HASP 2018 Final Flight and Science Report

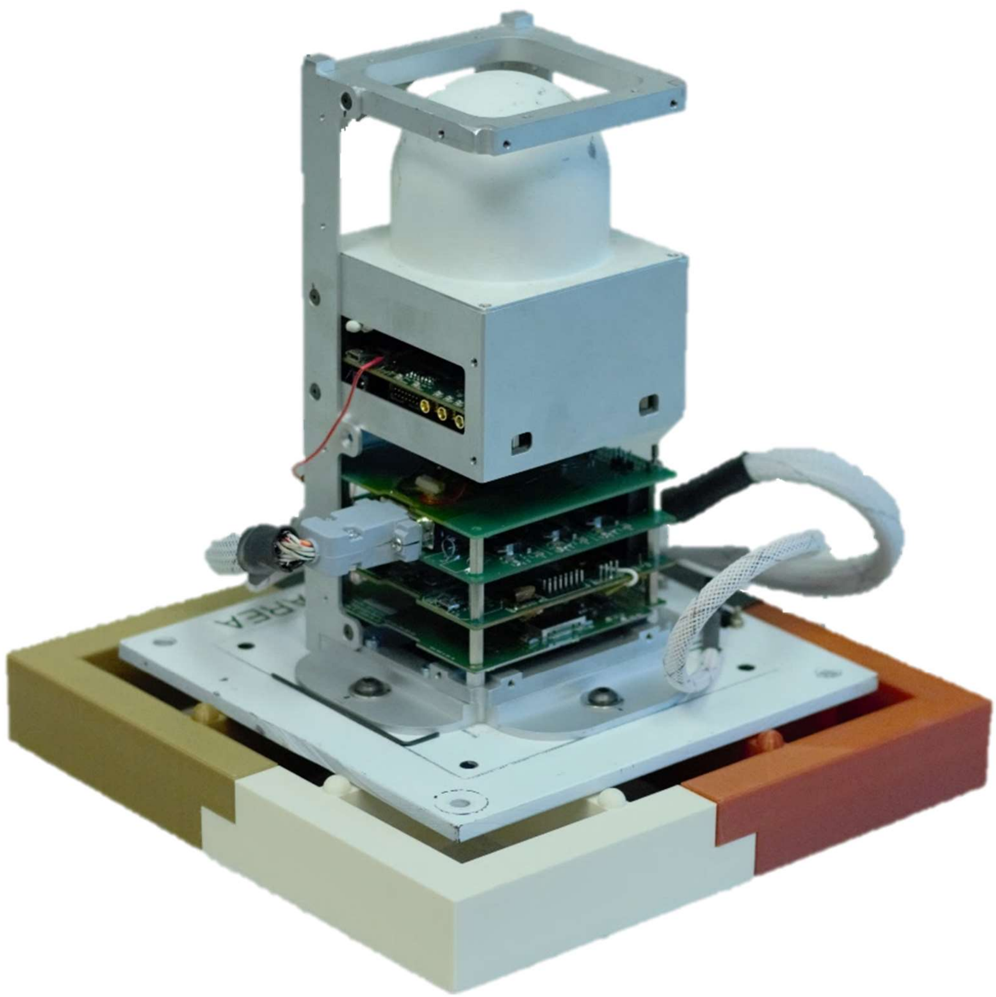
Stratospheric Measurements of Charged and Neutral Radiation

McMaster University

Submitted By: Erica Dao

Faculty Advisor: Dr. Soo Hyun Byun

Submitted On: December 14, 2018



1. Introduction

1.1 Motivation

Recent advancements in space technology have resulted in space exploration becoming a rapidly growing field, and the desire for human space exploration is drastically increasing. However, astronauts will risk receiving life threatening radiation doses from exposure to a hostile radiation environment that is more complex, intense, and variable than the one experienced on or near Earth. Cancer risk projections as a result of radiation exposure in space are still highly uncertain[1–7] as they rely on estimates for the radiation quality factors and on biophysical models of relative biological effectiveness derived from radiobiological studies performed using terrestrial particle accelerator sources. Recent estimates by Cucinotta et al.[2, 8] showed the uncertainty in cancer risk projections for a typical Mars mission are approximately 400 – 600% and identified uncertainties in radiation quality factors as the dominant source of error.

Active radiation dosimeters are necessary to measure radiation quality factors and characterize the radiation exposure to astronauts. Personal and area monitoring radiation dosimeters are required on every manned spaceflight in order to confirm compliance with regulations and to indicate when dose rates become too high for a particular mission phase, such as extra-vehicular activities. Radiation dosimeters for manned spaceflight missions must be designed to accurately measure the absorbed dose using materials that closely match human soft tissue, separate the effects of charged particles and neutrons, and be used in the vacuum of space.

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 HASP 2017 program allowed for major achievements in mechanical, electrical, and software development of the CNP-TEPC instrument and supporting technologies. In HASP 2018, we aimed to further the progress of the previous mission and advance this radiation detection system greatly. The HASP 2018 goals included:

1. Demonstrating stable operation of the CNP-TEPC instrument in near space-like conditions.
2. Transmission of CNP-TEPC spectral data using the newly developed communications sub-system, and verification of received information using the HASP communication interface.
3. Measuring altitude variations in radiation dose and quality factors of charged particles and neutrons.
4. Acquiring experience in the development of conventional CubeSat sub-systems such as an Electrical Power and Attitude Determination Sub-System, as well as overall system integration.

1.2 Principle of Operation

The 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 instrument, shown in Figure 1, consists of two detector technologies combined to enable real-time separation of absorbed dose and quality factors from charged particles and neutrons. The first component is a spherical Tissue Equivalent Proportional Counter (TEPC), which has an isotropic response and is the central component that enables real-time radiation dosimetry, as it records the lineal energy distribution of incident radiation. The lineal energy distribution can then be used to calculate the absorbed dose and estimate the mean quality factor of radiation. However, 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. This technique is often adopted in space borne 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.

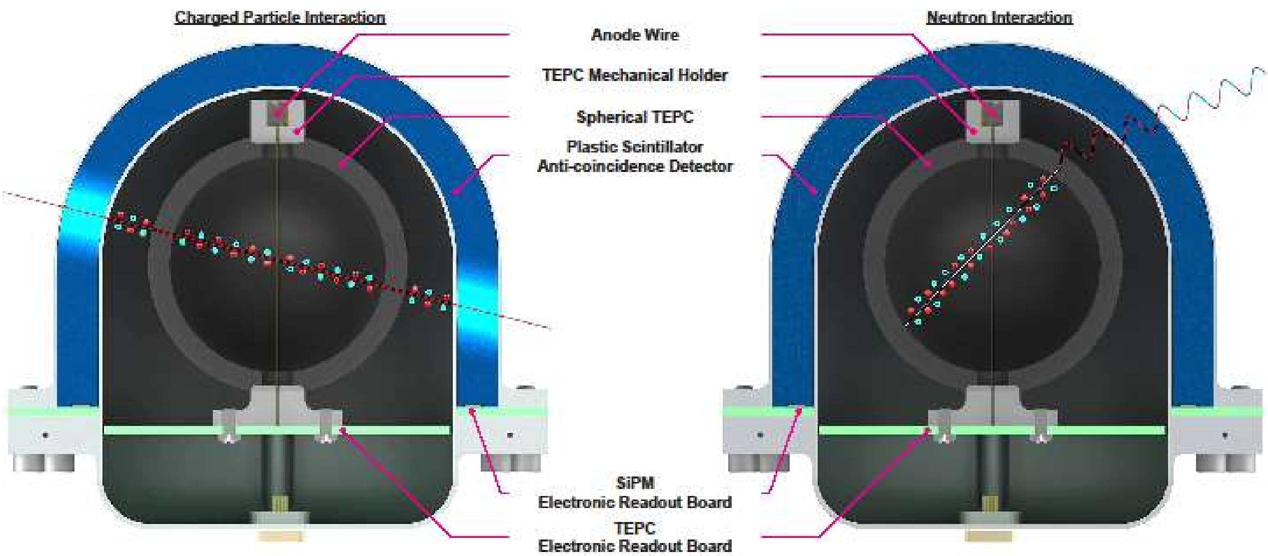


Figure 1: *The CNP-TEPC instrument separates the dose from charged particles and neutrons by monitoring the signal from a hemispherical plastic scintillator Anti-Coincidence Detector (ACD), which surrounds a spherical TEPC detector. When charged particles interact with the instrument, shown on the left, 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.*

Cover Page Photo: *Overall Payload Assembly (excluding side rail). Sub-systems from base to top: HASP mounting plate, Communications Board, Attitude Determination System Board, Electrical Power System Board, Interface Board, CNP-TEPC Instrument.*

2. Payload Description

2.1 CNP-TEPC Instrument Specifications

The CNP-TEPC instrument's overall mechanical and electrical designs remained the same from HASP 2017 however, nearly every component and PCB was re-designed or had a new revision. The Silicon PhotoMultiplier (SiPM) read-out board was a notable exception, because it showed no major design flaws and had a high fabrication cost due to the photomultiplier sensors.

One of the largest problems encountered during HASP 2017 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 detecting charged and neutral radiation. During an investigation after HASP 2017, it was discovered that the cause of the leak was improper welds of the electrical connectors. Several welding experts were consulted and this led to the improvement of the mechanical design of the electrical feed-through connectors. Welding geometry was kept in mind during placement of the features and the number of needed feedthroughs was reduced from two to one by moving the ultra-high voltage (UHV) module inside the pressure vessel. Unfortunately, due to scheduling restraints there was not enough time to fabricate the pressure vessel's internal electronics and as such, the TEPC portion of the instrument was not operational for HASP 2018. However, the pressure vessel was successfully sealed and pumped down to near vacuum for the HASP 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 in order to achieve successful output triggers on radiation events (Figure 2). 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 reduced by combining buck switching convertors and low-dropout regulators.

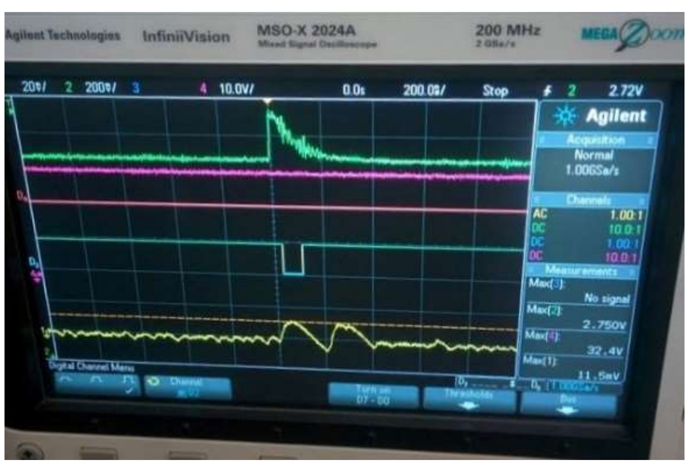
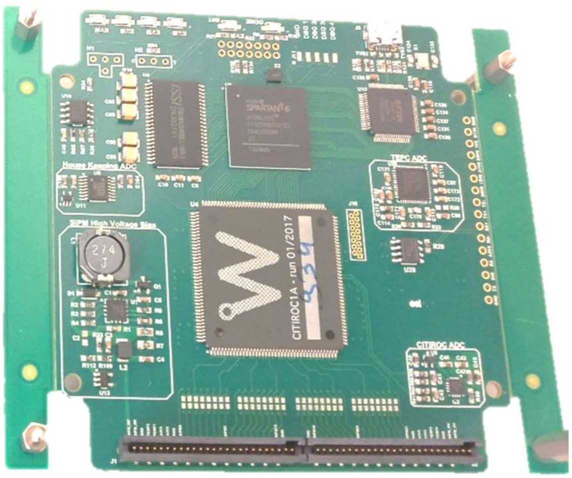
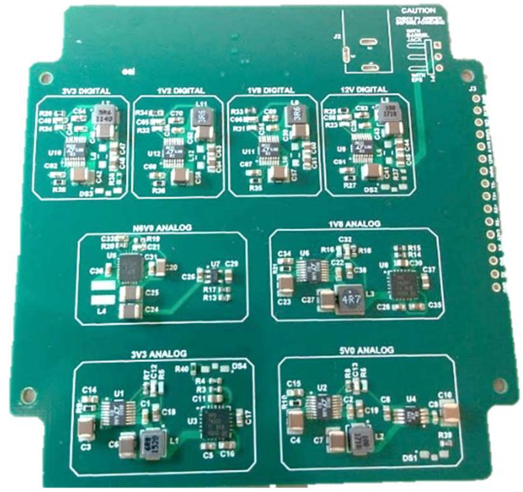


Figure 2: *Lab Testing showing SiPM and CITIROC digital signals generated using Sr-90 + Y-90 source. Green signal is the raw SiPM Anode output, Blue signal is the CITIROC output trigger routed to the FPGA and Yellow is a CITIROC analog shaped output.*





Figures 3 & 4: *Latest revisions of Data Acquisition and Power Distribution Boards respectively,*

2.2 Communications Sub-System Specifications

The communications subsystem on board the 2018 HASP payload used a custom-designed radio system developed by McMaster students. The system uses two Texas Instruments CC1125 radio transceivers to generate modulated RF signals in the UHF frequency band and receive signals in the VHF frequency band. The UHF transmitter section uses 435 MHz, while the VHF receiver uses 146 MHz.

The antenna used on the communications system was a commercial, off-the-shelf dual-band VHF/UHF antenna. However, we only intended to test the UHF transmitter on the HASP 2018 flight, and thus configured the antenna for peak performance in the UHF bands. The antenna was affixed to the outside of the HASP payload and pointed downwards, ensuring the propagation of the radio waves travelled in a downwards direction to the awaiting ground station.

In order to legally operate our VHF/UHF radio, several team members pursed HAM Radio Operator licences and successfully passed their written qualifications tests. A ground station was designed and built as shown in Figure 5, with the intention to be transported and assembled in New Mexico for the flight. Students attending the flight planned to track the HASP platform with the provided GPS data, re-assemble the ground-station and receive packets from the payload during the flight.

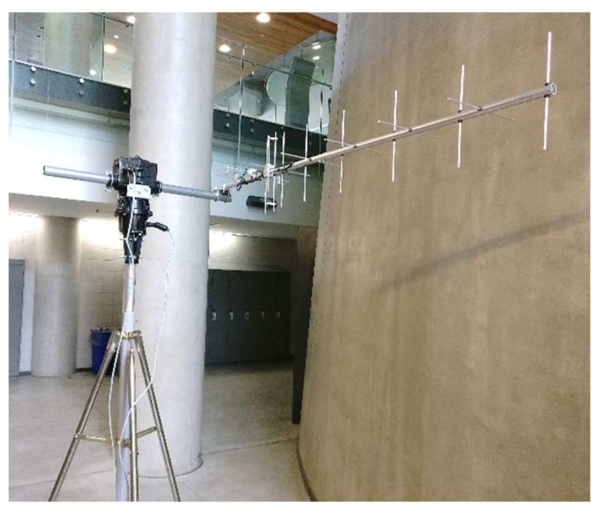


Figure 5: *Student designed and fabricated communications ground station*

2.3 Additional Sub-System Specifications

With the eventual goal of flying the CNP-TEPC in low earth orbit as a CubeSat payload, the team decided that the HASP mission would be a perfect opportunity to develop and test standard CubeSat hardware. With the previous success designing power distribution modules and other PCBs flown on HASP 2017 this decision was deemed low enough of a risk. An additional power distribution module that is referred to as the Electrical Power Sub-System (EPS) and an Attitude Determination Sub-System (ADS) were chosen. These two boards provided new students joining the team a first project to gain experience with the guidance of more experienced students.

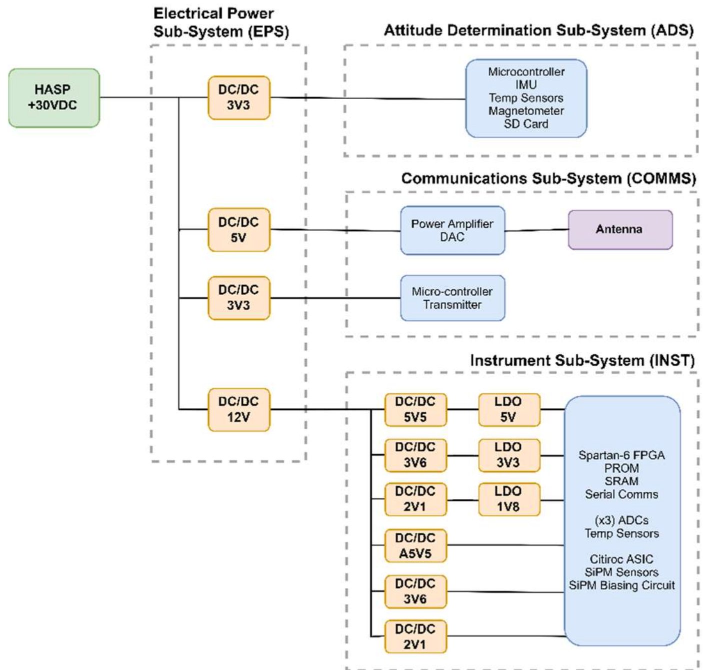


Figure 6: *Power Flow and System Block Diagram for the overall payload.*

The EPS was built to interface with HASP power and communications lines through a DB-9 connector. The EPS took the supplied 30V power rail and generated the individual voltage rails needed for each sub-system (Figure 6) with buck switching regulators that were flight proven last year at HASP 2017. The EPS also routed the connection between HASP's RS232 communication line and the CNP-TEPC instrument. Interfacing with the rest of the sub-systems was made with a CubeSat standard 104 pin block header.

An ADS was also designed to measure telemetry such as the angular rate and magnet field (Figure 7). Featuring a microcontroller this sub-system's data would be stored on-board a micro-SD card and recovered afterwards.

Figure 7: *Two ADS PCBs were assembled by the students, one for flight and one for validation.*

3. Payload Performance

3.1 Overall Payload Performance

The mechanical structure of the payload performed without any issues throughout the flight and suffered little to no damage from the descent. All enclosed circuit boards were intact and showed no mechanical issues when examined following the flight. To the best of our knowledge the pressure vessel is still under near vacuum however this cannot be verified because the fill port is crimped shut and no internal pressure sensor was flown on the flight.

The payload drew an average of 3 W during nominal operation, which can be seen in Figures 9 and 10. While testing the radio during TVAC2, the power draw during data transmission reached a worrying 14 W, with 15 W resulting in a complete payload shut-down. The radio was kept powered off for the flight and no other large power draws were recorded by the HASP telemetry. A notable observation is the 0.1 A ripple current that occurred during the payload's flight (Figure 9). This magnitude was not seen during the previous TVAC tests and the cause of the 3 W fluctuation will need to be further investigated.

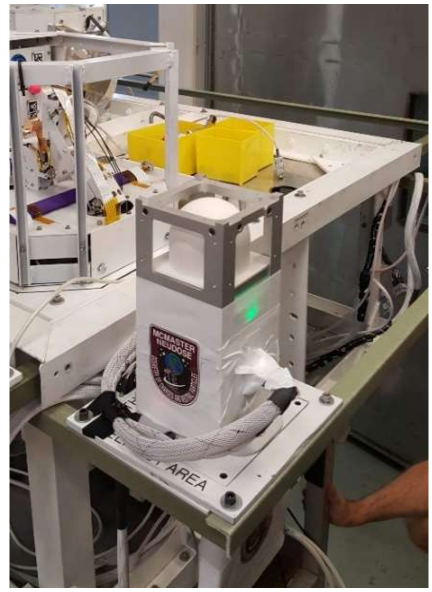


Figure 8: *Payload successfully integrated onto HASP platform following a Thermal Vacuum Chamber Test.*

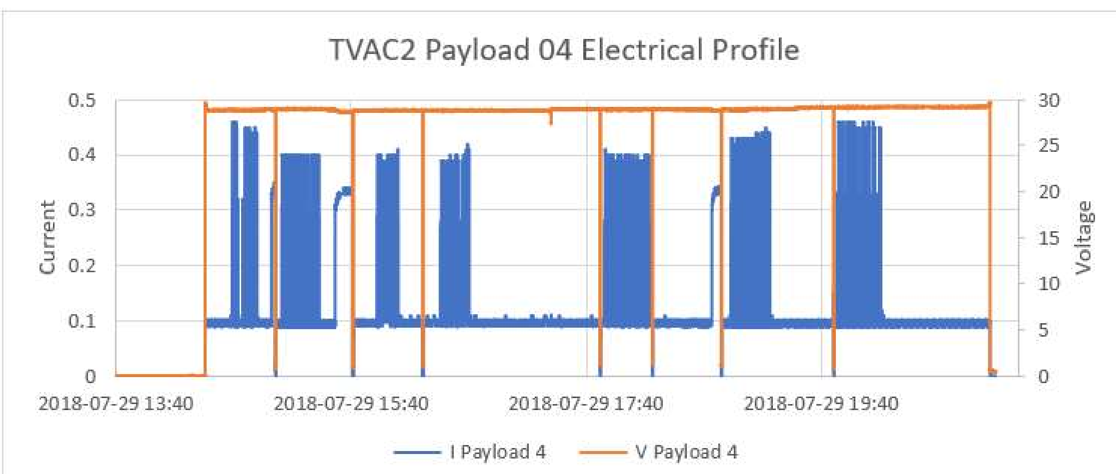


Figure 9: *Payload voltage (orange) and current (blue) measurements during TVAC2. The spikes in current were due to the Communication Sub-System radio as the functionality of communications was being tested.*

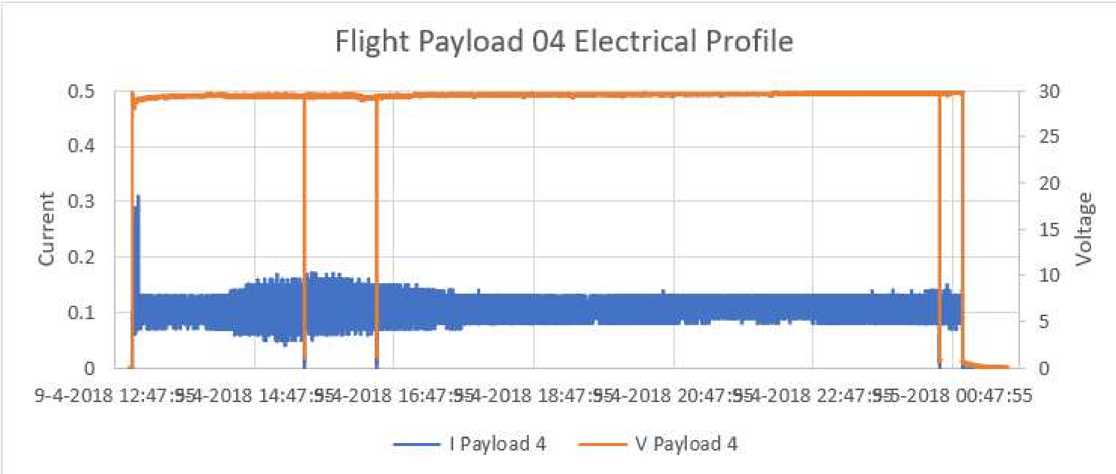


Figure 10: *Payload voltage (orange) and current (blue) measurements during the HASP 2018 flight. The drops in voltage coincide to power cycles of the payload.*

3.2 CNP-TEPC Instrument Performance

Temperature telemetry from the CNP-TEPC instrument was transmitted via HASP's RS232 interface and can be seen in Figure 11, compared to the platform's Serial Control Unit average temperature. A power cycle around T+90 minutes occurred as the instrument's temperature sensors began to show an anomaly. This anomaly was also observed during both TVAC tests but was not resolved. Despite the gap in data, the other temperature readings are considered reliable. The payload's low thermal mass explains the large range of 30 to -40 °C, and despite worries of overheating, the payload never reached 40 °C. The SiPMs went below their recommended minimum operating temperature of -40 °C briefly during the balloon ascent.

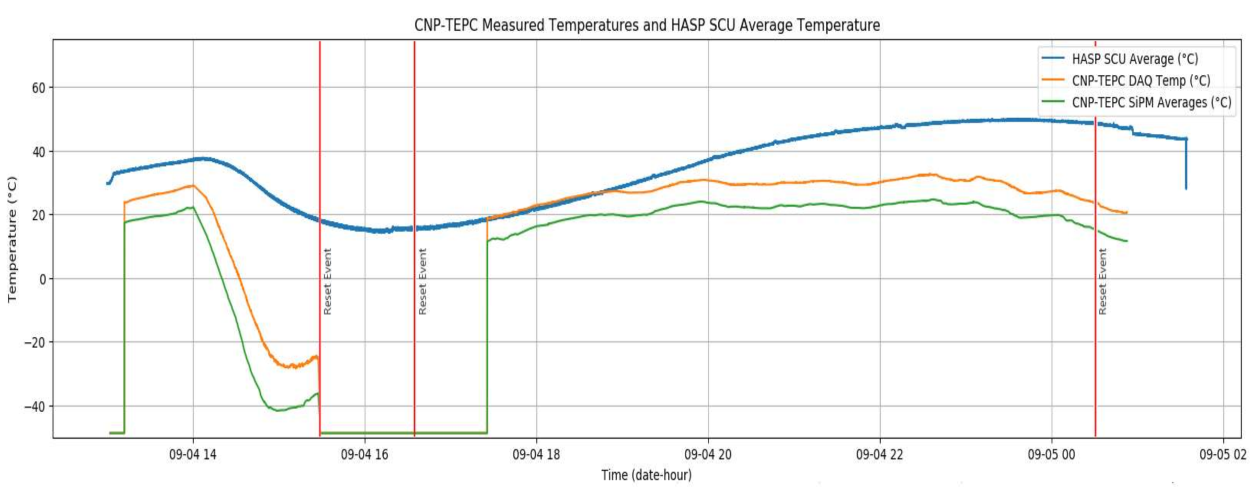


Figure 11: *CNP-TEPC Instrument temperature measurements (orange and green lines) made during balloon flight. HASP's SCU average temperature is also shown as the blue line.*

3.3 Communications Sub-System Performance

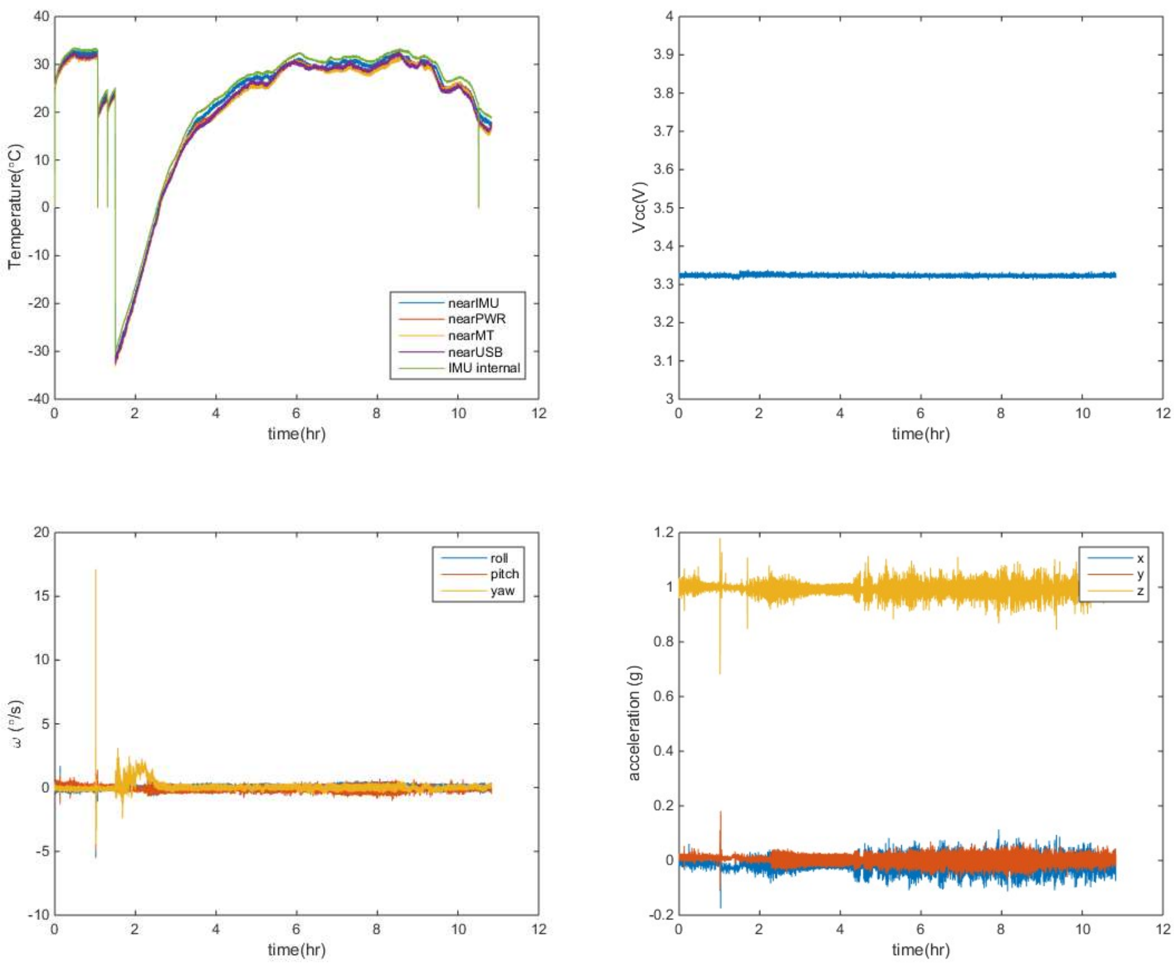
During the first TVAC test, the communications system was tested using a 100% duty cycle. This test was intended to stress test the communications system and ensure it would be able to transmit under adverse environmental conditions. With a 100% duty cycle, the output power amplifier on the communications sub-system would be active continuously, generating a significant amount of heat. This duty cycle is never meant to be observed in practice, as our intended operational duty cycle is 10%. The first TVAC test proceeded without incident. The ground station antennas and receivers (external to the TVAC apparatus) were able to receive the radio signals produced by the communications system. Additionally, commands were sent to turn the radio systems on and off to observe the system current consumption; these values were well within tolerances.

During the second TVAC test, the communications system firmware and hardware were updated to receive data from our science payload instrument. The payload instrument has an interface to the HASP bus and the RS-232 signal from HASP was routed through the payload to the communications system. The communications system has its own bus to communicate with the payload, which was added as a redundancy. During the second TVAC test, the communications radios stopped transmitting approximately twenty minutes after receiving a 'Radio ON' command. Additionally, sending a 'Radio OFF' and then 'Radio ON' command sequence to reset the radios did not immediately resolve the issue. This pointed to the communications firmware possibly having a race condition or similar bug in its timing interrupts. After further investigation, this issue was isolated to the Attitude Determination sub-system that fed data to the communications system. This other sub-system was unable to forward packets to the communications sub-system, and thus the ground station receiver stopped receiving packets from the communications sub-system. Once isolated, the bug was fixed, and the problem disappeared. disabling

Unfortunately, the communications system was turned off for the balloon flight by physically disabling the 5 V and 3.3 V power rails. In the lead up to flight, the communications sub-system was running nominally as it did during the TVAC tests. The communications sub-system received 'Radio ON' and 'Radio OFF' commands, and packets were able to be received using the ground station antennas and receiver. However, it was discovered that the microcontroller onboard the communications sub-system was unable to be programmed for any firmware updates. Additional testing showed that the flash partitions on the microcontroller became corrupted and new firmware could not be flashed to the microcontroller before the flight deadline. Deemed as a flight risk, the decision was made to disable the sub-system for the flight.

3.4 Electrical Power & Attitude Determination Sub-Systems Performance

The EPS system performed nominally over the course of HASP and the high-altitude balloon flight. All sub-system voltage requirements were met, and the board properly interfaced with HASP's provided power and serial connections. The ADS had sub-optimal results. It's magnetometers were unable to be flown due to an improper circuit layout, however it successfully recorded temperature, accelerometer and gyroscope data (Figures 12-15). The temperature data showed anomalies most likely due to power cycles and unfortunately the accelerometers and gyroscopes data is mostly noise. Overall, the experience of integrating multiple sub-systems was a challenge due to all the coordination that needed to be done between the separate sub-systems, but the experience was certainly invaluable.



Figures 12-15: *Data recorded on-board the Attitude and Determination Sub-System. Going clockwise starting from the top-left: Temperature Data, Supply Voltage Rail, Accelerometer Data, Gyroscope Data.*

4. Science/Technical Results

The CNP-TEPC instrument produced the science data shown in Figure 16. Since the TEPC electronics were not completed in time, data was only collected from the Anti-Coincidence portion of the detectors which is comprised of a scintillator and 32 SiPM sensors. The SiPM signals were pre-amplified by the CITIROC ASIC located on the data acquisition board which outputted digital trigger signal to the nearby Spartan-6 FPGA. These counts were processed, tallied and outputted to the HASP communication interface in 300ms packet intervals.

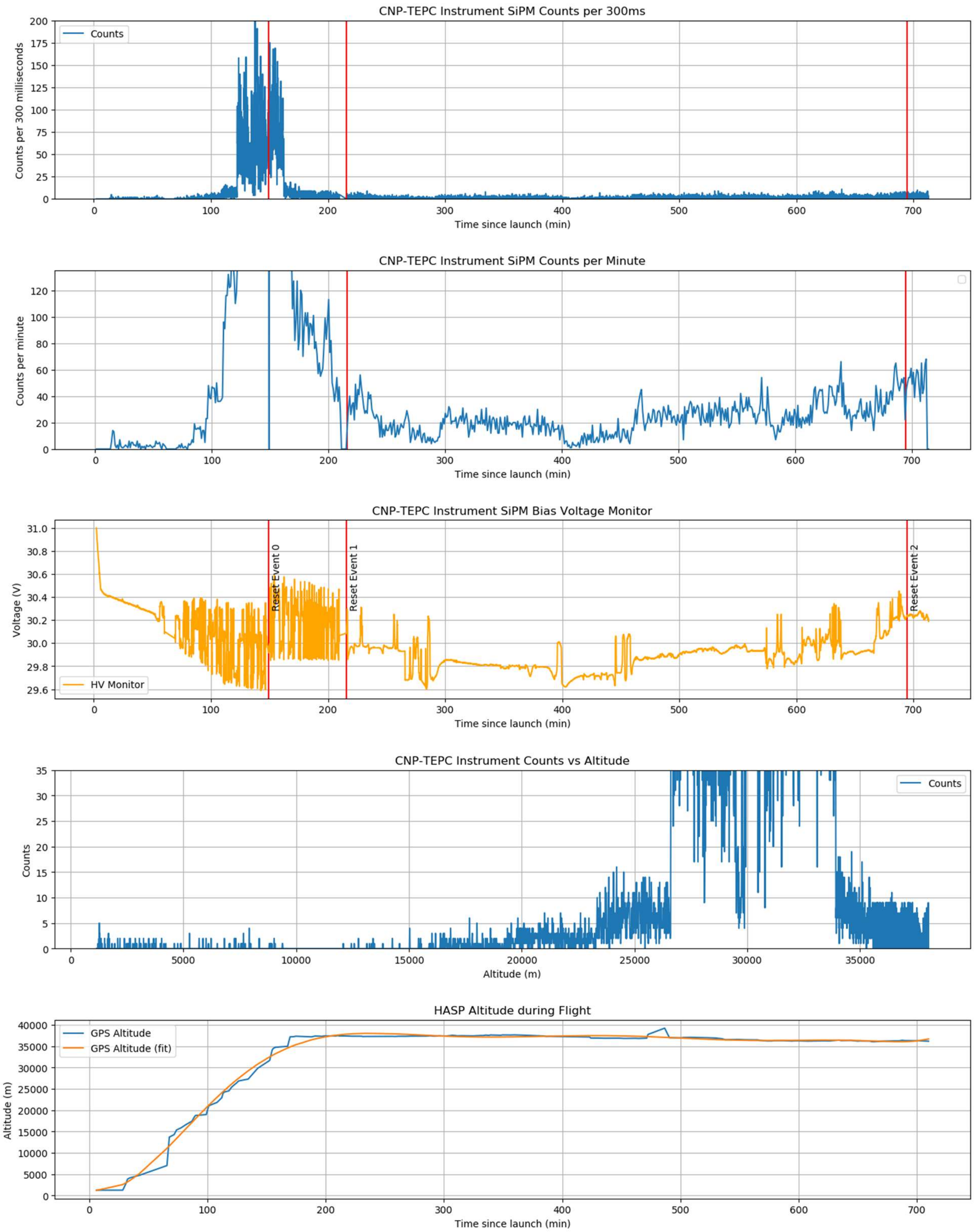


Figure 16(A-E): *CNP-TEPC Instrument science data collected during the HASP 2018 balloon flight.*

Figure 16A shows the raw data over the duration of the flight and Figure 16B shows the same data in a more digestible format. An average count rate of 10 per minute were observed for the first 100 minutes when the balloon was first released and ascended. At the T+100 minute mark (approximately 20km altitude) there was a local maximum of 50 counts per minute. This is perhaps the most important portion of the payload data as it correlates with an expected maximum count rate at an altitude of 17-24km due to the Regener–Pfotzer maximum [12]. However, following this event the data count rate spikes dramatically for the remainder of the balloon climb which coincides with the SiPMs approaching temperatures outside of their recommended operation (Figure 11).

The SiPM's bias voltage telemetry (Figure 16C) showed that the supply voltage was not fully stable. This bias voltage was not compensating for the changing temperature which would've been crucial during the temperature drop seen by the SiPMs while the balloon was climbing (Figure 11). The SiPM's bias voltage was additionally not maintained for optimal performance that accounted for the individual sensors' dark count rates, crosstalk, after-pulses or pile-up pulses. All these factors certainly played a role in the unusual data obtained.

Once the balloon was at float altitude (35-36km), the count rate stayed at an average of 30 counts per minute (T+200 - 700min). This count rate is higher than the average seen in the first portion of the flight suggesting that we were indeed receiving the expected results of more radiation events at altitude compared to at ground level. However, in this period a correlation can be seen between the SiPM count rate and bias voltage which further suggests an anomaly in the data obtained.

Overall, we are pleased with our collected data during the HASP 2018 flight. Despite the strange results, with further processing and characterization this data will certainly help in the development of the instrument.

5. Lessons Learned

HASP 2018 provided the team with a multitude lessons ranging from engineering, testing and validation, to team organization and management. Despite flying in our second HASP mission, some mistakes were repeated and re-enforced the need for proper mission planning. Listed below are some of most notable lessons learned:

1. Be cautious of scope creep and over-engineering. An example was the design of inter-systems communication protocol in which RS-485 was settled on. This protocol worked however during integration it showed problems between two sub-systems and was replaced by running a fly-wire UART line between the systems. The original design decision consumed plenty of team time and the resources maybe could've better been used else where.
2. Plan better for the absence of graduating students. Recruit more students to the project and emphasise transfer of knowledge from old to new.

6. Public Relations/Outreach Articles

Student team prepares for International Space Station Launch with flight program

McMaster University | Faculty of Engineering | News Article | September 7,2018

https://www.eng.mcmaster.ca/sept/news/student-team-prepares-international-space-station-launch-flight-program

How Canadian technology could protect Space Force troops

Fiona E. McNeill, Professor of Radiation Sciences, McMaster University | Article | August 16, 2018

http://theconversation.com/how-canadian-technology-could-protect-space-force-troops-101373

7. Student Involvement

Name	Start Date	End Date	Role	Student Status	Race	Ethnicity	Gender	Disabled
Erica Dao	12/01/17	Present	Student Team Lead	Grad Student	Asian	Non-Hispanic	Female	No
Ryan Scott	12/01/17	Present	Mechanical Team	Undergrad	Caucasian	Non-Hispanic	Male	No
Farazdak Bohra	12/01/17	Present	TEPC Team	Grad Student	Asian	Non-Hispanic	Male	No
Luis Lopera	12/01/17	Present	TEPC Team	Undergrad	Caucasian	Hispanic	Male	No
Jordan Cowan	12/01/17	Present	DAQ Team	Graduated	Caucasian	Non-Hispanic	Female	No
Eric Dyer	12/01/17	Present	DAQ Team	Grad Student	Caucasian/Asian	Non-Hispanic	Male	No
Bhavesh Kakwani	12/01/17	Present	DAQ Team	Graduated	Asian	Non-Hispanic	Male	No
Chelsea Urquico	12/01/17	Present	DAQ Team	Graduated	Asian	Non-Hispanic	Female	No
Alex Melnichuk	12/01/17	Present	ACD Team	Undergrad	Caucasian	Non-Hispanic	Male	No
James Warburton	12/01/17	Present	Data Handling Team	Undergrad	Caucasian	Non-Hispanic	Male	No
Liubov Trofimova	04/01/18	Present	Data Handling Team	Undergrad	Caucasian	Non-Hispanic	Female	No
Hira Nadeem	04/01/18	Present	Data Handling Team	Undergrad	Asian	Non-Hispanic	Female	No
Devan Wagner	04/01/18	Present	Power Team	Undergrad	Caucasian	Non-Hispanic	Male	No
Mitchell Kurnell	04/01/18	Present	Power Team	Undergrad	Caucasian	Non-Hispanic	Male	No
Kyle Jackson	12/01/17	Present	GUI Development	Undergrad	Caucasian	Non-Hispanic	Male	No
Aaron Pitcher	12/01/17	Present	Communications Team	Grad Student	Caucasian	Non-Hispanic	Male	No
Jimmy Nguyen	12/01/17	Present	Communications Team	Graduated	Asian	Non-Hispanic	Male	No

The following students have graduated from their program of study at McMaster University this year:

Name	Degree Completed	Graduation Date	Current Position
Ryan Scott	B.Eng.	June 15, 2018	Currently employed at Canadensys (Aerospace Company) as a Mechanical Engineer.
Farazdak Bohra	MSc in Radiation Sciences	June 14, 2018	Currently employed at Ontario Power Generation's Darlington Nuclear Reactor as a Research Scientist.
Eric Dyer	M.A.Sc. Electrical Engineering	Nov 23, 2018	Currently employed at L3 Wescam (Aerospace & Defense) as a Software Engineer.
Alex Melnichuk	B.Eng.	June 15, 2018	Currently employed at ecobee (Home Automation) as a Hardware Engineer.
Devan Wagner	B.Eng.	June 15, 2018	Currently enrolled in a M.A.Sc Engineering Physics Graduate Program at McMaster University
Mitchell Kurnell	B.Eng.	June 15, 2018	Currently enrolled in a M.A.Sc Engineering Physics Graduate Program at McMaster University

References

[1] D. J. Brenner and C. D. Elliston. “The potential impact of bystander effects on radiation risks in a Mars mission”. In: Radiation research 156.5 (2001), pp. 612–617.

[2] F. A. Cucinotta et al. “Space radiation cancer risks and uncertainties for Mars missions”. In: Radiation research 156.5 (2001), pp. 682–688.

[3] F. A. Cucinotta and M. Durante. “Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings”. In: The lancet oncology 7.5 (2006), pp. 431–435.

[4] F. A. Cucinotta, M.-H. Y. Kim, and L. J. Chappell. Space radiation cancer risk projections and uncertainties-2010. Tech. rep. NASA TP-2011-216155. Washington, DC: National Aeronautics and Space Administration, 2011.

[5] F. A. Cucinotta and L. J. Chappell. “Updates to astronaut radiation limits: radiation risks for never-smokers”. In: Radiation research 176.1 (2011), pp. 102–114.

[6] F. A. Cucinotta, M.-H. Y. Kim, and L. J. Chappell. Space radiation cancer risk projections and uncertainties-2012. Tech. rep. NASA TP-2013-217375. Washington, DC: National Aeronautics and Space Administration, 2013.

[7] F. A. Cucinotta. “Review of NASA approach to space radiation risk assessments for Mars exploration”. In: Health physics 108.2 (2015), pp. 131–142.

[8] F. A. Cucinotta. “A new approach to reduce uncertainties in space radiation cancer risk predictions”. In: PloS one 10.3 (2015).

[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] Carlson, P., Watson, A.A., 2014. Erich Regener and the ionization maximum of the atmosphere. Hist. Geo- Space Sci. 5 (2), 175, ()