HASP 2021 Final Flight and Science Report

Stratospheric Measurements of Charged and Neutral Radiation

McMaster University

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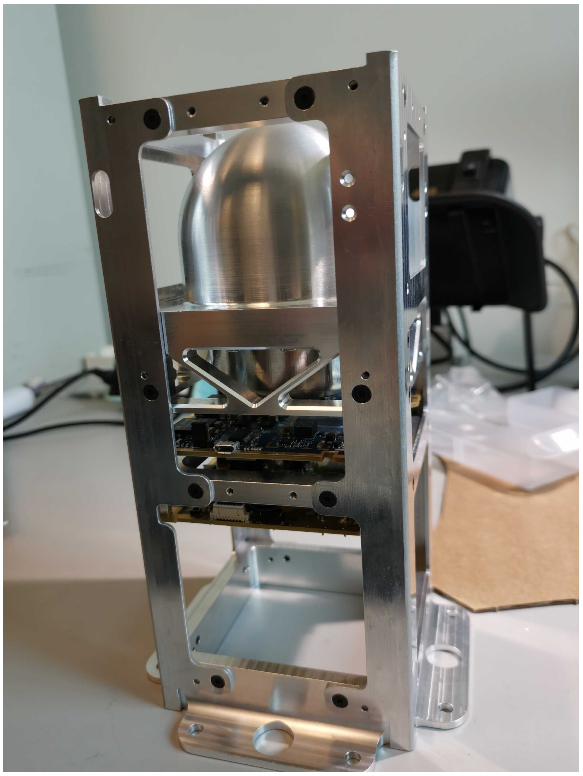


Overall Payload Assembly with the CNP-TEPC Instrument mounted into the rails and including the HASP mounting plate.

1. Introduction

1.1 Motivation

Human exploration to interplanetary destinations such as the Moon and Mars, and anticipated missions to further planets will become true in an expectable future. However, the current radiobiology study based on terrestrial accelerator sources cannot accurately assess the biological effectiveness and stochastic risk upon astronauts in hostile and complicated radiation environments during deep space missions [1-3]. For example, the estimated uncertainties of the projected cancer risk for a typical Mars mission are about 400 to 600% sourced from the uncertainties in radiation quality factors [2]. In order to better understand the potential radiation-induced health risk, *in situ* measurements of space radiation lineal energy spectra are needed. With the measured lineal energy spectra, the quality factor can be updated to provide more realistic estimation of the radiation dose in outer space.

The quality factors relate to absorbed dose and vary with the unrestricted Linear Energy Transfer (LET) in water as defined [4], but restricted LET is a more practical approach. The Tissue-Equivalent Proportional Counter (TEPC) is a microdosimetric instrument made by tissue-equivalent plastic and filled with tissue-equivalent propane gas and can provide accurate real-time absorbed dose measurement in human tissue. The lineal energy spectra measured by the TEPC with centimeter-sized sensitive volume can be used as a good approximation of restricted LET. TEPCs had been used for the Space Shuttle and International Space Station (ISS) program to monitor the radiation dose absorbed by astronauts since 2000 [5]. The first generation cylindrical TEPC was replaced by a laminated spherical type TEPC which overcomes up to 22% underestimation of dose due to non-isotropic response [6]. The laminated spherical type TEPC alone responds to all kinds of ionizing radiation which causes technical difficulties in separating the neutron component and charged particle from the total dose. The dose from neutrons is important to study as secondary neutrons generated by charged particles contribute a large portion of the total dose equivalent [7,8]. The direct detection and measurements of neutron energy spectra is problematic due to intense charged particles field [8]. The limits of individual dose measurement of charged particles and neutral particles constrains the steps toward interplanetary manned mission.

Space qualified radiation dosimeters, developed for Space Shuttle and International Space Station (ISS) missions have now exceeded their design life and do not satisfy the radiation monitoring requirements of long-duration missions into deep space [9-11]. More importantly, none of those instruments have been designed to actively monitor exposure to neutrons, which have a high relative biological effectiveness, can affect blood-forming marrow in bones, and may account for up to 20% of the total radiation dose received by astronauts on the ISS. To overcome these limitations, we have developed the Charged & Neutral Particle Tissue Equivalent Proportional Counter (CNP-TEPC): a radiation dosimeter capable of separating the dose from charged particles and neutrons in real-time.

The NEUtron DOSimetry & Exploration (NEUDOSE) CubeSat is a miniature satellite being developed at McMaster University which is planned to be launched into Low Earth Orbit (LEO) where it will make detailed measurements of microdosimetry at a near-Earth asteroids radiation environment. The primary scientific payload, the Charged & Neutral Particle Tissue Equivalent Proportional Counter (CNP-TEPC), is a novel radiation dosimeter containing a spherical TEPC detector surrounded by plastic scintillator – the Anti-Coincidence Detector (ACD). With the on-board electronic coincidence techniques, CNP-TEPC can separately map the interactions of charged particles and neutrons in real time and measure [12]. Due to negligible shielding of the cubesat, the lineal energy spectra measured by the CNP-TEPC reflects the situation experienced by astronauts during extra-vehicular activities [12].

The HASP 2017 and 2018 programs allowed for major achievements in mechanical, electrical, and software development. In HASP 2021, we aimed to further the progress of the previous mission and advance this radiation detection system greatly. The HASP 2021 goals include:

1. Demonstrate stable operation of all CNP-TEPC subsystems in a near-space environment
2. Validate the functionality of new revisions of the DAM and SiPM Module
3. Transmit CNP-TEPC spectral data using our previously developed and flown UHF/VHF communications module and verify with the HASP communication interface
4. Measure variations in dose and quality factors of charged and neutral radiation
5. Practice the full payload assembly procedure
6. Validate thermal range functionality in TVAC

1.2 Principle of Operation

The Charged and Neutral Particle Tissue Equivalent Proportional Counter (CNP-TEPC) is an advanced radiation monitoring instrument developed to measure, in real-time and for the first time, the microdosimetric spectra of charged particles and neutrons that could pose serious health threats to astronauts during future manned missions into deep space. The CNP-TEPC consists of two radiation detectors combined to enable the real-time separation of absorbed dose and quality factors from charged particles and neutrons.

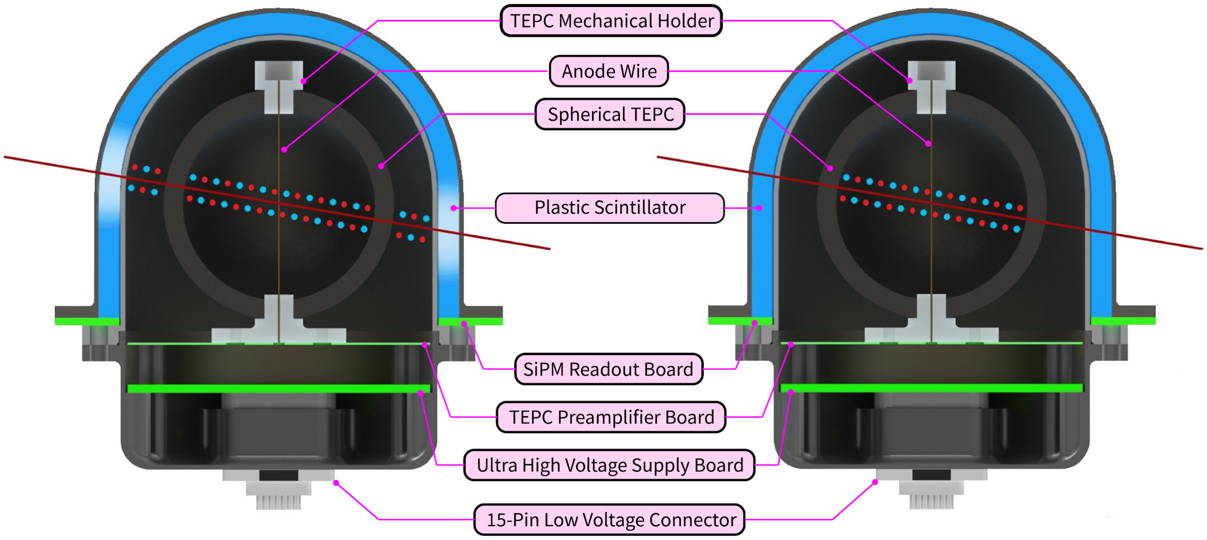


Figure 1: *The CNP-TEPC instrument separates the dose from charged particles and neutrons by monitoring the signal from a hemispherical plastic scintillator Anti-Coincidence Detector (ACD), which surrounds a spherical TEPC detector. When charged particles interact with the instrument, shown on the left, they simultaneously deposit energy in the ACD and spherical TEPC. However, neutron interactions, shown on the right, deposit energy in one or the other but typically not both.*

The inner radiation detector is the Tissue Equivalent Proportional Counter. This component is composed of a sphere made of A-150 tissue-equivalent plastic with a gold anode traversing through the centre held by two rexolite mounts. Since the TEPC is sensitive to all ionizing radiation, the measured lineal energy distribution often consists of a complex mixture of charged particle and neutral interactions which are difficult to separate. To separate the neutral component of lineal energy from that produced by charged particles, the CNP-TEPC instrument implements an Anti-Coincidence Detector (ACD) that surrounds the spherical TEPC and provides a trigger signal whenever charged particles traverse it. The ACD features a polyvinyl toluene scintillator which, when traversed by ionizing radiation, emits light at a wavelength of 425nm. This light is detected by the 32 silicon photomultipliers (SiPMs) arranged at its base. This technique is often adopted in spaceborne gamma- or x-ray instruments to eliminate the charged particle background and is based on the fact that all charged particles traversing the spherical TEPC detector must also traverse the ACD. On the other hand, neutrons and other neutral particles will deposit their energy in either the TEPC or the ACD, but typically not both.

2. Payload Description

2.1 CNP-TEPC Instrument Specifications

The CNP-TEPC instrument's overall mechanical and electrical designs remained the same from HASP 2018 however, nearly every component and PCB was re-designed or had a new revision. Additionally, the firmware has undergone significant development since 2018.

Electrical

For this year's flight on HASP, new revisions of all circuit boards were developed when compared to the electronics flown on the HASP 2018 mission. On HASP 2021, five different circuit boards were flown: two within the pressure vessel, one fastened underneath the anti-coincidence detector lid, one fastened to the payload housing, and one fastened to the mechanical rails used to support the payload on the HASP interface plate. Below, descriptions for each of the electronic boards can be found.

Data Acquisition Module

The Data Acquisition Module (DAM) is the heart of the scientific data acquisition system. It interfaces with each of the other circuit boards on the payload, acquires scientific data, processes timing events and anti-coincidence events for particle interactions, and acquires housekeeping data. All of this information is controlled by an onboard FPGA responsible for centralized programming and control of all of functions carried out by the CNP-TEPC instrument. Onboard this circuit board are several different power regulators responsible for converting the inputted power to different voltages for all scientific equipment interfacing with the DAM. This board is also responsible for communicating and transmitting the acquired scientific data via a passthrough RS232 connector to the Power Distribution Module. Figure 2 below shows the top and bottom views of the DAM flown on the HASP 2021 mission.

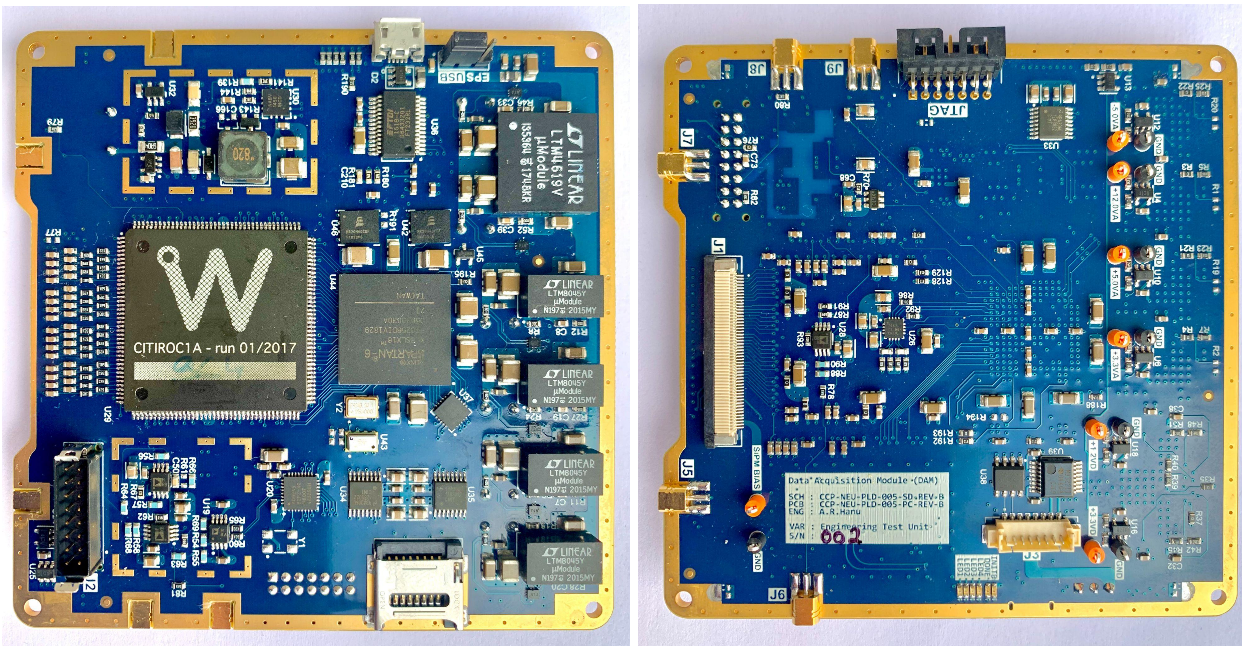


Figure 2: *Top and bottom Views of the Data Acquisition Module*

The Data Acquisition Module is mounted at the bottom of the CNP-TEPC housing, which can be seen in the mechanical summary in Figure 7 below.

Power Distribution Module

The Power Distribution Module (PDM) is a new board specifically made for the HASP 2021 mission. This board was used to create the necessary power supplied to the DAM, as well as interface with the HASP interface plate. The board received the 30V supplied from the HASP gondola and converted to +5V for the DAM, which then further distributed power to the rest of the CNP-TEPC scientific instrument. The PDM was also responsible for transferring the scientific data from the DAM to the HASP gondola. The PDM took the RS232 transmission from the DAM through a single connector where both power and communication passed through, and passed it through to the HASP interface plate.

This board has several other logging provisions, including peripherals for tracking housekeeping data, provisions for measuring solar panel power production, as well as humidity, pressure and temperature sensing. The top and bottom of the PDM can be found in Figure 3 below.

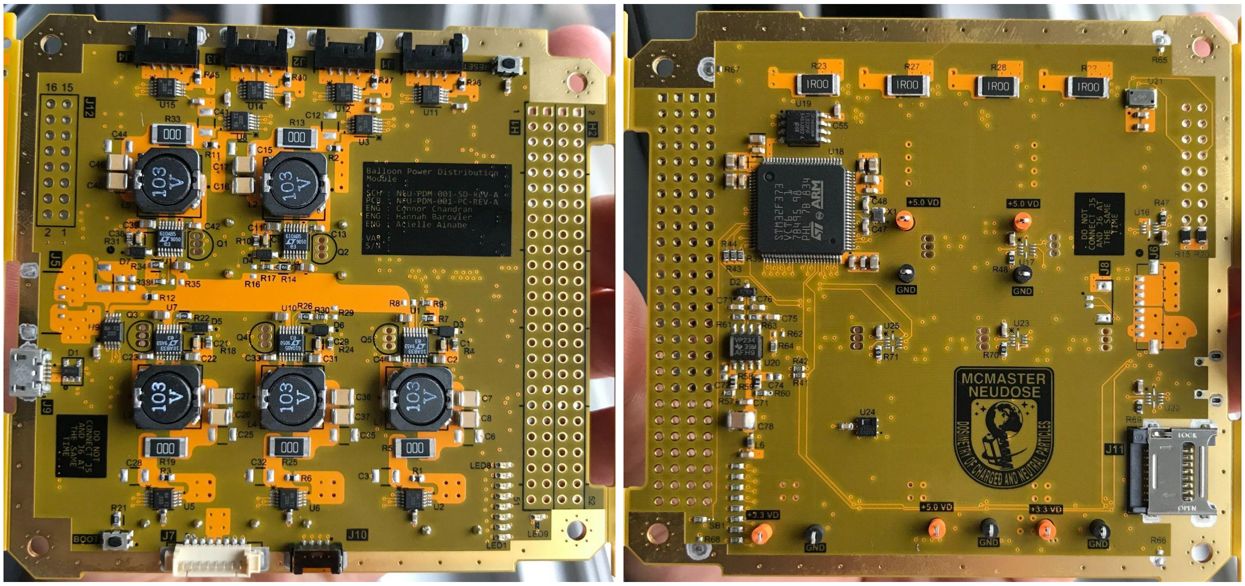


Figure 3: *Top and bottom Views of the Power Distribution Module*

The Power Distribution Module is fastened to the mid z tray connected to the rails supporting the CNP-TEPC instrument.

Preamplifier Module and High Voltage Module

The next two electronic circuit boards flown on HASP 2021 were the Preamplifier Module and the High Voltage Module. These two circuit boards are located within the pressure vessel, and are secluded from the rest of the circuit boards on the CNP-TEPC instrument. The Preamplifier Module is responsible for acquiring the deposited charge in the anode wire running through the centre of the TEPC, running it through an amplification and filtering circuit before being transmitted to the DAM. The High Voltage Module is responsible for creating the high potential difference needed to produce the electric field within the TEPC. As well, the High Voltage Module has a barometric sensor to read the pressure of the tissue equivalent gas within the pressure vessel, used for housekeeping. Images of the Preamplifier Module and High Voltage Module can be found below in Figure 4 and 5, respectively.

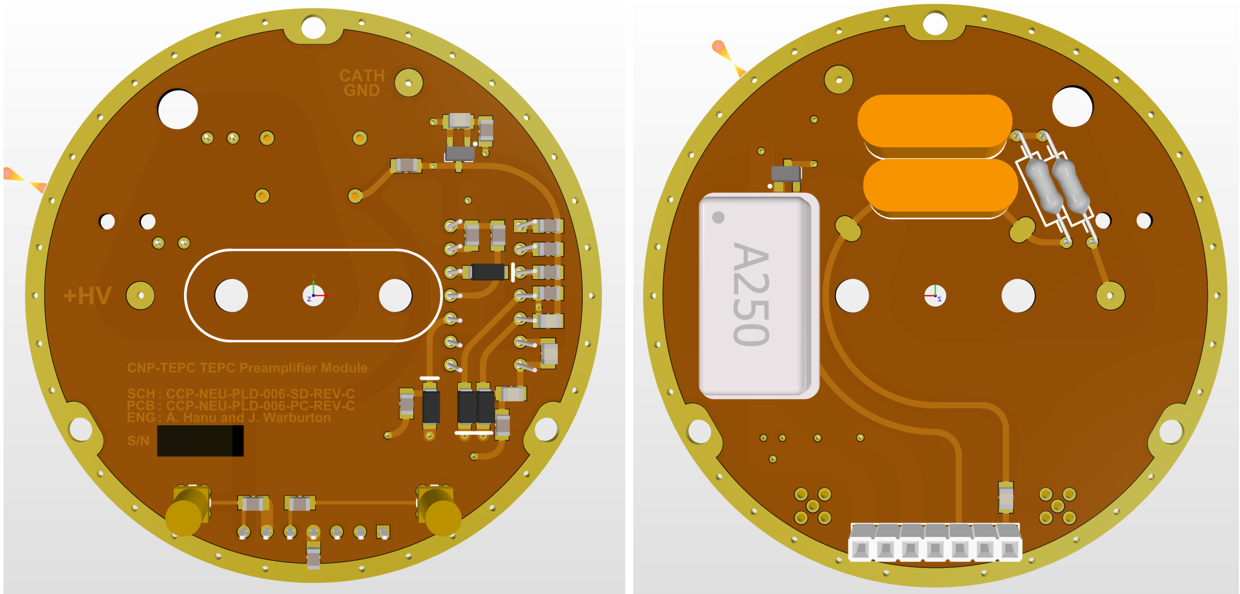


Figure 4: *Top and bottom Views of the Preamplifier Module*

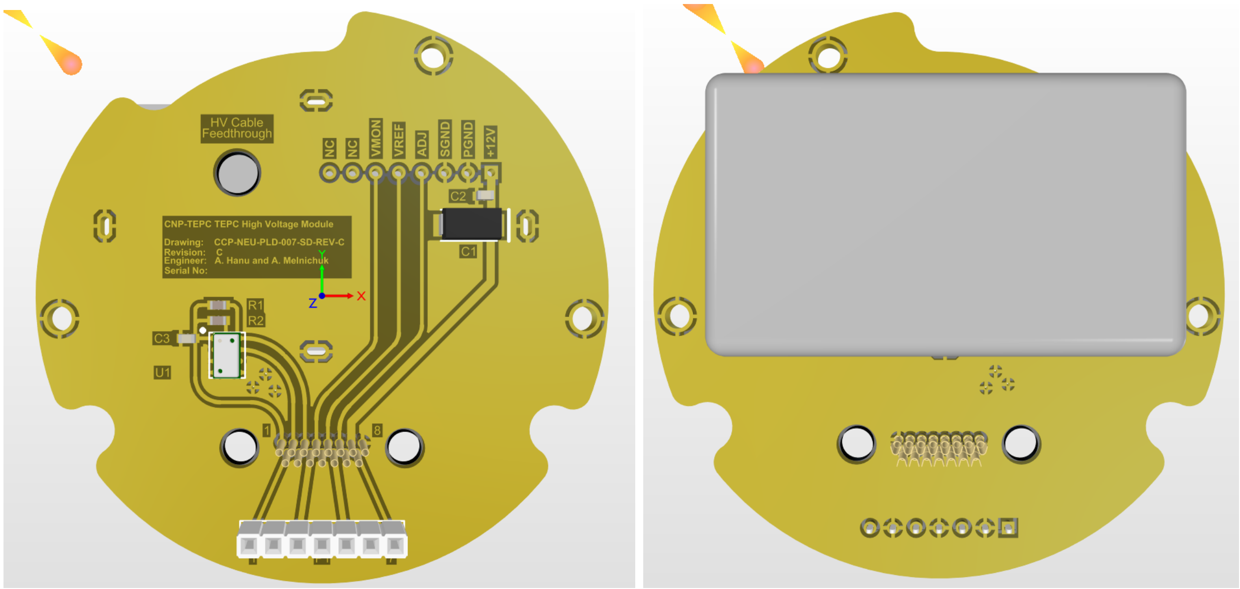


Figure 5: *Top and bottom Views of the High Voltage Module*

Silicon Photomultiplier Module

The Silicon Photomultiplier Module (SiPM Module) is located between the anti-coincidence detector lid and the pressure vessel lid. This circuit board houses 32 silicon photomultipliers used to detect specific wavelengths of ultraviolet and visible light produced from the scintillator. The scintillator emits a violet light with each charged particle interaction which in turn can be read out by the silicon photomultipliers. The SiPM Module is used to house these photomultipliers as well as supply them with the required bias voltage. An image of the SiPM Module can be found below in Figure 6.

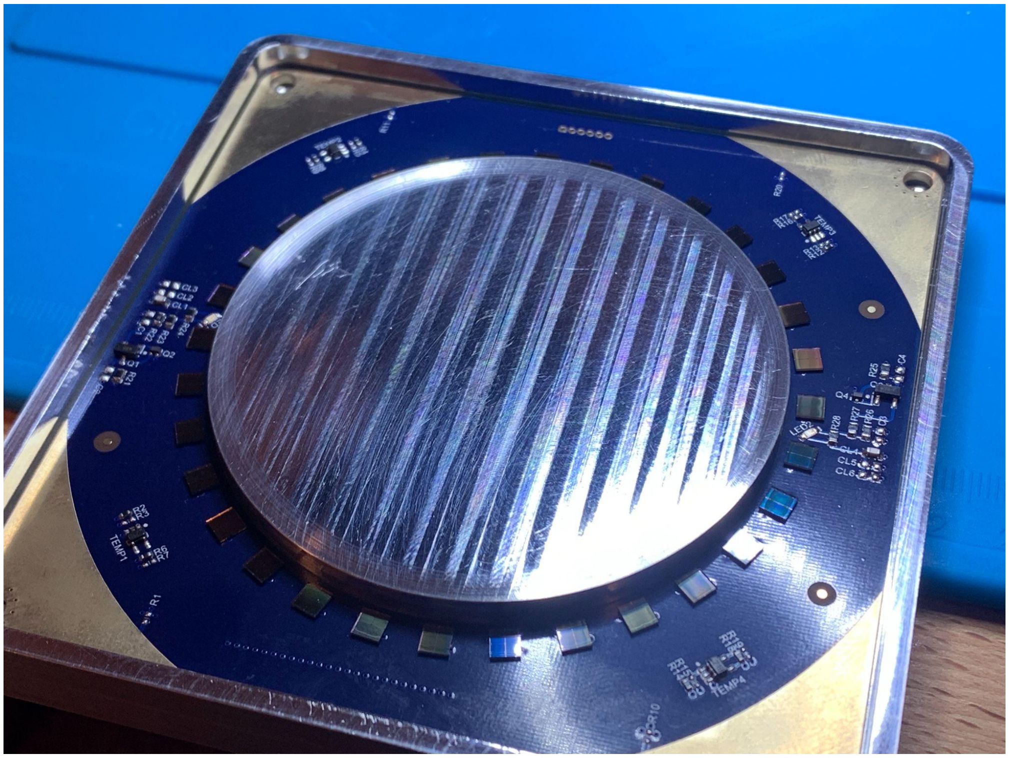


Figure 6: *View of the Silicon Photomultiplier Module*

Mechanical

The mechanical structure has gone through some major revisions since our flight in 2018. The mechanical layout consists of 2 main assemblies: the CNP-TEPC instrument and the mounting structure that houses the CNP-TEPC and the Power Distribution Module (PDM) systems. Figure 7 below illustrates the location of the CNP-TEPC within the main structure and the main mechanical elements that make up the structural design.

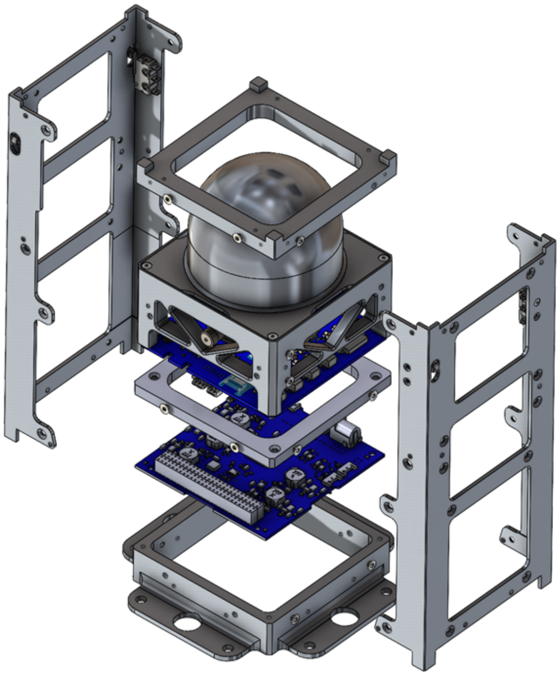


Figure 7: *Components of the payload shown in exploded view.*

The new revision of the instrument housing featured a thicker structure with greater cutouts in the design. This has allowed for an increase strength while maintaining a low mass. The new instrument housing is shown in Figure 8.

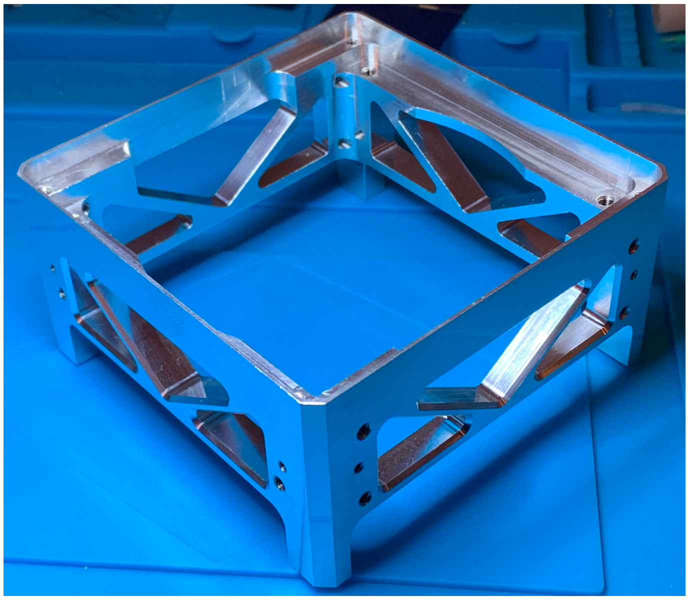
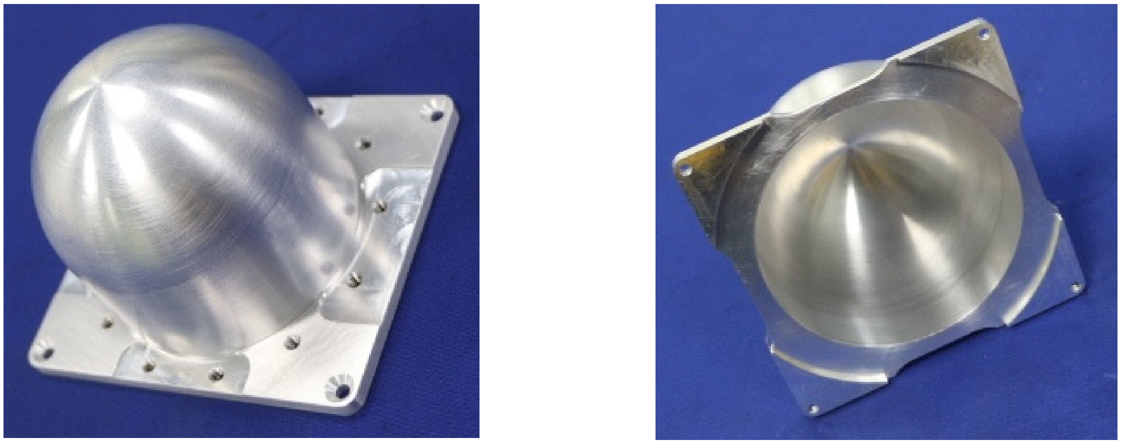


Figure 8: *The fabricated redesign of the payload housing featuring a thicker structure and more cutouts.*

In the detector vessel, modifications were done to the detector vessel lid and the anti-coincidence detector lid. Previously, the anticoincidence detector was clamped over the scintillator, which sat over the detector vessel lid. This had the potential to trap air around the scintillator. Therefore, channels were cut into the bottom of the ACD lid and the top of the detector vessel lid to alleviate the pressure. Figure 9 shows the new cutouts in the pressure vessel and anti-coincidence detector lids.



a) ***b)***

Figure 9: *The fabricated redesign of the a) detector vessel lid, and b) anti-coincidence detector lid.*

Firmware

The firmware underwent a complete redesign driven by the need to implement increasingly complex functionality in the memory available on the Spartan-6 FPGA. A bare-metal, non-preemptive, dynamic priority scheduling operating system served as the base of the system. This approach was chosen since it was simple to implement and allowed students to write functionally optimized code without worrying about its execution being interrupted by the operating system.

Drivers and high-level controllers were built on top of the operating system to communicate with onboard peripherals for data collection and send housekeeping and science packets down to the ground. One of the main challenges in this area was conforming to the HASP commanding specification, which was limited to two bytes per command. This limit conflicted with the design choice of allowing changes to our 32bit scientific instrument parameters during operation. By implementing a command buffering system on the payload, this limit was overcome. This system buffers four 2-byte commands and, once received, interprets all four of them as a single 8-byte command.

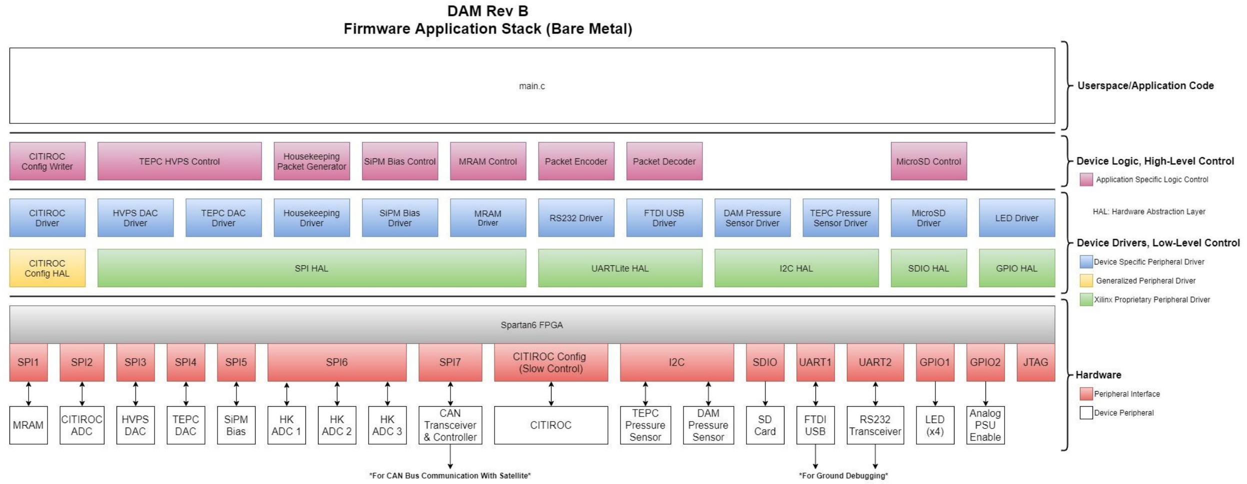


Figure 10: *The firmware architecture implemented for HASP 2021. All components above Xilinx HALs were implemented by the firmware team in the months of January to April 2021.*

One of the largest problems encountered during HASP 2018 was the inability to fully seal the instrument's pressure vessel. Keeping the propane-based tissue-equivalent gas sealed within the pressure vessel is critical to properly detect charged and neutral radiation. The mechanical design of electrical feed-through connectors was improved, and the procedure of welding was kept in mind when placing these features. This design exercise led to the reduction of needed feedthroughs from two to one, which was accomplished by moving the ultra-high voltage (UHV) module inside the pressure vessel. For HASP 2021, the pressure vessel was successfully sealed and pumped down to near-vacuum for the July integration and flight.

With the movement of the UHV module into the pressure vessel, the TEPC and ACD data acquisition system boards could be consolidated into a single PCB. A new revision was designed and fabricated which featured the existing flight-tested hardware, including the Spartan-6 FPGA and CITIROC ASIC. Extensive hardware testing was completed with the SiPMs and CITIROC to achieve successful output triggers on radiation events. The instrument's individual power distribution module had another revision with an increased focus on reducing ripple on voltage supplies. Analog supply rail noise was improved by combining buck switching converters and LDOs.

3. Payload Performance

3.1 Overall Payload Performance

During Integration at the CSBF, the payload experienced two cycles of TVAC: one cycle as received with black solar panel PCBs mounted on the outside of the satellite, and one cycle with white duct tape enveloping the satellite. This was done to observe the effect of the exterior colour on the internal temperature of the boards. Figure 11 shows the TVAC profile detected by the temperature sensor on the Data Acquisition Module with the black exterior and Figure 12 shows the TVAC profile with the white exterior.

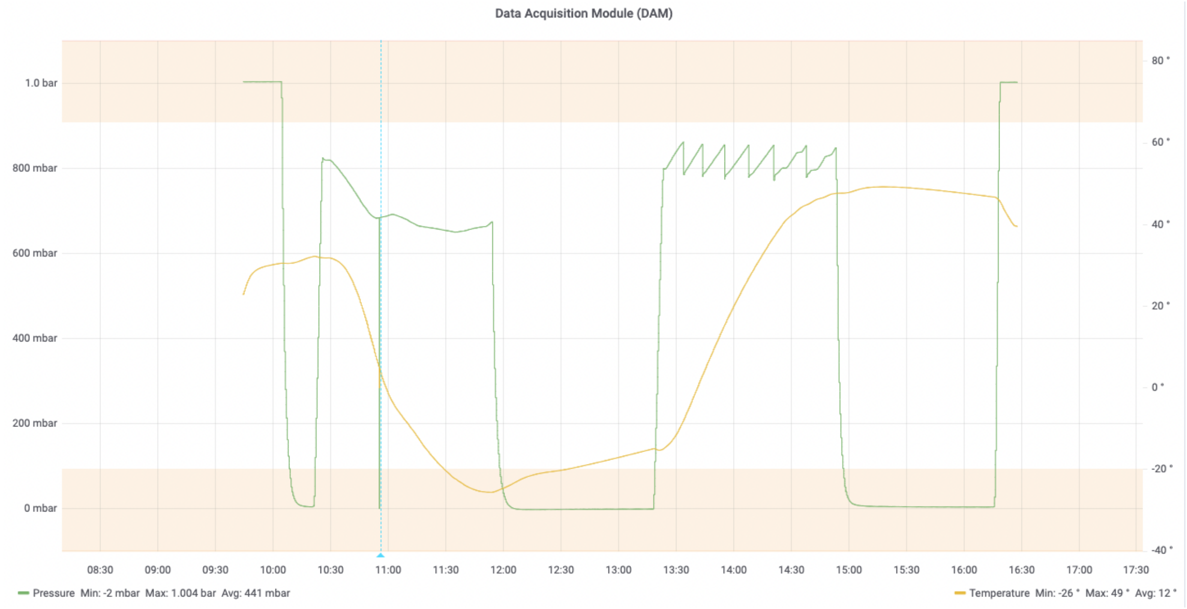


Figure 11: *Payload 01 temperature and pressure measurements from the Data Acquisition Module during TVAC Run 1 on 07/28/2021. The exterior material was black solar panel PCBs.*

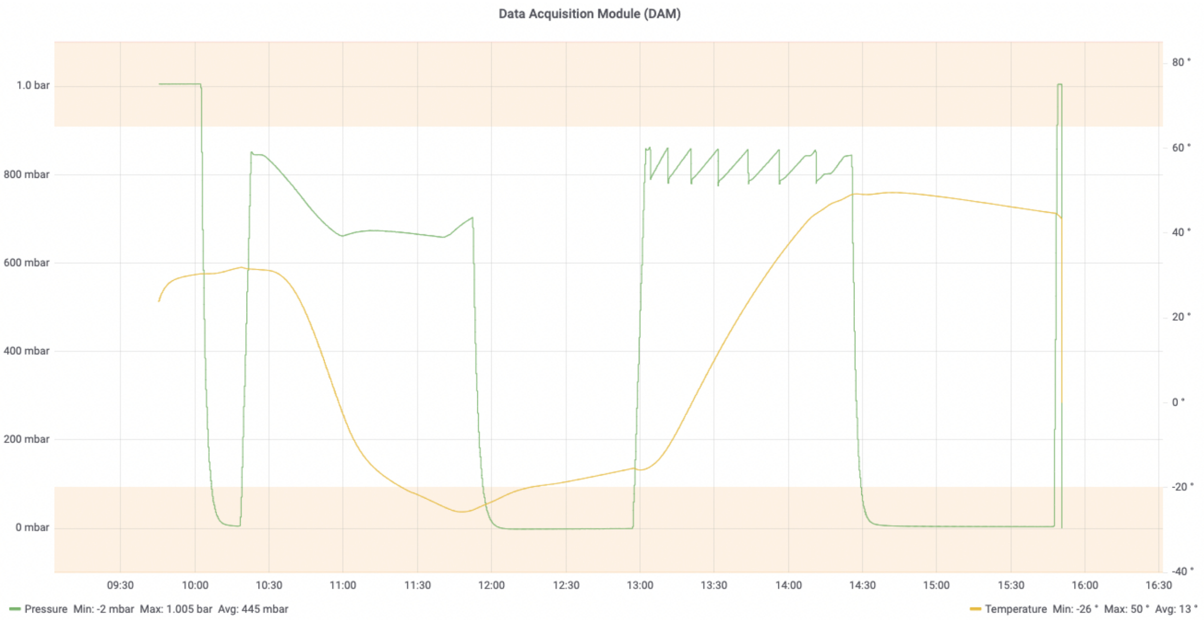


Figure 12: *Payload 01 temperature and pressure measurements from the Data Acquisition Module during TVAC Run 2 on 07/30/2021. The exterior material was white duct tape.*

The temperature ranges measured by the Data Acquisition Module for TVAC1 and TVAC2 were -25 - 49℃ and -26 - 49℃, respectively. This indicates that the exterior colour of the satellite did not have a significant effect on the temperature of the internal boards. All internal components of the satellite survived and were functional after each TVAC.

The mechanical structure of the payload performed excellently throughout the flight and suffered little to no damage from the descent. The TEPC and SiPM boards were still intact and showed no mechanical issues when examined following flight. However, the DAM and PDM proved to be problematic. Upon reviewing the voltage and current data on our dashboard and provided from the HASP gondola, there was a spike in current at 1:15.13pm, which resulted in a complete shut off of the payload.

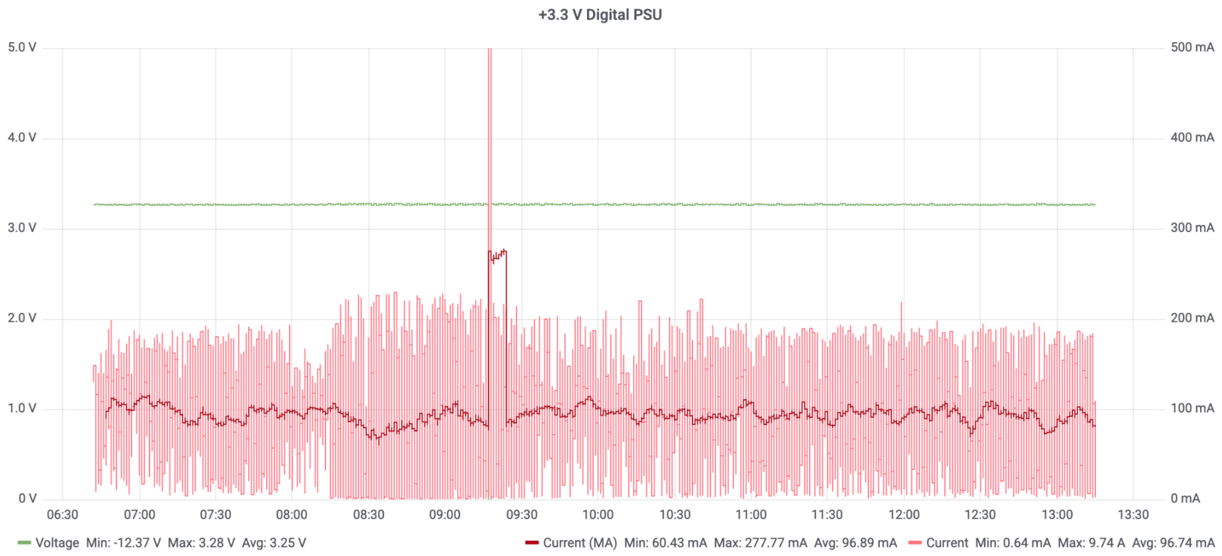


Figure 13: *Payload 01 voltage and current measurements acquired from the Data Acquisition Module during HASP flight.*

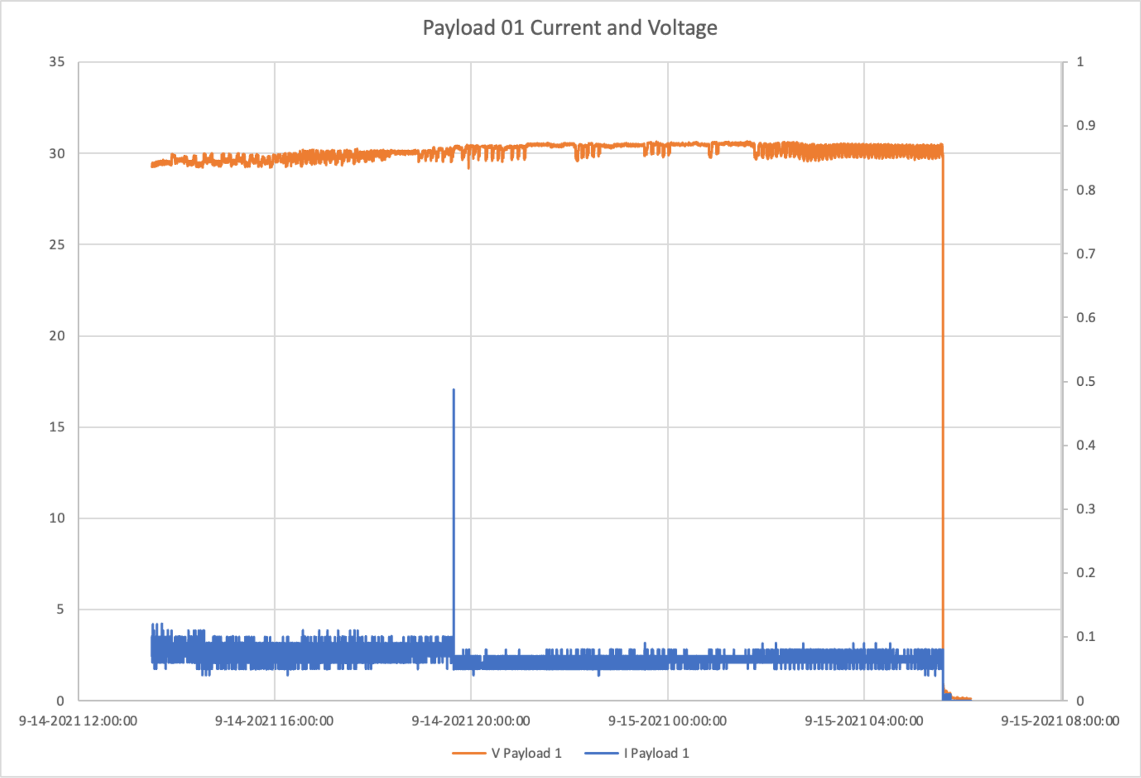


Figure 14: *Payload 01 voltage and current measurements acquired from the HASP telemetry during flight.*

The payload drew an average of 3.3W during nominal operation and a spike in current occurred at 1:15.13pm, resulting in a loss of communication and power shutoff. In Figure 13, the spike is visualized nominally around 9:15 am, as the data was displayed in the local timezone. A corresponding spike was identified in the HASP telemetry, as shown in Figure 14. This was unexpected as there was no indication of component failure during the TVAC tests, and further investigation will be conducted to verify the critical temperature ranges of the components.

3.2 CNP-TEPC Instrument Performance

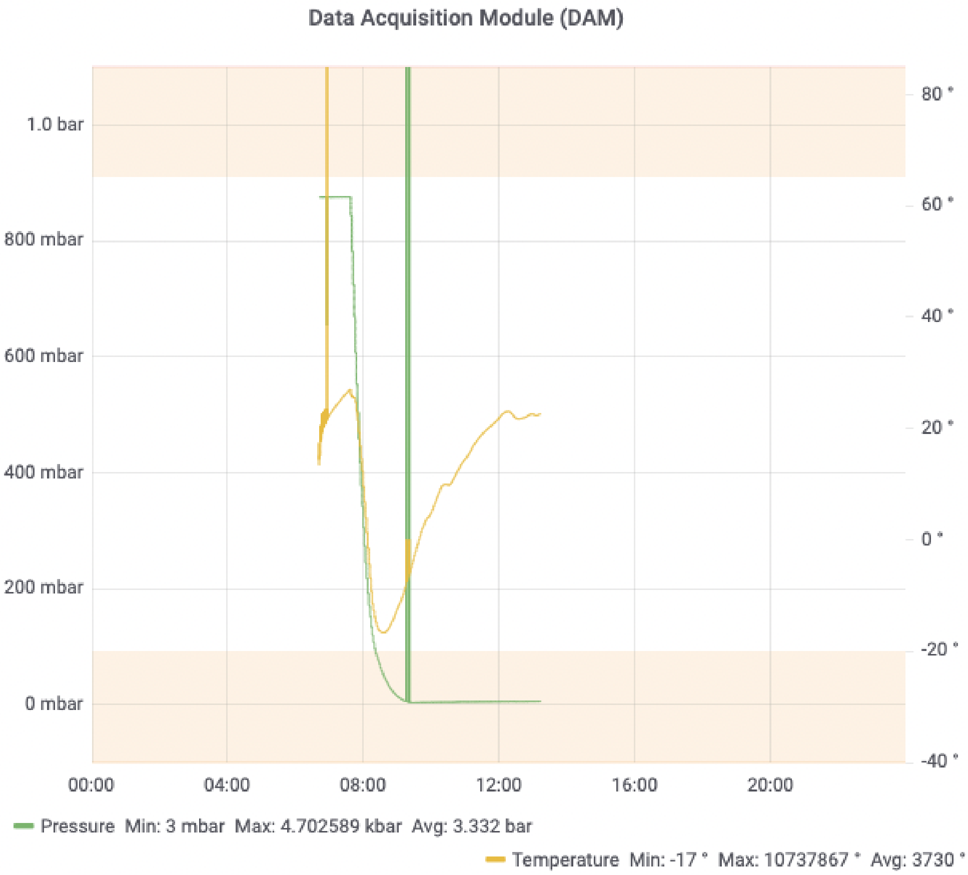


Figure 15: *Payload 01 temperature and pressure measurements acquired from the Data Acquisition Module during flight.*

Temperature telemetry from the CNP-TEPC instrument was transmitted via HASP's RS232 interface and can be seen in Figure 15. The temperature and pressure readings follow the measurements from the gondola, shown in Figure 16, until the sudden failure at 1:15.13pm. However, comparing the temperature readings, the temperature measured by the gondola reached approximately -60℃, where the Data Acquisiton Module only measured approximately -16℃. This temperature drop is expected to be the cause of the board failure. During TVAC, the temperature only cycled to -30℃ which is within the survivable temperature range of all payload components. It is expected that during the increase in temperature following the drop resulted in the formation of condensation on the Data Acquisition Module, which caused the power supply to short and shut off the payload for the remainder of the mission.

The Data Acquisition Module exhibits a spike in pressure upon reaching FLOAT, which may have resulted from the sensor reaching its lower pressure limit.

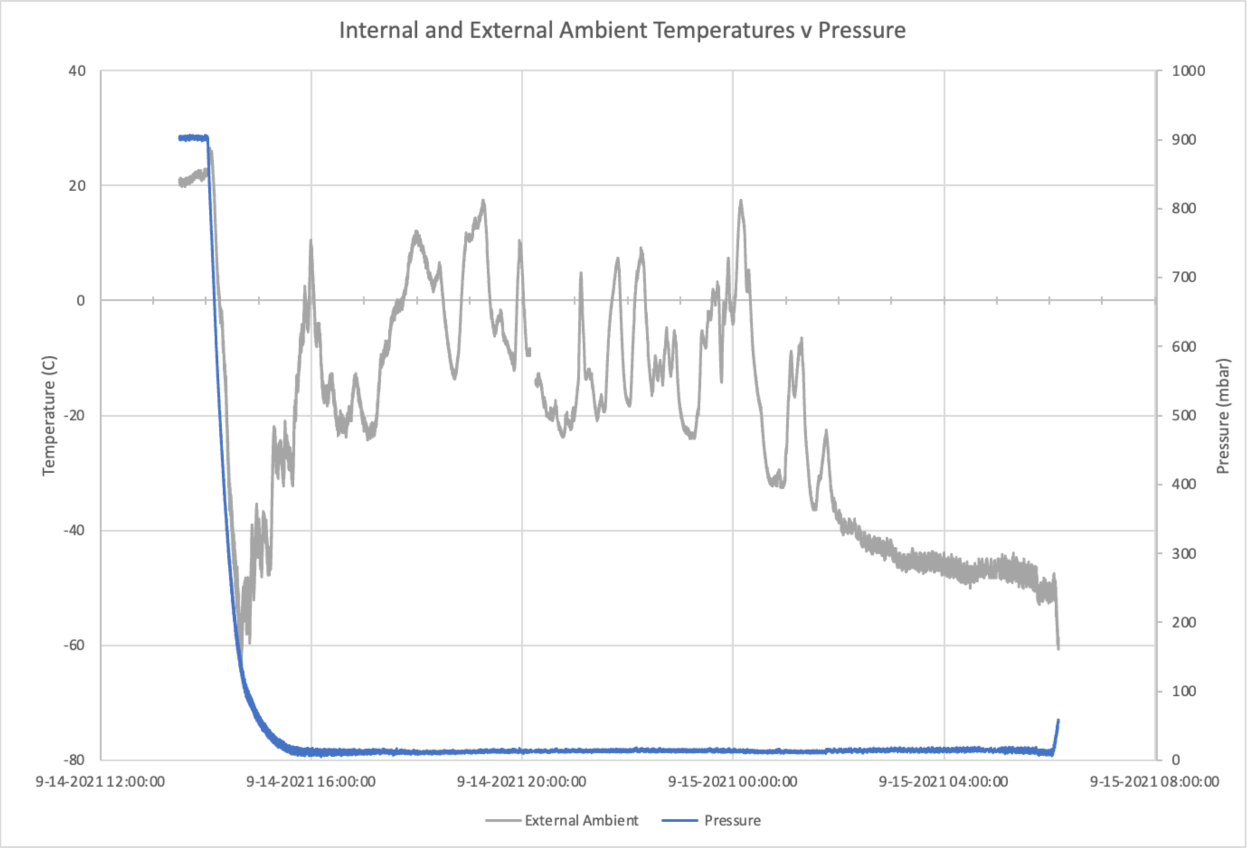


Figure 16: *Payload 01 temperature and pressure measurements acquired from the HASP telemetry during flight..*

4. Science/Technical Results

Unfortunately, due to COVID-19 travel restrictions and miscommunication with shipping the payload back to McMaster after integration, no proper science data was collected. The last-minute loss of approval resulted in a rushed assembly to ensure that the Payload arrived at the CSBF in time for the first integration and TVAC sessions. The payload was planned to return to McMaster after integration but due to a misunderstanding, the payload was shipped directly to Fort Sumner. By the flight date, based on our expected leak rate of the pressure vessel, there should have been no tissue-equivalent gas left in the detector. Although there was no relevant science data, the HASP 2021 campaign provided the opportunity to test the new revisions of the Power Distribution Module and Data Acquisition Module, as well as collect valuable health and housekeeping data. As shown in Figure 10 and 11, the system successfully was integrated and the Data Acquisition Module was able to accurately measure the temperature and pressure cycles. Additionally, this housekeeping data was displayed on the team's dashboard in real-time, allowing validation of the Mission Operations and Control display.

At 1:15.13pm, the current spike shown in Figure 12 resulted in a loss of power on the Data Acquisition Module, therefore stopping all data transmission from the board. Upon investigation when the instrument returned, it was concluded that condensation on the board caused the power supply to short. The boards did not have conformal coating so they were not protected against condensation.

This emphasizes the importance of conformal coating during the future and development of our boards. The engineering models of all PCBs on board the satellite will be conformally coated before any environmental testing.

5. Lessons Learned

HASP 2021 provided the team with a multitude of lessons ranging from engineering, testing and validation, to team organization and management. With the added difficulties of trying to streamline development during the pandemic as well as a complete team turnover since the previous flight in HASP 2018, some mistakes reinforced the need for proper mission planning. Listed below are some of the most notable lessons learned:

1. Plan for earlier integration and testing. Due to the pandemic, only two students were allowed in the lab, which is shared with graduate students, at a time so booking sessions to test the instrument were more difficult than expected. Additionally, only a select group of students were able to receive lab access and training due to additional restrictions pertaining to gaining lab access.
2. Plan better for the absence of graduating students. As this project spans the graduation period, several students were lost from the project. In the future, more students should be recruited and the transfer of knowledge should be emphasized.

3. Plan for more iterations of assembly procedures. Due to the limited personnel allowed in the lab, students who had not worked on the mechanical components were tasked with the assembly of the instrument. During this process, it was learned that the assembly procedures needed more clarity and detail.

6. Conclusion/Future Work

The HASP 2021 mission was an incredible experience to showcase and test the CNP-TEPC scientific instrument in space-like conditions. As McMaster's mission has progressed into through Assembly, Integration, and Testing phase, the HASP mission has pushed the development timeline and provided critical information about the system. Although challenges were faced during the flight campaign and in-person attendance was cancelled due to travel restrictions, the instrument was validated during the two TVAC runs, proving successful integration of the system.

The team is now continuing to push the development to the qualification and flight models, for a projected launch date of December 2022. In partnership with the Canadian Space Agency participating in the Canadian CubeSat Project, the payload will be integrated with the rest of the subsystems and launched from the International Space Station to orbit the Earth for one year. Following this mission, the team hopes to continue development of the instrument for further space applications and promote space innovation within and beyond the McMaster community.

7. Student Involvement

The following students took part in the design and development of the McMaster University Payload for HASP 2021.

Name	Start Date (MM/DD/YY)	End Date	Role	Student Status	Race	Ethnicity	Gender	Disabled
Amy Ling	10/01/18	Present	Student Lead	Undergrad	Asian	Non-Hispanic	Female	No
Gabriel Teichman	05/01/20	Present	Mechanical Lead	Graduated	Caucasian/Asian	Non-Hispanic	Male	No
Connor Chandran	05/23/20	Present	Electrical Lead	Undergrad	Caucasian/Asian	Non-Hispanic	Male	No
Graham Power	01/06/20	Present	Firmware Lead	Undergrad	White	Non-Hispanic	Male	No
Xingzhi Cheng	01/06/19	Present	Instrument Scientist Firmware Engineer	Graduate	Asian	Non-Hispanic	Male	No
Bobby Tang	01/06/20	Present	Firmware Engineer	Undergrad	Asian	Non-Hispanic	Male	No
Roy Sun	01/06/20	Present	Instrument Scientist	Graduate	Asian	Non-Hispanic	Male	No
Nick Phan	06/15/20	Present	Mechanical Engineer	Undergrad	Asian	Non-Hispanic	Male	No
Juliana Onesi	06/15/20	Present	Mechanical Engineer	Undergrad	White	Non-Hispanic	Female	No
Alessia Dinardo	09/01/20	Present	Mechanical Engineer	Undergrad	White	Non-Hispanic	Female	No
Arielle Ainabe	09/01/20	Present	Electrical Engineer	Undergrad	Black	Non-Hispanic	Female	No
Hannah Barovier	11/29/20	Present	Electrical Engineer	Undergrad	White	Non-Hispanic	Female	No
Jordan Bierbrier	06/01/20	Present	Firmware Engineer	Undergrad	White	Non-Hispanic	Male	No
Ayesha Siddiqi	06/26/20	Present	Firmware Engineer	Undergrad	Asian	Non-Hispanic	Female	No
Adam Tyedmers	03/01/20	Present	Thermal Engineer	Undergrad	White	Non-Hispanic	Male	No
Michael Chen	10/01/18	Present	Electrical and Power Systems Lead	Undergrad	Asian	Non-Hispanic	Male	No
Nicolas Vrzovski	10/01/18	Present	Mission Operations and Controls	Undergrad	White	Non-Hispanic	Male	No
Veronica Kurkjian	05/01/20	Present	Mission Operations and Controls	Undergrad	White	Non-Hispanic	Female	No
Rachna Singh	05/01/20	09.01/21	Firmware Engineer	Graduate	Asian	Non-Hispanic	Female	No
Liam Taylor	05/01/20	05/01/21	Firmware Engineer	Undergraduate	White	Non-Hispanic	Male	No
Ricardo Polo	05/01/20	05/01/21	Firmware Engineer	Undergraduate	White	Hispanic	Male	No

8. References

[1] Cucinotta, F. A. (2015). Review of NASA approach to space radiation risk assessments for Mars exploration. Health physics, 108(2), 131-142.

[2] Cucinotta, F. A., Schimmerling, W., Wilson, J. W., Peterson, L. E., Badhwar, G. D., Saganti, P. B., & Dicello, J. F. (2001). Space radiation cancer risks and uncertainties for Mars missions. Radiation research, 156(5), 682-688.

[3] Cucinotta, F. A., & Durante, M. (2006). Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings. The lancet oncology, 7(5), 431-435.

[4] Dietze, G., Bartlett, D. T., Cool, D. A., Cucinotta, F. A., Jia, X., McAulay, I. R., ... & Sato, T. (2013). Icrp publication 123: Assessment of radiation exposure of astronauts in space. Annals of the ICRP, 42(4), 1-339.

[5] United States. National Aeronautics and Space Administration. Office of Inspector General. (2011). A review of NASA's replacement of radiation monitoring equipment on the International Space Station. [Washington, D.C.]: Office of Audits, Office of Inspector General, National Aeronautics and Space Administration.

[6] Glenn, V. D. (2006). NTRS: NASA Technical Reports Server. Reference Reviews.

[7] Armstrong T, Colborn B. Predictions of secondary neutrons and their importance to radiation effects inside the international space station. Radiat Meas 2001; 33:229–34.

[8] Badhwar, G. D., Keith, J. E., & Cleghorn, T. F. (2001). Neutron measurements onboard the space shuttle. Radiation measurements, 33(3), 235–241.

[9] United States. National Aeronautics and Space Administration. Office of Inspector General. A review of NASA's replacement of radiation monitoring equipment on the International Space Station. Tech. rep. IG-11-027. Sept. 2011.

[10] National Aeronautics and Space Administration. International Space Station Program. International Space Station Medical Operations Requirements Document (ISS MORD). Tech. rep. SSP 50260 Rev C. Feb. 2006.

[11] CSEW6 steering committee. Canadian Scientific Priorities for the Global Exploration Strategy). Tech. rep. CSEW6 Report. Dec. 2008.

[12] Hanu, A. R., Barberiz, J., Bonneville, D., Byun, S. H., Chen, L., Ciambella, C., ... & Jhirad, A. (2017). NEUDOSE: A CubeSat Mission for Dosimetry of Charged Particles and Neutrons in Low-Earth Orbit. Radiation research, 187(1), 42-49.