Ohm-itted Gravity: A New Solution to Offer More Affordable Hypersonic Glider Flight Research

A Technical Report submitted to the Department of Electrical Engineering

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In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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Technical Project Team Members

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisors

Adam Barnes, Department of Electrical Engineering

I. Statement of Work

Luke Bulmer: I was fully responsible for the design, fabrication, and population of the printed circuit board (PCB) that integrates the satellites on-board computer (OBC) with the transceiver, and partially responsible for testing the software and overall integration of the project. This involved working extensively with Connor, who was responsible for designing the software necessary for communication between the OBC and the transceiver, as well as working with the Communications and Software & Avionics subteams from the MAE CubeSat team to ensure that my design would fit within the various design constraints of the mission.

I began my work by extensively researching the Iridium 9603 Transceiver, Endurosat OBC, and the existing documentation for the HEDGE mission. Additionally, I spent time researching standards for designing space-worthy PCB's, to ensure my design would survive the entire course of the mission. After completing this research, I designed the first revision of my board using KiCad. After finding several issues with my design during initial testing, I redesigned the board for the final revision, this time using the SoldiWorks CAD software to verify the physical mounting of the transceiver on the board. After the second revision was fabricated, I took the board to WWW Electronics for population, which involved creating detailed instructions for the boards assembly. Finally, I worked with Connor to integrate and test the software for the transceiver, and then With Justin and Yul to integrate and test both subsystems together.

Justin Casotti: I was responsible for design and fabrication of the PCB that communicates analog data from the thermocouples and pressure transducers to the satellite's on-board computer (OBC) and partially responsible for testing this system. Before any design work was performed I had to understand the purpose of each component individually along with how they all functioned in tandem to produce the expected output. This meant I had to consult the notes assembled by the MAE Cube Satellite (CubeSat) team and understand the devices they chose for this portion of the electronics system. After becoming familiar with the selected ADC chips, thermocouple, and pressure transducer through their corresponding data sheets, I began to design a schematic using KiCad with relevant pinouts for each component.

After understanding and illustrating the system's wiring through a schematic, I began to transfer the design to a PCB layout also on KiCad. This required designing custom footprints based on the dimensional data located in device datasheets and downloading pre-built footprints from electronics distributors, such as DigiKey and Mouser. After the first PCB design was completed, I used FreeDFM to ensure manufacturability and ordered the board along with necessary components to get soldered for testing. We did not have the tools to solder the pressure transducer ADC chip independently, so I had to take the board to WWW Electronics (3W) so that they could solder it using precise and automated tools along with a reflow oven. On my own, I was able to verify the power circuitry that converts five volts to approximately twelve volts to power the pressure transducer, but I received help from Yul in testing the thermocouple circuitry, as his embedded SPI code was necessary in ensuring proper communication. After hardware and software troubleshooting throughout the first two iterations of the PCB, the final PCB was designed and ordered according to the CubeSat's specifications and space-tolerant features. After soldering and physical board implementation during the last week of class, Yul's code was used once again to test and troubleshoot the thermocouple and pressure transducer ADC functionality.

Yul Goodman: I was responsible for writing and testing the software for interfacing between the On-Board Computer (OBC) and the thermocouples and pressure transducers. Before the circuit boards that Justin designed were completed, I was primarily focused on devising the overall software system design along with Connor and Will Plunkett, one of the Mechanical Engineering students. We determined that we would be using a software framework called Core Flight Systems (cFS) to control the entire CubeSat software. When we learned that the OBC would not be arriving until after the scope of our capstone, we pivoted to alternative computer options that would be able to work in place of the OBC. We initially tried using a Raspberry Pi, however it could not work with freeRTOS, the operating system of the OBC. Instead, we chose to use a MSP432 board which ran an operating system much more similar to the OBC than a Raspberry Pi. Once I was able to run cFS on the MSP432, I could begin writing SPI code to use on the circuit board.

I began coding by writing simple SPI read and write commands. After testing those commands and confirming that they worked, I wrote functions to utilize the read and write commands and get raw data from the two different types of ADCs. The thermocouple ADCs were simple as they only had a data out pin, so the function for those reads the 16 bits of data every time the function was called. The pressure transducer ADC required writing to a few different register in order to be able to read the 24 bit output. When raw data was able to be read, I developed code to convert the raw data into usable values. Once the functions were written, they were integrated and tested using the circuit board that Justin designed and assembled.

Connor Schichtel: In my role on the project, I collaborated closely with Yul to develop the overarching software system design. Our initial plan involved implementing the Core Flight

Systems (cFS) framework on the Endurosat On Board Computer (OBC) to control the CubeSat software. However, when we encountered delays in receiving the OBC, we swiftly adapted our strategy to align with the project's timeframe. In exploring the limitations of using a Raspberry Pi, it was found to be incompatible with freeRTOS, the operating system of the OBC. We opted instead to replace the OBC with an MSP432 microcontroller. This decision was motivated by its compatibility with the OBC operating system, setting the foundation for a seamless integration process. I then installed and ran the cFS framework on the MSP432 in conjunction with starting my software development.

My primary responsibility involved writing the software to establish a connection between the MSP432 board and the Iridium Transceiver, substituting for the delayed OBC. This task involved the creation of UART serial code, encompassing numerous functions for both receiving and transmitting different forms of data bit by bit. Rigorous testing procedures were implemented through the Putty terminal to ensure the functionality and reliability of these UART codes. Moreover, I was actively engaged in writing AT commands necessary for configuring communication with the transceiver and transmitting messages. These commands were tested, first by directing them through UART to the transceiver and then through the computer to a Putty output terminal. To guarantee the accuracy and effectiveness of UART and these commands, I performed thorough tests by connecting the MSP432 to an AD2, monitoring the input channel on the step analyzer to verify the reception of the correct ASCII characters. The seamless integration and testing of these functions were accomplished on the circuit board designed and assembled by Luke, ensuring a functioning and coordinated system.

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III. Abstract

Our mission is to launch a Cube Satellite into space, where it will orbit Earth for 1 week. During re-entry into the Earth's atmosphere, the CubeSat will employ thermocouple sensors and a pressure transducer to measure the temperature and pressure of the aircraft. This data will be transmitted through the Iridium satellite network back to Earth. Our objective is to demonstrate the feasibility of affordable CubeSats as a platform for hypersonic glider flight research.

IV. Background

The purpose of this project is to develop two electronic subsystems in a CubeSat satellite that collects and transmits pressure, temperature, and location data to demonstrate the effectiveness of hypersonic glider flight (Overview slides). The electronic subsystem development will be separated into two distinct efforts: thermocouple and pressure transducer sensor configuration, and Iridium transceiver configuration. The team leading the first effort, Yul and Justin, are responsible for fabricating a PCB that can house inputs from the thermocouples and pressure transducers along with power a power network and amplifier and ADC boards that can process sensor readings. The Endurosat on-board computer (OBC) must also be programmed to process data from the amplifiers and ADCs via SPI protocol. The team leading the second effort, Luke and Connor, must create a PCB that can house a 9603 Iridium Transceiver and program the Endurosat OBC to communicate with the device via UART protocol. A crude block diagram detailing the connection between on-board electrical components is displayed in Figure 1.

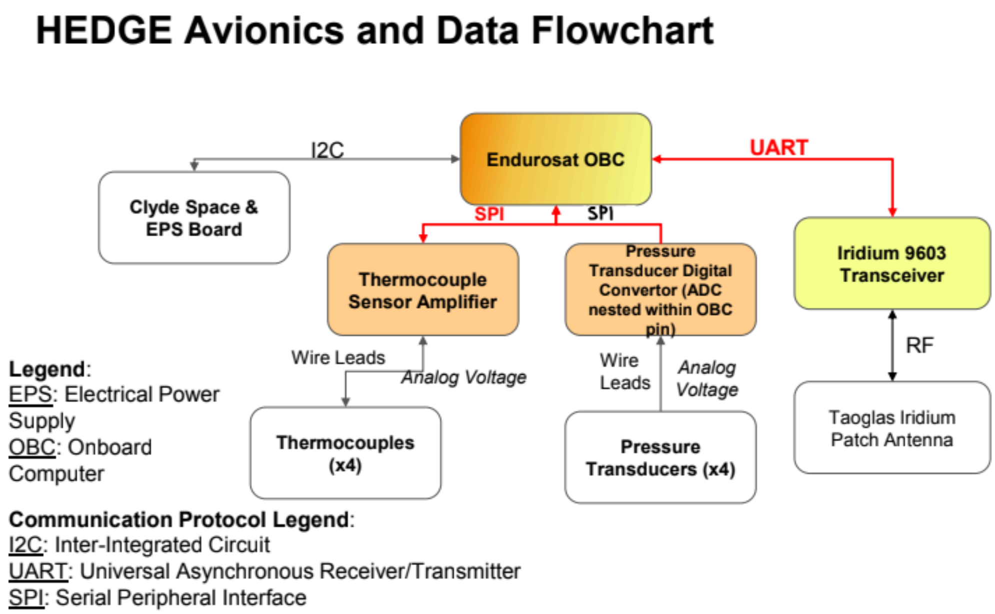

Figure 1. CubeSat Electrical Block Diagram

The Ohm-itted gravity group chose this project because they were intrigued by the application of circuitry and embedded programming knowledge benefitting a university-driven hypersonic space flight effort. Each of the group's members completed the entire ECE Fundamentals sequence, which provided baseline knowledge regarding circuit analysis, signals and systems, and semiconductor devices. The circuit analysis component of this sequence is most applicable to the PCB-development portion of the project, where component calculations and fabrication techniques are necessary to develop a suitable product. The third ECE Fundamentals course and Electromagnetic Energy Conversion provide a robust base of knowledge on how to manage power when designing a circuit, which is critical in ensuring the functionality of PCB-mounted amplifiers and transceivers. Introduction to Embedded Programming is most applicable in programming the satellite's OBC to communicate with the sensor-driven devices. There was even an entire chapter of the course dedicated to configuring SPI communication between components on a microcontroller.

V. Societal Impact Constraints

CubeSats in general have a significant societal impact on the scientific community. Aerospace research is a traditionally expensive field to work within, so less affluent institutions and countries are unable to participate in such research due to the high costs. CubeSats are relatively cheap options that open the doors to previously gate-kept groups who have interest in aerospace research. Instead of having to build an entire spacecraft capable of reaching space, users of CubeSats only have to worry about the payload of a project, the CubeSat itself, which is carried on other crafts into space and then ejected. This frees up large amounts of budget that are often spent on ensuring that a spacecraft can exit the Earth's atmosphere.

More specific to our project, the circuit boards we created will only be used in a lab setting and onboard the CubeSat, so the general public should not be concerned with the safety implications of our project. The engineers who will be installing our board and operating the CubeSat, however, should be careful not to touch the board while it is running. The transceiver board will have currents of over 1 amp when transmitting data, so accidentally touching the circuit when this is occurring could be dangerous or even lethal. Though the thermocouple and pressure transducer board will not have currents that high, some components could still heat up, so anyone working on it should still be wary. The boards should be safe to handle when they are not plugged in, so those who will be using our boards after our capstone ends should take care to unplug the boards whenever they are not being used and must be moved.

After the CubeSat has been launched into space and is beginning its re-entry into Earth's atmosphere, the spacecraft should burn up and not be hazardous to anyone on the ground. Those designing the CubeSat should still be cautious, though, as any component that does not burn up during re-entry could be dangerous and cause serious injury if it strikes a person while landing. Additionally, if this occurs but does not hit a person, the space junk would be pollution and could remain on the ground if no one picks it up. In this case, it is unlikely that the space junk would decompose as most of the CubeSat components are plastic or metal and will remain for many years.

VI. Physical Constraints

In the course of our project, various physical constraints significantly influenced the design and implementation processes. The biggest among these were our customer constraints, which shaped the overall project scope and resource allocation. In working conjunctly with the Mechanical and Aerospace Engineering Department, meeting their requirements proved challenging specifically as these fluctuated throughout the design process. The boards needed to be developed to fit within the frame of the CubeSat while allowing wires to pass through. On the software side, the demands of the customer needed to be met which led to operating systems being traded frequently which, until set, delayed initial progress.

The budget limitations guided decisions on material selection, component choices, and manufacturing processes. These financial considerations played a crucial role in determining the feasibility of certain features and functionalities, ultimately impacting the final product's specifications. With the main bulk of the project being supplied by our customer, the main limitation became space-proofing the boards themselves. While accentuating copper weight heightened the durability and heat dissipation capabilities of the boards, this addition also proved to be the main contributor to our cost concerns.

In addition to increasing costs, ensuring a level of space resistance within the boards led to manufacturing constraints encompassing limitations imposed by our PCB suppliers. In increasing the weight of the copper traces, it became evident that there weren't any manufacturing companies that were able to produce boards with 4 oz copper with trace thickness under 10 mils. This was vital as the maximum trace width that can be used with the cable connector for the transceiver is 6 mils. In further research, a more suitable plan of switching from two 4 oz copper layers to four 2 oz layers provided the same level of heat dissipation albeit having a trace width manufacturable by the company.

Manufacturing constraints extended beyond our capabilities, with our customers informing us that the Endurosat On Board Computer (OBC) would not be delivered in time for the project as originally intended. Worse, the Iridium Transceiver activation was held up with delays within the company itself. These delays in parts availability posed challenges in adhering to project timelines. Adaptability and contingency planning were essential to mitigate the impact of these constraints on the project's overall schedule and success. To replicate the OBC, the NASA core Flight System (cFS), UART, and SPI software was instead temporarily run on an MSP432 microcontroller which was readily available. Furthermore, the Iridium Transceiver was activated near the end of the project completion for use with testing the UART and AT command capabilities as well as the Transceiver board.

The tools utilized throughout the project played distinctive roles in achieving our objectives. NASA cFS proved essential for ensuring the stability of the OBC when in space as it has an abundance of flight heritage. C++ was instrumental in programming the system, with Code Composer providing a dedicated environment for embedded systems development. KiCad proved indispensable for simulation and design, allowing us to validate and refine our hardware implementations and provide our customers with models for them to begin implementation. The team had little experience with KiCad, which ate up some design time. Similarly, NASA cFS is a vast flight framework and lended a steep learning curve, leading to delays in software development. Learning and improving skills on these tools were iterative processes, with each tool contributing to different facets of the project's success. Ultimately, the strategic application of these tools enabled us to overcome physical constraints and deliver a sound and secure end product.

VII. External Standards

There are four primary external considerations relevant to this project in the development of space-grade electronics: cleanliness, volume, radiation/temperature tolerance, and vibration tolerance. Each of these will be discussed in further detail and in relation to the compliance of standards that address each issue.

Given the amount of time for which the satellite electronics must be operational and the cost of the entire project, it is imperative that each PCB remains clean during fabrication and implementation. Chemical residue could affect the performance of mounted components and conductivity of traces, potentially skewing device communications and the data transmitted from the satellite. To mitigate the impact of unclean electronics, NASA standard NASA-STD-8739-6A [13] outlines approved methods of cleaning PCBs. Deionized water, isopropyl alcohol, and ultrasonic cleaning are all approved substances or methods for cleaning PCBs. The first two chemicals are easy for the group to obtain, while obtaining an ultrasonic cleaning device is more difficult and costly. When addressing each issue, the group must ultimately exercise prudence over the degree of adherence to a particular standard. Certain approved practices are simply too costly, time-consuming, or unreasonable for the scope of the project. After wet cleaning, standard NASA-STD-8739-6A indicates that de-moisturizing must be executed by placing the cleaned component in an oven for at least four hours at approximately 194 degrees Fahrenheit. The presence of fluid will drastically impact the performance of electronics, so this section of the standard must be strictly adhered to. The standard also mentions how time must be dedicated to preventing adhesives and materials that could cause residue from contacting the PCB. From NASA-STD-8739-6A, the group came up with a process for ensuring PCB cleanliness. First, all residue must be removed from the blank PCB using either deionized water or isopropyl alcohol. Then the PCB must be de-moisturized by placing it in an oven for four hours at 194 degrees Fahrenheit. Throughout the soldering and component-mounting process, careful attention must be dedicated to avoiding contaminants and removing leftover substances from the PCB surface. Tools such as anti-static brushes will help in maintaining continual cleanliness.

The second external factor that must be considered is the combined volume of the electronics. As a crude approximation from the last meeting where the CubeSat shell was present, the cube that houses the electronics has a side length of six inches. Some of that space is already used by the on-board computer, meaning that the PCBs must be designed to fit in a confined space. This means that components must be mounted as closely as possible without positioning conflicts and convoluted trace/wire routing. Additionally, the PCB components will most likely receive sensor readings via board-mounted wiring connectors. These connectors cannot take the form of standard PCB jumpers, as the height required to make these connections would limit the amount of available space. A potential solution to this problem is mounting wire connectors to the top or bottom of the PCB facing parallel to the board’s surface. Connecting sensors at the sides of the PCB will reduce height and yield a more compact design. Depending on the availability of space, the circuit designs produced by the two sub-groups might have to be combined into a single, larger PCB.

The third external consideration is radiation/temperature-related stressors on the electronics. Heat concentrations experienced by the PCB can overheat circuit components and drastically reduce device performance. Therefore, heat dissipation methods must be employed to account for the extreme temperature conditions of outer space and the Earth's atmosphere. Firstly, all PCBs must be fabricated out of heavy copper, as they support "elevated current through the board and assist in transferring the heat to an outer heat sink for more efficient heat dissipation" (PCB International). The use of heavy copper PCB material provides for a rugged design that is more tolerant to the temperature-related pressure of the mission's environment. Regarding circuit design, thermal vias must be placed under specific components that are prone to overheating, such as the thermocouple amplifier and the pressure transducer ADC quad chips. Thermal paste is susceptible to outgassing, which is when a lack of pressure in the vacuum of space causes bubbles to form in the chemical's surface, potentially impacting device performance and creating residue around the PCB and interior of the satellite.

The fourth external consideration that must be accounted for in the electrical design is the elements of outer space creating a high load/vibration environment. During atmospheric reentry and potentially during the initial launching stages, the satellite will be exposed to a considerable amount of force and vibration. The electrical systems must be designed such that these forces do not affect device functionality or the structural integrity of components. NASA standard NASA-STD-8739-6A recommends the use of staking before the mounting of PCB components. This involves staking paste being applied to the sides of mounted components to hold them in place and make them more resistant to shock and vibration. Staking paste is cheap and easy to use and the NASA standard dictates how it can be best applied to circuit components of different shapes. In addition to device mounting, the PCBs themselves will most likely be mounted with screws to ensure stability. NASA-STD-8739-6A recommends the use of thread-locking methods to ensure that screws are tightly bound and mitigate the impact of extraneous forces. Finally, the standard indicates the necessity of using conformal coating during the final stages of PCB development. Conformal coating can be applied to a PCB via a brush to increase resistance to foreign elements and bolster structural integrity. The coating must first be applied to a dummy PCB to discern the appropriate thickness of the coat before being applied to the actual board. From NASA-STD-8739-6A three steps will be taken to ensure the PCB resilience to vibration: staking after part mounting and testing, thread locking, and conformal coating during the final stages of development.

There are some general considerations outside of the four main external factors that must be accounted for when designing electronics for space travel. NASA adheres to IPC standard J-STD-001FS [14], which mandates the use of lead-free tin solder. The reason for this decision was surprisingly not directly stated in the standard, the group assumes that this was due to the health concerns surrounding lead or potential material residue that could affect circuit functionality. Standard IPC-A-610 [15], which indicates measures for quality electronic assembly, recommends that all components, when mounted to a PCB, are meticulously inspected for damage and insecurity and that all soldering joints are perfectly formed. The standard also recommends marking each component to improve organization and traceability. There will not be an excessive number of components on the group's PCB boards, but adhering to this standard would still be good practice. The group is not yet familiar with the types of external wires and connectors the PCB will have to interface with, but once they are informed, referring to NASA standard NASA-STD-8793 [16] will be helpful in designing a secure wiring harness.

VIII. Intellectual Property Issues

In discerning the patentability of an invention, Section 101 of the U.S. Patent Act is most useful, which states: “Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefore, subject to the conditions and requirements of this title.” [1]. This section explicitly indicates two qualifications: utility and novelty. A third, tangibility, is implied in the indication of the object’s required substance: “process, machine, manufacture…” [1]. In its interpretation and application, a fourth requirement, of the invention being “non-obvious”, is observed [16].

Both the data acquisition and transceiver CubeSat systems satisfy the “statutory” requirement that relates to the substance of the object in question [16]. Both are not only explicitly defined systems that have a set of requirements for operation and an expected result, but are also physical systems that require the assembly of components on a PCB for implementation. Since these systems require manufacture and fabrication for physical use, the third requirement of Section 101 is satisfied by the object of this Capstone project. Literature and music are two cited examples that fail to satisfy this requirement and one can easily see how the CubeSat electronic systems differ significantly in essence from these works [16]. The “tangibility” requirement for patentability is also satisfied by the data acquisition PCBs.

The first requirement of Section 101 in the U.S. Patent Act of 1952 requires that the invention be useful. While this is subject to interpretation, the object simply needs a purpose, regardless of gravity. The purpose of the CubeSat data acquisition system is to convert analog thermocouple and pressure transducer data into digital SPI signals, which can be interpreted by the satellite's on-board computer. The transceiver system is designed to communicate the aforementioned and all other data to an Iridium satellite via antenna, which is then received at a ground station. This succinct purpose means that this capstone project satisfies the usefulness patentability requirement.

In order to discern novelty, one must consider relevant prior art. One patent that is similar to the CubeSat's data acquisition and transmission circuitry is the patent entitled, "Aircraft flight data management data system and corresponding method", which illustrates an "on-board data acquisition, storage and transmission system" [7]. At a high level, the on-board computer system contains a "data acquisition module", which handles various sensor inputs and communicates them through an interface to a microcontroller within the "storage and control module", which handles data storage and memory through an FPGA. Data at the interface is also communicated to the "communications module", where it is transmitted to a satellite and then to a ground station through a gateway. Additionally, the invention is capable of transmitting the data to a user via email [7]. Although the overall goal of this patent is similar to that of this Capstone, the application is different, likely affecting the system architecture, and it is much more complex. The communication module in the patent is similar to the Iridium transceiver PCB, although it contains a "satellite modem", "RS 222 interface", and an "optical isolation component", which is beyond the scope of this project. The OBC can be likened to the storage control module, although hardware breakdown of the computer itself is not relevant to the Capstone. Finally, the pressure transducer and thermocouple ADC chips perform part of the task allocated to the data acquisition module in receiving sensor signals, but differ in using SPI to communicate with the

OBC. These discrepancies between the invention outlined in the selected patent and the capstone project show that while the CubeSat electronics are not necessarily more complex, they describe a fundamentally different system, indicating novelty. In the patent, “Self-Contained Flight Data Recorder With Wireless Data Retrieval”, de Leon and Quiros present a design for an on-board device that captures and stores flight data, such as “G forces, flap position, cockpit voice and others”, and transmits them to a computer via RF transceiver. In the sensor architecture, the raw temperature signal must first pass through a differential amplifier and the air pressure signal must first pass through a “noise de-coupling filter” before reaching the microcontroller. While the overall concept of recording flight data and transmitting it to a ground station is the same as that of the CubeSat, the application and implementation of the electronic systems differ. The patent’s design is meant for “small aircraft” while that of capstone is meant for satellite applications [10]. As an example for how discrepancies may manifest, the CubeSat PCB must contain radiation-tolerant components, heat dissipation methods, and increased stability measures, while PCBs meant for aircraft likely do not need to account for these constraints. Additionally, rather than using a differential amplifier and noise de-coupling filter for temperature and pressure signals, respectively, the raw sensor signals are directed into MAX11254 and MAX6675 ADC chips directly for processing by the OBC via SPI. Perhaps the biggest difference is that rather than using a complex microcontroller architecture for data processing, the CubeSat simply uses the designated OBC with all necessary functionality built-in. Similar to the previous two selected patents, in “System, Methodology, and Process for Wireless Transmission of Sensor Data Onboard an Aircraft to a Portable Electronic Device”, Warner and Rucker present a data “monitoring and reporting” system for aircraft applications. In the enclosed system, a data recorder intakes and processes data from external sources and transmits it to an electronic flight bag or receiver device via wi-fi network. There are also system architectures for how the data transfer can remain encrypted and displayed [21]. Aside from the specific data acquisition components, the CubeSat system differs from the described invention in that the PCB-mounted Iridium transceiver is meant to communicate data from the OBC to a satellite and eventually to a ground station via RF transmission, rather than through a local encrypted wi-fi network. Through a reasonable patent search, the differences found between the CubeSat electronics and the aforementioned patents indicates a degree of novelty, satisfying the final requirement for patentability and indicating that the developed data acquisition and transmission systems could be patented with confidence that the project is novel, tangible, and useful.

IX. Project Description

A. Performance Objectives and Specifications

The end user will be receiving two circuit boards, one for the thermocouples and pressure transducers and one for the transceiver, and code to carry out the data acquisition and transmission of the CubeSat. The circuit boards are built with the PC104 standards which define the footprint of the boards and allow them to be stacked and installed into the CubeSat. Once installed and wired, the circuit boards should be able to utilize the provided code to interface with the OBC and transmit data. The thermocouples will gather data from the function ThermocoupleDataRead(...), which reads the SPI MISO signal from the proper ADC. The pressure transducer will gather data from the function PressureTransducerDataRead(...), which reads the SPI MISO signal from the proper register within the pressure transducer ADC.Lastly, the transceiver will use functions such as UART_OutString(...) and UART_InString(...) to send and receive data. Different data types can be sent and received by swapping the “String” part of the command for other data types.

B. Functionality

For the pressure transducer and thermocouple portion of the capstone, four pressure transducers, which are located at different points around the satellite, are connected to four terminals located at the top of the PCB. The two pressure transducer outputs, the positive and negative references for the analog signal, are connected to the MAX11254 chip. The positive and negative input terminals are connected to the 1S7B upconverter, which supplies just over 12 volts so that the ADC can receive pressure data. The upconverter schematic is shown below, which includes several capacitors and an inductor to ensure proper signal separation [24].

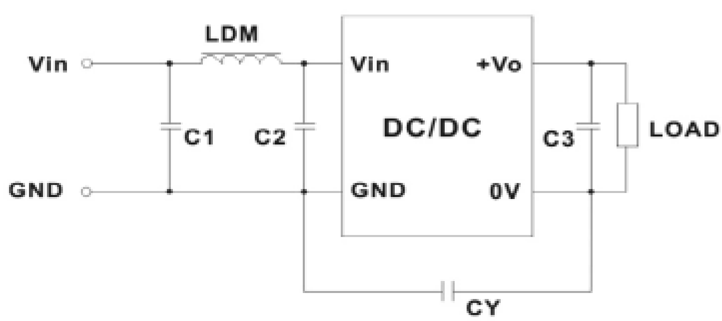

Figure 2. Upconverter Circuit Schematic

According to other specifications in the upconverter datasheet, the “LDM” inductor was chosen to be 6.8 uH. Capacitors “C1” and “C2” were chosen to be 4.7 uF each. Capacitors “CY” and “C3” were chosen to be 270 pF and 2.2 uF, respectively. The input “V_{in}” was connected to a 5-volt input from the OBC and the voltage produced across the load was found to be just over 12 volts during testing. In the case of our project, the “load” is the negative and positive input terminals of the four pressure transducers.

Four type-k thermocouples are connected to terminals on the right side of the PCB. Since these devices do not require a power supply, the positive and negative outputs of each are connected to their own MAX6675 ADC chip. All of these chips are powered by the same 5-volt bus and are connected to the same ground node from the OBC. Each chip, including the MAX11254 has a designated chip select SPI bit, connected to different pins on the OBC. All of the chips’ data output pins are connected to an SPI MISO node from the OBC. The OBC’s clock pin produces a clock signal used by all chips to time SPI data packets. The MAX11254 chip’s data input is connected to the MOSI pin on the OBC, so that commands can be written to the ADC in order to select registers and program the “ready” bit. In the case of the thermocouple amplifiers, once a chip is selected via the OBC code by pulling the corresponding chip select bit low, the data will appear on the on MISO node and ideally be read and interpreted by the OBC processor. In the case of the MAX6675, the commands written through the MOSI pin allow the data conversion bit to be pulled low and for the proper analog input register to be selected. Through its corresponding chip select bit, data will ideally appear on the MISO node for processing and interpretation by the OBC. The positive reference, analog power supply, and digital power supply are all powered through two 3.3-volt pins from the OBC and all negative reference points on the chip are connected to ground. The chip’s datasheet specifies the use of shunt capacitors of different sizes at different connections, including 1nF capacitors separating positive and negative pressure transducer output, which were all observed during PCB design. The same is true for the MAX6675 chips, which recommended 0.1uF capacitors between 5-volt supply and ground pins.

Before PCB design, a schematic was developed detailing pin routing between devices. This schematic is depicted below, but is outdated; the wheatstone bridges were found to be unnecessary and the pinout for the OBC is incorrect. However, after more research was conducted on the ADCs and the PCB was developed, the PCB was used as the “schematic”, as it detailed all necessary connections and was iterated upon to save time. Time was not taken to learn how to seamlessly transfer a schematic to a PCB layout on KiCad, although this is a future consideration, as trace routing time would have been saved during the design phase.

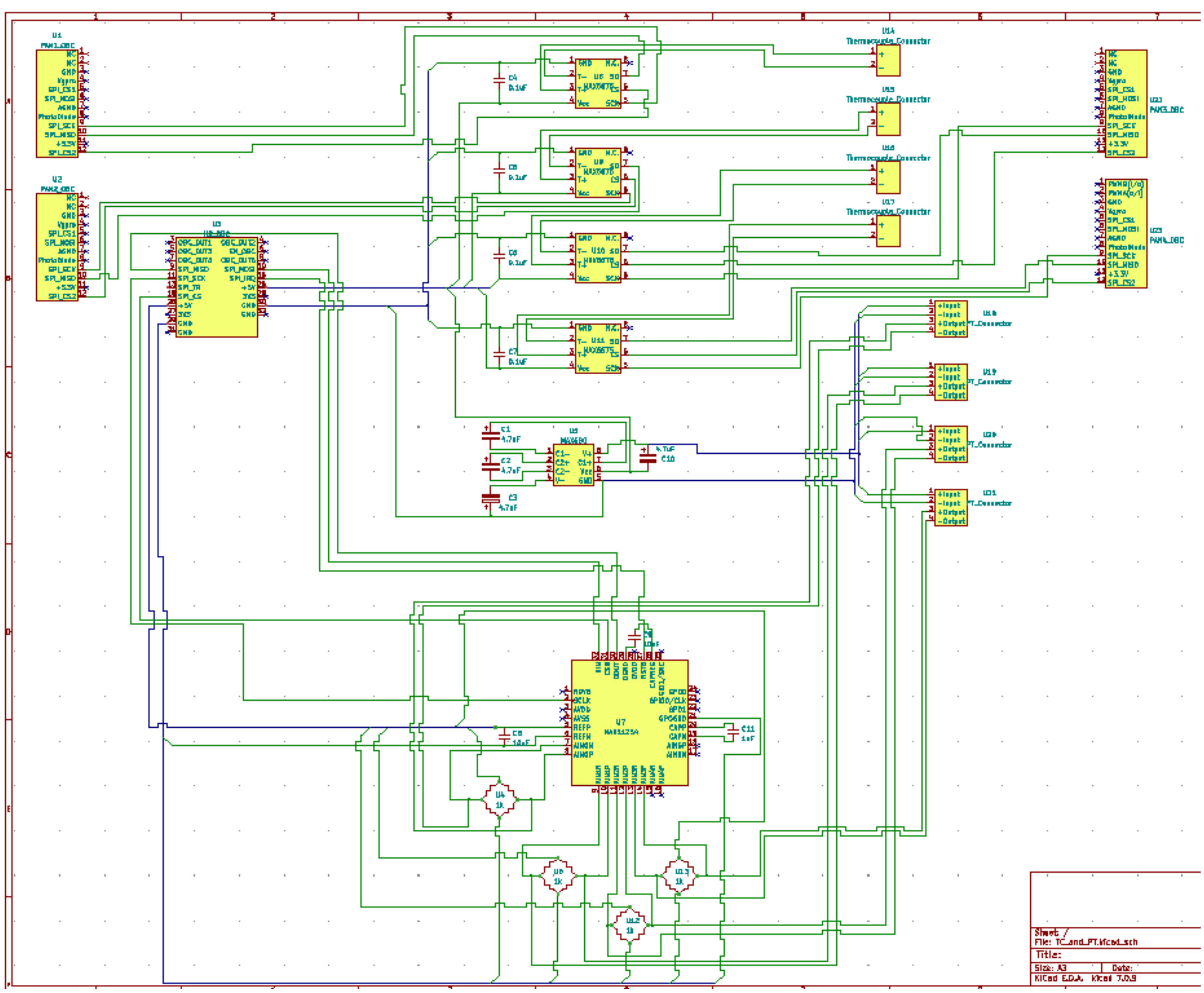

Figure 3. Early Schematic for Pressure Transducer and Thermocouple

Although somewhat difficult to see, the pressure transducer architecture is located towards the bottom of the schematic, while the thermocouple architecture is located at the top. At the time, a MAX680 upconverter chip was used for the pressure transducer, but this was not included during the final design because Justin forgot that he had ordered it and thought that it was out of stock, prompting new power circuitry design. After traces were manually routed on the PCB and multiple iterations were designed, the first board was ordered. Once it was discovered that the MAX11254 traces were too small for 3W to solder in, which will be elaborated upon later, the board was redesigned and is displayed in the figure below.

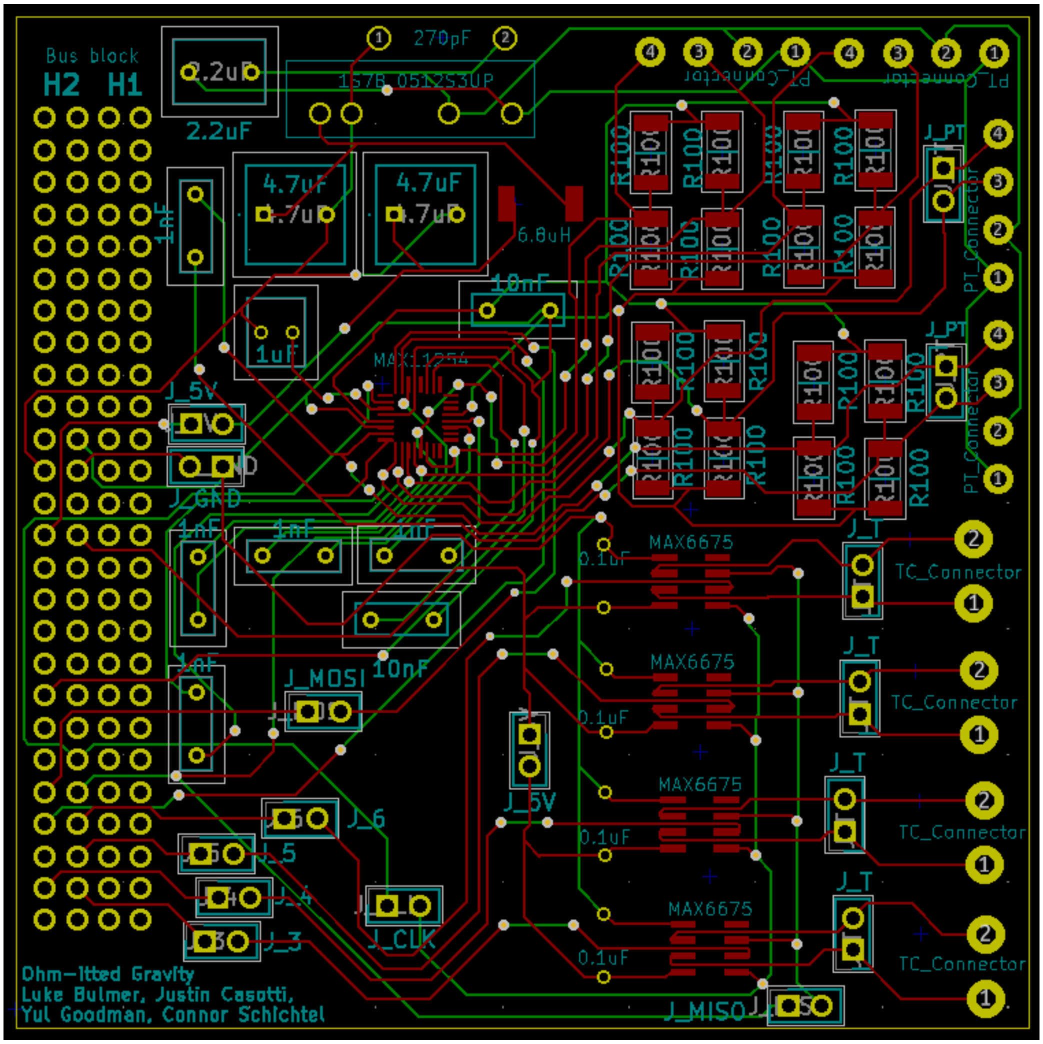

Figure 4. Pressure Transducer and Thermocouple PCB Layout: Revision 2

After several attempts at testing with the embedded software, which are detailed below, a final revision was created for testing before the end of the semester, which is displayed in the figure below.

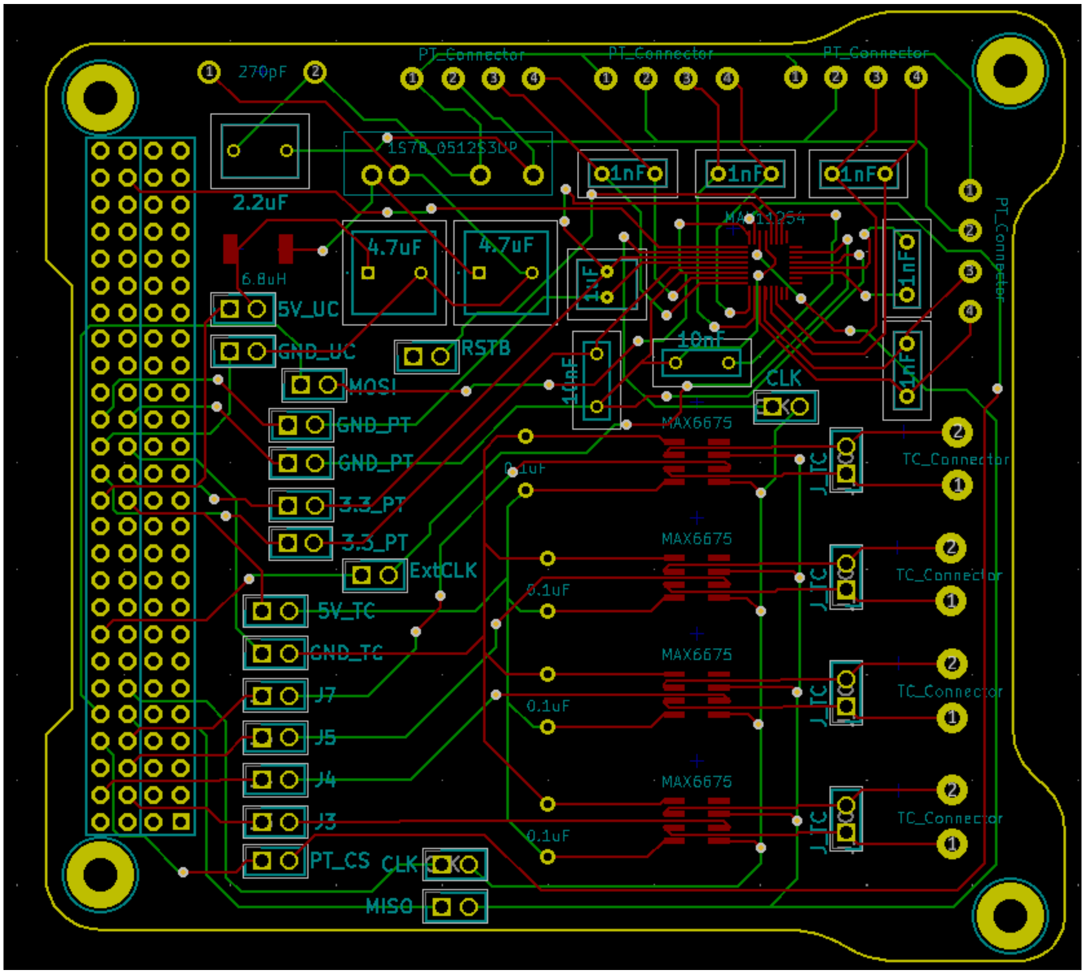

Figure 5. Pressure Transducer and Thermocouple PCB Layout: Final Revision

Some of the differences between the final board and the second revision is that there are no more wheatstone bridges, there are more two-pin test points, and the board outline changed to comply with the PC104 standard. Screw holes have also been included for more secure board mounting.

The transceiver portion of the capstone project consists of integrating the Iridium 9603 transceiver with the Endursat OBC. The transceiver requires 5V for power, which is supplied by the OBC and thus does not require any conversion. Additionally, the transceiver takes in 0V-3.3V digital signals, which again is supplied by the OBC without requiring any voltage conversion. A schematic of the electrical connections between the transceiver and the OBC is shown below.

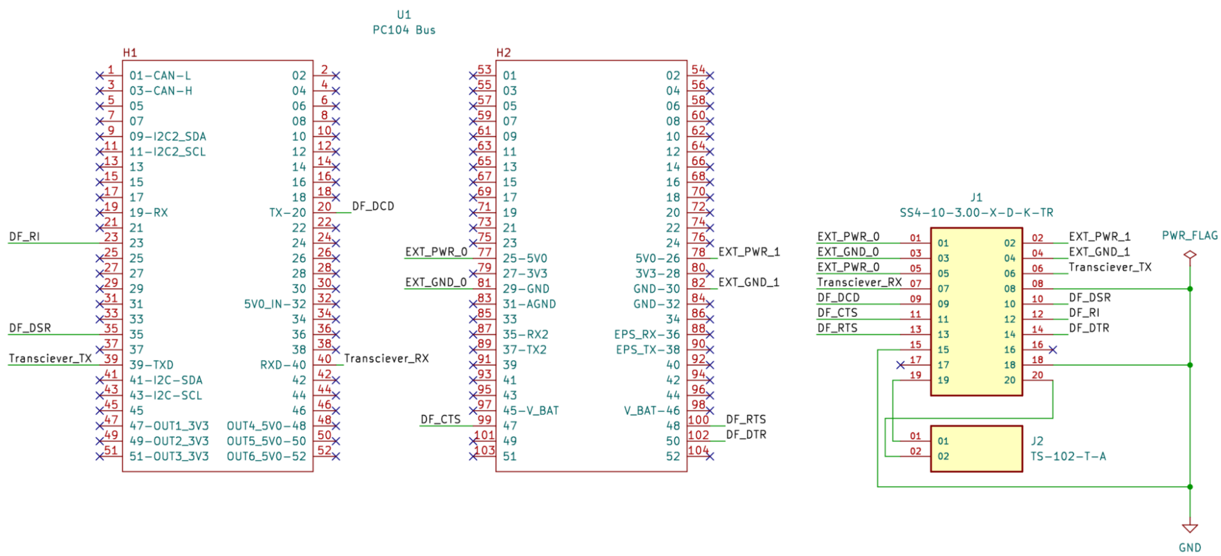

Figure 6. Transceiver OBC Integration Circuit Schematic

As shown above, pins 1 and 2 of the transceiver are connected to the OBC 5V supply, while pins 3 and 4 are connected to the OBC ground. This ensures that the transceiver is powered with adequate current flow and the grounds for the OBC and transceiver are connected. Pins 8 and 9 are the Tx and Rx pins for UART communication between the transceiver and OBC. Pins 11-17 provide optional additional communication between the OBC and transceiver to assist in debugging when using the transceiver according to standard RS-232. Pins 8, 15, and 18 provide additional connections to ground. Finally, pins 19 and 20 are also designed to assist in verifying the functionality of the transceiver. Pin 19 indicates when the transceiver has visibility of the Iridium satellite network, and pin 20 indicates when the transceiver is on and powered. These pins are connected to test points to assist in the testing process for the transceiver.

The PCB layout for the board integrating the transceiver with the OBC is shown below in figure 7. The transceiver was connected to the PCB using the Samtec SS4 connector, as this cable header is compatible with the connector on the transceiver. The PCB adheres to the PC/104 design standards, which specifies the size and shape of the PCB, the bus connector shown on the left side of the PCB, as well as the through holes at each of the corners of the PCB. By adhering to these specifications, the PCB is able to easily fit within the physical constraints of the CubeSat, and is able to be "stacked" with the OBC and pressure transducer and thermocouple PCB. Finally, additional holes are drilled into the PCB in order to mount the transceiver onto the board, ensuring that the transceiver remains connected to the board throughout the duration of the mission. The transceiver is mounted using 2-56 thread screws and nuts, as well as 6mm long spacers.

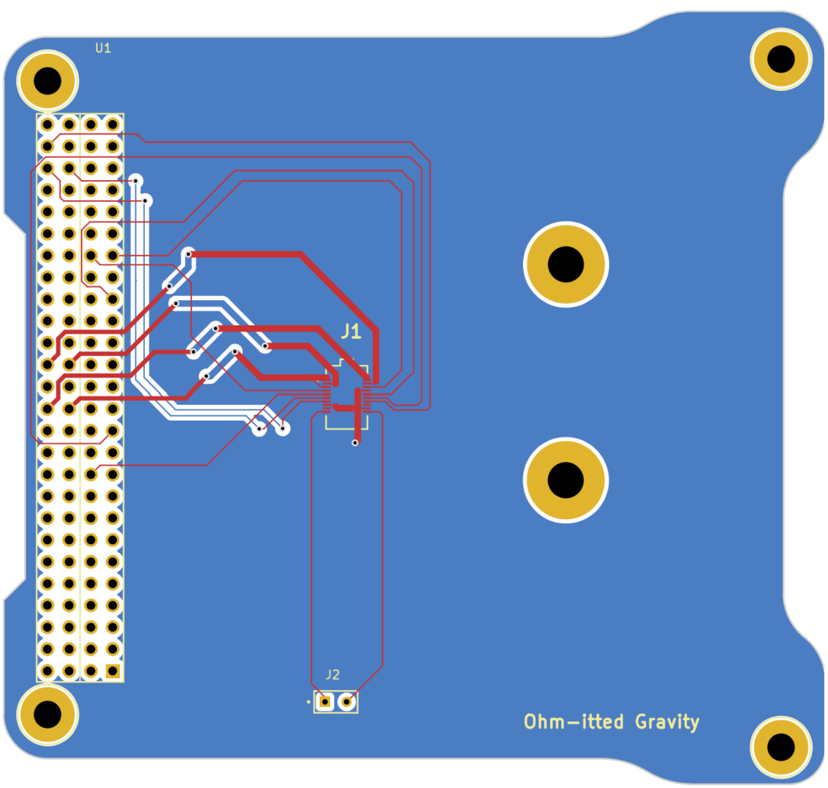

Figure 7. Transceiver OBC Integration Circuit Layout

For the software side of linking the Iridium 9603 Transceiver with the OBC, AT commands are used for intercommunication. AT (Attention) commands play a crucial role in configuring the modem's functionalities, especially for establishing network connections and obtaining status information. These commands are sent to the modem over a UART (Universal Asynchronous Receiver-Transmitter) connection, consisting of two wires for transmit (TX) and receive (RX). The UART transmit function sends the AT commands as plain text, adhering to the syntax "AT<COMMAND><SUFFIX><DATA><CR>". The <COMMAND> field specifies the desired modem action, with some commands being basic and others extended, denoted by a + sign. The <DATA> and <SUFFIX> fields vary based on the command type, including read, set, test, and execute. 'Read' polls a modem configuration setting, 'set' configures a modem setting, 'execute' triggers a modem operation, and 'test' checks whether a modem supports the named command. The <CR> command terminates the AT command, signifying the end.

Upon issuing an AT command, the modem may respond with an 'OK' or 'ERROR' message through the UART receive function, indicating whether the command was received and processed successfully. These responses are crucial for debugging and ensuring proper modem operation. Depending on the command, the modem may generate an 'information response' with relevant data. For the transceiver, specific AT commands are utilized for tasks such as providing firmware information, configuring the transceiver for message sending, and initiating the transmission of a message.

For instance, commands like AT+CGMR are used to provide firmware information, while AT&K0, AT&R1, and AT+SBDMTA=1 are employed to configure the transceiver for sending messages. The sequence of AT commands for sending a message involves queuing the message content with AT+SBDWT='Message' and initiating the message transmission with AT+SBDIX.

These AT commands collectively enable effective communication between the Iridium 9603 Transceiver and the OBC.

C. Technical Details

The project will consist of both a transceiver board and a sensor board. For the transceiver portion of the project, the most important component is the transceiver itself: the Iridium 9603 [6]. This component was selected and deemed viable for a variety of reasons. It is small enough to fit within the weight and dimensional constraints of the CubeSat and has the operating temperature range (-40° C to 85° C) necessary to operate on a space mission. The transceiver also has a data transmission rate of 340 bytes per burst, with bursts occurring every 10 seconds, which allows for the necessary data transmission for the mission. Finally, the transceiver has 100% global coverage, preventing the risk of data loss. As shown in figure 1, the transceiver will communicate with the OBC via UART.

The second portion of the project is focused on the board which will house the sensors and connect the sensors to the OBC. The board will consist of four thermocouples and four pressure transducers. The selected thermocouple is the Omega Inconel Type-K [15], which will be mounted on the board using the Labfacility AM-K-PCB [9] mount and routed through the Analog Devices MAX6675 ADC [3] which will communicate with the OBC via SPI. The thermocouples were selected due to their operating range of up to 480 C meeting the expected in-flight values, and the ADC was selected due to its compatibility with type-k thermocouples, high resolution (24-bit), and SPI compatibility. The selected pressure transducer is the Kulite XCE-80 [8], which will be interfaced with an Analog Devices MAX11254 ADC [2], which will then communicate with the OBC via SPI. The selected pressure transducer has a temperature limit of 270 C which is suitable for space conditions. Furthermore, the compact design of the pressure transducer is beneficial given the size constraints of the CubeSat. Each thermocouple will be interfaced with one MAX6675 ADC, and each MAX11254 ADC will receive input data from two pressure transducers, resulting in six total ADCs being used. Given that all of the ADCs will be communicating using SPI and will only be sending data, each ADC will require three pins from the OBC (MISO, SCLK, CS), resulting in 18 total pins on the OBC required for this portion of the project. According to the selected pressure transducer datasheet, 10 to 12-volt excitations are required as an input for the device in order to receive any output. Since the OBC does not have a 10 to 12-volt power supply, external power supply circuitry had to be developed in order to receive analog signals from the pressure transducer. A voltage upconverter was selected capable of converting a 5-volt DC signal to a 12-volt DC signal. However, several capacitors and an inductor were necessary for proper signal isolation and were included in the design of the PCB. The 5-volt and ground inputs to the upconverter are labeled "5V_UC" and "GND_UC", respectively, on the silkscreen layer. The positive output of the upconverter is connected to pin 2 of the pressure transducer terminal and the negative output is connected to pin 1.

Both of the boards for this project will adhere to the PC/104 specifications [17]. PC/104 outlines standard dimensions, buses, vias, signal timing, and signal levels that are consistent across all PC/104 boards. This specification has been chosen for several reasons. First, PC/104 enables boards to share a common bus and be stacked on top of one another, which will be beneficial when routing from the transceiver and ADCs to the OBC. This stacking will also allow the boards for the project to fit within the limited space requirements of the CubeSat. Additionally, the standardized bus signal assignments of PC/104 are used by the OBC, which will make integration between the shared bus of the boards and the OBC seamless. Finally, use of PC/104 will allow for future boards built for the project to be easily integrated with existing boards, as both the dimensions of the board and connectivity will already be accounted for.

Given that these designs must operate in space, there are many factors that must be considered with regard to layout and manufacturing that would not otherwise be necessary. These designs must endure factors such as broader temperature ranges, ionizing radiation, physical stress at launch and reentry, extended operation, and more. Because of these additional constraints, there are several design practices and standards for layout and manufacturing that will be followed in order to maximize chances for success. A 2021 paper by Franconi et al outlines a NASA Goddard Space Flight Center outlines a PCB design methodology for space applications and describes a specific example of this methodology using a CubeSat [14]. While many of the major components for the project have already been selected and justified above, the bulk of the paper describes a PCB layout methodology which will be beneficial for ensuring an optimal PCB design and limiting potential failures.

Both of the boards designed for this project will be heavy copper printed circuit boards, which are defined as boards with at least 3 oz of copper on either the external or internal layers of a PCB [4]. The benefits of using heavy copper PCBs include higher temperature tolerance and current tolerance and increased physical strength. Heavy copper boards are commonly used in aerospace applications, and although they are more expensive, the added strength will be necessary for a space mission. In addition to using heavy copper boards, the boards will be applied with a conformal coating to ensure the components receive additional thermal and radiation protection. Conformal coating has been shown to improve the reliability of PCBs in extreme conditions provided it is applied correctly [20]. NASA has provided a standard for ensuring that conformal coating is properly applied to circuits which will be adhered to for the project [18].

The software portion of the project will involve configuring the serial communication protocols used to communicate with the transceiver and ADCs, as well as creating an API to easily configure the OBC for use. As previously stated, the transceiver will rely on UART for communication, while the ADCs will rely on SPI for communication. The API will consist of functions to send and receive data from the transceiver, process instruction received on the transceiver, read data from the sensors, and package the data from the sensors for the transceiver. Although this portion of the project is more straightforward than the hardware portion of the project, there are still several major design considerations. First, the software must be optimized such that it can receive data from the sensors, package the data, transfer the data to the transceiver, and transmit the data from the transfer within the necessary 10 second burst window. Given that the transceiver will be transmitting 10 seconds worth of data for 8 separate sensors in each burst, a data structure must be created to organize the sensor data being sent. Finally, and most importantly, given the power constraints of the CubeSat, the software architecture must be designed to be as power-efficient as possible [13]. The software must satisfy the timing, power, and data constraints in order for the project to be functional.

D. Test Plans

For the thermocouple and pressure transducer portion of the project, the test plans did not change significantly across the duration of the semester, especially since testing was taking place up until the week before the deadline. After all necessary components were soldered onto the PCB, a “beep” test with a multimeter was completed to ensure proper electrical connections and solder joints for each board revision. The power circuitry that converts 5 volts DC to 12 volts DC for the pressure transducer was tested using a power supply and digital multimeter. The positive power supply rail was connected to the input of the upconverter and the voltage difference between the output terminals was measured to ensure approximately 12 volts was maintained. On a breadboard, the output leads were simply connected to the positive and negative scope terminals on the AD2 or VirtualBench. On the PCB, the first and second pads of each pressure transducer terminal, connected to the negative and positive upconverter outputs, respectively, were tested in the same manner. Due to a misunderstanding in the MAX11254 datasheet, we initially thought that the pressure transducer analog inputs required wheatstone bridges for processing. This was not the case, as the schematic that depicted the wheatstone bridges was for an application separate from the CubeSat. This was not discerned until the final PCB revision, however, so initial testing stages necessitated proper wheatstone bridge functionality. This included inputting a waveform into the pressure transducer terminal and measuring voltage levels at different points in the bridge. The observed values were verified using an interactive simulation on Multisim. The wheatstone bridge testing, however, is not relevant for the final design of this Capstone project. From a software perspective, the SPI code simply needed to compile before testing with the thermocouple and pressure transducer processors.

The MAX6675 thermocouple amplifier contains seven active pins: ground, negative thermocouple input, positive thermocouple input, V_{cc}, data output (MISO), chip select, and clock. During testing, the V_{cc} pin for a selected amplifier was connected to the positive 5-volt rail of an AD2 power supply and the ground pin was connected to the AD2 ground. The negative and positive thermocouple inputs were connected to the AD2's function generator. In order to simulate realistic waveforms, both DC and AC, data for a typical type-k thermocouple was referenced [22]. The clock signal was generated from an MSP microcontroller via Yul's embedded code and was connected to the clock pin of the thermocouple amplifier. The data output of the amplifier was connected to the assigned MISO pin on the microcontroller. The chip select ports of both devices were also connected.

The code for the thermocouples was relatively simple due to the thermocouple ADC only using the MISO signal and not MOSI. After the code initializes the correct pins on the MSP432, the function to get the thermocouple data is periodically called. This function lowers the chip select pin, and then reads 16 bits before raising the chip select pin to end the data transfer. The data received by the MSP432 is the raw data, so to convert it to a readable value, the raw value is divided by 4 since the precision of the chip is 0.25℃. Once the conversion has been completed, the data is ready to be sent via the transceiver.

The MAX11254 pressure transducer quad ADC contains many pins, but a select few are necessary for testing. The positive reference, the digital power supply, and the positive analog power supply pins all require 3.3 volts. Using the test points on the PCB the positive rail of a 3.3-volt AD2 power supply was connected to each of these pins and ground was connected to each MAX11254 pin that required it. The "3.3_PT" and "GND_PT" labeled terminals on the final PCB revision allow for easy power and ground supply for multiple pins. Traces were routed such that the experimenter has the option to use an external clock or the device's built-in clock generator for SPI communication. During testing, the MSP microcontroller's clock was connected to the external clock pin. The "RDYB" was connected to a pin on the OBC to visualize data conversion processes internal to the chip, and a jumper connected to the "RSTB" pin to enable hardware reset functionality. The MOSI pin on the microcontroller was connected to the serial data input pin on the quad so that commands could be written to the processor. The

MISO pin on the microcontroller was connected to the serial data output pin of the quad, so that the digitized pressure transducer data could be recorded. The AD2's function generator was connected to the pressure transducer terminal inputs in order to simulate pressure data. According to the selected pressure transducer datasheet, the device has a full scale output of 100mV, so a 50mV DC function along with a low-frequency AC waveform that held values around 50 mV were for testing [8]. During the initial stages of testing, when 3.3 volts was supplied to the analog and positive reference pins of the quad chip, the AD2 immediately shut off due to an excessive current draw, indicating a short. A VirtualBench multimeter indicated that this current draw was approximately 1 amp, which was far greater than the anticipated value. After physical troubleshooting and isolating portions of the PCB by cutting traces with a knife, the problem was still not located. Since the project deadline was rapidly approaching, however, the final PCB had to be designed and time had to be allocated for delivery and further testing. When redoing MAX11254 traces, Justin noticed that the digital supply was not receiving power, providing a potential reason for the short. After the PCB arrived and was taken to 3W for quad chip soldering, Benjamin Kidd, a 3W employee, revealed a problem in how the chip had previously been oriented. The chip footprint was designed according to the diagram shown in the datasheet, which is shown below [2].

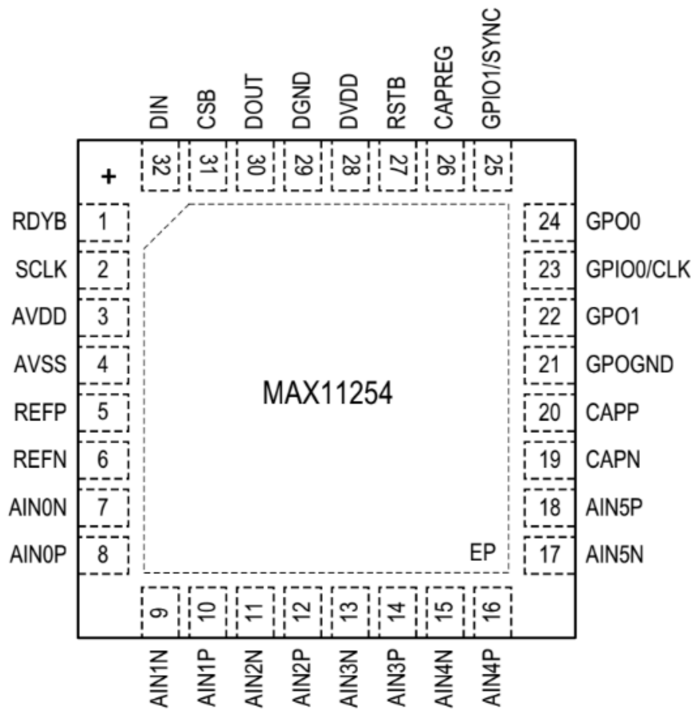

Figure 8. MAX11254 Pin Configuration

Here, pin 1, which is in the top-left corner next to the abridged footprint corner, can be used as a reference. Justin, without paying attention to the abridged corner, thought that if the letters on top of the footprint were facing upward, in reference to the PCB board, that the pins would be in their proper orientation. In reality, the layout shown in the above figure has nothing to do with the physical pin layout on the chip and the abridged corner had to be used as the real reference. Benjamin also found that at the bottom of the MAX11254 datasheet, the layout had the outline number: 21-0140. In consulting a 21-0140 outline datasheet, the following image was depicted [23].

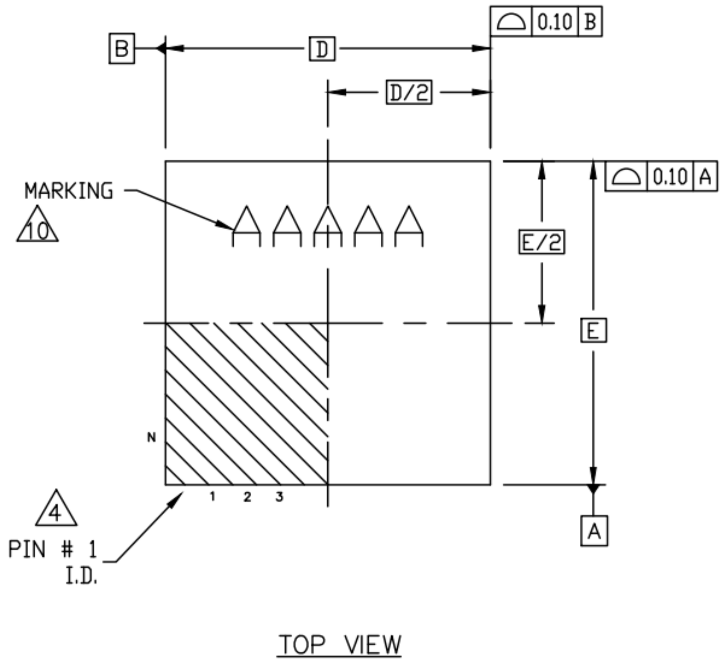

Figure 9. 21-0141 Outline Diagram

One can see that when the markings on top of the chip are facing upward, pin 1 is actually located at the bottom left corner. This means that in the initial iteration, the chip was rotated 90° clockwise out of place, almost certainly explaining the short that was observed during testing. This conclusion aligns with the behavior observed during testing, as after different components were isolated, the problem very clearly seemed to be coming from the chip, although it was dismissed due to the chip being brand-new and professionally soldered. Needless to say, Benjamin was able to reorient the MAX11254 chip for the final PCB.

The code for the pressure transducer ADC was more involved than the thermocouple code because the pressure transducer ADC has many control registers and data registers to accommodate different modes and 4 different pressure transducers simultaneously. Like the thermocouple code, first the MSP432 is initialized and then the ADC code is run periodically. In order to get a pressure transducer reading, the code must first send a command to the ADC to make a data conversion from the sensor to the data register. The code must then wait until the RDYB pin of the ADC drops low, which indicates that the conversion has completed. The code then writes 8 bits to the ADC to specify which register to read, and then reads 24 data bits. Once again, this data is a raw value which must be converted before it is ready to be sent.

X. Timeline

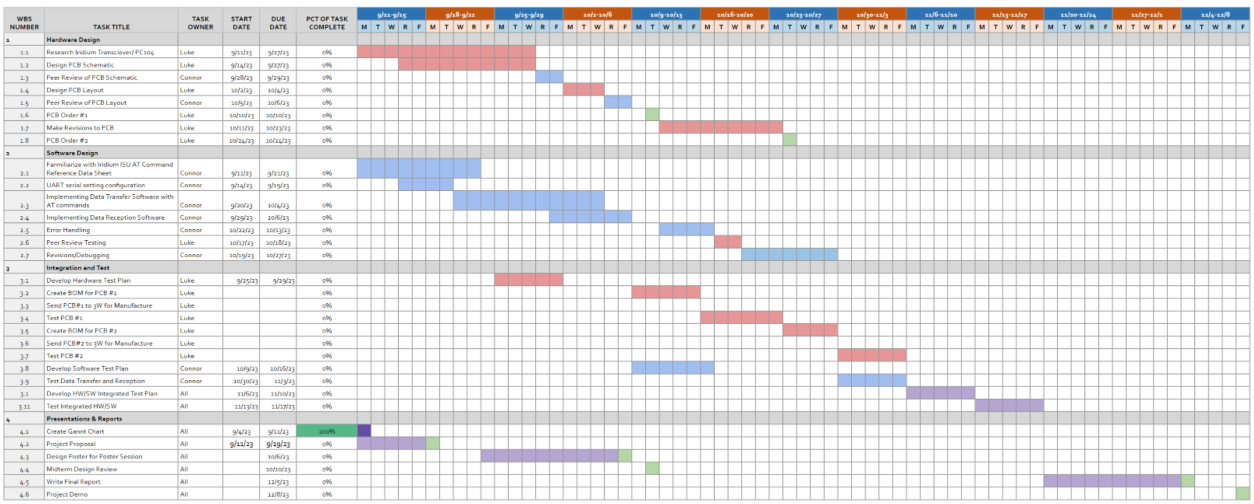

Figure 10: Luke and Connor Gantt Chart

Our timeline for the Iridium Transceiver end of the project was carefully structured to ensure efficient progress and successful completion. The Gantt chart (Figure 10: Luke and Connor Gantt Chart) delineates tasks that can be carried out in parallel and those that must follow a sequential order. Luke's primary responsibilities encompassed schematic/PCB design and project management, with a secondary responsibility of software verification. These tasks drew on his expertise in circuit analysis techniques from FUN I and II and power conversion knowledge from FUN III and EM Energy Conversion. Connor was tasked with the primary responsibility of software design and secondary hardware verification, using skills and embedded coding techniques from Intro to Embedded Programming and Advanced Embedded Systems. Luke and Connor worked separately on hardware and software design, respectively, and collaborated on verifying each other's work and seamlessly integrating the software and hardware components at the project's conclusion.

Throughout the project timeline, we encountered several challenges and delays that impacted the adherence to the initial Gantt chart. One significant setback was the delay in receiving the Endurosat On-Board Computer (OBC), a critical component that was central to the project's software architecture. This delay led to the transition to an alternative computer solution. To maintain progress, the NASA Core Flight System (cFS), UART, and SPI software were temporarily deployed on an MSP432 microcontroller, which was readily available. This adjustment allowed us to continue software development and testing while awaiting the OBC's arrival. However, this shift introduced a learning curve and required additional time for us to adapt to the new software environment, contributing to delays in the software development phase outlined in the Gantt chart.

In addition to software challenges, delays in hardware ordering further complicated the project timeline. Issues with the design and manufacturing constraints, particularly related to the board’s specifications and copper weight, led to unanticipated delays. The decision to increase copper weight for improved durability and heat dissipation inadvertently contributed to cost and manufacturing concerns, requiring us to reevaluate and modify the manufacturing plan. Additionally, constraints imposed by PCB suppliers on trace thickness forced a shift from two 4 oz copper layers to four 2 oz layers, adding another layer of complexity to the manufacturing process. This coupled with unforeseen delays in the delivery of the Iridium Transceiver and its activation forced adaptability and planning to navigate integration within the designated project timeline. Despite these obstacles, our commitment to problem-solving allowed us to successfully address these challenges and deliver a robust end product that met the project's objectives.

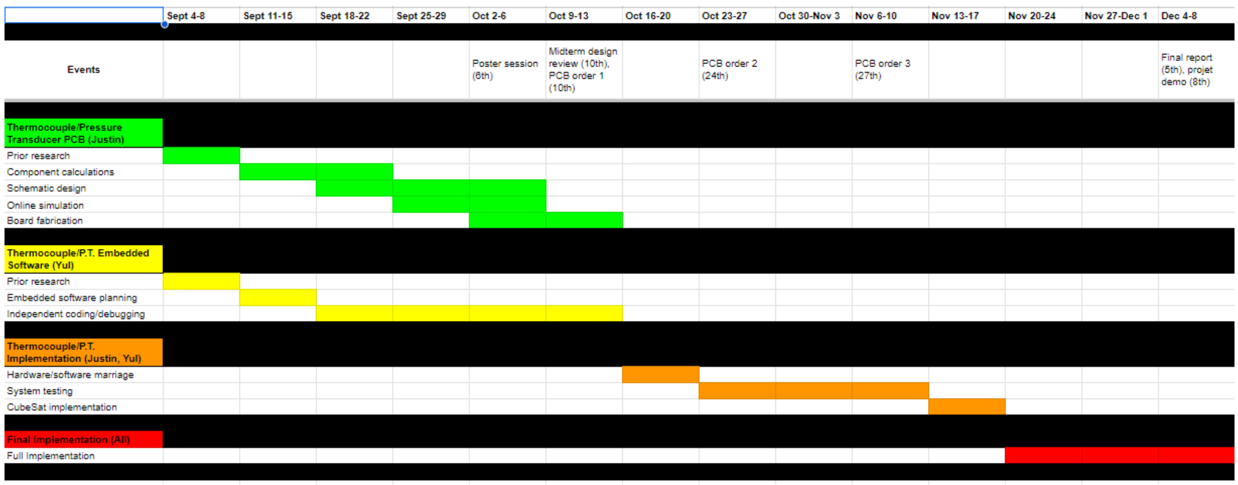

Figure 11: Justin and Yul Gantt Chart

Similarly, the timeline for the thermocouple and pressure transducer (PT) sensor end of the project has been structured to keep its members on track and guide the project to success. As the Gannt chart for this part (Figure 11: Justin and Yul Gantt Chart) shows, the tasks required to successfully complete the project have been separated into four categories: Thermocouple and PT PCB, Thermocouple and PT Embedded Software, Thermocouple and PT Implementation, and Final Implementation. Justin's main responsibilities were designing and building the PCB housing the thermocouple and pressure transducer sensors. This primarily drew on the circuit analysis and PCB design skills gained from FUN I, II, and III. Justin also handled software verification. Yul's main responsibilities were designing the software to interface with the thermocouple and PT devices. This primarily drew on the knowledge gained from Introduction to Embedded Computer Systems and Advanced Embedded Systems. Yul also handled hardware verification. Justin and Yul shared the responsibilities of implementation, which includes testing the hardware and software together and integrating the board into the CubeSat device.

For the first half of the semester, this portion of the project remained relatively on-track with the goals of the Gantt chart. On the hardware side, the schematic was developed and the PCB was designed and submitted in-time for the first class-wide PCB order. The software was slightly behind due to the difficulty of finding an alternative once we had learned that the OBC would not arrive until after the end of our capstone, but there were no immediate concerns with timing. One major factor that was not initially accounted for in the Gantt chart was the time spent for PCB delivery and the time necessary for soldering at WWW Electronics. Through the class-wide order, PCBs took at least one week to arrive and through JLCPCB, slightly less than one week. Little work could generally be completed during this time due to the physical nature of troubleshooting PCB-mounted systems. Additionally, two business days had to be allocated for WWW Electronics to solder in the pressure transducer ADC chip, and since they closed at 4:30 PM, scheduling was often difficult during the work week. Perhaps the greatest hiccup in timing was after the first board revision, where Justin was told by 3W that the copper leads for the pressure transducer ADC pins were too short for soldering and needed to be extended, adding at least another week for the design and delivery of a new board. These periods of downtime in the hardware production fortunately allowed time for the software development to catch up, so that both parties were ready to test the system at the first possible chance. Needless to say, these delays pushed back the checkpoints in the second half of the semester, so that rather than performing a full-system test during the last few weeks, the thermocouple and pressure transducer system test was occurring during the last week of the semester. It was difficult to predict the delays and time necessary to reach certain checkpoints at the start of the Fall, but throughout the semester, lessons certainly have been learned in accounting for these roadblocks for future Gantt chart design.

XI. Costs

A high level overview of the costs of the project is shown below in table x, while a full cost breakdown is featured in the appendix. A distinction is made in both this table and in the appendix between components purchased by us, and components provided by the MAE department CubeSat team. Many of the more costly components of the project, such as the transceiver, pressure transducers, thermocouples, and the ADC's, were provided by the MAE department, and are noted separately as these did not come out of our $500 budget. The total spent by our team on the project was $456.32, which fell within the provided budget. Also noted in the table is the estimated cost for mass producing our design. While the costs of the PCBs and some of the components will decrease, many of the costlier components will remain at the same price. These estimates were made by using Advanced Circuits quotes for large quantities, as well as the cost of purchasing digikey components in large quantities.

Table 1. Cost Summary

Category	**Key Items**	**Cost**	**10000 Unit Cost ($)**
PCB Fabrication	Transceiver PCB, Pressure & Thermo PCB	$181.86	$15
PCB Population	3W Assembly for both PCBs	$30.00	$3
Soldered Components	Resistors, Capacitors, Connectors, IC's	$223.96	$50

Mechanical Components	Screws, Nuts, Spacers	$20.50	$2
Purchased Total		**456.32**	**$70**
MAE Provided Components	Transceiver, ADC's, Thermocouples, Pressure Transducers	$750.09	$575
Total		**$1206.41**	**$645**

XII. Final results

For the transceiver portion of the project, a PCB was successfully created to integrate the transceiver with the OBC. Mechanically, the PCB perfectly met the required specification for the PC/104 standard and for fastening the transceiver to the board. All of the electrical connections on the PCB were verified to ensure that all necessary connections were made and that there were no unintentional shorts. The transceiver itself was turned on, and outputs from the transceiver verified that it had been turned on, and when an antenna was connected, the outputs from the transceiver indicated that it could communicate with the satellite network. For the software portion of the transceiver, the final prototype operates consistently to acquire and display accurate temperature and pressure data. The code takes in real-time temperature and pressure readings as float values from the connected thermocouples and pressure transducers. Through UART serial communication, this data is then transmitted to the Putty terminal in Figure 12, where it is displayed. To ensure continuous updates, the data transmission occurs within a while loop. During testing scenarios, such as subjecting the thermocouple sensors to a heat gun, the temperature values dynamically increase, validating the responsiveness of the UART communication. The software was also tested in serial communication to an AD2 and scrutinized within a step analyzer. Test AT commands were sent through UART, with the correct ASCII output displaying on the AD2. This successful integration of the software aligns with the initial success criteria, specifically in terms of real-time data acquisition, transmission via UART, and dynamic response to environmental changes.

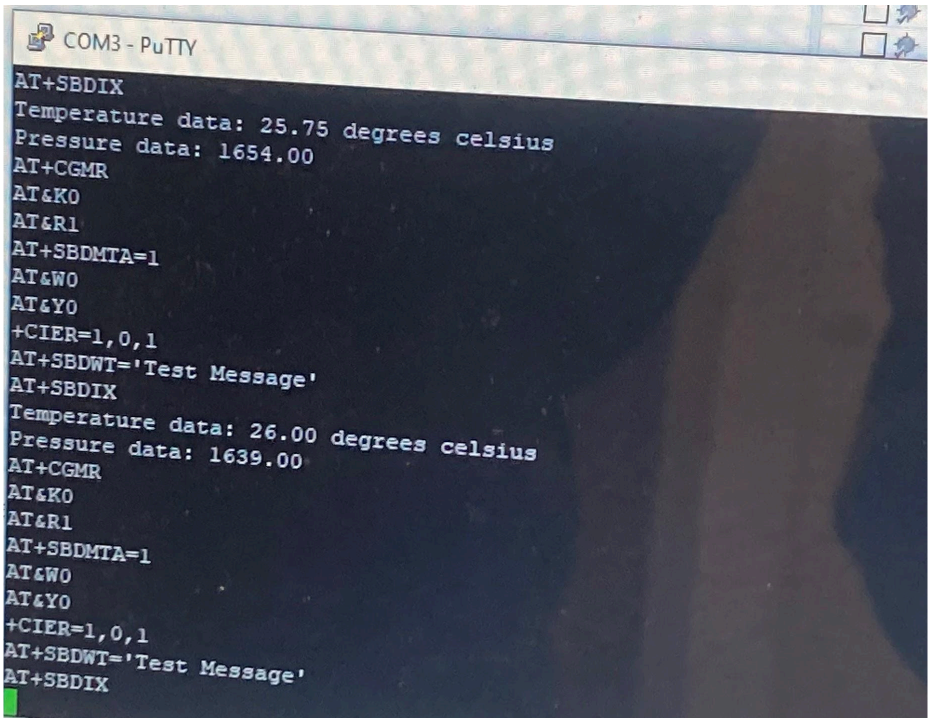

Figure 12: Putty Terminal Output

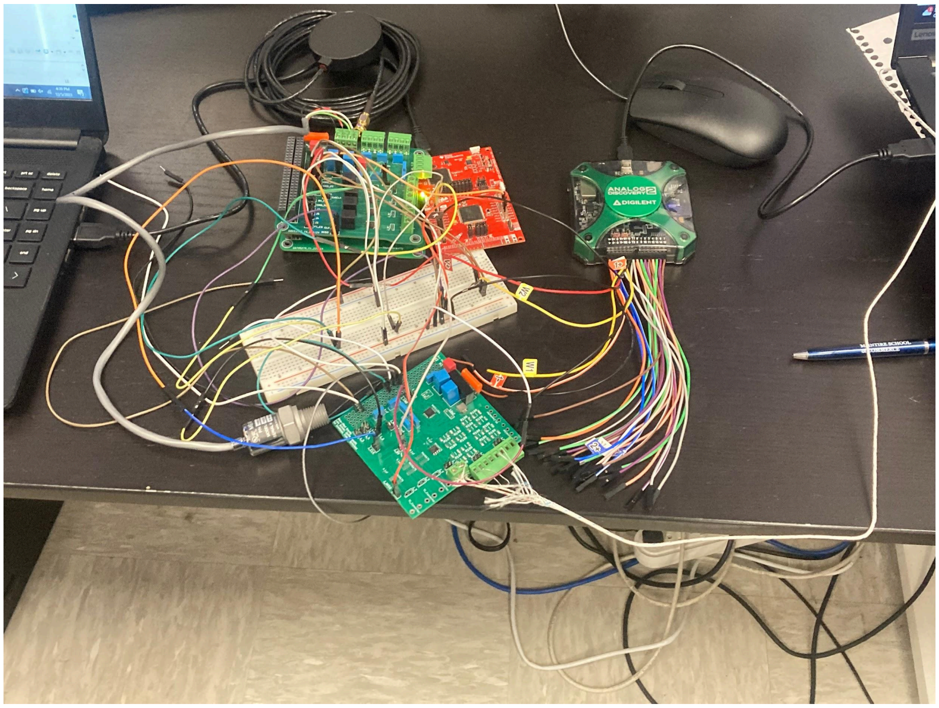

Figure 13: Final Implementation Layout

For the thermocouple and pressure transducer portion of the project, by the time of submitting the final report, the thermocouple amplifier soldered to the second revision PCB was working and the pressure transducer ADC soldered to the final revision PCB was working. This is because the thermocouple amplifiers soldered to the final PCB were most likely burned due to excessive solder iron temperatures. As a lesson for the future, care should be given to the thermal limits of a device before it is met with a soldering iron. This problem will attempt to be rectified before the final project demonstration. In order to test the pressure transducer system, a function generator that produced a DC voltage was passed into the negative and positive pressure transducer terminals. A reasonable output was observed that changed with the voltage input, but more time will need to be dedicated to understand the pressure reading units, as the pressure transducer datasheet is not very specific in this regard and the ADC is not specifically designed for pressure data processing, unlike the thermocouple amplifier. From a single pressure input terminal, the experimenters found that the MAX11254 produced reasonable analog-to-digital conversion results, which were observed on the MSP microcontroller. The chip was also tested with a physical pressure transducer, but since the atmospheric pressure could not be immediately changed, the output was not incredibly meaningful, other than serving as a reference for the room's current pressure. The pressure transducer's output was also connected to a multimeter and the experimenters found that a small change in voltage occurred when a cover was placed on top of the detector part of the transducer, confirming the operation of the upconverter power circuitry.

In testing the thermocouple amplifiers on the second revision PCB, a DC signal was passed through the positive and negative thermocouple terminals. The MSP microcontroller was used to confirm the MISO data, which was found to increase when the voltage increased and decrease when the voltage decreased, demonstrating sufficient analog-to-digital conversion. In order to convert the arbitrary data value into degrees celsius, the bottom three bits and topmost bit were omitted from the data packet. In other words, the value had to be bit-shifted down by 3 and the topmost bit had to be masked [3]. A thermocouple was also connected to the input terminals of the amplifier ADC and a heat gun was used to vary the temperature experienced by the device. The temperature reading was found to increase considerably when the heat gun was pointing directly at the thermocouple and decrease when it was taken away, confirming the functionality of the thermocouple system. Figure 13 illustrates the pressure transducer and thermocouple readings at the time of submitting the final report.

The experimenters can confidently say that the upconverter power system that serves as an input to the pressure transducers works. If the number produced by the MAX6675 ADC can be converted to a useful pressure value and tested with all four pressure transducer inputs, the functionality of the pressure transducer system can be confirmed. If at least one of the four thermocouple amplifier chips can get fixed on the final board and produce reasonable results, the functionality of the thermocouple system can be confirmed. Instructions will be given to the mechanical and aerospace teams for next semester on how to safely solder in the rest of the thermocouple amplifiers.

XIII. Future Work

The work that was done on this project could be improved or expanded upon by future students by utilizing a different pressure transducer ADC chip from the one used on this project. The current pressure transducer ADC is a sophisticated chip that has many advanced features that are not being utilized with our current project. The chip is relatively expensive compared to simpler counterparts, and the only reason this particular device was chosen is because of the precision it can achieve with its 24 bit output. Future students could save costs while also simplifying the circuit board at the same time. Also, future students could investigate other pressure transducer options that have a different input voltage. The pressure transducers that are currently being used in the project require a 10-12V input, which is more than any other device on the board. As a result, there is additional circuitry to accommodate a step up from the 5V that all the other devices use to the 10-12V required. Making a change in the pressure transducers could eliminate the need for this extra circuitry and create more space on the board.

Incorporating these potential changes would allow more devices to be on the board, which could allow the Transmitter board and the ADC board to be merged into one board. Space is always an issue within the CubeSat, so reducing the number of circuit boards within the spacecraft would allow more room for other devices. There is currently concern about the Power subsystem requiring more space than previously planned, so reducing the space required for the Electronics subsystem would be beneficial for the overall project.

XIV. References

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XV. Appendix A. Full Cost Breakdown

Line #	Category	Name	Quantity	Per Unit Cost	Cost
1	Components	Thermocouple connectors	10	$0.70	$6.81
2	Components	Pressure transducer connectors	10	$2.41	$21.49
3	Components	MAX680 upconverter (never used)	5	$7.55	$37.75
4	Components	SS4-10-3.50-L-D-K-TR (transceiver cable connector)	1	$3.96	$3.96
5	Components	Stacking header pin (40)	2	$2.50	$5.00
6	Components	2-pin headers	1	$0.51	$0.51
7	Components	Nuts	1	$10.81	$10.81
8	Components	Aluminum spacers	2	$0.47	$0.94
9	Components	Screws	1	$8.75	$8.75
10	Components	1uF capacitors	5	$1.66	$8.30
11	Components	Stacking header pin (40)	3	$2.50	$7.50
12	Components	100ohm resistors	20	$0.22	$4.42
13	Components	4.7uF capacitors	10	$1.07	$10.70
14	Components	10nF capacitors	5	$0.33	$1.65
15	Components	1nF capacitors	5	$0.36	$1.80
16	Components	0.1uF capacitors	5	$2.12	$10.60
17	Components	1S7B voltage upconverter	2	$3.04	$6.08
18	Components	Vertical header pins (11)	10	$0.15	$1.54
19	Components	2-pin jumpers	50	$0.08	$3.94
20	Components	Stacking header pin (52)	4	$7.06	$28.24
21	Components	100 ohm resistors	20	$0.22	$4.42
22	Components	2.2uF capacitors	3	$1.46	$4.38
23	Components	270pF capacitors	3	$2.62	$7.86
24	Components	1nF capacitors	10	$0.24	$2.38
25	Components	10nF capacitors	3	$0.33	$0.99
26	Components	Thermocouple connectors	5	$0.70	$3.50
27	Components	Pressure transducer connectors	5	$2.41	$12.05
28	Components	6.8uH inductors	10	$1.11	$11.10
29	Components	100 ohm resistors	30	$0.22	$6.63
30	Components	1nF capacitors	5	$0.47	$2.35
31	Components	10nF capacitors	5	$0.33	$1.65
32	Components	0.1uF capacitors	3	$2.12	$6.36
33	PCB	Transceiver Board 1st Revision	1	$33.00	$33.00
34	PCB	Temperature/Pressure Board 1st Revision	1	$33.00	$33.00
35	PCB	Temperature/Pressure Board 2nd Revision	1	$22.40	$22.40
36	PCB	Transceiver Board Final Revision	1	$54.53	$62.33
37	PCB	Pressure/Temperature Board Final Revision	1	$31.13	$31.13
38	3W Assembly	Temperature/Pressure Board 2nd Revision Assembly	1	$10.00	$10.00
39	3W Assembly	Temperature/Pressure Board Final Assembly	1	$20.00	$20.00
40		**Purchased Components Subtotal**			**$456.32**
41	MAE Provided	Iridium 9603 Transceiver	1	$156.00	$156.00
42	MAE Provided	M3021-000005-10KPG Pressure Transducer	4	$105.49	$421.96
43	MAE Provided	MAX11254 Pressure Transducer ADC	1	$12.13	$12.13
44	MAE Provided	MAX6675 Thermocouple ADC	4	$18.45	$73.80
45	MAE Provided	K-Type Bolt-on Thermocouple	4	$21.55	$86.20
46		**Provided Components Subtotal**			**$750.09**
47		**Total**			**$1,206.41**

XVI. Appendix B Transceiver Supplementary Documentation for MAE Team

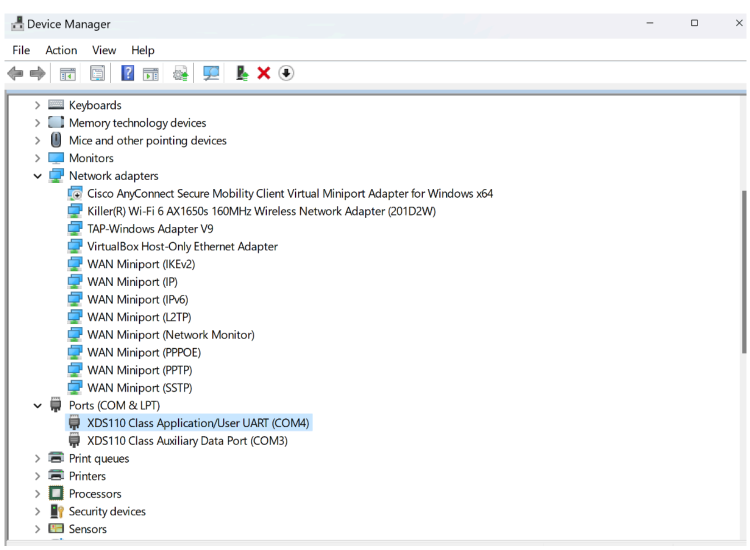
Iridium Transceiver Documentation For Future Use

UART

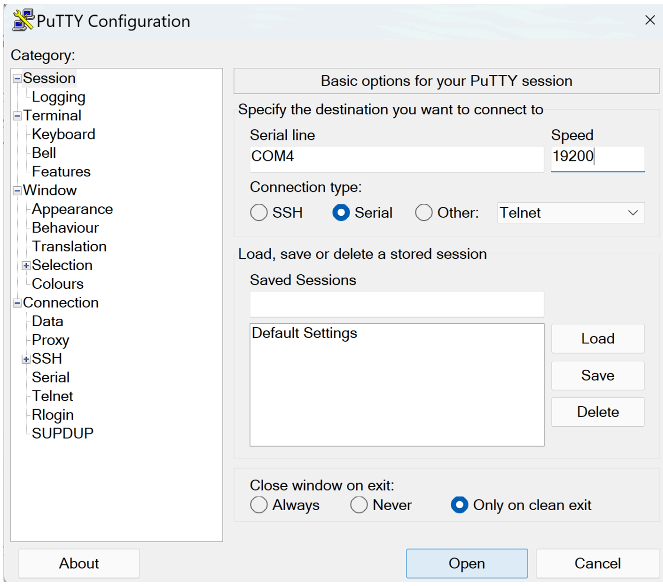
Info

UART (Universal Asynchronous Receiver/Transmitter) is a serial communication protocol for exchanging serial data between two devices. In serial communication, data is transferred bit by bit through character ASCII codes. UART is the only serial communication protocol that can be used with the Iridium 9603 Transceiver.

Setup (for MSP432 microcontroller UART to computer putty terminal)

- Boot up Code Composer Studio
- Connect MSP432 to computer via usb cable
- Check Your Computer Device Manager for which COM port is configured for UART
    - For Windows:
    - 

- Boot up Putty

- Set settings with connection type as serial, serial line as COM(COM number of UART), and speed as 19200 (for transceiver baud rate)
- 

- Click open
- Debug and build code
- Run code using COM initialization and send commands
- Check output in putty

Setup (for MSP432 microcontroller UART to transceiver)

- Boot up Code Composer Studio
- Connect MSP432 to computer via usb cable
- Connect MSP432 to Iridium Transceiver using jumper cables
    - P3.2 is UART receive
    - P3.3 is UART transmit
- Debug and build code
- Run code using normal initialization and send/receive commands

UART Commands

Initialization Commands:

- Output_Init()
  - Calls UART0_Init
- Output_COM_Init()
  - Calls UART0_COM_Init
- UART0_Init()
  - Calls UART_Init and turns off buffering
- UART0_COM_Init()
  - Calls UART_COM_Init and turns off buffering
- UART_Init()
  - Used for Initializing UART serial connection to transceiver
- UART_COM_Init()
  - Used for Initializing UART serial connection to computer putty terminal

UART Send Commands:

- UART_OutChar(char data)
  - Used for sending one character through UART ("a", "b", "1", "!") to transceiver
- UART_COM_OutChar(char data)
  - Used for sending one character through UART ("a", "b", "1", "!") to computer putty terminal
- UART_OutString(const char *str)
  - Used for sending multiple characters at once through UART ("hi", "rocket", "temperature", "pressure") to transceiver
- UART_COM_OutString(const char *str)
  - Used for sending multiple characters at once through UART ("hi", "rocket", "temperature", "pressure") to computer putty terminal
- UART_OutFloat(float f)
  - Used for sending a number with decimals through UART ("20.01", "17.6", "95.334", "4.2") to transceiver

- UART_COM_OutFloat(float f)
  - Used for sending a number with decimals through UART ("20.01", "17.6", "95.334", "4.2") to computer putty terminal

UART Receive Commands:

- UART_InChar()
  - Used for receiving one character through UART ("a", "b", "1", "!")
- UART_InString(char *buffer, int maxLength, char terminator)
  - Takes three inputs of a buffer, an integer of the max length of string received, and a terminator character that when received will terminate operation
  - Used for receiving multiple characters at once through UART ("hi", "rocket", "temperature", "pressure")

Iridium Transceiver

Info

AT (Attention) commands play a crucial role in configuring the modem's functionalities, especially for establishing network connections and obtaining status information. These commands are sent to the modem over a UART (Universal Asynchronous Receiver-Transmitter) connection, consisting of two wires for transmit (TX) and receive (RX). The UART transmit function sends the AT commands as plain text, adhering to the syntax "AT<COMMAND><SUFFIX><DATA><CR>". The <COMMAND> field specifies the desired modem action, with some commands being basic and others extended, denoted by a + sign. The <DATA> and <SUFFIX> fields vary based on the command type, including read, set, test, and execute. ‘Read’ polls a modem configuration setting, ‘set’ configures a modem setting, ‘execute’ triggers a modem operation, and ‘test’ checks whether a modem supports the named command. The <CR> command terminates the AT command, signifying the end.

Upon issuing an AT command, the modem may respond with an 'OK' or 'ERROR' message through the UART receive function, indicating whether the command was received and processed successfully. These responses are crucial for debugging and ensuring proper modem operation. Depending on the command, the modem may generate an 'information response' with relevant data. For the transceiver, specific AT commands are utilized for tasks such as providing firmware information, configuring the transceiver for message sending, and initiating the transmission of a message.

For instance, commands like AT+CGMR are used to provide firmware information, while AT&K0, AT&R1, and AT+SBDMTA=1 are employed to configure the transceiver for sending messages. The sequence of AT commands for sending a message involves queuing the message content with AT+SBDWT='Message' and initiating the message transmission with AT+SBDIX. These AT commands collectively enable effective communication between the Iridium 9603 Transceiver and the OBC.

Setup

AT commands are sent through UART with the command:

- UART_OutString("AT&EXAMPLE")

After sending an AT command to the transceiver, the transceiver will send a message back (typically OK). This needs to be received through UART using the command:

- UART_InString(char *buffer, int maxLength, char terminator)

Then, this received message needs to be output to the computer putty terminal to visualize the response. To do this, initialize for UART through COM using the command:

- Output_COM_Init()

Then, send the command:

- UART_COM_OutString(myBuffer)

with myBuffer being the buffer passed into UART_InString(). The “OK” (or other message) will then be output in the putty terminal.

AT Commands Info

Provide Firmware Info

- AT+CGMR // provide firmware info

Configure Transceiver for sending a message

- AT&K0 // set flow control
- AT&R1 // Ignore CTS from DTE (always send)
- AT+SBDMTA=1 // status of send
- AT&W0 // store current configuration
- AT&Y0 // Designate a default reset basic profile
- +CIER=1,0,1 // check connection

Send a message

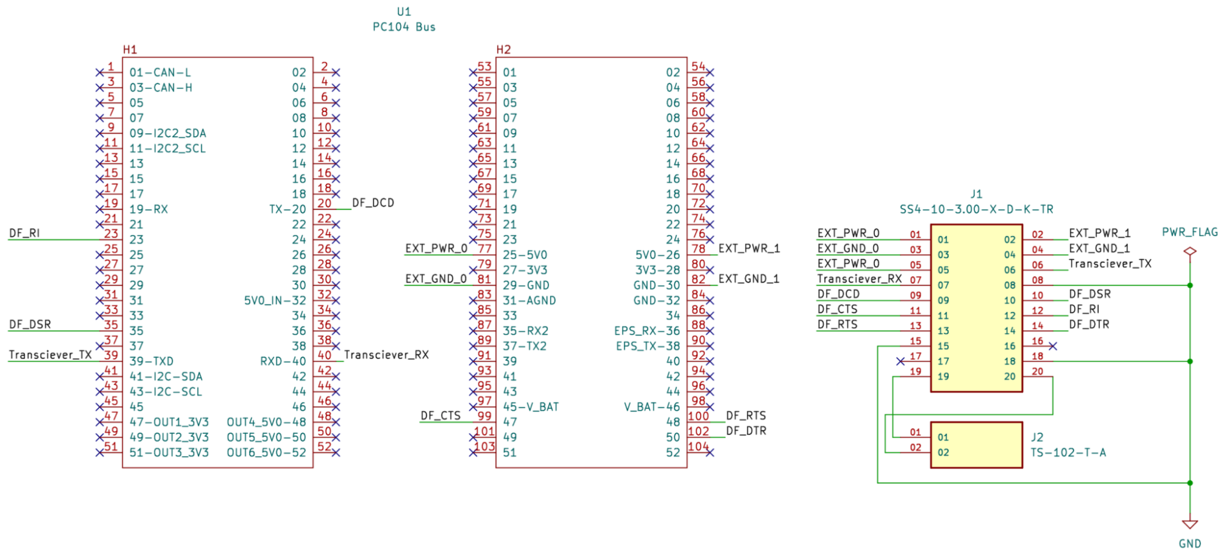
- AT+SBDWT='Test Message' // queue message with contents ‘Test Message’
- AT+SBDIX // send message

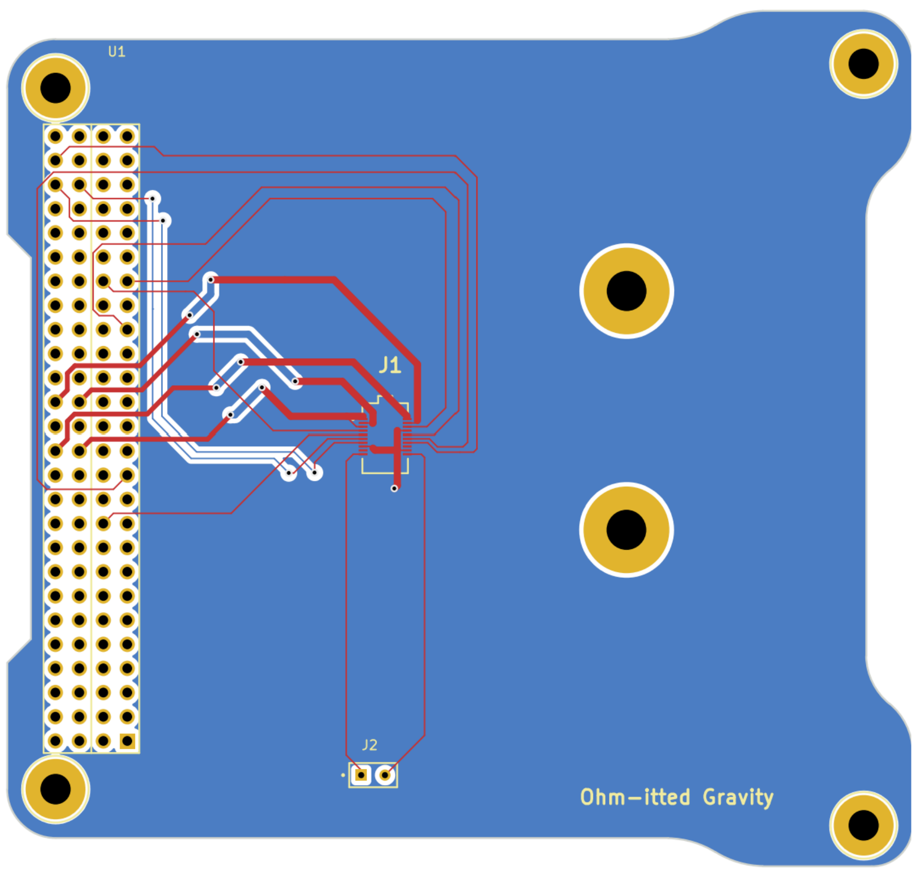
Transceiver Hardware

The below table shows the pinout for the transceiver, as well as the corresponding connections for the OBC. The name indicates which signal corresponds with each pin. The Tx and Rx pins for the transceiver are the two UART Pins. **Note: Transceiver Tx is connected to OBC Rx, and Transceiver Rx is connected to OBC Tx**. Pins 9-14 are not strictly necessary, and are instead provided to assist with debugging. Finally, pins 19 and 20 indicate whether the transceiver is turned on and receiving power; these pins are not connected to the OBC, and instead are connected to test points to assist with debugging. The remaining pins correspond with power, and are all either always 0V or always 5V.

Transceiver Board Pinout			
Name	**Chip Pin #**	**Bus Pin #**	**Value**
EXT_PWR_0	1	H2-25	5 V
EXT_PWR_1	2	H2-26	5 V
EXT_GND_0	3	H2-29	0 V
EXT_GND_1	4	H2-30	0 V
ON/OFF	5	H2-26	5 V
Transciever_TX	6	H1-39	0/3.3 V
Transciever_RX	7	H1-40	0/3.3 V
SIG_GND	8		0 V
DF_ DCD	9	H1-20	0/3.3 V
DF_ DSR	10	H1-35	0/3.3 V
DF_ CTS	11	H2-47	0/3.3 V
DF_RI	12	H1-23	0/3.3 V
DF_ RTS	13	H2-48	0/3.3 V
DF_ DTR	14	H2-50	0/3.3 V
SIG_GND	15		0 V
Reserved	16		
Reserved	17		
SIG_GND	18		0 V
NETWORK AVAILABLE	19		0/3.3 V
SUPPLY_OUT	20		0/3.3V

On the next page, the circuit schematic and printed circuit board (PCB) layout are provided, showing the electrical and physical connections for the board.


U1
PC104 Bus
H1
01-CAN-L
03-CAN-H
09-I2C2_SDA
11-I2C2_SCL
19-RX
TX-20
5V0_IN-32
39-TXD
RXD-40
41-I2C-SDA
43-I2C-SCL
47-OUT1_3V3
49-OUT2_3V3
51-OUT3_3V3
OUT4_5V0-48
OUT5_5V0-50
OUT6_5V0-52
DF_DCD
DF_RI
DF_DSR
Transciever_TX
Transciever_RX
H2
25-5V0
27-3V3
29-GND
31-AGND
35-RX2
37-TX2
45-V_BAT
5V0-26
3V3-28
GND-30
GND-32
EPS_RX-36
EPS_TX-38
V_BAT-46
EXT_PWR_0
EXT_GND_0
DF_CTS
EXT_PWR_1
EXT_GND_1
DF_RTS
DF_DTR
J1
SS4-10-3.00-X-D-K-TR
EXT_PWR_0
EXT_GND_0
EXT_PWR_0
Transciever_RX
DF_DCD
DF_CTS
DF_RTS
EXT_PWR_1
EXT_GND_1
Transciever_TX
DF_DSR
DF_RI
DF_DTR
PWR_FLAG
J2
TS-102-T-A
GND


U1
J1
J2
Ohm-itted Gravity