# Final Report
# Mesh Network Positioning System

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# 1. Introduction

## 1.1 Background

Spaceshot from the Illinois Space Society is working towards being one of the first collegiate teams to build and launch a completely student designed vehicle 100 kilometers to the edge of space; Also known as the Kármán line. Besides physically getting to space, a critical challenge is being able to prove that you reached space. Many commercial systems like Global Positioning Systems (GPS) are not operable in those extreme conditions. Suitable internal inertial navigation systems are cost prohibitive for amateur applications, and for mission critical applications multiple novel redundant methods are highly prefered. Therefore, a new method to reliably track objects and resolve their position in these extreme applications is needed.

*(Spaceshot recently broke the University's 7-year standing altitude record in June of 2024, and is looking to do so again in the summer of 2025. Kairos II Launch)*

## 1.2 Solution

This project aims to create a novel off grid radio positioning system that can be used to track objects with the only limitation being link budget. Due to the practicality of testing to 100 km, this system will focus on creating the foundational hardware and software to track objects needed to track objects at long ranges at a cheaper price than available professional alternatives. However, for demonstration purposes the scope will be over much shorter ranges. In the future better antennas could be used to drastically extend range. Depending on progress this system may be flight tested at a launch in April.

### 1.2.1 Overview

There are two primary system components. Anchor nodes are stationary position reference nodes that then communicate with Rover nodes to resolve a Rover node's position. By timing the round trip call and response of a radio signal, the distance between transceivers can be calculated with the known speed of light constant. Using at minimum 3 ground based Anchor nodes with known positions, a moving Rover node can be sequentially pinged and its position calculated through trilateration. Rover nodes would be attached to the desired tracking assets of unknown position. Anchor nodes must  also have synchronized time to allow for Time Division Multiple Access (TDMA) communication with an asynchronous Rover node.

### 1.2.2 Additional Applications

- Drone tracking and drone swarms
- Warehouse asset & robotics tracking that require indoor and outdoor positioning
- Autonomous vehicles tracking

## 1.3 Visual

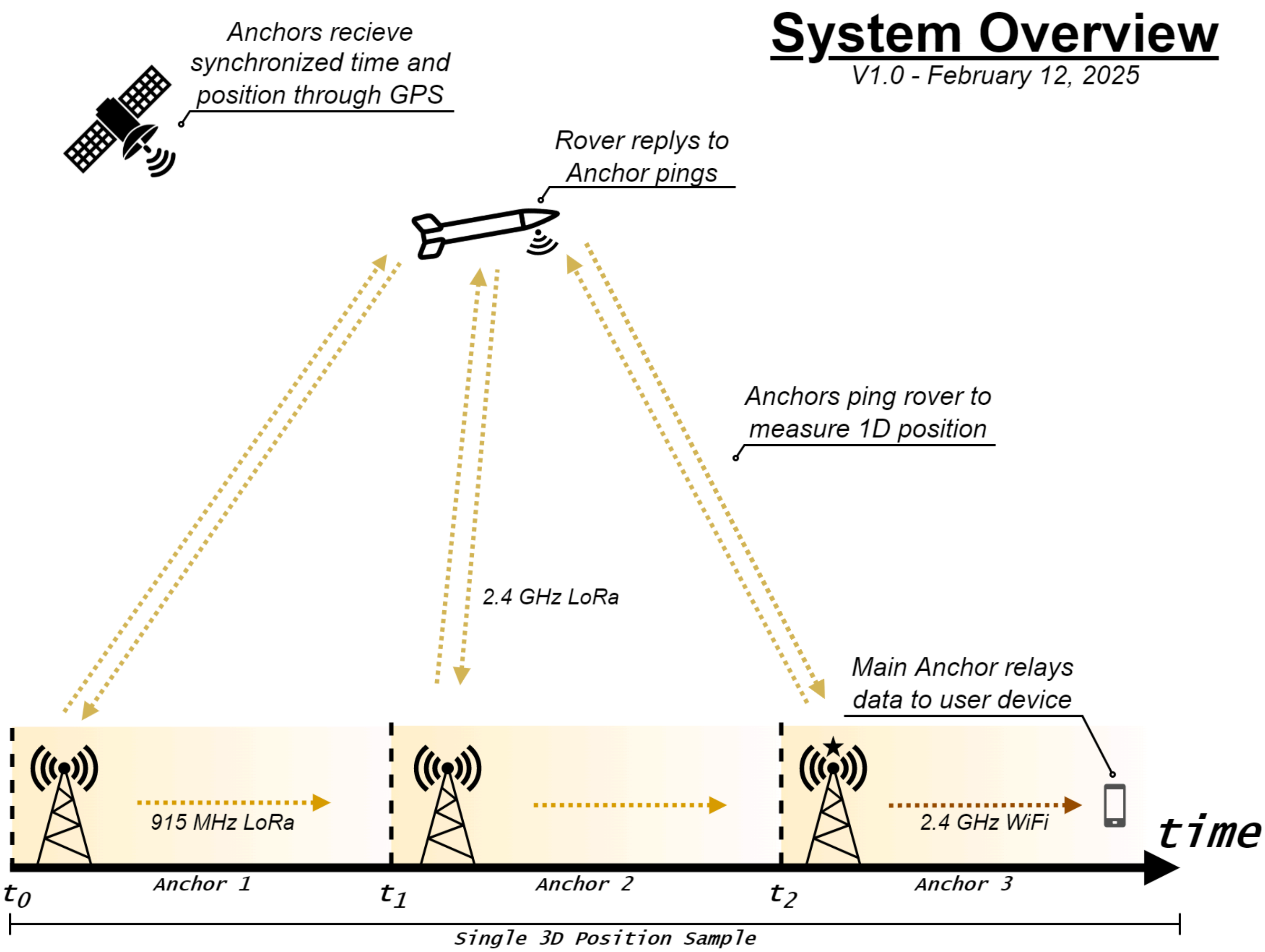


*Figure 1. System Overview*

## 1.4 High Level Requirements

1. Perform 3D trilateration of a Rover node at a minimum distance of 20 meters from at least one anchor node with a sample rate of at most 2 second. Sample rate is defined as the time period a position reading is resolved.

2. Relay barometer, GNSS, and at minimum one other data point to another node in the network with a latency of less than 2 seconds. Latency is defined as the time from an initial sensor reading to reception by another member of the network.

3. Publish position data to a local WiFi network in at most 5 seconds delay between receiving initial sensor or calculated data to receiving on WiFi.

# 2. Outline of Subject Matter

## 2.1 Block Diagrams Detailed

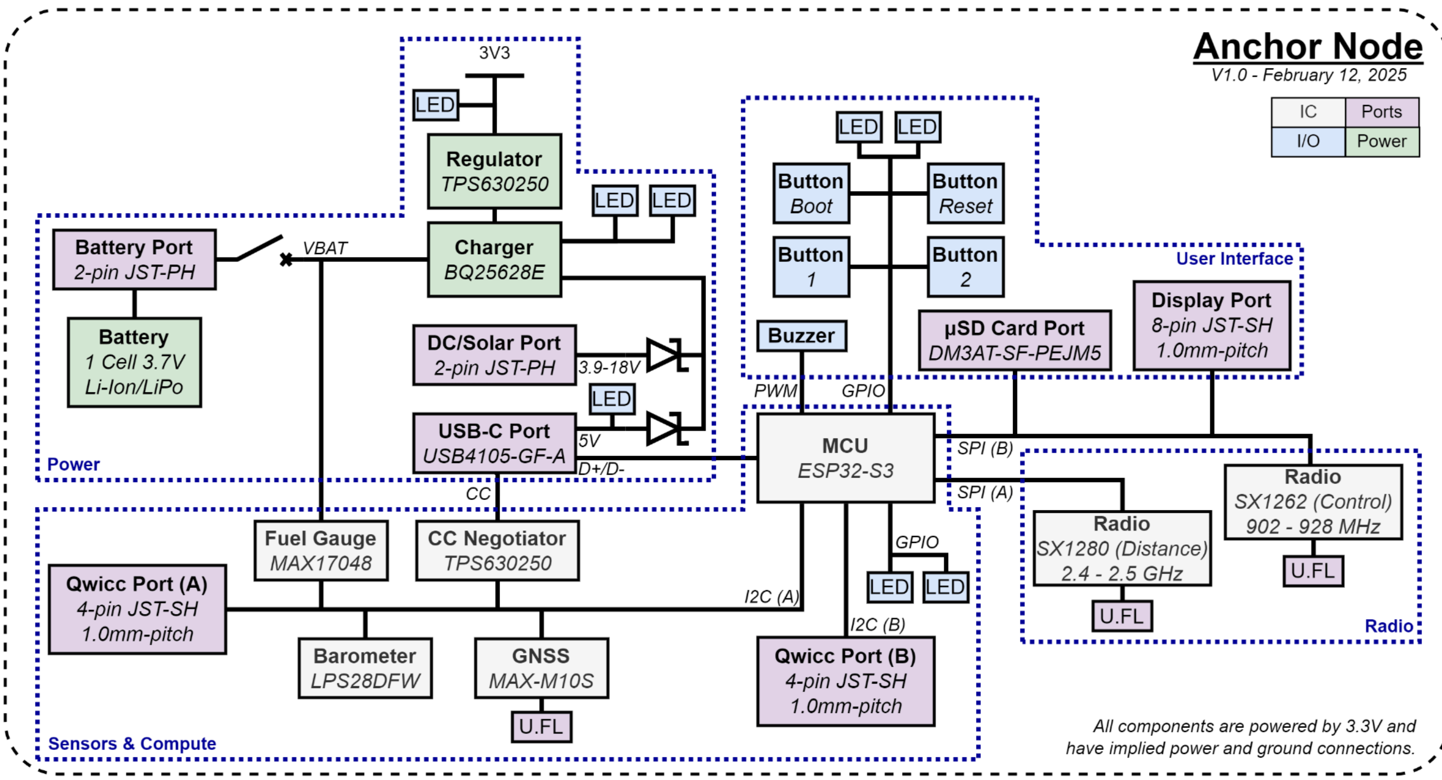


*Figure 2. Anchor Node Detailed Diagram*

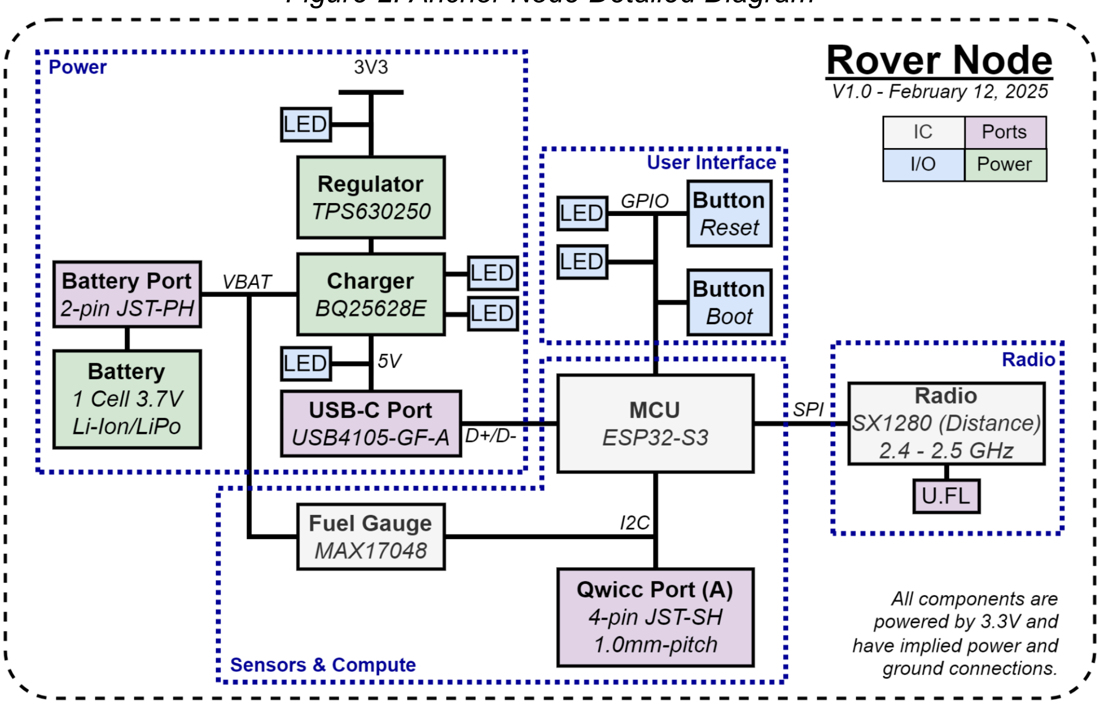


*Figure 3. Rover Node Detailed Diagram*

## 2.2 Block Descriptions

### 2.2.1 Anchor

Anchors are reference nodes with synchronized time and fixed positions. Schematics can be found in the appendix sections.

- *Requirement 1: Anchor nodes must have synchronized time with less than 200 ms offset*
- *Requirement 2: Anchor must be able to receive GPS transmissions at least once every two seconds*
- *Requirement 3: Anchor must have at least two status LEDs and at least one I2C expansion port*
- *Requirement 4: Anchor must be able to operate from 4.2V battery*
- *Requirement 5: Anchor must be able to determine altitude from two or more means (GPS & Barometer)*

### 2.2.2 Rover

Rovers are roaming nodes with unknown position or time attached to a tracking asset. Schematics can be found in the appendix sections.

- *Requirement 1: Nodes must automatically respond to Anchor ping requests in less than 500μs.*
- *Requirement 2: Rover must have at least two status LEDs and at least one I2C expansion port*
- *Requirement 3: Rover must be able to operate from ~3.3V battery*

### 2.2.3 Power

Each node is battery operated with the option to charge and power the device through a USB-C port. The BQ25628E controls power switching and battery charging. A thermistor is used to ensure the battery does not overheat during charging. For Anchor nodes an additional generic DC input port is available that can be used for solar panels or other power sources. It's able to optimize voltage draw for near maximum power draw and employs a buck-boost convert to ensure it outputs at most 4.5V. The TPS630250 regulates the input voltage to a stable 3.3V for all system components. Additionally a few debug LEDs for 3.3V, 5V, Power Good, and Charging are connected to these circuits. The goal is to enable portable deployments with seamless charging or extended usage in fixed locations.

- *Requirement 1: Voltage regulator must output 3.3V and supply 2A at maximum*
- *Requirement 2: Battery charger must be configurable with GPIO and resistors, or I2C*
- *Requirement 3: Battery charger must accept 1S 3.7V LiPo batteries and automatically switch between USB and battery power sources.*

### 2.2.4 Radios

Each node contains an SX1280 which has a built in ranging engine that is able to ping another radio and calculate the distance. This is then telegraphed over SPI to the user without the need for extensive timing and tuning of the radio front end. The SX1280's ease of use for ranging is what directly enables this project to maintain a focused and achievable scope. Anchor nodes also contain an SX1262 which serves as a command and control backbone for anchor nodes to share data while not congesting the primary ranging radios. The SX1280 uses 2.4 GHz LoRa and the SX1262 uses 915 MHz LoRa. LoRa enables low power usage yet longer ranges.

- *Requirement 1: Radio systems must use seperate frequency bands to avoid congestion*

- *Requirement 2: Radios must occupy ISM bands for license free operation*
- *Requirement 3: Radios must use SPI or I2C for communication with MCU*

### 2.2.5 User Interface

Anchor and Rover nodes each contain boot and reset buttons for programming the microcontroller (MCU). However, Anchors which are not at a premium for space have additional buttons and a buzzer for the user to interact with and configure the devices. An optional display can also be added via the display port. Anchors feature a MicroSD card port to allow for long term data logging. Each node also has debug LEDs that are user programmable.

- *Requirement 1: MCU must have SPST buttons to enable programming*
- *Requirement 2: MicroSD card must interface with at most 32GB FAT32 cards over SPI*

### 2.2.6 Sensors & Compute

Each node has an ESP32-S3 MCU as the core control unit. These MCUs feature WiFi/Bluetooth connectivity for additional user interaction. Anchor nodes feature a GPS module for precise synchronized timing and deducing their own position and a fuel gauge to measure battery charge over time. A water resistant barometer is used to further resolve their vertical position. Anchors have a USB-C Configuration Channel (CC) negotiator to ensure proper USB power delivery.

- *Requirement 1: All sensors must communicate over at least one of the following protocols – SPI, I2C, PWM – and draw 3.3V.*
- *Requirement 2: Barometer must output a resolution of at least 1 meter*
- *Requirement 3: GPS module must output 1 Hz time pulse and position within 3 meters*
- *Requirement 4: Fuel gauge must read cell voltage and communicate over at least one of the following protocols – SPI, I2C, PWM*
- *Requirement 4: MCU have a clock speed greater than 100 MHz and communicate over all of the following protocols – SPI, I2C, PWM – to interface with all modules.*

### 2.2.7 Antennas

Rover nodes only have one antenna that will require a U.FL connector. Depending on their space constraints patch antennas will most likely be the optimal solution. Anchor nodes also have three U.FL connectors. An internal active patch GPS antenna will be mounted inside the case, while two U.FL to SMA bulkhead adapters will be mounted through the case wall. This will enable the user to switch antennas for their specific needs.

In regular usage omnidirectional antennas for the 915 MHz and 2.4 GHz LoRa radios can be used, but if long range usage is required more directional antennas may be used. The MCU's have an embedded antenna for WiFi/Bluetooth connectivity.

## 2.3 Design

One key aspect of our design is ensuring 1D ranging accuracy provided by each SX1280 module. There are a multitude of ways ranging could be degraded such as multipath reflections and doppler shift caused by high velocity tracking assets. However, calibration of the SX1280 to account for different RF front ends is the most prevalent for mitigating error and the focus of this tolerance analysis.

### 2.3.1 Calibration

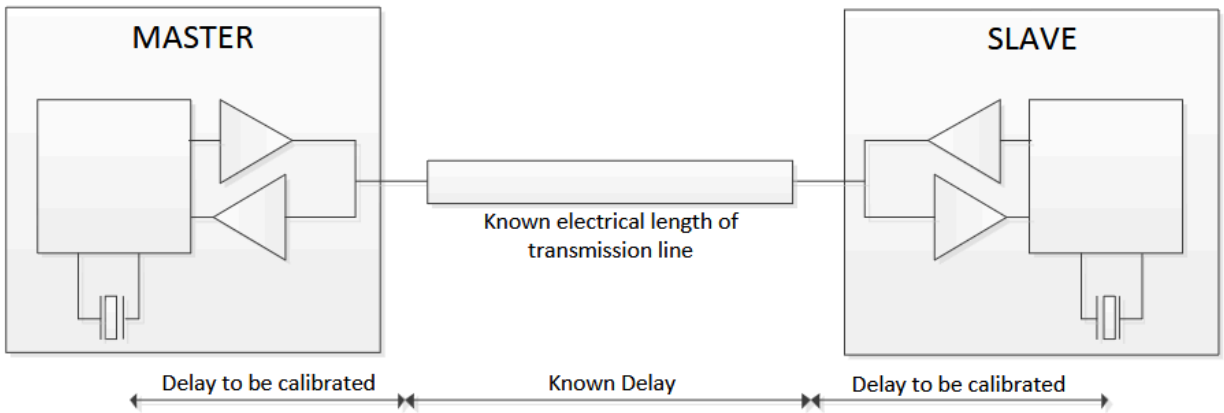


*Figure 4. [6] Semtech, Ranging Calibration Setup*

Using a coax cable of known length the system delay can be isolated to just the RF front end of the ranging devices. This offset would then be applied to future ranging measurements.

$$D_{uncalibrated} = (RangeResult \times D_{LSB})/2$$
$$D_{calibrated} = (D_{uncalibrated} - D_{cable})/2$$
$$Calibration = D_{calibrated} / D_{LSB}$$

Additionally, outdoor line of sight measurements can be conducted when the nodes are separated at known fixed distances. Their measured vs actual error can be calculated and then applied as a linear offset. More advanced offsets could also be used if you take into account alternate frequencies and LoRa parameters.

### 2.3.2 Manufacturer Testing

Semtech, the manufacturer of the SX1280, conducted outdoor 1D range testing after calibration at a distance of 170 meters with an estimated error of less than 4 meters for single sample pings, and less than 1 meter accuracy for larger sample ping sizes of 70.

### 2.3.3 External Testing

Additional 1D testing conducted by Stuart Robinson has revealed an error rate of about 0.2% at 40.65 kilometers [16]. Robinson was also able to achieve a measured ground distance of 89.237 km [16] with a small directional antenna; Further suggesting this system's potential for ranges in excess of 100 km.

### 2.3.4 Tolerance Expectations

Ultimately, the team expects to achieve relatively high positional accuracy. However without the ability to test the system they are hesitant to guarantee a specific error tolerance. External testing has revealed the SX1280 can be highly accurate, but it is to be seen if similar accuracy can scale down to shorter distances of around 25 meters for the purposes of a demonstration. With this in mind, the team is expecting less than a 10% 1D distance error.

| Expected Accuracy | | |
|---|---|---|
| **Semtech Test** | **Robinson Test** | **Expected** |
| 170 m | 40.65 km | 30 m |
| 2.23% | 0.20% | 10% |

Table 1. Expected Accuracy From Tolerance Analysis

# 3. Verification

| Requirement | Verification | Results |
|---|---|---|
| **High Level** | | |
| 1. Perform 3D trilateration of a Rover node at a minimum distance of 20 meters from at least one anchor node with a sample rate of at most 2 second. Sample rate is defined as the time period a position reading is resolved. | Option 1: Read trilateration calculations from Anchor 0 micro SD card and note the timestamps between calculations<br><br>Option 2: Use WiFi webpage to observe Rover node position changes *(Assuming WiFi webpage updates in less than 2 seconds instead of 5 seconds.)* | Option 2: **Verified.** Used WiFi webpage to observe Rover node position changes during final demo. Latency was within 2 seconds. |
| 2. Relay barometer, GNSS, and at minimum one other data point to another node in the network with a latency of less than 2 seconds. Latency is defined as the time from an initial sensor reading to reception by another member of the network. | Option 1: Compare the data logged packets on each Anchor's micro-SD card and compare data timestamps<br><br>Option 2: Use WiFi webpage to observe changes *(Assuming WiFi webpage updates in less than 2 seconds instead of 5 seconds.)*<br>- Barometer: Change height of either Anchor 0 or 1<br>- GPS: Observe timestamp changes to real world<br>- Ranging: Observe distance measurement changes<br><br>Data Points: Barometer, GPS, Ranging | Option 2: **Verified.** Used WiFi webpage to observe sensor reading changes during the final demo. |
| 3. Publish position data to a local WiFi network in at most 5 seconds delay between receiving initial sensor or calculated data to receiving on WiFi. | Option 1: Compare GPS packet timestamp on the WiFi webpage to the actual time on a phone/laptop<br><br>Option 2: Set an Anchor to max height on its tripod. Then move it to its lowest position and observe a change in barometric pressure on the WiFi webpage | Option 1: **Verified.** Used WiFi webpage to observe less than 5 second difference between webpage current time and phone/laptop real time. |
| **2.2.1 Anchor** | | |
| 1. Anchor nodes must have synchronized time with less than 200 ms offset | Option 1: Observe synced LED flashing triggered by the 1 pulse per second GPS signal<br><br>Option 2: Read ranging data and observe that 15 samples are taken sequentially between Anchors without collisions across the span of 300mS | Option 1: **Verified.** Observed synced LED flashing triggered by the 1 pulse per second GPS signal during final demo. |

| | | |
|---|---|---|
| 2. Anchor must be able to receive GPS transmissions at least once every two seconds | Option 1: Read data log on an Anchor micro SD card<br><br>Option 2: Observe GPS timestamp on WiFi webpage. (Assuming WiFi webpage updates in less than 2 seconds instead of 5 seconds.) | Option 2: **Verified.** Observed GPS timestamp on WiFi webpage update in less than 2 seconds. |
| 3. Anchor must have at least two status LEDs and at least one I2C expansion port | Option 1: Observe the multiple LEDs on an Anchor | Option 1: **Verified.** Observed the multiple LEDs were operational on an Anchor during the final demo. |
| 4. Anchor must be able to operate from 4.2V battery | Option 1: Connect a standard 4.2V LiPo battery and observe power on | Option 1: **Verified.** Connected battery to Anchor board during the final demo to observe powerup. |
| 5. Anchor must be able to determine altitude from two or more means (GPS & Barometer) | Option 1: Read GPS and barometric data on Anchor micro SD card<br><br>Option 2: Observe GPS and Barometric altitude on WiFi webpage. (Assuming WiFi webpage updates in less than 2 seconds instead of 5 seconds.) | Option 2: **Verified**. Observed GPS and Barometric altitude on WiFi webpage. |
| **2.2.2 Rover** | | |
| 1. Nodes must automatically respond to Anchor ping requests in less than 500μs. | Option 1: Observe ranging and trilateration occurring on the WiFi webpage or micro SD card. | Option 1: Could not verify as we do not have access to a network analyzer with this resolution. But, we observed instantaneous responses from Rover. Overall this was a bad requirement before the LoRa protocol was understood because it may take milliseconds to transmit a packet. |
| 2. Rover must have at least two status LEDs and at least one I2C expansion port | Option 1: Observe the multiple LEDs on a Rover | Option 1: **Verified.** Observed the multiple LEDs on a Rover during the final demo. |
| 3. Rover must be able to operate from ~3.3V battery | Option 1: Connect a standard 3.3V/4.2V LiPo battery and observe power on | Option 1: **Verified.** Connected a standard 3.3V/4.2V LiPo battery and observed power on during the final demo. |
| **2.2.3 Power** | | |
| 1. Voltage regulator must output 3.3V and supply 2A at maximum | Option 1: Measure Vdd power rail with multimeter<br><br>Option 2: Observe power up of all components and device functions like ranging. | Option 2: **Verified.** We observed power up of all components and device functions during the final demo. |
| 2. Battery charger must be configurable with GPIO and resistors, or I2C | Option 1: Connect battery and see if it charges<br><br>Option 2: Communicate with the battery charger of I2C | Option 2: **Verified.** Communicated with the Rover battery charger over I2C during the final demo. |

| | | |
|---|---|---|
| 3. Battery charger must accept 1S 3.7V LiPo batteries and automatically switch between USB and battery power sources. | Option 1: Switch between USB and battery power and observer any power drop outs | Option 1: **Verified.** Switched between USB and battery power and did not observe any power drop outs during the final demo. |
| **2.2.4 Radios** | | |
| 1. Radio systems must use separate frequency bands to avoid congestion | Option 1: Observe radios with software defined radio spectrum analyzer<br><br>Option 2: Observe ranging and communication functions which use chips fundamentally on different frequency bands with different tuned antennas | Option 2: **Verified.** Observed interference-free ranging and communication during the final demo. |
| 2. Radios must occupy ISM bands for license free operation | Option 1: Observe radios with software defined radio spectrum analyzer<br><br>Option 2: Observe ranging and communication functions which use chips that fundamentally only operate in the ISM bands. | Option 2: **Verified.** Observed ranging and communication functions which use chips that fundamentally only operate in the ISM bands. |
| 3. Radios must use SPI or I2C for communication with MCU | Option 1: Observe radios sending messages between Anchors and to the Rover<br><br>Option 2: Monitor SPI/I2C bus with oscilloscope | Option 1: **Verified.** Observed WiFi webpage displaying relevant data of all Anchors during the final demo and communication chips interface to ESP32 only through SPI, so SPI must be implemented correctly. |
| **2.2.5 User Interface** | | |
| 1. MCU must have SPST buttons to enable programming | Option 1: Observe buttons on nodes and subsequent program running on devices from programming | Option 1: **Verified.** Observed buttons on nodes and subsequent programs running on Anchor and Rover during the final demo. |
| 2. MicroSD card must interface with at most 32GB FAT32 cards over SPI | Option 1: Observe data logging to the micro SD card on Anchor nodes | Option 1: **Verified.** Presented data logs from SD card from Anchor nodes during the final presentation. |
| | | |
| **2.2.6 Sensors & Compute** | | |
| 1. All sensors must communicate over at least one of the following protocols – SPI, I2C, PWM – and draw 3.3V. | Option 1: Observe sensor data logging to the micro SD card on Anchor nodes or the WiFi webpage | Option 1: **Verified**. Observed sensor data logging to the WiFi webpage during the final demo. |
| 2. Barometer must output a resolution of at least 1 meter | Option 1: Set an Anchor to max height on its tripod. Then move it to its lowest position and observe a change in barometric pressure on the WiFi webpage or micro SD card. *(Tripod is* | Option 1: **Verified**. Using the following routine during the final demo: set an Anchor to max height on its tripod. Then move it to its lowest position and observe a change in barometric |

| | | |
|---|---|---|
| | *about 1 meter tall)* | pressure on the WiFi webpage. |
| 3. GPS module must output 1 Hz time pulse and position within 3 meters | Option 1: Observe green LED on Anchor nodes that pulse every second (1 Hz) and view GPS location on WiFi webpage or micro SD card | Option 1: **Verified.** Observed green LED on Anchor nodes that pulse every second (1 Hz) and viewed GPS location on WiFi webpage to be within 3 meters of actual position. |
| 4. Fuel gauge must read cell voltage and communicate over at least one of the following protocols – SPI, I2C, PWM | Option 1: View fuel gauge serial output on Rover node | Option 1: **Verified.** Viewed fuel gauge serial output on Rover node during the final demo. |
| 5. MCU have a clock speed greater than 100 MHz and communicate over all of the following protocols – SPI, I2C, PWM – to interface with all modules. | Option 1: View successful programming with clock config set to above 100 MHz for the MCU and observe normal device operation. | Option 1: **Verified.** Observed normal device operation during the final demo and observed MCU clock configuration of 120 MHz. |

*Table 2. Requirements, Verification, and Results Table*

# 4. Board Design

## 4.1 Anchor Layout

Anchors were designed with all parts to be on the front side to allow for quicker assembly and reduce pick and place costs for machine assembled orders. All user I/O is located near the edges to be easily accessed in a case. The RF section is also spaced from the power regulators to try and mitigate noise. The back layer is used as a vertical bridge to connect the MCU to the upper section of the board.

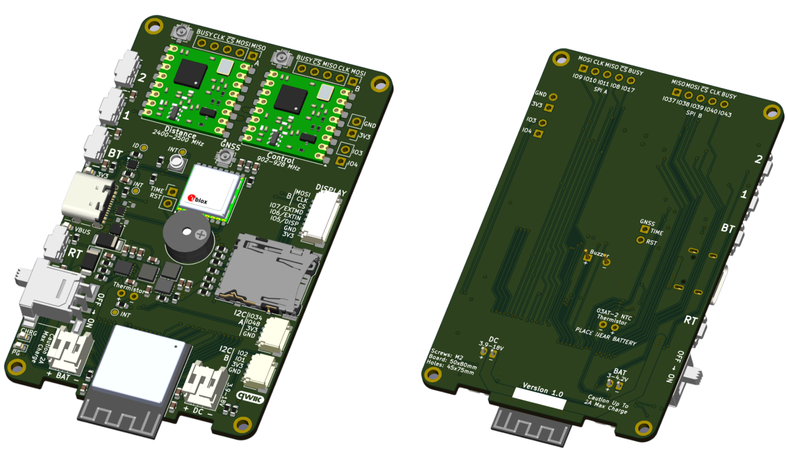

*Figure 5. Anchor Node 3D View (Front: L Back: R)*

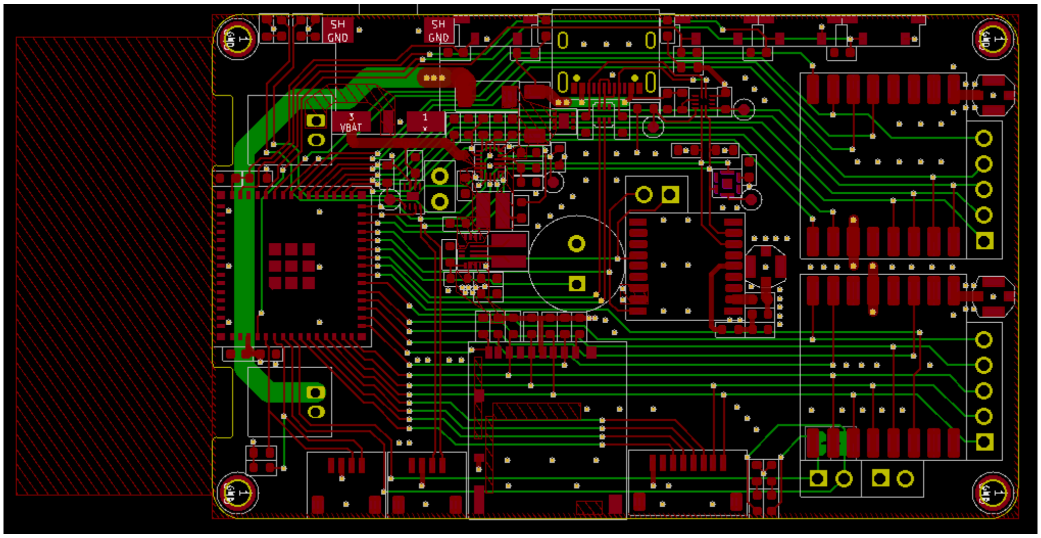


*Figure 6. Anchor Routing*

## 4.2 Rover Layout

Unlike Anchors, Rovers are extremely space constrained to optimize their placement on tracking assets. Therefore, they have parts on both sides. Only two screw holes are used to save space since the boards have little mass. Similarly user I/O is located near the edges

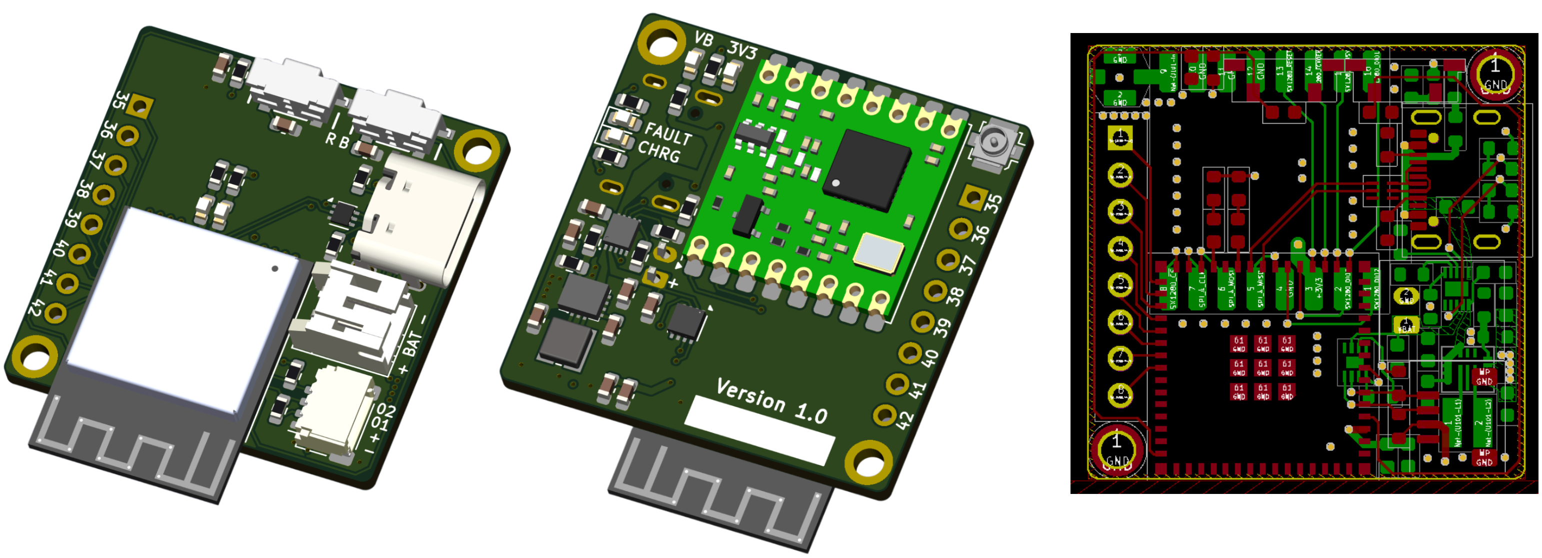


*Figure 7. Rover 3D View (Front: L Back: C) & Routing (Right)*

## 4.3 General Layout

Each board is four layers and follows a similar stackup plan. The front and back layers are used primarily for data signal (SIG) traces, and the inner layers are reserved for power. The only difference is the location of the ground (GND) plane which is immediately underneath the layer with RF traces. Anchors have all RF components on the front while Rovers have all RF traces on the back. This allows for 50Ω impedance controlled boards with specific trace widths.

## 4.4 Component Integration Results

Each component on the Rover and Anchor nodes have been individually tested with basic software scripts to ensure they appear and perform their basic desired functionality during the board bring up processes. This unit testing helped isolated and soldering issues and uncovered a few non-critical design defects. The table below outlines the functionality of each component's design. Over 10 scripts were written but for brevity only a few will be discussed in depth.

| Type | MPN | Result |
|---|---|---|
| Microcontroller | ESP32-S3-MINI-1-N8 | Fully Operational |
| GNSS | MAX M10S | Fully Operational |
| Distancing Radio | NiceRF SX1280-T | Fully Operational |
| Control Radio | NiceRF SX1262-915 | Fully Operational |
| Barometer | LPS28DFW | Fully Operational |
| Voltage Regulator | TPS630250 | Fully Operational |
| Battery Charger | BQ25628E | Fully Operational |
| Battery Charger | BQ25185 | Fully Operational |
| Fuel Gauge | MAX17048 | Partially Operational |
| USB-C Port | USB4105-GF-A | Fully Operational |
| Buzzer | AT-0927-TT-6-R | Fully Operational |
| SD Card | DM3AT-SF-PEJM5 | Fully Operational |
| Buttons | TL3330AF260QG | Partially Operational |
| USB-C Negotiation | TPS630250 | Not Functional |

*Table 3. Component Bring Up Results*

## 4.5 Fuel Gauge

The fuel gauge is supposed to read battery voltage and estimate the state of charge while filtering out noise from current draw. It is marked as partially operational because it is able to turn on however it was only reading 3.3V.

After looking over the schematic it was discovered that VDD is supposed to be connected to the battery (VBAT). It is powered and samples the battery from the same pin [4]. This means that it was reading the 3.3V from the regulator. A simple fix was to cut the VDD trace and short the VDD and CELL pins which are right next to each other on the footprint. However, this solution was only implemented on the Rover node. It was deemed not worth the risk of damaging the Anchor boards which already had built in battery monitoring with the BQ25628E. This component is not needed to complete the project's overall function which is why more severe action was taken. It just serves as a good quality of life improvement that will be addressed in potential future revisions. The following figure shows the schematic and on board Rover fix.

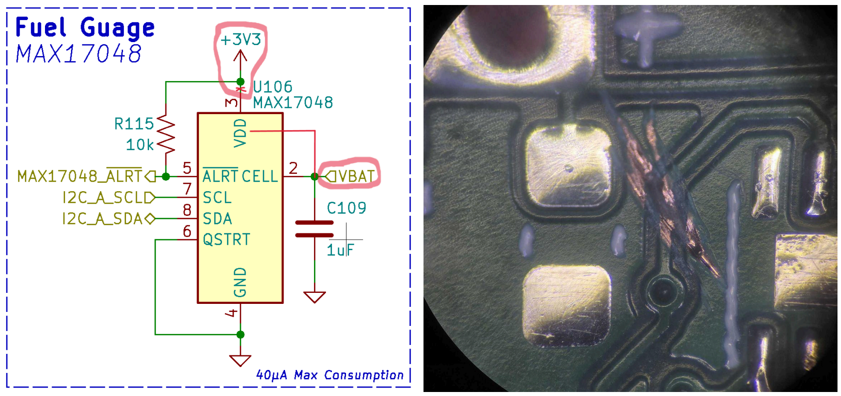


*Figure 6. Fuel Gauge Schematic (L) Rover Cut Trace Fix (R)*

## 4.6 USB-C Negotiation

This chip never worked and could ultimately not be diagnosed because it was not communicating over I2C. After reanalyzing the schematic no obvious design flaws were uncovered Ultiamtley this chip was abandoned because USB-C power delivery was not needed for the Anchor boards to operate. They already received enough power from standard USB-C or the battery. Instead 5.1kΩ resistors were used to manually set USB-C to 5V without issue for the remainder of the project.

## 4.7 Buttons

A simple test was conducted of continuously reading all the button inputs every second to see if they would be high or low depending on if the user was pressing them. Additionally they were attached as hardware interrupts to test out software functionality. During testing it was revealed that the buttons initially worked, but they would sometimes stay stuck in their logic state. This was attributed to two primary causes. The buttons had been thermal cycled repeatedly during soldering and subsequent debugging leading to their deformation and becoming less responsive. Secondly, the internal hardware pulldowns provided by the MCU are not strong enough. As a contingency these buttons can be replaced and have pull down resistors wired in parallel with the capacitors already present on the board C117 and C118. However, these are not critical for the core functionality of our board and can be descoped. They are primarily used for debugging and future feature expansions so they can be descoped as needed. The Reset and Boot button appear to work normally as we are able to reset and program the MCUs with ease.

# 5. Mechanical Design

All mechanical design is focused on Anchor nodes as Rover nodes will be mounted to the tracking asset while Anchor nodes are free standing across the tracking area.

| **Board Dimensions *(mm)*** |
|---|

| Layer | Anchor | Rover |
|---|---|---|
| Edges (W x L) | 50 x 80 | 30 x 30 |
| M2 Holes (W x L) | 45 x 75 | 26 x 26 |

Table 4. Board Dimensions

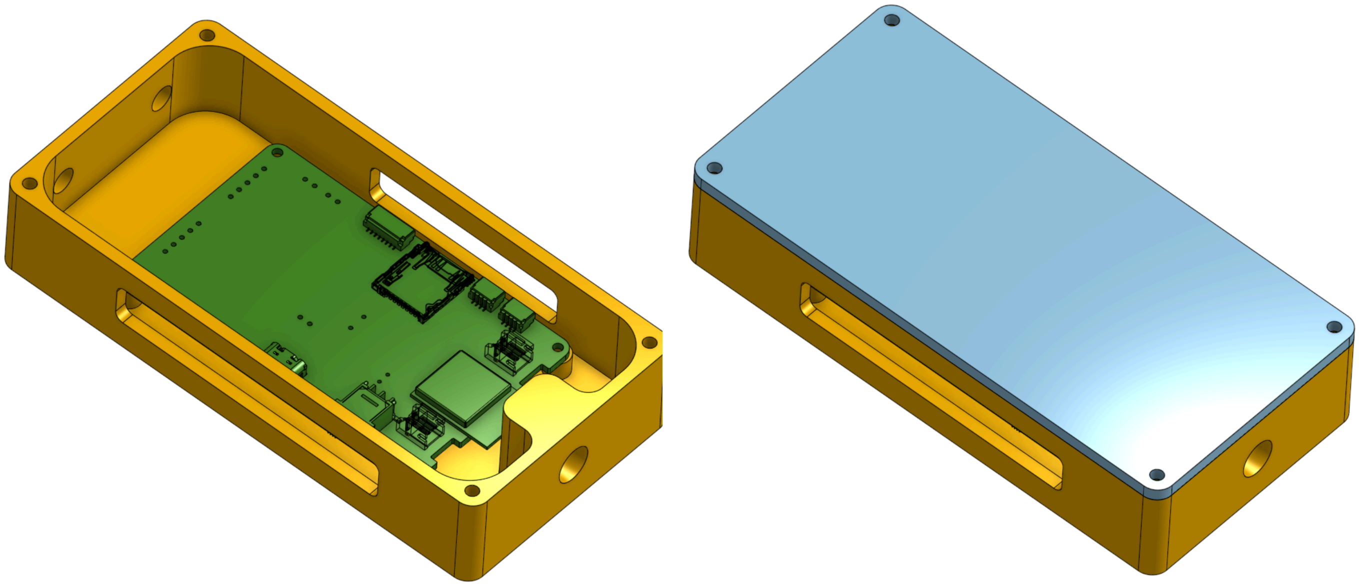

*Figure 8. Anchor Case and Lid*

The Anchors and a flat cell battery will sit inside of a 3D printed case to protect them from the outdoors while still allowing access for the user I/O. There will be rubber covers around the ports which are not depicted. More importantly these cases also act as a strain relief on the SMA cables used to attach the two radio antennas. The GPS antenna will be placed inside the case. Additionally, each case will have a tripod mounting hole to allow for easy setup in the field.

*Figure 9. Tripod Stand*

# 6. Cost Analysis

## 6.1 Engineering Labor

| Engineering Labor Cost | | | | |
|---|---|---|---|---|
| **Engineers** | **Hours/Week** | **Wage/Hour** | **Weeks** | **Total** |
| 2 | 2 | $33 | 12 | $1,584 |

Table 5. Engineering Labor Cost

## 6.2 Bill of Materials

A more detailed cost breakdown per board can be found in the appendix section. These prices are strictly for a single node.

| Node Cost | |
|---|---|
| **Anchor** | **Rover** |
| $74.0597 | $21.2389 |
| Assumes MOQ part price but only counts consumed parts. | |

Table 6. Node Cost

## 6.3 Current Expenditures

With all the parts needed to assemble three Anchors and one Rover node not many expenditures are expected unless soldering issues are encountered. The only remaining orders include parts to mount the Anchor nodes into their mechanical enclosures with a total of $150 estimated for M2 screws, M2 heat inserts, TPU filament, and tripods.

| Current Expenditures | | |
|---|---|---|
| **Type** | **Cost** | **Description** |
| Amazon | $73.20 | Development Board |
| LCSC | $129.27 | PCB Parts 1st Round |
| Mouser | $81.88 | PCB Parts 1st Round |
| Digi-Key | $31.20 | PCB Parts 1st Round |
| Digi-Key | $75.27 | PCB Parts 2nd Round |
| Data Alliance | $96.13 | RF Adapters & Antennas |
| **Total** | **$486.95** | |

Table 7. Current Expenditures

# 7. Ethics

## 7.1 FCC Regulations

We will follow all FCC regulations that concern the ISM Band, provided here: eCFR :: 47 CFR Part 18 -- Industrial, Scientific, and Medical Equipment[18][19][20], as they relate to our RF equipment such as general practices and spectrum usage.

## 7.2 Tracking Assets

All assets being tracked will be owned by the team and not another individual without their explicit consent.

## 7.3 Feedback

As this is an experimental project we plan to maintain an open mind when creating this novel system by listening to ideas given from mentors, course staff, students, and others throughout the project. We will take notes in their lab notebook on any feedback received to ensure it is properly documented and considered.

# 8. Safety

## 8.1 Batteries

Following the *Safe Practice for Lead Acid and Lithium Batteries* guidelines all batteries will be charged in their recommended conditions, and stored in a flammables cabinet when not in use. When handling batteries they will be treated with care and monitored for degradation. If disposal is needed batteries will be left in the battery cabinet until proper disposal is available.

# 9. Conclusion

## 9.1 Successes

We feel that our team created a good trilateration minimum viable product. Our system performs as expected and its tracking accuracy and precision is also within expectations. We feel that this is most attributed to the fact that we performed efficient timeline management during this semester, specifically for finalizing our system schematics and PCB layout within the first few weeks of the semester.

This project is intended for use within the Illinois Space Society, and with our user-friendly design with basic operation and its LEDs, programmable GPIO and buttons, copious amounts of test points, we feel that we have also achieved our goal of creating a hardware test platform for which future Illinois Space Society projects can develop from.

## 9.2 Challenges

We had to overcome more than a few challenges during the development of this project. These challenges include but are not limited to: 1. Soldering ESP32-S3 with QFN pads, 2. Buttons being too fragile, 3. Real-time telemetry and data logging, 4. Noise in distance readings, 5. Concerns for PCB layout affecting RF performance.
Even during the final demo we had concerns with the soldering of our ESP32-S3 with QFN pads: one of our Anchor boards could not interact with the majority of its GPIO pinouts. While, fortunately, this did affect our final results, this is a concern that we would like to address for future work. We believe that the MCU is not aligned properly with the QFN pads.
We also have concerns with our inconsistent RSSI readings across our Anchors. We performed calibration and found consistent and significant received signal strengths for each of the boards, and we attribute this to our inexperience with PCB layouts for RF devices.

## 9.3 Future Work

There is a variety of future work potential for this project. From the software front better Kalman filtering and outlier detection can be implemented to further fine tune the system. The WiFi webpage could also become more interactive for the user to program parameters through it. The PCB is in a mostly good state however any future design runs should find more durable SPST buttons that do not deform during hot air soldering. The Fuel gauge could also be fixed to measure Battery. The Mechanical cases could also be made stronger and have rubber lids added to them for waterproofing the device ports. Finally, there are multiple additional tests that can be performed to further fine tune the system such as longer range testing and integrated flight tests with vehicles.

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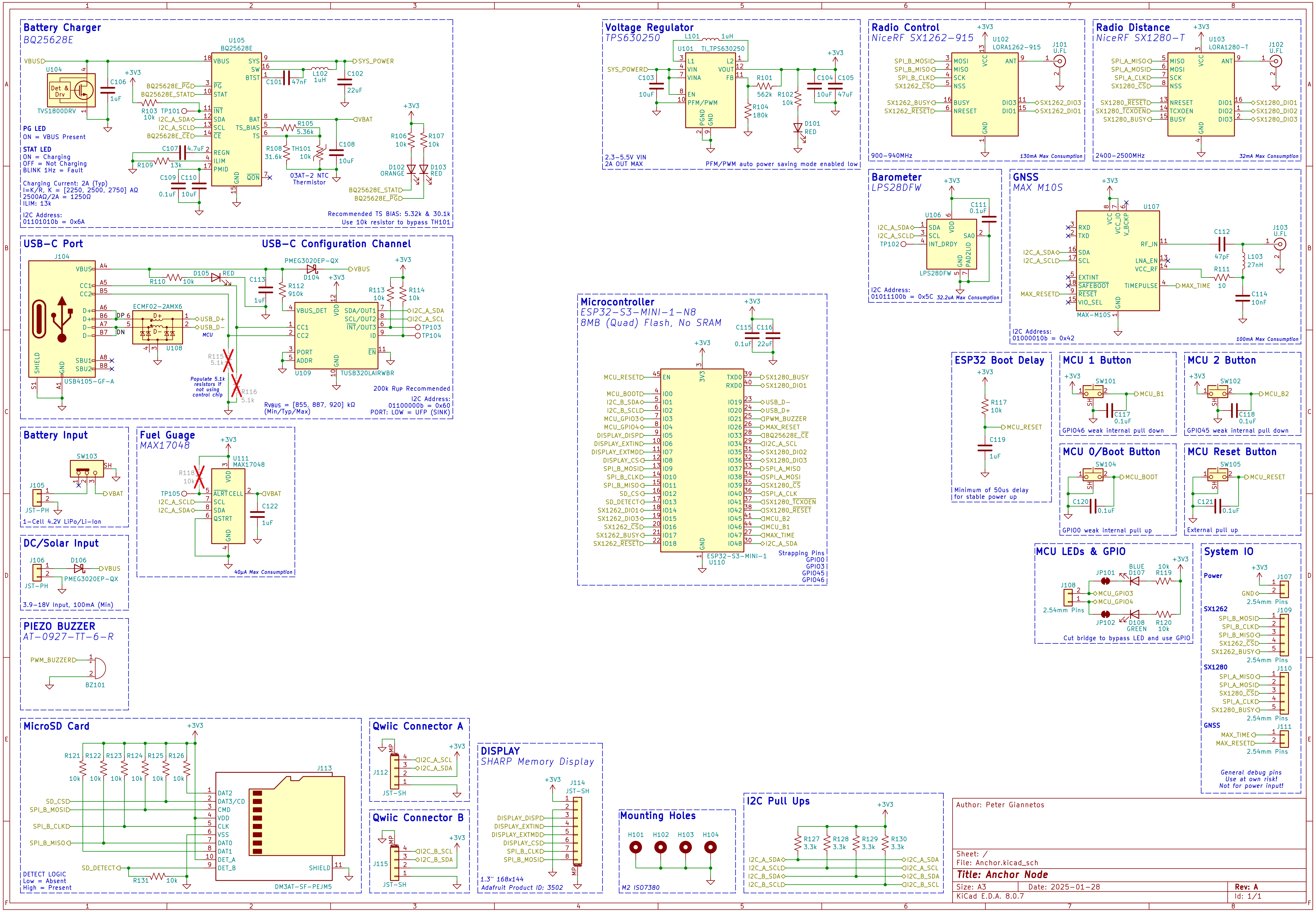
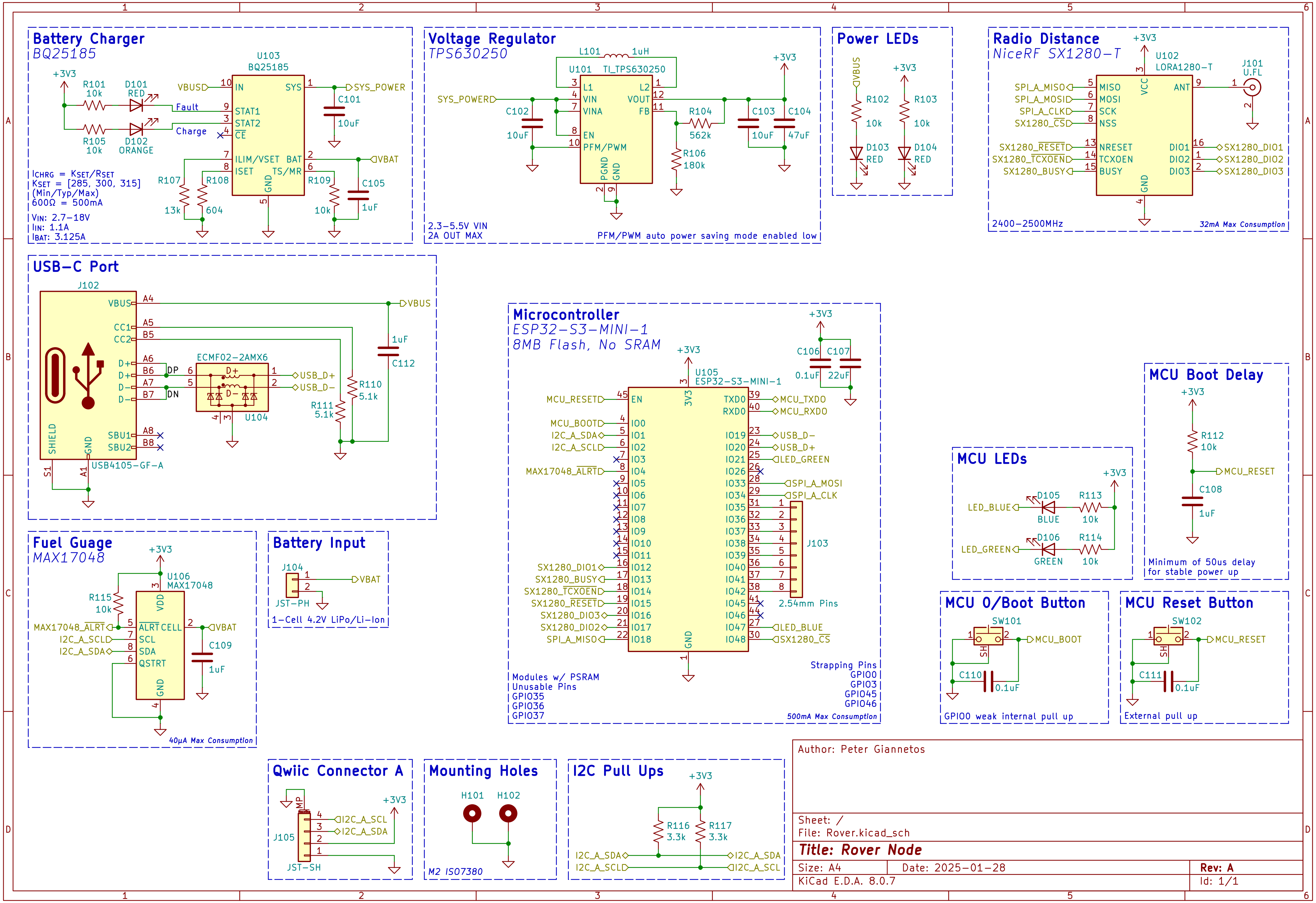
# Appendix A: Schematics



Battery Charger
BQ25628E
PG LED
ON = VBUS Present
STAT LED
ON = Charging
OFF = Not Charging
BLINK 1Hz = Fault
Charging Current: 2A (Typ)
I2C Address:
01101010b = 0x6A
Recommended TS BIAS: 5.32k & 30.1k
Use 10k resistor to bypass TH101
Voltage Regulator
TPS630250
2.3–5.5V VIN
2A OUT MAX
PFM/PWM auto power saving mode enabled low
Radio Control
NiceRF SX1262-915
900–940MHz
130mA Max Consumption
Radio Distance
NiceRF SX1280-T
2400–2500MHz
32mA Max Consumption
USB-C Port
USB-C Configuration Channel
200k Rup Recommended
I2C Address:
01100000b = 0x60
PORT: LOW = UFP (SINK)
Barometer
LPS28DFW
I2C Address:
01011100b = 0x5C
32.2uA Max Consumption
GNSS
MAX M10S
I2C Address:
01000010b = 0x42
100mA Max Consumption
Microcontroller
ESP32-S3-MINI-1-N8
8MB (Quad) Flash, No SRAM
Strapping Pins
GPIO0
GPIO3
GPIO45
GPIO46
ESP32 Boot Delay
Minimum of 50us delay for stable power up
MCU 1 Button
GPIO46 weak internal pull down
MCU 2 Button
GPIO45 weak internal pull down
MCU 0/Boot Button
GPIO0 weak internal pull up
MCU Reset Button
External pull up
Battery Input
1-Cell 4.2V LiPo/Li-Ion
Fuel Guage
MAX17048
40μA Max Consumption
DC/Solar Input
3.9–18V Input, 100mA (Min)
PIEZO BUZZER
AT-0927-TT-6-R
MCU LEDs & GPIO
Cut bridge to bypass LED and use GPIO
System IO
General debug pins
Use at own risk!
Not for power input!
MicroSD Card
DETECT LOGIC
Low = Absent
High = Present
Qwiic Connector A
Qwiic Connector B
DISPLAY
SHARP Memory Display
1.3" 168x144
Adafruit Product ID: 3502
Mounting Holes
M2 ISO7380
I2C Pull Ups
Author: Peter Giannetos
Sheet: /
File: Anchor.kicad_sch
Title: Anchor Node
Size: A3
Date: 2025-01-28
Rev: A
KiCad E.D.A. 8.0.7
Id: 1/1



Battery Charger
BQ25185
U103
BQ25185
+3V3
R101 10k
D101 RED
R105 10k
D102 ORANGE
VBUSD
IN
SYS
SYS_POWER
C101 10uF
Fault
Charge
STAT1
STAT2
CE
ILIM/VSET
BAT
VBAT
ISET
TS/MR
GND
R107 13k
R108 604
R109 10k
C105 1uF
ICHRG = KSET/RSET
KSET = [285, 300, 315]
(Min/Typ/Max)
600Ω = 500mA
VIN: 2.7–18V
IIN: 1.1A
IBAT: 3.125A
Voltage Regulator
TPS630250
L101 1uH
U101 TI_TPS630250
SYS_POWER
C102 10uF
L1
L2
VIN
VOUT
VINA
FB
EN
PFM/PWM
PGND
GND
R104 562k
R106 180k
C103 10uF
C104 47uF
+3V3
2.3–5.5V VIN
2A OUT MAX
PFM/PWM auto power saving mode enabled low
Power LEDs
VBUS
+3V3
R102 10k
R103 10k
D103 RED
D104 RED
Radio Distance
NiceRF SX1280–T
+3V3
U102
LORA1280–T
J101
U.FL
SPI_A_MISO
SPI_A_MOSI
SPI_A_CLK
SX1280_CS
MISO
MOSI
SCK
NSS
VCC
ANT
SX1280_RESET
SX1280_TCXOEN
SX1280_BUSY
NRESET
TCXOEN
BUSY
DIO1
DIO2
DIO3
SX1280_DIO1
SX1280_DIO2
SX1280_DIO3
GND
2400–2500MHz
32mA Max Consumption
USB–C Port
J102
VBUS
CC1
CC2
D+
D–
SBU1
SBU2
SHIELD
GND
USB4105–GF–A
VBUS
1uF
C112
DP
DN
ECMF02–2AMX6
U104
USB_D+
USB_D–
R110 5.1k
R111 5.1k
Microcontroller
ESP32–S3–MINI–1
8MB Flash, No SRAM
+3V3
C106 0.1uF
C107 22uF
U105
ESP32–S3–MINI–1
MCU_RESET
EN
3V3
TXD0
RXD0
MCU_TXD0
MCU_RXD0
MCU_BOOT
I2C_A_SDA
I2C_A_SCL
MAX17048_ALRT
IO0
IO1
IO2
IO3
IO4
IO5
IO6
IO7
IO8
IO9
IO10
IO11
IO12
IO13
IO14
IO15
IO16
IO17
IO18
IO19
IO20
IO21
IO26
IO33
IO34
IO35
IO36
IO37
IO38
IO39
IO40
IO41
IO42
IO45
IO46
IO47
IO48
USB_D–
USB_D+
LED_GREEN
SPI_A_MOSI
SPI_A_CLK
J103
2.54mm Pins
SX1280_DIO1
SX1280_BUSY
SX1280_TCXOEN
SX1280_RESET
SX1280_DIO3
SX1280_DIO2
SPI_A_MISO
LED_BLUE
SX1280_CS
GND
Modules w/ PSRAM
Unusable Pins
GPIO35
GPIO36
GPIO37
Strapping Pins
GPIO0
GPIO3
GPIO45
GPIO46
500mA Max Consumption
MCU Boot Delay
+3V3
R112 10k
MCU_RESET
C108 1uF
Minimum of 50us delay
for stable power up
MCU LEDs
+3V3
LED_BLUE
D105 BLUE
R113 10k
LED_GREEN
D106 GREEN
R114 10k
Fuel Guage
MAX17048
+3V3
U106
MAX17048
R115 10k
MAX17048_ALRT
I2C_A_SCL
I2C_A_SDA
VDD
ALRT
CELL
SCL
SDA
QSTRT
GND
VBAT
C109 1uF
40μA Max Consumption
Battery Input
J104
JST–PH
VBAT
1–Cell 4.2V LiPo/Li–Ion
MCU 0/Boot Button
SW101
MCU_BOOT
C110 0.1uF
GPIO0 weak internal pull up
MCU Reset Button
SW102
MCU_RESET
C111 0.1uF
External pull up
Qwiic Connector A
J105
JST–SH
+3V3
I2C_A_SCL
I2C_A_SDA
Mounting Holes
H101
H102
M2 ISO7380
I2C Pull Ups
+3V3
R116 3.3k
R117 3.3k
I2C_A_SDA
I2C_A_SCL
Author: Peter Giannetos
Sheet: /
File: Rover.kicad_sch
Title: Rover Node
Size: A4
Date: 2025–01–28
Rev: A
KiCad E.D.A. 8.0.7
Id: 1/1

# Appendix B: BOM Cost Analysis

| Reference (A) | Reference (R) | Value | Qty (A) | Qty (R) | MPN | Link | MOQ | Cost | Distributor | DPN |
|---|---|---|---|---|---|---|---|---|---|---|
| BZ101 | | Buzzer | 1 | | AT-0927-TT-6-R | https://w | 1 | $0.8700 | Mouser | 665-AT0927TT6R |
| C101 | | 47nF | 1 | | CGA0603X7R473J500JT | https://w | 100 | $0.0029 | LCSC | C36911405 |
| C102, C116 | C107 | 22uF | 2 | 1 | CL10A226MQ8NRNC | https://w | 20 | $0.0074 | LCSC | C59461 |
| C103, C104, C108, C110 | C101, C102, C103 | 10uF | 4 | 3 | CGA0603X5R106M250JT | https://w | 50 | $0.0144 | LCSC | C6119874 |
| C105 | C104 | 47uF | 1 | 1 | CL10A476MQ8QRNC | https://w | 10 | $0.0438 | LCSC | C730416 |
| C106, C113, C119, C122 | C105, C108, C109, C112 | 1uF | 4 | 4 | CGA0603X5R105K250JT | https://w | 100 | $0.0035 | LCSC | C6119818 |
| C107 | | 4.7uF | 1 | | CL10A475KQ8NNNC | https://w | 50 | $0.0037 | LCSC | C8032 |
| C109, C111, C115, C117, C118, C120, C121 | C106, C110, C111 | 0.1uF | 7 | 3 | TCC0603X7R104J500CT | https://w | 100 | $0.0030 | LCSC | C282518 |
| C112 | | 47pF | 1 | | FN18N470J500PSG | https://w | 100 | $0.0023 | LCSC | C525253 |
| C114 | | 10nF | 1 | | CC0603JRX7R8BB103 | https://w | 100 | $0.0037 | LCSC | C519510 |
| D101, D103, D105 | D101, D103, D104 | RED | 3 | 3 | XL-1608SURC-06 | https://w | 100 | $0.0029 | LCSC | C965799 |
| D102 | D102 | ORANGE | 1 | 1 | YLED0603O | https://w | 100 | $0.0053 | LCSC | C19273153 |
| D104, D106 | | PMEG3020EP-QX | 2 | | PMEG3020EP-QX | https://w | 1 | $0.4500 | Mouser | 771-PMEG3020EP-QX |
| D107 | D105 | BLUE | 1 | 1 | NCD0603B1 | https://w | 50 | $0.0142 | LCSC | C84266 |
| D108 | D106 | GREEN | 1 | 1 | PSC-1608U52GC-G4 | https://w | 50 | $0.0078 | LCSC | C22371297 |
| J101, J102, J103 | J101 | U.FL | 3 | 1 | 734120110 | https://w | 1 | $0.3463 | LCSC | C434806 |
| J104 | J102 | USB4105-GF-A | 1 | 1 | USB4105-GF-A | https://w | 1 | $0.7400 | Mouser | 640-USB4105-GF-A |
| J105, J106 | J104 | JST-PH | 2 | 1 | S2B-PH-K-S | https://w | 1 | $0.1000 | Digi-Key | 455-1719-ND |
| J112, J115 | J105 | JST-SH | 2 | 1 | SM04B-SRSS-TB(LF)(SN) | https://w | 5 | $0.1685 | LCSC | C160404 |
| J113 | | DM3AT-SF-PEJM5 | 1 | | DM3AT-SF-PEJM5 | https://w | 1 | $2.6600 | Mouser | 798-DM3AT-SF-PEJM5 |
| J114 | | JST-SH | 1 | | SM08B-SRSS-TB(LF)(SN) | https://w | 5 | $0.2351 | LCSC | C160407 |
| L101, L102 | L101 | 1uH | 2 | 1 | 74438336010HT | https://w | 1 | $1.4600 | Digi-Key | 732-74438336010HTCT-ND |
| L103 | | 27nH | 1 | | LQG18HN27NJ00D | https://w | 10 | $0.0492 | LCSC | C162550 |
| R101 | R104 | 562k | 1 | 1 | FRC0603F5623TS | https://w | 100 | $0.0009 | LCSC | C2933238 |
| R102, R103, R106, R107, R110, R113, R114, R117, R119, R120, R121, R122, R123, R124, R125, R126, R131 | R101, R102, R103, R105, R109, R112, R113, R114, R115 | 10k | 17 | 9 | FRC0603F1002TS | https://w | 100 | $0.0008 | LCSC | C2906982 |
| R104 | R106 | 180k | 1 | 1 | FRC0603F1803TS | https://w | 100 | $0.0008 | LCSC | C2906999 |
| R105 | | 5.36k | 1 | | FRC0603F5361TS | https://w | 100 | $0.0009 | LCSC | C2930112 |
| R108 | | 31.6k | 1 | | FRC0603F3162TS | https://w | 100 | $0.0009 | LCSC | C2933196 |
| | R108 | 604 | | 1 | FRC0603F6040TS | https://w | 100 | $0.0009 | LCSC | C2930123 |
| R109 | R107 | 13k | 1 | 1 | FRC0603F1302TS | https://w | 100 | $0.0009 | LCSC | C2906992 |
| R111 | | 10 | 1 | | RTT0310R0FTP | https://w | 100 | $0.0009 | LCSC | C103222 |
| R112 | | 910k | 1 | | SCR0603J910K | https://w | 100 | $0.0008 | LCSC | C3017672 |
| | R110, R111 | 5.1k | | 2 | SCR0603F5K1 | https://w | 100 | $0.0005 | LCSC | C3016319 |
| R127, R128, R129, R130 | R116, R117 | 3.3k | 4 | 2 | SCR0603F3K3 | https://w | 100 | $0.0005 | LCSC | C3016312 |
| SW101, SW102, SW104, SW105 | SW101, SW102 | SW_Push_Shielded | 4 | 2 | TL3330AF260QG | https://w | 1 | $0.3600 | Mouser | 612-TL3330AF260QG |
| SW103 | | Slide Switch SPDT | 1 | | 500ASSP1SM6QE | https://w | 1 | $5.1600 | Mouser | 612-500ASSP1SM6QE |
| TH101 | | 10k | 1 | | 103AT-2 | https://w | 1 | $0.5800 | Digi-Key | 4316-103AT-2-ND |
| U101 | U101 | TI_TPS630250 | 1 | 1 | TPS630250RNCR | https://w | 1 | $2.2800 | Digi-Key | 296-47380-1-ND |
| U102 | | LORA1262-915 | 1 | | LORA1262-915TCXO | https://w | 1 | $10.0000 | Tindie | Lora1262-915 |
| U103 | U102 | LORA1280-T | 1 | 1 | LORA1280-TCXO | https://w | 1 | $8.7054 | LCSC | C19632391 |
| U104 | | TVS1800DRV | 1 | | TVS1800DRVR | https://w | 1 | $0.5500 | Mouser | 595-TVS1800DRVR |
| U105 | | BQ25628E | 1 | | BQ25628ERYKR | https://w | 1 | $2.8000 | Mouser | 595-BQ25628ERYKR |
| | U103 | BQ25185 | | 1 | BQ25185DLHR | https://w | 1 | $1.8000 | Mouser | 595-BQ25185DLHR |
| U106 | | LPS28DFW | 1 | | LPS28DFWTR | https://w | 1 | $4.8100 | Mouser | 511-LPS28DFWTR |
| U107 | | MAX-M10S | 1 | | MAX-M10S-00B | https://w | 1 | $21.0000 | Mouser | 377-MAX-M10S-00B |
| U108 | U104 | ECMF02-2AMX6 | 1 | 1 | ECMF02-2AMX6 | https://w | 1 | $0.5300 | Mouser | 511-ECMF02-2AMX6 |
| U109 | | TUSB320LAIRWBR | 1 | | TUSB320LAIRWBR | https://w | 1 | $1.8100 | Mouser | 595-TUSB320LAIRWBR |
| U110 | U105 | ESP32-S3-MINI-1 | 1 | 1 | ESP32-S3-MINI-1-N8 | https://w | 1 | $3.1000 | Mouser | 356-ESP32-S3-MINI1N8 |
| U111 | U106 | MAX17048 | 1 | 1 | MAX17048G+T10 | https://w | 1 | $1.1226 | LCSC | C2682616 |