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A Deeper Look into the Ionospheric Scintillation eXplorer (ISX): A Failure Analysis

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ABSTRACT

The Ionospheric Scintillation eXplorer (ISX) mission is a collaboration between SRI International and Cal Poly. The ISX space weather investigation seeks to better understand the physics of naturally occurring Equatorial Spread F ionospheric irregularities by deploying a passive UHF radio scintillation receiver. Rocket Lab's Electron-4 launch vehicle successfully placed ISX into a nearly sun synchronous orbit 500km above the surface of the Earth, however contact was never made with the spacecraft. Since this anomaly, Cal Poly has taken an extensive look into the possible failure causes on ISX, including a system level fault tree and additional testing with the engineering test unit. The primary takeaway from the failure analysis is the importance of testing beyond what is considered normal for CubeSats. The second main conclusion reinforces the important role that adequately documenting the spacecraft design, fabrication, and testing plays in performing a post hoc failure analysis. In addition to presenting analysis outcomes, this paper addresses both of these main takeaways.

INTRODUCTION

The Ionospheric Scintillation eXplorer (ISX) mission is an NSF funded collaboration between Cal Poly's CubeSat Lab (CPCL) and SRI International. ISX seeks to better understand the physics of naturally occurring Equatorial Spread F ionospheric irregularities by deploying a passive UHF radio scintillation receiver. Plasma irregularities are naturally occurring ionospheric structures that can significantly degrade the performance of satellite-based communication and navigation systems. In particular, ionospheric storms causing major equatorial ionospheric disturbances strongly degrade Global Positioning System (GPS) signals over the equatorial regions.

ISX was launched on December 16th, 2018 as part of the ELaNa-19 mission. Rocket Lab's Electron-4 launch vehicle successfully placed ISX into a nearly sun synchronous orbit 500km above the surface of the Earth, however contact was never made with the spacecraft. Since this anomaly, Cal Poly has taken an extensive look into the possible causes of this failure mode on ISX, including a system level fault tree and additional testing with the engineering test unit.

The failure analysis included reviewing design, processes, procedures, and potential anomalies that may have slipped through the cracks. A methodic approach to failure analysis is even more important in a university setting due to the high turnover rates of students and the number of other activities vying for their limited time. Documenting failures, solutions, and lessons learned allows the organization to grow, rather than remain stagnant. The process begins by determining every possible cause of a no-contact condition on orbit, including all material, electrical, and software faults. Then, all available documentation is reviewed for any evidence that would provide insight into each possible cause. An additional benefit of this process is that it highlights specific areas where additional documentation or inspections are warranted. Additional testing, using the flight-similar engineering unit, is performed as appropriate. From there, the likely causes of the anomaly are identified, and process changes for future missions are put into place.

The primary takeaway from the failure analysis is the importance of testing beyond what is considered normal for CubeSats. The second main conclusion reinforces the important role that adequately documenting the spacecraft design, fabrication, and testing plays in performing a post hoc failure analysis. The remaining sections of this paper include a more detail description of ISX's mission, a more detail description of the spacecraft architecture, a recap of the most applicable branches in the fault tree, and a conclusion that addresses the main takeaways.

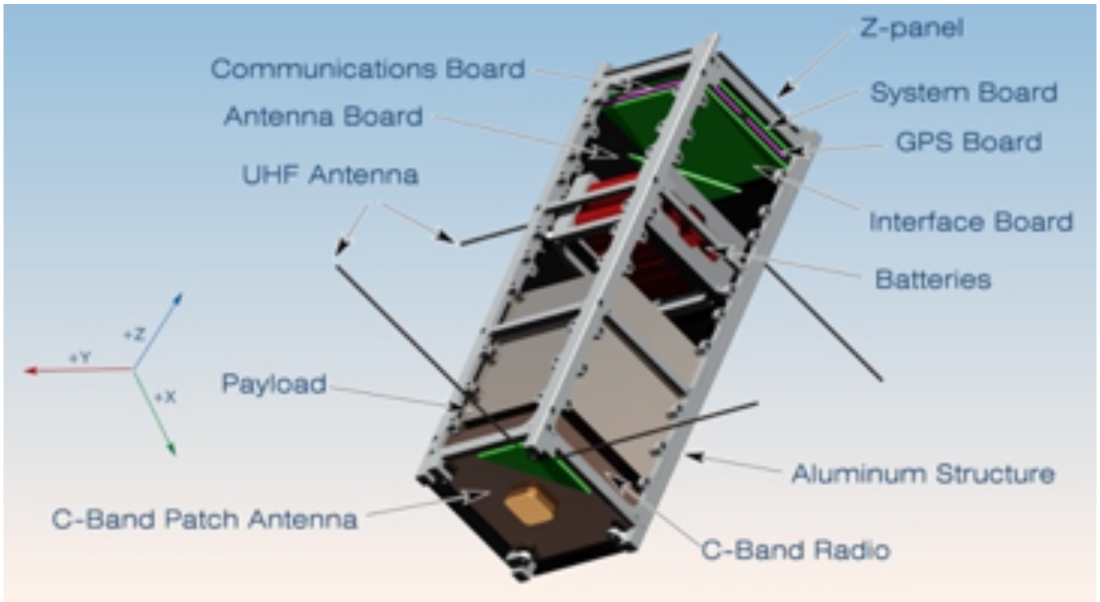

Figure 1: The physical layout of the 3U ISX CubeSat

ISX MISSION

ISX is an ionospheric passive UHF radio mission developed in response to NSF's 2014 CubeSat-based Science Missions for Geospace and Atmospheric Research solicitation. ISX mission goals are to better understand the physics of naturally occurring Equatorial Spread F ionospheric irregularities—a space weather phenomenon that can severely degrade the performance of U.S. national communication and navigation assets. Deploying a passive radio scintillation receiver, the ISX mission will acquire worldwide digital television broadcast signals with an on-orbit CubeSat radio receiver to yield a unique geometry for characterizing the climatology and evolution of 100-m-scale ionospheric structures—features inaccessible to ground-based observation. These globally observed ionospheric irregularities, driven by interaction of naturally occurring strong electric fields and ionospheric plasma gradients, result from a chaotic interplay of solar magnetic and ultraviolet forcing of Earth's upper atmosphere.

The ISX mission investigates ionospheric irregularities from multiple vantage points to gain insight into dissipation of Equatorial Spread F (ESF) structures, which have been measured only in two dimensions. By gauging the 3D distribution of these ionospheric irregularities, the ISX mission will advance the state of space weather forecasting.

SPACECRAFT DESIGN OVERVIEW

ISX is a 3U CubeSat [1], based on Cal Poly's in-house satellite bus design. Figure 1 shows the spacecraft's physical layout, identifying the key components. The primary C&DH board, with flight heritage on five other Cal Poly missions, combines traditional C&DH functionality with EPS and UHF communication support in a highly integrated package. The primary processor is an Atmel ATSAM91G45 running a heavily customized embedded Linux operating system. It provides general management of the satellite bus and provide an interface to the UHF radio that commands the satellite. It contains 64MB of redundant flight software storage. An additional 512MB of NAND flash memory and 8GB on a microSD card is available to store telemetry data.

The integrated UHF radio is combined with a near omni-directional L dipole antenna to serve as the primary radio for commanding the spacecraft. A second L dipole is located on the nadir pointing end of the satellite to serve as the 500-700MHz antenna for the ISX payload receiver. The UHF radio is capable of up to 1W of transmit power with years of operating heritage at 9600 bits per second.

The avionics bus incorporates a built-in EPS that includes a variety of electrical protection systems. Four 8.4W (on Sun nominal) 3U panels support power generation, and a standalone battery pack of nine Lithium-Ion cells provides 77 Wh of storage. The solar panels charge the battery pack at a nominal 11.1V with a maximum voltage of 12.6V. Power for the satellite is provided by 24 UTJ solar cells mounted on the side panels. All the cells on one panel are connected in series. Each panel is connected in parallel using direct energy transfer.

ISX uses six solar angle sensors, coupled with six tri-axis magnetometers to provide the system with 3-axis attitude determination. The spacecraft includes this variety of sensors to introduce redundancy and provide multiple measurements for the attitude filter. The orbital position of the spacecraft is determined using a GPS receiver which can utilize GPS and GLONASS constellations. This orbital position is used to assign a coordinate location and time to scientific measurements, and feed into the on-board IGRF magnetic field model used in conjunction with the attitude determination. Attitude control is achieved by a passive magnetic system consisting of natural magnets to align the satellite with the Earth's magnetic field.

The ISX payload was designed and fabricated by SRI International. It contains the sensitive SDR to observe the digital TV transmissions, a SATA III SSD storage device for recording data during an observation, a Tegra-3 processor for post-processing the data after an observation, and the necessary bus connections for moving the data around. Since it isn't important to the failure analysis, further details of the payload architecture are omitted from this work.

LAUNCH AND ANOMOLY

ISX was launched on December 16th, 2018 from Launch Complex 1 located in Mahia, New Zealand, as part of the ELaNa-19 mission. Rocket Lab's Electron-4 launch vehicle successfully placed ISX into a nearly sun synchronous orbit 500km above the surface of the Earth. Successful deployment was confirmed both by sensors on the launch vehicle and the number of distinct objects detected by radar tracking facilities.

ISX was configured to automatically deploy its antenna 165 minutes after separation from the launch vehicle, at which time it should begin autonomously transmitting a telemetry beacon every 7 seconds. Cal Poly began tracking ISX immediately after launch but was unable to observe the beacon or otherwise establish contact with the spacecraft. This early setback was initially attributed to the uncertainty caused by ISX being one in a cluster of fifteen spacecraft deployed at a similar time. As the days wore on and reports from amateur operators trickled in, it became increasingly clear the spacecraft was not transmitting. ISX was monitored for nine months from multiple geographically different tracking stations without observing a single transmission.

In addition to monitoring, Cal Poly attempted active recovery of ISX. The spacecraft is designed such that the radio, when not actively transmitting, is always listening for ground commands. This provides an opportunity to uplink commands even if the downlink RF chain isn't working correctly. Specifically, the command to deploy the antenna and turn on the transmitter was sent to ISX multiple times in case the on-board logic had malfunctioned. A basic link check, in the form of a "ping" command, was also attempted without success.

FAILURE ANALYSIS

Cal Poly undertook a months-long fault tree analysis [2] after it became clear the spacecraft was experiencing an anomaly. Although the analysis didn't identify a single responsible fault, the process and information generated is beneficial for future missions. During the course of the failure analysis numerous tests were performed on the ISX engineering unit to either refute or support branches of the fault tree. Documentation kept during the development and testing of ISX, including procedures, test reports, and pictures, were also reviewed during the investigation.

The investigation was broken into three top-level categories: material, electrical, and software. Important contributors from each category are detailed in the following sections.

MATERIAL FAILURE MODES

This category includes all material-related failures that could have led to the spacecraft anomaly. The possibilities presented here are the failure of a deployment switch, thermal damage to PCB traces, the failure of a wire modification, and the failure of the antenna to deploy.

ISX has two deployment switches, connected in series, that turn the spacecraft on after separation from the launch vehicle. If one, or both, of these switches failed the spacecraft would not turn on. Experience with the switches across multiple missions has taught us the tiny devices are fragile and the plastic lever arm that actuates the button can snap off easily. However, when the arm breaks the switch fails closed and the spacecraft would still boot. The possibility of the wire connecting the switch to the electronics breaking due to the launch environment was also considered, but considered unlikely based on assembly documentation, the expected low loads on the solder joints themselves, and two prior vibration tests of the flight unit to GEVS levels without a similar failure. It was determined that the anomaly was unlikely the result of a deployment switch failure.

ISX experienced a ground testing anomaly after a thermal backout test involving one of the traces on the PCB that controls the power-on sequence. The trace expanded and cracked in such a way that minor physical pressure was required to the board in order for it to turn on. This issue was resolved pre-flight by adding a wire modification that bypasses the fragile trace. After the modification was added the board returned to its expected behavior. It is possible that other traces may have experienced a similar failure, however that possibility is reduced both by ground environmental testing that originally identified the broken trace and the small number of times we have successfully flown the same avionics board with the same wire modification. It is also possible that the wire modification itself failed. The light weight of the additional wire, plus installation procedures that include both staking and conformal coating, and vibrations testing of the modification make this particular failure also unlikely. Figure 2 shows the wire modification staked to the system board prior to conformal coating.

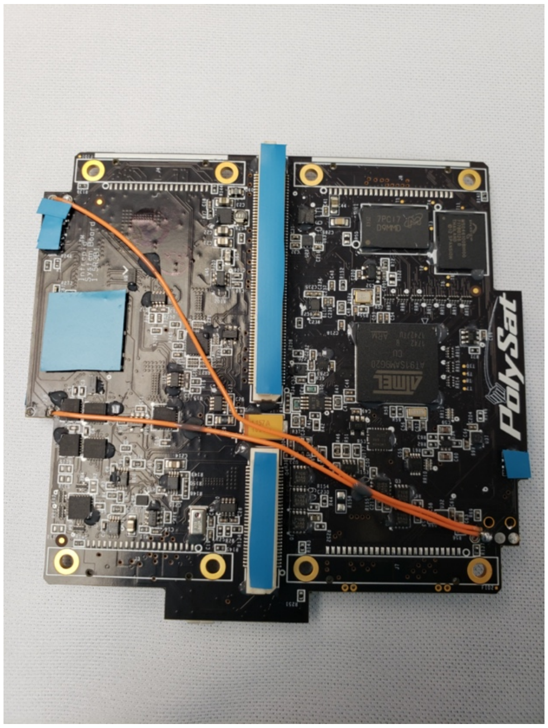

Figure 2: Wire mod to bypass fragile trace applied to the system board

Another possibility considered is that the spacecraft antenna failed to deploy. There are two primary concerns if the antenna doesn't deploy. First, the signal strength of the radio transmissions is noticeably reduced, making it nearly impossible to close the link, however the transmissions are typically still visible using a software defined radio. One of our previous missions, ExoCube, experienced an antenna failure which resulted in this situation. That failure was most likely caused by a bad solder joint. Based on the lessons learn from ExoCube the antenna deployment mechanism was redesigned and all solder connections are now on a PCB. Redundant burn circuits were also added to allow recovery if one of the circuits fails. This new design, as seen in Figure 3, was extensively tested on the ground with different simulated environments. It has also successfully flown on the DAVE mission prior to ISX. Since no signal was observed from ISX across many months of passes this failure mode is unlikely to have occurred.

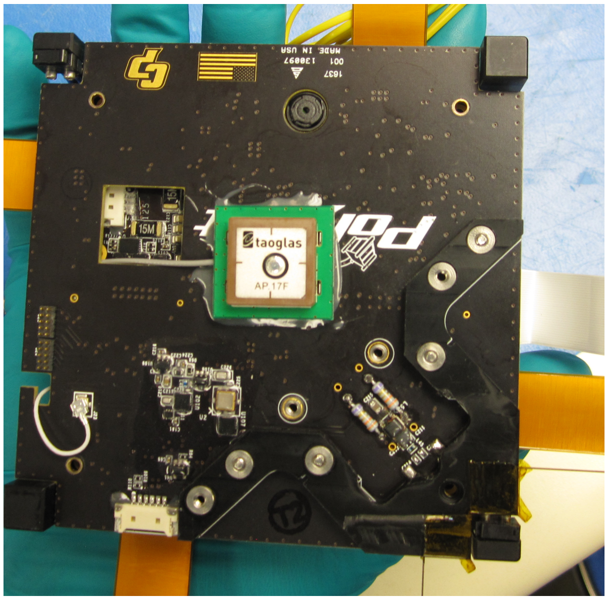

Figure 3: The ISX -Z panel, showing the antenna deployment mechanism in the lower-right corner. Note the antenna is deployed in this picture.

The second concerning outcome of a failed antenna deployment is that power reflects off the stowed antenna and causes the power amplifier to blow out. This creates a break in the RF chain preventing all transmissions. This failure has been observed multiple times while ground testing radio hardware when proper handling procedures were not followed. There is no telemetry or other data available to refute this, other than the extensive testing and flight heritage of the deployment mechanism.

ELECTRICAL FAILURE MODES

Causes evaluated in this category are all related to electrical failures that may result in the spacecraft's failure to transmit. The three modes discussed in this paper include the failure of the antenna burn resistor, a low battery voltage during the burn event, and a failure to charge the onboard batteries.

The failure of both burn resistors would cause the antenna to not deploy. The consequences of a stowed antenna were discussed in the material section. The process of heating up the resistor enough to melt the restraining line requires exceeding the design limit of the part, causing internal damage to the component. Ground testing showed a resistor is viable for three burns before it needs to be replaced. Due to this limitation the burn resistors flown on ISX had never been used (replacing them after testing is part of the standard operating procedure). They are also protected from accidental burns by shorting them with an ammeter. These procedures, and the redundant resistors, make it unlikely a faulty burn resistor caused the ISX anomaly.

Another possibility is the battery voltage was too low to properly drive the burn resistors, but still high enough to operate the other spacecraft electronics. A low battery state was observed on the flight unit during the final battery charge activity. Due to launch vehicle delays the spacecraft sat integrated in its dispenser for approximately seven months. There was an opportunity about a month prior to launch to de-integrate and recharge the batteries. At that time the batteries were too low for the spacecraft to boot, increasing the likelihood of a low state of charge on deployment. However, the solar cells on ISX should have been able to provide enough charge in the time between dispenser deployment and antenna deployment to drive the burn resistors.

This naturally leads to question whether ISX experienced a charging failure, which, when combined with a low deployment state of charge, prevented the antenna from deploying or the radio from transmitting. During spacecraft checkout all cells were shown to generate voltage in the cleanroom. Absent an accurate solar simulator, however, their actual power generation was never measured. Given the redundancy that comes with the electrical layout of 4 series of cells, it is less likely that all four groups failed at the same time independently of each other. The passive magnets used to orient the spacecraft ensure the cells are illuminated, reducing the possibility that poor pointing impacts power generation. The overall power budget for the spacecraft without the payload operating (the default state on deployment) was exceptionally positive, reducing the likelihood that an under provisioned system prevented charging.

SOFTWARE FAILURE MODES

The failure analysis for ISX focused on two areas, a general startup error and a timing error within the radio code.

The CPCL flight software is based on Buildroot embeded Linux [3] using busybox [4]. The startup sequence uses a System V style init script architecture [5]. One of the initialization scripts, named "S61", would occasionally hang for an extended period of time on startup. In all observed ground cases, the hardware watchdog built into the spacecraft's avionics would successfully recover from the hang. If the hang occurred on orbit, and the built-in recovery mechanisms couldn't resolve it, the spacecraft couldn't boot. While possible, this was rated as an acceptable risk due to the numerous ground observations of the recovery process never failing.

During the later stages of testing the ISX flight software a radio issue was identified in the transmit chain of the half-duplex radio. Based on diagnostics that the time it was determined the most likely cause was a timing issue when the software didn't wait long enough between switching the RF amplifier on and transmitting data. A change was made to increase the time between the two events. After the change the anomaly was not observed. The same anomaly was not observed on previous missions, despite using the same hardware and software. It is possible that batch inconsistencies in the underlying electronics either masked or exasperated the anomaly.

CONCLUSIONS

The ISX anomaly and resulting fault tree analysis lead to a number of valuable conclusions. First, it emphasized the need to always test the spacecraft well beyond the launch-provider requirements. That was done with ISX, including many antenna deployment and radio tests, but it was insufficient to identify the anomaly on the ground.

The second takeaway is that the importance of documentation in an anomaly investigation cannot be understated. There were many branches to the fault tree that should have been deemed highly unlikely, but, due to less rigorous documentation, could not be closed out. Recollections of responsible engineers are not sufficient in this case.

Finally, specific details about potential anomaly causes is expected to help the larger CubeSat community in there continued push to improve mission success.

ACKNOWLEDGEMENTS

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