Recovery of a Lost Satellite: The ARMADILLO Mission

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ABSTRACT

After 949 days in space, contact with the ARMADILLO CubeSat from the University of Texas at Austin has been established. After a complete reconstruction of the ground command software, the Space System Design Laboratory (SSDL) at Georgia Tech has commanded and received acknowledgements and data downlinks from ARMADILLO as well as commanded a hard reset. The Georgia Tech Ground Station Network (GT GSN) has leveraged its autonomous contact capability to maintain consistent contact with ARMADILLO, enabling it to remain online for longer than a week. Something ARMADILLO had previously never accomplished due to the ground contact condition for onboard reset never being satisfied. This has prompted the development of a late-life commissioning plan that currently indicates that ARMADILLO has the potential to accomplish its original science goals.

INTRODUCTION

University CubeSats are typically secondary payloads ridesharing on launch vehicles, and therefore suffer tight schedules and deadlines. These tight deadlines can lead to disaster when paired with inconsistencies in documentation standards, procedures, experience throughout the team, and rapid student turnover. With so much focus on delivering a satellite that may or may not work, there is typically little time to consider the ground station infrastructure that is necessary for many of these missions to be successful, and this can only compound the issues faced after deployment. Deployment is a key moment in every satellite mission and is one of the most critical for CubeSats. University CubeSats have a serious infant mortality concern. ARMADILLO is an example of what can happen when several the aforementioned issues occur within a CubeSat program. From its launch and support at the University of Texas at Austin in 2019 until present day, ARMADILLO has had an incredibly tumultuous lifetime. Without contact for two and a half years, ARMADILLO has recently acknowledged commanding from the Georgia Tech Ground Station Network for the first time. Since then, it has downlinked over two thousand packets of onboard mission data. The ARMADILLO mission now shows promise in delivering on the original mission goals. Of the currently known onboard issues, none seem insurmountable, and with further development on the ground station infrastructure, could be negated. There is a clear-cut plan to fully checkout ARMADILLO and establish its true capability.

The most anticipated and critical moment in any CubeSat mission timeline is the launch. This is the milestone when a mission that has been under careful development for years is finally set to begin operation. For CubeSats, deployment is an especially strong moment of pressure, as between 12.89% and 24.38% of CubeSats are dead-on-arrival and between 26.76% and 41.06% fail within 100 days. This problem is compounded for univeristy teams, as by expert elicitation, just under 50% of university CubeSats are expected to fail within the first 6 months of operation.[1] This paper provides an inside look at many of the factors that contribute to challenges for university CubeSats in the context of the ARMADILLO mission, an Air Force University Nanosatellite Program (UNP) mission. This paper will also provide an account of the mission timeline, the sequence of events prior to and after launch, and the current status of ARMADILLO.

ARMADILLO

ARMADILLO, Attitude Related Maneuvers And Debris Instrument in Low (L) Orbit is a 3-Unit CubeSat that was developed at the University of Texas at Austin (UT-Austin) that was designed to detect sub-millimeter space debris via a Piezo Dust Detector (PDD) developed by the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University.[2] Additionally, ARMADILLO is equipped to perform radio occultation measurements via a software-defined FOTON GPS receiver developed by the Radionavigation Laboratory at UT-Austin.

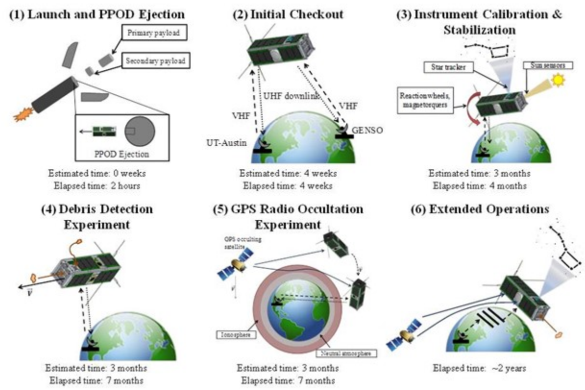

Figure 1: ARMADILLO Concept of Operations

ARMADILLO is one of three missions from the Texas Spacecraft Laboratory (TSL) to use a modular and reusable CubeSat Bus, alongside BEVO-2 and RACE, which were built at approximately the same time in the TSL. ARMADILLO was selected for flight as part of the UNP-7 cohort in 2014, and was launched on June 25th, 2019 on the Falcon Heavy STP-2 launch.

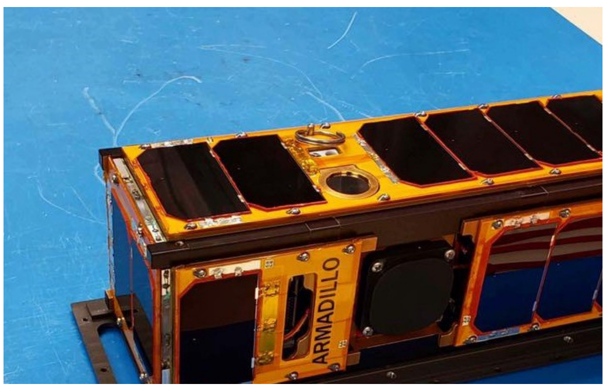

Figure 2: ARMADILLO CubeSat

University CubeSat Mission Common Issues

University CubeSat teams face uniquely challenging issues such as incredibly tight schedules, inconsistencies in documentation standards, procedures, experience throughout the team, and rapid student turnover. These issues typically compound if a given laboratory is exclusively undergraduate, as the retention time is four years or less. Not to mention the incredibly low budget of these missions.

CubeSat Launch and Early Operations (LEOP)

A commonly unknown consideration for university missions due to personnel turnover is the typical launch and early operations timeline. Nominally launch and deployment can take anywhere from instantaneous to 2 hours. Then begins the wait for confirmation that the satellite is operational.

Figure 3: Nominal CubeSat LEOP Timeline

The reception of the first beacon typically takes half a day up to a full day. This is where SatNOGs can have a real impact, as their database and dashboards provide valuable information on spacecraft deployment and health. The GT-1 mission from Georgia Tech was able to receive its first health beacon within an hour of deployment via SatNOGs.

Once the excitement of deployment day dies down, then comes the wait for identification of NORAD objects. This time frame of 1 week to a month is completely dependent on the number of objects being deployed, and if they provide additional aid in identification. If a satellite is operational and is beaconing, then the Satellite Tracking toolkit for Radio Observations (STRF) can be leveraged to minimize satellite identification time. [3]

Finally, the rest of the CubeSat's lifetime relies on regular ground station contacts. This will be the bulk of the science and data downlink phases prescribed per mission.

SatNOGs

SatNOGs is an Open-Source global network of satellite ground-stations[4] that has truly changed how universities can approach their mission ground data segment. SatNOGs is entirely run by volunteers who track satellites in their free time. They host an online database of contacts, each sorted by satellite and quality, that include the pass spectrogram, audio, and even demodulated data.

SatNOGs also hosts a series of dashboards, where if an entity provides them with a packet decoder, one can create a dashboard per satellite. This is typically used to display general health data, to provide a heartbeat per mission.

Figure 4: ARMADILLO SatNOGs Dashboard[4]

University Ground Stations

A commonly disregarded component of university CubeSat missions is the ground station infrastructure. This is typically not due to negligence, rather an inability to allocate resources to developing and maintaining ground station infrastructure outside the operational window of an ongoing mission. University ground stations are typically amateur grade equipment set-up in a short time frame. This results in mission operations being wrought with issues caused by ground station failure.

Figure 5: Montgomery Knight Ground Station Disassembly for Maintenance

The lack of reliable systems wreaks havoc on personnel morale during the operational window by slowing mission progress.

ARMADILLO MISSION TIMELINE

ARMADILLO began as a University Nanosatellite Program (UNP) Nanosatellite-7 mission and began development in January of 2011 and won first place in the CubeSat category at the Flight Selection Review (FSR) in January 2013. ARMADILLO was originally slated to deliver a flight unit in June 2013 with an assumed launch in 2014.[2] The delivery was delayed multiple times until 2018.

During that time Texas Spacecraft Laboratory (TSL) director Dr. Glenn Lightsey moved to the Georgia Institute of Technology. The project remained at UT-Austin staffed by a skeleton crew of four members and a temporary advisor until their graduation. In 2016 the TSL was revived under the leadership of Dr. Noble Hatten, and ARMADILLO was re-staffed with undergraduate students.

The author supported ARMADILLO as the communications lead at UT-Austin through the Ground Operations Readiness Review (GORR) in February 2018. For GORR we had implemented flight rehearsals with anomalous conditions and regular ground station validation through regular amateur radio satellite contacts. Due to the TSL's relationship with Georgia Tech, GT was the secondary operations center for ARMADILLO.

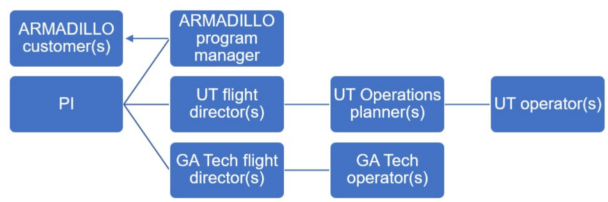

Figure 6: ARMADILLO Chain of Command

In May of 2018, the UT-Austin Aerospace department announced a building move, resulting in the destruction of the Student Ground Station (SGS). Shortly thereafter the launch was postponed another year, meaning that the trained personnel for ARMADILLO would be graduating before the launch. In December of 2018 the TSL Director would leave, resulting in a completely undergraduate run lab. In January of 2019 the new building was under construction, and the SGS had yet to be relocated.

On June 25th, 2019, ARMADILLO was launched on STP-2 without a working ground station. Initial deployment worked well, and within 12 hours the first health beacon would be received over Japan.

The SGS would find a new home on top of the attached parking garage and share a space with another laboratory. It would take until July 20th, 2019, to receive the first ARMADILLO beacon at UT-Austin.

This would not be the end of the problems for ARMADILLO. The SGS was not automated, so all passes had to be done manually occasionally unsavory times. To make matters worse, all attempts to ping ARMADILLO failed. It was soon discovered that the ground control software did not incorporate doppler shift in the radio controller. This issue was only compounded due to the FSW being written in-house by a student who had since graduated.

Georgia Tech also attempted to ping ARMADILLO and failed to get any responses. Eventually the SGS at UT-Austin failed a hardware fault in early August and put all contacts on hold. The ARMADILLO team would then be downsized in the favor of newer missions, and cycle through operators until the mission was closed in 2020.

In January 2022, ARMADILLO responded to a renewed set of ping attempts from Georgia Tech and has since been in commissioning.

GEORGIA TECH PING ATTEMPTS

The initial Georgia Tech ping attempts with ARMADILLO were fundamentally flawed. Due to the tightly integrated nature of the ARMADILLO ground control software, it was not possible to forward the command packets through a different radio controller. The solution was to record an output ping command packet from the ARMADILLO operations software (OPS-Monster) and transmit the packet through a separate chain that has controlled doppler shift. This did not result in any return pings.

The renewed effort in January 2022 resulted in a complete reconstruction of the ground control software that was implemented with the Georgia Tech Ground Station Network (GT GSN) that enables autonomous generation of commands and repeated transmission throughout any given pass. This ground control software implementation builds each command as the original ground control software would, however it enables the output to be piped to any sink whether that be a radio for transmission or a file for storage.

ARMADILLO COMMANDING

Since confirmation of ARMADILLO’s commanding capabilities, there has been an effort to confirm functionality of different commands (Table 1) as well as downlink the onboard data from deployment.

Satellite Cybersecurity

As physical attacks on satellites are not currently

Table 1: ARMADILLO Command Testing

Command	Description	Arguments	Executed
ACK_GND	Acknowledge the ground station	N/A	Yes
SET_TIME	Set the onboard time	Date Time	No
DEPLOY_ANTENNA	Deploy the Antennas	N/A	No
SILENCE	Silence the Radio	N/A	No
UNSILENCE	Unsilence the Radio	N/A	No
SUPP_POW	Provide power to specified subsystems	Subsystem, power on/off	No
DOWNLINK_MISSION_DATA	Downlink the first 1000000 bytes of onboard telemetry	N/A	Yes
REREQUEST_PACKETS	Re-request specific packets	List of packet IDs	No
DELETE_MISSION_DATA	Delete select mission data between two specified packet IDs	Minimum packet number, maximum packet number	No
UNPAUSE_PACKET_BEACON	Un-pause packet beacon	N/A	No
SET_TELEMETRY_COLLECTION_RATES	Set the telemetry collection rates for each of the telemetry files	Mission period, measurement period, attitude period, health period, eps period, and GPS period	No
PURGE_ALL_HEALTH	Purge all onboard health data	N/A	No
SET_PACKET_BEACON_RATES	Set the rates at which the beacons are transmitted	Low power rate, nominal rate	No
HARD_RESET	Hard reset the spacecraft	N/A	Yes
SOFT_RESET	Soft reset the spacecraft	N/A	No
SET_ADC_MODE_FILE	Set the ADC mode file	Desired quaternion, service mode, pointing mode, sun constraint, pointing quaternion, target quaternion, and orbital elements	No
LOG_OCCULTATION	Log a radio occultation with a given GPS satellite for a given time	PRN, and time	No
RUN_PDD	Run the piezo dust detector	Detector thresholds, ranges, monitor, overall duration, and maximum data stored	No
SET_FOTON_UPDATE_RATE	Set the rate at which the GPS updates	Time	No

prevalent, it is imperative that each satellite has command encryption. This is most commonly implemented with the Advanced Encryption Standard (AES), as it is effective resisting brute force attempts.

There are different modes of operation for the AES encryption standard, and for CubeSats it commonly implemented in Electronic Codebook Mode (ECB). This takes plaintext and any given cryptographic key and creates reproducible ciphertext.[5] AES is symmetric, therefore the same key used to encrypt the command packet is used to decrypt it onboard.

Protocol buffers

ARMADILLO opted to instead implement protocol buffers for both command uplink and telemetry downlink. Protocol buffers are Google's language-neutral, platform-neutral, extensible mechanism for serializing structured data.[6] Protobuf was designed to be lighter weight than XML, and as long as you have the required protobuf files, you can construct and deserialize the data.

ARMADILLO's implementation of protocol buffers is recursive in nature. For the telemetry downlink, as seen in Figure 7, Any given telemetry packet is serialized in a file type identifier protocol buffer. Then if the packet is an acknowledgement, then the data payload from the original file is deserialized by a separate protocol buffer file. The packet beacon is not serialized via protobuf, as it enables amateur operators to decode the beacon with the packet beacon struct.

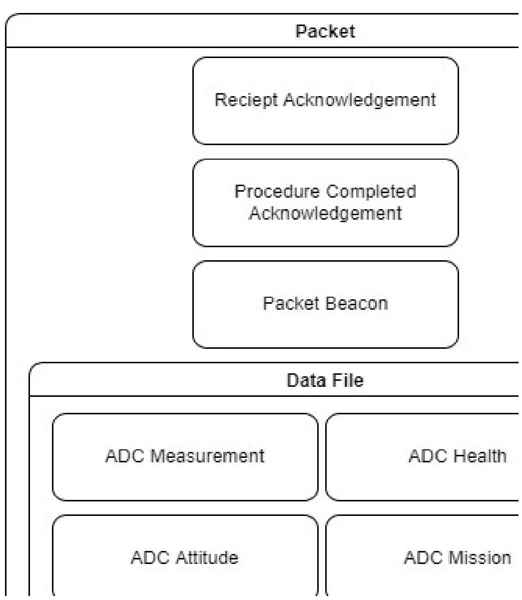

Figure 7: ARMADILLO Downlink Packet Structure

Finally, the data files are deserialized via a protobuf that indicates what file type they are, and then the payload is passed to the specific file protobuf file for deserialization. For commanding, the command is serialized with a given operational code and the arguments.

ARMADILLO Acknowledgements

Using the Van Leer Station in the GT GSN and the packet spammer with a 6 second period, we were able to ping ARMADILLO on January 29th 2022. We received 85 receipt acknowledgements. The next few passes continued to return ACKs from ARMADILLO. Unfortunately, shortly thereafter there were some ground station maintenance issues that had to be resolved and delayed the contact attempts.

Figure 8 shows the spectrogram from the first pass with receipt ACKs. The plot has been doppler shifted so that the ARMADILLO beacons are directly down the center. The Van Leer ground station at this time implemented an RF relay to switch from the TX to RX. This is evident from the lines that run across the entire plot when the ground station switches from the loud TX end to the RX end.

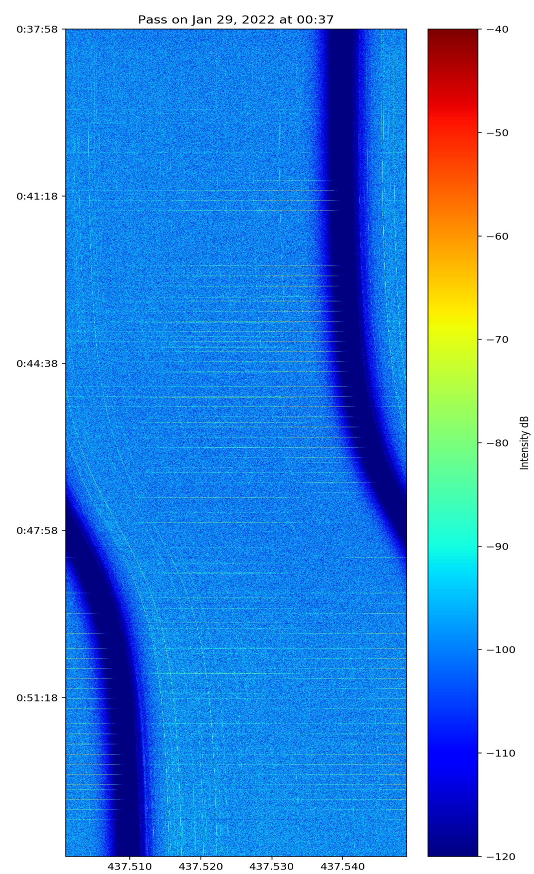

Figure 8: ARMADILLO First ACKs

These initial ACKs confirmed that the command structure and serialization method for the new commanding software was working appropriately. The next step was to begin commissioning ARMADILLO by requesting the initial deployment data and performing a health checkout.

This is a non-trivial task, as ARMADILLO has been on orbit 1,044 days as of May 2022 and has been logging health data for the entire time frame. ARMADILLO currently has 29.72 megabytes of health data onboard.

ARMADILLO Data Downlink

Per data downlink ARMADILLO enqueues and packetizes up to the first megabyte of data onboard and downlinks them as quickly as possible over radio. The most packets seen in a data downlink thus far for ARMADILLO was 1350 packets in one pass as seen in Figure 9.

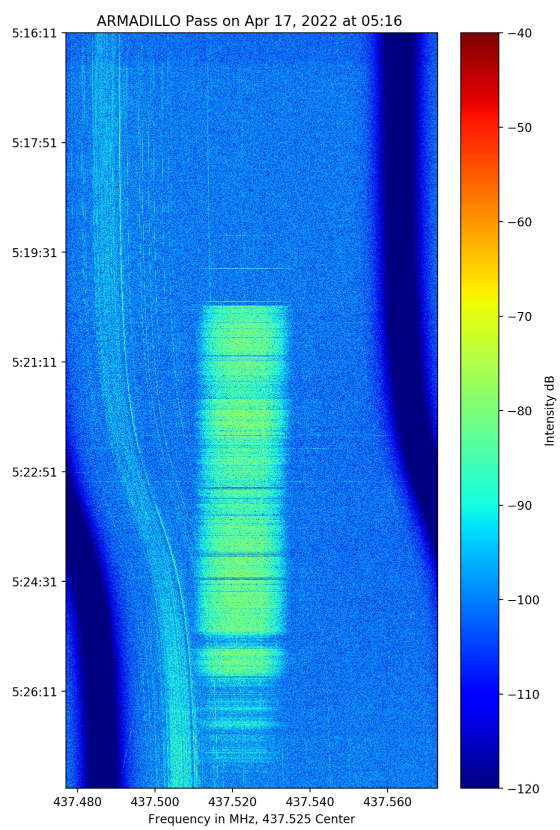

Figure 9: ARMADILLO Data Downlink

This resulted in a total data transfer of approximately 321,600 bytes from onboard NVMe. A consistent downlink every pass of this size would take ~93 passes to gather all the onboard health data. The available onboard non-volatile memory can be seen in Figure 10.

A key issue that prevents us from performing consistent data downlink contacts is the onboard power. After performing four contacts for data downlink sequentially, ARMADILLO went into safe mode due to continued data downlink after the contact window. The most important data onboard is the LEOP data before the first watchdog reboot after not establishing contact with the ground. This data is prioritized, and the rest will be deleted.

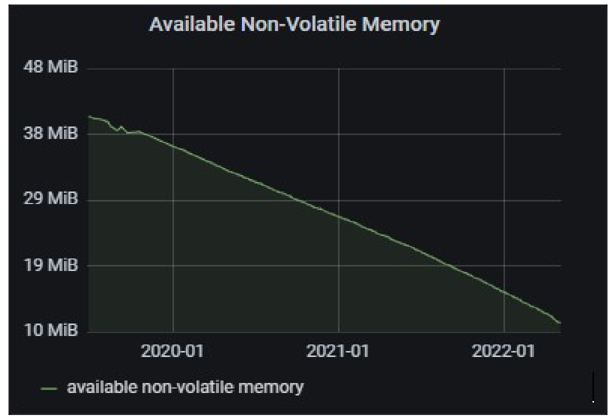

Figure 10: ARMADILLO Available NVME

ARMDILLO Hard Reset

Once ARMADILLO was put into safe mode by exceeding the minimum voltage limit by the last data downlink, it was expected to recharge and come back online after ~4 days based on a charging profile derived from the health beacon data. When it did not return after 7 days a hard reset was issued, and ARMADILLO came back online. ARMADILLO's methodology for handling power states can be seen in Figure 11.

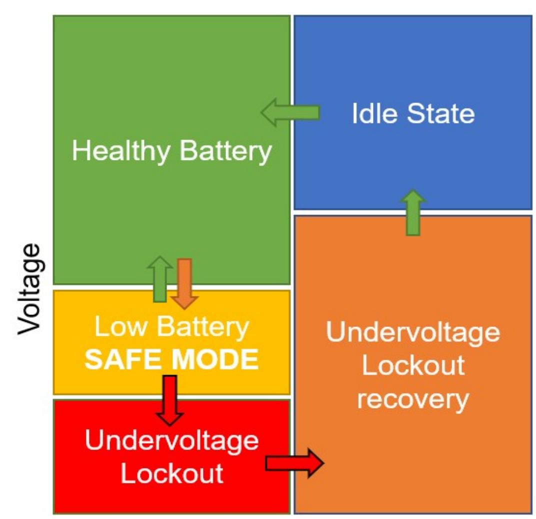

Figure 11: ARMADILLO EPS Failsafe Mechanism

The current analysis of the telemetry surrounding the shut down time shows that it is likely that ARMADILLO exceeded the safe mode limit by continuing to attempt to downlink mission data and went into undervoltage lockout (UVLO). Then after the undervoltage lockout recovery, ARMADILLO sat in the idle state and did not re-enable the beacon.

CURRENT STATE

One of the preliminary concerns after deployment was that ARMADILLO was tumbling relatively fast, ~27.4 degrees per second about the worst axis, and the detumble needed to be executed before the two-day ground contact watchdog rebooted ARMADILLO. This did not occur due to the aforementioned ground station blockers, and ARMADILLO has continued to spin since as the ADCS is not re-enabled after a watchdog reboot. This spacecraft spinning causes the data downlink to have inconsistent RSSI and makes consistent contact a challenge.

ARMADILLO has also experienced a number of Single Event Upsets (SEUs) over the last two and a half years. A minimum of 6 SEUs have been recorded in Table 1.

Table 2: ARMADILLO Documented SEUs

Field Affected	Time
Battery Voltage	08-07-2019
Battery Voltage	03-27-2020
EPS Temperature 4	08-23-2020
X Axis Rotation Rate	08-23-2020
Spacecraft Brownout	02-22-2022
Onboard Time	Unknown

Otherwise, ARMADILLO has remained healthy and in good condition. The battery has remained in a nominal state, and the watchdog reset every two days (without contact) has cleared the system of SEUs after they have occurred. The only lasting SEU impact has been on the onboard clock, as the Foton GPS has not been enabled to update it. This has overall not had a large impact on the commanding attempts, as the time offset from current epoch time to onboard epoch time has been established.

Historical TLEs and Orbit Health

The historical TLEs for ARMADILLO were pulled from SpaceTrack for an inspection of orbtial health. [7] From this dataset the altitudes of the apogee and perigee were calculated and plotted in Figure 12. As can be seen in this figure, ARAMDILLO's orbit is circularizing as the apogee drops to meet the perigee. The perigee overall has only dropped ~23 kilometers, while the apogee has dropped ~311 km.

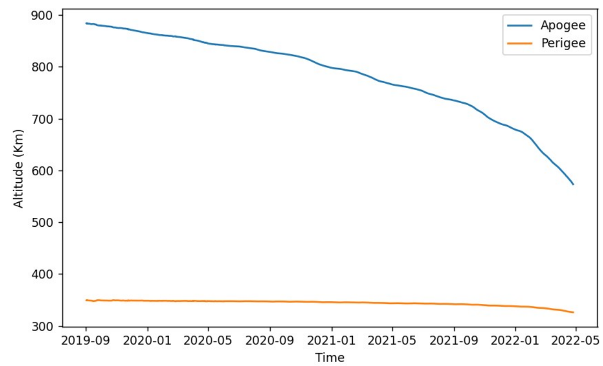

Figure 12: ARMADILLO Altitude vs Time

SatNOGs Data

For battery health ARMADILLO has not dropped below 15.03 volts, other that the presumed UVLO during mission data downlink. The average recorded battery voltage is 16.542 volts, and the case in which the battery dropped to 15.03 volts was due to a thermal battery protection mode triggered by a system brownout when the orbit had its largest eclipse fraction.

A graph of ARMADILLO's battery history can be seen in figure 13. In the plot you can clearly see the SEUs that made the battery voltage return as 0, and in more recent time the drop and recovery form the brownout. The red line is the trigger for safe mode.

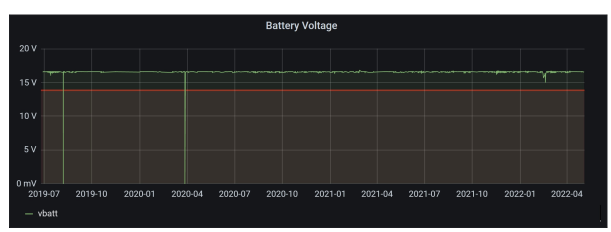

Figure 13: ARMADILLO Battery Voltage

Similarly, the EPS has red keep out zones for the minimum and maximum temperature ranges. As can be seen in Figure 14, the temperature ranges onboard are within the constraints except for the SEU experienced on 08-23-2020 and the drop in temperature after the brownout on 02-22-2022 where the temperature remained just below the operational range for 5 days.

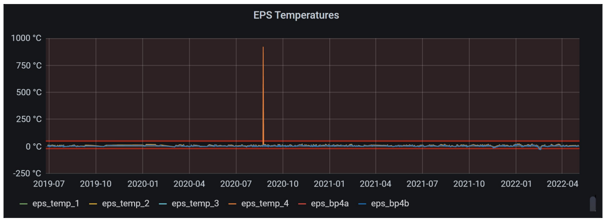

Figure 14: ARMADILLO EPS Temperature

From the ARMADILLO input current in Figure 15, it is evident that the spacecraft is still spinning, and that the average input current is 63.52 mA. Although this is rather low, the EPS output currents on record are even lower. From Figure 16, the average system current draw is just 28.88 mA.

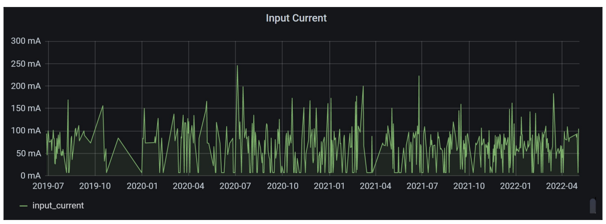

Figure 15: ARMADILLO Input Current

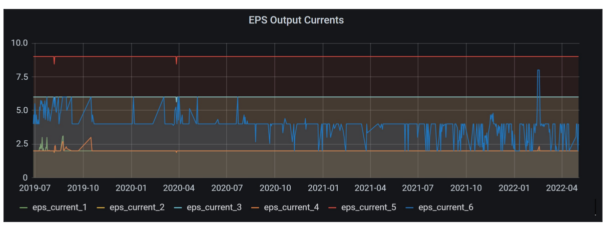

Figure 16: ARMADILLO EPS Output Current

Overall, the Spacecraft is in good health. The concerns currently surround the ADCS and the Foton GPS. The ADCS has been off since the initial deployment, and there is concern that it may no longer operational. The ADCS is responsible for waking the Foton for GPS updates at set intervals, as the Foton is too hot to be left on. There is also worry that the Foton's coin cell battery is dispensed and will prevent ARMADILLO from getting a GPS fix. This unfortunately would prevent ARMADILLO from performing the Radio Occultation Science.

Due to an SEU as previously mentioned, ARMADILO's onboard clock believes it is September 17th, 2002. This can be either reset with a command or the Foton GPS once it receives a lock. Finally, the last main concern with ARMADILLO's ADCS is that the onboard International Geomagnetic Reference Field (IGRF) model expired in 2020.

STEPS FORWARDS

Georgia Tech is leveraging its involvement in a number of high-profile CubeSat missions to build out a more robust set of ground stations and to integrate the GT GSN with the Georgia Tech Mission Operations Center (MOC). Currently ARMADILLO commanding is a completely autonomous operation, but soon the GT GSN will have real-time commanding capability in addition to the autonomous capability from the central GT MOC.

For ARMADILLO the autonomous commanding capability currently implemented is relatively rudimentary. To ensure that commands get uplinked, the command time is set in the future and the packet is sent repeatedly. To remedy this the ground command software for ARMADILLO will repeatedly ping the spacecraft until a confirmation ACK is received, then it will proceed to uplink a preloaded sequence of commands for any given contact until a reception ACK is confirmed. This will allow for much more complex choreographed subsystem checkouts and will ensure overall spacecraft safety.

In addition to the commanding tool, the current downlinked data per pass is saved to box. This is excellent as an archive, however, does not provide a quick and simple display like the SatNOGs pipeline does. To remedy this, an internal server has been set up in the GT MOC to host this information and to provide an access point for real-time displays.

Commands with Arguments

As of May 2022, the GT GSN is testing a time set command for ARMADILLO that will validate the implementation of commands with arguments. This is critical for enabling the subsystem power and collecting science data. This however will not validate the SET_ADC_MODE_FILE command, as that command has its own serialization file and will require further testing.

ARMADILLO Checkout

For ARMADILLO checkout to be deemed as complete there is a series of steps that must occur. First the complete data downlink of the first two days of ARMADILLO's lifetime must be downlinked and processed. This both requires good data downlink passes, and the packet re-request functions to operate as expected.

Once the initial data downlink is complete, then the onboard health data can be purged. This will enable easy downlink of data from the checkout tests. Once the health data is purged, subsystem health tests must occur. These tests consist of power cycling the subsystems and ensuring that the data downlink shows subsystem health. These general health tests can be done relatively quickly with the exception of the ADCS.

Before the ADCS general health test can be conducted, an analysis of the expired IGRF model must be done. Once that is complete, the desired mode file must be uplinked and validated. Finally, during a live pass, ARMADILLO must enable and disable the ADCS for a very short window, and a data downlink executed. Once the ADCS is deemed 'Safe', then ARMADILLO will be commanded into a communications pointing mode.

CONCLUSION

ARMADILLO has beaten all the odds. A mission that has gone through numerous turnovers, internal strife, and a slew of onboard issues, yet it still has the potential to accomplish its original goals. As of May 2022, none of the onboard issues seem to be show-stoppers. ARMADILLO has also demonstrated its robustness through SEU recovery, Undervoltage Lockout, and Thermal control. The mission still has life to it, and there is a clear-cut plan of action to get the spacecraft in a state to produce the science that it is theoretically capable of.

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