectives

The objective of the 2019 HASP mission is to fly multiple optical particle detectors to make multi-hour measurements of stratospheric particulate concentrations and size distributions, and to compare low-cost, mid-cost, and high-cost optical particle detector measurements in actual stratospheric conditions. We propose to use and compare the following optical particle detectors:

1. Alphasense OPC-N3 (mid-cost)
2. Light Optical Aerosol Counter (LOAC) (high-cost)
3. Plantower PMS5003 (low-cost)

For convenience, these sensors will be referred to as just, the “OPC-N3”, “LOAC”, and “PMS5003” respectively. The Alphasense OPC-N2 has previously flown on both local weather balloon flights and as a part of HASP 2018. This model has been discontinued, and we are in the process of switching our inventory to the updated OPC-N3 which is the model we plan to fly on the HASP 2019 mission. Note: we have the least experience with the Plantower PMS5003 device which was recommended to us by the HARBOR stratospheric ballooning team from Weber State University in Utah, so that is currently being tested to determine if it will be beneficial to include in our HASP payload. We will make a fly/no fly decision on this sensor by mid-March and the decision will be detailed in future documentation.

The LOAC appears to be the “gold standard” for making particle measurements [2] [4] at high altitudes, so the goal of the direct comparison between detectors is to determine if the low-cost and/or mid-cost detectors are capable of producing similar results to that of the LOAC, at least with suitable ground and flight experiments to help calibrate them for use in extreme (stratospheric) conditions.

2. Team Description

The Candler-MURI project at the UMN-TC is under the direction of Dr. Graham Candler of the Aerospace Engineering and Mechanics Department. Dr. Candler is an expert in hypersonic aerodynamics and computational fluid dynamics, and is responsible for investigating the role of atmospheric particles and turbulence in hypersonic boundary layer transition, as well as the financial aspect of the project. Working closely with Dr. Candler on the flow simulations is Joseph Habeck, an aerospace engineering graduate student at UMN-TC. Mr. Habeck will continue to also play a key role in calibrating the particle detectors in cooperation with the Mechanical Engineering Department at UMN-TC, as well as parsing and interpreting the recorded particle detector data from ground and flight tests.

The payload engineering will be performed under the guidance of Garrett Ailts, an aerospace engineering undergraduate at UMN-TC. Mr. Ailts has had previous experience with HASP as part of the CubeSat team which flew a mock-up of the SOCRATES CubeSat (still under development) on the 2018 HASP mission. Faculty advisors for the payload engineering will be Dr. James Flaten and Dr. Demoz Gebre-Egziabher. Dr. Demoz Gebre-Egziabher currently works as a faculty advisor for the CubeSat team and has overseen previous UMN-TC small-sat HASP flights. Dr. James Flaten works as the Assistant Director of the Minnesota Space Grant Consortium (MnSGC) and has headed the UMN-TC Stratospheric Ballooning team for over a decade. He provides valuable experience concerning the challenges of building and operating payloads in the “near-space” environment, both on HASP and on local weather balloon missions.

Development of the electronics and flight computer for the payload will be led by Jackson Holl, an electrical engineering undergraduate. Development of the structures for the payload will be led by David Richardson, an aerospace engineering undergraduate. Development of the thermal-vac for use in calibrating and simulating environments seen by the payload will be led by Jacob Meyer, an aerospace engineering undergraduate. The SHADOMS team will be divided into four sub-teams: Particle Detector, Structural, Electrical/Flight Computer, and Calibration and Simulation. The student leads of each of these subteams will report directly to the Student Project Lead, Mr. Ailts, who will in turn will report to the project lead, Dr. Candler. It is anticipated that Mr. Ailts and a representative from three subtreams (particle detectors, electrical/flight computer, and structural) will be present at the HASP 2019 flight next summer. The team and their respective roles are summarized in Table 1. These are students already involved in the Candler-MURI project but we anticipate some evolution of student team members on the HASP project as summer 2019 availability for these students, and others working in parallel on the Ballooning Team, becomes more clear.

Name	Email	Role
Dr. Graham Candler	candler@umn.edu	Project Lead
Dr. James Flaten	flate001@umn.edu	Faculty Advisor
Dr. Demoz Gebre-Egziabher	gebre@umn.edu	Faculty Advisor
Garrett Ailts	ailts008@umn.edu	Student Project Lead
Joseph Habeck	habec021@umn.edu	Particle Detector Lead
David Richardson	rich1299@umn.edu	Structural Lead
Jackson Holl	hollx047@umn.edu	Electrical / Flight Computer Lead
Jacob Meyer	meye2497@umn.edu	Calibration & Simulation (Thermal-Vac) Lead
Simon Peterson	pet0029@umn.edu	Electrical / Flight Computer Team Member
Asif Ally	allyx004@umn.edu	Electrical / Flight Computer Team Member
Billy Straub	strau257@umn.edu	Calibration & Simulation Team Member
Nathan Pharis	phari009@umn.edu	Structural Team Member

Table 1. UMN-TC Candler-MURI team.

2.1 Timeline

Currently we plan to send three members to integration in July. Each member will be a representative from three of our sub-teams: Structures, Electrical and Power Systems, and Calibration. Below is our anticipated timeline for the project.

Date in 2019	**Activity**
February	Purchase LOAC sensor; Construct and test circuits; PCB layout and order PCB rev 1; Modify code from local flights for HASP use; Finalize structure rev 1; Construction of thermal-vacuum chamber
March	Make fly/no-fly decision on Plantower PMS5003; Test PCB rev 1 and integrate changes into rev 2; Test and debug code; Fabricate and test structure rev 1 and integrate changes into rev 2; Testing of thermal-vac chamber
April	Order and test PCB rev 2; Fabricate and test structure rev 2; Continue to debug code and testing with PCB; Calibrate particle detectors in thermal-vacuum chamber
April 26	Preliminary PSIP due
May	Final systems testing; Initial thermal-vac and cold soak testing
June	Integrate all components into payload; Final thermal-vac and cold soak testing
June 21	Final PSIP due
July	Verify flight ready payload for integration
July 15-19	Student payload integration; FLOP due
August	Correct any issues encountered at integration; HASP flight
September, October, November	Data analysis; Preparation for final scientific paper
December 13	Final flight/science report due

Table 2. Timeline of events.

3 Payload Description

The "main" part of the HASP payload will consist of the two particle detectors (OPC-N3 and LOAC), with a possibility of adding a third (PMS5003). All other payload parts are secondary payload parts tasked with supporting the flight of the particle detectors in various ways, and/or to test their functionality in doing so (as explained later for the Copernicus GPS). These other parts include the flight computer, digital temperature sensors, a Copernicus II GPS, mesh active heating pads, and the physical structure. The flight computer is responsible for logging GPS and sensor data as well as controlling heating and sensors through the relay switches. GPS and sensor data will be used by the flight computer to determine appropriate heating and power management measures, such as turning particle detectors and heaters on and off. A high level system diagram showing major components and their connections is shown below in Figure 6.

Although the area of interest for particulate measurements for the Candler-MURI project lies between 80,000 and 120,000 feet, the sensors will be turned on at payload activation and kept on for the duration of the flight unless they need to be temporarily turned off for power management reasons. (It is possible that the particle detectors may need to be off when heating elements are on, such as part way through the ascent (near the tropopause).). This will be done to compare the effectiveness of the various particle detectors at sub-stratospheric levels, of which there have been many successful flights of the LOAC [2], but fewer of the OPC-N3. These sub-stratospheric measurements will allow a more complete characterization of the atmosphere, as well as a better overview of the various sensors.

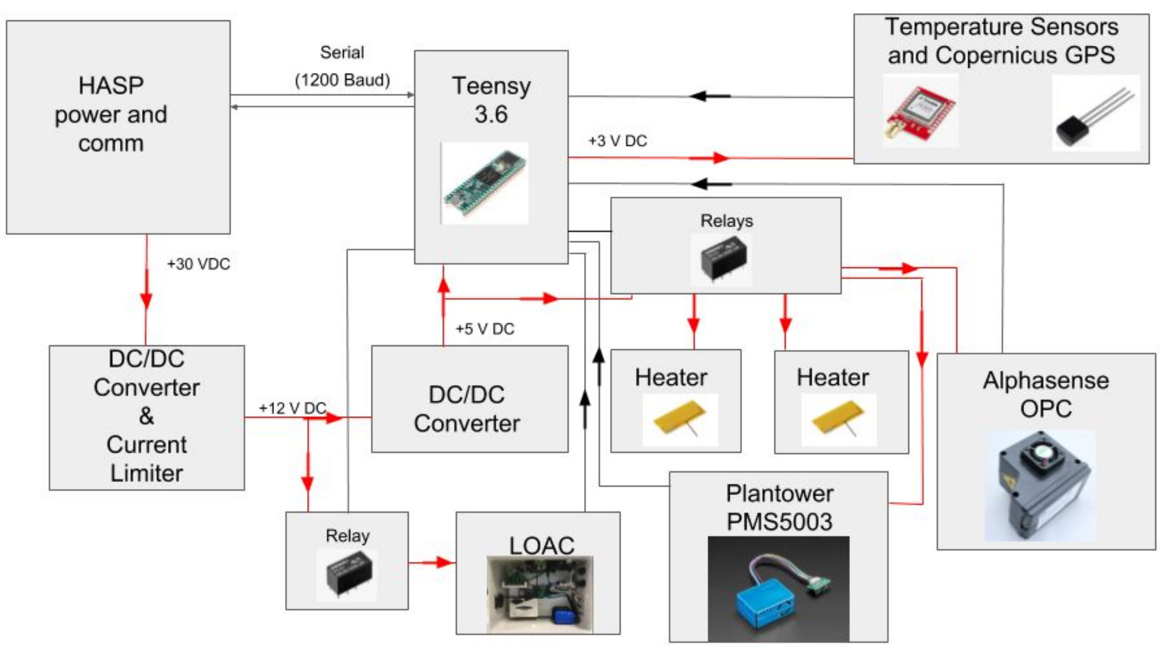

Figure 6. High level systems diagram of the SHADOMS payload.

3.1 Hazards

Each optical particle counter houses a class 3B laser that is used for counting and sizing particles as they move through the flow channel. These lasers are completely self contained and should not be a hazard to any systems on the HASP gondola, the balloon, or any of the surrounding payloads.

3.2 Payload Specifications

3.2.1 Structure

Technical leaflets provide limited information on the physical structure of the LOAC, but it has been confirmed by Renard et. al. in [4] that the LOAC optical unit and pump can fit in rectangular box with dimensions 20 x 10 x 5 cm. With this knowledge, a preliminary structure has been designed that is modeled after a 3U cubesat structure flew previously by the UMN Small Sat team on HASP. The casing is made of 6061 - T6 aluminum and held together with #4-40 self-locking 18-8 stainless steel socket head cap screws. The payload attaches to the HASP plate with 1.25" ATSM A307 $\frac{1}{4}$"-20 bolts that run through the bottom wall of the payload (see figure 14). The shell will be coated in alternating layers of mylar and insulating fabric which will inhibit energy loss and absorption due to radiation. This should keep the payload warm in the cold tropopause and prevent overheating at altitude. Below are preliminary CAD drawings for the shell and the OPC-N3. As mentioned earlier, the LOAC was modeled as a 20 x 10 x 5 cm box in order to create the shell. Once we have a LOAC detector in hand, an accurate CAD model of the optical unit will be drafted, and interior mounting specs will be finalized. Mechanical drawings are provided in Appendix A.

3.2.2 Thermal control

The thermal control system in the payload employs passive and active heating in order to maintain a stable operating environment. This two pronged approach to maintaining desired temperature in the payload is based on proven methods from 6 previous local Candler-Muri ballooning tests, The SOCRATES HASP 2018 payload, and dozens of local stratospheric ballooning flights by UMN-TC's ballooning team for other purposes.

The passive heating system is a shell surrounding the payload that consists of five alternating layers of mylar and insulating fabrics, exemplified in the preliminary CAD drawings below. These layers help to limit temperature fluctuations by preventing heat loss or gain from radiation. During flight in the tropopause, the insulating shell will prevent heat loss due to the extremely cold temperatures by blocking in the heat that would otherwise radiate out into the atmosphere. Once the payload exits the tropopause and reaches altitude, the shell will help to prevent heat gain by reflecting the heat radiating down on the payload from the sun. The passive heating system will help limit temperature swings that would otherwise jeopardize the experimental equipment.

In addition to a passive heating system, the payload also contains an active heating system. This active heating system consists of a 5cm by 15cm Sparkfun Heating pad, made of resistive material that gives off heat when current runs through it. This system is monitored by a temperature sensor near the heating pad and controlled by the Teensy 3.6 microcontroller. The current to the heating pad is controlled using a latching relay that limits power draw and prevents current from running through the sheet when the active heating system is unneeded. If the temperature sensor notes that the temperature in the region has dropped below 283 kelvin, the heater will turn on until the temperature has warmed the region to 289 kelvin. This provides a comfortable temperature of operation of the central control system, the particulate counters, and the batteries within the payload. Based on previous local MURI ballooning flights, this temperature range provides the best operation of all of the electronics without constantly drawing current. The active heating system is most active during flight through the tropopause, during which the most convection related heat loss occurs. During this time, the heating pad is expected to draw 6 watts of power, based on previous flight data. During other points of the flight, the passive heating system is sufficient to maintain a comfortable operating temperature for the electronics. Even in a worst case scenario, with the power draw from the heat system on for the entire duration of the flight, the payload's power draw lies under the power draw limitations defined by HASP. However, as a redundancy, the flight computer will be programmed to prevent the major power consuming devices- the heaters and particle counters- from exceeding the designated power draw. In the case of more power being requested than what can be provided, the system will distribute the power in a way that will collect the best possible data without compromising the payload. Together, the active and passive thermal control systems will help to keep the payload at an optimal operating temperature.

3.2.3 Flight computer and data logging

The flight computer is a Teensy 3.6 development board consisting of a MK66FX1M0VMD18 microcontroller. This computer will be running flight code written in the C language at 180MHz. The code is modified from code previously flown on local University of Minnesota MURI stratospheric balloon flights. The flight computer will control power supplied to all payload components external to the flight computer via relays. Both the LOAC and OPC-N3 support data logging internal to each sensor, and all data taken by these sensors will utilize this feature. It is anticipated that no communication will occur between the Teensy 3.6 flight computer and the LOAC. This is so that all data taken by the LOAC will be comparable to previous literature where the LOAC operated in isolation. All data taken by the OPC-N3 will be sent to the Teensy 3.6 and logged to an SD card for redundant storage. The Teesny 3.6 supports an onboard SD card via the development board via SPI communication. Other data logged to this SD card will include time and position data of both the internal Copernicus GPS and that received from the HASP flight system and temperatures of the LOAC, OPC-N3, and Teensy 3.6.

3.2.4 HASP communication

No extra discretes, analog channels, or serial uplink commands are expected to be utilized by the payload. GPS time and position data is anticipated to be requested from the HASP flight system at a time period of 5 seconds. Serial downlink will be utilized to monitor some key payload health parameters. As set forth by the HASP Student Payload Interface Manual, the serial link will be connected at 1200 baud using 8 data bits, no parity, and 1 stop bit. SHADOMS will initiate data transfer at a frequency of 1 Hz. The data packets sent via the serial downlink will be of the structure shown in Table 2. This implies 30 bytes of data will be sent per second, 300 bits per second including start and stop bits. The data rate and/or packet structure may change during the development of the payload to accommodate the transmission of data samples taken from either of the optical particle detectors. Any such changes will be detailed in future documentation. If any received data indicates flight is not proceeding according to plan, such as over-temperatures of any of the components, then a power off/power on command will be requested.

Byte	**Title**	**Description**
1-2	Header	Beginning of new data record
3-10	Time	Time string in hh:mm:ss since power-on
11-14	Latitude	Latitude from Copernicus II GPS
15-18	Longitude	Longitude from Copernicus II GPS
19-22	Altitude	Altitude from Copernicus II GPS
23-24	Temp_Int	Temperature of the Teensy 3.6 microcontroller
25-26	Temp_LOAC	Temperature of the LOAC sensor
27-28	Temp_N2	Temperature of the OPC-N2 sensor
29-30	Footer	End of complete data record

Table 2. Anticipated downlink packet format.

3.2.5 Power and weight budgets

The payload will make use of the provided HASP 30 volt power. The LOAC sensor runs at 12 V, requiring the voltage from the HASP to be stepped down to 12 volts and also stepped down to 5 Volts for use by the OPC-N3, PMS5003, heaters, and flight computer. All particle detectors and heaters are controlled through relays by the Teensy 3.6 microcontroller. Temperature sensors and GPS data are used to determine when to power the particle detectors and when to actively heat payload components using mesh heating pads.

Component	Mass (g)	Mass Uncertainty (g)	Power (W)	Power Uncertainty (W)
OPC-N3	105	10	0.875	0.035
LOAC (including pump)	300	10	6	0.025
PMS5003	42	5	0.5	0.05
Flight computer, board based sensors	20	5	0.37	0.015
Structure	960	20	0	0
Thermal (active and passive)	60	10	6	0.5
Total	1487	60	13.745	0.625

Table 4. Power and mass specifications.

Table 3 gives the power consumption for the payload. As shown in Figure 15, there will be two voltage converters in series- the first will convert from 30 to 12 volts to power the LOAC, and the second will step 12 volts down to 5 to power the Teensy3.6, OPC-N3, PMS5003, and heating pads. Not shown in Figure 13 is current limiting circuit to limit the input current to the maximum allotted 500 mA (The design for the limiter was decided upon at the time of the proposal). The total power consumption of 13.745 watts is under the maximum power provided by HASP. However, even though total consumption lies under the given limit, the flight computer will ensure that the major power-consuming devices - particle detectors and the heating pads - never exceed the power limit (and hence might not be allowed to be on at the same time). Based on previous balloon flight experience, it is only necessary to apply active heating during the ascent phase near the tropopause to keep the payload adequately warm, as at higher altitudes decreased convection occurs due to a very thin atmosphere.

3.2.6 Integration procedures

At integration, we plan to test our uplink/downlink capabilities to make sure we can reliably request temperature data on our particle counters and the status of the active heating system (which resistive heating blankets are active, and how long have they been on). During the first thermal-vac test, we plan to test the stability of our active heating system regarding keeping the temperature of the sensors within a small range sensors in order to ensure accurate data. We will also test sensor reset commands which we plan to use to restart the OPC-N3 sensor if it gets below its operating temperature (we do not plan to ever use a reset on the LOAC device, as one of the goals of our experiment is a comparison of particle counting systems i.e. the Teensy flight computer running the OPC-N3 vs the LOAC motherboard running the LOAC sensor). We'll then run the sensors post thermal-vac to check for any drift in the calibration

Appendix A. Figures

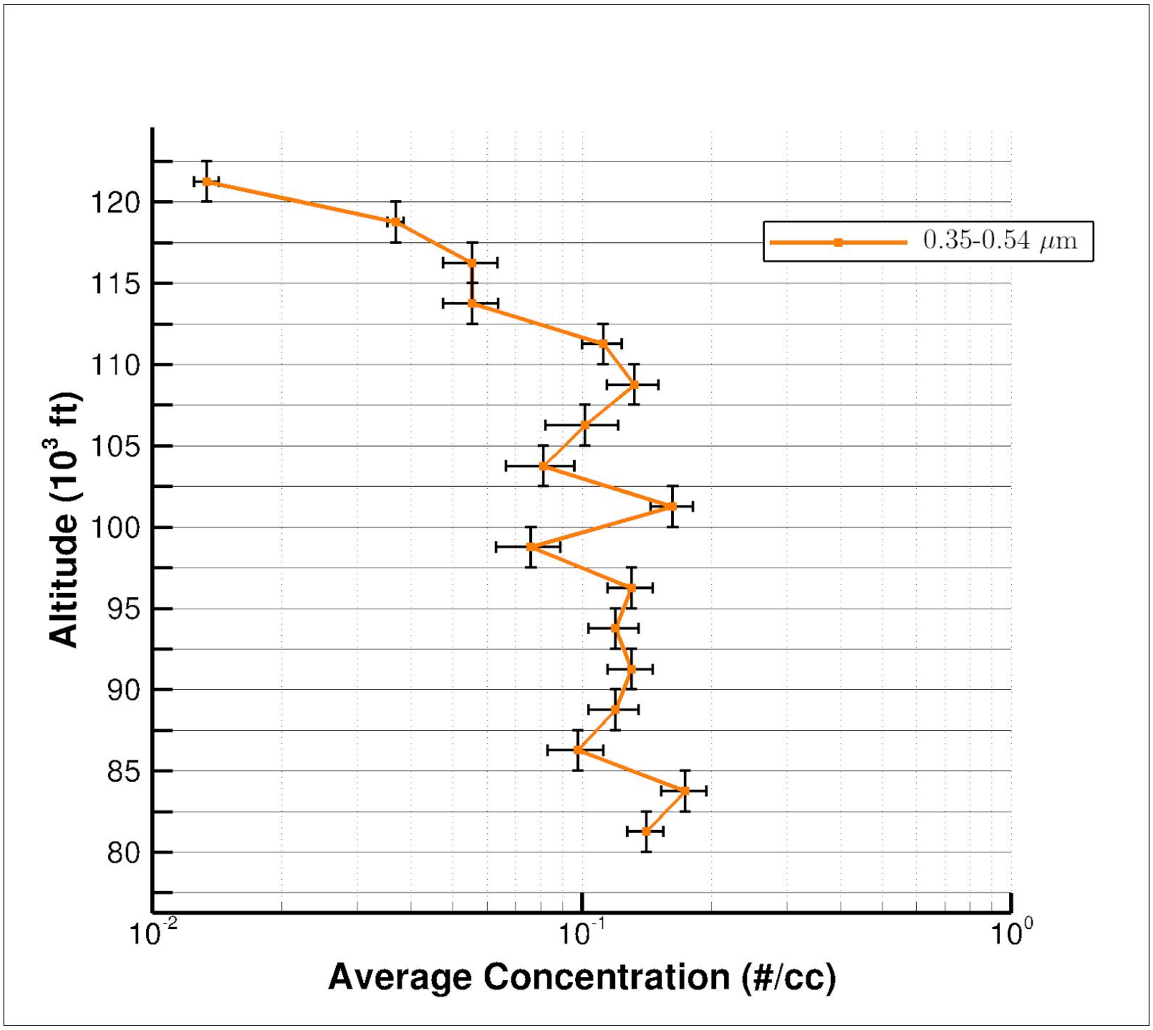

Figure 2. Average concentration (number of particles per cubic centimeter) of 0.35-0.54 μm size particles versus altitude (kilo-feet). This OPC-N2 data was collected on the 2018 HASP mission.

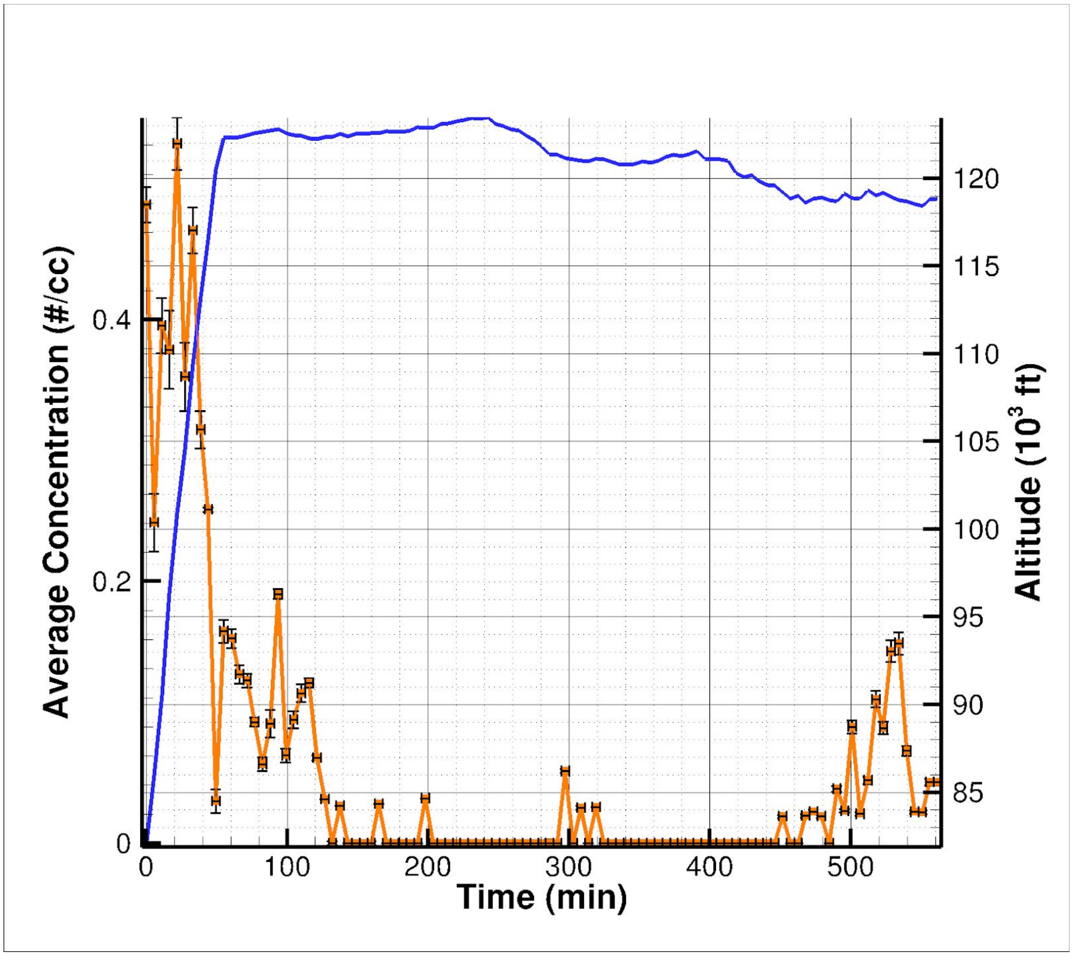

Figure 3. Average concentration (number of particles per cubic centimeter) of 0.38-0.54 μm size particles versus time (orange) and altitude (kilo-feet) versus time (blue). This OPC-N2 data was collected during the 2018 HASP mission.

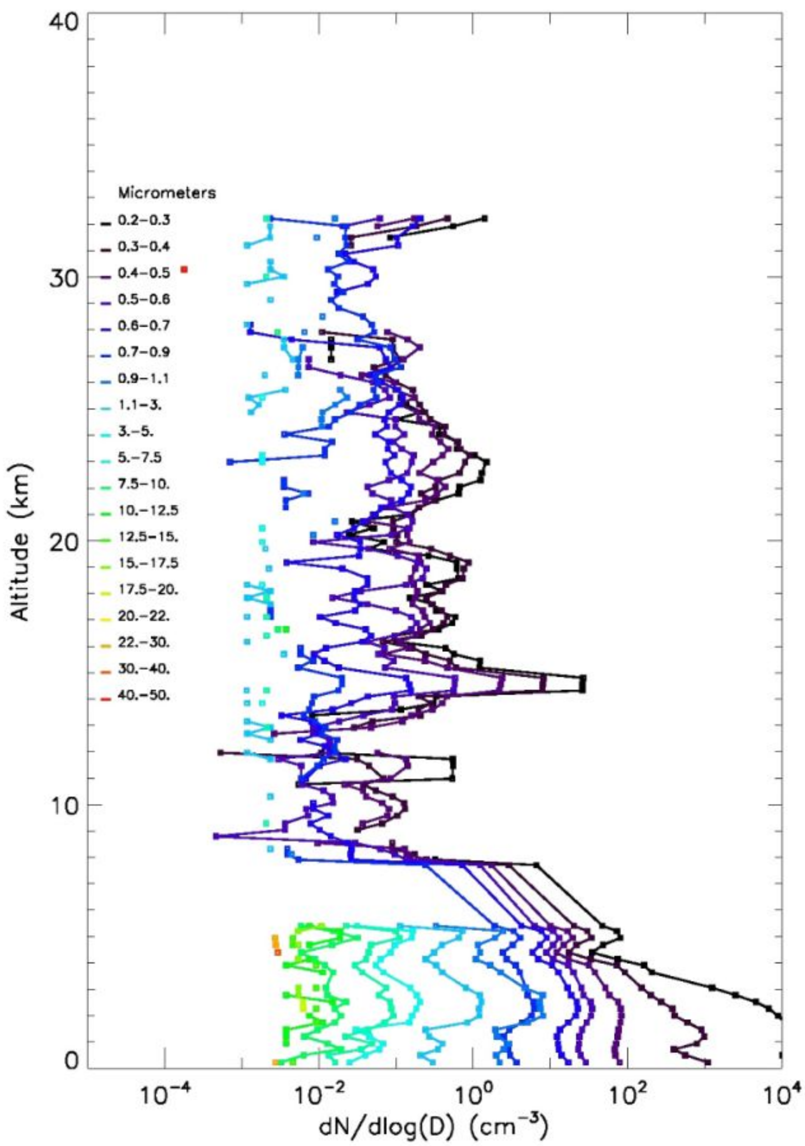

Figure 4. Particle concentrations for several size bins up to 32 km (105,000 feet) using the LOAC optical particle detector. This plot was taken from Renard et. al. [2].

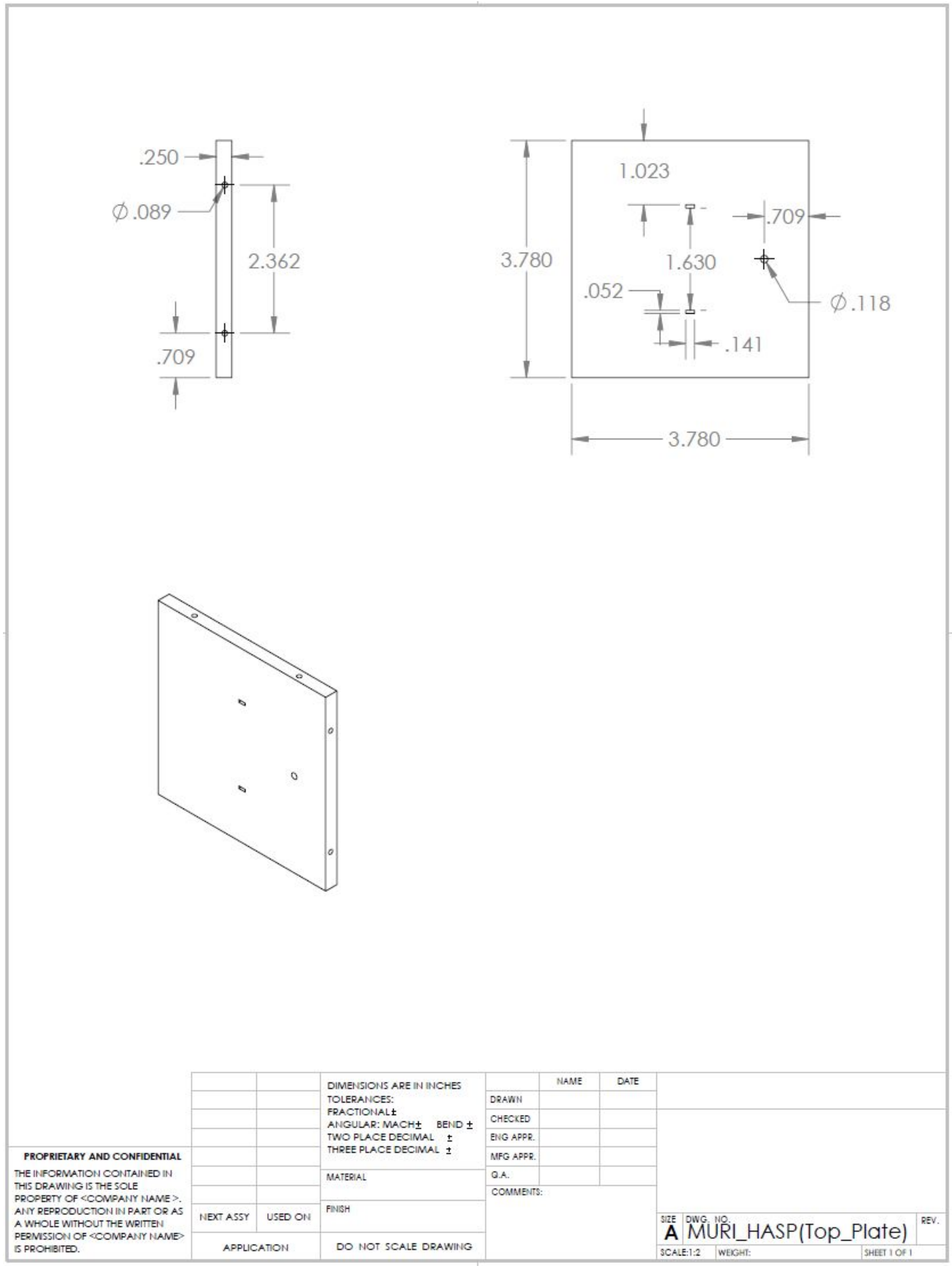

Figure 7. Mechanical drawing of top plate of MURI shell.

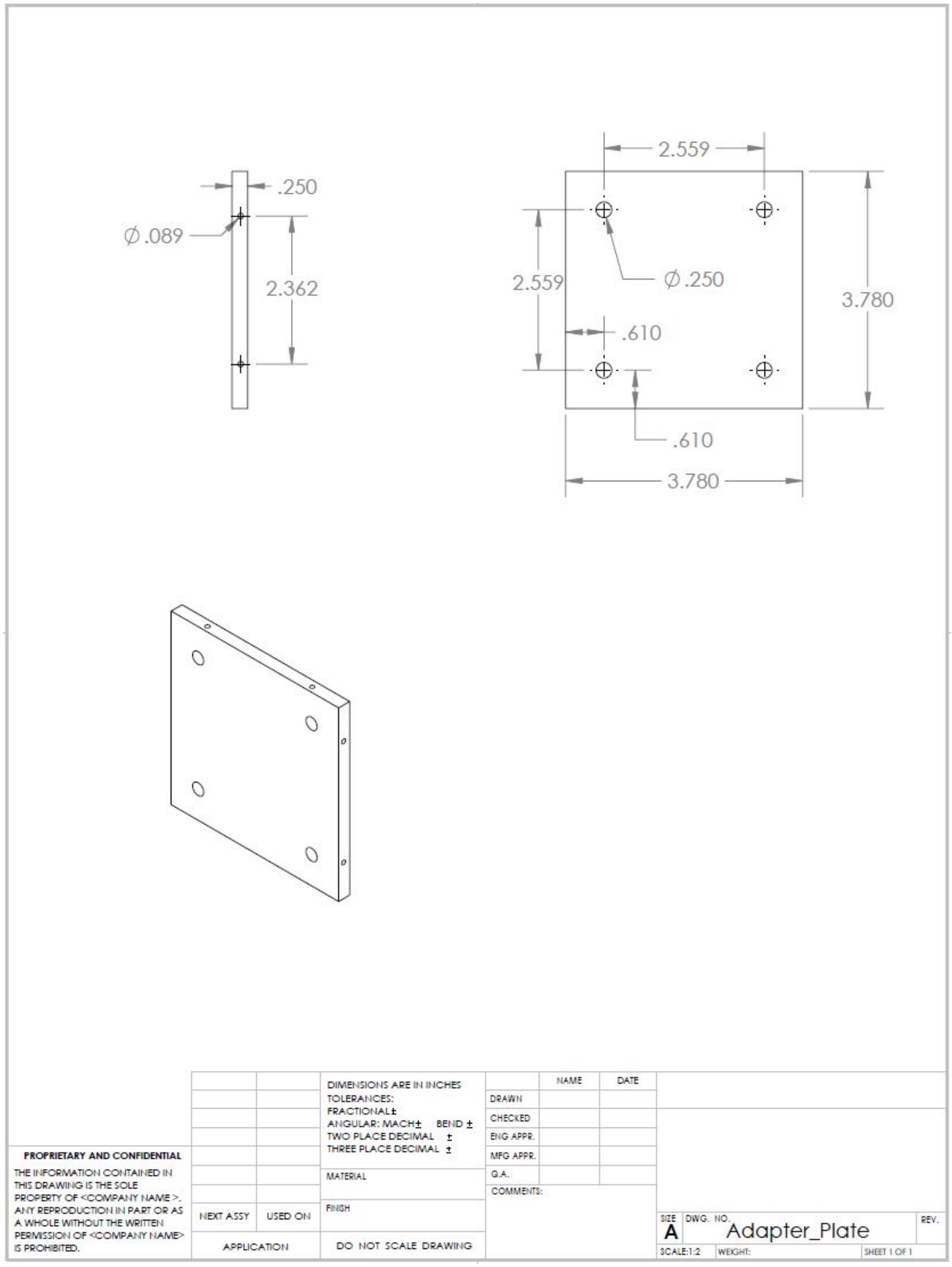

Figure 8. Mechanical drawing of the MURI shell adapter plate that will attach to the HASP plate.

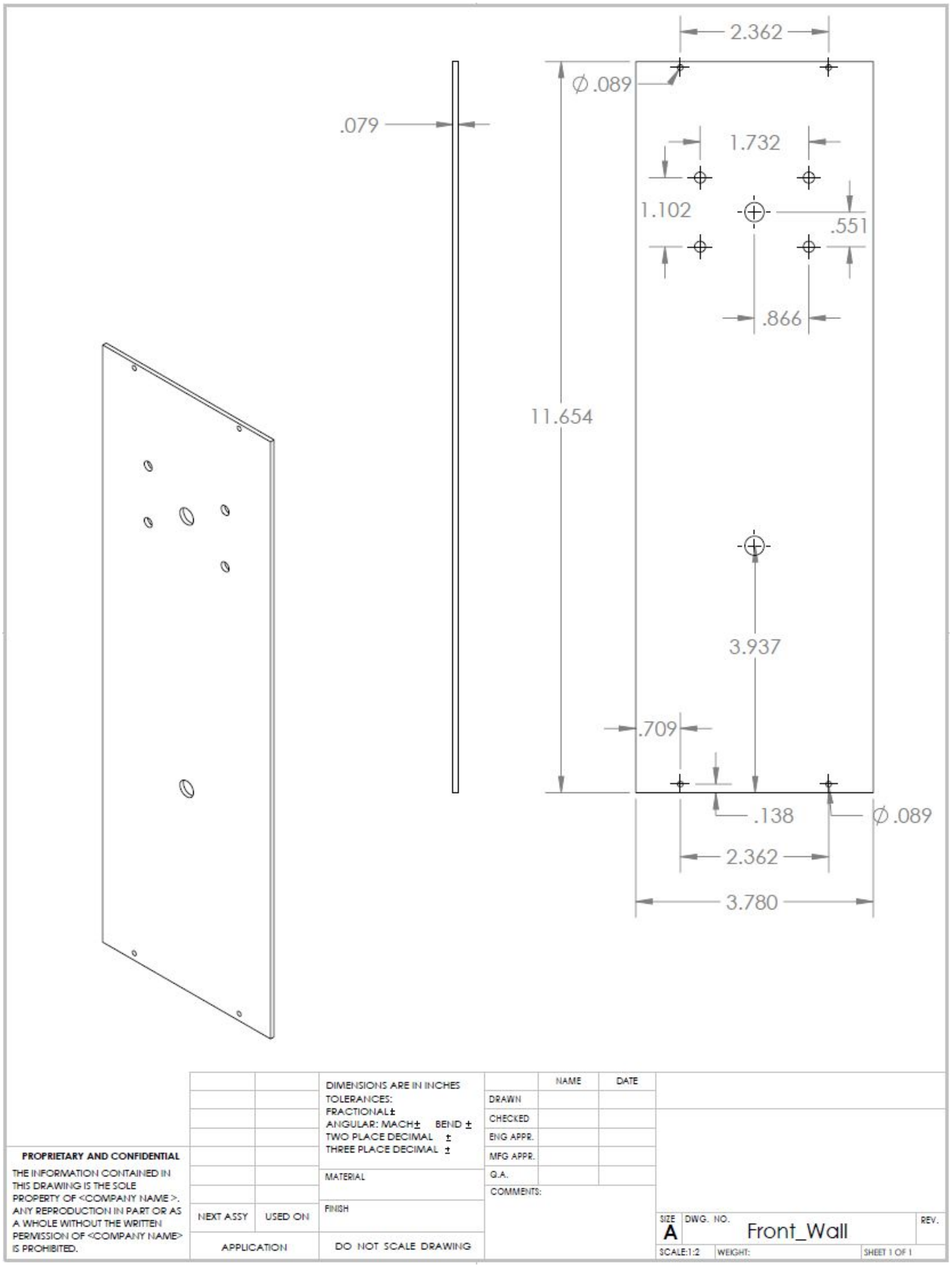

Figure 9. Mechanical drawing of the front wall of the MURI shell. The air intakes of all the optical particle counters will be flush with this wall.

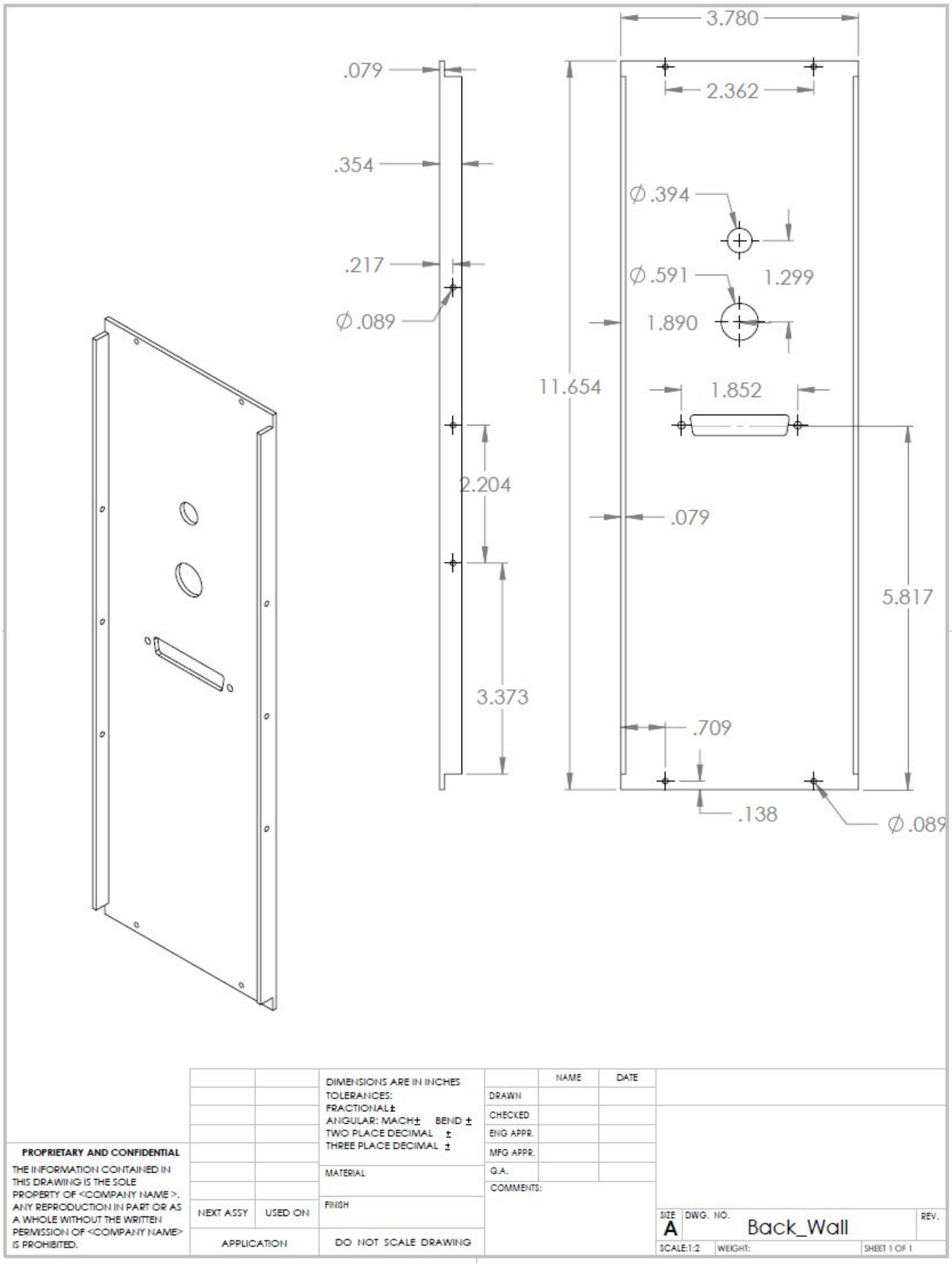

Figure 10. Mechanical drawing of the back wall of the MURI shell. The back wall has a hole for a DB-25 connector that provides power and serial communication from the HASP gondola as well as two exhaust holes for the particle counters.

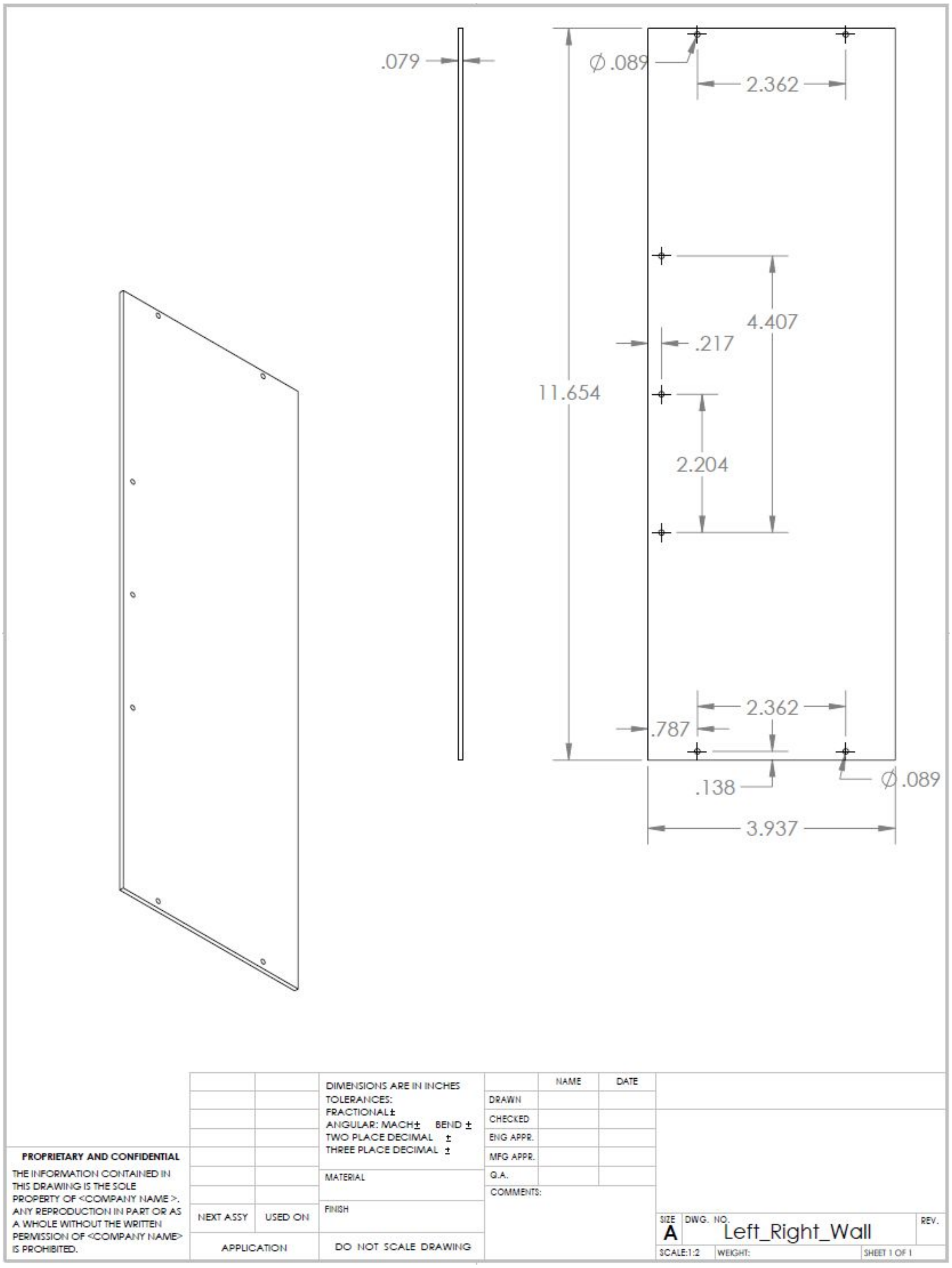

Figure 11. Mechanical drawing of left/right walls of the MURI shell.

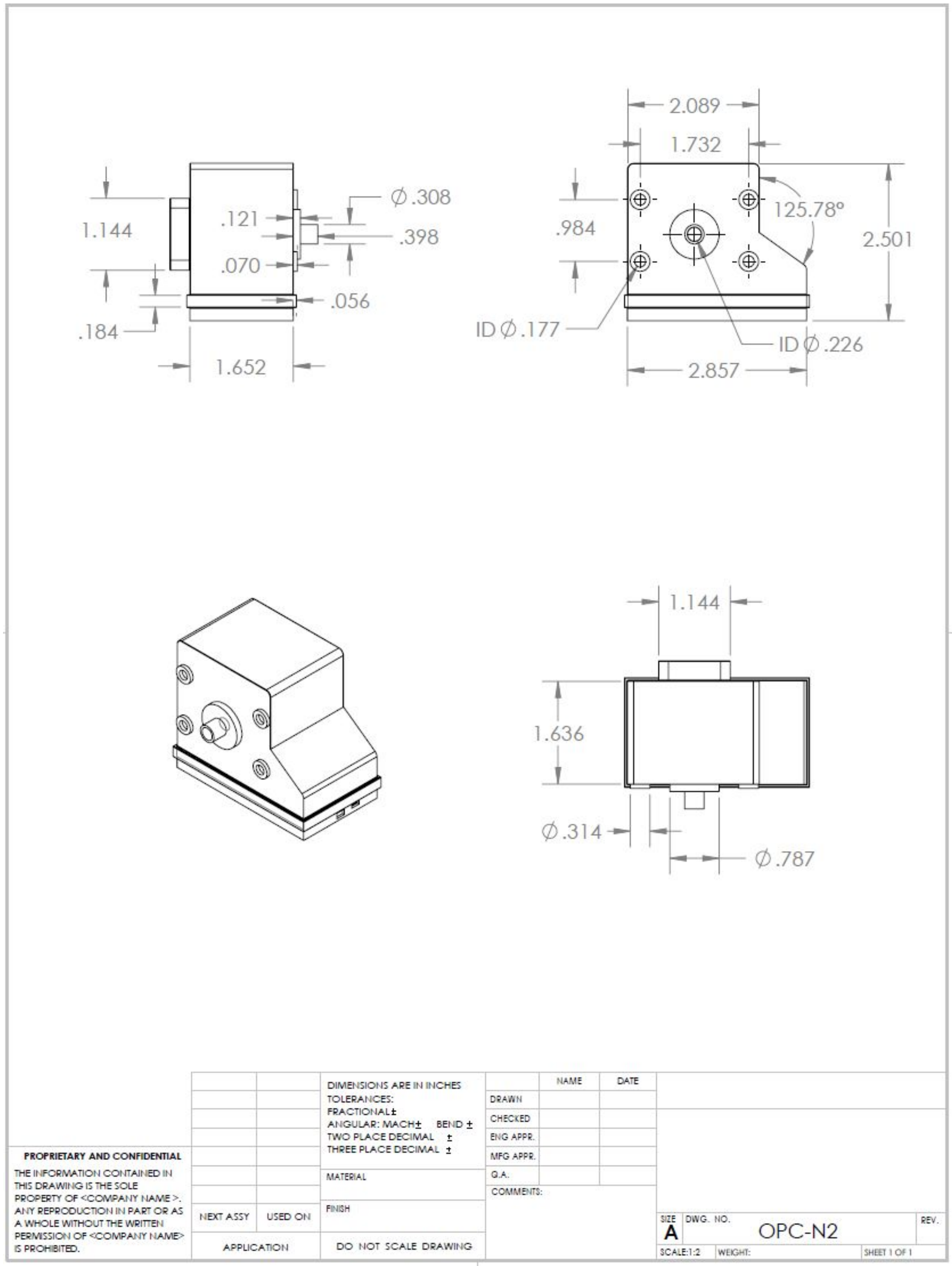

Figure 12. Mechanical drawing of the OPC-N2 (Alphasense optical particle detector). This detector was flown on the HASP 2018 mission.

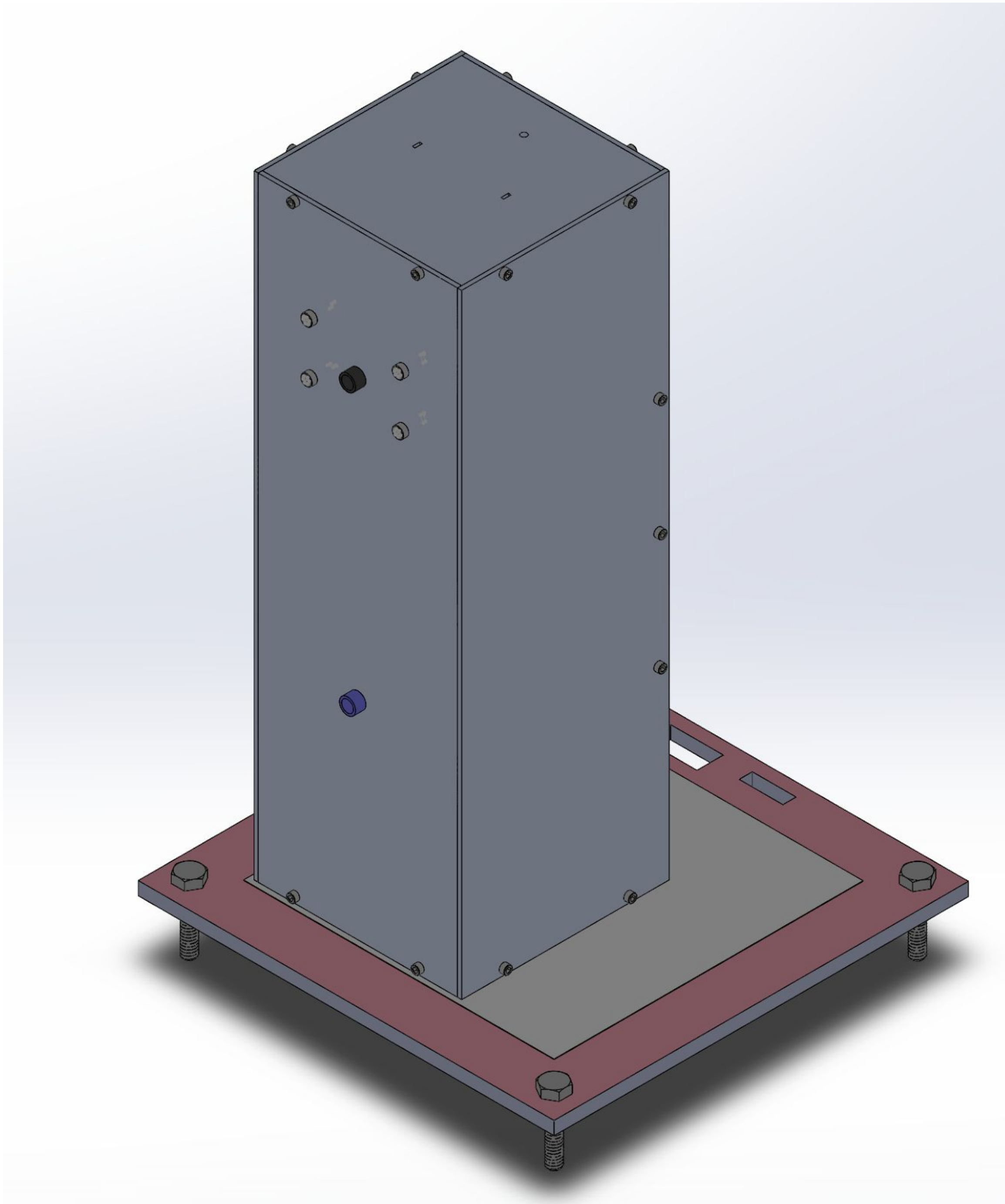

Figure 13.1: Isometric view of the MURI structure assembled on the HASP plate. The inlets of the Alphasense and LOAC devices can be seen protruding from the front wall.

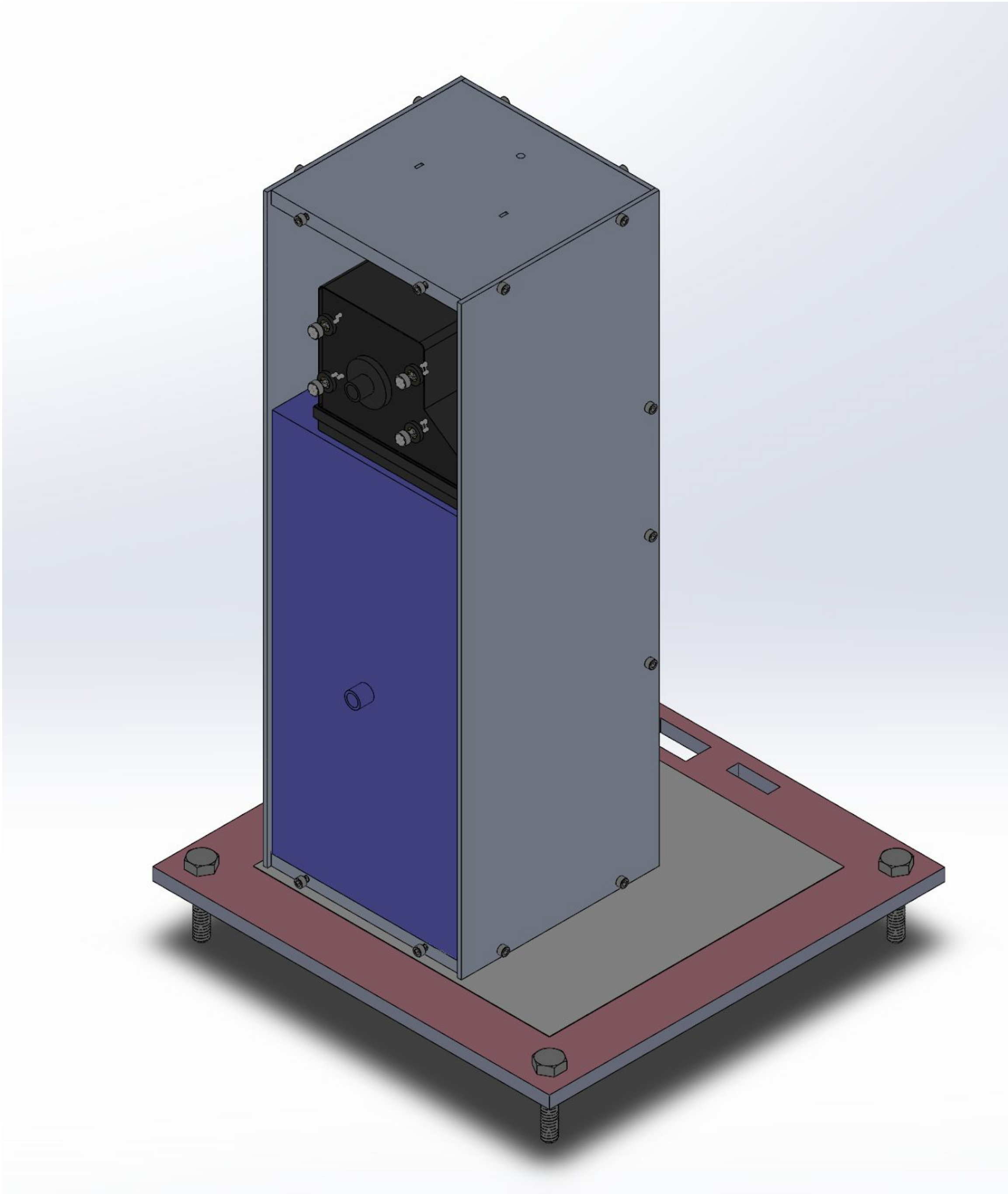

Figure 13.2: Isometric view of the MURI structure without the front wall. The OPC-N3 and the LOAC device can be seen inside.

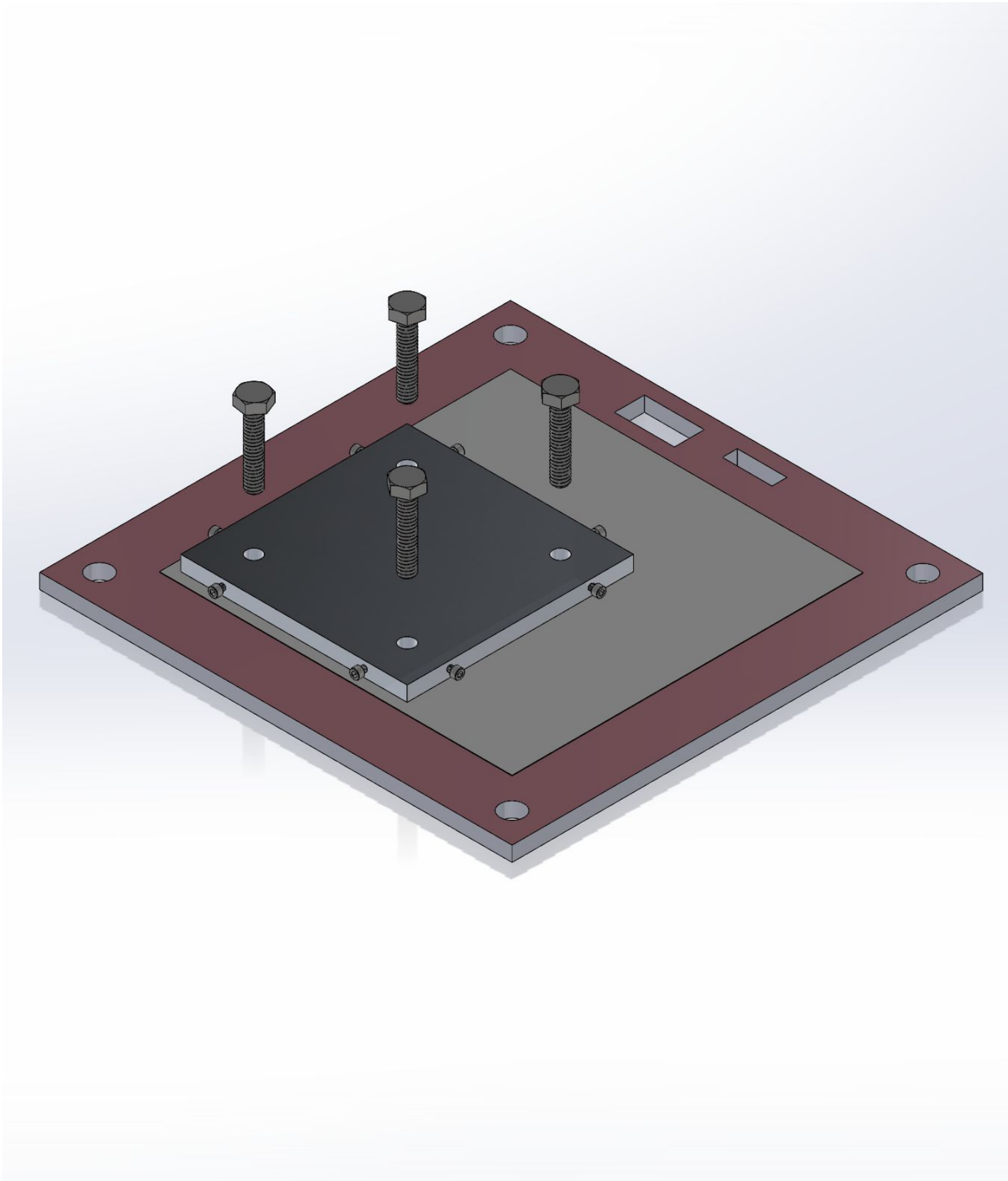

Figure 14: MURI adapter plate attaches to the HASP payload plate via 1.25" ATSM A307 $\frac{1}{4}$"-20 bolts.

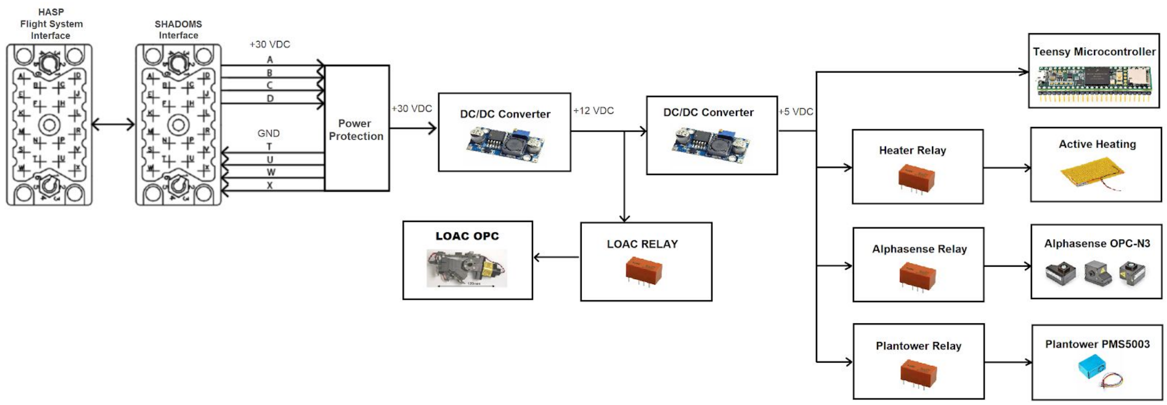

Figure 15.1: Schematic of HASP EDAC516 connector interface with the SHADOMS payload power system.

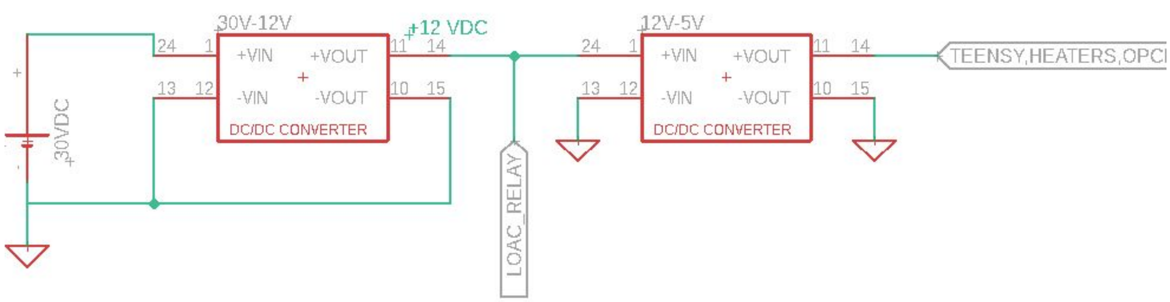

Figure 15.2 The basic power layout. The current limiter is not shown.

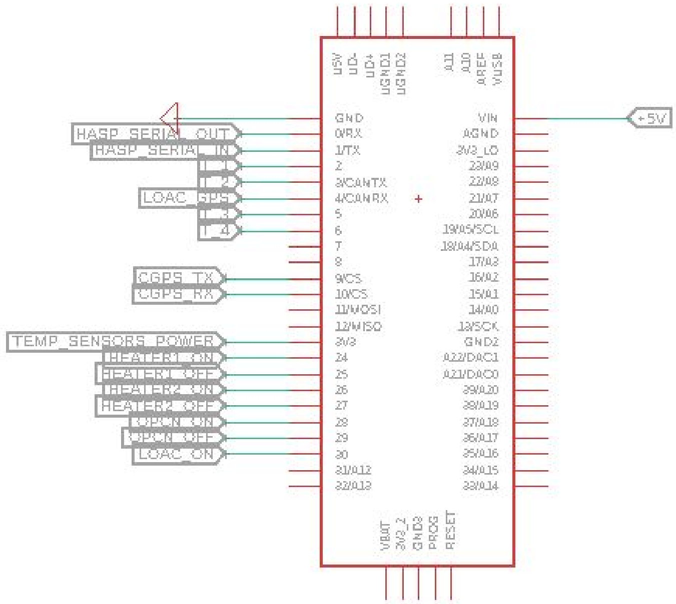

Figure 15.3. The connections to the Teensy 3.6 Microcontroller. Note that the 3.3 V pin provides power to the GPS and temperature sensors, as well as “On” and “Off” pins which can flip relays associated with various components (LOAC, OPC-N3, mesh heaters, etc.).

References

[1] Olsen, B., "Particle Calibration of Alphasense Model OPC-N2 Optical Particle Counters", Supplemental Report, Particle Calibration Laboratory, Department of Mechanical Engineering, University of Minnesota, 2018.

[2] Renard, J.B., "LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles- Part 2: First results from balloon and unmanned aerial vehicle flights", Atmospheric Measurement Techniques Discussions Papers, 2015.

[3] Kinh Tan, B., "Laboratory Evaluation of Low to Medium Cost Particle Sensors", University of Waterloo, Master's thesis, 2017.

[4] Renard, J.B., "LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles- Part 1: Principle of measurements and instrument evaluation", Atmospheric Measurement Techniques Discussions Papers, 2015.

[5] Leyva, Ivette A., "Introduction to challenges of hypersonic flight: The relentless pursuit of hypersonic flight", *Physics Today,* Nov. 2017.