Phoenix: A CubeSat Mission to Study the Impact of Urban Heat Islands Within the U.S.

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ABSTRACT

Phoenix is a student-led CubeSat mission, developed at Arizona State University (ASU), to study the effects of Urban Heat Islands in several U.S. cities through infrared remote sensing and educate students on space mission design. The spacecraft is designed using commercial off-the-shelf components (COTS) and several custom support boards developed by the student team. As such, the student team was responsible for the design, test, and validation of the spacecraft to demonstrate the capability of using COTS hardware to conduct high-fidelity science. This paper details the mission's concept of operations, as well as the spacecraft and ground system design that was developed to complete the mission objective. In addition, it details the mission's current status now that Phoenix has entered the operations phase, along with resources which have proved beneficial to the team while working with the spacecraft in orbit.

MISSION OVERVIEW

Phoenix is a 3U CubeSat with a primary objective to educate students on space mission design. The project was designed to be interdisciplinary and fully driven by undergraduate student effort, with minimal graduate student involvement. Approximately 80 students across various fields of engineering and geographical sciences collaborated over the course of a three-year period to develop Phoenix from a paper design to a flight system currently orbiting our planet.

Phoenix has a secondary objective to study Urban Heat Island (UHI) phenomenon within the U.S. using thermal infrared (IR) remote sensing. UHIs are defined as urban areas which are much warmer than their surrounding rural outskirts. This results from increased surface temperatures, which can be attributed to the choice of building materials, along with the layout of the city. Materials with a high emissivity, such as concrete and asphalt, absorb a significant amount of heat throughout the day, which is released back into the air during the evening, warming the surface temperature.[1] This ultimately leads to increased energy consumption and amplified heat waves, which have a negative effect on the environment and compromise human health and comfort.

To study the UHI effect, the payload was selected as the FLIR Tau 2 IR camera, which is available in a small form factor with a variety of lenses. To study the impact of UHIs, images had to be capable of resolving spaces on the order of city blocks. This resolution would permit the separation of regional differences in land use and thermal properties, known as Local Climate Zones (LCZs), within the observed cities. As a result, the payload was required to resolve at least 110 m/pixel, fit a 9 km squared area in the Field of View (FOV), and deliver a thermal sensitivity within 200 mK. Combined with a 100 mm lens, the imager provides a 640 x 512 pixel resolution with a 6.2° x 5.0° field of view.[2] This results in a ground spatial resolution of up to 68 m/pixel across a 32 x 43.5 km FOV from a 400 km orbit. In addition, the Tau provides a thermal sensitivity of 50 mK, allowing it to meet the science requirements.

Phoenix was selected and funded as part of NASA's Undergraduate Student Instrument Project (USIP) and launched through NASA's CubeSat Launch Initiative (CSLI). Additional project funding was provided by the NASA Space Grant Consortium and by ASU's Low Frequency Cosmology Laboratory. As part of ELaNa-25, Phoenix was launched on board the Cygnus NG-12 ISS resupply mission on November 2, 2019 and became ASU's first CubeSat to reach Low Earth Orbit (LEO). Phoenix was subsequently deployed from the ISS on February 19, 2020 to begin its operations phase. Phoenix follows an ISS-type orbit with 400km altitude and 51.6° inclination. The spacecraft will orbit the earth for two years before reentering the atmosphere but was designed to meet a 6-month mission baseline.

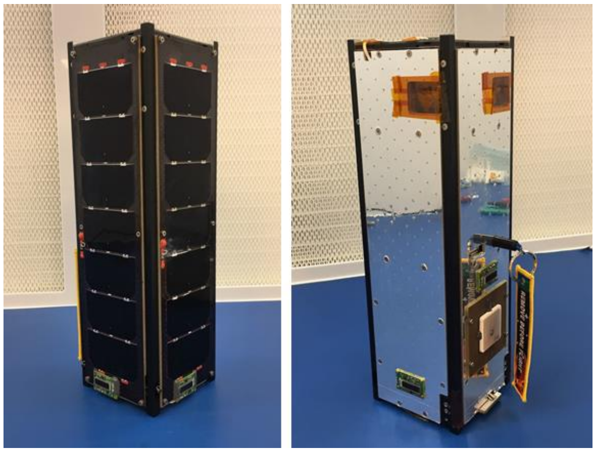

Figure 1: Phoenix Flight Assembly

CONCEPT OF OPERATIONS

To support the primary and secondary mission objectives, Phoenix has three modes of operation: Idle, Science, and Safe Mode.

Idle Mode

Idle Mode is the primary operational mode of the spacecraft, which accounts for 90–100% of an orbital period. This period is used as a low-power mode in which the spacecraft can charge its batteries, as well as collect and transmit telemetry. Every 30 seconds, Phoenix transmits a distinct health beacon over UHF amateur frequencies. The beacon was limited to a maximum of 256 bytes, and thus contains only the most critical telemetry from the spacecraft, such as power draw, temperatures, power generation, and system memory storage. This provides enough information to allow operators to make appropriate decisions and immediately identify potential issues. If necessary, the last five minutes of telemetry can be requested by operators. This provides more information on the state of the spacecraft without having to downlink a larger telemetry file over a longer period of time.

In addition to logging telemetry, Phoenix also maintains a record of events, which indicate whether operations were handled successfully by the onboard software. These event logs are meant to inform the operations team on whether command schedules were executed in full, if complications arose during command execution, and when onboard resets occurred.

Idle Mode is also used to conduct maintenance. Every six hours, a GPS is automatically powered on to collect the current UTC time and update the spacecraft's onboard clock. The clock can also be reset with a ground command in the event that the GPS becomes unresponsive. All other maintenance is performed manually by the mission operations team to reduce system complexity and risk. In addition, the operations team uses Idle Mode to request files and uplink command schedules while Phoenix is in range of the ground station.

Science Mode

Science Mode involves all operations related to payload calibration and image collection. Thermal images will be collected over seven major U.S. cities, including: Phoenix, Los Angeles, Houston, Chicago, Atlanta, Minneapolis, and Baltimore. All cities were selected for their wide variety of LCZs as well as their dense population, which gives scientists the opportunity to study how surface temperatures are affected by daily routines as well as a rapidly evolving urban climate.

A two-point image calibration is performed by imaging large bodies of water, such as oceans and lakes, which fill the FOV of the camera and are monitored for temperature. Bodies of water exhibit an emissivity close to 1, allowing them to serve as a useful blackbody target for on-orbit calibration. Similar methods are implemented by larger spacecraft, such as LandSat.[3] Calibration images will be taken before and after each science pass to evaluate image accuracy.

As the spacecraft approaches a target city, the ADCS is commanded to track the location's lat/long coordinates from ±25° off nadir. This tracking requirement was designed to provide a large enough imaging window to reduce image blur, while still being small enough to mitigate thermal reflections off buildings, as these would interfere with surface temperature measurements. The best spatial resolution is obtained at closest approach when the spacecraft is pointed nadir over the target city. All images are collected in a 14-bit compressed TIFF format and decompressed on the ground.

All images will be downlinked to the ground station at ASU. Due to their large file size and the spacecraft's use of only UHF bands, images will be downlinked over the course of multiple passes over the ground station. Once received, images will then be analyzed by the student team before being used to conduct scientific research. At this point, calibration data is examined, and known surface temperatures (public data provided by airports and weather stations within each target city) are used to assess the relative temperature accuracy within each image.

Safe Mode

The spacecraft will be declared in Safe Mode when the hardware experiences an event or fault which requires operations to be restricted for a period of time until the spacecraft can be declared healthy again. Such events/faults include: the battery level approaching its voltage cutoff limit (> 6.8 V), hardware temperatures approaching their Allowable Flight Temperature (AFT) limits, loss of communications with a component, off-nominal telemetry and/or power draw. No safe mode operations were made autonomous. As a result, in the event where the spacecraft enters Safe Mode, the operations team must assess the most appropriate path forward and uplink commands which will either resolve the issue or ensure that Phoenix remains safe for the immediate future.

SPACECRAFT OVERVIEW

Phoenix consists mainly of COTS components enclosed in an in-house-developed structure, while interface boards were designed and assembled by the student team to meet specific cabling or data interface needs.

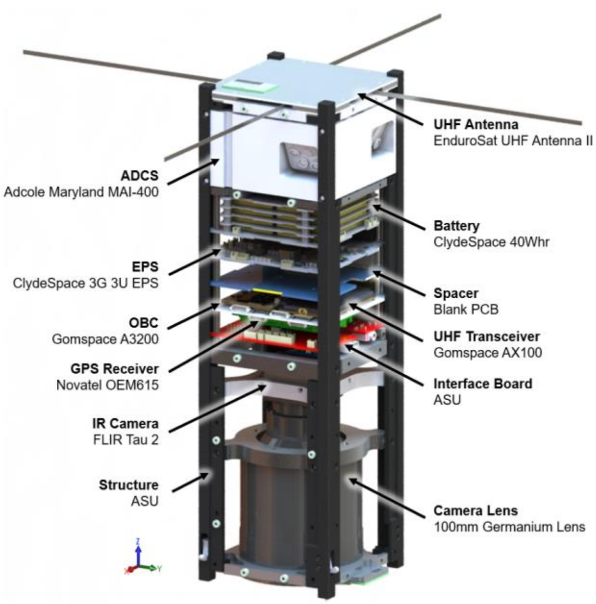

Figure 2: Phoenix Internal View

Payload

FLIR's Tau 2 640 model (Figure 3), running at 60 Hz and featuring a 17 µm pixel density was used as the payload. The total spectral response ranges from 7-15 µm, but the strongest absorption is between 9.5-12.5 µm. It features a shutter behind the lens which presents a uniform temperature to the sensor. This is used to cancel out the drift in pixel values over time, as well as fixed-pattern noise in a process known as Flat-Field Correction (FFC). To improve accuracy, FFC will be performed immediately before image capture.

The camera is attached to a 100 mm f1.6 lens manufactured by Ophir, which has a transmittance of 88%.[4] Given the sealing on the front element, and a 40,000 ft altitude rating on the body, the system risked over pressurizing in a vacuum if it was not properly vented. To guarantee the payload could withstand a 1.0 kPa flow rate upon entering the ISS airlock, two holes were drilled into the lens barrel using a #65 drill bit. This reduced the risk of debris entering the lens compared to a single larger hole. The total venting area was derived from a NASA requirement that the ratio between the total encapsulated lens volume and the effective vent area did not exceed 5080 cm.[5] This venting was tested over several pressure cycles, with no apparent damage to the payload.

Although the core is uncooled, temperature stability is still necessary. The output of the camera can change depending on its temperature, and any thermal gradients across the system. To mitigate this, the payload was tested across a range of target and camera temperatures, for a more accurate flux to temperature conversion. Temperature simulations were also used to validate the thermal contact of the camera and lens with the chassis. From benchtop testing, the system showed a resolution of 170 mK with an accuracy of ±276 K when heated to 306 K. That went to 320 mK, with ±274.7 K accuracy when heated to 325.7 K. Therefore, the performance of the system will depend on its operating temperature.

As far as we are aware, there are several intermediate processing steps between the sensor readout and the reporting of raw counts/digital numbers (DNs). A ‘gain calibration’ is prepared at the factory which is meant to normalize the manufacturing variation of the sensor and account for the light falloff/vignetting of the lens. It appears that this calibration can only work for static temperatures, as non-uniformity is introduced when the body temperature changes. An additional scaling term is driven by the lens f-number and transmittance parameters set in the camera. At some point in the chain, the information is interpolated according to the ‘bad pixel map’ to fill in dead pixels. These settings and others were recorded and held constant when testing the sensor’s response. The raw counts/DNs read from the sensor can be approximated using Equation (1), as the response was close to linear.

$$DNs = 40 \times (Target\ Temp) + 2000 \quad (1)$$

The camera offers both a high and a low gain mode for imaging. The high gain provides greater dynamic range, so it will be used for all measurements.

Figure 3: Tau 2 640 Infrared Imager and Lens

Attitude Determination & Control System (ADCS)

The main operational requirements of the ADCS are centered on its ability to point at a designated target city while the camera collects thermal images. This capability was separated into two classes of issues, the first being attitude knowledge and the second being attitude control. Attitude knowledge requires three things: high accuracy time information (±1 second), high accuracy orbital location information (±5 km), and high accuracy orientational knowledge (in concert with angular accuracy to achieve ±1.5°). Ensuring that these three conditions are met would allow for the camera to capture the primary science target within its field of view. The second class, attitude control, is based on three properties: the rate of rotation, applied torque, and accuracy. A moderate rate of rotation (1.1° sec^{-1}) allows for the continuous tracking of a target during a flyby. In addition, a moderate torque motor, with fine power control, ensures that the change in rotation rate can keep up with the target without inducing image jitter. Finally, the ADCS must be capable of high accuracy pointing control (±1.5° together with angular knowledge).

To meet these requirements, attitude determination and control is provided by the MAI-400, developed by Maryland Aerospace. This system includes three reaction wheels, which are aligned with the principal spacecraft axis to provide attitude control. The MAI-400 also contains three magnetorquers which can be used to dump accumulated rotational energy and detumble the spacecraft following deployment. Orientation above the earth is determined using an onboard magnetometer and two Infrared Earth Horizon Sensors (IREHS), which provide high accuracy measurements. In addition, six external sun sensors provide low-accuracy measurements of the spacecraft's orientation relative to the sun. Location knowledge is provided using onboard orbit propagators, which are updated periodically to maintain accuracy. These features allow the MAI-400 to target specific GPS coordinates on the earth while also keeping the solar panels pointed at the sun.

Upon comparing the MAI-400's orbit propagating abilities with predictions from STK 11, it was found that the two simulations diverged significantly after several minutes. As a result, we assumed the onboard propagator was insufficient to maintain orbital knowledge and planned to use higher fidelity ground-based models to update the ADCS's parameters before each imaging pass. TLE data would be used to model the spacecraft's expected position and velocity before each imaging pass. These terms could then be uplinked as part of the command schedule and used to update the MAI's pointing knowledge. This process ensures that Phoenix can maintain high accuracy pointing capabilities while collecting images of each target city. These more accurate models include higher order gravitational terms and aerodynamic drag, which add significant disturbances to the orbit. With the selected components and methods, the ADCS system can achieve its system requirements, apart from the eclipsed portion of the orbit.

Communications

All command uplink, as well as downlinks of images and telemetry, is performed using the UHF amateur band at a frequency of 437.35 MHz. Communications between the spacecraft and the ground are managed by a GomSpace AX100 UHF Transceiver, which was selected for its compatibility with the spacecraft's onboard computer (OBC) and support of standard amateur radio protocols. A deployable UHF antenna, developed by EnduroSat, was incorporated to provide omnidirectional communications.

To facilitate communications with the ground, Phoenix utilizes the AX.25 protocol with HDLC encapsulation. Packets are communicated at a 9600 baud packet rate and encoded with GMSK modulation, which are standard characteristics in UHF amateur radio. In addition, AX.25 packets are incorporated within the KISS protocol for communicating information between the ground station TNC and computer.

To ensure that larger files such as images and telemetry logs can be fully recovered by the operations team, a custom packetization method was developed which accounts for link latency. Large files (> 256bytes) are broken into smaller chunks on the spacecraft before being transmitted to the ground as individual packets and re-assembled into a single file. Any packets which are not received can be re-requested from the spacecraft until the entire file is obtained. File accuracy is further facilitated by CRC error checking which is implemented on all outgoing packets.

Electrical Power System

The electrical power subsystem consists of three major components: the power board, the battery, and the solar panel assembly. The power board chosen was a 3rd Generation XUA EPS (or FlexEPS, now called the STARBUCK-Nano), developed by AAC Clyde Space. It has multiple solar panel inputs which allow for both buck and boost configuration, and it includes four voltage rails: 3.3 V bus, 5 V bus, 12 V bus, and a 7.6 V (nominal) unregulated battery bus.[6] The system also includes battery charging functionality which is compatible with the 40 Whr CubeSat Battery from AAC Clyde Space (now called the OPTIMUS-40). This battery is configured in 2S4P configuration with a nominal end of charge (EoC) voltage of 8.26 V (with normal operation ranges at 6.2 V to 8.4 V) and a nominal capacity of 5200 mAhr.[7] Both the power board and the battery system provide telemetry to the main on-board computer over the I2C protocol. This includes temperature, charge level, voltages, etc. Two body-mounted 3U solar panels provide power generation, each consisting of seven 26.62 cm^2 Spectrolab ultra-triple-junction (UTJ) cells.[8] The maximum power produced during sun facing is about 14 W, but due to the operation scheme of the satellite, the average power generated during an orbit is around 6 W.

A power budget was developed using STK's Solar Panel Tool, with further analysis performed in MATLAB. STK was used to calculate power generation based on an ISS orbit. A model of the spacecraft was simulated over a six month mission timeline to examine long-term effects to the battery level. The results of the STK simulations were then imported into a MATLAB script, which calculated the spacecraft's power consumption and battery level based on worst-case Idle and Science Mode power assumptions. Both deployable and non-deployable solar panel configurations were examined. Body-mounted solar panels were ultimately chosen due to reduced system complexity and budget constraints.

Interface Board

An interface board (Figure 4) was designed to facilitate data and cable routing between components as well as provide flexibility to support the spacecraft’s unique design. The board also enabled workarounds for compatibility issues, which came as a result of selecting hardware from different vendors. For example, the board supported muxing between the ADCS and the payload, which allowed the flight software to switch between controlling either component upon command. This was implemented as a result of the system including more SPI devices than there were independent interfaces.

Further, the interface board also incorporated the ADCS magnetometer, as well as access port features, including a USB interface for uploading software, a DC port for external charging, and an RBF interface, which was designed from an audio jack connector. Finally, LEDs were added to the design to indicate when primary power lines were enabled. These were made externally visible to provide power status once the spacecraft was fully assembled. In addition, two smaller boards were developed to provide cable routing to the ADCS and the payload.

Figure 4: Main Interface Board

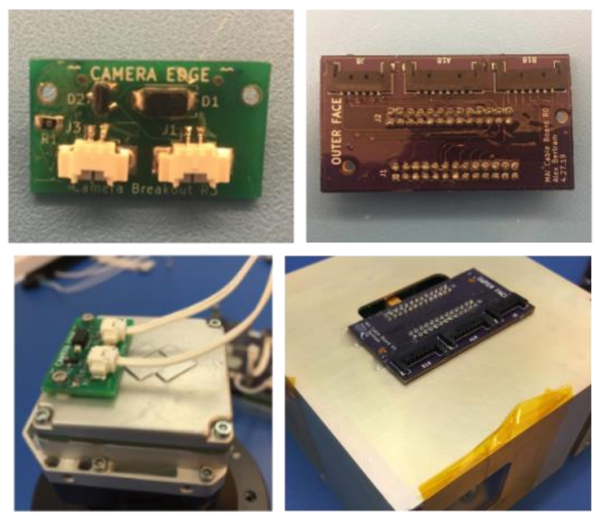

Figure 5: Payload (top/bottom left) and ADCS (top/bottom right) interface boards

Flight Software

The GomSpace NanoMind A3200 was selected as the on board flight computer. This was integrated on a NanoDock DMC-3 motherboard, which also housed the AX100 transceiver, as well as a NovAtel OEM615 GPS.

The flight software's solution stack consisted of four components. The lowest level utilized the NanoMind software development kit provided with the OBC. This incorporated the CubeSat Space Protocol (CSP) as the network layer, which was used to facilitate routing between the AX100 and the OBC, as well as error checking on incoming packets. FreeRTOS is utilized as the real-time operating system, which gave us the platform to build our primary software. On the recommendation of other CubeSat teams, NASA's Core Flight System (CFS) and Core Flight Executive (CFE) were selected as the application framework. CFS gave us critical functionality as well as a platform to extend with our own functionality. With CFS, mission responsibilities were divided into mission-specific applications for hardware, command ingest, and telemetry. A library was also written and registered with CFS to share code among all applications.

In addition to providing the application framework, CFS also provided an operating system abstraction layer (OSAL) which eliminated the need to develop directly with the FreeRTOS API. This abstraction layer also meant we could develop much of our functionality in Linux on various PCs, without requiring a massive reengineering effort when switching to FreeRTOS on the OBC. The CFS message bus was also heavily utilized. This mechanism allowed applications to share data, without having to develop explicit connections.

Hardware apps were programmed with one-to-one command mapping, in which commands were converted into hardware specific sequences of bytes. An option was implemented in the command parser which would allow mission operators to send a specific sequence of bytes directly to a piece of hardware. This was useful if a command had not been implemented in the software.

Two separate applications were developed for communicating with the ADCS, as it operated with two separate message buffers. One app facilitates commanding to orient the spacecraft, while another collects the 161 byte packet that is generated by the ADCS at a rate of 4 Hz. A camera app was developed for collecting images and telemetry from the payload, as well as performing any necessary calibration functions. Once images are taken, the app copies these from the camera's internal storage to the OBC's flash memory to prepare for downlinking. A GPS app facilitates regular time updates to the onboard clock. This ensures that commands can always be executed on schedule and negates the need for unnecessary command overhead from the ground operations team. The GPS app also gathers lat/long position updates and hardware telemetry. In addition, an EPS app provides direct control of the EPS through our scheduler app. This manages enabling and disabling power rails along with collecting telemetry from the battery and EPS units.

The UHF Manager (UHFM) application was designed to be an intermediary between the AX100 and the OBC. It is primarily responsible for transmitting data, including the satellite health beacon, images, and other telemetry files. Telemetry files are accessed directly from the OBC's flash memory storage by the app before being downlinked. In addition, the app is also responsible for performing various maintenance tasks from the ground, such as resetting the OBC and updating the onboard clock should the GPS fail to do so. Ground commands were interpreted based on the routing address of the packet and then handled appropriately by the OBC. Finally, the UHFM controls the deployment of the UHF antenna and reports the number of deployed antenna rods during telemetry collection.

In order to process commands on the satellite, we created our own command format. Commands which were uplinked to the spacecraft as part of a schedule file, were parsed, queued, and executed by the Command Ingest application. Each command is composed of a date and time for execution, a hardware target, and the parameters needed for the command. Commands are queued in the order of execution. To execute the queued commands, the app continuously polls the onboard clock for a matching time. Since OBC resets would cause the schedule to be parsed from the beginning, checks were added to ensure that old commands would not prevent the schedule from moving forward. If a command timestamp was older than the current time, it would be skipped. As onboard processing was found to gradually slow down with increased memory storage, a 45-second buffer was added to timestamp checks to ensure that commands could still be executed within a reasonable timeframe. Finally, functionality was added to execute scheduled commands immediately, in case of emergency. The status of each command's execution is written to an event log to inform the team of the success of scheduled operations. As Command Ingest was a critical piece of software for Phoenix, the application was tested rigorously to ensure that mistakes in a schedule file could not lead to non-recoverable errors in orbit. Cases such as incorrect parameters, an incorrect number of parameters, or (but not limited to) non-standard characters were tested.

To keep track of the spacecraft's health, every hardware application (apart from the ADCS) was made responsible for providing its telemetry to the CFS message bus. Every 45 seconds, the telemetry app requested telemetry messages from all hardware apps. Each piece of hardware was polled in the same sequence. Then, when the telemetry was written to a single file, it was labeled according to which piece of hardware the telemetry came from. To reduce individual file sizes, health status was continuously written to the file over a period of six hours, after which time a new telemetry file would be created and used for logging new data. Each file was named according to the date and the quarter over which the telemetry was collected. Hours of 0:00–6:00 UTC were registered as quarter 1 (‘q1’), 6:00–12:00 as ‘q2, and so on. In addition, the timestamp was recorded in the file each time telemetry was polled from the hardware, which would allow the team to correspond health status with any operation the satellite had performed.

Structures

Phoenix features a 3U CubeSat structure (Figure 5) which was designed and manufactured by the student team. The structure was designed to comply with structural and mechanical system interface requirements outlined in the Nanoracks CubeSat Deployer Interface Definition Document (NRCSD).[3] The NRCSD comprehensively describes the interface between the CubeSat structure and the deployer and thus a strict adherence to the established requirements is of prime importance for a successful mission. The NRCSD requirements that drive the structure design include external dimensions and tolerance, rail interface, allowable materials and finishes, mass properties, deployment switch interface, random vibration, and acceleration loads.

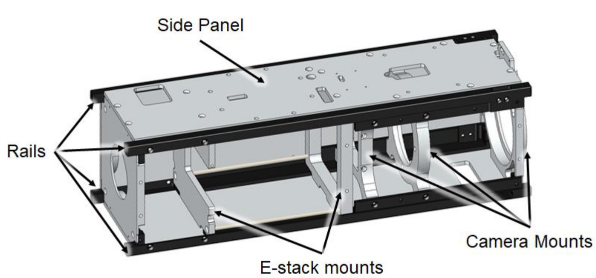

Figure 5: Phoenix 3U Structure

The Phoenix structure is composed of fourteen 6061-T6 Aluminum parts manufactured using a CNC mill: four rails, six supporting brackets, and four outer side panels. The rails have been anodized using a type-III hard anodizing process. The rails are the only part of the structure that directly contact the NRCSD and thus extra care was necessary to guarantee required flatness and uniformity. Mounting of components and mechanical connections are achieved through the use of M2.5 stainless steel screws throughout the structure. Where possible, threaded holes utilize Nitronic 60 stainless steel helical inserts to prevent binding without the use of potentially-outgassing lubrication.

The structures team followed an iterative design philosophy: a structure iteration was modeled, manufactured (initial iterations used 3D printing while later ones used CNC machining), and then assembled. With each subsequent iteration, the resulting assembly closely adhered to the NRCSD requirements. Ultimately, this iterative process allowed the team to efficiently recognize and address interferences, along with manufacturing issues. In particular, complying with the outer dimensional tolerance requirement (±0.1mm) required multiple design and assembly iterations that considered not only the solid geometry of structural parts, but also bending due to mechanical compliance.

Thermal Control

ISS orbital conditions result in a thermal environment with a maximum beta angle of ±75.1° in hot orbits, when 80% of an orbital period is spent in direct solar flux. For cold orbits, where 52% of an orbit is spent in direct solar flux, the beta angle is 0°.

Thermal modeling and analysis were performed using Thermal Desktop. Two models were created, to perform baseline and detailed simulations with 28 nodes and 668 nodes, respectively.

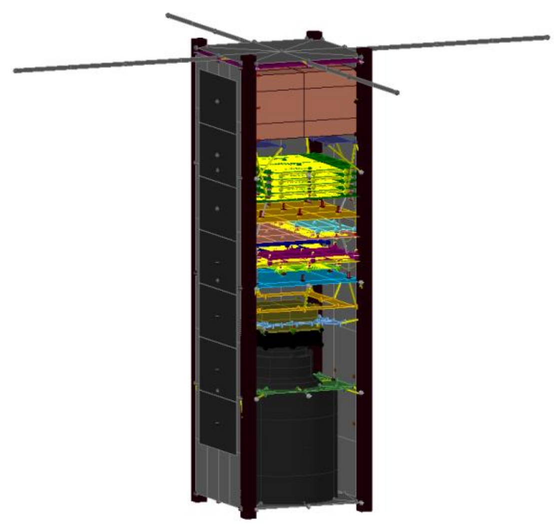

Figure 6 : Detailed Thermal Desktop Model

Allowable flight operational and non-operational temperatures were derived based on JPL standard requirements. A margin of +15ºC and -20°C was applied to the minimum and maximum hardware temperature limits respectively, to dictate the allowable temperature range. From this, Phoenix’s thermal control system was designed to be primarily passive, with the only active component being the battery's built-in heaters.

As the payload contained an uncooled microbolometer, the thermal control system was originally developed around the FLIR camera to optimize the science return. A control system was designed to maintain the payload within an optimal temperature of around 10°C. The ideal design would incorporate a TE cooler for active thermal control, which could maintain the detector at colder temperatures. However, due to budget and volume limitations, a passive thermal control system was designed which would keep the detector cold by mounting a thermal strap to the radiator. Ultimately, schedule constraints and a lack of resources caused the thermal control system to be descoped. As a result, thermal requirements were adjusted to keep the camera within its Allowable Flight Operating (AFO) temperatures, rather than optimize its thermal range for the science objective.

As a result, the final thermal control system was designed based on the hardware with the most restrictive temperature range. This was the Li-Ion battery system, which was required to stay within AFT limits of min -5ºC and max +42ºC. To help regulate component temperatures, one 3U structural panel is designated as a radiator. To increase its emissivity, the radiator is covered with silver Teflon tape. The tape was donated to the team by NASA Goddard and has a BOL absorptivity and emissivity of 0.1±0.02 and 0.73, respectively, and an EOL absorptivity and emissivity of 0.2±0.02 and 0.77, respectively. With this, the radiator has a total Idle Mode radiating power of 8.5W at 14.4ºC in hot orbits and 5.6W average at -16.75ºC during cold orbits.

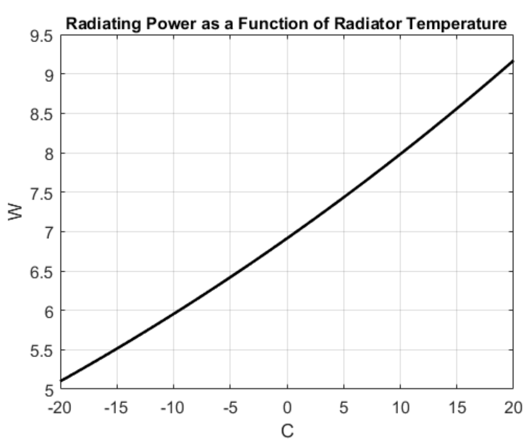

Figure 7: Phoenix Radiating Power as a Function of Radiator Temp.

This design was sufficient to keep all internal hardware within their AFO temperatures, but it caused the batteries to fall too close to their AFO limits. Simulations of the spacecraft in Idle Mode showed the batteries approaching a maximum temperature of 40.5ºC and a minimum temperature of -1.1ºC in hot and cold cases respectively. The simplest way to bring the batteries away from these limits was to modify the thermal conductive paths by changing the material of the standoffs that secured the electronics stack. This would control the heat flow between electronics and the chassis. As a result, a trade study was conducted to determine what standoff material would result in the most optimal temperatures for the batteries, as well as the rest of the spacecraft bus. Based on the results of the trade study (Table 1), Phoenix was designed with a combination of aluminum (AL) and stainless steel (SST) standoffs. While this design did not decrease the battery temperature, it did produce the lowest operational time of the battery heater per orbit. This reduced the total amount of power the battery generated in colder orbits, which increased the battery's efficiency and also reduced the temperature of the EPS and the ADCS.

Table 1: Standoff Trade Study

Spacer Type	Max Temperature (°C)	Min Temperature (°C)	Heater Duty Cycle
AL	40.45	-1.1	77.1%
SST	39.7	0.85	56.2%
AL and SST Combination	40.6	0.8	51.1%

GROUND OPERATIONS

General ops / GS Overview

Phoenix is operated from the ASU Ground Station. All operations are conducted by the student team, which is responsible for monitoring the day-to-day health of the spacecraft, uplinking commands, and processing the thermal images once they are downlinked. In the event the ASU ground station becomes non-operational, the ground station at Embry Riddle Aeronautical University in Prescott, AZ will be used to conduct operations.

To receive messages from Phoenix, the ASU ground station utilizes a high gain Yagi antenna which is mounted to a SPID rotor system for tracking the spacecraft throughout each pass. All packets are then received by an ICOM 9100 radio and Kantronics KPC-9612 Plus TNC, which demodulates each received packet and communicates these to the ground station computer. Signal strength is further increased with the addition of a KP-2/440 preamp. Tracking is facilitated by Gpredict and Hamlib, which controls antenna pointing and manages Doppler shift effects to the satellite's frequency. All command generation and file assembly is handled by a custom ground station code developed by the student team.

On average, Phoenix will pass over the ground station 2-3 times per day at an elevation of >30°, at which point the spacecraft will be high enough above the horizon to establish two-way communications. Passes last for about ten minutes on average. However, communication time will be limited depending on the maximum elevation.

Phoenix's health beacon will be further monitored by the SatNOGS community, which is a free and open-source network of international ground stations dedicated to tracking spacecraft and recording decoded health beacons. As such, SatNOGS provides a powerful resource to the operations team by allowing them to monitor the health of the spacecraft between passes over ASU and prepare for the next pass accordingly if health beacons exhibit off-nominal behavior.

Ciphering

Since Phoenix has an Experimental FCC license in the amateur bands, it operates under an open, but limited communications link. To maintain operational control over the spacecraft, encryption is incorporated into uplinks of all command schedules. All commands for spacecraft attitude control, tracking, image capture, and other mission critical operations are protected by a rotating cipher key which uses a simple substitution scheme. The cipher list is known only to the student team and protected with gpg public/private key pairs. During schedule uplinks, the satellite will evaluate the uplinked command for a valid cipher passcode. If the passcode sent matches what the spacecraft expects, the schedule will be stored on the OBC and commands will be executed according to the schedule. Image data and all other associated telemetry are not considered proprietary and thus are not encrypted prior to being downlinked.

However, to encourage public participation with Phoenix during the operations phase, amateur radio operators are permitted to send simple ping commands, which allow them to establish two-way communications with the spacecraft. Instructions on how to communicate with Phoenix from orbit, as well as a public version of the team's custom ground station code has been made available on the project website (http://phxcubesat.asu.edu/).

MISSION STATUS

Following deployment from the ISS, Phoenix's health beacon was received by several independent amateur radio operators and other ground stations within the SatNOGS database. The operations team established two-way communications with the satellite using the ASU ground station and uplinked a basic schedule to collect more data from the spacecraft. This became the first direct operation of a CubeSat in orbit performed at ASU.

Several hours after deployment, Phoenix entered an error state, in which a stream of packets were continuously transmitted to the ground. These could not be disabled, which led to a gradual loss of power until the battery dropped below its voltage cutoff level of 6.8 V and disabled power to all operating hardware. The spacecraft was eventually able to recharge its battery, but upon regaining power, it was found that the functionality of the OBC had become impaired.

To better understand the state of the spacecraft, the team transmitted various low-level CSP commands, such as hardware pings, to debug issues on Phoenix. Debugging efforts were further assisted by amateur radio operators, who could send commands to the spacecraft when it was out of range of the ASU ground station. This combined effort significantly improved the efficiency of on-orbit testing, allowing the team to more quickly diagnose the state of the hardware.

Through this process, it was discovered that while the AX100 transceiver was operational, the OBC did not respond to any packets beyond short ping commands. Further, ping communication only occurred successfully during daytime passes. This suggested that Phoenix was likely not tracking the sun using the ADCS, preventing the battery from charging sufficiently to power the spacecraft during eclipses.

Upon further investigation into the error state, the anomalous stream of packets was linked to a syn-ack packet flood. Benchtop testing with an engineering model of the AX100 transceiver and conversations with the vendor indicate that a single bit flip in the packet checksum could have enabled the Reliable Data Protocol (RDP). This would have introduced the syn-ack stream in an effort to verify a link between the ground station and the spacecraft, resulting in a gradual drain of the battery level. However, while the packet stream issue is considered resolved, it is still unclear as to why we can only receive CSP ping packet responses from the OBC after the power reset.

CONCLUSION

Although Phoenix's science objective was not achieved, the spacecraft can still be utilized for other purposes. The ability to conduct two-way communications allows the spacecraft to be useful for calibrating ground stations to communicate with CubeSats in LEO. With the help of the SatNOGS community, Phoenix's TLE was confirmed as NORAD ID: 45258, which can easily be tracked using resources such as CelesTrack or space-track. Due to the state of the OBC, Phoenix does not transmit a health beacon, but one can be turned on upon request. Information regarding operations is discussed further on the project website for those interested in communicating with the spacecraft.

Ultimately, the development, implementation, testing, delivery, launch, and on-orbit operations of Phoenix has been an extremely rewarding experience for the ASU team. This opportunity has provided many students with valuable experience in the areas of interdisciplinary teamwork, project management, and space mission engineering. As a result, Phoenix has helped propel many of our student team members to careers in aerospace, and it has established student satellite programs at ASU. In this sense, Phoenix has completed its mission objective.

Acknowledgments

We are deeply appreciative of the support of everyone involved in taking Phoenix from a paper concept to reality, including our university administration and advisors, NASA and the USIP program managers, our vendors and launch provider, the amateur satellite community, and all of our student team members.

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