University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

Raytheon Technologies: SpaceNet

1.Information

1.1.Project Customers

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2.Project Description

2.1.Purpose

This project aims to explore the possibility of applying low fidelity and low cost receivers into a large array, in order to provide a framework that can be utilized by software for the discrete task of tracking satellites. Given the ever growing population of robotic inhabitants in orbit around our pale blue dot, it’s imperative to be aware of their locations for the purpose of collision avoidance, orbital anomaly detections (as in a satellite disappearing from a predetermined and predicted orbit), as well as an optimization that can be applied other higher fidelity and high cost uplink and downlink ground stations and tracking systems.

With the influx of spacecraft over the past few years and the many years ahead still to come, low Earth orbit(LEO) is evolving rapidly into a highly contested and congested location that is bound to become more complex with time. Bringing into focus the necessity for proper monitoring and tracking, which will be in significantly higher demand due to the ongoing launches of large satellite constellations such as Starlink, Kuiper, and OneWeb. Furthered by the Defense Intelligence Agency claims which point towards a sharp increase of space congestion in the somewhat near future, necessitating "better capabilities to track and identify objects and prevent a collision in space."[1] To this endeavor and ensuring the future of space exploration, the aerospace community will continue to push for the development of a full picture of Space Domain Awareness(SDA).

High fidelity ground systems to track space debris are costly and not easily built. As a result, current ground tracking system infrastructure is sparsely scattered across the world. To provide a bigger net to track satellites, Raytheon proposed SpaceNet. SpaceNet focuses on creating low cost and manufacturable sensor units. These sensor units will have a low fidelity but will make up for this in ground covered and increased network capability. Ideally, thousands of sensor units could be deployed across the continental US and provide data back to a central database. This project will focus specifically on developing a proof of concept with four sensor units being able to determine a satellite's orbit. In addition, SpaceNet will have the capacity to monitor the characteristics of a satellite's signal (e.g. amount of data being transmitted, change in downlink location, etc)

2.2.Previous work

Based on the provided Defense Intelligence Agency "Challenge to Security in Space" [1] document, there has been considerable amount of work done in the field of Space Domain Awareness. In addition to the contributions made in the U.S., both China and Russia have developed several different methods to determine a space object's location and predict its future location.

In general this high fidelity tracking uses an array of sensors that monitor an object and use relative timing in combination with the sensors know geographical location to determine an orbit. One example is LeoLabs network that currently utilizes three of six large phased-array radars to monitor objects in LEO. These types of phased-array radars are significantly less susceptible to varying weather conditions but are costly and time consuming to build. Additionally these radars can theoretically become "oversaturated" and fail to catch all debris in its view. In addition to LeoLabs network there are other large radar networks owned by various entities.

Opposite of the large phased-array radar networks there are amateur projects that attempt to monitor objects in LEO using off the shelf components and software defined radios(SDR). These amateur projects are exponentially cheaper than the large radars but have much lower fidelity and limited field of view(FOV).
This summary is a small amount of the total work that has been put into improving SDA. Relative to the aforementioned solutions, SpaceNet will be a small contribution to SDA focusing on using budget sensors in a theoretically large array to support more expensive high fidelity sensors.

2.3.High level Functional Requirements

The following outlines the High level functional requirements for the project. These requirements must be satisfied in order for base mission success. These requirements will flow down into more specific requirements to drive design.

Table1: High level Function Requirement

Functional Requirement	Description
FR1	The sensor unit shall survive outdoors in all expected weather conditions.
FR2	The sensor unit shall be able to detect radio signals from satellites in low Earth orbit.

FR3	The sensor unit shall continuously upload recorded data through the internet while operational.
FR4	The received sensor data shall be utilized by orbital determination algorithms to estimate a satellite's orbit and position in orbit.

2.4.Specific Objectives

The following lists specific objectives for each of the project's core components. Sections are subdivided into various levels of mission success. Level 1 being marginal performance that meets the project objective of orbital determination. The highest level implies fulfilment of the lower levels and represents completion of the entire project scope.

Table 2: Specific Project Objectives

Sensor Unit Packaging	
Level 1	*Sensor Packaging shall integrate all hardware *Sensor Packaging shall weigh less than 100 lbs and be contained within 5'x5'x5' volume
Level 2	*Sensor packaging shall keep components within operating temperature range in all expected temperatures and conditions (direct sunlight, rain, cold, wind, variable (snow)) *Sensor shall be a self-contained with access to an external power source and network interface *Packaging shall use standard USB connectors, Coaxial Radio Frequency(RF) connectors, and National Electrical Manufacturers Association(NEMA) 5-15 socket
Level 3	*Sensor packaging shall withstand 3 weeks of autonomous operation with no sign of compromise (no box leaks, or physical damage) *One unit produced (w/ schematics, procedure, and manufacturing analysis)
Sensor Unit Data Acquisition Subsystem	
Level 1	*Sensor shall use an commercial SDR unit *Sensor shall use standard connectors for ease of manufacturability *Sensors shall collect Ultra High Frequency (UHF) radio signals. *Unit shall be networked enabled with the ability to be commanded remotely from a PC
Level 2	*Onboard software shall be able to transmit data over a network. *Software shall be able to return to nominal operation after an power or network outage *Sensors shall be equipped with a Global Positioning System (GPS) receiver for RF signal timing
Level 3	*Unit shall record and transmit data on 24/7 basis, assuming constant power and network connectivity - Unit demonstrates ability to collect and transmit data over a 24 hour period with additional verification during the planned 3 week field test.
Level 4	*Sensor shall collect UHF and Very High Frequency(VHF) signals (Dual Band)
4 Sensor Network	
Level 1	*Time Delay of Arrival (TDoA) algorithm produces position vectors with a test data set..
Level 2	*Networked data is visible on remote computer *TDoA algorithm produces position vector with networked data

Level 3	*Four units produced, mounted, and operational. *Manufacturing documentation (schematics, procedure, manufacturing analysis, suggested improvements, and ways to drive down cost) *TDoA result can be used for orbital prediction *Error analysis report comparing SpaceNet to higher fidelity alternatives - Compare the data gathered with SpaceNet with the data gathered by higher fidelity - systems, like LASP ground station.

2.5.CONOPS

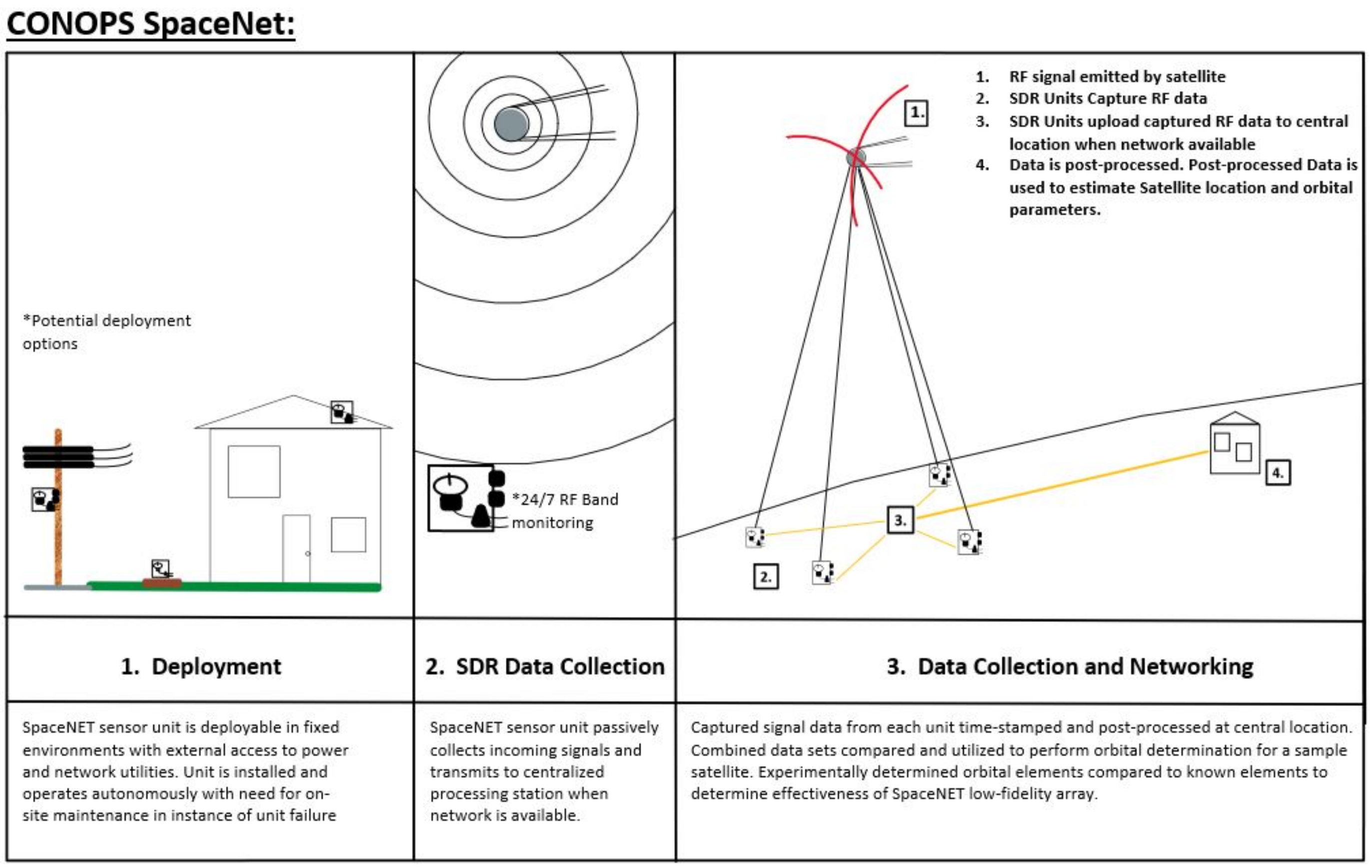

Figure 1: Sensor Deployment and Data Acquisition Concept of Operations

A sensor unit is installed in a location with access to a NEMA 15 outlet and hard-lines network access. The unit will need to be manually connected to the network on deployment. In case of power failure after deployment the unit is capable of automatically reconnecting to the network and rebooting the SDR for data collection. For this project the four ground based sensors will receive a radio signal from the target satellite. The data from the 4 units can be used for a multilateration calculation to approximate the orbital parameters of the target.

The project uses 4 stations as a proof of concept. The goal would be to have a large number of these sensors so multiple multilateration calculations could be performed to track various satellites. If the orbital parameters determined by the array are outside of an acceptable range (TBD), the target satellite would be passed on to more specialized ground based tracking agencies.

2.6. Functional Block Diagram

Below is a high level functional block diagram of an individual sensor unit. Some components of the systems have been marked as "SDR dependent" as their inclusion will be dependent on the chosen SDR and potentially the operating location of the sensor unit due to various unknowns such as ground noise, cable losses and antenna performance. The intended operation is as follows.

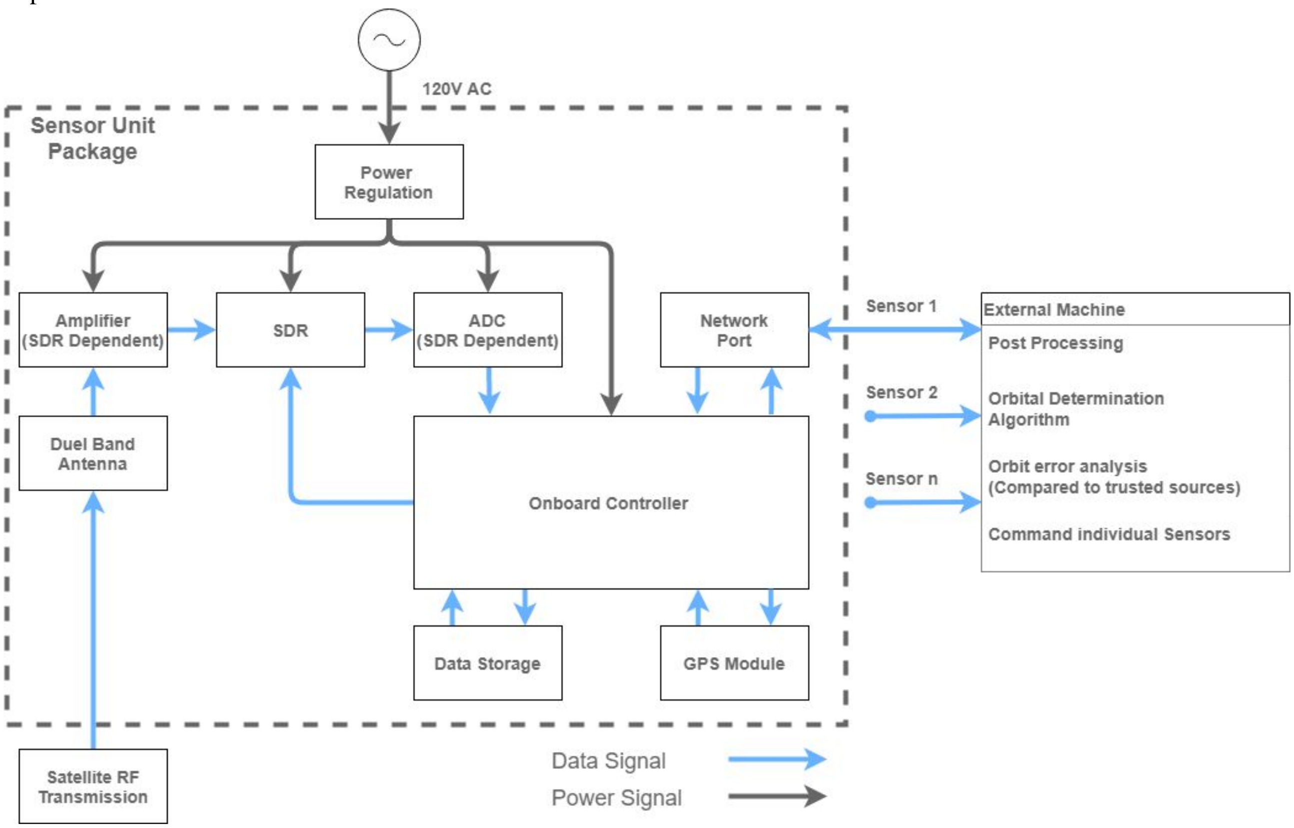

Figure 2: Proposed Functional Block Diagram of a Single Sensor Unit

A radio signal is received by each sensor unit package, amplified, converted to digital, and sent to a central computer for post-processing via a wired network connection along with a GPS time stamp. At the central computer, the metadata of the satellite signal is processed to parametrize the orbit of the target to quickly verify that the satellite is operating nominally. If, after examination, the target satellite is outside of accepted orbital and transmitting parameters, the information regarding the target satellite is to be forwarded to appropriate agencies (e.g USSF, NSA, etc) for further, more in depth, analysis and observation.

3. Design Requirements

The following details the specific design requirements that define each functional requirement. Each requirement is defined with a motivation and a specific method of verifying the requirement has been met. Each requirement is designed such that it can be verified via test, analysis or inspection.

FR 1: The sensor unit shall survive outdoors in all expected Colorado weather conditions.

Motivation: This is necessary based on the nature of the project. In order for communication to occur between the satellite and sensor unit it must be placed outdoors. The sensor will be remotely controlled and must survive without regular maintenance.

Verification: Test - The sensor will be deployed for 3 weeks or equivalent. Sensors shall not turn off or stop transmitting due to failed sensor components. Failure is not defined by power source or network drops.

DR 1.1: Sensor unit shall weigh no more than 100 lbs and will be contained within a 5'x5'x5' volume.

Motivation: Customers have mandated this as the max size and weight. The sensor unit must be easy to deploy in the field. By constricting the max size, deployment can be done by a single person, and units can be placed in confined places such as a backyard or telephone pole.

Verification: Inspection- measuring the dimensions and mass of the final sensor unit.

DR 1.2: All system components shall fit inside the packaging excluding the antenna.

Motivation: For ease of setup, the sensor unit shall be full assembled when being deployed. Deployment should require no electrical assembly except plugging in the sensor unit to an outlet and connecting an ethernet cable.

Verification: Inspection- The SDR, on-board computer, gps module, power management, low noise amplifier, bandpass filter, and any other electronic hardware specified will fit within the packaging.

DR 1.3: The packing shall have mounting for the antenna(s).

Motivation: Antennas will not have their own mounting to the utility pole, so to ensure they can be interfaced smoothly, the sensor unit shall have mounting for the antenna.

Verification: Test-Mount the antennas or equivalent load onto the sensor units during the deployment test to ensure prolonged loads can be handled.

DR 1.4: Sensor unit shall have connections to supply power,RF signals, and network accessibility.

Motivation: The sensor unit requires all these ports to be power hardware, to detect radio signals, and to transmit data to the network.

Verification: Test - Upon completion of the unit, each outlet shall be tested for functionality.

DR 1.4.1: Sensor unit shall have a NEMA 5-15 socket.

Motivation: The Customer mandated this requirement.

Verification: Test - Check all voltages output by the power management are equal to their expected value, respectively.

DR 1.4.2: Sensor unit shall have one ethernet port..

Motivation: To transmit data through a network, ethernet ports are often the most versatile solution.

Verification: Test - The port can transmit data to the internet.

DR 1.4.3: Sensor unit shall have two SubMiniature version A(SMA) connectors.

Motivation: SMA connectors are the common connection for RF signals. Two SMAs are required to support the possibility of dual band.

Verification: Inspection- Confirm two SMA ports are installed to the packaging and can continuous connection.

DR 1.5: Sensor unit shall be designed for IP55 rating (dust protected and resistant to water jets.)

Motivation: IP55 rating protects against dust and water jets from any angle. This rating is more than necessary for expected conditions.

Verification: Test-This requirement will be verified during the deployment test on the packaging.

DR 1.6: Sensor unit interior shall stay in the operational temperature range of -40°C to 85°C

Motivation: These values were derived from the operating temperature of the on board electrical components.

Verification: Test-During the deployment test, a temperature sensor shall be on board to monitor the temperature for the duration of the test. If the temperature range is exceeded for more than 10 minutes, the test shall be considered a failure.

DR 1.7: Each sensor unit interior shall cost less than $1000

Motivation: Given a $5000 budget, making four sensor units shall give $5000 in unexpected cost and flexibility.

Verification: Analysis- The financial lead shall produce a financial report of spending of the budget. The financial lead will be incharge of enforcing this requirement.

FR 2: The sensor unit shall be able to detect radio signals from satellites in low Earth orbit.

Motivation: A large number of small and amature satellites transmit from LEO. Small Satellites and amature constellations are part of the justification for improving SDA. These satellites are largely representative of the desired use case.

Verification: Test - The sensor unit will be monitored and compared to a known good ground station during a flyover.

DR 2.1: For Band A (assumed as UHF), a minimum threshold G/T of -15 db/K or greater

Motivation: This requirement was informed by the customer. By baselining the ground station hardware within this value the rest of the system is easier to isolate and makes it easier to spec components.

Verification: Analysis-Link budget analysis will be used to verify the sensor units G/T

DR 2.2: For Band B (assumed as L-Band), a minimum threshold G/T of -13 db/K or greater

Motivation: This requirement was informed by the customer. By baselining the ground station hardware within this value the rest of the system is easier to isolate and its easier to spec components.

Verification: Analysis-Link budget analysis will be used to verify the sensor units G/T

DR 2.3: The GPS breakout board and antenna will be off the shelf and not require extensive hardware modification

Motivation: This requirement was set in order to ensure ease of manufacturability

Verification: Analysis-GPS breakout board specs meet system requirements

DR 2.3.1: The GPS will be capable of <20s nanosecond timing synchronization.

Motivation: Nanosecond synchronization reduces drastically educces error in orbital position estimate

Verification: Test - The sensors would be sent a pulse synchronously and the relative time will be measured.

DR 2.4: The sensor unit computer will be off the shelf and not require extensive hardware modification

Motivation: This requirement was set in order to ensure ease of manufacturability

Verification: Analysis-Sensor Computer breakout board specs meet system requirements

DR 2.5: The SDR unit will be off the shelf and not require extensive hardware modification

Motivation: this requirement was set in order to ensure ease of manufacturability

Verification: Analysis-SDR specs meet system requirements

DR 2.5.1: The SDR shall cover the following frequency range: 100MHz - 2.5GHz

Motivation: This frequency covers a large of the desired bands

Verification: Inspection - SDR data sheet will be used to ensure tunable range

DR 2.5.2: The SDR shall have 700 KHz tunable bandwidth

Motivation: This frequency accounts for the largest expected doppler shift.

Verification: Inspection - SDR data sheet will be used to ensure tunable bandwidth

DR 2.6: The sensor unit will able to boot up and enter nominal operation autonomously

Motivation: This requirement was informed by the customer such that the system can recover if there is a black out or network outage.

Verification: Analysis-Sensor Computer breakout board specs meet system requirements

FR 3: The sensor unit shall continuously upload recorded data through the internet while operational.

Motivation: Sensor unit shall run autonomously and monitor multiple satellites during deployment.

Verification: Test- During the infield test, the sensor unit shall upload state data to a network for the duration of the test. This will include temperature data, and moisture data to confirm FR1.

DR 3.1: Sensor unit shall upload the SDR output data.

Motivation: The bare minimum radio data is just if there is a signal and the frequency of the signal. For TDoA, the modulated data is irrelevant. Therefore, being able to identify the signal frequency and when the signal shows up is more than adequate.

Verification: Test-The sensor unit will be given a known signal, yet the software team will not know it. The software team must be able to tell what the signal was and when it was transmitted.

DR 3.2: Sensor unit shall upload the time of when the signal is detected.

Motivation: Time Delay of Arrival relies on the specific time the signal is detected. By accurately measuring the time

Verification: Test-The sensor unit will be given a known signal, yet the software team will not know it. The software team must be able to tell what the signal was and when it was transmitted. This will be verified at the same time as the SDR requirement 3.1.

DR 3.3: Each sensor unit shall have an unique ID.

Motivation: Being able to tell the sensor units apart will be imperative to finding the time delay of arrival. There will be one "master" unit. All other units will take a time differential with respect to the "master" unit.

Verification: Inspection- Confirm all units have an individual ID. This will be done in the software, and in the network to confirm no confusion.

DR 3.4: Each sensor unit shall be able to receive commands through the network.

Motivation: Controlling the sensors remotely will be important to ensure control of the frequency range of the SDR. Also the being able to synchronize clocks on command

Verification: Test-Start by transmitting a single frequency signal. Confirm it is detected by the SDR through the network. Next, Change the frequency SDR remotely while the single frequency is still on. If it disappears, change the frequency source to the frequency of the SDR. Check if the new frequency is detected.

FR 4: The received sensor data shall be utilized by orbital determination algorithms to estimate a satellite's orbit and position in orbit.

Motivation: This is one of the goals of spacenet to produce orbital data on easily trackable satellites so that high fidelity sensors can be used elsewhere.

Verification: Test - The orbit and orbital prediction will be compared to the object's known orbit and orbital position and orbital parameter.

DR 4.1: The system shall provide ≥3 times of arrival for the same satellite signal

Motivation: This is the minimum number of data points necessary for Multilateration tracking of an object.

Verification: Test- Confirm the signals arrive at different times through a test with a known source and expected times of arrival. Each unit will be spaced a certain distance away from the source ping.

DR 4.2: Sensor data shall be usable with doppler shift to provide estimated speed of the signal source

Motivation: The velocity vector can be used to further classify the objects state in orbit

Verification: Test-The calculated velocity can be compared to a known velocity calculated from the known orbit.

4.Key Design Options Considered

4.1.Satellite target

While the ultimate goal of SDA and this project is to track a wide variety of satellites it is convenient to monitor one or two satellites as a proof of concept. This section summarizes various satellite candidates and their assets. The major areas of consideration for the tracking candidate are: how often the satellite will pass over our local area, how easily we will be able to verify and quantify the tracking systems performance compared, and what frequencies the satellite transmits at. As long as the transmitting satellite can be identified relative to background noise and other satellites it does not matter what the satellite is transmitting or what its mission is. All the satellite candidates are in LEO and have a period of approximately 90 minutes.

LASP CSIM: The first sat, the Compact Spectral Irradiance Monitor(CSIM), is a miniature satellite designed and built at the Laboratory for Atmospheric Space Physics(LASP). CISM gets its name from its mission objective which is to use a compact spectral irradiance monitor to collect physical data on the Sun. CSIM is physically smaller than a microwave oven This small size can be problematic for some phased-array sensors. CSIM has the huge advantage of being based locally here at CU Boulder; LASP has agreed to let us use their facilities and sensor to verify SpaceNets data and tracking capabilities. CSIM downlink is at 437.250 MHz and it has a near polar orbit.

Pros	Cons
Local contact operated by CU Boulder	
Precise orbital and transmission data readily accessible for system verification	
Small form is ideal for proof of concept	

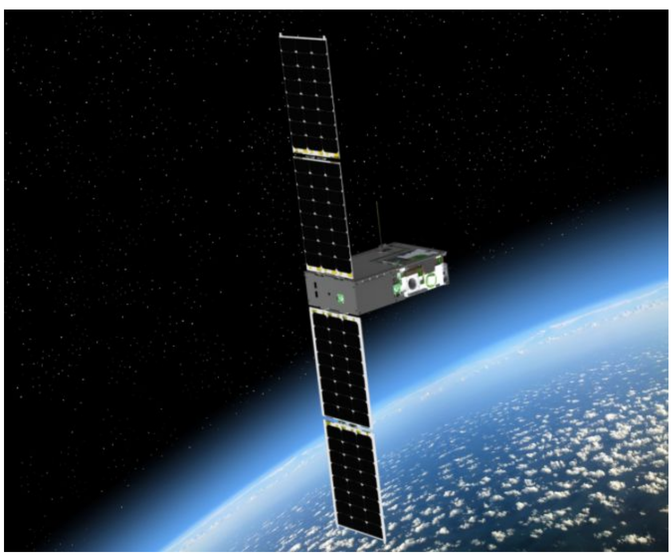

Figure 3: CSIM Satellite

NOAA 15: NOAA 15 is a weather forecasting satellite monitored by the National Oceanic and Atmospheric Administration(NOAA). NOAA 15 has a near polar LEO and is commonly used for amature tracking projects. NOAA 15 was chosen due to its polar nature but other NOAA satellites could also be considered. NOAA 15 has a working downlink of 1702.5 MHz.

Pros	Cons

Strong community for tracking NOAA satellites	
Is forced to use omnidirectional antenna due to issues with its high gain antenna	

Figure 4: NOAA 15 Satellite

XW2 Constellation: XW2 is a constellation of three identical Chinese micro satellites used for physics experiments and amature radio missions. The amateur communications payload has ~ 145 MHz CW beacon and telemetry downlinks.

Pros	Cons
Very comparable to LASP's CSIM	
Amature constellations like this are part of the drive for SDA	

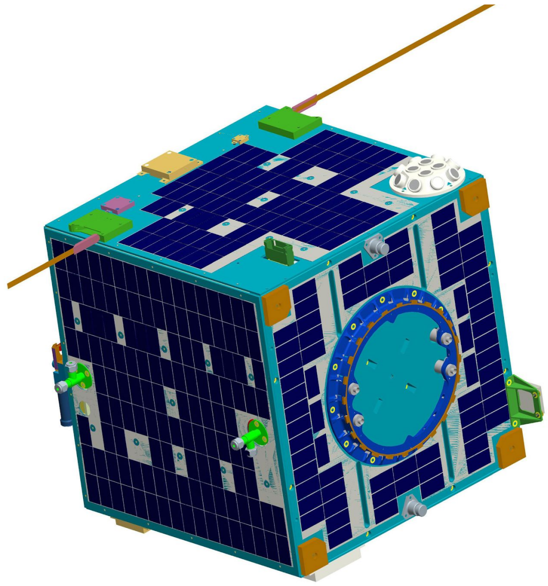

Figure 5: A XW2 Constellation Satellite

OSCAR 11(UoSAT 2): UoSAT-2, also known as UoSAT-OSCAR-11 was built by a team of engineers at the university of Surrey in Guildford. The satellite has been in orbit since 1984 and is still transmitting till this day. The satellite has since become a popular target for amateur sensors due to its near polar low earth orbit. The satellite downlinks at 145MHz and beacons at 2401 MHz.

Pros	Cons
strong community for this kind of project	no longer maintained

Figure 6: OSCAR 11(UoSAT 2) Satellite

4.2.On-board Computer

The on-board computer will handle communication between the sensor unit and the external control and possessing machine. In the event of a power outage the on-board computer must be able to recover autonomously to a state that it can be commanded from the control computer. The on-board computer must be able to command and receive data from the SDR . The on-board computer must also be able to handle the incoming data from the GPS module to determine an accurate location of the unit for better networking capabilities between the other units. With the seemingly large amount of data that will be received and handled by the units, the on-board computer must have adequate memory and speed to manage this information without data loss. The computer must provide all necessary connections for the required hardware or must be easily adaptable.

Intel® NUC 8 Pro Board - NUC8i3PNB: The NUC computer from Intel provides a very compelling on-board computer for the units to be made in this project. The NUC has hardware that is typical for a regular lab workstation but all within a small form factor. A downside to the NUC is its price, as the NUC is much more expensive compared to the other smaller microcontroller candidates in this trade study. It also has no General Purpose Input/Output(GPIO) support for peripherals. The NUC comes with an Ethernet port, which will be helpful for the network capabilities for the units. The NUC is overspeced for the sensor units needed but that allows the team more flexibility when choosing how to command the SDR.

Pros	Cons
High End hardware	High Cost
Has a large number of usb and networking ports	no baked in GPIO support
Can run a windows operating system	

Figure 7: Intel® NUC 8 Pro Board - NUC8i3PNB

Raspberry Pi 4 (2GB / 8GB): The Raspberry Pi is well known to have comparable performance with a desktop computer, and maintain a small size as well. The Raspberry Pi 4 comes with different choices of Random Access Memory(RAM) depending on what is necessary for the application. The Raspberry Pi 4 is capable of running a linux operating system. The pi has a decent selection of peripheral ports and built in gpio header. The Raspberry Pi 4 also comes with an Ethernet port, which will be helpful for the network capabilities for the units. There is also a large community surrounding the Raspberry Pi 4 on its applications, and there is great amounts of support found for running GNU Radio and other SDR applications on it as well.

Pros	Cons
Decent Clock Speed	Smaller number of usb ports by default
Able to choose between different amounts of RAM (2GB, 4GB, 8GB)	Confined to a linux based system

Great community and forums to help implement SDR software	
Inexpensive	
Lots of GPIO ports to use extra sensors	

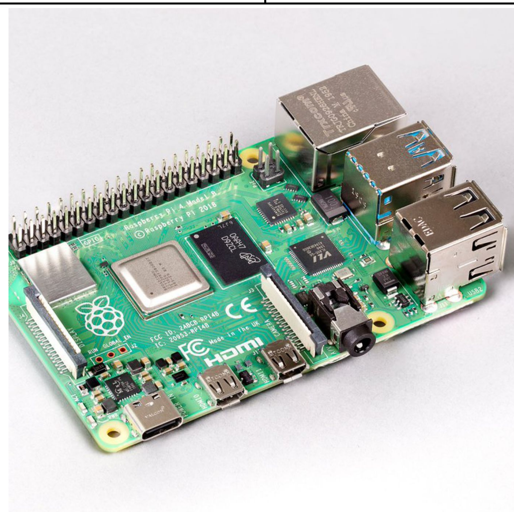

Figure 8: Raspberry Pi 4

Beaglebone Black: The Beaglebone Black has been proven adequate for SDR operation and satellite tracking projects such as satnog. The Beaglebone Black is one of few candidates recommended on the GNUradio wiki.The Beaglebone Black sits somewhere between the INTEL NUC and Raspberry Pi 4 in terms of processing power. It is limited to a linux based system as with the Raspberry Pi 4. As with most of the other microcontrollers in this trade study, Beaglebone Black is small with lots of GPIO ports and only a few USB ports peripheral ports. The Beaglebone Black has SD card support allowing for cheap expandable storage without the use of a usb port. The board is also equipped with an ethernet port.

Pros	**Cons**
Great community and forums to help implement GNU Radio	More expensive than a Raspberry Pi 4
more powerful than a pi	
Lots of GPIO ports to use extra sensors	

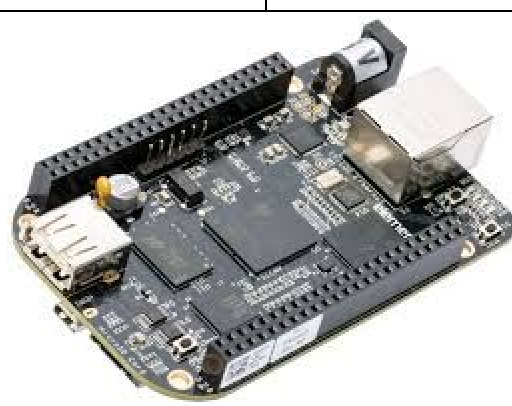

Figure 9: Beaglebone Black

Beaglebone AI: The Beaglebone AI sports similar features to the Beaglebone Black with more processor power. The main thing that sets these two Beaglebone microcontrollers apart is their price, with the Beaglebone AI being about 2 times more expensive than the Beaglebone Black.

Pros	**Cons**
Same support as the Beaglebone Black	Small number of USB peripheral ports
Faster than the Beaglebone Black	Fairly expensive

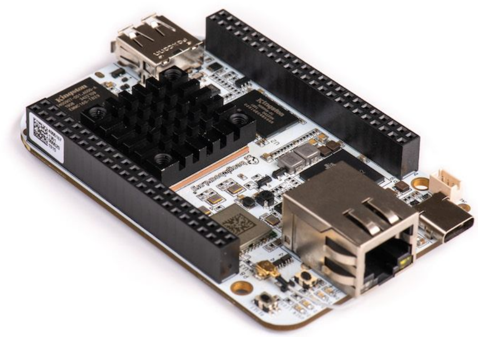

Figure 10: Beaglebone AI

Arduino Uno: Like the Raspberry Pi, the Arduino microcontroller is known for being a cheap and open source option to use for engineering projects. There is seemingly a large community and forums for the Arduino with a large number of cheap breakout boards available. The Arduino Uno has very low amounts of RAM memory, and a very small clock speed compared to the other candidates. The arduino processor is not designed for the same breath of applications as the others so it would be unable to leverage GNU radio and linux. The limited bandwidth of the arduino would also be a concern. If the Arduino Uno is a feasible option in this project, it has the advantage of being very inexpensive and very small in size, but implementing it would require custom hardware.

Pros	**Cons**
Inexpensive	Low clock speed
readily available	Comparatively no Ram
	No native SDR support

Figure 11: Arduino Uno

4.3.SDR

The Software Defined Radio(SDR) controls what satellites can be tracked based on frequency and bandwidth. The customer requested the SDR requirement. The SDR will be responsible for detecting the radio signal, determining the frequency, and digitizing the signal. Since the project will be trying to track multiple satellites, a large tunable range is a key consideration for the SDR. The downlink frequencies of interest fall in VHF and UHF bandwidths. These frequencies will be the main factor in SDR selection. The SDR will need a reasonable signal resolution after digitization; this will be important for determining time delay of arrival. Finally, the SDR must have an adequate sampling rate to detect the signal and doppler shift from the satellite flying by. The doppler shift will be useful to determine the satellite's velocity.

RTL-SDR v3: The RTL-SDR v3 is an inexpensive SDR with a large amateur community. The design is built on DVB-T TV tuner with the RTL2832U chipset. For the low price of $25, the RTL-SDR has a surprising amount of versatility. SatNOGs, a ground-based amateur satellite radio network, recommends using the RTL-SDR for building a ground station. The multiple on-board computers support the RTL-SDR, including the Raspberry Pi 4. The RTL-SDR is the smallest SDR candidate. It is about the size of a flash drive. The RF connection is a female SMA, and it sends data and receives power through a USB 3.0 port. Signals are digitized to 8 bits, but the Effective Number of Bits(ENOB) is estimated at ~7 bits. This SDR covers frequencies from 5MHz up to 1766MHz. One of the limiting factors for this SDR is a low sampling rate at only 2.56MS/s. This will significantly limit the bandwidth.

Pros	**Cons**
Large community of amateur satellite observers.	Low sample rate
Very inexpensive(~6 RTL for 1 Pluto)	Low bit Resolution
Bandwidth covers VHF and UHF	No S-band coverage

Figure 12: RTL-SDR v3

HackRF One: The HackRF One was developed by Great Scott Gadgets. It can both receive and transmit signals which go beyond the needs for the sensor unit. One large advantage of the HackRF One is the massive frequency range, 1MHz to 6GHz. This frequency range includes all of VHF, all of UHF, and all of S-Band. For connections, it has three SMA connectors for receiving(RX) and transmitting(TX) as well as external clock input, and a USB 2.0 for power. It has a large sampling rate of 20MS/s, which allows for bandwidths up to 20MHz. The drawbacks are the price and bit resolution. The cheapest price found was $300 from sparkfun. While the bit resolution is only 8-bits. The HackRF One also supports GNU Radio.

Pros	Cons
Large Frequency Range	High price due to transmit capabilities
Large Bandwidth	Low bit resolution
GNURadio support	

Figure 13: HackRF One

ADALM-PLUTO: The ADALM-PLUTO is manufactured by Analog Devices. The PLUTO is often used to learn the fundamentals of an SDR. It has transmitting and receiving capabilities. Some of it's advantages include the bit resolution, sampling rate, and easy to learn interface. There is support for GNU Radio, MATLAB, and Simulink. The PLUTO has a 61.44MS/s and has bandwidths of 20MHz. For connections, the PLUTO has a USB 2.0 for power and data transmission and SMA connectors for radio signals. The PLUTO is strengthened by a 12 bit resolution. The PLUTO's drawback is the frequency range, 325MHz to 3.8GHz. This range has virtually none of VHF, which will limit dual band capabilities. The cost is fairly reasonable at $150.

Pros	Cons
High Sampling rate	Frequency Range does not include VHF.
High bit resolution	Fairly high power consumptions
GNU Radio and Matlab support	

LimeSDR Mini: The LimeSDR Mini is manufactured by Lime Microsystems. It is a smaller version of the LimeSDR. It has capabilities to transmit and receive RF signals. The main advantages of the LimeSDR Mini are the bit resolution, bandwidth, and frequency range. The bandwidth is the largest of the candidates with 30.72MHz. It also has a bit resolution of 12 bits which matches the PLUTO. It has the ability to connect an external clock. The frequency range is from 10MHz to 3.5GHz, which covers all of the satellite candidates. The main drawback is the price at $190.

Pros	Cons
Highest bandwidth	Relatively high price.
GNU Radio and Matlab Support	High power consumption
External Clock Accessibility	

Figure 14: LimeSDR Mini

4.4.GPS Module

The GPS chip unit will be the main timing unit for the SDR, therefore making the chips key components the tracking capabilities of the units. There are other methods that can be used to gain accurate timing such as updating a "Real Time Clock" via the network. This solution is cheap but does not provide the geolocation of the sensor that will be necessary for ultimate calculations. Having a GPS unit on board makes the system more robust and removes any human factor that may exist when determining sensor position.

SparkFun GPS Breakout - NEO-M9N: The SparkFun NEO-M9N GPS Breakout is a high quality, GPS board with equally impressive configuration options. The NEO-M9N module is a 92-channel u-blox M9 engine Global Navigation Satellite System(GNSS) receiver, meaning it can receive signals from the GPS, Global Navigation Satellite System(GLONASS), Galileo, and BeiDou constellations with ~1.5 meter accuracy. This breakout supports concurrent reception of four GNSS maximizes position accuracy in challenging conditions increasing precision and decreases lock time and thanks to the onboard rechargeable battery.

Pros	Cons
Well used by hobbyists, has excellent customer support.	Expensive
Complete system, including an antenna in the breakout board.	High Current Draw
High update Rate	

Figure 15: SparkFun GPS Breakout - NEO-M9N

Adafruit Ultimate GPS : The breakout is built around the MTK3339 chipset, a no-nonsense, high-quality GPS module that can track up to 22 satellites on 66 channels, has an excellent high-sensitivity receiver (-165 dB tracking), and a built in antenna. It can do up to 10 location updates a second for high speed, high sensitivity logging or tracking. Power usage is incredibly low, only 20 mA during navigation.This GPS Breakout board is the cheapest option in our candidate list, and the smallest. has the connections for an external antenna.

Pros	**Cons**
Small size	Low Update Rate of Candidates
Complete system, including an antenna in the breakout board.	Low Number of Channels
Low Cost	

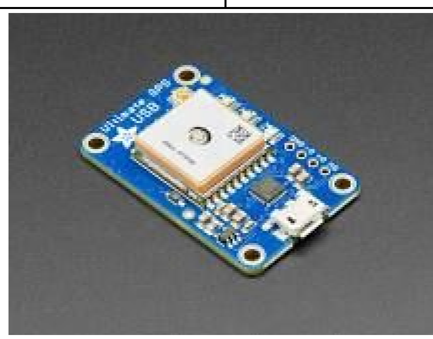

Figure 16: Adafruit Ultimate GPS

SparkFun GPS Breakout - U.FL, ZOE-M8Q (Qwiic): The SparkFun ZOE-M8Q GPS Breakout is a high accuracy, miniaturized, GPS board. The on-board ZOE-M8Q is a 72-channel GNSS receiver, meaning it can receive signals from the GPS, GLONASS, BeiDou, and Galileo constellations. This increases precision and decreases lock time. Additionally, this u-blox receiver supports I2C (u-blox calls this Display Data Channel) which makes it perfect for the Qwiic compatibility so we don't have to use up UART ports. This GPS board is the smallest out of the group studied here; however, it falls in the middle for a lot of the evaluation criteria established. It also has the least horizontal accuracy out of the bunch and does not come with a built-in antenna.

Pros	**Cons**
Small in size	Lower accuracy

Relatively cheap	Low update rate

Figure 17: SparkFun GPS Breakout - U.FL, ZOE-M8Q

ACROBOTIC Breakout Board - NEO-M6N: The ACROBOTIC Breakout Board - NEO-M6N is a very low cost versatile board equipped with the NEO-M6N chip. The board has uart communication but no usb connections. Like other boards the chip can be programmed using the u-center software. This is a huge benefit for the chip as it can be instructed to use its full communication capabilities for timing once a geo location has been established. The NEO-M6N has 50 channels which is far less than the other candidates meaning it cannot access as many satellites as the other candidates however, if run in a time only mode this shouldn't be a problem.

Pros	**Cons**
Small in size	Lower accuracy
Cheapest candidate	Low Number of Channels
	Low update rate

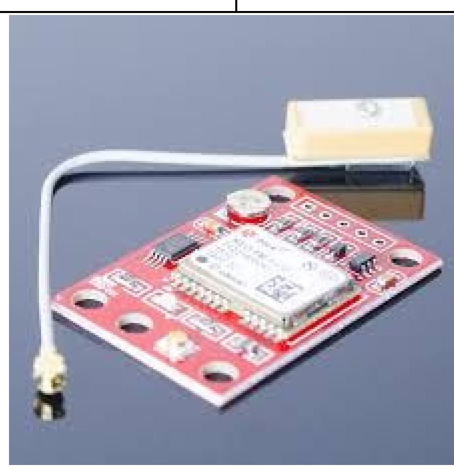

Figure 18: ACROBOTIC Breakout Board - NEO-M6N

4.5.Sensor Unit Housing

The housing is necessary to protect the sensor unit from its environment during operation. Based on the geographical location of this project the housing will have to keep the equipment in operating range given large amounts of rain and snow. In addition to environmental protection, the housing ideally will be easily manufacturable and a readymade product that can be adapted to incorporate the necessary power and signal pass throughs. The exact size requirement of the housing is unknown as the exact components and the physical interplay between them is unknown until they are in hand. The size is also directly related to the cost of each housing candidate. As such this trade study is more a preliminary look into the various options and how they compare to one another based on the desired criteria.

Pelican Case: Pelican cases are widely used to protect gear with a high durability and waterproofing. These cases feature open-cell cores and solid wall construction making them lightweight along with improved durability compared to cases with a solid-core wall construction. These cases are equipped with a tongue-and-groove fit case coupled with a pressure-equalization valve that automatically releases built-up pressure. Pelican cases come in clear variants that make for easier system monitoring and better GPS compatibility.

Pros	Cons
Multiple Sizing Options	Paying for the unnecessary impact resistance
High Durability	Expensive
Weatherproof	Requires custom implementation for external hardware/components

Figure 19: Example Pelican Case

PVC Container: PVC has been used in many outdoor applications such as electrical cable protection and water management. Assembled correctly PVC provides a water tight seal, along with high customization in terms of fittings. The sizing can be varied from ½" to 8" in diameter and various lengths as needed by the user. This allows for ease of manufacturing and accessibility since it requires no special tools to be fitted and constructed. Along with no special tools required these products can be found readily available in many hardware stores and can be easily customized by the user.

Pros	Cons
Weatherproof	Circular form factor
Low cost	Limited sizing
Easily accessible materials	

3D Printed Case: Utilizing a 3D printed case allows full customization for mounting and sizing options for the enclosure. This allows the box to easily be customized for mounting of internal and external components. Using a 3D enclosure does require a custom tool but allows for step by step implementation and integration of new design requirements and changes.

Pros	Cons

Multiple Sizing Option	Full custom implementation
Fully Customizable	Requires High Weatherproofing
Low cost	No weather resistance rating

Electrical Enclosure: Electrical enclosures are used for many outdoor electrical products such as generators, transformers, and electrical panels. These products offer a high customization with other electrical components along with various size options to store and protect equipment. This allows easy integration within the box to various power sources and external components with readily available connectors and extensions. There are various rated boxes specifically those that are waterproof/rated to be used in outdoor operation. These boxes feature moderately high durability and multiple mounting options available. This allows situational mounting options to be readily applied and available for the user.

Pros	Cons
Multiple products/fittings already made for the box for integration of external hardware/components	Expensive
Products is available in a variety of sizes and ratings	Require same rated (NEMA rated) components to be used with the box
Parts are off the shelf available	
Weatherproof	

Figure 19: Stainless Steel Electrical Enclosure

4.6. Antenna and Low Noise Amplifier and Bandpass Filter

The main objective of SpaceNet is to try and make low cost units that can be manufactured and placed in a wide variety of locations. As stated by the customer there will be no pointing system for the antenna. This is done to reduce system cost and complexity. Without control over the antenna orientation an antenna should be chosen that has a pattern similar to what is shown below in Figure 20.

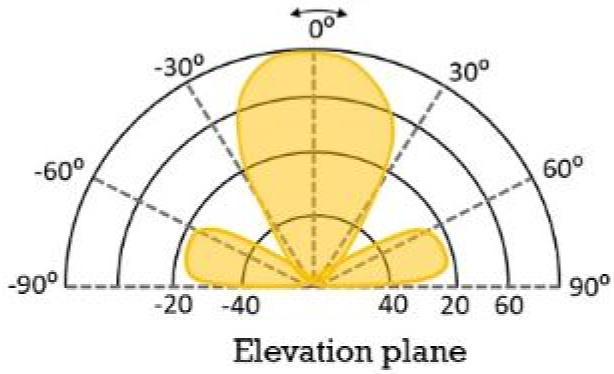

Figure 20: Diagram of desired antenna gain

The antenna pattern should be designed with a 360 degree FOV around the azimuth and have ~10 degree angle relative to the horizon/azimuth plane. This antenna pattern will maximize its gain toward the area of interest and limit the amount of terrestrial noise that is being observed.

The antenna system will most likely use a low noise amplifier(LNA) and band pass filters to help identify the desired signal out of the noise floor. All of these components and their designs will be driven by a link budget analysis. The link budget analysis ultimately determines the overall signal to noise ratio(S/N) given system parameters. The budget is typically adjusted by changing components until it meets the desired S/N, however for this project there is no S/N ratio requirement as the system works as intended if a signal can be identified as defined in the requirements section and the ground station meets the G/T budget.

From the listed satellite candidates the team has predicted a worst case UHF isotropic signal loss at ground of ~ -147dBW. It has also been listed by the customer that for this band the ground station must have a figure of merit, G/T ≥ -15 dB/K. However, this information is not enough to fully define the system as the type of terrestrial noise that the antenna sees will directly influence the Low Noise Amplifier(LNA) and band pass filters.

The team is planning SDR based experiments to build intuition and help inform the expected noise level before fully defining the system. The fully defined system will still be compliant with the G/T spec given by the customer.

5.Trade Study Process and Results Satellite Target

5.1.1.Metrics and Weighting

The main metric for the satellite trade study was the orbital parameters. The orbit decides the necessary gain for the signal and whether the satellite flys over Colorado at all. The orbit gave a good metric of how feasible it would be to track the satellite, hence the team gave the orbit the highest weight of the metrics. To be able to track the satellite, it is important for the SDR to be able to reach its radio frequency. The frequency will also play a large role in required gain to link to the satellite. The availability of satellites plays a crucial role in testing the accuracy of the device. For example, satellites that might transit only once a week are much less favorable than satellites that transit almost daily. Accessibility is important as the more data that exists tracking the satellite the easier it is to verify the system in a compelling fashion. Similarity to End Goal Target compares the satellite to large constellations like Starlink. Finally, doppler shift is included to add the ability to measure the satellite's velocity.

Table 3: Explanation of Weights

Metric	Weight	Requirement	Rationale
Orbital Parameters & Ground Track (altitude, inclination, eccentricity)	35	FR 2, FR 4, DR 4.1, 4.2	The location and velocity of an overhead satellite will play a factor in tuning the sensor system to verify its operational capabilities. The more time the sat passes

			over our local area the more opportunities there will be to monitor its position
transmission receivability	20	DR 2.5.1, 2.5.2	Some satellites only transmit on their high gain low field of view antennas while others transmit on an omnidirectional antenna. The ideal scenario is transmission on both antennas in a range that can be received by the SDR candidates.
Accessibility	15	FR 2	For the purpose of verifying the accuracy of our system, it is important that we have access to reliable, precise, consistent data regarding the target satellite.
Similarity to End Goal Target	25		The goal of this project is to prove the concept of using amateur like radars to track smaller satellite constellations. The concept is easier to validate if the test analog is a more accurate representation of the target.
Doppler Shift	5	DR 4.2	Doppler shift can give a measure of the satellite's velocity. A larger shift makes this process easier but it can theoretically be done with any shift.

5.1.2.Metric Quantification

To quantify the possible orbits, the team ranked the ability to receive data and chances to track the highest. Naturally, this led the team to highly ranking Low Earth Orbit(LEO) sun-synchronous orbits the highest. For the satellite's bandwidth, a key requirement is the ability for SDRs to reach the downlink frequencies. Next, the satellite's accessibility was quantified by how well we can prepare for a track. If the satellite operates through LASP, the satellite was given a higher score based on the data accessible. How comparable the target is to the end goal constellations such as Starlink is also considered. Finally, the doppler shift of the satellite can have major errors for the target frequency, so avoiding large shifts would be ideal.

Table 4: Point Allocation

Metric	**0**	**1**	**2**	**3**	**4**
Orbital Parameters/Ground tack (altitude, inclination, eccentricity)	Orbit never passses over the Boulder area and is too high for signals to be detected	Orbit passes over Boulder, but the signal is too weak for the sensor to pick up. IE Geostationary orbit	Orbit passes over Boulder, the inclinations less than 45deg	Orbit passes over Boulder. Inclination is less than 75 deg.	LEO Polar orbit. (75<i<105)
Bandwidth receivability	Neither VHF or S-band	Frequencies is covered by 1 SDR and has overlap with possible other	Frequency covered by two SDR candidates, but is close to	Frequency is covered by most SDR candidates, S-Band	Frequency is covered by all SDR candidates

		transmitters	common other frequencies (wifi)		
Accessibility	The satellite is classified and has limited public information	Given some orbital parameters.	Given all orbital parameters, but no live tracks	Amateur satellite websites have general orbital tracking.	Able to get high fidelity data of the satellites orbit from space agency
Similarity to End Goal Target	Sat has nothing in common with end goal targets	Satellites are in a LEO	Satellites share frequency range with the end goal targets and are in a LEO	Satellites share frequency range, and physical size with the end goal targets and are in a LEO	Satellites are classified as part of the end goal target set
Doppler Shift	Doppler shift is less than 500 Hz	Doppler shift is greater than 500Hz	Doppler shift is greater than 1kHz	Doppler Shift is greater than 5 kHz	Doppler shift is greater than 10kHz

5.1.3.Trade Results

Based on the trade study results, the CSIM satellite will be the best target. It transits Boulder almost daily and downlinks to LASP, so the antenna will be on during the transit. Since LASP operates CSIM, detailed calculations of the orbit can be obtained with their permission. CSIMs two antennas are both in tunable ranges for most SDR candidates. The doppler shift is on both sides of the spectrum: the S-band will produce a large easily detectable doppler shift around 60kHz, while UHF will produce a smaller doppler shift to focus in on the position.

Table 5: Trade Study Results

Metric	**Weighting**	**CSIM**	**NOAA 18**	**OSCAR 11**	**XW2 satellites**
Orbital Parameters/Ground tack (altitude, inclination, eccentricity)	35.00%	4	4	4	4
Bandwidth receivability	20.00%	4	3	3	3
Accessibility	15.00%	4	4	0	3
Similarity to End Goal Target	25.00%	3	2	2	4
Doppler Shift	5.00%	4	2	4	2
Total	100.00%	3.75	3.2	2.7	3.55

5.2. On-board Computer

5.2.1. Metrics and Weighting

As stated prior the on board computer handles transmitting data and commanding the SDR. The below metrics were defined based on the hardwares ability to meet this goal as well as its ability to physically support the necessary subdevices like the SDR and GPS module. The metrics are accompanied by the weighting and rationale.

Table 6: Metric Rationale

Metric	Weight	Requirement	Rationale
Clock Speed	15.00%	FR 3 DR 3.1-3.4	The clock speed of the on-board computer will determine how fast data and instructions can be sent throughout the unit and between different peripherals
Memory (RAM)	15.00%	FR 3 DR 3.1	It will be important for the on-board computer to be able to collect, store, and send data to another off unit location. So it is important for there to be sufficient RAM memory to facilitate basic unit functionality and store recorded data to be sent off.
Peripheral Ports	20.00%	DR 1.4.2, 2.5	There are several other systems that need to be implemented in this unit, so being able to use peripheral ports on the on-board computer will be an efficient way to connect other systems to the on-board computer.
Upgradability	5.00%	DR 2.4	It would be beneficial if the on-board computer is able to be upgraded in regards to its memory or peripheral ports.
GNU Usability	20.00%	FR 3 DR 3.1-3.4	It was recommended from the customer to utilize GNU Radio to provide the main functionality of the unit.
Cost	25.00%	DR1.7	It is important to have a feasible on-board computer in the units, but the units should be as low cost as possible.

5.2.2. Metric Quantification

The quantification of the metrics for the on-board computer seen below were mainly based on the project's functional requirements, as well as the available on-board computers candidates on the market. There are several metrics in the table that aren't quantified by a specific numerical value like the upgradability, GNU usability, and peripheral ports capabilities of the on-board computer. It can be seen that the on-board computers that were upgradeable, use GNU radio, and had peripheral ports scored higher than other candidates. Because of the large market of microcontrollers, the clock speed and RAM memory seems to vary largely for different scores pertaining to these metrics.

Table 7: Point Allocation

Metric	0	1	2	3	4
Clock Speed	MCU has clock speed >= 16 MHz	MCU has clock speed <=500 MHz	MCU has clock speed <= 1 GHz	MCU has clock speed <= 1.5 GHz	MCU has clock speed <= 2.5GHz
Memory (RAM)	MCU has RAM >= 1 GB	MCU has RAM >= 2 GB	MCU has RAM >= 4 GB	MCU has RAM >= 8GB	MCU has RAM >= 16GB
Peripheral Ports	MCU has no connections	MCU has only a USB connection	MCU has an ethernet and USB connection	MCU has 2>USB connections, 1	MCU has 3> USB connections, 1

				Ethernet, 1 SD card	Ethernet, 1 SD card,
Upgradability	Can not vary the product easily	Product has external purchasable upgrades	Ability to add storage.	Ability to increase RAM	Ability to increase RAM and storage
GNU Usability	No documentation or forums of GNU use in past projects	There is little documentation or forums of GNU use in past projects	There is some relevant documentation of GNU use in past projects	There is several relevant documentation of GNU use in past projects	Has multiple projects and forums that utilize GNU radio for reference
Cost	MCU cost exceeds $200	MCU cost exceeds $150-$200	MCU cost: $100 -$150	MCU cost exceeds $100-$50	MCU costs less than $50

5.2.3.Trade Results

In the table below are the results of the trade study, which shows that the Raspberry Pi 4 is the most optimal on-board computer for the units. It has a decent clock speed with good amounts of RAM memory, and it also has good amounts of peripheral and GPIO ports. For its high performance characteristics, and its low cost, the Raspberry Pi proves why it is the optimal choice in this on-board computer trade study. Later on in the project if it is determined that the Raspberry Pi 4 is not as feasible as this trade study made it seem, we will use either the Beaglebone Black microcontroller or the Intel Nuc computer. The Beaglebone AI could be substituted for the Beaglebone black. Lastly, the Arduino Uno has shown to be the worst candidate in this trade study, lacking the necessary hardware and functionality that our units need.

Table 8: Trade Study Results

Metric	**Weighting**	**BeagleBone AI**	**Intel® NUC 8 Pro Board - NUC8i3PNB**	**Raspberry Pi 4(8GB)**	**Beaglebone Black**	**Arduino Uno**
Clock Speed	15.00%	3	4	3	2	0
Memory (RAM)	15.00%	0	3	3	0	0
Peripheral Ports	20.00%	2	4	2	2	1
Upgradability	5.00%	2	1	2	2	1
GNU Usability	20.00%	3	1	3	3	1
Cost	25.00%	2	0	3	3	4
Total	100.00%	2.05	2.1	2.75	2.15	1.45

5.3.SDR

5.3.1.Metrics and Weighting

The team determined SDR metrics based on customer requirements and similar projects such as SatNOGS. In Table 9, the metrics are laid out with their weighting, requirement and rationale.

Table 9: Metric Rationale

Metric	Weight	Requirement	Rationale
Tuning Range	40%	FR 2 DR2.5.1	The tuning range must be fairly large. Satellites have a large range of frequencies. This is to accommodate dual band applications.
Bit resolution	20%	DR 2.1,2.2	The Bit resolution needs to be precise. The better bit resolution will allow for more accurate time of arrival.
Power Supply/Voltage	5%	DR 1.4.1	Power supply depends on what will be available. This will likely come from a wall outlet, so the power is not too much of a concern.
Sampling Rate	10%	DR 2.5.2	The SDR's sampling rate is important for the bandwidth available for signals. This will be useful for doppler shift and modulated signals.
Size/Weight	5%	DR 1.2	Mass is not too constricting. The main concern is the ability to fit into packaging. Also the mass should be limited to
Connection	15%	DR 1.4.2 1.4.3, 2.5, 2.5.1	The connection is important for interfacing with the microcontrollers and power supply.
Cost	15%	DR 1.7	Given the budget of $5000, the cost must be affordable and easy to obtain four SDRs.

5.3.2.Metric Quantification

The SDR metrics scoring were determined based on the commercially available SDRs and target satellites. Since the sensor units will only detect signals and not transmit signals, more weight was applied to the tuning range and bit resolution of the SDR. The tuning range was given more value for wider ranges so more satellites can be tracked. Since the project will likely have a wall power supply, the SDR's power consumption was given less weight.

Table 10: Point Allocation

Metric	0	1	2	3	4
Tuning Range	The SDR is limited to frequencies outside of VHF and S-band	The SDR only covers part of S-Band or VHF.	SDR can cover only UHF, S-Band, or VHF.	SDR can cover S-band or all of VHF and UHF	SDR Covers all of VHF, UHF, and S-band f_low<30MHz f_high>4GHz
Bit resolution	No ADC on on board	ADC has a resolution of 6 bits or less	ADC has a resolution of 8 bits or less	ADC has a resolution of 10 bits or less	High resolution 12bits
Cost	SDR cost exceeds $400	SDR cost exceeds $300	SDR cost exceeds $200	SDR cost exceeds $100	SDR costs less than $100
Power Consumption	Greater than or equal to 4W	Less than or equal to3.5W	Less than or equal to 2.5W	Less than or equal to 2W	Less than equal to 1.5W

Sampling Rate	Bandwidth less than 1MHz	Bandwidth greater than 1MHz	Bandwidth is larger than 10MHz	Bandwidth greater than 20 MHz	Sampling rate can produce a bandwidth over 100MHz
Size/Weight	SDR is larger that 150cm^2	Smaller than 150cm^2	Smaller 90 cm^2	SDR is smaller than 50cm^2	SDR is smaller than 20cm^2
Connection	No connections except for solder mounting	Only SMA connector	USB only	SMA and USB	SMA, USB Connection, and external Clock

5.3.3.Trade Results

In the trade study results in Table 11, the selected SDR is the LimeSDR Mini, Mini for short.This is due to its tuning range including VHF, UHF, and S-band. With a high sampling rate, the Mini will be able to detect and demodulate most signals as well as track the doppler shift. The LimeSDR Mini has support for an external clock. The main drawback is the power consumption of the Mini. The power given is 4.5W, but this figure was calculated as an upper maximum. Documentation claimed the LimerSDR Mini would function on USB 3.0 which supplies 4.5W of power.

Table 11: Trade Study Results

Metric	Weighting	RTL-SDR V3	HackRF One	ADALM-PLUTO	LimeSDR Mini
Tuning Range	35.00%	3	4	3	3
Bit resolution	10.00%	2	2	4	4
Cost	15.00%	4	1	3	3
Power	5%	4	2	1	0
Sampling Rate	20.00%	1	2	2	3
Size/Weight	5.00%	4	1	2	3
Connection	10.00%	4	3	3	4
Total	100.00%	2.85	2.6	2.75	3.05

5.4.GPS Module

5.4.1.Metrics and Weighting

The team determined the GPS metrics based on preliminary error calculations and research. These were driven by the major GPS hardware specs that affect clock synchronization and less so by the GPS ability to be reliable at all times.

Table 12: Metric Rationale

Metric	Weight	Requirement	Rationale
Size	10%	DR 1.2	The main concern is the ability to fit into packaging.
Update Rate	30%	DR2.3, 2.3.1	The update rate of a GPS module is how often it recalculates and reports its position. Since our system isn't moving (hopefully) this isn't as big of a concern

Positional Accuracy (m)	30%	DR 2.3.1	Most modules can get it down to +/-3m, but price goes up exponentially with finer resolution.
Cost	30%	DR 1.7	Given the budget of, the cost must be affordable to build four systems.

5.4.2.Metric Quantification

The GPS unit's metrics scoring were determined based on the commercially available GPS breakout boards. The Size of the GPS boards are all relatively small, so the weighting of this metric was low. The overall accuracy of the sensor's clock and position determination is dependent on the update rate, channels available and positional accuracy. The number of channels and their effect on accuracy is up for debate and based on our research anything above 20 channels should be reasonable for accurate timing. The final metric was cost and trying to justify the higher cost of a gps clock as opposed to a real time clock module that is network updated.

Table 13: Point Allocation

Metric	0	1	2	3	4
Size	Size >= 5.8 cm^3	5.5 cm^3 < Size =< 5.8 cm^3	5.0 cm^3 < Size =< 5.5 cm^3	3.0 cm^3 < Size =< 5.0 cm^3	Size =< 3.0 cm^3
Update Rate (Hz)	Update Rate isn't high enough to report the timing of the system (Update Rate < 1 Hz)	The Update Rate is standard (Update Rate = 1 Hz)	The update rate is modifiable to go above 1 Hz.(Update Rate > 1 Hz)	The update rate is modifiable to go above 5 Hz.(Update Rate > 5 Hz)	The update rate goes above 10 Hz. (Update Rate > 10 Hz)
cost (USD)	cost =<$60	cost =<$50	cost =<$40	cost =<$30	cost =< $10
Positional Accuracy (m)	horz. accuracy > 2.5m	2.0 m < horz. accuracy =< 2.5m	1.5 m < horz. accuracy =< 2.0 m	1 m < horz. accuracy =< 1.5 m	horz. accuracy=< 1 m

5.4.3.Trade Results

The trade study results in Table 14, the selected GPS Unit is the ACROBOTIC NEO-6M. This is due to the sensor's lower cost coming in at $10, $30 dollars below the competition. The sensor has the required ability to accept an external placeable antenna. The unit has a customizable update rate, that can be used to squeeze more performance out of the system if necessary. The timing mode that is available on the chip can be used to ensure that we are getting accurate timing with the data sheet claiming given a 30 m position the unit can provide times with up to millisecond accuracy and with a 1 m position accuracy the unit can provide a nanosecond timing accuracy.

Table 14: Trade Study Results

Metric	**Weighting**	**SparkFun NEO-M9N**	**Adafruit Ultimate GPS**	**SparkFun ZOE-M8Q (Qwiic)**	**ACROBOTIC NEO-6M GPS Module Breakout Board**
size	10.00%	2	0	4	4
Update Rate	30.00%	4	4	4	2

Cost	30.00%	0	1	2	4
Positional Accuracy	30.00%	3	2	1	2
Total	100.00%	2.3	2.1	2.5	2.8

5.5.Sensor Unit Housing

5.5.1.Metrics and Weighting

The equipment housing as stated before plays a major role in ensuring operation and protection of the internal hardware. While the result of the trade study may change due to the electronics hardware selection and the need for devices such LNAs the following metrics highlight the thought process and reasoning that will be used to ultimately select a housing. Metrics are displayed below along with their corresponding weights.

Table 15: Metric Rationale

Metric	Weight	Requirement	Rationale
Weatherproof	30%	FR 1, DR 1.5, 1.6	The housing must be able to maintain operating conditions for hardware and components. This is to meet the 3 week requirement placed by Raytheon and cope with the snowy environment the sensors will be exposed to.
Manufacturability	15%	DR 1.1, 1.7	The housing must be easily manufactured to ensure ease of duplication and integration (Maximize off the shelf products)
Accessibility	10%	DR 1.2, 1.4, 1.4.1-3,	Housing materials/boxes must be easily accessible to ensure product can be manufactured and obtained readily
Hardware Integration	15%	DR 1.2, 1.3, 1.4, 1.4.1-3,	Housing must be customizable to in order to provide system needs and allow easy integration of components/hardware
Cost	20%	DR 1.7	Housing must be moderately low in cost to be able to produce 4 units containing all necessary hardware to achieve project objective
Size	5%	DR 1.1	Housing must be able to store the required hardware in a compact and optimizable box.

5.5.2.Metric Quantification

The scoring criteria are described in the following table. In general, metrics which were directly related to key project requirements were weighted higher. The compatibility metric scores were determined by comparing the housings ability to withstand outdoor use without the need of additional application of weatherproofing material and products along with the housings ability to be manufactured with off the shelf products. The metric also includes the accessibility, cost, and ease of integrating the external and internal components to the structures that can be varied in size. Due to the unknowns with the hardware these criteria are somewhat general. Once the exact requirements for the box get defined by the chosen hardware metrics and study can be reevaluated if need be.

Table 16: Point Allocation

Metric	0	1	2	3	4
Weatherproof	Housing can not protect hardware in all weather conditions (rain,snow, heat) from base design	Housing can protect hardware in all weather conditions (rain,snow, heat) but requires large amounts of additional weatherproofing	Housing can protect hardware in all weather conditions (rain,snow, heat) and requires moderate additional weatherproofing	Housing can protect hardware in all weather conditions (rain,snow, heat) and requires little to no weatherproofing	Housing is NEMA or IP rated to withstand and protect hardware in all weather conditions (rain,snow, heat)
Manufacturability	Parts to assemble housing are not readily available and require custom implementation and integration.	25% of the parts to assemble housing are readily available but still require custom implementation and integration.	50% of the parts to assemble housing are readily available but still require custom implementation and integration.	75% of the parts to assemble housing are readily available but still require custom implementation and integration.	Parts to assemble housing are readily available, provide ease of assembly, and do not require long manufacturing time (off the shelf availability)
Accessibility	Parts to assemble housing are accessible only through custom manufacturing.	Parts to assemble housing are accessible and require mostly custom manufacturing.	Parts to assemble housing are accessible through specific suppliers and require 5 or less items through custom manufacturing.	Parts to assemble housing are accessible through specific suppliers and require 3 or less items through custom manufacturing.	Parts to assemble housing are easily accessible via manufactures/supply stores and require 1 item to be custom manufactured
Hardware Integration	Integrating external and internal comoponets the the housing cannot be done without specialized tools,equipment, and professionals.	Integrating external and internal comoponets the the housing can done but requires specialized tools, equipment, with help from a professional	Integrating external and internal comoponets the the housing can done by a non professional individual but requires specialized tools or equipment	Integrating external and internal comoponets the the housing can be done by a non professional individual but minimal specialized tools or equipment.	Integrating external and internal comoponets the the housing is easily done by a non professional individual without requiring specialized tools or equipment. (Includes option for a clear cover)
Cost (Based on 12"x12"x12" Box)	The main housing box is greater than $100 (per box).	The main housing box is $75 - $100 (per box).	The main housing box is $50 - $75 (per box).	The main housing box is $25 - $50 (per box).	The main housing box is under $25. (per box).

Size	The main housing cannot support/ be customizable for any dimension (length,width, height)	The main housing can support/ is customizable for 1 specified dimension (length, width, height).	The main housing can support/ is customizable for 2 specified dimensions (length,width,height)	The main housing can support/ is customizable for 3 specified dimensions (length,width,height).	The main housing box can be manufactured/available off the shelf in more than 3 different dimensions (length,width,height) and provide customizable options.

5.5.3.Trade Results

Table 17: Trade Study Results

Metric	Weighting	Pelican Case	PVC Container	3D Printed Enclosure	Electrical Enclosure (Nema Rated)
Weatherproof	30.00%	4	3	2	4
Manufacturability	15.00%	3	3	3	4
Accessibility	10.00%	3	3	3	3
Hardware Integration	15.00%	3	2	4	4
Cost	25.00%	1	3	4	2
Size	5.00%	3	1	4	3
Total	100.00%	2.8	2.75	3.15	3.35

When comparing the four enclosures the trade study resulted in the electrical enclosure. The electrical enclosure, although featuring a higher cost per box versus the PVC and 3D printed enclosures, provides off the shelf availability with various sizes available. The electrical enclosure received a 4 in the weatherproofing, manufacturability, and hardware integration categories. This box provides various NEMA ratings such as NEMA 1,2,3,3R,3RX,3S,4,6 ratings followed by IP65, IP66, IP67, IP68 ratings. These ratings ensure protection against falling rain, sleet, snow, and external ice formation and provides an additional level of protection against corrosion. Following the optimum outdoor capability, the enclosure and parts needed to integrate external components to the enclosure are readily available off the shelf with provided ratings to be used with the housing allowing intuitive hardware integration followed by manufacturability. The enclosure was determined to be a 3 in terms of accessibility for an internal mounting bracket will need to be custom manufactured to secure all the components within the housing which provides pre-existing mounting to fasten the bracket to the box. Finally the enclosure was ranked a 3 in terms of size as it provides multiple existing sizing options providing variability in length, width and height of the enclosure. As of now based on the tradestudy the team intends to use off the shelf electrical enclosures with custom internal mounts for the hardware. If the hardwares physical compatibility seems to invalidate the metrics used here the study will be redone with new metrics.

6.Selection of Baseline Design

To select the baseline design from each of the critical elements each of the trade study results were quantitatively assessed but also qualitatively considered with respect to the project goal. The project is being approached as a proof of concept to see if small low cost ground stations can be used to monitor the orbit of satellites and their positions. Some the metrics chosen above may not completely reflect this goal in their weighting or application. As such this section is designed to try and limit any inappropriate weights or metrics that may have been used and could lead to a qualitatively worse baseline design.

6.1.Trade Result Analysis

6.1.1.Satellite target

The Satellite target trade study was designed to choose a satellite that would be used for the proof of concept experiment. The trade study suggests that LASP's CSIM be used for the project's primary candidate. CSIM overall is very similar to the other candidates and is a small bodied cubesat very representative of its class overall. CSIM is remarkably similar to the WX2 satellite constellations as well however due to our location here at CU boulder and a team members connection we can use LASPs facilities and data to quantitatively compare our data and validate our systems performance. This combined with the zero compromises CSIM offers makes it a great choice.

6.1.2.On-Board Computer

The On Board Computer trade study suggested the hobby enthusiast pick of the Raspberry Pi 4. The Raspberry Pi 4 does not have the highest processing speed nor the largest amount of RAM however with its 4 USB ports 2 of which have USB 3 to prevent bottlenecking the SDR it can easily support our USB peripherals. Additionally the Raspberry Pi 4 has a great community behind it providing a large amount of forum support and hardware compatibility such as the chosen GPS module which does not support USB connection making it and its cost saving unusable on the Intel Nuc. It is readily available from various suppliers and is the cheapest usable option above the arduino. The final nail in the coffin is that the Raspberry Pi 4 has attached ethernet and has been reported to perform similar and even more tasking versions of its intended operation on this project.

6.1.3.SDR

The SDR trade study metrics are debatable as they are harder to define due to the unknown nature of the link budget analysis. Some of the metrics such as bit resolution, and sampling weight are of debatable importance as there is no reason to demodulate the received signal. But at the same time the faster the bit rate the better the signal resolution and the easier it should theoretically be to identify the satellites signal. Taking all of these into consideration the LimeSDR mini still seems like an appropriate option despite its extra features such as acting as a transceiver not just a receiver. The tunability of the device seems to outway all other factors. A single RTL-SDR will be used as a preliminary test SDR to help familiarize the group with the technology due to its low cost but the LimeSDR mini will be used for the 4 sensor units.

6.1.4.GPS

The GPS is one of the most important elements of the system as without accurate clock synchronization it will be impossible to perform any kind of multilateration calculation accurately. The GPS trade study selected the $10 ACROBOTIC NEO-6M break board based on equal weightings between cost, update rate and positional accuracy. The final weighting was allocated to board size. The metrics and weightings were chosen based around the minimum required accuracy with the high end of the spectrum being above the predicted required accuracy level. The NE0-6M on paper wins out over the rest due to its much lower cost however, while not explicitly stated in the data sheet the NE0 -6M is capable of providing the same timing accuracy as the other sensors if commanded to operate in a time specific mode after being placed in a stationary location. This feature is only available on genuine chips from the manufacturers but the cost of a genuine board is far less than the other candidates and provides the same accuracy.

6.1.5.Sensor Unit Housing

The housing chosen via trade study was the premade Nema rated electrical enclosures. These cases are standardized for a wide variety of applications and come with a community of cheap environmentally rated connectors for cable passthrough and connection covers. The down side to the premade electrical cases is that they are relatively expensive as opposed to 3d printed enclosure however, the base housing size used for the cost analysis was oversized to ensure whatever components were chosen would fit in the box without increasing the price further as it is semi proportional to the box volume. Based on the rest of the hardware it appears that we will be able to downsize the box and cut back on cost. Having easy access to Nema rated enclosures and pass throughs will save the team time during assembly and potential headache during weather testing. 3D enclosure can even be used beforehand to ensure that the hardware will fit in a mock box

6.2. Overall Baseline Design

1. LASP CSIM
2. Raspberry pi 4
3. Lime Mini SDR
4. ACROBOTIC NEO-6M breakout board
5. Nema rated Electrical Enclosure

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