University of Colorado
Department of Aerospace Engineering Sciences
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Project Final Report (PFR)

PROS8: **P**assive **R**adio Frequency **O**bservation **S**ystem 8

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Project Customer

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List of Acronyms

COTS Commercially Available off the Shelf Systems
EM Electromagnetic
FFT Fast Fourier Transfer
HPBW Half Power Beam Width
LOS Line of Sight
NOARD North American Aerospace Defense Command
OD Orbit Determination
RF Radio Frequency
SDR Software Defined Radio
SGP Simplified General Perturbations
SNR Signal to Noise Ratio
TLE Two Line Element

Nomenclature

Δt	Time in-between Viewing
ω	Angular Velocity
ρ’	Range Rate
σ	Largest Magnitude of the Complex Eigenvalue of the Matrix A
τ	Torque

$\vec{\dot{r}}$	Velocity Vector of the Satellite
$\vec{R}$	Position Vector of the Ground Station
$\vec{r}$	Position Vector of the Satellite
I	Inertia Component
m	Mass
$\mathbf{I}$	Inertia Matrix
R_x	Position of the Ground Station in the X-Direction
r_x	Position of the Satellite in the X-Direction
R_y	Position of the Ground Station in the Y-Direction
r_y	Position of the Satellite in the Y-Direction
R_z	Position of the Ground Station in the Z-Direction
r_z	Position of the Satellite in the Z-Direction
v_x	Velocity of the Satellite in the X-Direction
v_y	Velocity of the Satellite in the Y-Direction
v_z	Velocity of the Satellite in the Z-Direction

1. Project Purpose

Author: Quinton Nietfeld

This project is in collaboration with Orbit Logic and is an addition to their existing software. Orbit Logic specializes in mission planning and scheduling including space situational awareness software. They utilize their software package, called Heimdall, for scheduling observations of known and uncharacterized space objects. This software requires the user to define optical and radar sensors for ground-to-space and space-to-space observations and then creates an optimized, deconflicted observation plan for the user. Heimdall does this by first defining the sensor configuration (location, range, unavailable times, etc.), then defining the orders which is the target in space that is requested to be observed. The software determines if the order is visible to the assigned sensors that will be used. Optimization algorithms are then applied to generate observation opportunities and a observation schedule is created. PROS8 will be a preliminary add-on for Orbit Logic's Heimdall software using passive radio frequency transmissions from satellites. Since Heimdall only considers radar and optical sensors, Orbit Logic is interested in making observations with passive radio frequency sensors. The team was tasked with researching radio frequency and how it can be utilized for satellite observations. This research primarily consisted of the range of radio frequencies that are transmitted by satellites, how those radio frequencies travel through different mediums and their interactions with atmospheric phenomenons, and the collection process of these radio frequency signals. With all of this information the team designed a software package that mirrors Heimdall but for radio frequency observations. This software that will be developed will then be tested in the upcoming months with a physical ground station. This ground station will be developed by PROS8 and it's primary objective will be to collect radio frequencies from orbiting satellites to test the developed software. This passive radio frequency system will be able to stand beside optical and radar to offer another method for observing satellites. Radio frequency has some advantages over radar and optical and can offer a number of different viewing opportunities that optical and radar cannot offer.

2. Project Objectives and Functional Requirements

Authors: Kieran O'Day, Quinton Nietfeld

2.1. Objectives and Levels of Success

PROS8 is primarily a software package that relies on a passive radio frequency ground station for testing. Considering this relationship, there are important objectives and success levels for both the software and ground station components of PROS8. Shown in Table 1 are the various levels of success for PROS8. Level one for each category is meant to represent the basic functions PROS8 will need to perform in order to be considered a success. Levels three and four represent the more complex objectives that we will be designing to.

Level	Signal Reception	Signal Processing	Scoring	Scheduling	Controls
1	Receive 6 RF signals from a satellite	Isolate signals of a desired frequency	Determine what sensor and target parameters are the most important for scoring observations	Schedule feasible observations times/locations within a given time frame for one satellite	Point system at fixed locations commanded via manual input
2	Receive RF signals from satellites in multiple orbit geometries	Calculate the doppler shift of the satellite	Create a formula for scoring satellites and observation opportunities	Schedule observations taking into account their scores	Point system along a given orbit path commanded via manual input
3	Receive RF signals from a satellite in various conditions		Calculate the relative error between the actual orbit and the observation	Schedule observations of multiple satellites taking into account their scores	
4	Receive RF signals from multiple satellites in various conditions				

Table 1. Specific Objectives for the System

2.2. System Operation and CONOPS

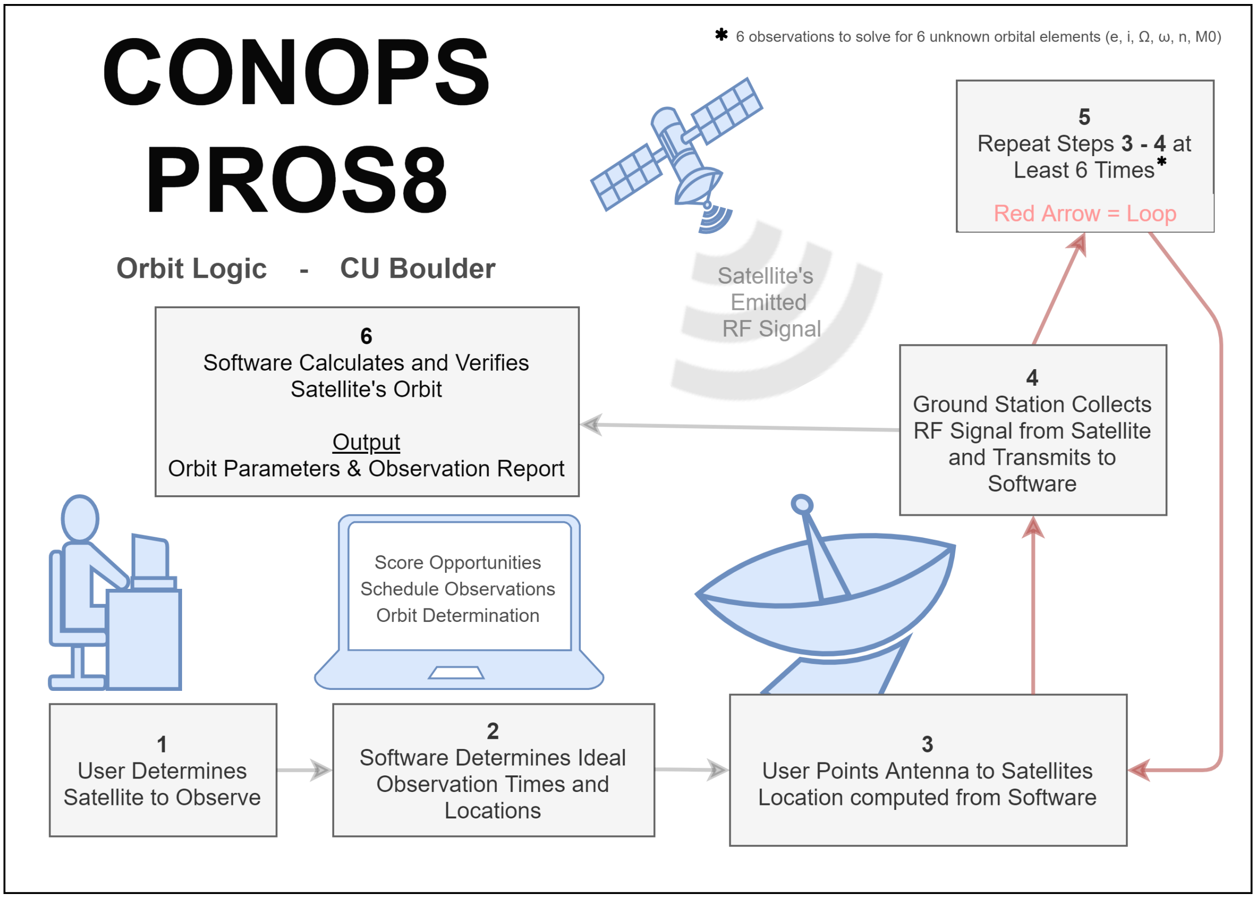

Figure 1. Concept of Operation

Figure 1 shows the concept of operation for PROS8. This is a diagram that shows how the data collection process will take place. It is important to note that a large portion of the project was software development and the software can be seen in operation in boxes 2 and 6, however this CONOPS is not a full account of how the software works, it is an account on how the entire system works from a user standpoint.

Box 1 shows that the user needs to determine the satellite(s) that they want to observe and then inputs that into the software. This is fairly straightforward and once the satellite(s) has been chosen and inputted to the software the process moves to box 2.

Box 2 details that the PROS8 developed software will determine the ideal observation times and locations of those ideal observations of the chosen satellite(s). This box is very important to understand, since PROS8 is a very software heavy project most of the development in the project is concealed to this box. The software takes the user inputted satellite and finds the TLE data (or GPS ephemeris data if observing GPS satellites) to simulate the satellites orbit. The software will propagate the satellite's orbit when it is in view of the ground station and will determine a number of observation opportunities that can be performed by the ground station. The software will then consider a number of variables and score each of those observations. With each observation scored, the software then develops a observation schedule that will be executed by the ground station. This observation schedule will be in the form of a Gantt chart for readability and the user will then take the computed observation schedule and proceed to box 3.

Box 3 indicates that the observation schedule has been developed and the ground station will be controlled via manual input from the user to the pointing controller to point the antenna to the scheduled observation location.

Box 4 states that the ground station will collect the RF signals that have been emitted from the desired satellite. The antenna will be pointed at the emitting satellite and the antenna will pickup any incoming L1 band radio frequency signal that will then be processed with the SDR into a digital frequency signal that is uploaded to the software package.

Box 5 states that box 3 and box 4 will be repeated at least six times. The observation schedule detailed in box

2 will have already scheduled at least six observations and each repetition of box 3 and 4 will be for each of the scheduled observations (i.e. all scheduled observations will be executed). This ensures that we have 6 different frequency measurements to compute the estimated Doppler shift for a single satellite of interest. These 6 observations on an individual satellite will allow for 6 different Doppler shift calculations and these can be used to compute the 6 different orbital elements of the satellite's orbit. With 6 observations we get a set of 6 equations and these are used to determine the 6 orbital elements.

And finally, box 6 indicates that the software will then calculate the experimentally determined orbit of the satellite and then compare the experimental orbit with the initial TLE determined orbit. This was mentioned above for rationale in box 5, however box 6 is where this process is executed. The software used the frequency measurements to calculate the Doppler shift and the satellite's orbit. This is then compared to the initial truth data (TLE/Ephemeris) and a understanding of how well the scoring was applied can be had.

This CONOPS shows the observation of one satellite at a time, but it is important to keep in mind that the PROS8 system will have been able to observe multiple satellites within the given observation time frame window.

2.3. Project Deliverables

PROS8 has 4 main deliverables for the course; the software, ground station, RF research, and all observation data. However, the primary deliverables for Orbit Logic are the software, research, and data, as they are a software company and will seek to integrate RF capabilities into their existing Heimdall software package.

Software

- Radio Frequency Observation Scoring Software
- Radio Frequency Observation Scheduling Software
- Orbit Determination and Simulation Software

Ground Station

- Antenna Dish
- Antenna Pickup
- Pointing Controller
- Pointing Hardware
- Software Defined Radio
- Tripod
- Power Regulator
- GPS Disciplined Clock

Passive Radio Frequency Observation Research

Radio Frequency Observation Data

2.4. Functional Block Diagram

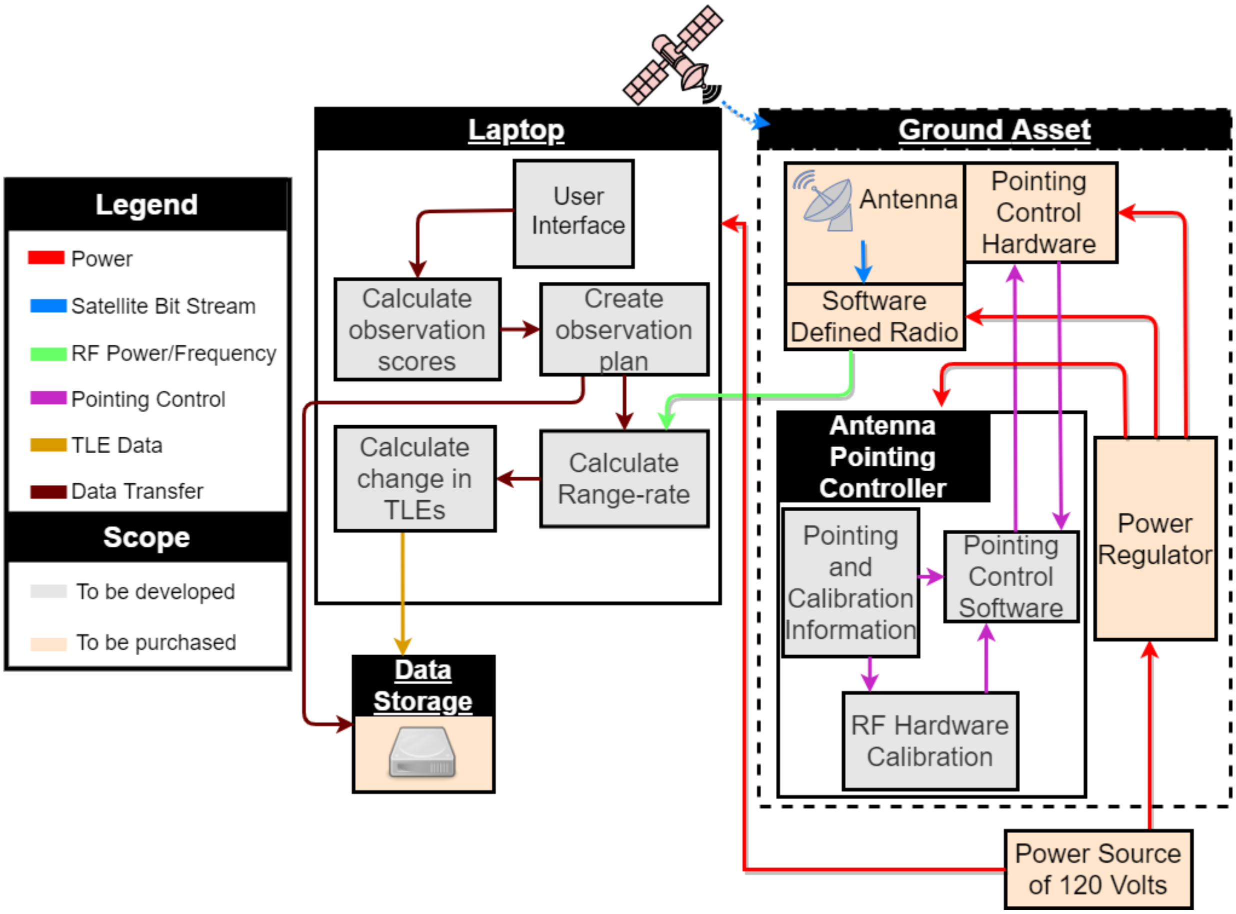

Figure 2. Functional Block Diagram

The functional block diagram is broken up into separate blocks for software (laptop) and hardware (ground asset). Starting with the ground asset block, the components included are the antenna, SDR, pointing control hardware (motor), pointing controller, and power regulator.

Beginning with the power flow (red arrows), the input to the system is the power from a standard wall outlet (120 Volts). A portion of this with power the laptop, and the rest will go through the power regulator which will distribute power to the pointing controller, pointing hardware, and SDR.

The pointing control flow (purple arrows) begins with calibration and pointing information inputted to the controller, and then feeds into the hardware calibration and pointing controller software. This software inside the antenna pointing controller will control the azimuth and elevation of the pointing control hardware. This system utilizes a feedback loop to ensure the hardware is moving to the correct location.

Lastly for the ground asset side is the satellite bit stream flow (blue arrows). The analog signal from the satellite is received by our antenna system and passed to the SDR. The SDR converts this analog signal to a digital signal representing the frequency and power of the satellite transmission and then sends it to the laptop (green arrow), where it is then used as an input for the PROS8 orbit determination software.

The laptop will contain the software components of PROS8. There will be a graphical user interface (GUI) where the user will interact with the software and be able to visualize the outputs. Following the software flow (dark red arrows), the user will input a list of satellites they wish to observe and the scoring software will score the observation opportunities of the satellites based on a number of parameters. The satellite to be observed will be chosen based on the scoring and then the scheduling software will create an observation plan for 6 or more observations to be taken (the reason for requiring 6 observations will be discussed later in the document) and this plan will be sent to an external data storage unit (orange arrow). Then the SDR-processed digital signals from the satellite will be inputted into the orbit determination software, where the range rate of the satellite will be calculated. Lastly, the range rate data will be used to calculate a refined orbit in the form of TLE data, which will be stored in the external data storage unit.

2.5. Functional Requirements

Signal Reception - FR 1: PROS8 shall Receive RF signals from satellites in various conditions, with multiple orbit geometries.

FR 1 comes from the need for PROS8 to receive signals from a satellite at different discrete times, which will correlate to different conditions. Additionally, PROS8 requires the ability to receive RF signals from different satellites which will have different orbit geometries.

Signal Processing - FR 2: Convert L1 band analog RF signal into a digital signal.

The signal emitted from a given satellite will be an analog radio frequency signal. The SDR will handle the signal processing and convert the analog satellite transmission into a digital signal. FR 2 is necessary for the project in order for the PROS8 software to read the frequency and power of the satellite transmission determine the orbit of the satellite.

Scoring and Orbit Determination - FR 3: The scoring software shall provide scores for each planned observation and update orbit estimates after observation.

This software package will take into consideration a number of variables that have an effect on the quality of the observation. These variables are discussed in length in the following sections. It will also be responsible for taking in the digital signal and calculating the Doppler shift to compare and update the orbital estimation.

Scheduling - FR 4: The scheduling software shall develop an observation plan for given satellites.

This software package will be responsible for creating a observation plan for a given list of satellites. This will utilize the results of the scoring software and develop a observation schedule that can be followed by the user when taking RF signal observations. This software will be able to be read easily by the user to ensure a efficient observation procedure.

Pointing Control - FR 5: Point system along an orbit path commanded by a manual input with 1° pointing accuracy.

FR 5 is crucial for the data collection ability of PROS8. The antenna must be able to receive the transmission of the satellite intended for observation and the pointing hardware will aim it based on a calculated azimuth and elevation for a satellite at a given time. The 1° was determined because it is well within the estimated half-power beamwidth of the PROS8 antenna system, and is large enough to account for errors in the TLE data used to calculate azimuth and elevation.

3. Design Process and Outcome

Authors: Mamdooh AlKalbani, Zachary Arbogast, Ryan Cameron, Zakariya Laouar, Colton Ord

3.1. Design Alternatives

Pointing Controls

The pointing controls dictate everything in regard to the movement of the antenna on the ground. This includes the actuation, resolution, and slew rates of the system used to point the antenna.

3.1.1. Actuation Method

In order to collect a downlink signal from a satellite, the ground station antenna must be able to re-orient itself to point at the right place at the right time. To do this, a set of motors must be attached to the antenna in order to provide enough torque to move the antenna to the desired location. For this purpose, two options were considered: Commercially available off the shelf systems (COTS), and an in-house custom design. A trade study was performed to determine the best option for the pointing control system.

Commercial Off the Shelf System

Commercially available antenna actuators are widely used by professionals, hobbyists, and even everyday commoners looking to watch satellite TVs. The capabilities of these COTS systems have been proven by users world wide. They are capable of actuating antennas with high precision along with relatively quick actuation speeds. Moreover, these actuators usually come with default controlling hardware and software. COTS systems are generally more reliable and accurate. However, the most prominent downside is the cost. Also, were a custom actuation software to be developed, integration could prove troublesome. The custom interface between an antenna and the actuator also need to be considered. Nevertheless, lots of COTS systems already come with pre-made mounts for particular antennas. Moreover, being able to purchase COTS systems may very well save the team a lot of time in terms of manufacturing.

In House Solution

Preliminary research has shown that homemade rotor assemblies have been attempted by many amateurs. Most have proven to be successful, albeit with limited capabilities. Given the skill sets possessed by members of PROS8, manufacturing said system is indeed feasible. Systems manufactured in house would most likely be cheaper than COTS systems. Another advantage is that in house systems can be made tailored specifically to the team's requirements. Also, since the controlling software is written from the ground up, there would be less issues in terms of having to interface with pre-existing software. However, making the system in question may require a significant amount of research, design, and iteration time. Moreover, the consistency of parts manufacture in house may not be as good as COTS systems. This could lead to significantly decreased capabilities.

Pros and Cons

Table 2. Pointing Controls Pros and Cons

Options	Pros	Cons
Commercial Systems	Higher Capabilities Reliable Comes with Controller Hardware and Software	Higher Costs Difficulty in Modifying Software
In House Systems	Easier Integration between Hardware and Software Cheaper More customizable	Requires Intensive Research and Designing Less Capabilities Comparing to COTS systems

Trade Study

This subsystem must satisfy two design requirements in order to be successful for the end design. Based on the pointing controls requirements, five metrics with their associated weights were decided upon to carry out the study. Those are shown below in Table 3.

Table 3. Pointing Controls Trade Study Metrics

Metric	Weight	Requirement	Description
Software Complexity	0.1	5.1	The software complexity metric evaluates how challenging the implementation of control algorithms and software will be with the actuation system the team decides to use.
Manufacturing Complexity	0.2	5.1	The manufacturing complexity metric is a measure of how challenging designing, machining, and assembling the actuation system will be.
Cost	0.4	ALL	This is a measure of how costly the system will be with respect to the allotted budget ($5000).
Precision	0.2	5.1	This evaluates how precise the pointing of the system will be and how much error (estimated) will be associated with the actuators.
Power	0.1	5.2	This is a measure of the estimate amount of power the system will consume with respect to the constraints in the requirements.

Next, for each of these metrics, a description and ranking was associated with each category. Those descriptions are shown in Table 4 below.

Table 4. Actuator System Rankings

Metric	1	2	3	4	5
Software Complexity	Nearly impossible to overcome; majority of time and resources to implement.	Drives the schedule, holds up production.	Presents only small issues that do not hold up production.	Minimal issues with software implementation.	Pre-packaged and ready-to-use without changes.
Manufacturing Complexity	Nearly impossible to overcome; majority of time and resources to implement.	Drives the schedule, holds up production.	Presents only small issues that do not hold up production.	Minimal issues with manufacturing production and assembly.	Pre-packaged and ready-to-use without changes.
Cost	Major design driver. Buying vastly affects the ability to purchase other items.	Drives the purchasers decision. Buying other quality products is still possible.	Failure in the system still allows for purchase of an extra.	Most other buying decisions don't affect the ability to purchase.	Easily purchasable no matter the other materials.
Precision	Pointing precision will not satisfy design requirement.	Depending on other structure, unlikely to satisfy design requirement.	With iteration of structure, will likely satisfy requirement.	With minimal effort, pointing system will satisfy the requirement.	Will satisfy requirement no matter the structure (not including oversized structure).
Power	Unlikely to leave enough power for the rest of the project.	Will be the largest design driver. Will be very challenging and time consuming.	With mild effort and iteration, likely to be solved.	Power draw is minimal. Not a design driver.	No matter the power draw of other components, this will satisfy the requirement.

Finally, the trade study was done and each system being traded was assigned a value for each category. Those values and the results are shown below in Table 5.

Table 5. Trade Study of Pointing Control System

Scoring Item	**Software Complexity**	**Manufacturing Complexity**	**Cost**	**Precision**	**Power**	**Total**
Weight	0.1	0.2	0.4	0.2	0.1	**1**
Commercial System	3	4	2	4	4	**3.1**
In House System	2	2	3	2	5	**2.7**

From this table, it is clear that the COTS is the best option for the PROS8 team to use. This was mainly due to the lack of complexity in both the software and the manufacturing which will save the team lots of time that will be used for the software development and testing.

Justification

Commercial off the Shelf System
Software Complexity - This system comes with a controller that takes the azimuth and elevation coordinates and sends the correct voltages at the right times to the motors to rotate them to the correct position. All feedback loops and control is included in the black box provided. On the downside, the team is unsure of whether there is any capability to connect any software to the controller that automatically feeds it azimuth and elevation coordinates. For this reason, the score was bumped down to a 3.
Manufacturing Complexity - All necessary motors and casing is directly provided with everything already assembled so there will be no need to change those components. The only thing that will need to be manufactured is a piece that connects the rotor to the antenna itself.
Cost - This system will cost close to 800 dollars which is a significant portion of the budget. While other high-quality products will still be purchased, it puts a strain on the amount of other products that can be bought.
Precision - There are two different variations of the COTS system that were researched, a high and low resolution version. Even the low resolution version has a degree accuracy of 0.5° which will satisfy the requirement.
Power - The power draw can be pulled from a wall outlet with the additional purchase of a linear power regulator that is also supplied. With that product there will be no problem pulling power from the wall outlet.

In-House Design
Software Complexity - The software complexity for the in-house system was given a score of 2 because everything will have to be designed in-house including the interfaces with the other systems as well as an effective control algorithm. This will add more software to build which will then start to dominate the schedule and hold up other parts of production.
Manufacturing Complexity - The manufacturing was also given a score of two because all of the motors and gear boxes would need to be purchased separately and interfaced in-house. Building a rotor system could then take up much of the schedule as well and combined with the software complexity, this will hold up the rest of the project as well.
Cost - As far as cost, this system would most likely cost less than the COTS system, which is why it was given a score of 3 and not 2. As in most things, the cost of all of the separate parts is cheaper than buying the pre-built system because labor costs are not involved.
Precision - This was given a score of 2 because there is no expertise on the team in building precision measurements. This process often involves high-quality manufacturing which is possible to do in-house, but would take up a lot of the schedule that needs to be utilized elsewhere. For this reason, building this in-house would most likely satisfy the pointing requirements.
Power - While both systems will most likely satisfy the design requirement for power, the in-house design is given a higher score because the power regulation system would be built into the design as opposed the COTS where a separate power regulator is needed.

Signal Reception

Antenna selection determines the conditions necessary for making observations. Antenna selection goes hand in hand with determining the kind of satellites we will observe. The items in this category were all picked because they are components needed to receive an RF signal and amplify it to desirable strength.

3.1.2. *Frequency Selection*

The frequency selection is based on which types of satellites we pick to score. There are very distinct advantages and disadvantages for each kind of bandwidth. For example if a larger frequency is chosen, the antenna will not need to be that large. This is due to the fact that as the frequency increases, the size of the antenna decreases. This means that the selection of a higher frequency is more desirable. The higher frequency range, is mostly used for communication satellites including GPS. The advantage of picking a lower frequency is that we would receive signals from mobile communication satellites[4]. The disadvantage is that there are not quite as many satellites as higher frequency bandwidths. Due to this fact, the frequency range under consideration will be L Band to Ka Band. This range is between 1 to 18 GHz. (A more detailed look at these bands is shown in Appendix A).

Summary

Frequency	Pros	Cons
L Band	Decent amount of satellites GPS satellites are constantly emitting	Lowest frequency
S Band	Some satellites are constantly emitting	Large amount of satellites
C Band	Has satellites that are constantly being emitted	Type of satellite is shared by two bands
X Band	Decent amount of satellites	Military band
Ka Band	Highest frequency	Large number of satellites Type of satellite is shared between two bands

Table 6. Pros and Cons Summary for Frequency Selection

3.1.3. *Antenna Design*

When deciding on the antenna design, it is important to consider how many antennas are required. The biggest drawback in having more than one antenna is the cost of getting two or more antennas. The price range of the antennas we consider makes it impractical to use more than one antenna.

Design features such as the antenna gain and directivity, the choice of buying vs manufacturing the antenna, and the effective necessary antenna area to achieve a desired acceptable antenna gain for the system, will depend on the frequency band we choose to operate on. We will consider Yagi-Uda, Logarithmic, Parabolic, Flat Panel, Hybrid Parabolic with Logarithmic Pickup, Hybrid Parabolic with Horn Pickup, and Antenna Arrays. (A more in depth look at the functionality of each of these is presented in Appendix B).

Summary

Antenna Design	Pros	Cons
Yagi-Uda	High directional Inexpenisve	Low gains if small High gains if huge Huge bandwidth means huge design
Logarithmic	High directional Higher bandwidth	Low gain Expensive
Parabolic	Least Complex Inexpensive High directional	Size depends heavily on gain and frequency
Flat Panel	Can be highly direcctional High gains	Expensive Narrow bandwidth
Hybird Para with Log	High gains Wide bandwidth High directional	Expensive Requires additional equipment
Hybrid Para with Horn	High gains High directional Reliable in bandwidth	Expensive Very complex
Antenna Array	Can be very directional High gains	Very expensive Requires additional equipment

Table 7. Pros and Cons Summary for Antenna Selection

3.1.4. Frequency Selection

Note that in order to begin the design requirements and other aspects of this project the trade study on the frequency selection had to be done first. This is why the design requirement 1.3 already states the bandwidth we are receiving from. The trade study is shown here.

Trade Study Metrics

Metric	Weight	Requirement	Description and Rationale
Type of Satellite in Band	0.3	1.3	The type of satellite in each band is very important. The reason it is important is due to the fact that it affects the type of antenna we will use and how our ground station is set up. If we chose a satellite in our band that has a weak signal, then we have to design a ground station that is able to receive that signal and amplifiy it to a desireable level. This is considered the middle weight since it is not as important as the frequency of their emissions but more important than the possible number of satellites in the band.
Is There Satellites That Constantly Emit	0.5	1.3	This is the heaviest item since it controls our testing in the future. If we chose a band that does not have a satellite that is constantly emitting, we then have to plan the testing around when each of the satellites will emit. It also affects the number of obvservation we can take.
Possible Number of Satellites in Band	0.2	1.3	The possible number of satellites is considered the lightest item since almost each band has a decent amount of satellites in it, it depends on if there are too many satellites near each other emitting at a close frequency.

Table 8. Metrics and Weights - Frequency Selection

Trade Study Quantification

Metric	1	2
Type of Satellite in Band	We are not allowed to receive signals	We are allowed to receive signals
Are There Satellites That Constantly Emit	There are no satellites that constantly emit	There are satellites that constantly emit
Possible Number of Satellites in Band	It may be hard to distinguish our desired satellite	We can distinguish our desired satellite

Table 9. Metric Values - Frequency Selection

	Weight	L Band	S Band	C Band	X Band	Ka Band
Type of Satellite in Band	0.3	2	2	2	1	2
Is There Satellites That Constantly Emit	0.5	2	2	2	2	1
Possible Number of Satellites in Band	0.2	2	1	1	2	1
Total	1	2	1.8	1.8	1.7	1.3

Table 10. Trade Study Results - Frequency Selection

Justification

L Band

Type of Satellite in Band: 2. This is not the band used for the military which means that we could receive those signals from the satellites. Some of the satellites may require additional paperwork or cost, but we can still receive the signals.

Are There Satellites That Constantly Emit: 2. This band is comprised of GPS and mobile phones satellites which means that most of the satellites are constantly emitting a signal.

Possible Number of Satellites: 2. This is the band that has the least amount of satellites in it, showing that there are not too many satellites emitting near the same frequency.

S Band

Type of Satellite in Band: 2. There are no restricted military satellites within this band meaning that we should be able to receive signals from most of the satellites.

Are There Satellites That Constantly Emit: 2. There are some weather satellites that are constantly emitting.

Possible Number of Satellites: 1. Since this band is comprised of mostly Earth observation satellites, and since that is the second largest type of satellite, it was given a 1.

C Band

Type of Satellite in Band: 2. Since satellite TV is within this band, it is possible to receive the signal. This might cost money to do so, but it is possible.

Are There Satellites That Constantly Emit: 2. In this band, there is satellite TV which is constantly emitting to deliver entertainment.

Possible Number of Satellites: 1. This band mostly has communication type satellites in it. Communication satellites are the highest number of satellites in orbit and thus might be hard to tell our satellite apart from others.

X Band

Type of Satellite in Band: 1. This is the band that the military primarily uses, which means that receiving signals from this band is unwise and may be prohibited.

Are There Satellites That Constantly Emit: 2. In this band, there are some satellites that are constantly emitting.

Possible Number of Satellites: 2. This band contains roughly 175 satellites which is the second to least number of satellites within a band.

Ka Band

Type of Satellite in Band: 2. There are not a lot of military satellites within this band. This means it is possible to receive signals from this band.

Are There Satellites That Constantly Emit: 1. In this band, there are mostly communication satellites. Most of the communication satellites do not need to be constantly emitting.

Possible Number of Satellites: 1. This band faces the same issue as the C band. Since there are a huge number of communication satellites, it might be hard to tell our satellite apart from others.

3.1.5. Antenna Design

Each of the antennas listed above had its own overall advantage and disadvantage. The key items being looked for in this project are the HPBW, gain value, bandwidth, overall size of the antenna, the frequency capability, and the price. All of these were picked because all of them except two can be derived from our design requirements.

Trade Study Metrics

Metric	Weight	Requirement	Description and Rationale
HPBW to Size	0.3	1.1	HPBW is very important in order to get an accurate reading of the satellite. If there are two more or satellites where we are scanning, then with the given HPBW, distinguishing them will be doable. This design factor depends on the size of the overall design and must be taken into consideration. This is why it is weighted heavier than most other.
Gain to Size	0.35	1.2	For the software to be able to receive the desired signal, we need to have enough gain to counter the losses that naturally occur when a satellite transmits its signal. The gain can be increased with amplifiers, but we must have a base gain on our antenna to properly receive the signal. In some designs the gain depends on the size of the antenna and should be taken into consideration. The gain is weighted as a heavier item since it affects how well the signal is received.
Bandwidth	0.15	1.3	The bandwidth of the antenna determines what kinds of signal we can receive and thus what kinds of satellites we are able to receive from. Most antennas are able to be bought or built at a certain bandwidth, but how broad the bandwidth depends on the antenna. For these reasons the bandwidth is weighted as a lighter item.
Frequency Capability	0.05	1.3	Most of the antennas are able to be designed to work at any frequency, but not all. This is why this it is a lighter item, since most can handle any frequency, and there are few that can't. Also for this project we want our antenna to work at higher frequencies.
Price	0.2	N/A	Since we are given a set budget and are required to stay within that budget, we have to always take it into consideration. The price is weighted as the middle item since the price of the antenna will be one of the more expensive options but it is not necessarily the most expensive.

Table 11. Metrics and Weights - Antenna Selection

Trade Study Quantification

Metric	1	2	3	4
HPBW to Size	Unable to produce desired HPBW at any size	Able to produce desired HPBW with designs bigger than given storage	Can produce desired HPBW with designs that can fit into the given storage	Can produce desired HPBW or better with designs that can fit into the given storage
Gain to Size	Cannot provide desired gain regardless of size	Size is too big to store in given storage for gain	The size fills in the given storage with little room for other items	The design size for the gain can fit into the given storage with other items
Bandwidth	Can only receive one frequency	Can only receive within one bandwidth	Can receive signals from two different bandwidths	Can receive signals from three different bandwidths
Frequency Capability	Can only work in one particular bandwidth	Works only with low frequnicies	Works only with high frequenices	Works at all frequenices
Price	>$4000	$3999-$3000	$2999-$2000	<$2000

Table 12. Metric Values - Antenna Selection

	Weight	Yagi-Uda	Log	Parabolic	Flat	Hybrid Para (Log)	Hybrid Para (Horn)	Array
HPBW to Size	0.3	4	4	3	3	3	3	3
Gain to Size	0.35	1	1	3	3	3	3	3
Bandwidth	0.15	3	4	2	2	4	3	3
Frequency Capability	0.05	3	4	4	3	4	4	4
Price	0.2	4	3	4	4	4	1	1
Total	1	2.65	2.75	3.15	3.1	3.35	2.65	2.65

Table 13. Trade Study Results - Antenna Selection

Justification

Yagi-Uda
HPBW to Size: 4. The overall design on a Yagi-Uda is meant to have a good directional with a small number of elements.
Gain to Size: 1. Yagi-Uda itself does not produce a high gain and would require amplifiers to counter this issue. It is possible to add more elements to increase that gain, but that would require a lot of elements.
Bandwidth: 3. For the Yagi-Uda, the bandwidth is determined by distance between each element. This means that depending on the bandwidth desired, it can be capable of receiving signals from two different bandwidths.
Frequency Capability: 3. The frequency a Yagi-Uda design can receive depends on the spacing between each element. This means that it can work at low frequnicies but it would be a large antenna.
Price: 4. The overall design of a Yagi-Uda is fairly simplistic which makes it easier to produce more so than other antennas. This makes it a more inexpensive option.

Logarithmic Periodic
HPBW to Size: 4. The HPBW is coupled with the gain. To keep the good directional of the design, the gain is relative low. If the HPBW is sacrifice instead, the desired gain would still be hard to accomplish without any external equipment.
Gain to Size: 1. The reason for such a low score is described above. To have good directionality and a reasonably size antenna, the gain must be small.

Bandwidth: 4. The bandwidth of a logarithmic antenna is determined by a logarithmic function of the distance between element. This allows for a greater bandwidth since the overall length of the antenna will reasonable.
Frequency Capability: 4. The antenna has no issues working with low or high frequencies.
Price: 3. Preliminary research of different kinds logarithmic periodic antenna show that they can be quite expensive.

Parabolic
HPBW to Size: 3. Figure 52 shows what the HPBW is for various diameters. Though not shown in the plot, the necessary diameter for our design requirement is less than 2 meters.
Gain to Size: 3. As shown in figure 51 to get within our desired gain we would need a dish that is approximately 2 meters or less.
Bandwidth: 2. The design of the parabolic dish to meant to be great at receiving a certain signal range and not much more. If frequenices outside of the bandwidth are used, their gain and directionality are not as good as if it was in the bandwidth.
Frequency Capability: 4. If the antenna is designed properly to work at a certain frequency range it will work in that range.
Price: 4. The simplistic design allows for parabolic dishes to be made easily and makes them relatively cheap.

Flat Panel
HPBW to Size: 3. The directionality of a slot antenna is considered good without changing much of the base model.
Gain to Size: 3. The gain depends on the number of overall slots in the flat panel antenna. This can greatly increase the size of the antenna.
Bandwidth: 2. The bandwidth depends heavily on the size of each slot in the antenna which forces the antenna to a narrow bandwidth to receive any signal well.
Frequency Capability: 3. It possible to use them at a lower frequency, but is not common place. The reason the size of the slot determines what kind of signals can be received, and lower frequencies have large wavelengths.
Price: 4. This is considered one of the least expensive options to receive signals.

Hybrid Parabolic Dish with Logarithmic
HPBW to Size: 3. The main idea behind the hybrid parabolic dish with logarithmic antenna is to combine the best qualities of both antennas. In this case the directional of the parabolic dish is used.
Gain to Size: 3. The gain to size ratio follows the same idea as stated above, this hybrid gets the best parts from each antenna. In this case it is the gain of the parabolic antenna.
Bandwidth: 4. The bandwidth is determined by the logarithmic antenna since it is the focal point of the parabolic dish.
Frequency Capability: 4. Both designs do not have a problem working at any frequency range as long as it is designed for that range.
Price: 4. The price of this hybrid is approximately the same as just adding the parabolic dish to the logarithmic antenna.

Hybrid Parabolic Dish with Double-Ridged WaveGuide Horn
HPBW to Size: 3. The HPBW is dependent on the design on the parabolic dish aspect of this hybrid.
Gain to Size: 3. The gain from the double-ridge is low, but when it is coupled with the parabolic dish, it increases the overall gain to the gain of the dish.
Bandwidth: 3. The bandwidth of this antenna depends heavily on the ridges of the horn. If the ridges are made large enough, it can receive a large bandwidth of signals.
Frequency Capability: 4. The design of this antenna has no issue handling either low or high frequencies.
Price: 1. The idea is to add the price of a parabolic dish with a double-ridge waveguide. The issue is that most double-ridge waveguides are already outside of the budget.

Antenna Array
HPBW to Size: 3. The directionality requires more elements to increase the HPBW, but the overall design can be made to have a decent directional.
Gain to Size: 3. The base model of an antenna array has a high gain, but it may not be our desired gain. To increase the gain we would need an array that is quite large.
Bandwidth: 3. It is possible to have a wider bandwidth for an antenna array, but the overall design would become more complex than it currently is.
Frequency Capability: 4. The antenna array can be designed to work in any frequency range.
Price: 1. Due to the complex design of an antenna array, it is very hard to manufacture it and is very expensive.

Signal Processing

When designing a radio system for an RF application, the main area of exploration is how much software should the radio system include. The Software Defined Radio (SDR) has been growing in popularity for various uses including the smart phone. The SDR has the capability to replace hardware radios in various applications including signal processing and filtering. The design options below, highlight the pros and cons of a hardware heavy radio system and a software heavy radio system.

Summary

Options	Pros	Cons
Hardware Defined Radio	Works out of the box	Expensive Non customizable Closed Source (hardware)
Software Defined Radio	Open Source (software and hardware) Cheaper More customizable	Requires more user input (time and effort)

Table 14. Possible systems for radio communication

3.1.6. Radio System

Trade Study Metrics

Metric	Weight	Description and Rationale
Price	0.5	This project has the potential of being a highly expensive project and possibly out of budget. PROS8 must be extra cautious of price with any of the project components and reserve most of the money for the more critical elements like antennae
Bandwidth	0.2	While the bandwidth of the radio is important to consider, PROS8 is willing to narrow down the bandwidth of interest to save money and make it easier for the team
Customization	0.3	It's important to be able to customize the various functionalities included in the radio system such as demodulation, signal processing etc.

Table 15. Metrics and Weights - CPU

Trade Study Quantification

Metric	1	2	3
Price	>$2500	$2500-$500	<$500
Bandwidth	Low Frequency (10kHz-2GHz)	High Frequency (9GHz-13GHz)	Ultra Wide Band (3-10GHz)
Customization	No parts can be customized	At least 2 parts	4+

Table 16. Metric Values - CPU

	Weight	Hardware Radio	Software Defined Radio
Price	0.5	1.5	2.5
Bandwidth	0.3	2.5	1
Customization	0.2	1	3
Total	1	1.7	**2.15**

Table 17. Trade Study Results - CPU

Justification

Hardware Radio
Price: 1.5 - Hardware radios vary in price yet still are generally more than $2500 in price. The price depends generally on the bandwidth it supports and more specifically the receiver hardware that allows for the wider bandwidth.
Bandwidth: 2.5 - Hardware radios can support a wide variety of bands because of the advanced receiver design found in many hardware radios.
Customization: 1 - Hardware radios are notoriously not flexible in terms of adding, removing, or replacing radio communication components within the system.

Software Defined Radio
Price: 2.5 - The increased effort in development and support of SDRs has decreased the price more and more over time. The cheapest RTL-SDR can be purchased at only $10. For more features SDRs can get fairly expensive.
Bandwidth: The low price of SDRs comes at a disadvantage of bandwidth. SDRs are mostly meant for amateur radio communication with common bandwidths ranging from 0-2 GHz.
Customization: The term "Software" in the name gives away that SDRs are extrememely customizable and require only a laptop and any OS (Windows, MAC OS, Linux).

Resulting Design

3.1.7. Central Processing Unit (CPU) (No Trade Study)

A CPU can be bought by itself and then be put into a motherboard along with all the other parts required to build a PC or it can come with when you buy a single-board computer or laptop. This was the deciding factor when considering the CPU.

Single-Board Computer

Single-board computers, such as the Raspberry Pi or Tinker Board, are an appealing option for this project. This is due in part of their small size (about the length of a credit card), lower power consumption, and the price range[6]. Yet in order to use them they need additional parts, such as keyboard, monitor, and operating system. All of those are considered inexpensive because in this project does not require complex items. Rather it needs those items can be basic. Another drawback is how powerful the CPU is or if the single-board computer will have enough storage capacity[34].

Figure 3. Raspberry Pi 4[25]

Laptop

A laptop is the first choice for this project. The ability to pick which processor, how much RAM, and storage capacity is the main reasons why the laptop is a desirable option. Being able to pick all of those options means that the team is able to pick the processor that will be the fastest. This will bring with it the drawback of how costly the price of a laptop can be. Another drawback is the power consumption of the laptop. Though with a laptop, it will already come with all necessary parts to start functioning.

Figure 4. Laptop[27]

Summary

CPU	Pros	Cons
Single-Board Computer	Small Inexpensive Low power consumption	Required additional equipment Less RAM Less clock speeds Small storage capacity
Laptop	More RAM Higher clock speeds No additional parts Huge storage options available	Expensive High power consumption

Table 18. Pros and Cons Summary for CPU

3.1.8. Data Storage (No Trade Study)

Internal Storage

An internal storage device means that all the data stored can only be accessed in a few cases. Those cases are when an external storage drive is attached and all data is transferred to it, taking the entire CPU system with you when wish to access the data, or uploading the data to a cloud storage. Two of the cases outlined above requires that the data be sent to an external storage device, while the other option means that our processor will begin to slow down since it is multitasking doing post-process of the data and the tracking. With an internal storage device, our CPU could have the potential to have a Solid State Drive which can boost the overall performance of our ground station.

Figure 5. Internal Storage[37]

External Storage

With an external storage device, we are able to take the data with us as we allow the ground station to continue its process. The external drive also have the ability to be a Solid State Drive but this is considered a more expensive options compared to the alternates of a USB drive or a SD card. The external storage will also be required to be compatible with the CPU we chose. If it is not, extra adapters will be required to interface with the CPU.

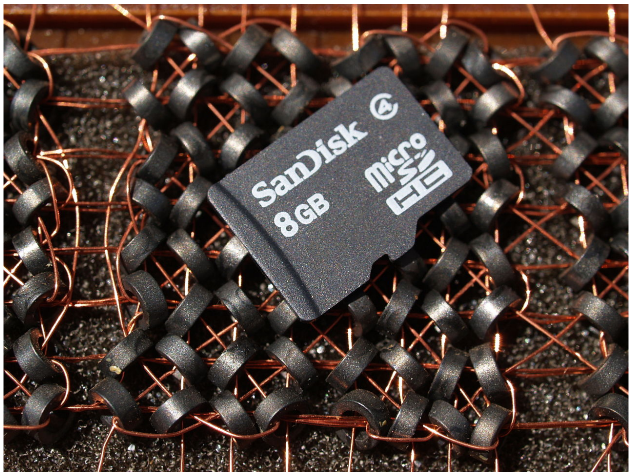

Figure 6. SD Card[32]

Data Storage Summary

Most options today for a CPU have at least one USB port on them and have built in storage. Therefore the best options is to use both, internal and external storage options. By doing both, we are able to to still have a fast internal data storage that comes with our CPU and then we are able to take the data with us with the external drive. As long as a common external storage device is chosen, the need for an adapter will depend entirely on the CPU selection, and if an adapter is required, most are relatively inexpensive.

Orbit Determination

One of the deliverables for this project is to output an updated orbit for the satellite. It is assumed, that to update the orbit of the satellite, that we have an initial guess of the satellite's orbit. Two methods will be considered, Doppler shift and Triangulation. (A more in depth look at these methods is presented in Appendix C).

Summary

Orbit Determination	Pros	Cons
Doppler Shift	One ground station Less expensive Known equations	Need at least six measurements
Triangulation	Needs three mesasurements Known equations	Needs two ground stations Expensive Double most equipment (Less storage space)

Table 19. Pros and Cons Summary for Orbit Determination

Trade Study Quantification

Metric	1	2	3
Number of Measurements	No number of measurements can do orbit determination	Six measurements are required to do orbit determination	Three measurements are required to do orbit determination
Number of Ground Stations	No number of ground stations is able to do orbit determination	Two or more ground stations are needed to do orbit determination	One ground station is needed to do orbit determination
Required Information of Satellite	Cannot do orbit determination with any known information about the satellite	Need to know the frequency of the satellite and its orbit	Need to know only the satellite's orbit

Table 20. Metric Values - Orbit Determination

	Weight	Doppler Shift	Triangulation
Number of Measurements	0.3	2	3
Number of Ground Stations	0.6	3	2
Needed Information of Satellite	0.1	2	3
Total	1	2.6	2.4

Table 21. Trade Study Results - Orbit Determination

Justification

Doppler Shift
Number of Measurements: 2. It has been shown through research, that in order to accurately update the orbit of the satellite, at least six Doppler Shifts need to be calculated.
Number of Ground Stations: 3. Doppler Shift requires that the system receive a signal and calculate the Doppler Shift. This means that as long as an antenna can receive the signal, it can calculate the Doppler Shift.
Required Information of Satellite: 2. Since Doppler Shift is based on the change in frequency, the system requires knowledge of the original frequency to calculate the change.

Triangulation
Number of Measurements: 3. With triangulation, it will only give the position of the satellite. This means that to update the orbit, Gibb's method can be used since it can calculate the orbit from positions, but Gibb's method needs three positions to do.
Number of Ground Stations: 2. To use triangulation, at least two positions must be known and when applied to this project, the two known positions have to be of the ground station.
Required Information of Satellite: 3. If the frequency of the satellite the system is looking at is known, it is a lot easier to confirm that that satellite is the desired satellite. This does not mean that the frequency needs to be known. As long as the system is able to recieve the signal, an FFT will be able to discern the peak of the satellite.

3.2. Requirements Flow-Down

Functional Requirement (FR) 1: Signal Reception.

PROS8 shall Receive RF signals from satellites in various conditions, with multiple orbit geometries given below…

- Elevation between 15° and 30°.
- Within 15° of the Sun.
- 0-30% cloud coverage.
- 70-100% cloud coverage.
- 2 hours before sunrise and sunset.[3]

In order to verify the quality of the predictive scoring software, many orbital geometries under potentially non-ideal conditions must be observed with the antenna subsystem. PROS8 will receive RF signals from at least one satellite in each of the following categories.

Design Requirement (DR) 1.1: Half-Power Beam-Width (HPBW) of the Receiver will be $3^\circ \leq \theta \leq 15^\circ$ for the worst case L-band bandwidth (1-2Ghz).
In order to successfully make a precise enough observation to distinguish between two satellites that are within 15° of each other emitting on the same frequency. Due to this we want our HPBW to be small enough to be able to distinguish the two. We also need our HPBW to be much greater than our pointing accuracy, to guarantee that we are able to view satellites when commanded. PROS8 will undergo bench tests with known emitters. We will analyze the radiation pattern to confirm a HPBW.

DR 1.2: The receiver will have an ideal gain of $G_A \geq 15\ dBi$ for the worst case for the L-band bandwidth (1-2Ghz).
Based on link budget analysis, we will need this gain for adequate signal to noise ratios in the worst case L-band (1-2Ghz) bandwidth. PROS8 will undergo bench tests with known emitters. We will analyze the power received to confirm a minimum Gain of 15 dBi.

DR 1.3: The receiver will be able to receiver frequency within the L bandwidth.
For this project to work, we need to be able to receive signals from the satellite(s) in question. The antenna subsystem will resolve L-band transmit signals during a bench test.

FR 2: Signal Processing

Convert L1 band analog RF signal into a digital signal

In order to calculate doppler shift for orbit determination, the signal from the satellite must be processed and a transmit frequency must be measured. When the ground station is in view of the satellite, the SDR will attempt to capture the satellite signal and the SDR Spike software will recognize a peak center frequency from the satellite transmitting within the L1 band (GPS satellites).

DR 2.1: SDR must have a resolution bandwidth (RBW) of at most 2 kHz

Along the satellites orbit, the lowest Doppler shift detectable occurs approximately 5 degrees off of nadir to the ground station which results in about 2kHz Doppler shift. The SDR will need to be operating in narrow band mode to be able to have a resolution bandwidth within 2kHz. The Signal Hound SDR chosen for this project has a resolution bandwidth down to 30 Hz which is more than sufficient.

DR 2.2: SDR must have a frequency range of at least 1 GHz—2 GHz

Our primary target satellites are GPS satellites which generally transmit in the 1-2GHz range. The SDR chosen for this project has a frequency range of 1Hz-4.4GHz which is more than sufficient.

FR 3: Scoring and Orbit Determination

The scoring software shall provide scores for each planned observation and update orbit estimates after observation

DR 3.1: The software shall take frequency measurements as its input and calculate Doppler shift
DR 3.2: The software shall calculate orbit estimates based on Doppler shift
DR 3.3: The software shall output scores for pre-planned scoring opportunities

Scoring and Orbit Determination are the two main components of this project. In this project, the customer seeks to develop scoring algorithms for scheduling purposes when using passive RF systems. The customer also seeks to develop algorithms for the determination of satellite orbits. Passive RF systems offer a large amount of stealth for covert operations. Unlike RADAR or LiDAR, passive RF requires no active transmission. This implies that the observations can be done covertly, without the satellite knowing that it is being tracked. In order to achieve this goal, a scoring system needs to be developed based on factors involved in measuring orbit via a passive system. Also, since the team only has a limited amount of budget, a Doppler shift based orbit determination system is chosen. This leads directly to DR 4.1 and 4.2. The scoring function directly leads to DR 4.1. All in all, all of the requirements have to be met in order for the project to succeed.

FR 4: Scheduling

The scheduling software shall develop an observation plan for given satellites.

DR 4.1: The software shall give the orbit of a satellite within a given timeframe.
The function requirement stems from the need to have a plan to tell the hardware when and where to look to receive a satellite's signal. The contents of the observation plan include the location of the satellite for each viewing and when each viewing needs to take place. None of this can happen unless the orbit of the satellite is known and can be propagated until the first viewing for the satellite. With the knowledge of the orbit, the observation plan knows where and when to look at to see the satellite, but it does not know how long it needs to look at the satellite.

DR 4.2: The software shall calculate the time between each viewing to be made.
The length of time for the observation is what drives the second design requirement. To ensure the system is efficient and knowing that to update the orbit of the satellite at least six viewings are required, the system needs to calculate the maximum time in-between each viewing. Having the maximum time in-between each viewing helps the system know how long an observation will be and the time to wait between each of its viewings in the observation.

DR 4.3: The software shall determine if an observation can be made.
Having the total time for an observation and the orbit of the satellite still is not enough information to fully make the observation plan, there needs to be a check to see if an observation can be made. The decisions if an observation can be made comes from the scoring software. If an observation can be made, the orbit is known, and the total time for

the observation has been calculated for a satellite, all required information is available to begin making an observation plan.

FR 5: Pointing Control

DR 5.1: Point system along an orbit path commanded by a manual input with 1° pointing accuracy

In order to reliably receive signal from the satellite, the antenna system has to maintain its pointing within the half-power beam with of the transmitting satellite. Test - Measure the actual pointing of the antenna via a laser pointer or other methods, and compare said pointing information to the encoder output provided by the antenna actuation system.

DR 5.2: The pointing system must have a slew rate of at least 1.2 deg/s

In order to maintain antenna pointing at satellites in various orbit regimes, the antenna must be actuated at a high enough angular rate. For a 200 km altitude circular orbit, the speed of the satellite is approximately 7788 m/s. This correlates to an angular rate of 1.2 deg/s. Achieving this requirement would allow the system to follow any satellite in any orbit. Test - A bench test will be conducted with the assembled system. An angular position command will be given to the system, and the time required for the system to actuate will be recorded. Angular velocity will then be determined by dividing the know actuation angle by the time required to actuate.

DR 5.3: The system shall run on 120V, 60Hz power

The testbed will run on power that comes from a standard wall outlet due to convenience. Each component will be tested for power draw.

3.3. Resulting Design

Pointing Controls

The pointing controls subsystem needs to be able to move the antenna to the correct location at the correct time given by the software package designed. This process includes controlling the motors to tell them where to go, verifying that the motor has enough torque to actually rotate the system, mounting the antenna to the motor, and connecting the logarithmic pickup to the parabolic dish. Combining all of these aspects will satisfy the necessary requirements for the pointing controls subsystem.

3.3.1. Controlling the Motor

The SPX-02 package includes both a motor system (Fig. 7) and the accompanying controller (Fig. 8).

Figure 7. Motor

Figure 8. Controller

Both of these systems will be purchased from RF Ham Design[24]. The controller takes in azimuth and elevation coordinates that are given manually, then internally decides the correct voltage levels to send to the motor and it sends the correct signals to move the motor to the desired azimuth and elevation. This system is calibrated by giving it a true north measurement as well as an altitude measurement of where it is on the ground.

3.3.2. Tripod

The tripod selected to hold both the pointing control hardware and antenna system is the STR-01 from RFHamdesign.

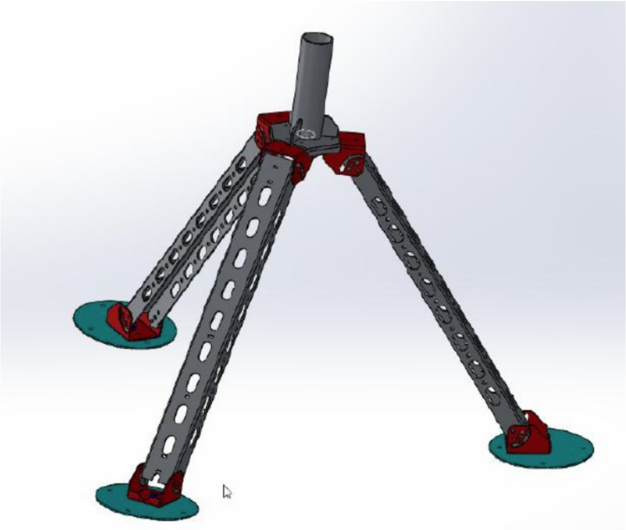

Figure 9. STR-01 Tripod Model from RFHamdesign

The STR-01 is a portable tripod designed for the SPX series pointing control hardware, allowing for easier assembly with the selected SPX-02 hardware than any other available tripod. The STR-01 height is adjustable and ranges from 0.67m to 0.83m. It weighs 11 kg and is designed for a max load of 30 kg, which is greater than the expected weight of the pointing controller and antenna system combined.

3.3.3. Mounting Antenna to Motor

Next, the rotor assembly needs to be able to connect to the antenna itself, and while a mounting bracket is supplied with the purchase of the SPX-02, it does not directly connect to the antenna. So, a mounting piece was design that connects to both the SPX-02 and the antenna bracket. A dimensioned drawing of that piece is shown below.

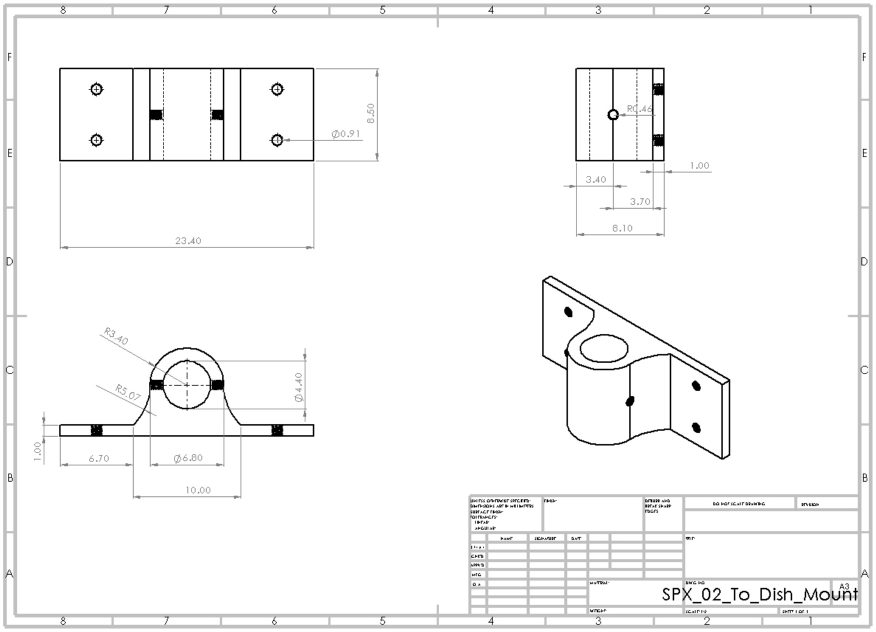

Figure 10. Mounting Piece from Rotor to Antenna (cm)

This piece was designed with the dimensions of the supplied mounting bracket in mind (shown in Fig. 11.

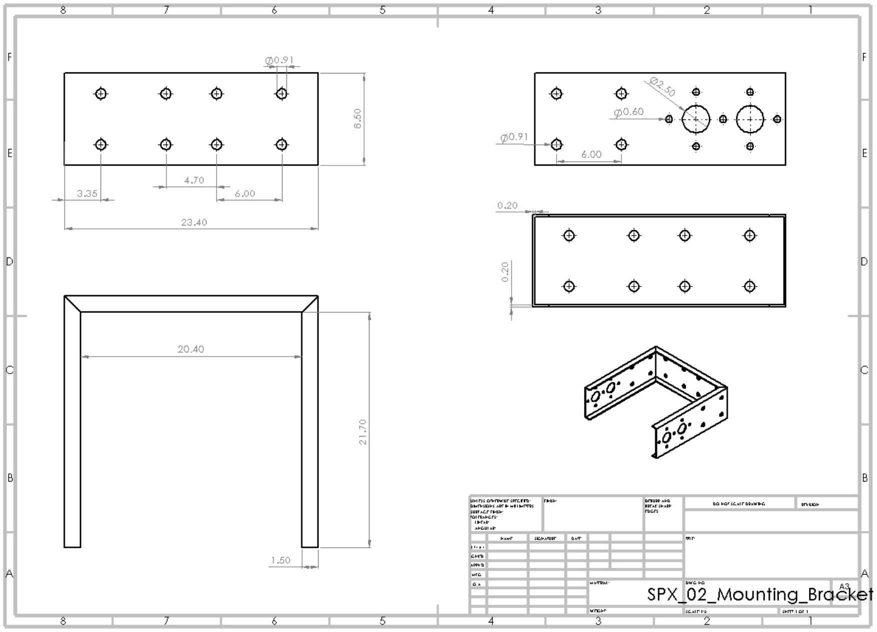

Figure 11. Supplied Mounting Bracket (cm)

These two pieces connect through four 1/4"-20 screws that thread through the holes in the custom mount piece and secured through nuts on the backside of the supplied mounting bracket. Then, the antenna dish comes with a bracket that holds a 1 5/8" pipe on the back of the dish. That pipe is meant to thread through the main hole in the custom mounting piece. A 1/4"-20 hole will be threaded through the pipe as well so that a bolt can be threaded through the whole assembly, secured in place with another nut. Through these measures, the rotor assembly will be secured to the antenna dish so that it can be moved to the correct position at the correct time.

3.3.4. Mounting Logarithmic Pickup to Antenna

The antenna comes with a mounting apparatus called an LNBF mount that has a diameter of 40mm. An example of that type of mount is shown below.

Figure 12. LNBF Type Mount

Then, the logarithmic pickup is designed to be able to screw into a tripod, so there is a threaded hole in the center of the pickup. With that information, an interface was designed in order to mount the pickup onto the antenna dish using the LNBF mount. The mechanical drawing of that piece is shown below.

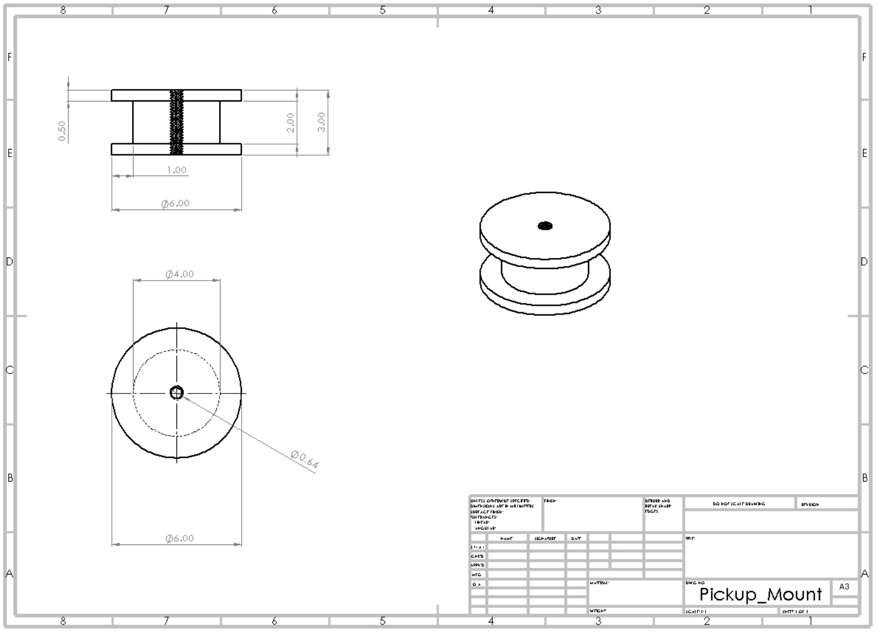

Figure 13. Pickup to Antenna Mount (cm)

A screw matching the thread of the logarithmic pickup can be used to connect the pickup to the piece which will be clamped into the LNBF clamp on the antenna. In this fashion, the pickup will be secured in the correct place to receive the signal focused by the dish.

3.3.5. *Torque Verification*

Next, it was necessary to ensure that the SPX-02 has enough torque to move the antenna at a large enough slew rate to get ahead of a satellite. These calculations were done using a worst case scenario of slewing to meet a satellite in LEO (400km). One of the lowest objects in the sky, and therefore the fastest, is the ISS which moves across the sky in approximately 6 minutes or 360 seconds. Assuming a total slew angle of 180°, that yields a slew rate of $\omega_{LEO} = .05\frac{deg}{s} = .008727\frac{rad}{s}$. So that is the slew rate the motor needs to be able to obtain. This is governed by the dynamic torque equation:

$$\tau = I\alpha \tag{1}$$

Here, I is the inertia about the axis of rotation while α is the angular acceleration of the object being rotated. The inertia matrices for each component about the axis of rotation were found using the mass properties feature of Solidworks. A few assumptions went into these calculations as well though. For the supplied mounting bracket, it was assumed that it was made of Aluminum 6061. With the specified material, Solidworks can calculate the volume and mass distribution of the piece. Note that for all components, the density is assumed to be uniform throughout. With this information, the ouput Solidworks gives as the inertia matrix taken at the center of mass of the component about the rotation coordinate system is:

$$\mathbf{I}_{bracket} = \begin{bmatrix} 0.0043 & 0 & 0 \\ 0 & 0.0026 & 0 \\ 0 & 0 & 0.0062 \end{bmatrix} kg * m^2$$

Next, the inertia of the custom dish mount needed to be calculated. This was done using the designed dimensions shown in Fig. 10 to calculate a volume and using the material properties of Aluminum 6061 as that is the material the piece is being manufactured from. This material was chosen because of its lightweight properties and easy machineability. With that information, the output inertia matrix in the same coordinate system is:

$$\mathbf{I}_{mount} = \begin{bmatrix} 0.0036 & 0 & 0 \\ 0 & 0.0014 & 0 \\ 0 & 0 & 0.0035 \end{bmatrix} kg * m^2$$

Lastly, the inertia of the dish assembly needed to be estimated. The team was not able to find exact dimensions on the size of the dish so it was estimated using the specifications found on the retailer's website[33]. The known variables were the approximate dimensions and a total mass of 12 lbs (or 5.443 kg) plus the mass of 0.27 kg for the logarithmic pickup came out as $m_{dish} = 5.713kg$. Assuming a constant density, Solidworks calculated an inertia matrix of:

$$\mathbf{I}_{dish} = \begin{bmatrix} 0.7910 & 0 & 0.4780 \\ 0 & 1.5879 & 0 \\ 0.4780 & 0 & 1.0966 \end{bmatrix} kg * m^2$$

Since these three separate inertial matrices were taken about the same coordinate system, the total resulting matrix is simply the sum of the three individual parts.

$$\mathbf{I}_{tot} = \mathbf{I}_{bracket} + \mathbf{I}_{mount} + \mathbf{I}_{dish} = \begin{bmatrix} 0.7989 & 0 & 0.4780 \\ 0 & 1.6312 & 0 \\ 0.478 & 0 & 1.1456 \end{bmatrix} kg * m^2$$

With this information, the inertia about the rotation axis needs to be defined. As a result of the coordinate system that was defined arbitrarily (but aligned with the rotation), the axis of rotation was the y-axis. Therefore, a single inertia about the y-axis is defined using Eq. 2.

$$I = \omega'_{rot} * \mathbf{I} * \omega_{rot} = 6.5348kg * m^2 \tag{2}$$

It is important to note here that a safety factor of 4 was multiplied into the final inertia value in order to account for the possible error in the estimated dimensions as well as the assumptions of constant density made throughout the calculations. Now that a final inertia about the rotation axis was calculated, Eq. 1 is used with the max torque of 80Nm supplied by the rotor, to find a maximum angular acceleration of $\alpha = 12.26\frac{rad}{s}$. Just from looking at this, it is seen that the motor has more than enough capability to move the antenna. But, to carry out the calculation, Eq. 1 can be integrated to find an expression for the slew rate.

$$\omega = \tau t \tag{3}$$

This is done using a starting slew rate of $0\frac{rad}{s}$ which is the worst case scenario. Then, plugging in the value for ω_{LEO} that needs to be met, it is found that the desired slew rate is met in a time of $t = 0.00071s$. This demonstrates that the motor has the capability to effectively rotate the dish in a suitable amount of time.

3.3.6. Power Regulation

The last thing that needs to be checked for the pointing controls subsystem of PROS8 is effective power regulation into the controller. It was mentioned to us by members of the ARGUS team in 2018-2019 that the controller can be shorted out if plugged directly into a wall outlet. To alleviate this concern, a power regulator module made for the SPX-02 controller will be purchased. This is the PW-32015 PSU that will also be purchased from RF Ham Design[23]. Using this module, any concerns regarding the regulation of the power going into the controller are alleviated.

Signal Reception

The purpose of the antenna subsystem is to guarantee two things. First, the radio frequency transmissions from the satellite we wish to observe are well above the noise floor when it reaches our orbit determination software (i.e is the signal we wish to view is more powerful/visible than the background noise we observe/create within our antenna subsystem). Second, the power of the signal is high enough that we can convert the signal from analog to digital (i.e. the ADC conversion has enough bins for adequate signal resolution). There are many factors to consider when designing for these objectives, and the following sections outlines each one independently.

3.3.7. Choice of Satellite

We looked at two different satellite constellations for our detailed design, Iridium and GPS. Iridium is a satellite constellation which provides call and messaging services globally for private subscribers. GPS is a public service which provides location information globally. In order to satisfy our FR 1, we need to be able to predict reliably when satellites we observe will be transmitting, as well as have an antenna subsystem capable of viewing the transmitted signal above the noise floor. The transmitted signal must also be at a predictable frequency and power. We chose to observe GPS satellites due to their consistent emissions and open source software for acquiring their signals.

3.3.8. Antenna Component Overview

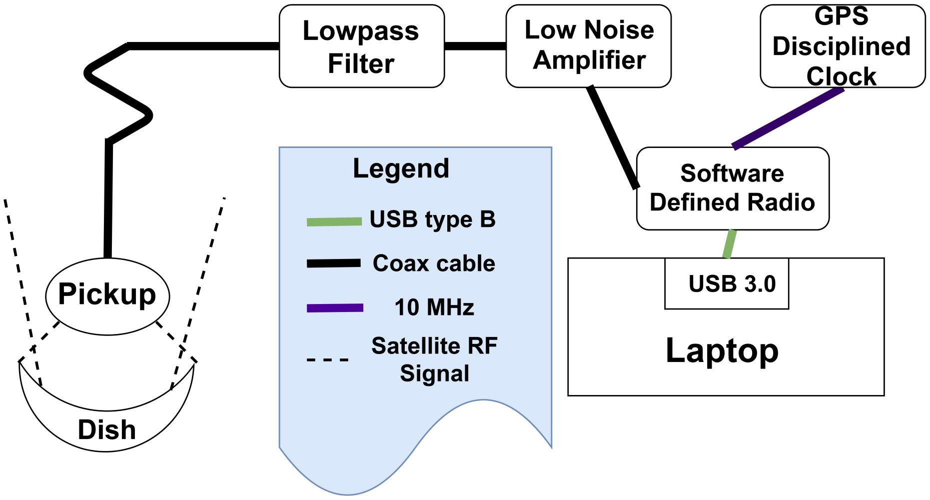

Figure 14. Antenna subsystem functional diagram

This section gives a detailed rationale for each component we've chosen to make up our antenna subsystem shown in figure 14. The first is the dish…

In order to satisfy our gain and half-power beam-width requirements of ≥ 15 [dBi] and $3 \leq \theta \leq 15$ respectively (from Design Requirement (DR) 1.2 and 1.3) we must remain in the design space defined by the following equations…

$$G_A = (\frac{\pi D_A}{\lambda})^2 * e_A \implies (\frac{\pi D_A}{\lambda})^2 * e_A \geq 15 \tag{4}$$

$$\theta = \frac{70\lambda}{D_A} \implies 3 \leq \frac{70\lambda}{D_A} \leq 15 \tag{5}$$

The dish we chose was the GeoSatpro 90CM Offset Satellite Dish and is shown to fall within our design space because of $G_A = 20.4$ $[dBi]$, and $\theta = 14.81°$

Figure 15. GeoSat Pro

The next design choice we had to make was for the linear pickup. We went against our logarithmic trade study after discussion with Professor Akos, a member of CU Boulder's faculty and an expert in Space Situational Awareness. We chose the Taoglas TG.08 shown in figure 16.

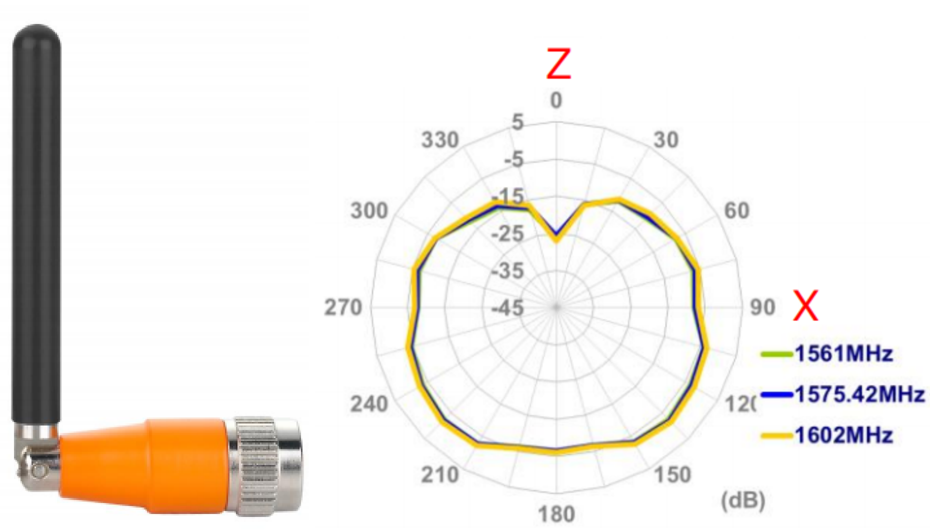

Figure 16. Logarithmic Pickup (left), Radiation pattern (right)

The next component is our Low Pass filter, the SLP-1650+. We chose this model to prevent any aliasing outside of L band in the software filters we plan to use when we process our signal. The design choices made here were to minimize noise added to the system by minimizing the insertion loss or power loss ratio of output power to input power (≤ 3 $[dBW]$ worst-case scenario).

Figure 17. Low pass filter

After our Low Pass filter comes the Low Noise Amplifier (LNA) which we chose the ZX60-53LNB-S+. The design choices here were to maximize gain while minimizing the noise figure within the L band. We also need to guarantee that our signal power is high enough to be converted to digital, and this amplifier does this.

Figure 18. Low noise amplifier

In between the LNA and SDR we have inserted a GPS disciplined oscillator (GPSDO). This will be used as an external frequency reference in order to guarantee that we can measure doppler shifts of 1 Hz. It also requires an antenna pickup for which we will purchase another Taoglas TG.08.

Figure 19. GPS Disciplined Oscillator

Finally comes our SDR, the USRP b200mini. This was chosen due to its high sample rate, and resolution bandwidth (which falls under DR 3.2)

Figure 20. Software Defined Radio

All connections between each listed component in Fig 14 are a coax cable with the proper female to male SMA connections respectively with the exception of the GPS DO which has a BNC-SMA coax cable.

3.3.9. Calculation of the Noise Floor

Now that our satellite has been chosen we can calculate the noise floor. The power of the noise floor is given by the equation

$$\begin{aligned} P_N &= kT_sB\ [W] \\ P_n &= 10log_{10}(k) + 10log_{10}(T_s\alpha) + 10log_{10}(B)\ [dBW] \end{aligned} \tag{6}$$

where $k = 1.38064852 * 10^{-23}$ $[\frac{m^2kg}{s^2K}]$ is Boltzman's constant, T_s $[K]$ is the noise temperature of the system, and B $[Hz]$ is the bandwidth of the signal we are looking at. T_s or noise temperature represents the temperature a resistor would have to be in order to introduce the same amount of noise into the signal as your system does[5]. It is calculated using the following equation

$$^{[26]}T_s = T_a\alpha + T_0(1-\alpha) + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1G_2} + \dots \tag{7}$$

T_a is the temperature of the antenna and represents all the noise introduced to the system before the signal reaches the antenna (i.e. atmospheric, sun, nearby transmitters). T_0 is a reference temperature (usually 290 $[K]$) that serves to convert power loss into noise increases. α is the line loss of the system and represents the ratio of the total output power to input power from the dish to the laptop. The sum following the first two terms ($T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots$) represents cascaded gain stages next to the laptop input, in our case it will be the noise temperature of a Low Noise Amplifier (given by $T_1 = T_{LNA} = (F_{LNA} - 1) * T_0$ and $G_1 = G_{LNA}$ where F_{LNA} is the noise figure of the Low Noise Amplifier), and the noise temperature of our Software Defined Radio (given by $T_2 = T_{SDR} = T_0(F_{SDR} - 1)$).

T_a is the sum total of all sources of noise present in the atmosphere at our selected center frequency (1621 $[MHz]$).

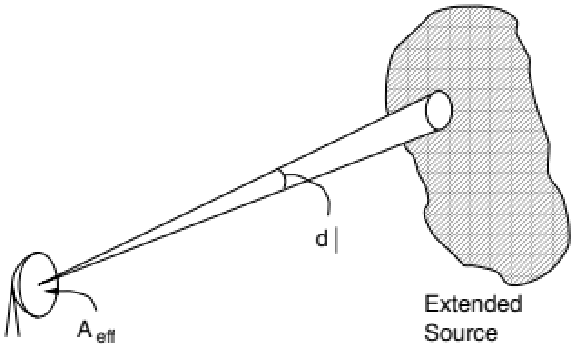

Figure 21. Antenna noise temperature from external sources

These values were provided by the International Telecommunications Union's (ITU) recommendation's from this year.[8] We assumed a worst-case scenario in order to satisfy our Functional Requirement (antenna pointing into the moon, on the horizon) according to our functional requirement 1. The sources of noise we considered are given below…

- Galactic (Background Radiation)
- Residential (Local Emitters)
- Cosmic (Background Radiation)
- Moon
- Atmospheric

Using the ITU recommendation paper[8], $T_{Gal} = 10^{\frac{(52-23*log_{10}(f))}{10}} * T_0 = 2.03$ $[K]$ where f $[MHz]$ is center frequency, $T_{Res} = 10^{\frac{(76.8-27.7*log_{10}(f))}{10}} * T_0 = 19.03$ $[K]$, $T_{Cos} = 2.7$ $[K]$, $T_{Moon} = 280$ $[K]$, and $T_{Atm} = T_{mr} * (1 - 10^{\frac{-A}{10}}) + 2.7 * 10^{\frac{-A}{10}} = 249$ where $T_{mr} = 275$ $[K]$ is a reference temperature recommended for clear and rainy days, and $A = 10.2$ $[dBW]$ is the atmospheric attenuation at the center frequency.[28]. The sum of all these external sources of noise is $T_a = T_{Gal} + T_{Res} + T_{Cos} + T_{Moon} + T_{Atm} = 843$ $[K]$.

α is calculated by summing up the total power losses of each component from the dish to our laptop as ratios of output power to input power in dB. We then convert back to a linear scale. The losses of each component shown in figure 14 is given by $L_r = 4 * L_{Con} + L_{Coax} + LLPF = -7.2dB$ where L_{Con} is the loss of each SMA interface connecting components to one another, L_{Coax} is the loss of the 10 [m] coax cable, and L_{LPF} is the loss of the Low Pass filter we chose.

T_{LNA} is given by the equation $T_{LNA} = (F_{LNA} - 1) * T_0 = 84$ $[K]$ where F_{LNA} is a component specification (typical values are ≤ 1.5). G_{LNA} is also a component specification.

T_{SDR} is given by the equation $T_{SDR} = (F_{LNA} - 1) * T_0 = 226$ $[K]$. Unfortunately, our chose of SDR did not list F_{LNA} as a technical specification, so we used the technical specification of a similar SDR (LimeMicro LMS7002M). This term of the equation is divided by the gain of the LNA (245) so the error from this approximation is more or less insignificant.

These calculations yield a system noise temperature of 480 $[K]$. Since we are considering GPS our bandwidth is 15 MHz. This yields a noise floor power of $P_n = -129.9$ $[dBW]$.

3.3.10. Calculation of the Signal Power

The calculation of the received signal power involves summing the total losses and gains of the signal on its way from transmission to the laptop. Those are as follows...[a]

- Effective Isotropic Radiated Power of the Transmitter (Satellite)
- Propagation Losses (spreading of the signal over distance)
- Pointing Losses (where in the field of view of the receiver is the transmitter)
- Polarization Losses (electro-magnetic orientation of the transmitted signal and the receiver)
- Atmospheric Attenuation (absorption of the signal by the atmosphere)
- Ionospheric Attenuation (absorption/reflection of the signal by the ionosphere)
- Gain of the Receiver
- Processing Gain
- Line Losses

The $EIRP = 26.5\ [dBW]$ was determined by obtained the transmitter specifications from the Federal Communications Commission (FCC).

Propagation Losses are defined by the equation $L_P = (\frac{4}{\lambda})^2\ [W]$ or $L_p = 10log((\frac{4}{\lambda})^2)\ [dBW]$ where d is the distance between transmitter and receiver, and λ is the wavelength of the transmitted signal. $L_p = -184.5\ [dBW]$.

Pointing loss is negligible for our antenna subsystem due to the pointing accuracy of our mechanical system being far less (0.5 << 14.81), but due to the beam roll off of the transmission antenna (i.e. GPS) we expect a maximum loss of $L_{pt} = -3\ [dBW]$ due to the fact that the half-power beam-width of GPS encompasses the entire earth.

We assume a worst-case scenario polarization loss of $L_{pol} = -3\ [dBW]$.

Atmospheric attenuation for this wavelength is -10.2 dbW, and Ionospheric losses are -0.8 dbW. Therefore $Latm = -11\ [dBW]$.[28]

Both the gain of our receiver and line losses of our system have previously been defined to be $G_A = 20.4\ [dBi]$ and $L_r = -7.2\ [dBW]$.

Processing gain is unique to GPS satellites as their transmission codes are known beforehand. It is given by $G_{proc} = 10log(\frac{1.023x10^6}{50}) = 43\ [dBW]$ where the code is transmitted over a 1 MHz bandwidth at a bit rate of 50 bps.

The signal power at the laptop is therefore $P_s = EIRP + G_A + G_{proc} + L_p + L_{pt} + L_{pol} + L_{atm} + Lr = -118.8\ [dBW]$. The required signal to noise ratio is 3 dBW (in order to determine half-power of the signal) and with 2 dBW margin our over signal to noise margin is 6.1 dBW.

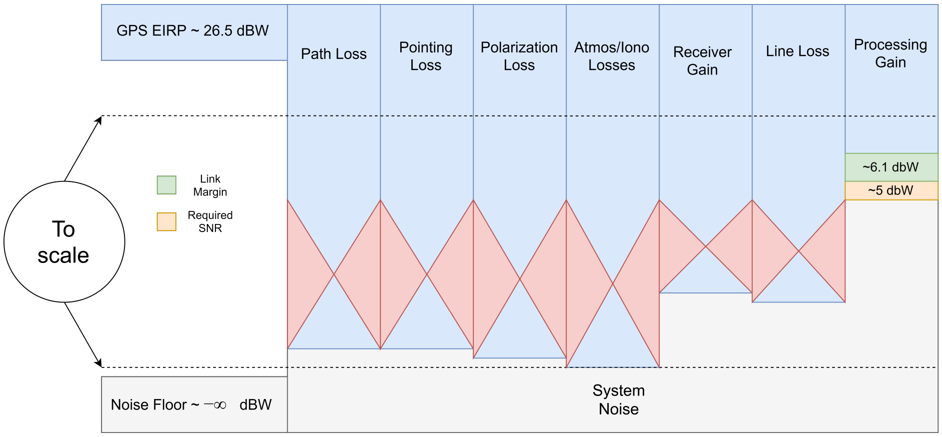

Figure 22. Signal to noise ratio

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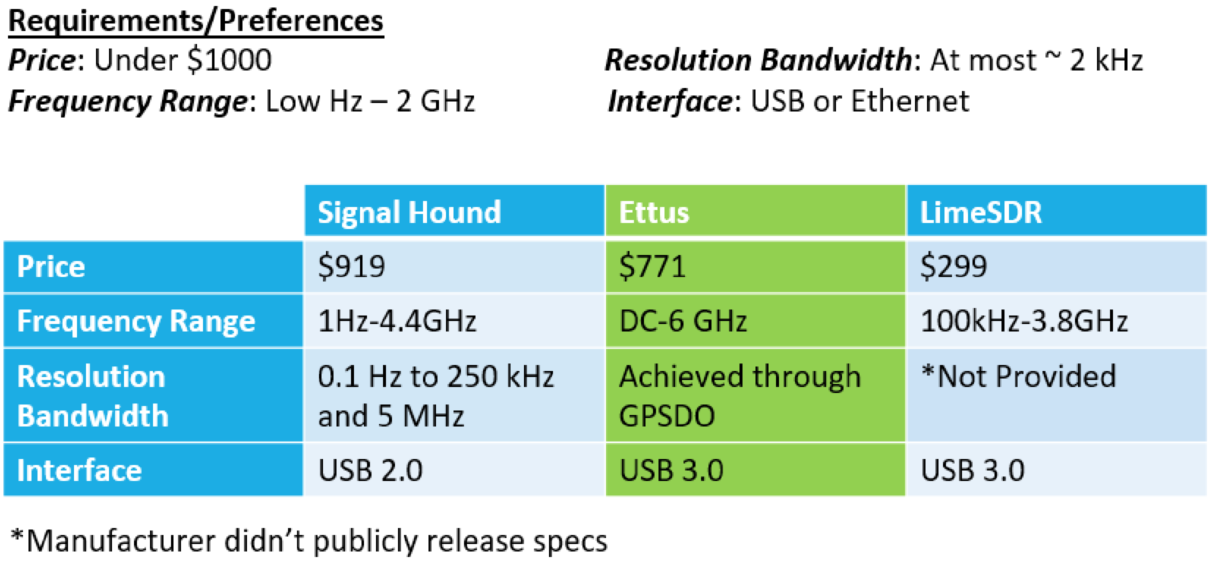
[a] Gain of the Low Noise Amplifier is left out for these calculations as it affects the power of the noise floor and signal equivalently and therefore has no effect on the signal to noise ratio

This guarantees the first condition for our antenna subsystem is met, but the second condition depends on the ADC conversion method of our SDR. Unfortunately, our chosen SDR does not list specifications for a minimum detectable signal, however using a similar model (as with the noise temperature, the LimeMicro LMS7002M) we estimate that our minimum detectable signal is -100 dBW. Since the gain of our chosen LNA is 23.9 dBW, this means that our signal will be seen by our SDR with a power of -94.9 dBW and a margin of 0.9 dBW. In the case that our estimates were off, we can also add gain stages to our system without affecting the signal to noise ratio, and with each LNA costing around $100, this mitigation effort is well within our budget.

Signal Processing

3.3.11. Software Defined Radio Specifcations

The signal processing related requirements are defined by FR 2: Convert L1 band analog RF signal into a digital signal and the associated design requirements of 1: SDR must have a resolution bandwidth of at most 2kHz and 2: SDR must have a frequency range of at least 1 GHz—2 GHz. The table below shows how the Ettus B200 SDR meets these requirements in comparison to competing SDRs. The resolution bandwidth requirement for the SDR is met indirectly however. The Ettus SDR fulfills this requirement through the input of the GPS disciplined oscillatior (GPSDO) described in section 3.3.8, and shown in figure 19. In brief, inputting the GPSDO into the SDR will ensure that Doppler frequency measurements of 1 Hz could be achieved.



Requirements/Preferences

Price: Under $1000

Frequency Range: Low Hz – 2 GHz

Resolution Bandwidth: At most ~ 2 kHz

Interface: USB or Ethernet

	Signal Hound	Ettus	LimeSDR
Price	$919	$771	$299
Frequency Range	1Hz-4.4GHz	DC-6 GHz	100kHz-3.8GHz
Resolution Bandwidth	0.1 Hz to 250 kHz and 5 MHz	Achieved through GPSDO	*Not Provided
Interface	USB 2.0	USB 3.0	USB 3.0

*Manufacturer didn't publicly release specs

Figure 23. Specifications of Baseline SDR Choice

The Ettus USRP B200 SDR is shown below in board form. The decision was made to purchase the SDR with an enclosure for safety and protection of the hardware.

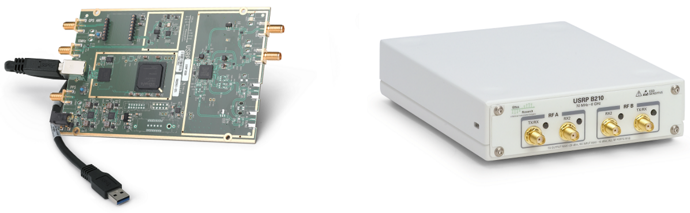


Figure 24. Ettus USRP B200 SDR

3.3.12. *GPS Receiver Specifications*

Apart from the hardware Ettus SDR, an internal software receiver is required to full process the GPS signal into a stream of digital, quantized data samples. The GNSS software defined receiver (GNSS-SDR) provides this functionality. It is a comprehensive open source software capable of performing signal acquisition and tracking of the available satellite signals, decoding the navigation message and computing the observables needed by positioning algorithms. Since the PROS8 solution is only concerned with calculating doppler shift frequencies, the GNSS-SDR will only be used to acquire the signal and by extension measure the received transmit frequency of the satellite. The GNSS-SDR software is organized into user and programmer friendly software blocks which allows the user to choose which part of the signal processing to perform. The block diagram below shows the high level operation structure of the GNSS-SDR.

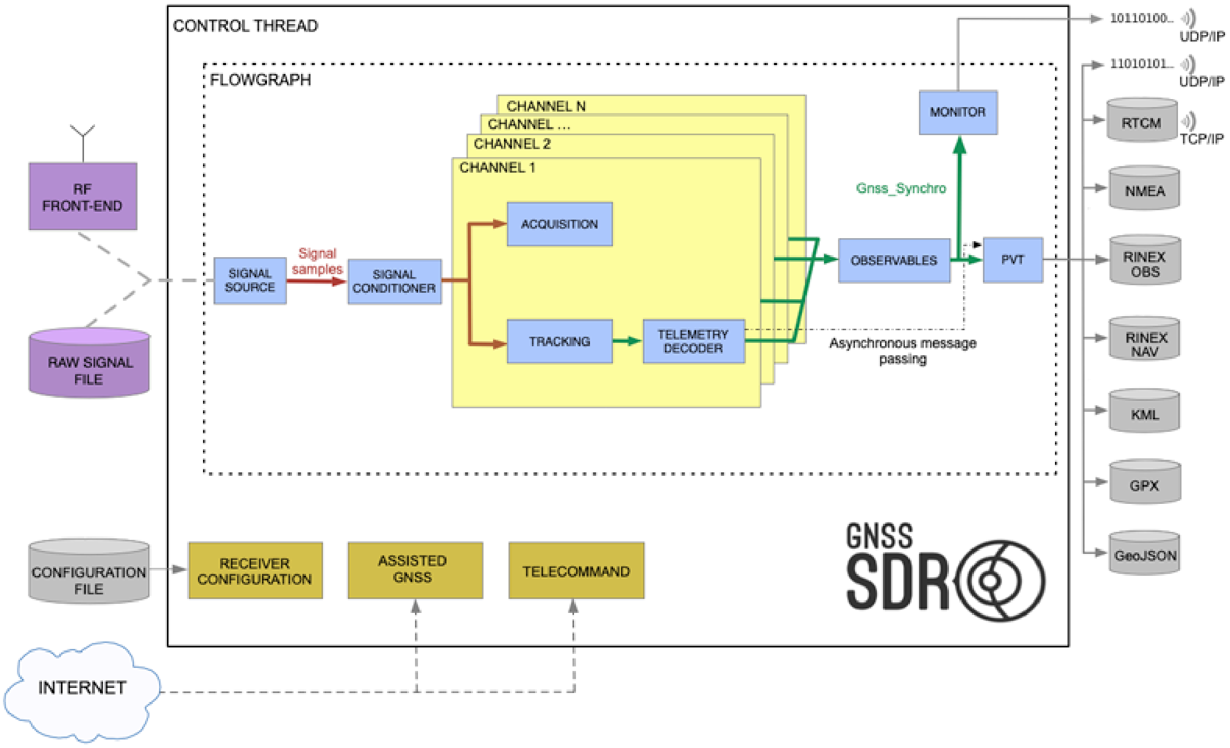


Figure 25. GNSS-SDR Block Diagram

3.3.13. Software Defined Radio/ GNSS-SDR Operation

The hardware Ettus SDR functions as the "air-to-computer" interface for signal processing applications. The SDR will perform the downshifting, filtering, and conversion of the signal to the digital domain. The software GNSS-SDR will then be performing the baseband processing including the tasks described in 3.3.12. In order to make the Ettus SDR and the GNSS-SDR compatible, the USRP hardware driver must be installed[13]. From there, the GNSS-SDR can identify access the SDR in a linux environment[11]. Then a varity of GNSS-SDR configurations can be run through the creation of a configuration file.

The figure below shows the high level signal processing flow from signal reception, through the hardware signal processing components, and finally to the software side of the SDR to obtain the actual transmit frequency and use the value in the orbit determination software.

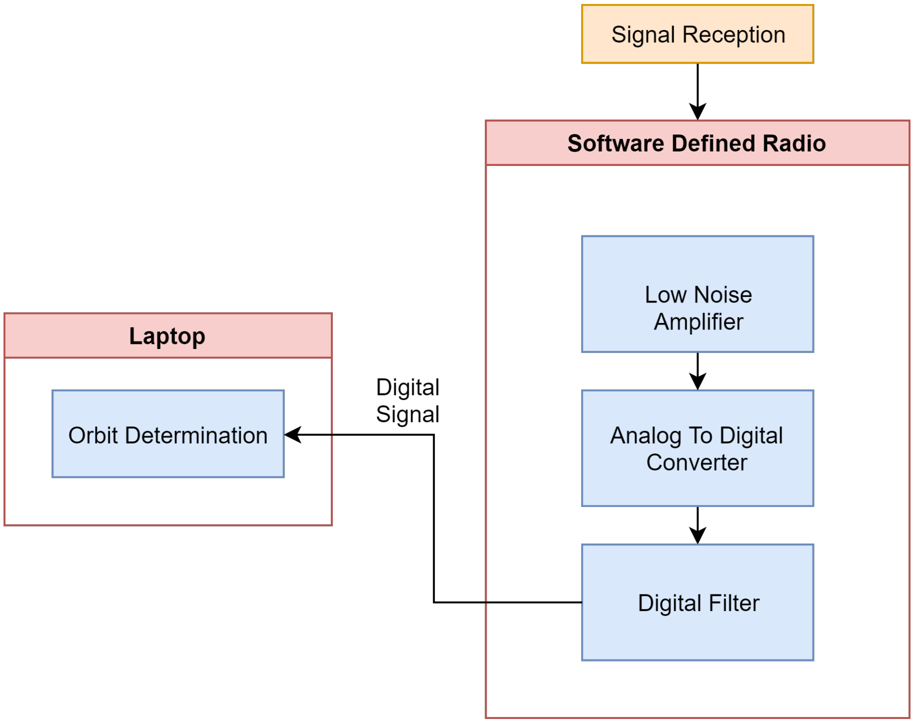


Figure 26. SDR Flow Diagram

Software

3.3.14. Scoring Software

The purpose of the scoring software is to provide each planned observation with a score for scheduling purposes. Scoring has multiple factors that can affect the score of the observation. Within scoring, there is a priority factor. Priority, itself, is not a part of the scoring formula, but a deciding factor for when two observations have the same score. Priority is a value ranging from one to a hundred. This measure of priority is determined by multiple factors, such as but not limited to the amount the customer paid for the service. Nevertheless, the priority does not reflect the actual scheduling order, the scoring formula does. The first factor in the scoring formula is determined by the signal-to-noise (SNR) ratio of the system. This is a zero or one multiplier. When the simulated SNR is lower than the system threshold, a multiplier of 0 is given. In other words, if the system cannot see the signal, there is no point in observing the satellite. On the other hand, when the simulated SNR is higher than the threshold, a multiplier of 1 is given. The second factor in the scoring formula is visibility. Visibility is defined as the possibility of having direct line-of-sight (LOS) with the target. This determines whether if the receiver can physically see the target. With most high-frequency bands, the Electromagnetic (EM) waves do not bend within the atmosphere. Therefore, the receiver can only see the target when there is direct LOS. Consequently, a multiplier of 0 is given to those views without direct LOS. Using the simulation developed, it is determined that the steady-state convergence error decreases as Doppler shift increases. Consequently, higher the Doppler shift, more useful the data. However, higher Doppler shift also means longer distance for the signal to travel through. Therefore, elevation also plays a role. To maximize scores for higher elevations (stronger signal), a ratio is used for elevation scoring.

$$Score = A * \frac{currentelevation}{maximumelevation} \tag{8}$$

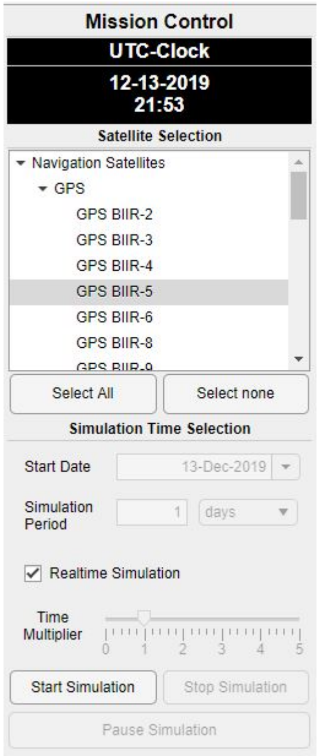
To maximize scores for higher Doppler shift, another ratio is used

$$Score = B * \frac{CurrentDopplerShift}{MaximumpossibleDopplershift} \tag{9}$$

Coefficient A and B are determined experimentally. These are values with a sum of 100, representing the maximum possible score. The score of an observation is the sum of all the scores of the required viewings. Note that parameters such as minimum elevation and SNR can be included as scoring factors. However, they are not currently implemented into the design.

3.3.15. Simulation Software

The Simulation software is a custom made software package that allows the full propagation of any number of satellites from their TLE data as seen in figure.27, which is then used to simulate an RF signal propagating down to the ground station. This software performs three main tasks which are to propagate the TLE data for the selected satellites, to realistically simulate a propagated RF signal received by a ground station and to also assist the scheduling and scoring software in performing their intended tasks by supplying them with the necessary propagated satellite data. This is achieved by taking in the current TLE data, and then acquiring the necessary current and forecast information for the atmospheric conditions, geometric and Orbital mechanics to simulate expected received signal that the ground-station would see.



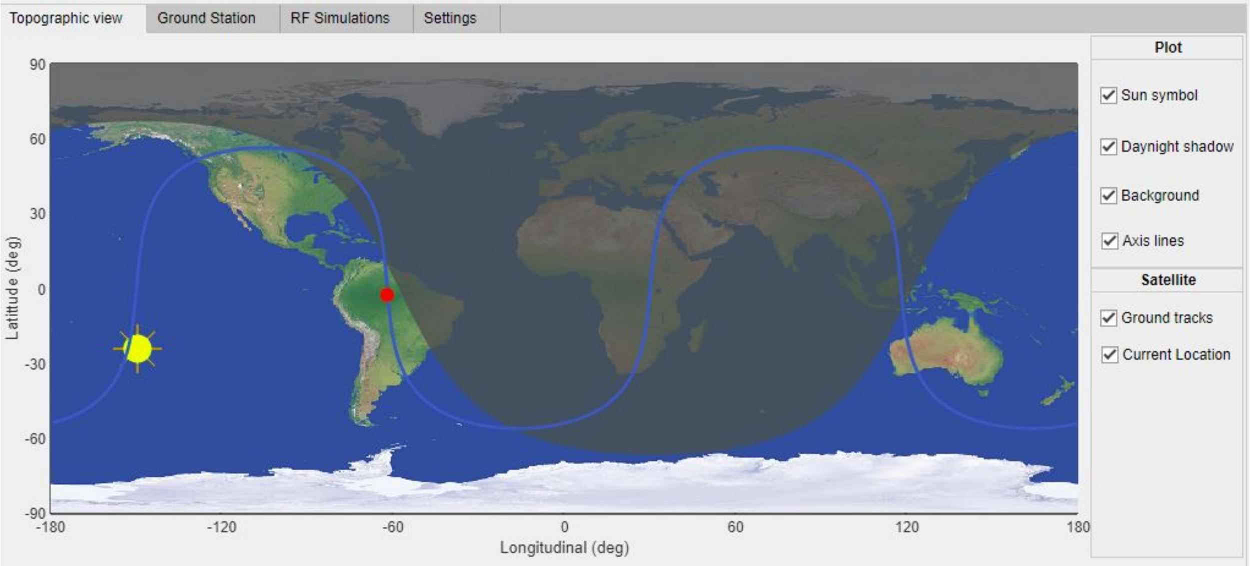
Start Date 13-Dec-2019

Simulation Period 1 days

☑ Realtime Simulation

Figure 27. The Mission control for the simulation software.

Unfortunately, the main obstacle encountered for the orbital parameters is that the TLE data can be incorrect for certain satellites due to their Orbital mechanics resulting in their orbital decay, this is a situation that is highly possible because the TLE data is only true at the specific time the orbital elements were measured at which is called the epoch time. To resolve this anomaly it was necessary to design a propagation method that would attempt to detect for an orbital decay by looking at the long and short term deep-space effects, and if found would adjust the TLE data as needed to accurately reflect the decay in satellite's orbit. This has been achieved and validated successfully with real-time online satellite tracking sources. The process of how this is done is by treating the orbit as a non-ideal system and to iterate through the orbital mathematical model until the orbital elements converge to a corrected current time solution.



☑ Sun symbol
☑ Daynight shadow
☑ Background
☑ Axis lines
☑ Ground tracks
☑ Current Location

Figure 28. Propagation part of the Simulation software

Figure.28 shows how once the solution for the orbital parameters has converged the next step is to use those corrected orbital elements for the propagation of the orbit of the selected satellite to obtain a more accurate and reliable orbital information which does include the orbital elements and satellite's position and velocity per second and actual ground track.

Figure 29. The Ground-Station view for the simulated satellite.

This propagated data is then used to further simulate the motion of the desired satellite relative to a ground station and to convert the information into now a useful slant-Range, azimuth and elevation information as shown in figure.29. The next step in the software is to detect and extract only the desired information when the satellite is only in view of the relative ground-station that is specific to an exact latitude/longitude and elevation. A second programmed function is then used to find the local position of the sun relative to the ground station, then all the gathered information is then fed into the second derived mathematical model for the RF-propagation until the solution converges to a second solution that is closer to the real-life conditions that would affect the radio signal. This realistic simulated radio signal is then used in the last part of the propagation software to help test and develop the scheduling and scoring software. Also, certain required data can also be saved and used separately for the scheduling and the scoring software to perform their tasks.

3.3.16. Scheduling Software

The TLE data, provided by NORAD, is populated using a model called Simplified General Perturbations 4 (SGP4). This model is also able to use the TLE data and propagate the satellite's orbit. This is the method used in the scheduling software to propagate the orbits. The SGP4 model is not the only model meant for near-Earth satellites. Another possible solution is the SGP8 model, but it is considered less compatible with the TLE data. To use the SGP4 model for this project, it needs the TLE data and the time until the desired timeframe since its last epoch and it can then give the propagated orbit.

With the orbit propagated to the start of the desired timeframe, the scheduling software still needs to calculate the time in-between each viewing and create the observation plan. In order to calculate the time in-between, the orbit must be known and propagated until the start of the given timeframe. Then to make an observation plan, the calculation of the time in-between each viewing is required. The time in-between helps with the creation of the observation plan since it calculates the total time needed for each observation. The observation plan is then used to tell the hardware when to start and when to end the observation of a satellite.

Since it was shown, after researching how to utilize Doppler Shift for this project, to update the orbital elements six different Doppler shift measurements were required. Knowing that each ground station has different slew rates and that there was gonna be delays between each reading, there is a constraint on the maximum time in-between each viewing. This maximum time is also calculated to prevent any aliasing that can happen to data. The way to find the maximum time in-between each viewing was to find the largest magnitude of the complex eigenvalue of a particular matrix. This matrix is the product of using state-space models. The equation used for the state-space model is shown in equation 10.

$$\rho' = \dot{\vec{r}} * \frac{\vec{r} - \vec{R}}{|\vec{r} - \vec{R}|} \tag{10}$$

To use the state space model, the state variables needed to be declared. The state variables were chosen to be the position components of the satellite based on the equation 10. Equation 10 then had to be split into vector components and then rearranged such that the derivative of the state variables were on one side. This lead to equation 11, where the subscript k represents the axes.

$$\dot{r}_k = \frac{\rho'|\vec{r} - \vec{R}|}{r_k - R_k} \tag{11}$$

Using the state variables and the equations (equation 11), the Jacobin matrix is calculated to make a linear model. The Jacobin is done by taking the partial derivative of each function with respect to each state variable. Each element of the Jacobin is shown in equation 12 to equation 20.

$$\frac{\partial f_1}{\partial r_x} = \frac{\dot{\rho}(2 * r_y * R_y - R_y^2 - r_y^2 - r_z^2 - R_z^2 + 2 * r_Z * R_z)}{(r_x - R_x) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (1, 1) \tag{12}$$

$$\frac{\partial f_1}{\partial r_y} = \frac{\dot{\rho}(r_y - R_y)}{(r_x - R_x) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (1, 2) \tag{13}$$

$$\frac{\partial f_1}{\partial r_z} = \frac{\dot{\rho}(r_z - R_z)}{(r_x - R_x) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (1, 3) \tag{14}$$

$$\frac{\partial f_2}{\partial r_x} = \frac{\dot{\rho}(r_x - R_x)}{(r_y - R_y) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (2, 1) \tag{15}$$

$$\frac{\partial f_2}{\partial r_y} = \frac{\dot{\rho}(2 * r_x * R_x - R_x^2 - r_x^2 - r_z^2 - R_z^2 + 2 * r_Z * R_z)}{(r_y - R_y) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (2, 3) \tag{16}$$

$$\frac{\partial f_2}{\partial r_z} = \frac{\dot{\rho}(r_z - R_z)}{(r_y - R_y) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (2, 3) \tag{17}$$

$$\frac{\partial f_3}{\partial r_x} = \frac{\dot{\rho}(r_x - R_x)}{(r_z - R_z) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (3, 1) \tag{18}$$

$$\frac{\partial f_3}{\partial r_y} = \frac{\dot{\rho}(r_y - R_y)}{(r_z - R_z) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (3,2) \tag{19}$$

$$\frac{\partial f_3}{\partial r_z} = \frac{\dot{\rho}(2 * r_y * R_y - R_y^2 - r_y^2 - r_x^2 - R_x^2 + 2 * r_x * R_x)}{(r_z - R_z) * \sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} = (3,3) \tag{20}$$

Once each partial is calculated, it is put in the following matrix.

$$\text{A} = \begin{bmatrix} \frac{\partial f_1}{\partial r_x} & \frac{\partial f_1}{\partial r_y} & \frac{\partial f_1}{\partial r_z} \\ \frac{\partial f_2}{\partial r_x} & \frac{\partial f_2}{\partial r_y} & \frac{\partial f_2}{\partial r_z} \\ \frac{\partial f_3}{\partial r_x} & \frac{\partial f_3}{\partial r_y} & \frac{\partial f_3}{\partial r_z} \end{bmatrix}$$

To finish making the linearized system, a nominal point had to be determined. The nominal point was then picked as the position in the satellite's orbit at the start of the observation spot. This ensures that the most accurate time in-between is calculated for that particular time. With the nominal point, the Jacobin matrix can then be evaluated giving the linearized matrix system. The eigenvalues of this matrix can then give the maximum time in-between. The maximum value is shown in equation 21, where σ is the largest magnitude of the complex eigenvalues.

$$\frac{\pi}{\Delta t} > 2\sigma \tag{21}$$

This then gives the maximum time in-between for each viewing and determines if the ground station is able to make such an observation with its slew rate. The time in-between is used to calculate the total time for an observation.

The calculation of the time in-between is just a step used when creating the observation plan. The goal of the observation plan is to be able to tell the hardware when and where to look at to receive the signal from the satellite. This mainly depends on the scoring of the satellite. The scoring aids in determining which satellite gets put into an observation spot. An observation spot is a timeframe during which all viewing takes place for one satellite. For a given observation plan, there is a finite number of observation spots because there is a finite amount of time.

To find an observation spot, multiple things must be known about the satellite, either from the user input or something that the software can calculate. The user must input the desired satellites, their associated priority value, the TLE data, the timeframe for all observations, and some basic information about the ground station. The satellites with their associated priority value help the observation plan decide which satellites get put into the observation plan. The TLE data is what lets the system where to look. The timeframe is meant to provide a starting and an end time to the observation plan. The last input helps with the scoring factors. Things that the software will need to calculate to make the observation plan is the time in-between each viewing, when the satellite is in the field of view of the ground station, and the scores for each observation.

The overall flowchart for the scheduling software is shown in figure 30. This figure outlines the steps needed to create an observation plan starting from the user input.

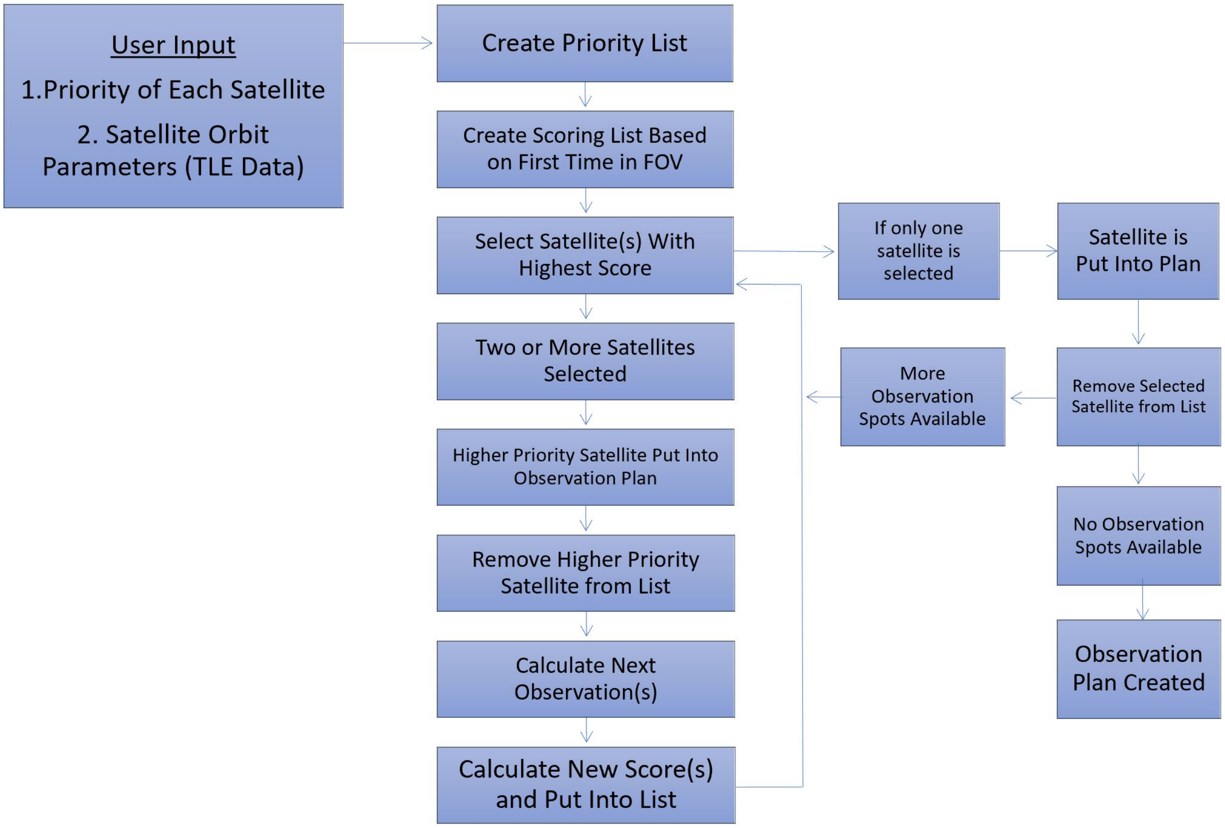


Figure 30. Scheduling Software Flow Chart

Using the user input of the satellites and their related priority, a priority list is created. The priority list is just a list that contains the name of all satellites and their priority in order from higher priority to lowest priority. By creating the priority list, the software now has a list of satellites it can use to see if all of the satellites have gotten an observation spot and it gives the satellite's priority in an easy format to use. Once the priority list is created a new list is created based on the scores and it is called the scoring list. The score for each satellite is computed for the first available observation spot. The observation spot is determined by calculating the first time the satellite is in the field of view. Since the scores are a gauge on the quality of observation, the higher the score the higher the probability of the satellite being put into the observation plan. Once the scoring list has been made, satellites are then able to put into the observation plan. Going down the scoring list, the highest score gets their observation spot in the observation plan and is then removed from the priority list. During this process, two issues might appear. The first is if the observation spot is already taken. If it is taken, a new score is calculated for the satellite at the next possible observation spot. To find the next possible observation, it depends on when the other satellite's observation spot is over and if it is still in the field of view at that time. If the satellite is no longer in the field of view, the new score is calculated based on the next time it is in the field of view, as long as that time is still within the user timeframe. Once the time goes outside of the user's timeframe, it is taken off of the priority list. The second issue is if two or more satellites have the same score and have an overlapping observation spot. In this case, the software must pick the satellite with a higher priority to be put into the observation spot. The satellite(s) not picked then no longer have an observation spot and must go through the process to be put back into the scoring list. This whole process continues until either the priority list is empty or until there are no more observation spots.

Since each observation spot is varying in amount time and when it happens, there is no set way to see if there are any more observation spots, rather the software performs a check to see if there are no more observation sport available. The check is to use the information provided in the observation spot to see if an observation is still possible. The observation spot can tell the software the total time the observation needs to be made while the timeframe givens the total amount of time for the observation plan. Each time something is added to the observation plan, the time it takes to make the observation is subtracted possible time remaining. If it is the first satellite to be put into the observation plan, then the time remaining is just the total time for the observation plan. If any satellites in the scoring list have an observation time that is bigger than the remaining time, the satellite is either removed from the scoring and priority list or it finds a new observation spot that is less than the time remaining.

Once the observation plan is created, the hardware can follow the plan and know when to make the observations. It will also output a Gantt Chart so that the user can see the times each satellite will be observed. During each observation, the hardware receives all necessary signals from the satellite to calculate the Doppler shift. The software can then complete its final step of updating the orbital elements.

3.3.17. Orbit Determination Software

The purpose of the Orbit Determination (OD) software is to conduct preliminary OD to determine whether if the satellite is conducting or has conducted orbital maneuvers. Any orbital maneuvers indicate a change in information being gathered. This is especially true with military satellites. For example, with a reconnaissance satellite, if they were to change their missile profile, they are most likely conducting reconnaissance in a different area.

The orbit determination algorithm utilizes linearization to calculate the difference between the estimated state and the "true" state of the orbit. Also, this algorithm assumes a two-body problem, meaning that the only force acting upon the satellite is gravity. Moreover, there are no perturbations of any sort (no oblate effects, no atmospheric drag, no solar pressure, etc.). As the system being designed is a passive RF system (i.e. receiver only), the orbit determination algorithm utilizes the change in frequency due to the Doppler shift to determine the orbit.

In a Keplerian orbit (i.e. two-body problem), orbits are described by six parameters. These six parameters can either be the six orbit elements (semi-major axis, argument of periapsis, inclination, eccentricity, right ascension of the ascending node, true anomaly), or a position and a velocity vector at a given time (which yields six scalar quantities). As the equation that relates range rate to the orbit elements is extremely non-linear and complicated, the method used here defines an orbit using position and velocity vectors.

The equation that relates range rate to position and velocity vectors is shown below:

$$\dot{\rho} = \vec{v} \cdot \frac{\vec{r} - \vec{R}}{|\vec{r} - \vec{R}|} \tag{22}$$

Expanding this equation yields:

$$\dot{\rho} = \frac{v_x(r_x - R_x) + v_y(r_y - R_y) + v_z(r_z - R_z)}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{23}$$

A partial is then taken with respect to every variable in the equation. This then yields

$$\frac{\partial \dot{\rho}}{\partial v_x} = \frac{r_x - R_x}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{24}$$

$$\frac{\partial \dot{\rho}}{\partial v_y} = \frac{r_y - R_y}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{25}$$

$$\frac{\partial \dot{\rho}}{\partial v_z} = \frac{r_z - R_z}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{26}$$

$$\frac{\partial \dot{\rho}}{\partial r_x} = \frac{r_y v_y R_x - v_y R_x R_y - R_z R_x v_z + v_x r_y^2 + v_x r_z^2 - r_x r_y v_y + v_x R_z^2 - 2 v_x r_z R_z + v_x R_y^2 - 2 r_y v_x R_y + r_x v_y R_y - r_x r_z v_z + r_x v_y v_z}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{27}$$

$$\frac{\partial \dot{\rho}}{\partial r_y} = \frac{r_x v_x R_y - v_x R_x R_y + r_z v_z R_y - R_z R_y v_z - r_x r_y v_x + v_y r_x^2 + v_y r_z^2 + v_y R_z^2 - 2 r_z R_z + v_y R_x^2 - 2 r_x v_y R_x + r_y v_x R_x - r_y r_z v_z + r_y v_y v_z}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{28}$$

$$\frac{\partial \dot{\rho}}{\partial r_z} = \frac{v_z r_x^2 + v_z r_y^2 + v_z R_x^2 - 2 r_x v_z R_x + v_z R_y^2 - 2 r_y v_z R_y - r_x v_x r_z - r_y r_z v_y + v_x r_x R_z + r_y v_y R_z + v_x r_z R_x - v_x R_z R_x + r_z v_y R_y - v_y R_z R_y}{\sqrt{(r_x - R_x)^2 + (r_y - R_y)^2 + (r_z - R_z)^2}} \tag{29}$$

Once these partials are computed, they are then put into a matrix in the form shown below:

$$A =$$

$$\begin{bmatrix} \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \\ \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \\ \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \\ \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \\ \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \\ \frac{\partial\dot{\rho}}{\partial r_x} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial r_y} & \frac{\partial\dot{\rho}}{\partial v_x} & \frac{\partial\dot{\rho}}{\partial v_y} & \frac{\partial\dot{\rho}}{\partial v_z} \end{bmatrix}$$

A few things to note about this matrix: Firstly, the values in every row are identical. Second, the number of rows changes depending on the number of viewings in the observation. Third, all of the partials above are evaluated at one point and one point only. Once the matrix is created, a linear set of equations is formed.

$$[\Delta\dot{\rho}] = [A][x] \tag{30}$$

where $\dot{\Delta\rho}$ is

$$\begin{bmatrix} \Delta\dot{\rho}_1 \\ \Delta\dot{\rho}_2 \\ \Delta\dot{\rho}_3 \\ \Delta\dot{\rho}_4 \\ \Delta\dot{\rho}_5 \\ \Delta\dot{\rho}_6 \end{bmatrix}$$

the A matrix is given above (the matrix with partials) and the x matrix is

$$\begin{bmatrix} \Delta r_x \\ \Delta r_y \\ \Delta r_z \\ \Delta v_x \\ \Delta v_y \\ \Delta v_z \end{bmatrix}$$

All the items listed with a Δ in front means that it is an error. $\Delta\dot{\rho}$ is the difference between the measured range rate and the expected range rate, and $\Delta\vec{r} and \vec{v}$ are the error in position and velocity elements. Once the x matrix is computed, the errors are then added back into the predictions to update the initial estimates. After the estimate is updated, the same process is repeated again in order to attempt to converge the solution. When the x matrix reaches 0 (or is sufficiently small), the process is stopped and the code outputs a new set of orbit data.

The flow chart below demonstrates the function of the OD software.

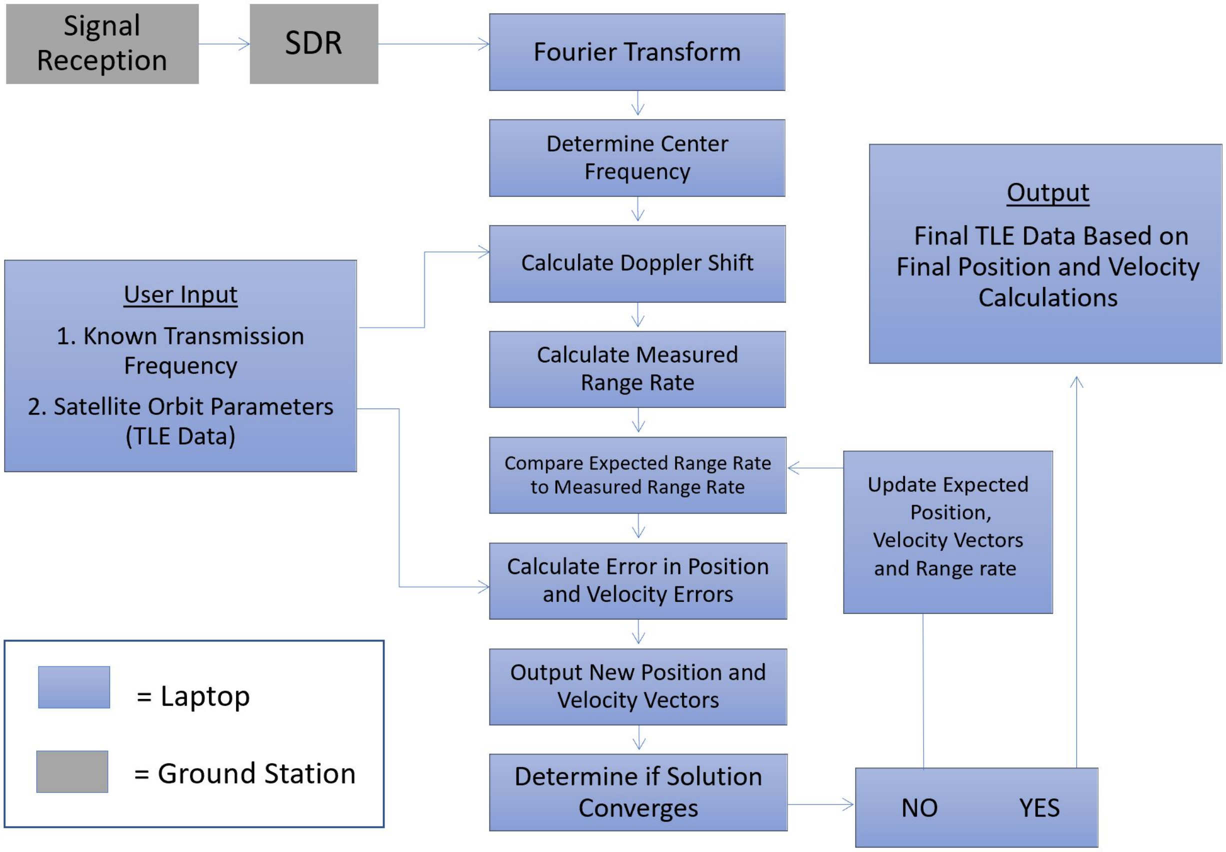


Figure 31. Orbit Determination Software Flow Chart

4. Manufacturing

Authors: Zachary Arbogast, Zakariya Laouar, Yang Lee, Colton Ord, Ryan Cameron

At the time when the project was terminated, all required parts for the project were ordered, but due to the virus two items were cancelled. The items cancelled was equipment needed for the GPS discipline clock.

4.1. Pointing Controls

The pointing controls was compromised of the tripod, tripod mount, rotor, controller, and rotor mount. When the project was ordered to halt manufacturing, all of the pieces had been ordered and with the exception of the tripod mount, had arrived. The piece that was being manufactured, the rotor mount, was in the process of being machined with the CNC tools in the Aeropsace Manufacturing Shop. The aluminum block had been machined down to the final size before the CNC program was carried out. In addition, the GCODE to run the program was written and can be found in the Appendix. After this step, and the tripod mount had arrived, final testing could be done on the pointing controls section.

4.2. Signal Reception

The antenna and electrical subsystem were all purchased and the only manufacturing required was to assemble the parts once they arrived. For the antenna the dish and pickup feed mount needed to be assembled. Then the inline components needed to be attached in the following order, pickup antenna, 10m coax cable, low pass filter, low noise amplifier and finally 6 in. coax cable extender to the SDR. Each of the components has the appropriate SMA adapter to match the next in the line. The antenna subsystem also requires the GPS DO to be attached to another antenna pickup and its output attached to the SDR via a BNC to SMA adapter cable. The LNA is powered by a USB 5V power adapter that is plugged into a female barrel jack which is soldered to the LNA power terminals. The whole assembly past the 10m coax cable and just before the SDR (not including the GPS DO) is covered in heat shrink to offer small protection from the elements and ensure soldered parts remain in contact with the correct terminals.

As far as the pointing controls are concerned the user manual outlines how to correctly attach the 8 wire split 30ft cable that controls the motor to both the PSU and controller. The controller itself also needs to be powered by this PSU via two cables already attached to it. For assembly outside, the PSU for the laptop, and pointing controls would be plugged into the power strip which would be plugged into a wall outlet via a 100ft extension cable.

4.3. Scoring and Scheduling Software

All software made for this project was made in MATLAB. The initial coding of the software began in the fall semester and continued until the project was considered finished in March. The software was split between three individuals in the team, where each individual took on certain aspects of the software. The main aspects were the graphic user interface, scheduling software, scoring software, orbit propagating, and Gantt chart creation. The software would then be coded up by the individual during either a software team meeting or at the individual's own discretion.

A big challenge faced by the software team creating independent code that would eventually be integrated together. This was a big probably when trying to make functions for the overall software due to issues with data types and what variables were available. This issue was mitigated with communication though. As long as all the individuals were updated on the progress of the others' software and knew the data types being used, it proved that this challenge could be overcome.

The fully developed software integrated into the system such that it would be able to tell the system when to look, where to look, and for how long to look. The software was calculating the observation plan of the system after a list of satellites was inputted. Once the observation plan is created, the software will tell the ground station where to look so that it can receive the signal. After the ground system is pointed in the right direction, the software would then rely on the ground station to receive the signal from the satellite and then calculate the doppler shift. Finally, the software would take the Doppler Shift measurements and give an update of the orbital elements.

4.4. Signal Processing

All the software for processing the GPS signal was obtained from the open source GNSS-SDR software. The components for this subsystem are a laptop (already owned), USB 3.0 cable (purchased), an Ettus USRP B200 SDR (Purchased), and a GPSDO (purchased). All the purchased materials for this subsystem arrived just as the transition to virtual classes occurred. Because the team didn't have a chance to test the signal processing subsystem, typical challenges such as bugs with the software were unencountered. A broad level manufacturing setup for this subsystem follows installing the USRP hardware driver (UHD) onto the SDR, installing the GNSS-SDR software on a linux running laptop, connect the GPSDO to the SDR and configure it to accept the GPSDO as a 10 MHz clock corrector, and finally run any configuration file living in the GNSS-SDR repository that meets the needs of calculating the doppler shift of a given satellite.

5. Verification and Validation

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5.1. Pointing Controls Verification

5.1.1. Resolution

The first test to be performed for the Verification and Validation of the pointing controls is to satisfy the functional requirement of having pointing resolution of at least 1°. This will be done by mounting a laser pointer to the top of the mounting bracket and orienting the pointer so it point horizontally as in Fig. 32.

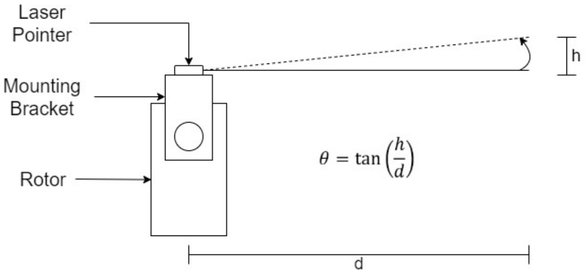


Figure 32. Pointing resolution test setup

As seen, the laser pointer will be mounted a distance *d* from a wall. Then, the rotor will move one step at a time and in between each step the distance the laser pointer moves on the wall will be measured. Using trigonometric relations, the angle the laser pointer moved through in a single step can be tested and verified. Once completed, this will endure that DR 5.1 is met and that the rotor has the accuracy required of the system.

5.1.2. Torque Validation

The test to verify the torque that the rotor can apply will be carried out using a dynamometer housed in the electronics lab of the Aerospace building. A picture of a DYNOmite Dynamometer is shown below, which is the model that is in the lab space.

Figure 33. Dynamometer test setup

This test apparatus applies torque to the motor using a pulley system, so a matching belt an pulley will be mounted onto the motor to connect to the machine. Once this is done, torque profile can be applied to the SPX-02 that will simulate a full series of slews across the sky. By doing this, the machine can simulate a full mission profile without the need for mounting the dish on the motor. This allows for a full unit test of the pointing controls subsystem and can verify that the motor has enough torque to run a full mission, which relates to DR 5.2.

5.1.3. Full Subsystem Test

This test is designed to verify the functional requirement in relation to the pointing controls. The objective of the test is to both verify that that the controller communicates properly with the rotor and that the rotor functions properly in its full range of movement. The way this is designed is that the rotor will first be calibrated at true north using a compass while correcting for declination shifts, as well as an initial elevation setting. Then, we will input corner cases representing the full range of movement (90° in elevation and 180° in azimuth). All that is needed for this test is the projects room and a wall outlet to connect the controller to. Once completed, this test satisfies DR 5.3 as well as functional requirement 5 as a whole.

5.2. Signal Reception

In order satisfy our customer's requirements, we need to verify that our antenna design satisfies both the gain and half-power beam-width requirements presented in section 4. This is done with our antenna selection process. We will then test the antenna as a whole and verify its ability to provide our signal processing subsystem with the necessary data to make Doppler shift readings.

5.2.1. L1 Band Reception Test

The purpose of this test is to verify that our antenna can receive L1 Band GPS signals centered about 1575 ± 14 MHz for the conditions we outlined in FR 1 (i.e. Elevation between 15° and 30°, within 15° of the Sun, 0-30% cloud coverage, 70-100% cloud coverage, and 2 hours before sunrise and sunset).

We need at least two people to perform this test, access to South Boulder Campus, and a protractor and compass. The test procedure is as follows...

- Arrive at location and assemble partial ground station[b]
- Locate the appropriate GPS satellites for observation under the conditions required of FR 1 using in-the-sky.org.
- Using the protractor and compass point the antenna at each of these satellites and observe whether or not we see signals centered about 1575 ± 14 MHz on the laptop display as output from our sdr.
- Verify that the signal is coming from the GPS satellite we intended using its associated PRN code.

We expect to see a signal centered about 1575 ± 14 MHz from each GPS satellite we choose to observe. This verifies our FR 1 as well as verifies that we have met our highest level of success for Signal Reception according to table 1.

---

[b] this includes the antenna and parabolic dish with its original mounting assembly (a pole), a laptop and sdr

5.3. Signal Processing

The signal processing tests in this section attempt to fulfill functional requirement **FR 2** listed in section 2.5 as the following: Convert L1 band analog RF signal into a digital signal.

5.3.1. SDR Connection Test

In order to fulfill the functional requirement above, the first step is to ensure the equipment is configured and ready to receive/process GPS signals. The facilities required for this test are, an Ettus SDR, a USB cable, and a Linux running laptop. The figure below shows the steps to take to ensure the SDR is properly connected and ready to collect data.

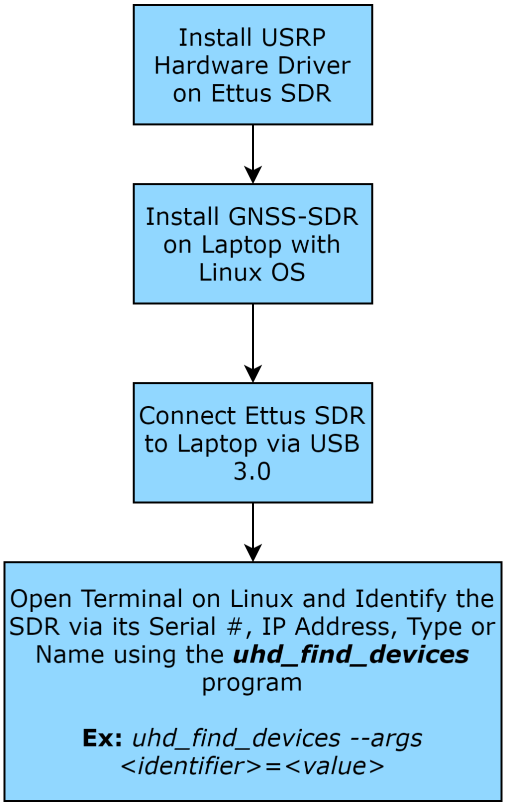
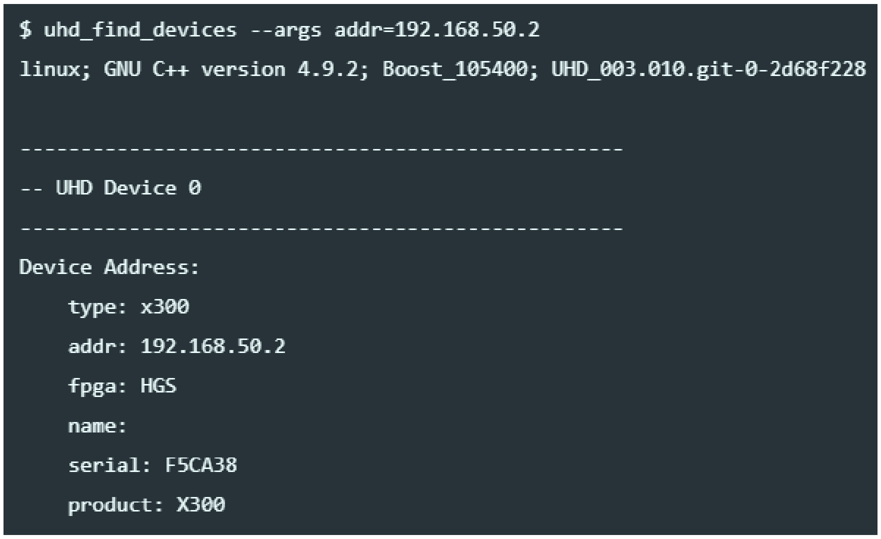


Figure 34. SDR Connection Test Setup

Here is an example of identifying the connected SDR:



```
$ uhd_find_devices --args addr=192.168.50.2
linux; GNU C++ version 4.9.2; Boost_105400; UHD_003.010.git-0-2d68f228

--------------------------------------------------
-- UHD Device 0
--------------------------------------------------
Device Address:
    type: x300
    addr: 192.168.50.2
    fpga: HGS
    name:
    serial: F5CA38
    product: X300
```

Figure 35. SDR Connection Test Example

5.3.2. *Signal Processing Test*

In order to confirm we are capturing and processing valid signal data from the GPS satellites, we will perform the GNSS-SDR internal parameter monitoring test. The facilities required for this test are, an Ettus SDR connected to an antenna, a USB cable, and a Linux running laptop. The GNSS-SDR software provides a 'monitor' block which allows for the real-time monitoring of up to 25 internal parameters which describe the performance of each channel of the GPS receiver[12]. The high level architecture of this monitor block is shown below:

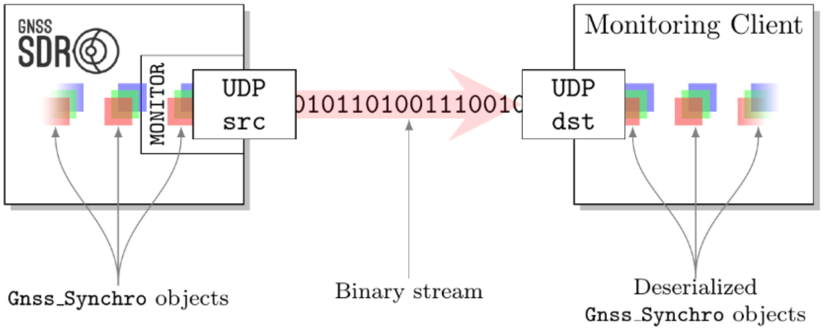
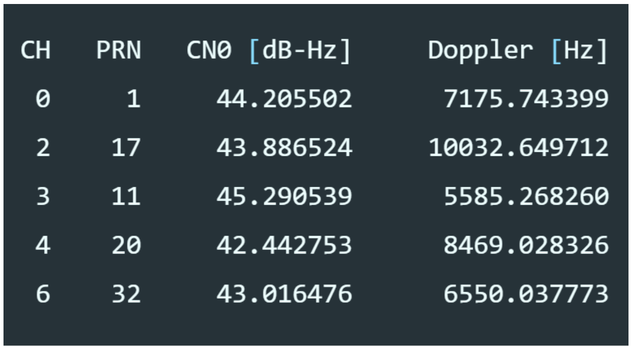


Figure 36. GNSS-SDR Software Monitor Block

The colored boxes in the image represent objects which contain information regarding the internal parameters of the receiver. Each color in a set represents a different channel of the receiver and each set of objects are moving along the receiver chain through a binary stream from the receiver to the monitoring client (printed to linux terminal running the C++ script).

The exected results when monitoring only the Doppler shift, Pseudo-random noise identifier (PRN), and Carrier-to-Noise ration (CN0) are shown below:



```
CH   PRN   CN0 [dB-Hz]     Doppler [Hz]
 0     1     44.205502      7175.743399
 2    17     43.886524     10032.649712
 3    11     45.290539      5585.268260
 4    20     42.442753      8469.028326
 6    32     43.016476      6550.037773
```

Figure 37. Expected Result from Signal Processing Test

Achieving this result means satisfaction of **FR 2** and readiness for a full-scale test.

5.4. Software Test

All of the software test are able to be done on a laptop that has MATLAB and the necessary files for testing downloaded. It only requires one individual to perform all of the test, and the individual only has to input the test cases and compare the out to the expected results.

5.4.1. Scoring Test

As per functional requirement 4, the scheduling software shall develop an observation plan for given satellites. In order to schedule satellite observation opportunities, scores for each opportunity is needed. This score evaluates how desirable said opportunity is for scheduling an observation. To test the functionality of the scoring software, a list of satellites with predetermined observation windows are put into the software. This list of satellites contains both satellites above and below the horizon during the observation window. The approximate score will be calculated by hand without the program. This list of scores are then compared to the software output. A successful test should yield a similar result between hand calculation and the software output.

5.4.2. Orbit Determination Test

As per Functional Requirement 4, orbit determination is needed in order to verify the functionality for the scheduling software. The purpose of this orbit determination function is to recreate an orbit using the observed Doppler shift data. The validity of our scheduling software can be determined by comparing the orbits recreated with and without scheduling to the "real" orbit data of the satellites. If our scheduling software works as intended, the orbit recreated would resemble the ’true’ orbit of the satellite obtained online. If not, our orbit estimate would be extremely off. To test the orbit determination software, a simulated observation is generated via the orbit propagation program. The program outputs simulated the frequencies received on the ground station. A set of $\dot{\rho}$ is then calculated based on these frequency measurements. Then, the program propagates an entire orbit based on initial orbit parameter guesses ($\vec{r}$ and $\vec{v}$). Another set of $\dot{\rho}$ is then calculated. Taking the difference of these two $\dot{\rho}$ yields $\Delta\dot{\rho}$, which is the error between the measured and ’estimated’ range rate. This list of $\Delta\dot{\rho}$ is then used for modifying the position and velocity vector guesses. The aforementioned procedure is repeated until the error matrix approaches zero. Once the error matrix approaches zero, the final position and velocity estimates are then compared to the original input to the orbit propagation program to determine the relative error.

5.4.3. Scheduling Test

To ensure the FR 4 is satisfied and the software was meeting the highest level of success, the scheduling software had to be tested so that when a list of satellites was inputted, the higher scores and priorities were put into the observation plan. The test was to be completed as soon as the scoring software test were completed. Having the scoring tests completed first was required because the scheduling software required the scores for an observation to accurately schedule each of the satellites. Different test cases were to be inputted into the scheduling software to ensure that it would work in a variety of cases. Some of the test cases would involved a list of satellites where there were no passes during the timeframe. This ensured that the software was able to use the calculated scores and not schedule a satellite with a zero score. Another important test was when there would be two same score satellites that had the same observation spot but different scores. The test would ensure the software knew when to pick a higher priority satellite. All of this would have been verified against hand calculation while also using an online satellite tracking source[7] to ensure that not only the satellite was within view but also where the software had predicted. This would then allow the full system testing with actual satellites to observe.

5.4.4. *Orbit Modeling Propagation Testing*

To schedule and score satellites, the orbit of the satellite is needed at a particular time. By propagating the orbit, the scoring software is then able to calculate a score (FR 3) for each observation which will then feed into the scheduling software (FR 4) to schedule each of the satellites for an observation spot. This ensures that the team meets the highest level of success for the scheduling software by ensuring the software takes into account the scores of each satellite when scheduling. Table 22 shows how the orbital modeling propagation software was tested on a randomly selected satellite, and then compared to an online satellite tracking source[7] to evaluate the reliability and accuracy of the propagation software. By having done this test, it shows that the software is working correctly and validates that the system is able to propagate orbits until a desired timeframe.

Table 22. Comparison between propagated data and online satellite tracking sources.

GPS BIIR-2
NORAD: 24876

Orbital Elements	Simulation Software	Online Tracking Source	Relative error
a - Semi-major axis [m]	$26558.6\text{x}10^3$	$26559\text{x}10^3$	$1.5061\text{x}10^{-5}$
e - Eccentricity	0.004090	0.004089	$2.4456\text{x}10^{-4}$
i - Inclination- [deg]	55.43	55.46	$5.4093\text{x}10^{-4}$
Omega - Longitude of the ascending node [deg]	191.41	191.42	$5.2241\text{x}10^{-5}$
omega - Argument of periapsis [rad]	67.41	67.40	$1.4837\text{x}10^{-4}$
n - Mean motion	29.229	29.23	$3.4211\text{x}10^{-5}$
m - Mean anomaly	29.0013	29.00	$4.4828\text{x}10^{-5}$

Geographic coordinate system (WGS-84)	Simulation Software	Online Tracking Source	Relative error
Latitude [deg]	54.9053	54.87	$6.4334\text{x}10^{-4}$
Longitude [deg]	172.7551	172.43	1.9e-03
Altitude [m]	$20099.86\text{x}10^3$	$20092\text{x}10^3$	$3.9123\text{x}10^{-4}$
Velocity [m/s]	$3.888\text{x}10^3$	$3.888\text{x}10^3$	$1.32\text{x}10^{-7}$

Relative to Ground Station	Simulation Software	Online Tracking Source	Relative error
Azimuth [deg]	318.4	316.5	$6\text{x}10^{-3}$
Elevtion [deg]	17.89	18.01	$6.7\text{x}10^{-3}$
Slant Range [m]	$23810.118\text{x}10^3$	$23813\text{x}10^3$	$1.2103\text{x}10^{-4}$
Rate of change of Slant Range [m/s]	-512.4	-509	$5.9\text{x}10^{-3}$

This test was done using a teammember's computer. The orbit propagating was done using SGP 4.

6. Risk Assessment and Mitigation

Authors: Kieran O'Day

Risks for PROS8 were discussed in team meetings from the preliminary design stage onward, however a formal risk assessment and mitigation plan was not created until CDR work began. In order to establish project risks, asses their likelihood and severity, and create mitigation strategies, the project was broken down into its subsystems before being analyzed as a whole system.

6.1. Communication Subsystem

6.1.1. COM-1

The first communication subsystem risk is **difficulty isolating the transmission of a specific satellite (COM-1)**. The rationale for this risk is that there will be many satellites within the beam width of our satellite dish, and if we cannot isolate the transmission frequency of the satellite we wish to observe then we will not be able to process the data from that satellite. The calculated risk level was moderate with a likelihood of 2 and severity of 3, because if the risk occurs we can simply move on to testing with different satellites. To mitigate the risk of COM-1, we will develop our SDR software early and test with available GPS satellite transmission data.

6.1.2. COM-2

The second communication subsystem risk is **insufficient signal received by antenna (COM-2)**, meaning the signal we receive is below the noise floor. This risk level is critical with a likelihood of 3 and severity of 5, because an insufficient signal received by our ground station would render the software portion (main deliverable) of our project useless. To mitigate the risk of COM-2, we have designed our antenna subsystem with a large factor of safety and a low-noise amplifier to ensure the received signal is strong enough for further processing.

6.2. Mechanical Subsystem

6.2.1. MECH-1

The first mechanical risk is **pointing controls malfunction (MECH-1)**. Based on research and past experiences with the SPX-02 antenna rotator we chose for our project, it was established that this device could malfunction due to power, motor, or control issues. The risk level of MECH-1 is low, with a likelihood of 2 and severity of 2, because we are not tracking satellites and simply slewing the satellite dish for stationary measurements. To mitigate MECH-1, we are purchasing a power supply unit from the manufacturer that is designed for the SPX-02 and creating a detailed test plan for early testing of this device.

6.2.2. MECH-2

The second mechanical risk is **assembly of the mechanical system takes longer than expected (MECH-2)**. This risk accounts for any integration errors we might encounter, such as needing additional parts. The risk level for MECH-2 is moderate, with a likelihood of 3 and severity of 2. To mitigate MECH-2 we have contacted the manufacturers for part specifications and will create a detailed CAD model before assembly in the Spring. Additionally, we will create a back up plan for mounting the satellite dish in case of part failure.

6.3. Software Subsystem

6.3.1. SOFT-1

Software risk 1 is **encounter unexpected software bugs that affect project performance (SOFT-1)**. These bugs could occur with any aspect of our software (scoring, scheduling or orbit determination) and considering the software is the main deliverable for our client the risk level for SOFT-1 is critical with a likelihood of 4 and severity of 4. To mitigate SOFT-1 we will develop our software early, ensure we maintain detailed documentation, and create a detailed test plan for software verification before using with the integrated system.

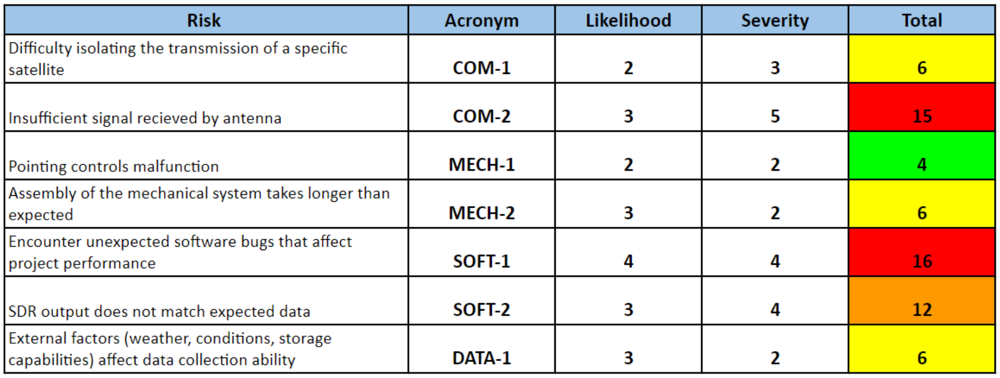
6.3.2. SOFT-2

Software risk 2 is **SDR output does not match expected data (SOFT-2)**. The SDR is our critical project element that relates to signal processing and turning the satellite analog RF signal into a digital signal for use with our software. If the SDR output is not what our software is expecting as an input, it will render our software useless. The risk level for SOFT-2 is high, with a likelihood of 3 and severity of 4. To mitigate SOFT-2 we have already downloaded the software developer kit for our chosen SDR (Signalhound) and have started to use their software. Additionally we will test the software we create for the SDR before integrating with the whole system.

6.4. Data Collection

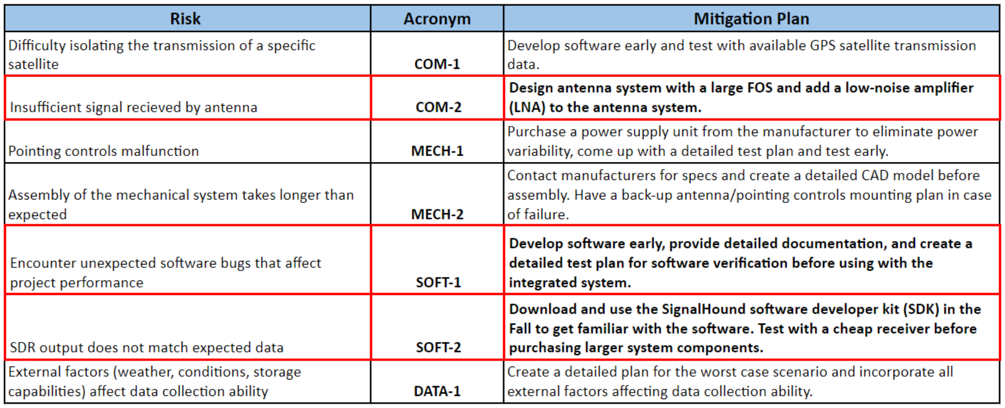
6.4.1. DATA-1

The risk associated with data collection is **external factors affect data collection ability (DATA-1)**. These external factors could be weather, location availability, storage capabilities, or others. The risk level for DATA-1 is moderate, with a likelihood of 3 and severity of 2, because this risk would only significantly impact our project if our system integration is delayed and our overall testing window is shortened. To mitigate DATA-1 we will create a detailed plan accounting for the worst case scenarios of external factors affecting our data collection ability.



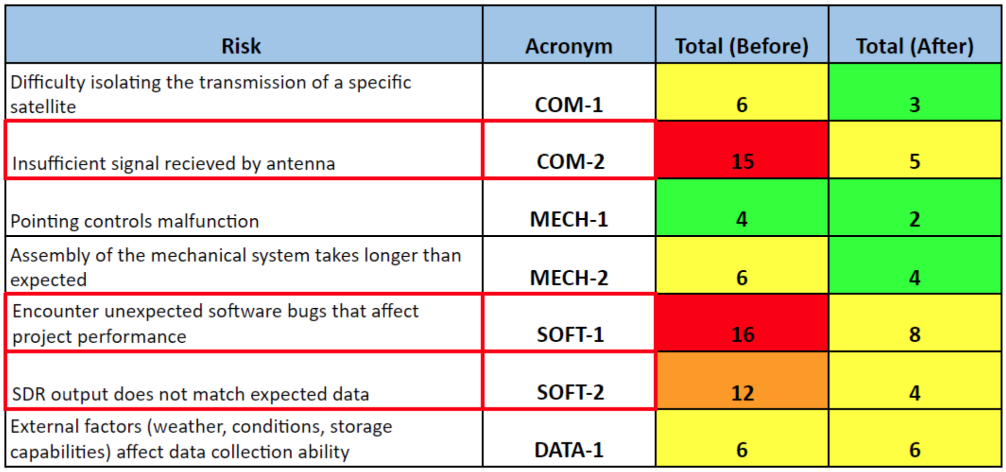
Risk	Acronym	Likelihood	Severity	Total
Difficulty isolating the transmission of a specific satellite	COM-1	2	3	6
Insufficient signal recieved by antenna	COM-2	3	5	15
Pointing controls malfunction	MECH-1	2	2	4
Assembly of the mechanical system takes longer than expected	MECH-2	3	2	6
Encounter unexpected software bugs that affect project performance	SOFT-1	4	4	16
SDR output does not match expected data	SOFT-2	3	4	12
External factors (weather, conditions, storage capabilities) affect data collection ability	DATA-1	3	2	6

Figure 38. Risk table with all subsystem risks



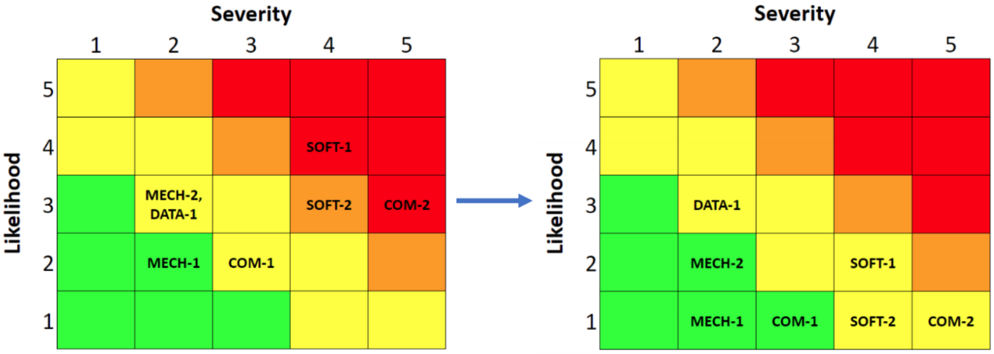
Risk	Acronym	Mitigation Plan
Difficulty isolating the transmission of a specific satellite	COM-1	Develop software early and test with available GPS satellite transmission data.
Insufficient signal recieved by antenna	COM-2	**Design antenna system with a large FOS and add a low-noise amplifier (LNA) to the antenna system.**
Pointing controls malfunction	MECH-1	Purchase a power supply unit from the manufacturer to eliminate power variability, come up with a detailed test plan and test early.
Assembly of the mechanical system takes longer than expected	MECH-2	Contact manufacturers for specs and create a detailed CAD model before assembly. Have a back-up antenna/pointing controls mounting plan in case of failure.
Encounter unexpected software bugs that affect project performance	SOFT-1	**Develop software early, provide detailed documentation, and create a detailed test plan for software verification before using with the integrated system.**
SDR output does not match expected data	SOFT-2	**Download and use the SignalHound software developer kit (SDK) in the Fall to get familiar with the software. Test with a cheap receiver before purchasing larger system components.**
External factors (weather, conditions, storage capabilities) affect data collection ability	DATA-1	Create a detailed plan for the worst case scenario and incorporate all external factors affecting data collection ability.

Figure 39. Risk mitigation strategies with the 3 most significant risks highlighted



Risk	Acronym	Total (Before)	Total (After)
Difficulty isolating the transmission of a specific satellite	COM-1	6	3
Insufficient signal recieved by antenna	COM-2	15	5
Pointing controls malfunction	MECH-1	4	2
Assembly of the mechanical system takes longer than expected	MECH-2	6	4
Encounter unexpected software bugs that affect project performance	SOFT-1	16	8
SDR output does not match expected data	SOFT-2	12	4
External factors (weather, conditions, storage capabilities) affect data collection ability	DATA-1	6	6

Figure 40. Risk levels before and after developing mitigation strategies



Likelihood \ Severity	1	2	3	4	5
5					
4				SOFT-1	
3		MECH-2, DATA-1		SOFT-2	COM-2
2		MECH-1	COM-1		
1					

Likelihood \ Severity	1	2	3	4	5
5					
4					
3		DATA-1			
2		MECH-2		SOFT-1	
1		MECH-1	COM-1	SOFT-2	COM-2

Figure 41. Risk matrix before and after mitigation strategies

6.5. Logistical Risks

PROS8 is unique considering our reduced team size. Our primary logistical risks stem from this fact, as we have to ensure that we remain organized and each aspect of the project receives enough attention from our team. As we proceed into the Spring semester, we will have to estimate the work needed for each subsystem, system integration, and testing before shifting responsibilities on the team to account for our findings. As an example, only one member of our team was focused on the antenna/communication subsystem, but we anticipate we will need two or three people working on this subsystem in the Spring to ensure our requirements are met and tested. Another logistical risk is amount of time we have for testing. Our scoring software will be developed before any data is taken from satellites, but ideally we will use our testing results to iteratively improve the scoring formula. The more data we collect, the better our software will be for achieving the goals set out by Orbit Logic. If any factors decrease the size of our testing window, we will have less data to work with for improving the PROS8 scoring software.

7. Project Planning

Author: Quinton Nietfeld, Colton Ord, Kieran O'Day

Planning was essential to the project's success, although the project was denied a closure the plans for the remainder of the project still remain and indicate how the project would have been finished. A majority of the planning needed to be completed at the beginning of the two semesters, as the semesters were the two main sections of the project's work - design phase and production phase. The planning for the fall semester that was completed around the project start date was difficult to assess. The scope of the project was widely out of reach for what the customer was interested in, and CU Boulder's Aerospace department had conflicting ideas of a senior project than the customer. This made management nearly impossible as it was very difficult to figure out requirements or even the basic motivation behind the project that would satisfy two different customers. It seemed that the customer and the university did not coordinate well when coming up with the project, and this lead to very difficult conversations and times to create the project. PROS8 still managed to determine an appropriate set of requirements and came up with the outline of the project. The beginning of the project also provided numerous obstacles, to name one we lost 4 members from a 12 member team, hence PROS8. The system was broken down into critical project elements that are also the functional requirements, then each of these functional requirements had a few design requirements that described the detailed design of the system.The critical project elements were: Signal Reception, Pointing Control, Signal Processing, Scoring Software, and Scheduling Software. Each of these sub-systems were lead by an individual on the team and then had 1 to 3 team members that were assigned to the sub-section to ensure no one point of failure. This can be visualized in the organizational chart of the team.

7.1. Organizational Chart

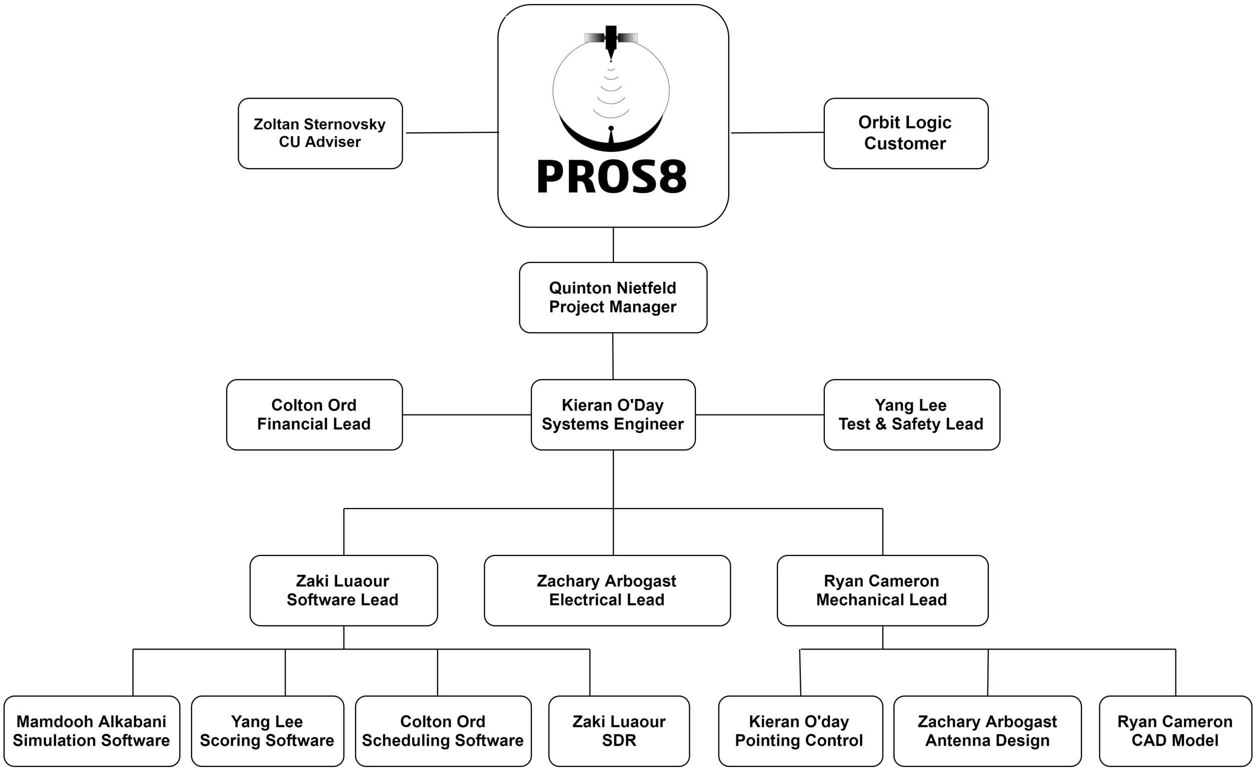


Figure 42. Organizational Chart

This organizational chart illustrates the lead responsibilities of each portion of the PROS8 project. It is important to note that each critical project element is covered by a lead role that a team member is responsible for. This chart shows only the lead responsibilities, each section also has a number of other team members working on that portion of the project and all work is being reviewed, as stated above.

7.2. Work Breakdown Structure

Once the scope of the project and the requirements were determined and agreed upon, an idea of the work that needed to be completed was created. This was illustrated in a work breakdown structure that has sub-categories that the work fits into. In the fall semester the work was broken up into deliverables, management, mechanical, software, and testing. This was a preliminary work breakdown structure that allowed the team to have a good understanding of the work in the fall semester. That illustration is resented below.

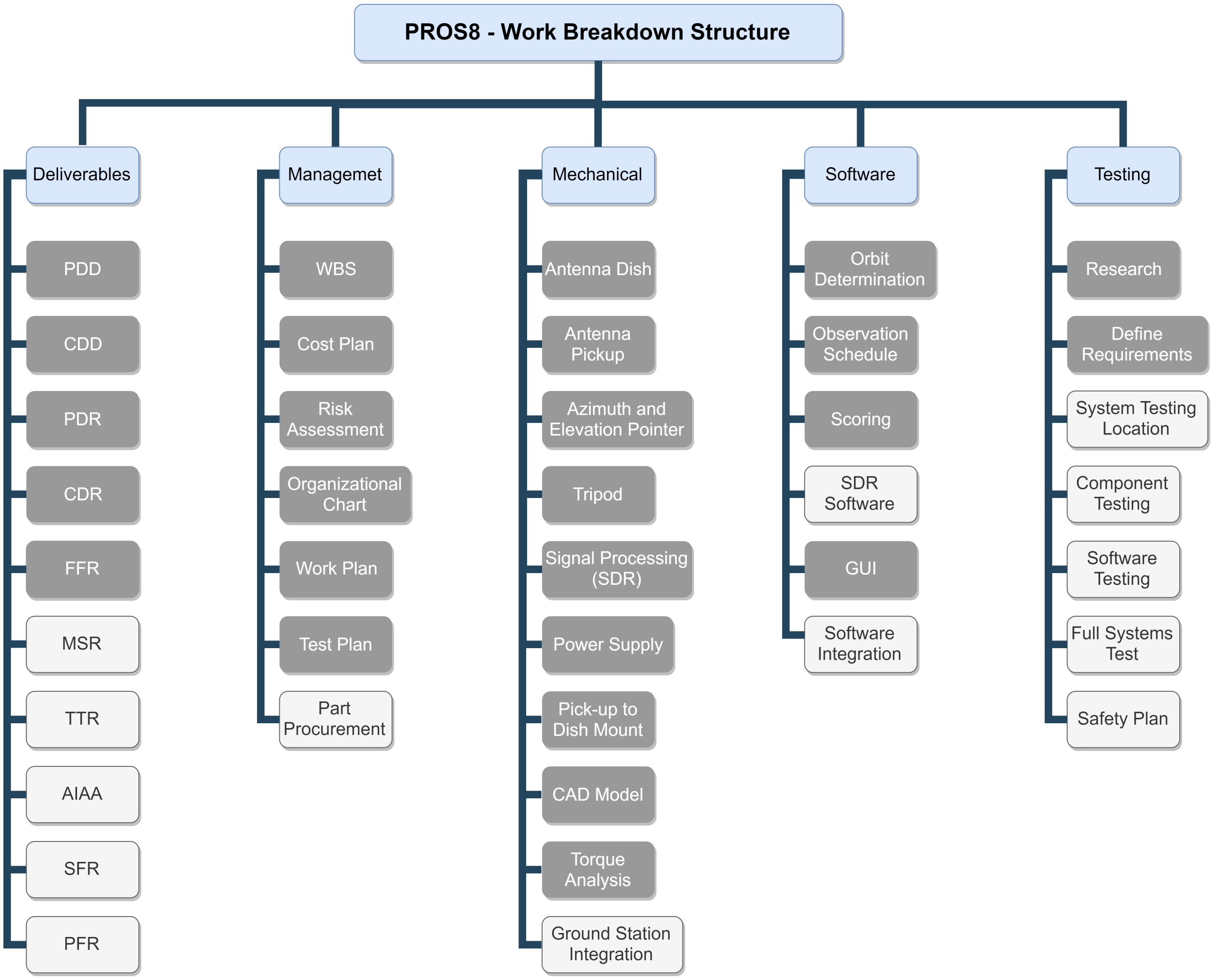


Figure 43. Fall Work Breakdown Structure

This work breakdown structure for PROS8 shows all of the general work that needs to be attended to. The blue boxes are categories of the work that needs to be completed. Then, underneath the work categories, we have all of the individual tasks that need to be completed. The dark gray boxes indicate work that was completed at the conclusion of the fall semester and completion of the Fall Final Report and then the light gray boxes indicate work that will be completed in the Spring Semester of 2020.

The spring semester brought the production of the project and the management decided to readjust the work breakdown structure to fit more closely with the requirements of the project. This was then divided by management and the five CPEs to determine the amount of work that needs to be completed by the project close. The spring work breakdown structure is below.

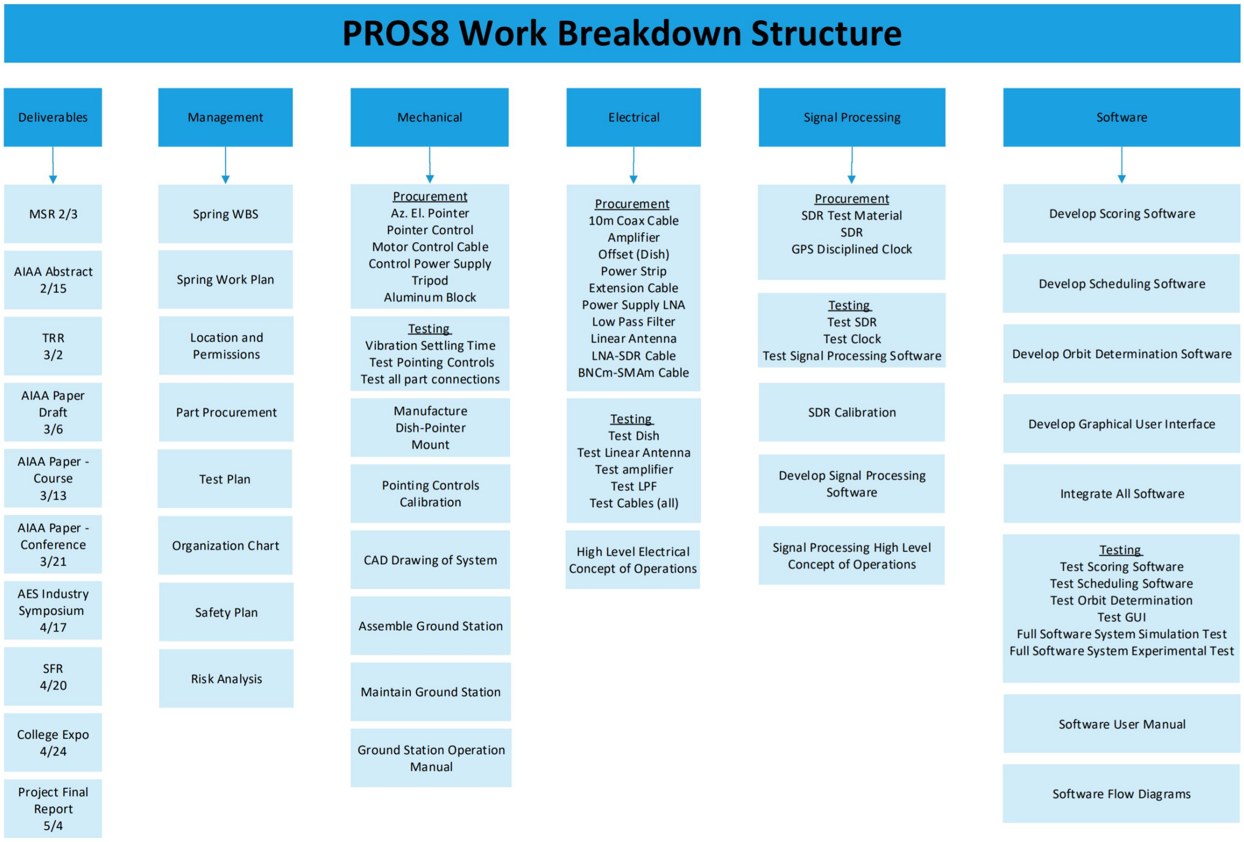


Figure 44. Spring Work Breakdown Structure

7.3. Work Plan

Following this work breakdown structure allowed all of the sub-system leads to know exactly what work needed to be completed in their respective sub-system. These work breakdown structures were also used to create the work plan for the project. This work plan was developed in a Gantt chart structure to easily understand the timeline and progress of the project. The PROS8 management created a work plan for the fall semester and the spring semester. The fall semesters work plan is below.

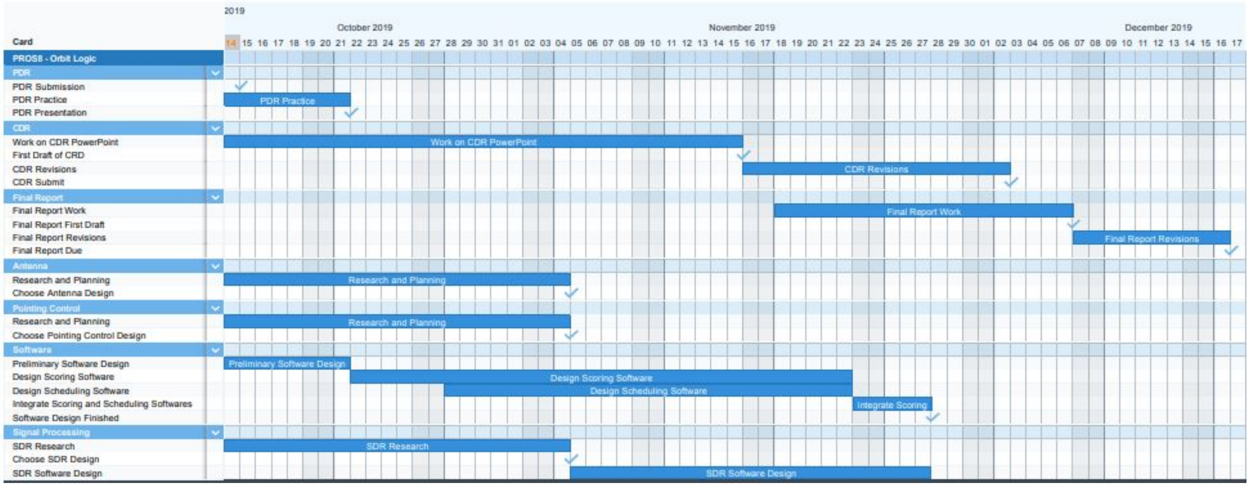


Figure 45. Fall Work Plan

We can see here that the Gantt chart style was not perfectly adhered too, however the fall semester was the design phase of the project and the timing of the work was determined by the assignment deadlines of the course. Most all of the work at the beginning of the fall semester was research, and planning, which is reflected in the PDD assignment. The design of the system and software came toward the middle to end of the semester. Where the PDR and CDR design reviews were presented and the design work followed those guidelines. There were no margins here and the critical path followed the assignment deadlines, as there were no extensions.

The spring work plan was developed in detail a bit more than the fall plan. This detail was needed as the project was under development at this stage and it was vital that the group stick to a work plan to ensure that all the components come together at the determined time for integration. This spring work plan can be seen below.

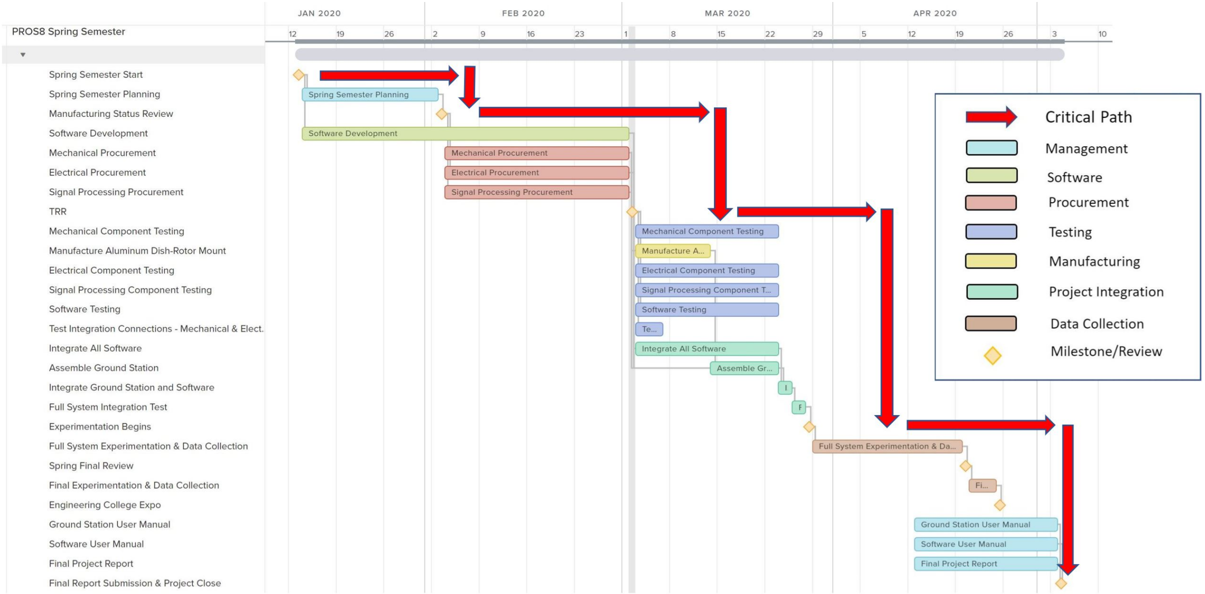


Figure 46. Spring Work Plan

It is obvious to tell that the spring schedule more represented a Gantt chart. This shows that there are a number of different categories that were derived from the work breakdown structure. Each task was in conjunction with the entire project so a cascading critical path could be applied to allow for an understanding of when the project is officially behind schedule and some intervention will be needed. The red arrow indicates the critical path. The Gantt chart software that was used did not have a margin feature, however, it is easy to understand the margins for the tasks that are on the chart, the space between the end of the task and the critical path shows the margin that was allowed for the timing of the spring semester tasks.

The project was officially halted at manufacturing on March 13th, and as you can see this would have been in the middle of the individual component testing. The group was able to finish minimal amounts of testing and most of the components were not allowed to be fully tested. This also means that the system was never fully integrated together and no data was ever taken. The project was essentially canceled about the same week that we received all of our components, allowing minimal testing and no manufacturing or development. The software was also not able to be fully tested and integrated together to create a single software package.

7.4. Cost Plan

The financial budget for this project is currently under budget with approximately 13.7% of the budget remaining. There are six major items for this project: antenna, SDR, antenna pointing, tripod, mounting, and miscellaneous items. Each of the major items have a budget margin over at least 15%. In figure 47, it shows the portion each major items takes of the budget. There is also an additional slice in the pie chart that shows how much funds is remaining. In table 23 it shows the price, the allocated amount, and the budget margin for each major item.

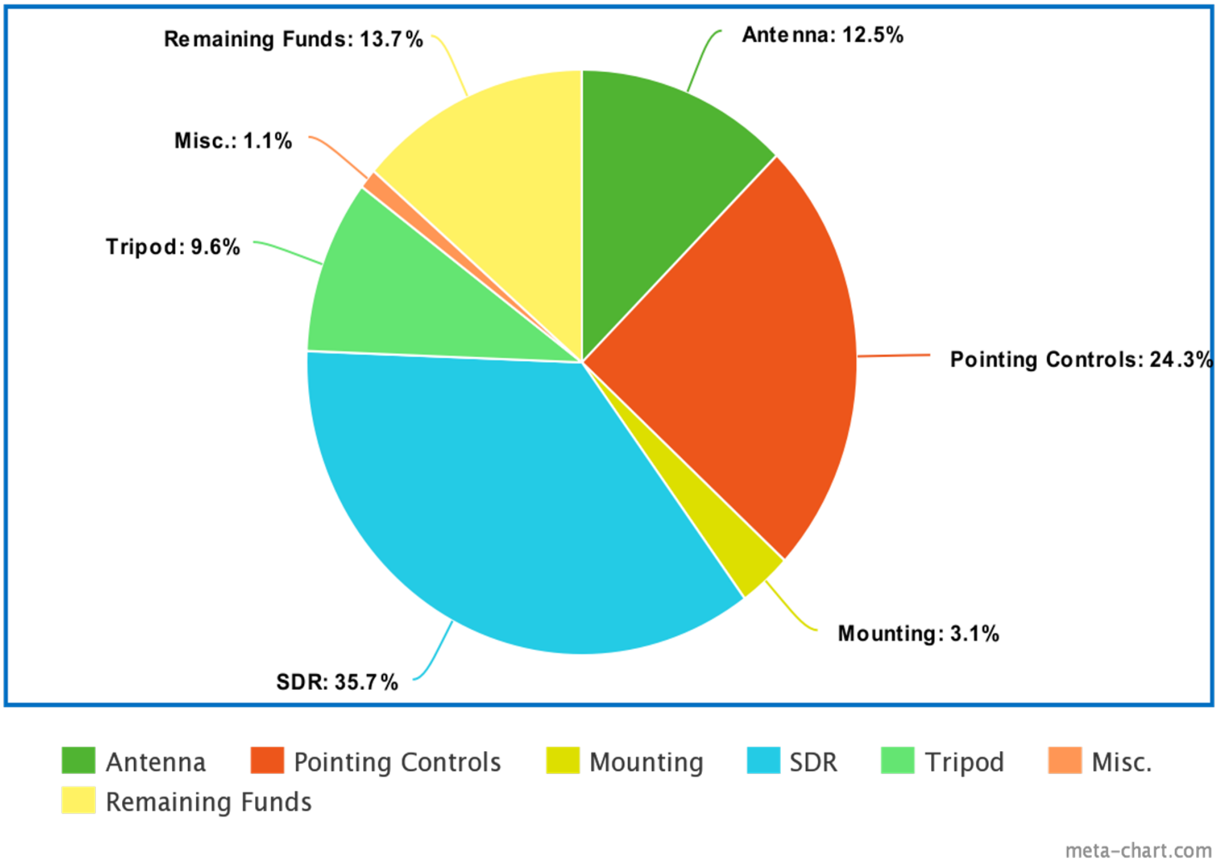


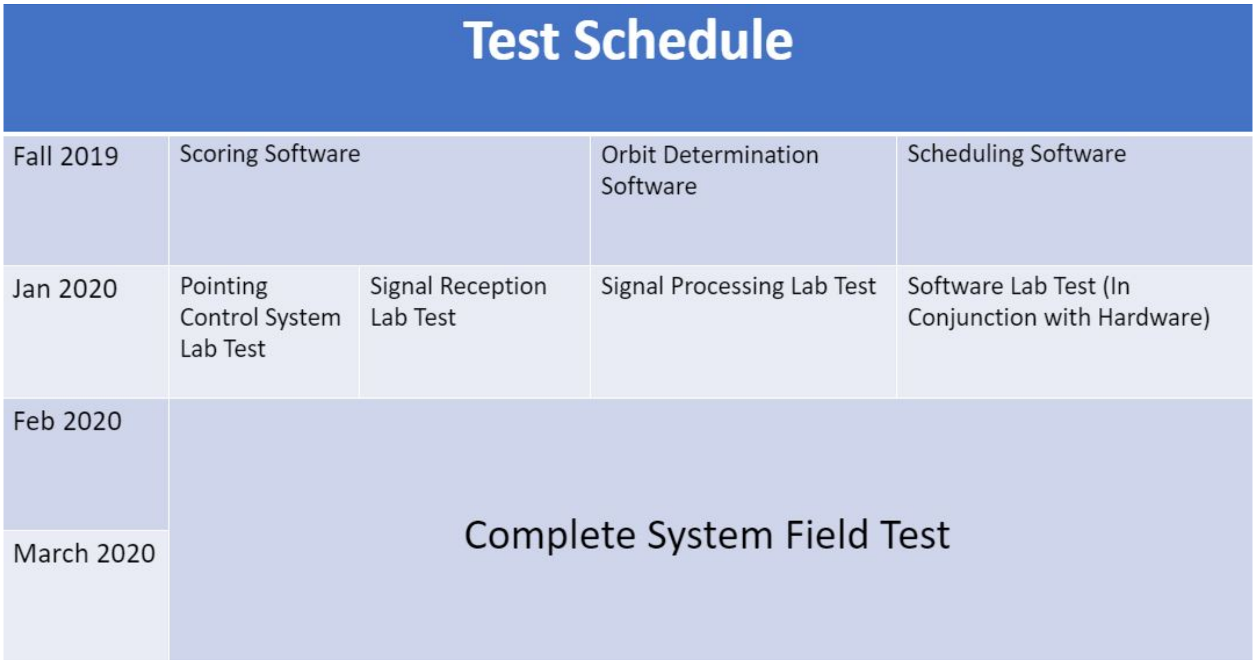
Figure 47. Budget Pie Chart

Component	Cost	Allocated Amount	Budget Margin
Antenna	$625.01	$1000	37.5%
SDR	$1782.90	$1800	0.95%
Antenna Pointing	$1215.63	$1400	13.17%
Tripod	$481.59	$500	3.68%
Mounting	$155.39	$200	22.31%
Misc.	$54.27	$100	45.73%
Total	$4314.79	$5000	13.7%

Table 23. Financial Budget

All of the major elements share the same uncertainty in their cost which is the cost to ship the items. This is not all of the uncertainties for the financial budget. One of the biggest uncertainties were with the antenna pointing. The antenna pointing was coming from a vendor in Europe which means that the actual cost of the item in US dollars was unknown until it was purchased. That was part of the reason why the antenna pointing had a more allocated funds because it was ensure that the budget was prepared for the exchange rate between the two different currencies. The shipping of the item was expected to be more than the other groups too, which is why it had a higher allocated amount. Another uncertainty comes from the miscellaneous items. The uncertainty was this group was meant to pay for any required. The SDR also had uncertainties that came from talking with professors. As more knowledge came about what would be needed for the SDR, which meant more funds had to be allocated for the SDR to ensure the project had all necessary components to succeed. This is why the budget margin is so low for the SDR, the funds for the SDR were taken from other groups with higher budget margins.

7.5. Test Plan



Test Schedule

Fall 2019	Scoring Software		Orbit Determination Software	Scheduling Software
Jan 2020	Pointing Control System Lab Test	Signal Reception Lab Test	Signal Processing Lab Test	Software Lab Test (In Conjunction with Hardware)
Feb 2020	Complete System Field Test			
March 2020				

Figure 48. Preliminary Test Plan

The table above is the preliminary test schedule developed to test the entire system. The software tests as listed above are already in progress. These software tests require little to no hardware to be present to be completed. Note that the hardware tests are limited by the team's ability to acquire the various hardware on time. As the team is not allowed to procure hardware this semester, all the hardware tests are scheduled to begin next semester. Also, not that the complete system field test is scheduled for a large time slot. This is due to the fact that the scoring and scheduling software may require further improvements due to hardware limitations.

8. Lessons Learned

Author: Quinton Nietfeld

The amount of lessons learned from this project is too high to count or even remember them all. As the project manager I was able to get experience in many different project management disciplines. The amount that I know now is dramatically larger than what I knew at the beginning of the project. The first lesson is that it is essential to take the extra time at the start of a project to devote purely to the planning of the upcoming project span. Even though there is a very high certainty that these initial plans will be changed and are not perfect, this will allow for an overarching understanding of what the project is, how it will be designed, how it will be developed and manufactured, and how it will be closed. This planning needs to include a organizational chart of the roles of the team members, a work breakdown plan that is organized with respect to the requirements of the project, and finally a work plan that indicates the timing of the tasks and work that needs to be completed in the project. If you give all three of these the time to fully understand the work and how it will get done will allow for a clear mind going into the project and a clear objective on how to execute it.

Another lesson that was learned the hard way was that there will inevitably be team personnel conflicts. These can come in many different forms, sometimes with a large issue that has disrupted the work of the entire project, and then sometimes they can be secretive and deteriorate the communications within the team. All of these conflicts need to be identified as soon as possible and treated like a risk in the actual project itself. This is needed because a conflict in the team can easily derail the entire project. Once identified, a resolution needs to be presented and this is the difficult part of the process. It is mostly situational and there needs to be ample amounts of communication to ensure a fair process where both parties can be heard and understood. There needs to be a way to resolve the conflict where the team can work without any disturbances.

Communication needs to stay strong and is the backbone of the entire project team. Without easy forms of communication when not in an in-person meeting the communication of the team can be harmed and there can be overlap of work and more critically work that was missed and not completed. Weekly team meetings and the use of Slack as an online communication tool proved to be effective.

9. Individual Report Contributions

9.1. Mamdooh Alkalbani

- Detailed Design - 5.2.Simulation Software
- Verification and Validation - 6.2.3. Orbit modeling propagation software

9.2. Yang Lee

- Conceptual Design - 3.1 Pointing Controls (CDD)
- Conceptual Design - 3.4 Orbit Determination (Proof Reading / Feedback)
- Design Requirement - FR 3 Scoring and Orbit Determination
- Detailed Design - 5.4.1 Scoring Software
- Detailed Design - 5.4.4 Orbit Determination Software
- Verification and Validation - 6.4.1 Scoring Test
- Verification and Validation - 6.4.4 Orbit Determination Test

9.3. Colton Ord

- Requirements Flow-Down FR 4
- Conceptual Design - 3.3.16 Scheduling Software
- Manufacturing - 4.2 Software

- Verification and Validation - 5.4.3 Scheduling Test
- Project Planning - 8.4 Cost Plan

9.4. Ryan Cameron

- Conceptual Design - 3.1 Pointing Controls
- Detailed Design - 5.1 Pointing Controls
- Verification and Validation - 6.1 Pointing Controls

9.5. Zachary Arbogast

- Design Description - Signal Reception
- Verification and Validation - Signal Reception
- Requirements Flowdown - FR 1 and all sub DRs
- Design Alternatives - Frequency Selection, Antenna Design, Radio System, CPU, Data Storage (proof reading from FFR)

9.6. Kieran O'Day

- Risk Assessment and Mitigation - 6.1 through 6.5
- Project Objectives and Levels of Success - 2.1
- Functional Block Diagram - 2.4
- Functional Requirements - 2.5
- Detailed Design - 5.1 Pointing Controls
- Test Plan - 7.5

9.7. Quinton Nietfeld

- Project Purpose
- Project Objective and Functional Requirements
- Project Planning
- Lessons Learned

9.8. Zakariya Laouar

- Requirements Development - FR 2
- Design Alternatives - 3.1 Signal Processing
- Resulting Design - 3.3 Signal Processing
- Verification and Validation - 5.3 Signal Processing

References

[1] Flat panel antenna. Personal photograph.

[2] High precision offset parabolic reflector. www.mvg-world.com/en/products/field_product_family/antenna-1/high-precision-offset-parabolic-reflector.

[3] Sunrise and sunset atmospheric effects. https://doi-org.colorado.idm.oclc.org/10.1029/2006RS003494.

[4] Radio frequencies for space communication. www.spaceacademy.net.au/spacelink/radiospace.htm#targetText=Most%20of%20the%20amateur%20radio,and%20435%2D438%20MHz%20bands, 2016.

[5] noise temperature. http://glossary.ametsoc.org/wiki/Noise_temperature, 2019.

[6] Power consumption benchmarks. www.pidramble.com/wiki/benchmarks/power-consumption, 2019.

[7] Real time satellite tracking and location predictions. https://www.n2yo.com/, 2019.

[8] Recommendation p.372-14. https://www.itu.int/rec/R-REC-P.372-14-201908-I/en, 2019.

[9] Space segment. www.gps.gov/systems/gps/space/, 2019.

[10] Ucs satellite database. www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.WL2lyPJCjNE, 2019.

[11] Gnss-sdr configuration. https://gnss-sdr.org/conf/#gps-l1-ca-receiver-using-a-usrp, 2020.

[12] Gnss-sdr parameter monitoring. https://gnss-sdr.org/docs/tutorials/monitoring-software-receiver-internal-status/, 2020.

[13] Usrp hardware driver manual. https://files.ettus.com/manual/page_install.html, 2020.

[14] European Space Agency. Satellite frequency bands. www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands, 2018.

[15] Andy. How many satellites orbiting the earth in 2019? www.pixalytics.com/satellites-orbiting-earth-2019/, 2019.

[16] Pete Bevelacqua. “yagi-uda antenna.” the yagi-uda antenna - yagi antennas. www.antenna-theory.com/antennas/travelling/yagi.php.

[17] Pete Bevelacqua. “slot antennas.” slot antenna. www.antenna-theory.com/antennas/aperture/slot.php, 2010.

[18] Pete Bevelacqua. Antenna arrays (phased arrays). www.antenna-theory.com/arrays/main.php, 2013.

[19] Pete Bevelacqua. “the horn antenna.” horn antenna. www.antenna-theory.com/antennas/aperture/horn.php, 2015.

[20] In S. Communication. Yagi antenna. Photograph.

[21] Sachdeva D. Basic yagi-uda antenna design. Photograph.

[22] Glen Dash. “designing log periodic antennas.” the secrets of the log periodic antenna. glendash.com/Dash_of_EMC/Log_Periodic/Log_Periodic.htm#targetText=The%20log%20periodic%20antenna%20works,as%20a%20half%20wave%20dipole, 2000.

[23] RF HAMDESIGN. Rf hamdesign - rotator accessories. https://www.rfhamdesign.com/products/spid-antenna--rotator/rotator-accessoires/index.php.

[24] RF HAMDESIGN. Spx-02 azimuth elevation rotor including control. https://www.rfhamdesign.com/products/spx-antenna-rotators/spx-02-az--el/index.php.

[25] Michael Henzler. Raspberry pi 4 model b from the side.

[26] Jan King. Tools for spacecraft communication and design. https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/, 2008.

[27] Robert Kllosterhuis. Lenovo's thinkpad business laptop, originally an ibm product.

[28] Van Nostrand-Reinhold Louis J. Ippolito, Jr. *Radiowave Propagation in Satellite Communications*, pages 33–34. Springer, 1986.

[29] Puri Manish. Design and simulation of double ridged horn antenna operating for uwb applications. `ieeexplore.ieee.org/document/6725860`, 2014.

[30] Bartz R. A large parabolic satellite communications antenna at erdfunkstelle raisting, the biggest facility for satellite communication in the world, in raisting, bavaria, germany. it has a cassegrain type feed. Photograph.

[31] Mess-Elektronik S. Log-periodic antenna, 250–2400 mhz. Photograph.

[32] Daniel Sancho. This microsdhc card holds 8 billion bytes. beneath it is a section of a magnetic-core memory (used until the 1970s) that holds eight bytes using 64 cores. the card covers approximately 20 bits (2 1/2 bytes).

[33] The Satellite Shop. Geosatpro 90cm offset satellite dish. `https://www.thesatelliteshop.net/geosatpro-90cm-offset-satellite-dish-p-2811.html`.

[34] Tiago De Sousa. The best memory cards for raspberry pi. `www.mymemory.co.uk/blog/the-best-memory-cards-for-raspberry-pi/#targetText=Most%20installs%20use%20an%208GB,SD%20card%20with%20no%20problems`, 2018.

[35] Stuart Sweet. "what's the difference between a log periodic antenna and a yagi antenna?" the solid signal blog. `blog.solidsignal.com/tutorials/whats-difference-log-periodic-antenna-yagi-antenna/`, 2018.

[36] Kuzmin V V. Large planar array antenna of a vhf russian mobile air defense radar, the nebo-m. it consists of 175 folded dipole antennas driven in phase. it radiates a narrow beam of radio waves perpendicular to the antenna. Photograph.

[37] Kenming Wang. 1tb seagate desktop sshd st1000dx001.

Appendices

10. Frequency Bands

L Band

The L band is the frequencies from 1 to 2 GHz. Most satellites in this band are GPS satellites and some mobile phone satellites[14]. There are approximately 135 satellites[15] in orbit that are dedicated to navigating and positioning. About 31[9] of those satellites are GPS satellites. This shows that there is a decent number of same kind of satellites emitting in the same band. An advantage of using the L band is that the GPS satellites are constantly emitting.

S Band

The S band is the frequencies from 2 to 4 GHz. The S band usually has weather satellites and communication satellites for the ISS[14]. There are about 710 satellites that are meant to be doing Earth observations[15]. This shows that there could be a lot of satellites emitting in a similar band, which could prove to be a challenge when observing our desired satellite. An advantage in this band is that some of the satellites are constantly emitting.

C Band

The C band is the frequencies from 4 to 8 GHz. C band offers more of the entertainment/communication satellites like satellite TV[14]. There are roughly 770 of these communication satellites[15]. That number does not represent the number of satellites used for satellite TV because communication satellites are also used for radios, telephones, and other things. But, there is a large enough number of communication satellites that pointing at our desired satellite may be hard. An advantage of this band is that satellite TV is constantly being emitted at high power.

X Band

The X band is the frequencies from 8 to 12 GHz. This band is not the best for us since it is mainly made up of military satellites[14]. The United States military have around 175[10] satellites currently orbiting. Even though this band does have a lesser number of satellites than most other bands, it is the band meant for the military. Since it is the military band, it could prove to be unwise to point at a their satellite and receive the signal.

Ka Band

The Ka band is the frequencies from 12 to 18 GHz. Those frequencies are used for communication satellites[14]. As previously state, there are about 770 communication satellites[15] in orbit. This suffers from the same issue as the other band, C band, that since there are a large number of communication satellites, it might prove to be difficult to observe our desired satellite.

11. Antennas

Yagi-Uda antenna designs

As shown in Figure 49, a Yagi-Uda antenna has multiple elements parallel to each other in a line. The design of the Yagi-Uda antenna consist of a single feed element while the rest of the elements are considered parasitic. Within the parasitic elements, there are two main groups, actual reflector elements that reflect the signal and director elements that direct and concentrate the signal[16]. Usually the directors are in the front of the design to help concentrate and increase the strength of the received signal while the reflectors are in the back to deflect any undesirable signals. The main design factors with a Yagi-Uda is the spacing between each element, how many elements, and the length of the elements. A Yagi–Uda antenna is a directional antenna which is a very cost effective available option, but it suffers from some drawbacks. Such antennas usually have low gains and would require an inline low noise amplifier to boost the gain to an acceptable level. It is also possible to add more elements to the antenna to improve on its overall gain performance, but this does require increasing the overall size and weight of the total antenna assembly. The second main issue is due to the antenna construction which consists of multiple parallel elements in a line that are usually half-wave dipoles made of metal rods. This means that for the bandwidth necessary for this project the dipoles required could range from 3.74mm for the 40GHz frequency all the way up to 188m for the 800MHz frequency. This shows that to use the Yagi antenna design on a broad bandwidth, the antenna would be considerable big and would hinder the steering of the antenna.

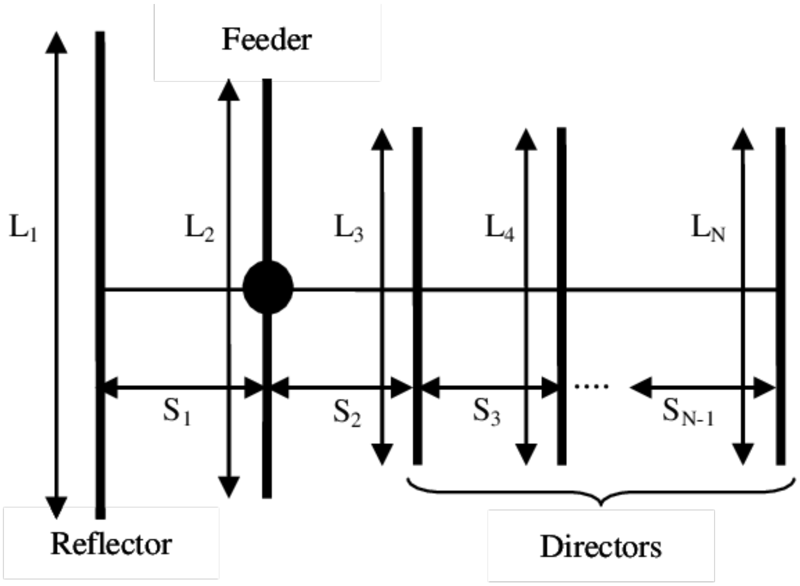


Figure 49. Basic Yagi Uda Antenna Design[21]

Logarithmic periodic antenna

A logarithmic periodic antenna is shown in Fig. 50. Even though it looks the same as a Yagi-Uda antenna, there are some key differences. Some of the differences are that the logarithmic periodic antenna has multiple sized elements which are usually half wave dipoles, with varying sizes and distance between each other. The distance between each element is based on a logarithmic function of the bandwidth of the antenna. Each element should decrease in size when compared to the previous element. The longest element is then meant for the lowest frequency in the bandwidth while the shortest is for the highest frequency within the bandwidth[22]. Another key difference is that each element in the logarithmic periodic antenna is receiving a signal while in the Yagi-Uda usually one element is receiving the signal[35]. The logarithmic periodic antenna is a small form factor multi-element, directional antenna specifically designed to operate over a wide band of frequencies. The passive option of this antenna type can have a total bandwidth ranging from 700MHz up to 35GHz on some models, which could cover the whole frequency bands that most satellites use. The main disadvantage of such a system would be the low antenna gain value of approximately 5dBi, this would imply that an inline low noise amplifier would be required to operate this antenna as a standalone option to increase its gain to an acceptable level for the system to use. The second disadvantage of this antenna type is the price of such an antenna. Some prices for this antenna are greater than our current budget. There is also the option of manufacturing this antenna which could become troublesome due to the difficulty in testing the antenna through its full frequency bandwidth to obtain a reliable gain reference for it.

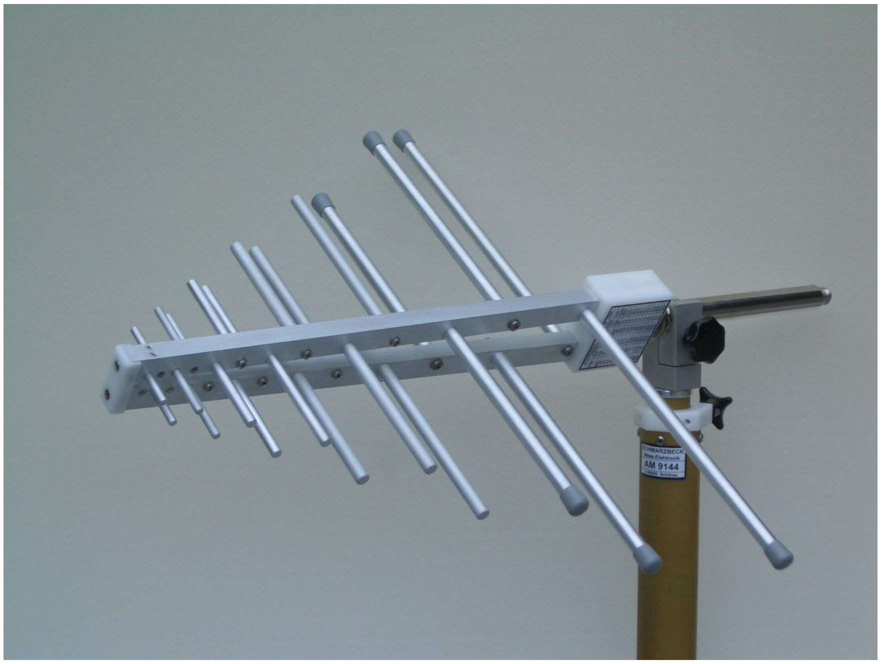


Figure 50. Logarithmic Periodic Antenna[31]

Parabolic antenna designs

The parabolic antenna is considered the least complex design options. A parabolic antenna is shown in figure 53. The parabolic antenna is an affordable type of antenna that uses a parabolic shaped curved reflector surface to direct the radio waves to a central focal point to be picked up.The main advantage of a parabolic antenna is its high directivity that allows it to receive radio waves from one particular direction only. The design of the parabolic involves a circular dish that reflects the signal to a focal point to be pickup. The design parameters with a parabolic antenna is the size of the dish which depends on the tuned frequency and the desired gain value, and the beam width angle achievable with that antenna size on that specific selected frequency.

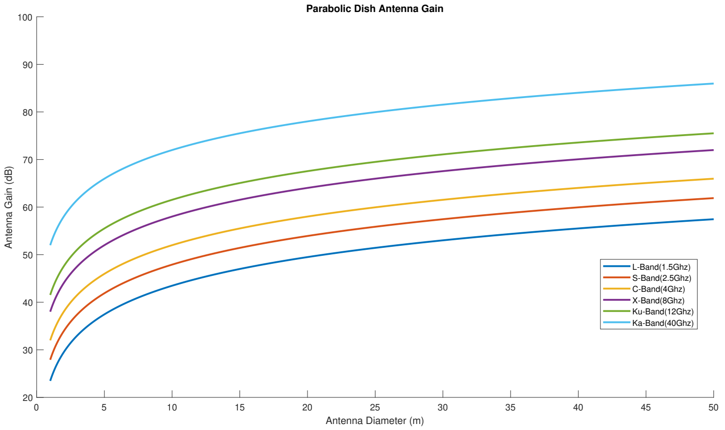


Figure 51. Ideal conditions Parabolic antenna gain vs antenna size plot

As shown in figures 51, and 52 this type of antenna has some of the highest gains and narrowest beam-widths from any other antenna type, but in order to achieve those gains and narrow beam-widths the parabolic reflector must be much larger than the wavelength of the radio waves used. Due to this fact, the parabolic antennas are usually used in high frequency bandwidth of the radio spectrum, since the wavelengths are small enough that a conveniently-sized reflector can be used. This means that the gain for a fixed sized parabolic antenna increases as the frequency increases and decreases as the received frequency decreases.

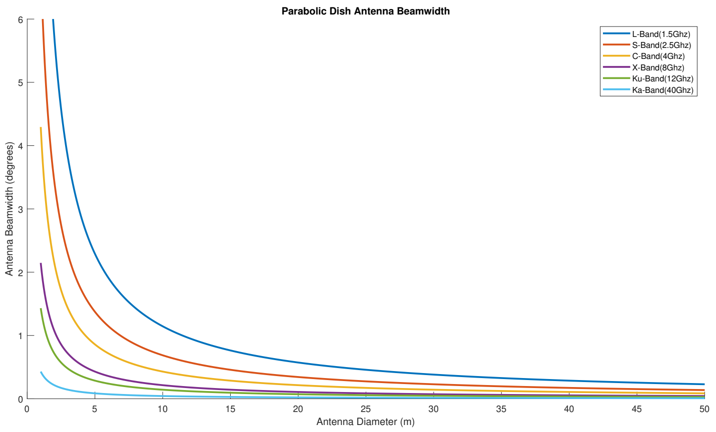


Figure 52. Ideal conditions Parabolic antenna beam-width vs antenna size plot

Figure 53. Parabolic Antenna[30]

Flat panel antenna designs

A flat panel antenna is a flat antenna with multiple slots in it which all act as smaller size separate antennas which are then combined to increase the overall gain of such an antenna. The slot size/shape and the number of slots are the design variables when choosing a flat plate antenna. The size/shapes of the slot depends on the frequency of the incoming signal while the total number of slots affects the total gain[17]. In figure 54 it shows a hypothetical flat panel antenna. Flat Panel antennas are an excellent option for their gain and directivity if size and weight are the most important factors in the antenna design. Unfortunately they are physically manufactured to only perform at a selected narrow bandwidth which is commonly at the Ultra High Frequency (UHF) frequencies.

Figure 54. Flat Panel Antenna[1]

Hybrid parabolic dish with logarithmic antennas

A hybrid parabolic dish with logarithmic antenna combines the best aspects of both antennas. The design has the reflector dish that reflects all of the signals to a focal point and the logarithmic antenna is then placed in the focal point. This allows the system to deflect and concentrate more of the signal than with a normal logarithmic antenna would normally be capable of achieving, while the logarithmic antenna at the focal point allows the reception of a wider bandwidth. Figure 55 shows an image of a hybrid parabolic dish with logarithmic antenna. The hybrid parabolic dish with a logarithmic antenna as the feed-horn is a unique antenna design that combines the benefits of the parabolic dish with the logarithmic antenna. The wide bandwidth receiving capability of the logarithmic antenna is added to the high gains and directivity which are only possible with the parabolic antenna reflector which then can produce a very versatile antenna receiver. The foremost disadvantage of such a system is the cost of the periodic logarithmic antenna and the necessary requirements that are needed to operate it. To operate it in that very broad frequency bandwidth of the logarithmic antenna the feeder line cable and the receiver have to both have the capability to work in that whole bandwidth with little attenuation and noise.

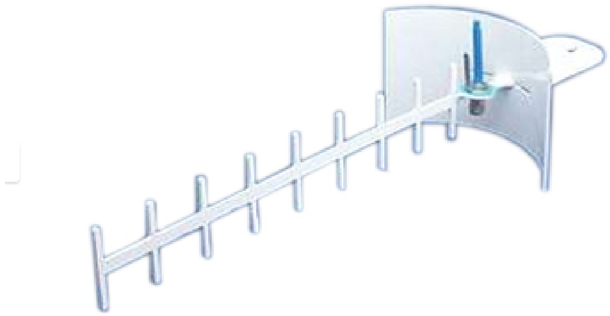


Figure 55. Hybrid Parabolic Dish with Logarithmic Antenna[20]

Hybrid parabolic dish with Double-Ridged Waveguide Horn Antenna

This is the most complex design considered because of all of the elements within. The parabolic dish helps feed and concentrate the signal to the horn antenna by reflecting the signal to the designated focal point, where the horn is. The horn can then be thought of as a funnel that guides the signal to the double-ridged antenna elements, where the designed logarithmic distance between the ridges chooses the overall bandwidth that the element can operate in. This is a very versatile antenna that can also achieve high power transmissions on the same broad-bandwidth it is design for. The reason is because it behaves as a variable slot antenna such that it tunes itself to the required ridge distance depending on the desired selected frequency[19]. It can be thought as a infinite logarithmic antenna due to the double ridge elements are actually designed using the same periodic logarithmic calculations used in the periodic logarithmic antenna[29]. A hybrid parabolic dish with double-ridged waveguide horn antenna is shown in Fig. 56. A hybrid parabolic dish with double-ridged waveguide is considered to be a very reliable antenna when picking up signals in its bandwidth, whether it is at high frequencies or low frequencies. The antenna design, by itself does not have a high gain, but in order to get a greater gain, the antenna must be coupled with a parabolic dish. With the additional parabolic dish, we have the option to pick its direction selectivity based on the parabolic dish's specifications. This antenna is also considered one of the more expensive options because it has the ability to transmit using high power and also receive on the same bandwidth it can operate on. The antenna itself gives us the options to pick its direction selectivity since it is dependent on the specification of the parabolic antenna itself.

Figure 56. Hybrid parabolic dish with Double-Ridged Waveguide Horn Antenna [2]

Antenna Arrays

An antenna array is shown in Fig. 57. The theory of an antenna array to place multiple sets of antennas together on the same surface[18]. Antenna arrays means that it can work in one plane or in 3D space thanks to new technologies. It also has a high gain for its desired bandwidth. The design also allows antenna arrays to be extremely directional depending on how many elements are used. For the antenna arrays to be used in our project, it will require additional parts such as inline amplifiers and a low noise solid state switch between elements. The scanning performance of the antenna array can be considerably improved if it is coupled with a real time spectrum analyzer. This antenna is quite expensive though, and it is extremely complex to build.

Figure 57. Antenna Array [36]

12. Orbit Determination

Doppler Shift

Doppler Shift is the change in frequency of a signal as it is either moving towards or away from the receiver. A good example of this is what an individual experiences when watching emergency vehicle goes by with its sirens going off. As the emergency vehicle is moving closer towards the individual, the individual hears a higher pitch while as the vehicle is moving away, the individual hears a lower pitch. The reason this happens is that the waves become more compressed on its way to the individual while it is more expanded when it is moving away. In Fig. 58, it shows a depiction of the emergency vehicles passing by. This can then be applied to determine the orbit of a satellite. When a satellite emits at a radio frequency, the ground station can then calculate the Doppler Shift. This can only happen, though, if the frequency the satellite is emitting is known. Another issue that comes with using Doppler Shift is that in order to calculate the orbit, at least six different Doppler Shifts must be observed for a particular satellite.

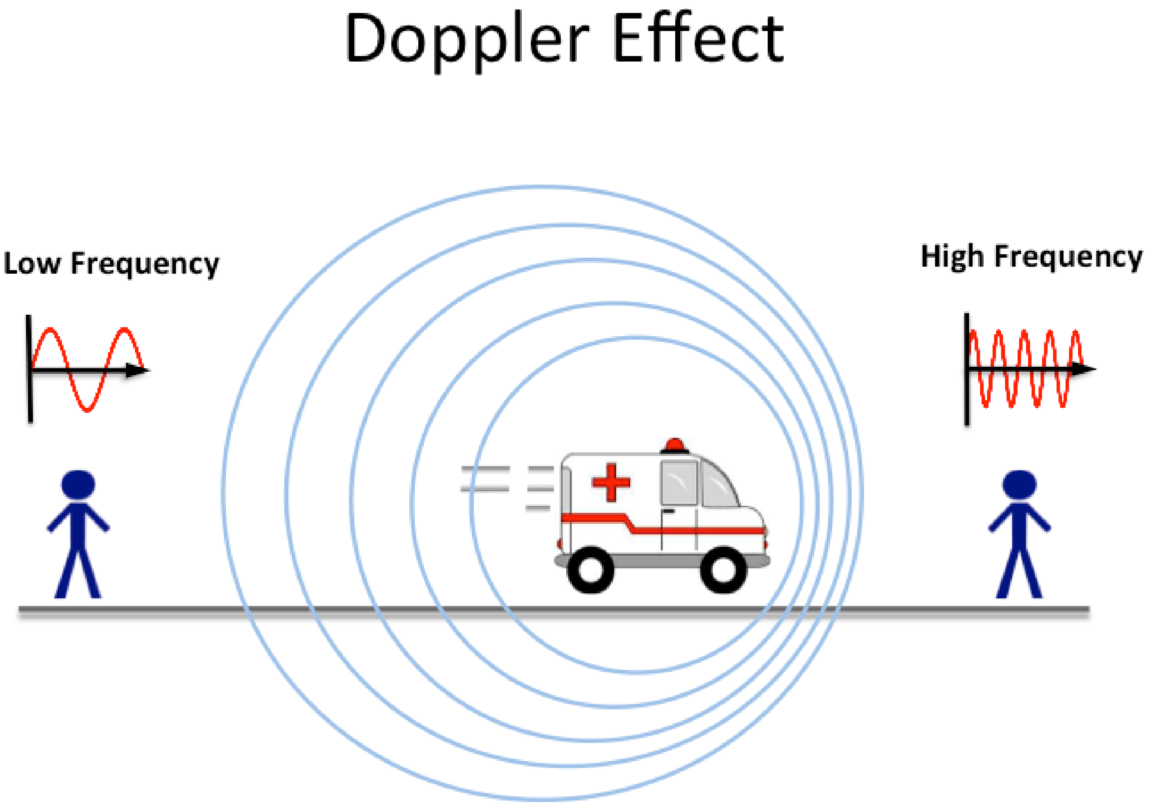


Figure 58. Depiction of Doppler Shift

Triangulation

Triangulation uses the known location of two points to find an unknown location of a third point. This is done by forming a triangle with the three points, which is shown in Fig. 59. To apply that to orbit determination, two ground stations, separated by a certain distance, have to receive the same signal from the satellite. Then triangulation is used to find the position of that satellite at that time. Triangulation only gives the position of the satellite and nothing else. To then do the orbit determination, 3 signals from the same satellite needs to be received from both ground stations. Once all 3 signals have been converted into positions of the satellite, Gibb's Method can be applied to determine the orbit of the satellite.

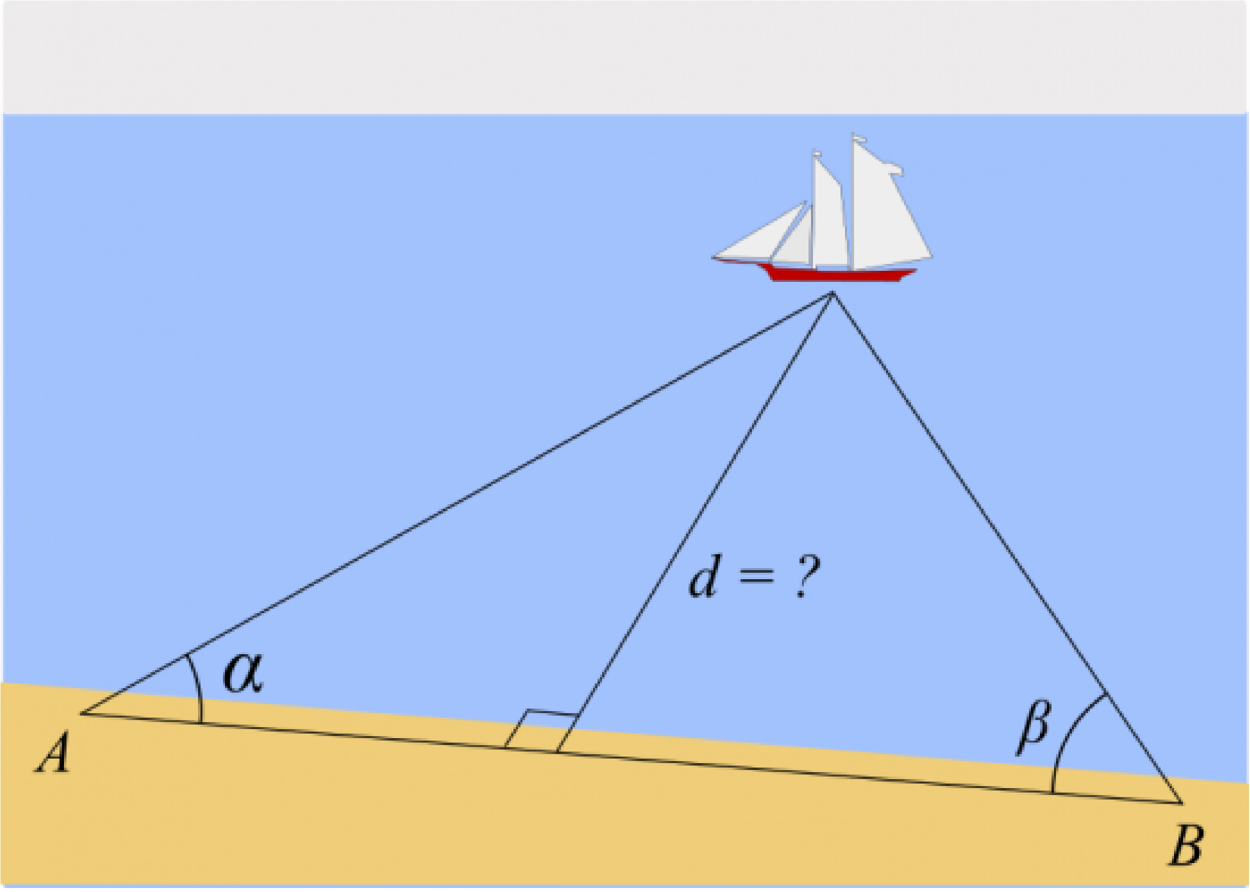


Figure 59. Depiction of Triangulation

13. CNC GCode

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