Integration, Launch, and First Results from IDEASSat/INSPIRESat-2 – A 3U CubeSat for Ionospheric Physics and Multi-National Capacity Building

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ABSTRACT

The Ionospheric Dynamics and Attitude Subsystem Satellite (IDEASSat) is a 3U CubeSat carrying a Compact Ionospheric Probe (CIP) to detect ionospheric irregularities that can impact the usability and accuracy of global satellite navigation systems (GNSS), as well as satellite and terrestrial over the horizon communications. The spacecraft was developed by National Central University (NCU) in Taiwan, with additional development and operational support from partners in the International Satellite Program in Science and Education (INSPIRE) consortium. The spacecraft system needed to accommodate these mission objectives required three axis attitude control, dual band communications capable of supporting both tracking, telemetry and command (TT&C) and science data downlink, as well as flight software and ground systems capable of supporting the autonomous operation and short contact times inherent to a low Earth orbit mission developed on a limited university budget with funding agency-imposed constraints. As the first spacecraft developed at NCU, lessons learned during the development, integration, and operation of IDEASSat have proven to be crucial to the operation of a sustainable small satellite program. IDEASSat was launched successfully on January 24, 2021 aboard the SpaceX Falcon 9 Transporter 1 flight. and successfully began operations, demonstrating power, thermal, and structural margins, as well as validation of uplink and downlink communications functionality, and autonomous operation. A serious anomaly occurred after 22
days on orbit when communication with the spacecraft were abruptly lost. Communication was re-established after 1.5 months for sufficient time to downlink stored flight data, which allowed the cause of the blackout to be identified to a high level of confidence and precision. In this paper, we will report on experiences and anomalies encountered during the final flight model integration and delivery, commissioning, and operations. The agile support from the international amateur radio community and INSPIRE partners were extremely helpful in this process, especially during the initial commissioning phase following launch. It is hoped that the lessons learned reported here will be helpful for other university teams working to develop spaceflight capacity.

INTRODUCTION

Since its establishment in Taiwan in 1962 as an outgrowth of the 1957/1958 International Geophysical year, which saw the launch of the first artificial satellites to study the near-Earth space environment (ionosphere and magnetosphere), National Central University (NCU) has had a strong focus on space physics, satellite remote sensing, and payload development. One important scientific need in the field of space weather is the need for an increased number of in-situ observations of the ionosphere (60 – 1000 km altitude). Ionospheric plasma significantly refracts and/or attenuates radio frequency (RF) signals ranging from the Medium Frequency (MF, 300 kHz – 3 MHz) and High Frequency (HF, 3 – 30 MHz) bands that are used for terrestrial over the horizon communication, as well as the L-band (1 – 2 GHz), S-band (2 – 4 GHz), C-band (4 – 8 GHz), and X-band (8 – 12 GHz) frequencies that are used for satellite navigation and communications. In response to this need, the NCU Department of Space Science and Engineering has developed the Advanced Ionospheric Probe (AIP) in-situ plasma sensor that has been operational on the large FORMOSAT-5 spacecraft since September 2017 [1]. To increase opportunities for flight, as well as the number of observations available, AIP has been further miniaturized into the Compact Ionospheric Probe (CIP), with a mass of 0.47 kg and a size of 0.72 U (10 x 10 x 7.2 cm).

To develop spacecraft engineering capacity at NCU, the Ionospheric Dynamics and Attitude Subsystem Satellite (IDEASSat) was proposed in response to the Taiwan Space Industry Pioneering Project defined by the National Space Organization (NSPO) in 2017. The mission was envisioned to serve as a platform for in-situ ionospheric measurements using CIP, as well as an opportunity for project-based learning in spacecraft design and the first iteration of an NCU developed satellite avionics system. The project was approved and initiated in 2017, with the preliminary and critical design phases taking place between 2017 – 2019, and flight model fabrication, integration, and test taking place from 2019 – 2020. The delivery deadline mandated by the selected SpaceX Falcon 9 launch was November 27, 2020. The development team was comprised almost entirely of graduate and upper division undergraduate students under the supervision of the PI. IDEASSat is the second spacecraft of the International Satellite Program in Research and Education (INSPIRE) consortium [2].

SPACECRAFT DESIGN & CONCEPT OF OPERATION

In this section, the IDEASSat flight model design and concept of operation is summarized. The reader is referred to Duann et al. (2020) [3] for a more detailed description. Key specifications required to support CIP observations included requirements for attitude control and knowledge less than 0.25° on all three axes, as well as the need to downlink 193.5 MB of science data per day at 100% duty cycle. The orbit is a 500 km Sun synchronous orbit (SSO), which allows for 4 passes over the NCU ground station per day, with a total of less than 40 minutes per day during which direct communications are possible. A mission duration of 1 year is required in order to resolve seasonal ionospheric variations.

A spacecraft is comprised of multiple subsystems, including attitude determination and control (ADCS), telecommunications (COMM), electrical power (EPS), command and data handling (C&DH), structure (STR), and thermal control (TCS). The IDEASSat spacecraft system is a combination of subsystems developed in-house at NCU with INSPIRE partners, as well as commercial off the shelf (COTS) components. The development strategy was to procure high technological readiness level (TRL) COTS components with prior flight heritage for subsystems with specifications that exceeded those that could be expected to be developed in-house in the allocated three-year project duration.

The subsystem solutions and current TRL for IDEASSat are listed in Table 1, while the structural design and body coordinate frame are shown in Figure 1. It can be seen that IDEASSat is a 3U CubeSat with two deployable and one body mounted (not shown) solar panels.

The spacecraft utilizes the COTS XACT ADCS unit from Blue Canyon Technologies, which integrates sensors including a star tracker, magnetometers, GPS receiver, coarse Sun sensor (CSS), inertial measurement unit (IMU), and actuators including 3 reaction wheels and 3 magnetorquers to provide the high level of 3-axis attitude control necessary for both inertial, local velocity local horizon (LVLH), and surface target pointing.
Table 1: IDEASSat Subsystems. Subsystems developed in-house denoted by asterisk.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Solution</th>
<th>TRL (2021/05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCS</td>
<td>Blue Canyon Technologies XACT</td>
<td>9</td>
</tr>
<tr>
<td>COMM (UHF)</td>
<td>SpaceQuest TRX-U Deployable monopole antenna*</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>AzurSpace TJ Solar Cell Assembly 3G30A</td>
<td>9</td>
</tr>
<tr>
<td>COMM (S-band)</td>
<td>SpaceQuest STX-C Transmitter SANT Patch Antenna</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>NCU EPS (controller board &amp; 18650 Li-ion battery pack)*</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>AzurSpace TJ Solar Cell Assembly 3G30A</td>
<td>9</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>NCU CDH Interface Board*</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Microsemi SmartFusion 2 System on Module</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Flight Software*</td>
<td>9</td>
</tr>
<tr>
<td>STR</td>
<td>NCU 3U Bus*</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 1: IDEASSat structural design and body frame coordinates. Body mounted panel removed to expose interior avionics.

Dual frequency communications are implemented using an ultra-high frequency (UHF) transceiver and S-band transmitter, both of which are COTS. To satisfy the tracking and telemetry requirements of the spacecraft, IDEASSat uses a SpaceQuest TRX-U transceiver and a deployable monopole tape measure antenna, the latter of which was manufactured in house. The lower 9600 bps data rate of the TRX-U is sufficient to satisfy transmission of the short beacon packets the spacecraft normally transmits to facilitate tracking and downlink of housekeeping data, as well as the reception of short command packets uplinked from the NCU ground station. The more omnidirectional antenna pattern of the monopole antenna ensures that beacon downlink and command uplink are possible without the need to point the main lobe at the ground station. For the larger volume science data, a CPUT STX-C transmitter is used with a higher data rate of 2 Mbps. This requires the use of a higher gain patch antenna located on the +Y face of the spacecraft, with a corresponding narrower beamwidth. This requires the antenna to be pointed at the ground station during data transmission, which is accomplished by slewing the entire spacecraft.

The EPS consists of the aforementioned solar panels, as well as a controller board (Figure 2) to facilitate power distribution, hard reset, and overcurrent protection, as well as a battery pack with four lithium-ion cells. All of these were designed and fabricated in-house, with the exception of the solar cells, which were procured from AzurSpace.

Figure 2: IDEASSat EPS controller board.

The C&DH consists of an on-board computer (OBC, Figure 3) running flight software (FSW) facilitating the autonomous operation of the spacecraft, both of which were designed in-house. The OBC includes a COTS Microsemi SmartFusion 2 System on Module (SOM), interfaced with an NCU-developed interface card. The SmartFusion 2 includes an ARM Cortex M3 processor, FPGA, RAM, real time clock (RTC), and watch dog circuit to ensure hard reset in the event of a flight software hang. The interface card provides interface hardware and protocols between the SmartFusion 2 and the other spacecraft subsystems, redundant RTC and watchdog, as well as two SD Cards upon which science and flight data are stored.

FSW was implemented in-house using C, Verilog, and assembly language, and includes the following two emergency and three nominal operational modes. Each mode allows for autonomous operation and power cycling of relevant subsystems.
Emergency operational modes are intended to minimize power consumption in the event of low charge, or anomalous events detected by FSW:

- Phoenix Mode: Very low power mode with no attitude control. Used at boot up, as well as at very low state of charge (SOC).
- Safe Mode: Low power mode with attitude control to point solar panels at Sun to maximize charging. Used if SOC > 40%

Nominal operations allows for the execution of the science mission:

- Science Mode: CIP is oriented in ram direction for science data collection. Used in eclipse.
- Charging Mode: Solar panels are oriented toward Sun to maximize charging when the spacecraft is in sunlight. Spacecraft is slewed to orient S-band antenna at selected ground stations when within line of sight to facilitate science data downlink.
- Transition Mode: Used during transition between Science and Charging modes.

Transition from Emergency to Nominal Operations only takes place upon uplink of the corresponding command from the NCU ground station as a safety precaution. Beacon packets with flight data are saved to the SD cards as they are transmitted to form a flight data log that can be replayed upon command. Beacon packets are transmitted and saved every 30 seconds in all modes, except for Phoenix mode, which uses a 60 second beaconing period to save power.

The spacecraft structure was designed and fabricated in-house using aluminum 6061. To ensure survival during the high loads and vibrations during launch, all fasteners, connectors, and harnessing on the spacecraft were epoxied or staked during flight model (FM) assembly. The only active thermal control aboard the spacecraft is a kapton heater in the battery pack, which has the narrowest operational temperature range of all the subsystems.

**FLIGHT MODEL (FM) INTEGRATION & TEST**

By December 2019, self-developed subsystems satisfying system requirements were fabricated after multiple iterations and COTS subsystems acquired. However, several more iterations of self-developed subsystems were found to be required during the integration process, as multiple instances of subsystem conflicts were experienced over the next five months. Time was also required for the student teams to familiarize themselves with COTS subsystems, as well as operation and testing methods. Ground support software to decode received beacon and science data packets, as well as to encode and uplink commands was implemented using the Matlab Runtime Environment. Signal processing software for modulation/demodulation of UHF transmissions was implemented using GNU Radio, as shown in Figure 4. S-band downlink was implemented using a COTS Teledyne Paradise Datacom satellite modem, due to the self-developed GNU Radio software exhibiting an unacceptably high bit error rate. The RF front end for the UHF ground segment was implemented using a USRP B210 software defined radio (SDR).

![Figure 4: UHF beacon decoding and signal processing software.](image)

Multiple fit checks were performed to develop the flight model integration procedure, as well as to ensure that the manufacturing tolerances of the spacecraft components was within an acceptable level.

The final FM components and integration procedure were ready by mid-August 2020. FM integration took place over the course of four days from August 21 – 24 with student operators in full anti-static protection gear in a bio cabinet to ensure cleanliness. The completed FM can be seen in Figure 5.
Following integration, environmental and functional testing were performed to ensure that the spacecraft would be capable of surviving the launch and orbital environments, as well as to verify that the core functions of the spacecraft required for execution of the mission were correctly implemented. Per SpaceX Falcon 9 Rideshare requirements [4], the spacecraft was subject to vibration and quasi-static load testing on all three axes, while integrated in a deployment pod. Resonance surveys were performed before and after the tests to verify that no significant changes in resonant modes had occurred, which would signify structural changes. A thermal vacuum test was also performed utilizing one survival and eight operational cycles, shown in Figure 6 and Figure 7.

Functional tests performed included end to end tests to verify uplink and downlink, solar charge tests, as well as a deployment test to verify that the spacecraft would correctly power on and deploy the UHF antenna and solar panels 30 minutes after deployment. It was found during the end-to-end tests in October 2020 that the UHF antenna was not impedance matched with the UHF transceiver, resulting in damage to the transceiver and loss of transmit capability. It was observed however, that the spacecraft FSW continued to remain active even when Tx capability was nonfunctional, and that the Rx functionality was not affected. Both the transceiver and antenna had to be de-mated from the spacecraft and returned for re-manufacturing and servicing. The spacecraft was re-integrated and requalified in mid-November 2020, before being delivered to the launch provider ISILaunch in the Netherlands just one week short of the November 27 deadline. The spacecraft was inserted into the deployer (Figure 8), which was then shipped to Cape Canaveral and integrated with the launch vehicle on December 22, 2020.

Figure 5: Completed IDEASSat FM with student operator.

Figure 6: Thermal vacuum test cycles.

Figure 7: IDEASSat inside thermal vacuum chamber with fixtures to ensure good thermal contact with heat exchanger.

Figure 8: IDEASSat inserted into launch deployer.
LAUNCH AND OPERATION

Launch and Deployment

IDEASSat was launched aboard the Transporter 1 flight of the SpaceX Falcon 9 on January 24, 2021. The spacecraft was successfully deployed and powered on, with the first beacon packet received by an amateur radio station in Germany approximately four hours after launch (T+4 hours). As can be seen in Figure 9, the spacecraft was verified to be operating in Safe mode with a very healthy battery SOC of 95.28%. It was also verified that the spacecraft was successfully engaged in Sun Pointing mode. These results demonstrated that IDEASSat had successfully engaged in 3-axis attitude control, and that the structural design of the spacecraft was satisfactory to survive the high stresses of launch.

![Figure 9: First IDEASSat beacon packet received at T+4 hours.](image)

Initial On-Orbit Performance

Over the next 22 days, IDEASSat was successfully tracked from the NCU ground station, INSPIRE partner stations, as well as by amateur radio stations of the SatNOGS network located around the world, producing 730 counts of flight data from orbit. The received flight data allowed for the performance of the spacecraft on orbit to be monitored and compared to values modelled during the design phase and produced during testing. During this time, the spacecraft remained in Safe mode pending commissioning with full 3-axis attitude control, resulting in a large power surplus and SOC consistently larger than 95%. The NCU ground station was initially unable to receive the spacecraft signals due to degraded performance from six years of outdoor exposure with minimal maintenance. Contact was successfully established after the degraded antennas, cabling, and low noise amplifiers (LNAs) were replaced. Uplink was initially also unsuccessful, and was found to be due to the output power from the USRP SDR being insufficient to drive the 80 W amplifier on the ground station transmit end. This anomaly was resolved by adding an additional preamplifier between the USRP and the amplifier input.

The thermal performance of the IDEASSat design is shown in Figure 10. Although the on-orbit temperatures are all within operational limits, a few interesting points can be observed. EPS and CDH are both located in the core PC-104 avionics stack of the spacecraft and show a temperature range higher than that predicted on the ground using Thermal Desktop simulations and during thermal vacuum testing. This may be attributable to the larger power draw of the spacecraft on orbit, compared to that simulated or in the thermal vacuum chamber, where regular UHF beaconing was not possible. The temperature range of the battery module on orbit was relatively lower than the two aforementioned locations despite being part of the same PC-104 stack, indicating that good thermal isolation was achieved. The temperature of the UHF transceiver was also considerably lower, despite regular power dissipation from beaconing. This was achieved by ensuring that the UHF transceiver was located in a separate compartment away from the PC-104 avionics stack, and was directly mated with the spacecraft chassis to ensure good thermal conduction.

![Figure 10: Thermal performance of IDEASSat battery module (Battery), solar panels (PV0: body mounted panel; PV1, PV2: deployable panels; UHF: UHF transceiver; EPS: EPS controller board; and CDH). Green bars indicate operational temperature range, turquoise bars indicate temperature range from thermal vacuum test (Tvac) and Thermal Desktop simulations (Predicted), blue bars correspond to temperature range measured on orbit.](image)
that of the body mounted panel (PV0), despite the fact that all three panels should theoretically be oriented in the same direction towards the Sun. Thermal Desktop simulations assuming incomplete deployment with different deployment angles showed that the two deployable panels were likely only deployed to between 30° - 45° of the stowed position. One possible cause for incomplete deployment could be increased friction from cold welding of the hinges. Another possible cause could be deformation of the hinge caused by the stress exerted by the warped solar panel PCBs, when forcibly flattened due to the contact of stoppers on both ends of the deployable panels with the guide rails of the deployer.

Another anomaly observed during this time was the initial inability of the XACT ADCS star tracker to produce a valid attitude solution. This was resolved at T+5 days when the ADCS was autonomously power cycled by FSW. This allowed the spacecraft to engage in fine reference pointing, although the uncertainty in the attitude solution was still classified as sub-optimal, potentially due to partial blockage of the star tracker field of view by a partially deployed solar panel. No similar problems were encountered with the on-board GPS receiver, which combined with the ADCS built-in orbit propagator, continued to return valid position and velocity solutions throughout this time.

The altitude as determined from the on-board GPS position data included in the received beacon packets are shown as a function of time in Figure 11. The integrity of the received beacon packets was verified using a CRC-16 checksum test. Blue points correspond to values from packets that passed the checksum test, indicating that all the data contained within was correctly received. Red points correspond to values from received packets that failed the checksum test and have the potential to be incorrect. It can be seen that the large outlying values correspond to packets that failed the checksum test, although not all of the data from a packet with bit errors is necessarily incorrect.

It is also apparent that the packet error rate jumped significantly after February 3, 2021. IDEASSat FSW is designed to transmit one of three different beacon packet formats: a normal 255 byte packet, a lite version which consists of the normal packet split into nine smaller packets to force constant resynchronization, and a 60 byte short packet. The rationale for the two smaller packet formats was to reduce the packet error rate (PER), since PER is proportional to packet length. Although a change in packet format can only be performed by ground command, this change occurred with no such command being uplinked and can likely be explained by a single event upset (SEU) from energetic particle impact occurring at the memory address where the corresponding FSW flag was stored [6].

Another anomaly that was observed corresponded to a rapid increase in the command reject count recorded by FSW, shown in Figure 12. Note that the count is mod 255. Rejected commands correspond to packets received by the spacecraft with the correct frequency and sync word that do not match the spacecraft command format. A possible explanation could be inadvertent reception of amateur packet radio traffic with characters matching the sync word used by IDEASSat. A widespread, global effort to repeatedly hack the spacecraft seems unlikely.

Work continued to be performed during this time as part of spacecraft commissioning to verify that the spacecraft and ground station functions required to execute the science mission were in place to begin nominal operations of CIP. This included verification of UHF uplink and downlink, S-band downlink, fine reference pointing mode, and adequate SOC. It was initially targeted to complete commissioning within the first month after launch.

Communication Blackout, Recovery, and Anomaly Analysis

Contact with IDEASSat was abruptly lost on February
15, 2020, following a successful pass over the NCU ground station at 01:40 UTC. No signal was received during a pass the same evening, despite a high elevation angle over 40°. The last beacon signal was received the same day at 04:09 UTC by an amateur ground station located in northwestern Canada. No further signals were received by any ground stations during the blackout, clearly indicating the fault that occurred on the spacecraft end.

Figure 13 shows the ground track of IDEASSat on February 15 for the five orbits recorded following the final contact with the Canadian ground station. As IDEASSat was routinely received by SatNOGS ground stations located in Europe, the time at which the fault occurred can be constrained to the time between the final contact and the first pass over Europe, which corresponds to four orbits across a period of six hours. During this time, the spacecraft passed through both auroral ovals, as well as the South Atlantic Anomaly, where the energetic particle flux is higher. The space weather during this time period was quiet, with no geomagnetic storms or solar flares.

![Figure 13: Ground track of IDEASSat on the five orbits following the final recorded contact before the UHF COMM blackout on February 15, 2021. Arrows denote the orbits during which the fault causing the blackout occurred.](image)

Several attempts were made to reestablish contact with IDEASSat. Commands for system reboot were transmitted during subsequent passes, in hopes to clear any potential FSW hangs. Commands were also uplinked to replay stored flight data via the S-band transmitter, in hopes of retrieving diagnostic data in the event of a failure in UHF transmit capability. Such attempts at S-band downlink were also scheduled during short 2 minute windows during which the position of the NCU ground station relative to the spacecraft was in the anti-sunward direction. Since the S-band antenna is located on the face of the spacecraft opposite that of the solar panels, which should be consistently pointing toward the Sun, it was hoped that this would allow for an S-band link to be established even if the ADCS was incapable of fine reference pointing. None of these attempts was successful.

During this period, a comprehensive review of the flight data downlinked before the blackout was performed, along with fault tree analysis to identify the cause of the blackout. One anomaly that was immediately the focus of attention was the anomalously high number of commanded reboots of the UHF transceiver by FSW. As shown in Figure 14, by the time of the blackout, the UHF transceiver had been rebooted a total of 13 times by FSW, far exceeding the single reboot of the ADCS, which was the only other subsystem to be rebooted by FSW. Conditions that can trigger a reboot of the UHF transceiver by FSW include anomalous telemetry returned by the transceiver to C&DH, non-response of the transceiver to commands sent by FSW, as well as telemetry from the EPS showing under-voltage or overcurrent provided to the UHF. Three possible failure mechanisms were proposed, with the first mechanism receiving the highest level of suspicion, given the number of reboots and the rushed servicing and re-integration of the UHF transceiver following the impedance mismatch incident:

- UHF Transceiver internal failure.
- FSW hang not recoverable by the dual watchdog circuits in C&DH.
- EPS internal failure.

After 1.5 months of silence, IDEASSat abruptly began beaconing again on April 2, 2021 and was received by the NCU ground station and several SatNOGS ground stations. Commands were successfully uplinked to replay stored flight data during this time. The final signal before a second blackout was received on April 5.

![Figure 14: UHF transceiver reboot count recorded in downlinked flight data.](image)

Analysis of the retrieved flight data drastically altered the assessment of the failure mechanism. Observed symptoms and clues include:

- The anomalously high UHF subsystem reset count.
- The fact that FSW was not operating and
logging data during the blackout, indicating that the spacecraft was likely powered off for the 1.5 month interval. As observed previously during the impedance mismatch anomaly on the ground, FSW would continue to function even in the event of a transceiver anomaly.

- There was no record of commanded reboots of the spacecraft by FSW, indicating that the power cycle and reboot were un-commanded.
- The 1.5 month blackout time, as opposed to a commanded or watchdog reboot, which would be completed within seconds.
- The first beacon packet received following the blackout showed an SOC of 85%, which was much lower than that observed during the first 22 days of operation. This suggests the possibility of reboot through full or deep battery discharge.
- Degrade UHF signal to noise ratio (SNR) following reboot.
- The second blackout after 4 days of operation.

The fact that the blackout was caused by a full power down of the spacecraft led to more in-depth analysis of possible single point failures on the EPS. A Single Gate CMOS Schmitt trigger inverter used in the EPS reset circuit was identified as such a point.

The schematic of the reset circuit is shown in Figure 15. A Schmitt trigger inverter (G1) forms a crucial component of the reset circuit. In the event that FSW commands a system wide power cycle (CDH_Reset), the output of a solid state relay (Q2) connected to the inverter input is pulled high. The inverter output connected to a solid state relay (Q4) is then pulled low, switching off the relay and disconnecting the main power bus from the battery, thus powering down the spacecraft. CMOS devices are at risk of a single event latchup (SEL) in the event of an energetic particle strike. In the event of an SEL, the power supply rails of the CMOS device will effectively be shorted out (red arrow), causing the spacecraft to power down until the latchup is cleared [6]. Permanent damage can occur if the overheating is sufficient to result in burnout.

An SEL is normally cleared by power cycling the device. However, a shortcoming of the IDEASSat EPS design was identified, in that the CMOS in question remains connected to the battery and powered following deployment (light blue trace). The latchup can therefore only be cleared through natural discharge of the battery to the point where it cannot provide enough current to sustain the latchup condition, which is consistent with the flight data showing an extended power down with evidence of deep battery discharge. The failure matrix analyzing the three possible mechanisms shown in Figure 16 shows to a high probability that the 1.5 month blackout was caused by a sustained latchup of this main power bus CMOS IC, with recovery occurring after sufficient battery discharge.

<table>
<thead>
<tr>
<th>Symptom / Failure Mechanism</th>
<th>Reboot Circuit CMOS Single Event Latchup</th>
<th>FSW Hang</th>
<th>UHF Internal / Power Anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomalous UHF Subsystem Reset Count</td>
<td>Possible undervolt / over current to UHF TIE</td>
<td>Would result in system reboot, not subsystem reboot.</td>
<td>Could be result of anomalous UHF telemetry / non-ideal power supply.</td>
</tr>
<tr>
<td>Un-commanded Non-Watchdog Power Cycle</td>
<td>Would result in short circuit and battery drain causing power cycle.</td>
<td>Trigger of one of two watchdogs should result in incremented reboot count.</td>
<td>Would require 30 UHF subsystem resets to trigger reboot recorded by FSW. Blackout after 12.</td>
</tr>
<tr>
<td>Non-functional FSW Flight Data Logging During Blackout</td>
<td>System cannot be powered during SEL and with drained battery.</td>
<td>Consistent, but not for one month.</td>
<td>FSW beacon logging not affected by UHF non-function during blackout.</td>
</tr>
<tr>
<td>One Month Blackout Time</td>
<td>Depends on discharge time and time to recharge while tumbling.</td>
<td>Dual watchdogs would have reset system over much shorter time (TBD).</td>
<td>Not consistent with FSW non-function during blackout.</td>
</tr>
<tr>
<td>Potential Full Battery Discharge</td>
<td>Would result in short circuit and battery drain causing power cycle.</td>
<td>Dual watchdogs would have reset system over much shorter time (TBD).</td>
<td>UHF short circuit would trigger overcurrent protection. Not consistent with FSW non-function.</td>
</tr>
<tr>
<td>Degraded UHF SNR Following Recovery</td>
<td>Possible degradation in EPS stability (TBD).</td>
<td>Not consistent with FSW hang.</td>
<td>Could result from degraded internal components.</td>
</tr>
<tr>
<td>Repeated Blackout 4 Days After Recovery</td>
<td>Consistent with degraded CMOS performance due to SEL and short (TBD).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 15: Reset circuit schematic for IDEASSat EPS. Light blue trace denotes direct connection between battery and CMOS Schmitt trigger inverter that is not latchup resistant. Red arrow denotes path between Schmitt trigger inverter power and ground that is at risk of latchup.](image)

The need to ensure that all key circuits are latchup-proof is an important lesson learned. Revisions have been made to the EPS design to implement overcurrent protection across the inverter power line to ensure that any latchup will result in the inverter power supply being cut. A two-step reset concept is also being implemented, wherein the inverter is normally in a powered down state, being powered up only in the event a reset is commanded. The inverter is not at risk of latchup when in a powered down state. Radiation tests using proton
bombardment will also performed for the revised C&DH EPS stack to verify the new design [7], as well as longer duration stress tests.

Although the science mission remains uncompleted as of this writing time, partial accomplishment of mission objectives is still gratifying for the first university spacecraft developed at NCU, especially considering that close to 40% of CubeSats are never heard from after launch [8]. Following this lesson learned, the EPS main power bus circuit was redesigned to ensure that power to the CMOS IC will be cutoff in the event of a latchup, ensuring that this fault will not occur in future spacecraft currently in development at NCU. The NCU ground station continues to track IDEASSat in the event the spacecraft recovers following the same annealing process.

CONCLUSIONS

In this paper, we report the design, integration, testing, and on-orbit performance of IDEASSat – the first of many spacecraft that will be developed at NCU. IDEASSat demonstrated success in surviving launch and verifying ADCS, autonomous operation, and duplex communication capabilities. The spacecraft also showed healthy thermal, power, and structural margins, validating the design and workmanship abilities of the student team. The spacecraft was found to be sensitive to single event latchups in the EPS reset circuit design, which is an important lesson learned for future spacecraft. Corrections have been applied to the EPS design to ensure that this fault is not present on future spacecraft developed at NCU, with the lessons learned from IDEASSat allowing for the continued development of NCU spacecraft avionics.

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References


