Spring Final Review

P4LO

Positioning **F**or **L**unar **O**perations

Team Advisor: Dr. Jade Morton

Agenda

1. Project Purpose and Objectives
2. Design Description
3. Test Overview
4. Test Results
5. Systems Engineering
6. Project Management

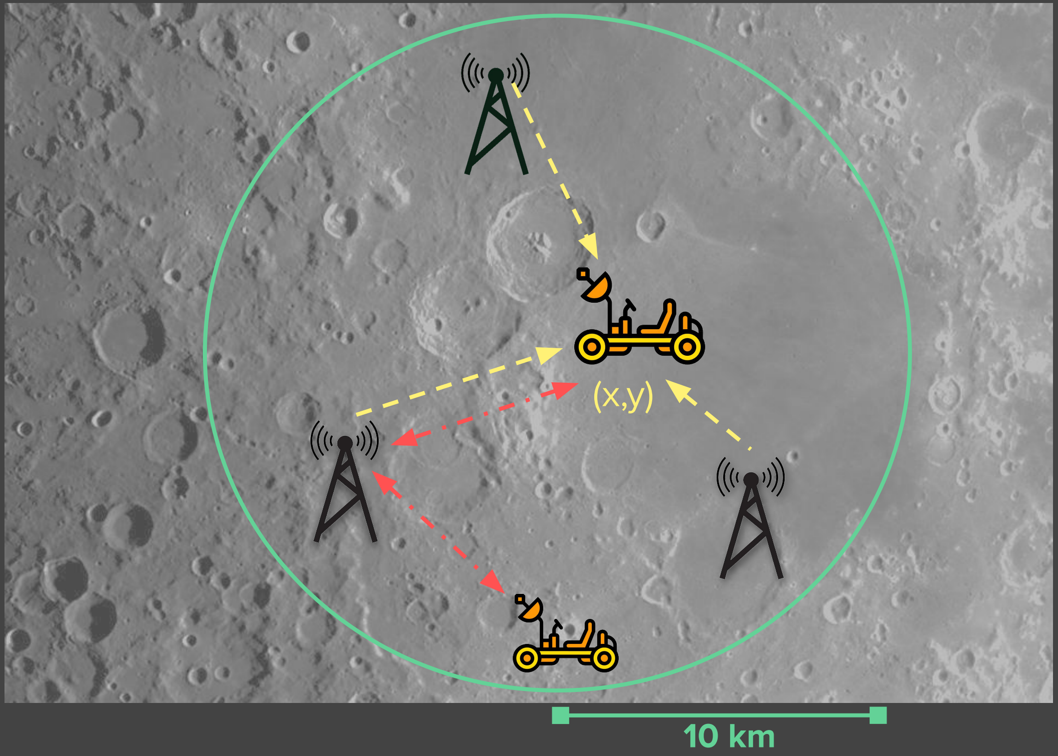
Project Purpose and Overview

Lunar CONOPS

- Provide ground-based positioning and communication to the South Pole
- 10 km radius region

One-way positioning messages

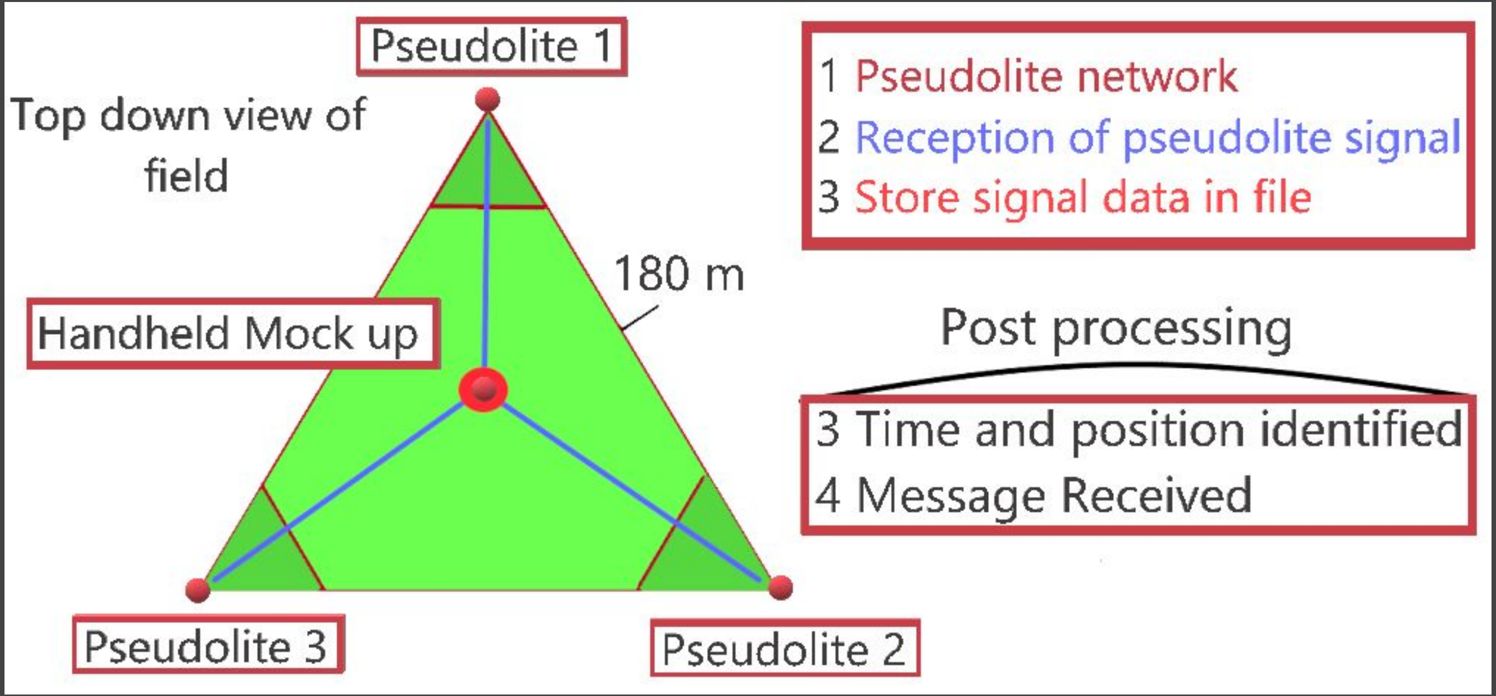
Two-way communications



Mission Statement

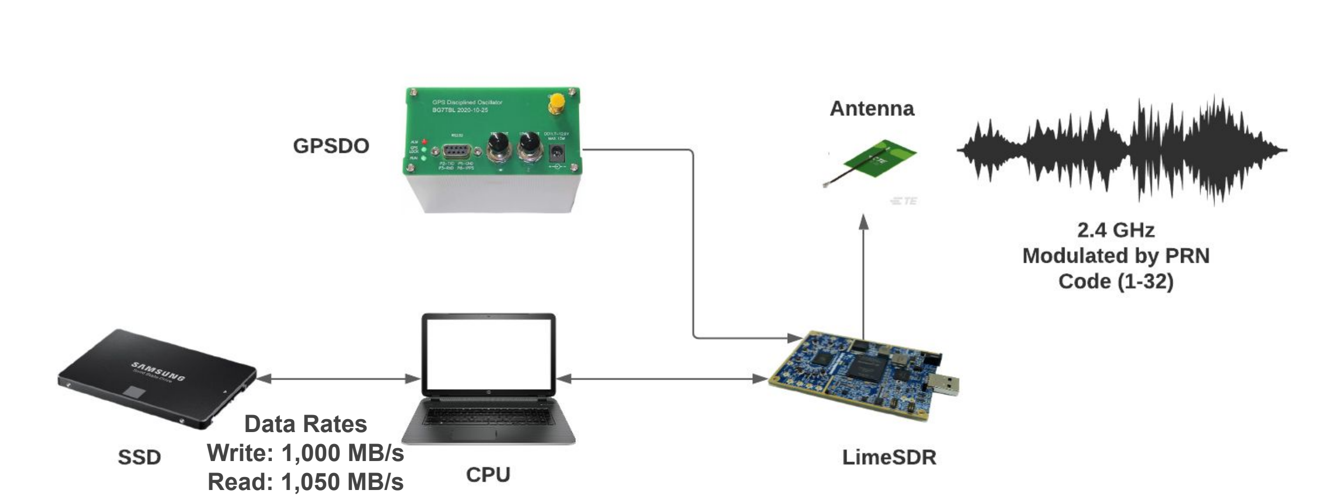
P4**L**O (**P**ositioning **For** **L**unar **O**perations) is a prototype network of software defined radios that demonstrates an architecture for the lunar communication and positioning system LunaNet.

P4LO CONOPS


Pseudolite 1
Top down view of field
180 m
Handheld Mock up
Pseudolite 3
Pseudolite 2
1 Pseudolite network
2 Reception of pseudolite signal
3 Store signal data in file
Post processing
3 Time and position identified
4 Message Received

What is a Pseudolite?

- A portable ground station
  - Transmits positioning messages
  - Receives user communication messages



Mission Success

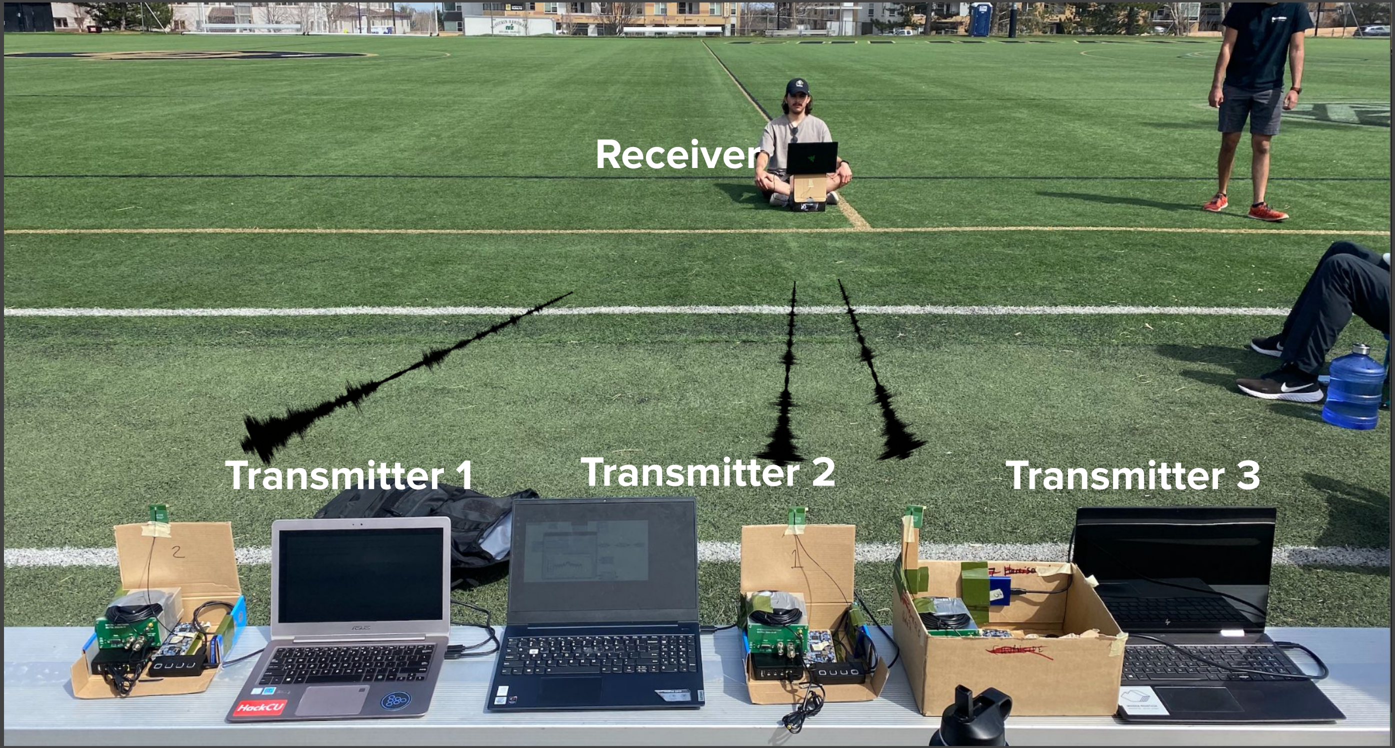
- Key Functional Requirements
  - Scalable Positioning System
    - Sub 10 (m) positioning within specified area
    - 30 ns 1-sigma transfer time
  - Communication Network
    - Communication operating between 2.4 - 2.48 GHz
    - 1 MHz Signal Bandwidth
    - Framework allowing for up to 170 users communicating within region
    - Data rate of at least 1 kilobit per second

Levels of Success

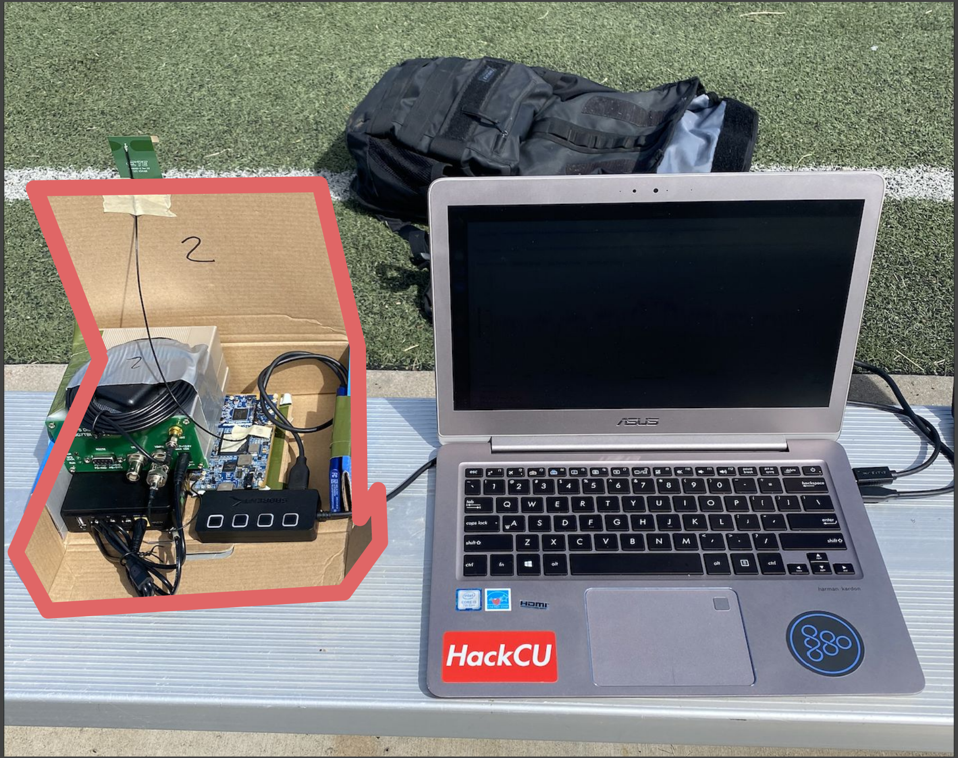
1	Hardware/Software interfacing	Ubuntu environment + dependencies, GNURadio, LimeSDR	Completed
2	Wireless Transmission	Wireless transmission. Getting LimeSDR to transmit over the air (simple tx/rx test)	Demonstrated
3	Acquisition	Acquiring PRN codes	Demonstrated
4	Positioning	Ranges from acquisition results + positioning algorithm to compute position solution	Capability In Place
5	Data Transmission	Transmit a .txt data file over the air at specified data rate	Capability In Place

Design Description

Design



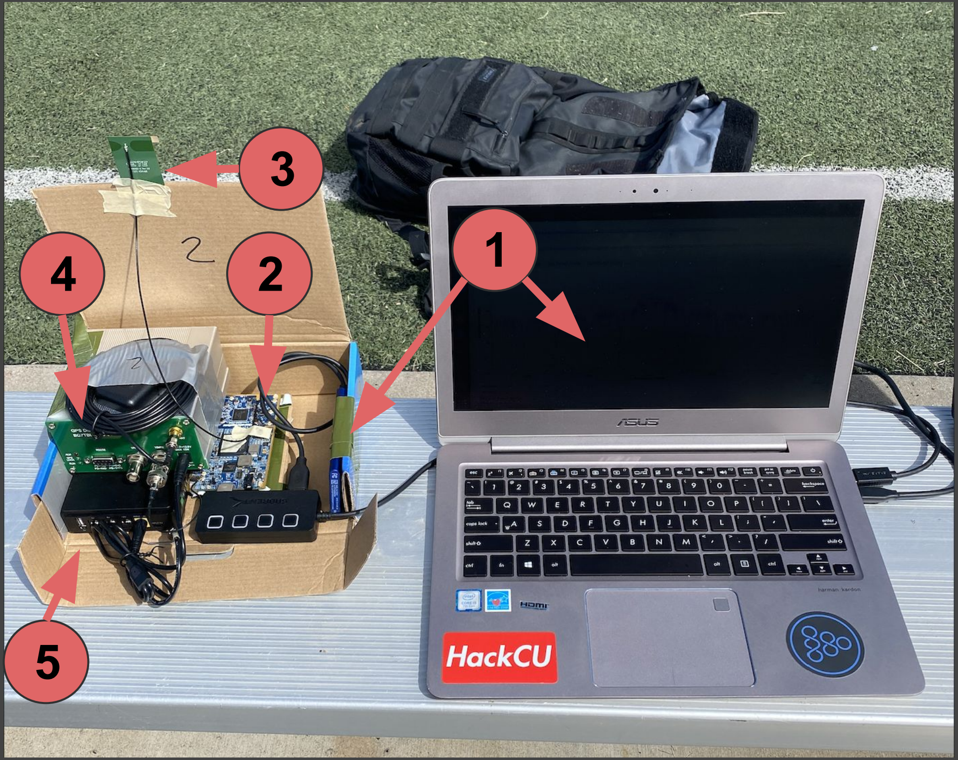
Changes since TRR



1 Housing:
- Used for portability and handling.

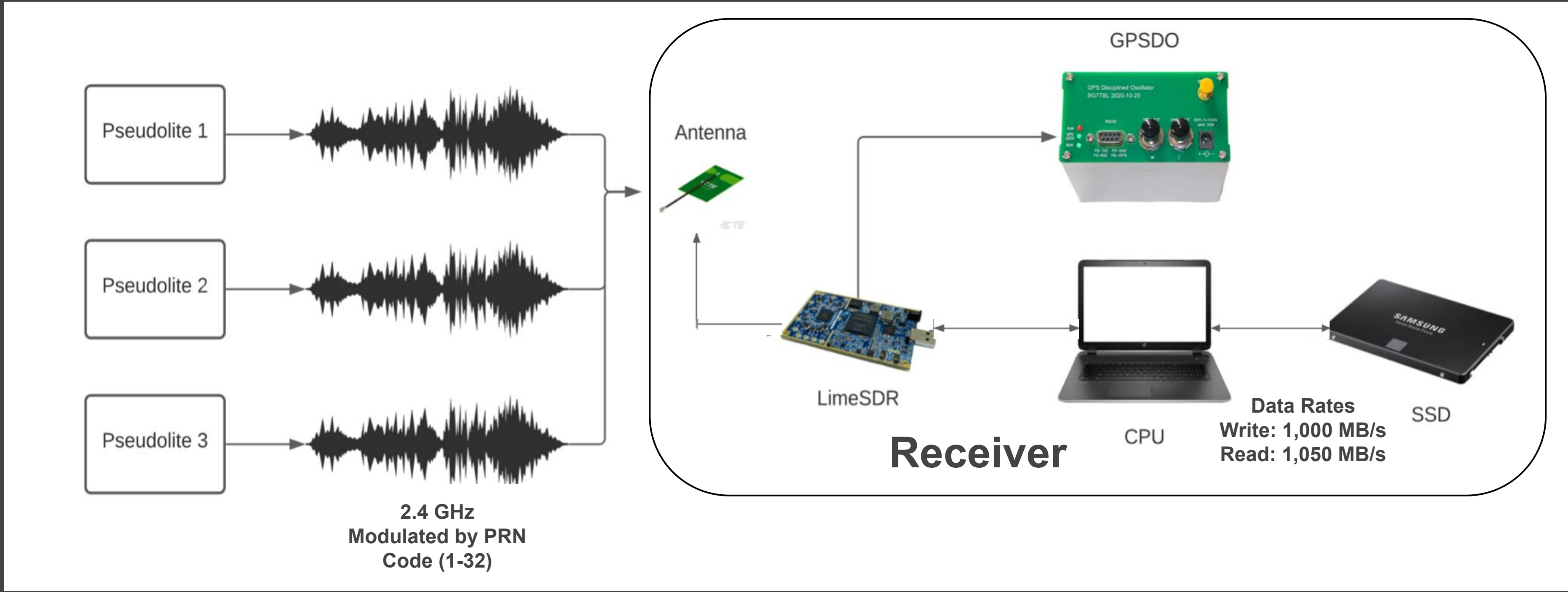
2 No Tripods.

Physical Design/Critical Project Elements

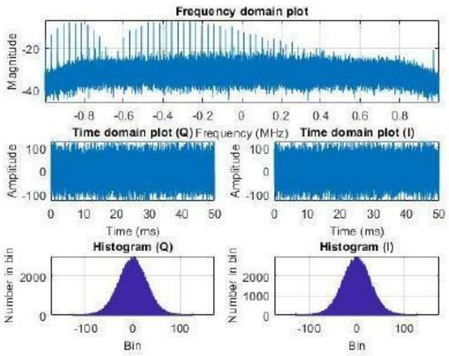


1. Laptop
   - GNU Radio
   - SSD (for Ubuntu OS)
2. LimeSDR
3. Antenna
   - [Range: 2.4 - 2.48 GHz]
4. GPS Disciplined Oscillator
   - Clock Override
5. Battery
   - 10,000 mAh, 12V @1.25A

Hardware FBD

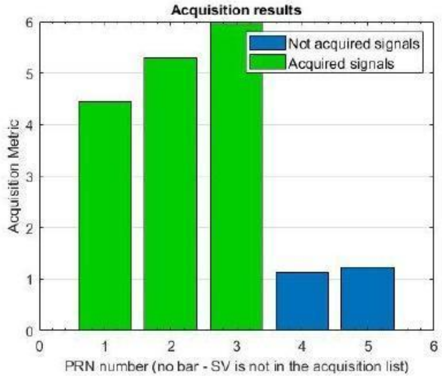


Software FBD



Raw data collection

→



Pseudolite synchronization & range determination

→

$$d_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2}$$

$$d_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2}$$

$$d_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2}$$

Position calculation

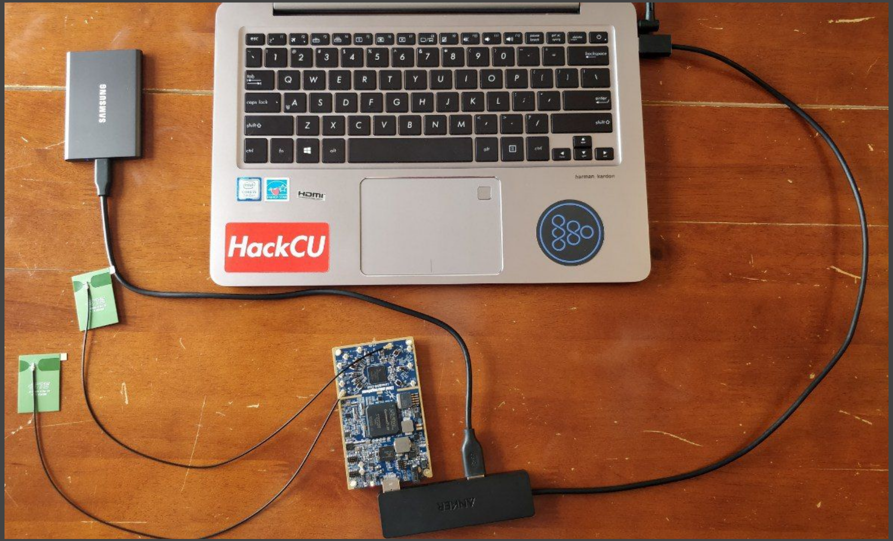
Test Overview

Testing Overview

- Basic communication between TX and RX
- Oscillator override
- Short-range acquisition (Multi-TX)
- Long-range acquisition (Multi-TX)

Basic Communication Test

- Integrate hardware and software
- Transmit one FM audio file from SDR transmit port and receive it on the SDR receive port, play results



Level of Success: 1

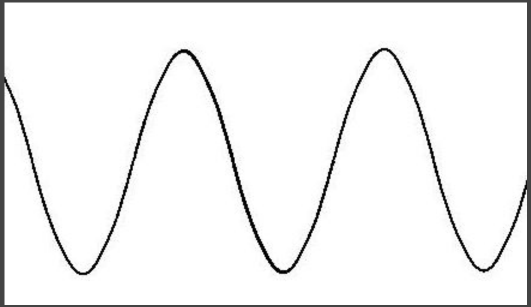
Oscillator Override

- Require a more stable oscillator for higher quality transmission and reception
- Will be using a GPS-disciplined oscillator (GPSDO)
- Verification will be done by setting receiver as a GPS receiver and comparing position solutions

LimeSDR

+

GPSDO



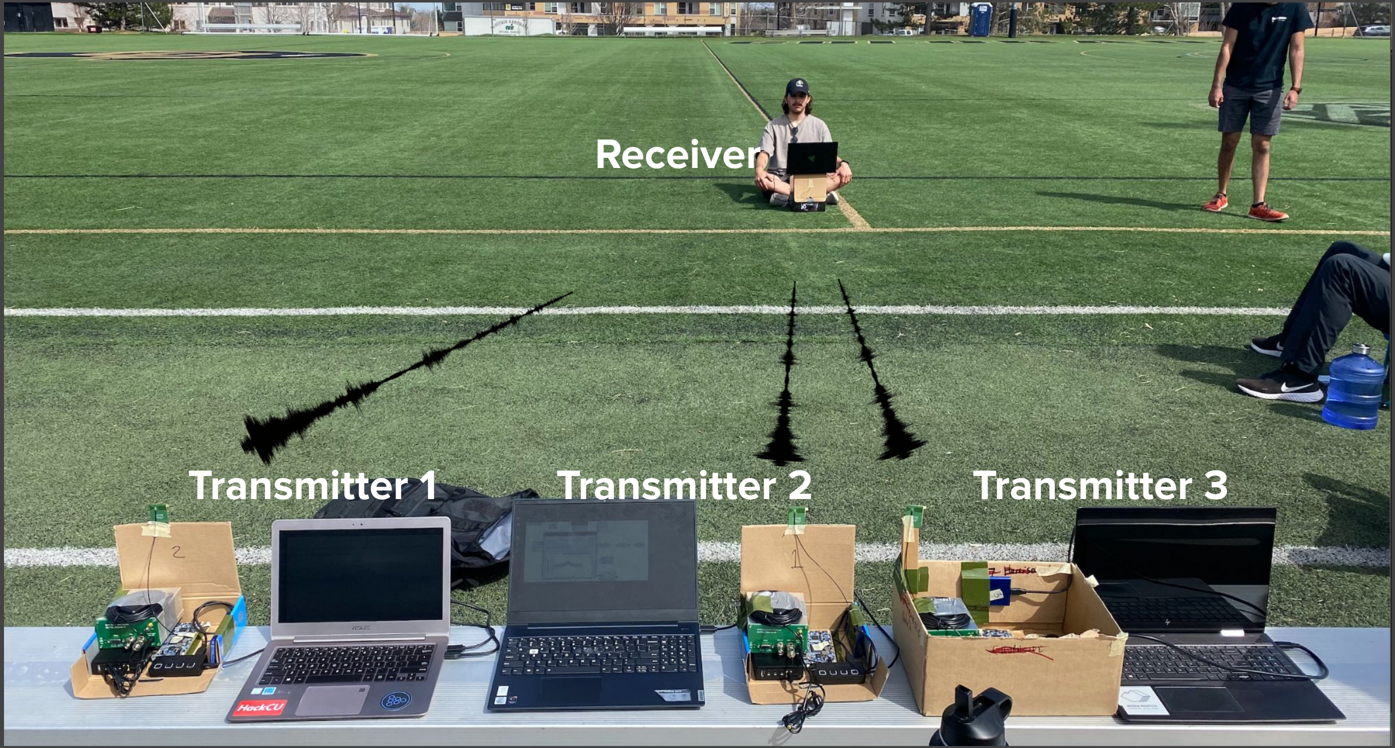
Level of Success: 2 and 5

Short range acquisition (multi-tx)

- Acquisition
  - All transmitters are sending signals on the same frequency
  - Each signal is modulated by a unique Code Division Multiple Access (CDMA) code
  - Acquisition allows for the receiver to pick out individual signals
    - Language analogy
- Test
  - Have 3 pseudolites transmitting at 2.4GHz with their unique codes
  - Receiver in same room
  - Pick out the individual signals

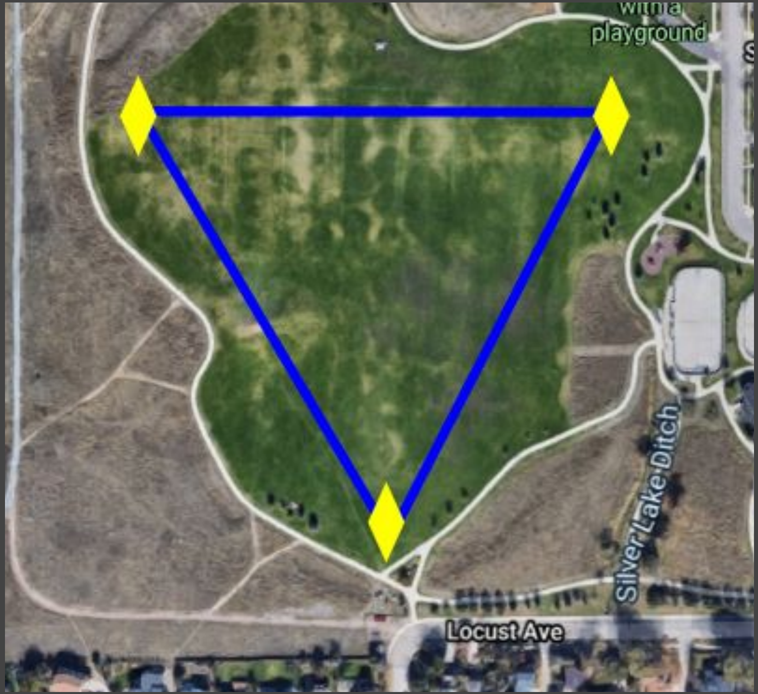
Level of Success: 3 and 4

Short range acquisition (multi-tx)



Long range acquisition (multi-tx)

- Test
  - Same setup as before, but now transmitters are positioned at a distance >100m
  - Will be done outdoors
  - Right: Wonderland Park, pseudolites represented by yellow diamonds



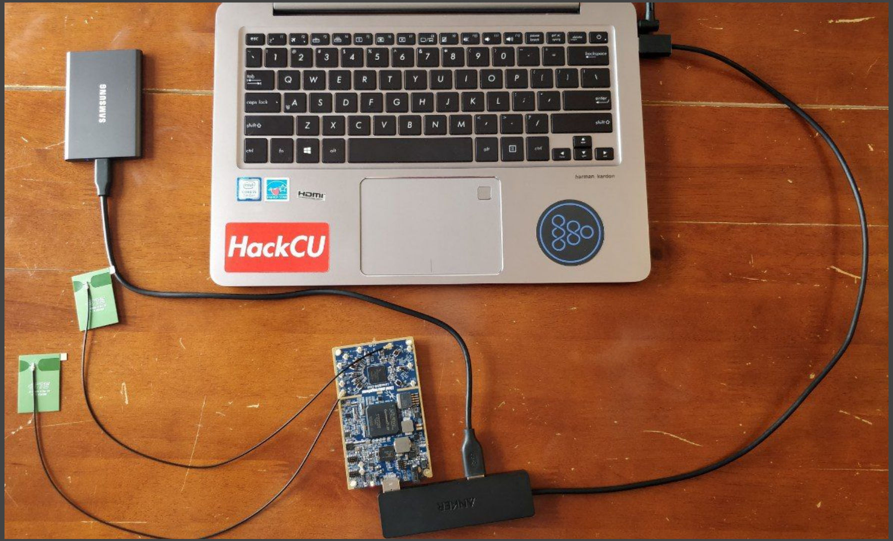
Level of Success: 3 and 4

Test Results

Basic Communication Test

- Integrate hardware and software
- Transmit one FM audio file from SDR transmit port and receive it on the SDR receive port
- Verifies **FR4** and **FR5, DR1.2**

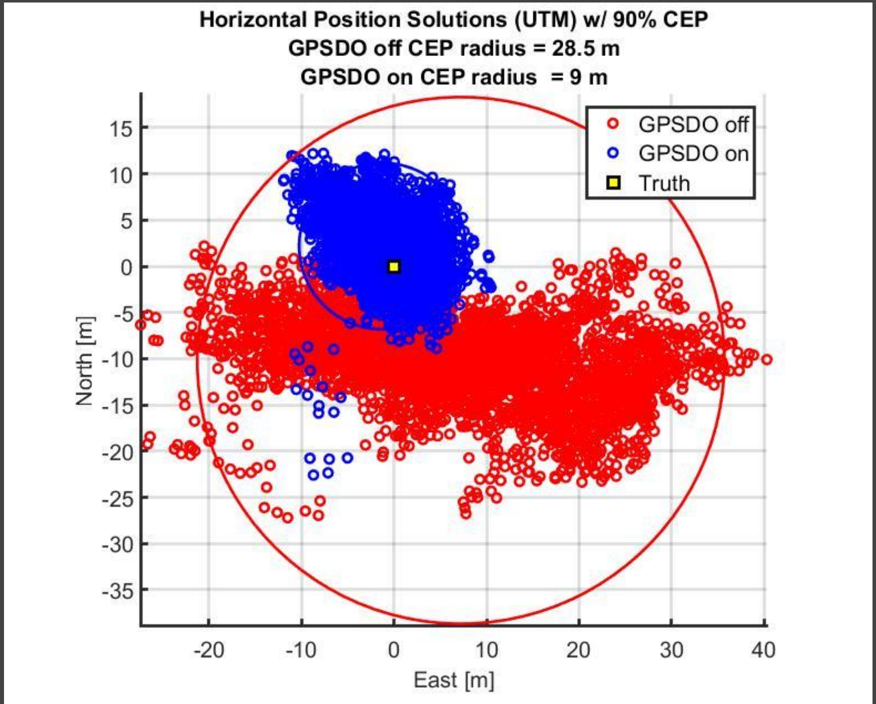
Level of Success: 1



Clock Override Test

- Compared performance of:
  - LimeSDR + onboard oscillator
  - LimeSDR + GPS-disciplined oscillator (GPSDO)
- Setup LimeSDR as a GPS receiver
- Indirect measure of clock stability/performance

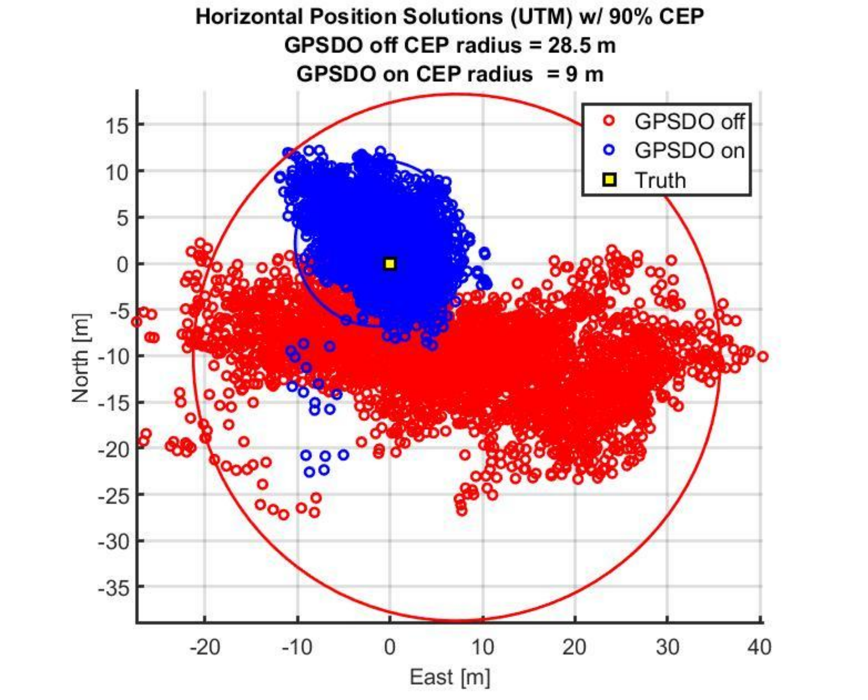
	CEP 90% radius (m)	Mean pos. Error (m)
Onboard	28.5	39.5
GPSDO	9	16.5



Clock Override Test

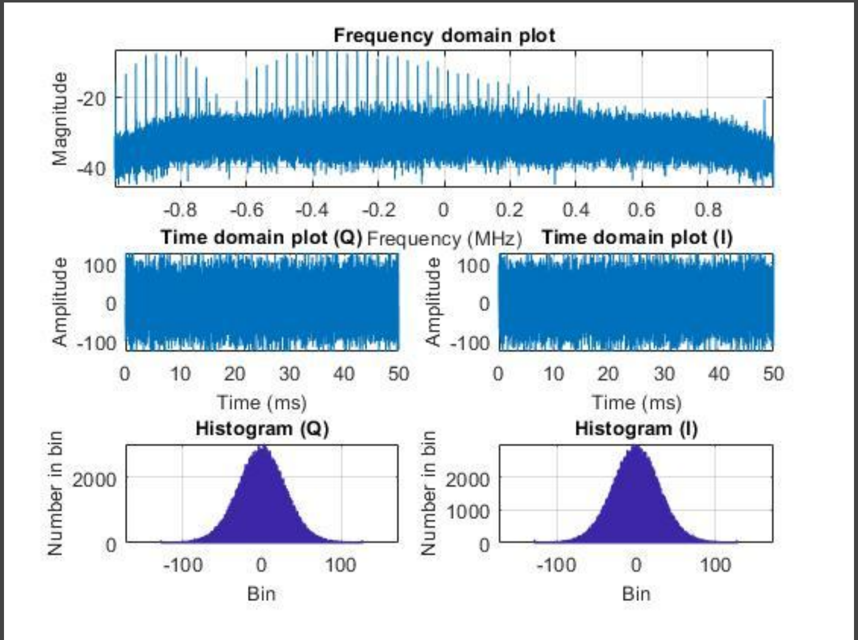
- Demonstrates that positioning algorithm works
  - CEP radius satisfies <10m positioning requirement
- Using GPS satellites as opposed to the P4LO pseudolites
- Verifies **FR3, DR3.2.**

Level of Success: 2 and 5



Short Range Acquisition (Multi-Tx)

- Transmitted PRNs 1-3
- Raw data collected by receiver
- Spectrum and time domain plots can be seen on the right,

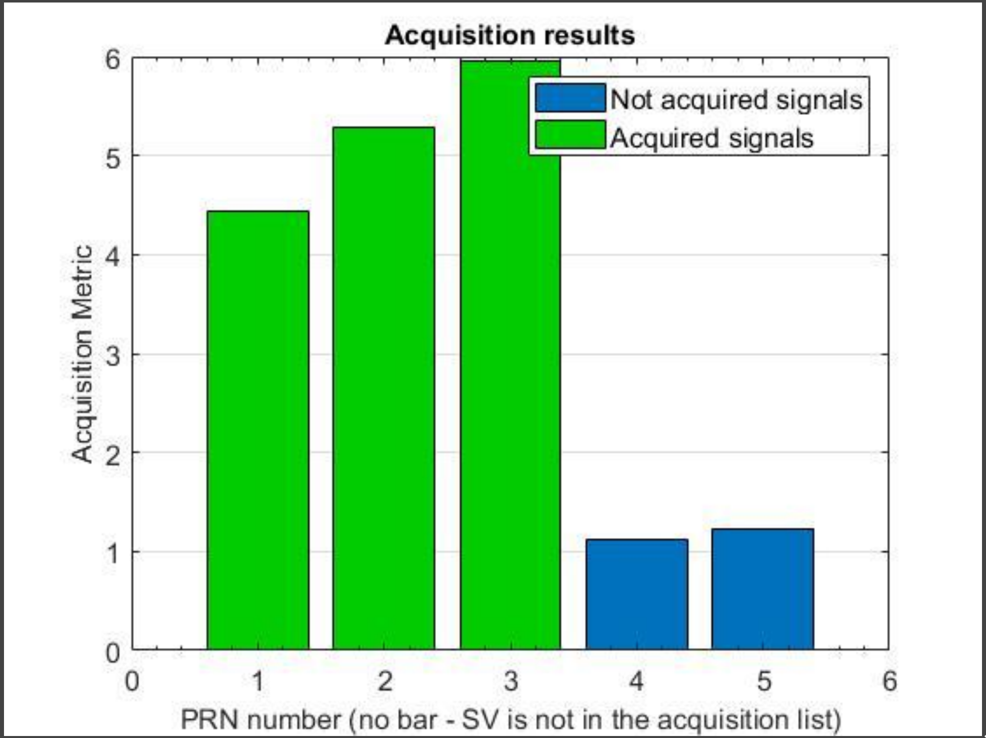


Purpose | Design | Test | **Results** | Systems | Management

Short Range Acquisition (Multi-Tx)

- Transmitted PRNs 1-3
- Attempted to acquire PRNs 1-5
- Acquired 1-3
- Acquisition metric: ratio between 1st and 2nd strongest correlation peak
  - A measure of SNR
  - >2 for successful acquisition
- Verifies **FR6** and **DR6.1**

Level of Success: 3 and 4

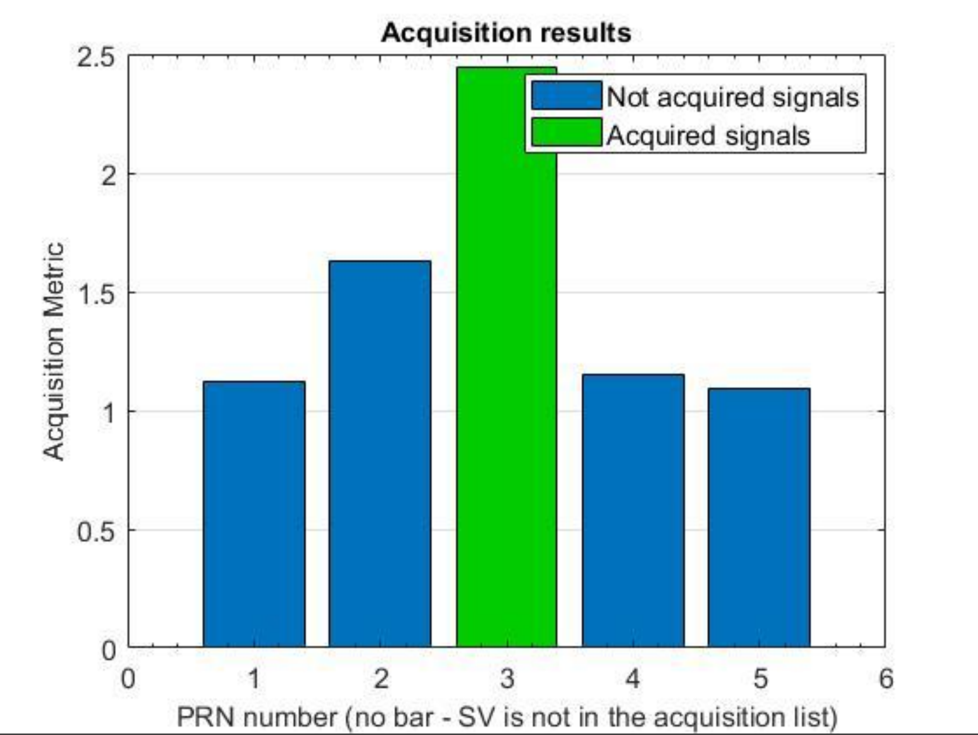


Long Range Acquisition (Multi-Tx)

- Rx-Tx Distances >100m
- Managed acquisition but with major caveats
  - Longer processing times (very noisy signals)
  - Needed better antennas and signal amplification (tx)
- Shows foundation for **DR6.2**

Level of Success: 4

Level of Success: 5

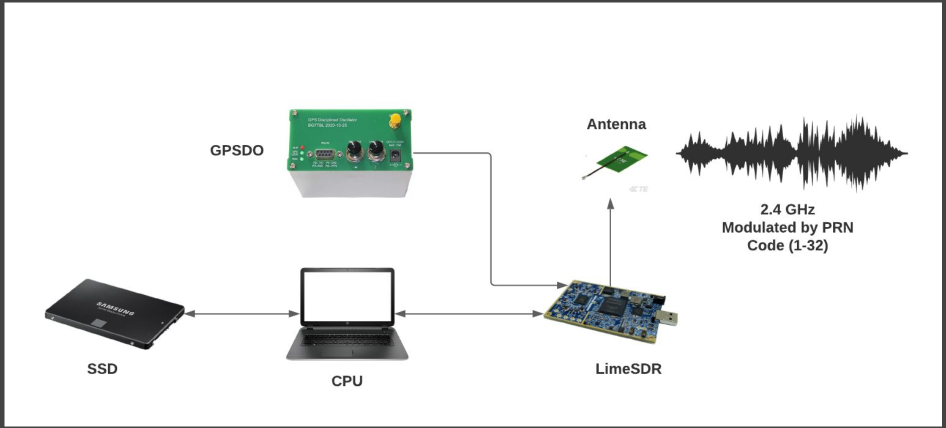


Long Range Acquisition (Problem Solving Approach)

- **Problem**
  - Low Power
  - Noise
- **Ran the following tests**
  - Wired Power Test
  - Antenna angle test
  - Upgrade system with a low noise amplifier (LNA) and different antenna

Wired Power Test

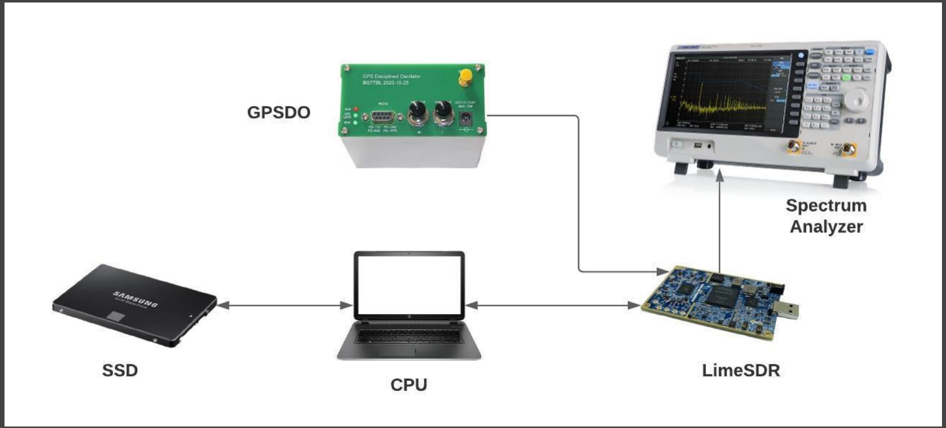
- Wired setup to test power coming out of LimeSDR



Original transmitter setup

Wired Power Test

- Wired setup to test power coming out of LimeSDR
- Transmitter -> Spectrum Analyzer
- 1mW or 0dBm
- Validates transmit power requirements
- Narrows issues to an antenna efficiency problem

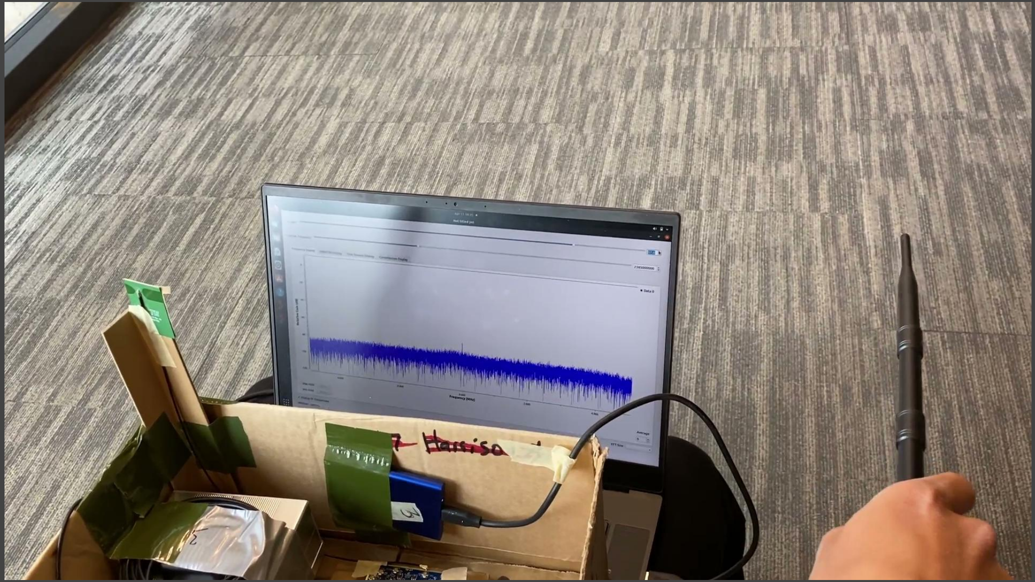


Wired transmitter setup

Wired Power Test: ✔

Antenna Orientation Test

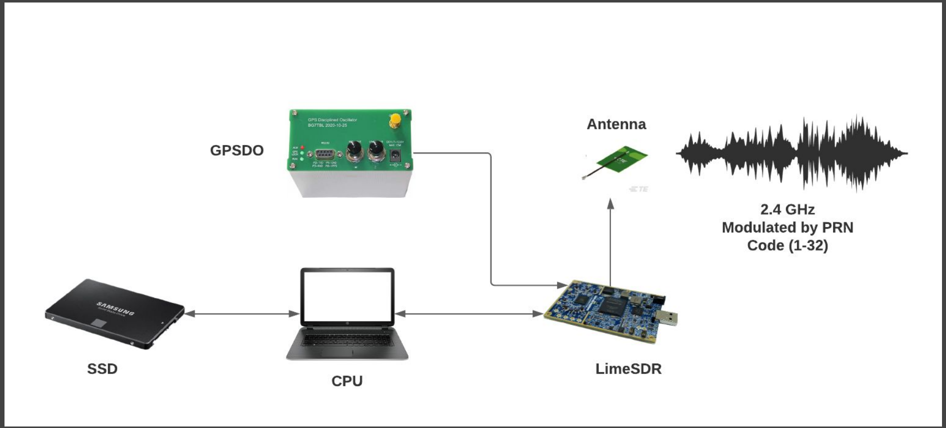
- Verified inconsistencies in patch antenna polarization and gain pattern
- Alignment in rx/tx antennas responsible for long-distance acquisition issues



Problem Identified: Antenna Gain Pattern

Upgraded pseudolite

- More reliable antenna
  - Better documentation
  - Known polarization
  - Known gain pattern
- Low-noise amplifier (LNA)
- Upgraded ⅓ of pseudolites
- Demonstrated performance improvements
  - Increased 1m received power from -35 dBm to -15 dBm



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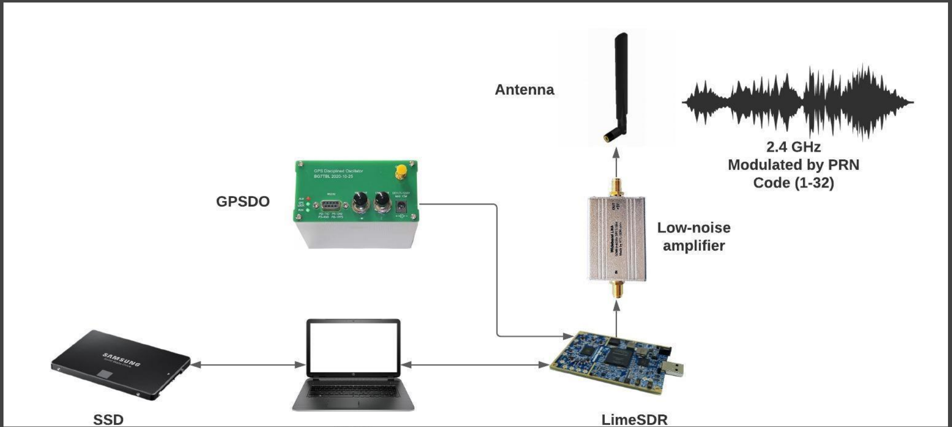


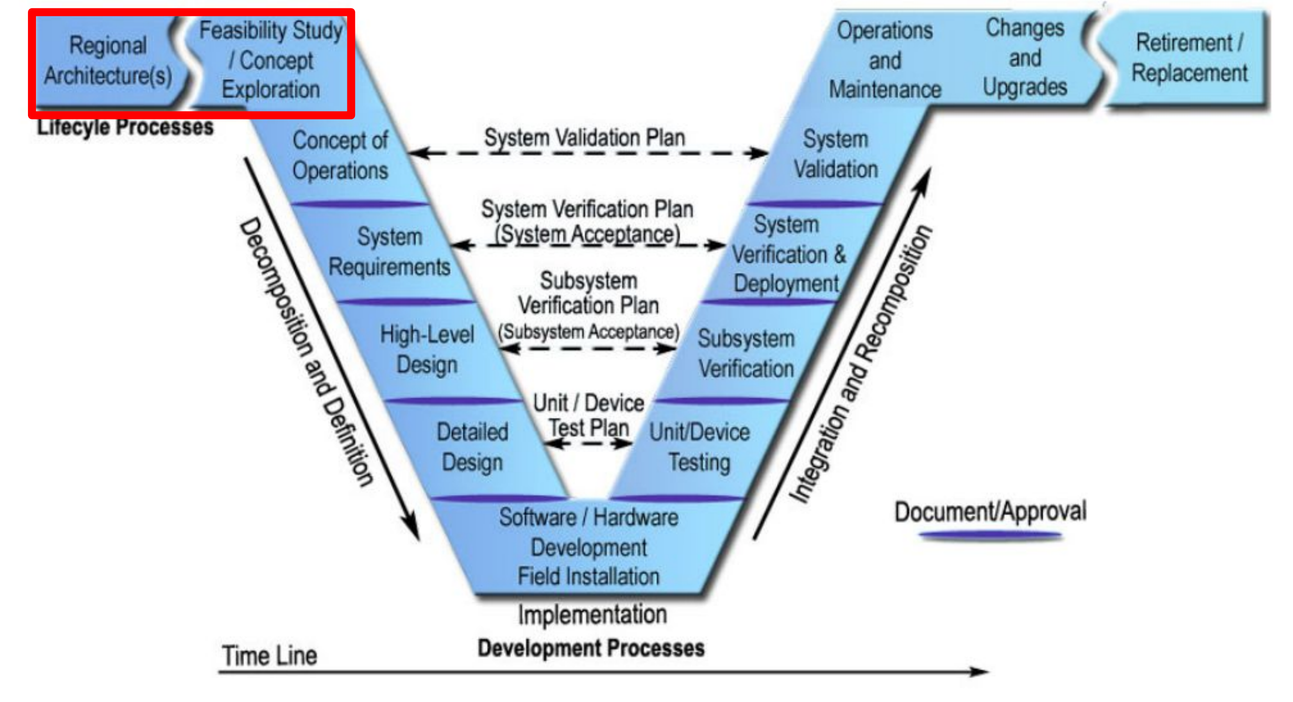
Upgraded transmitter setup

Consistent Long Range Acquisition: ✓

Positioning Capability in Place: ✓

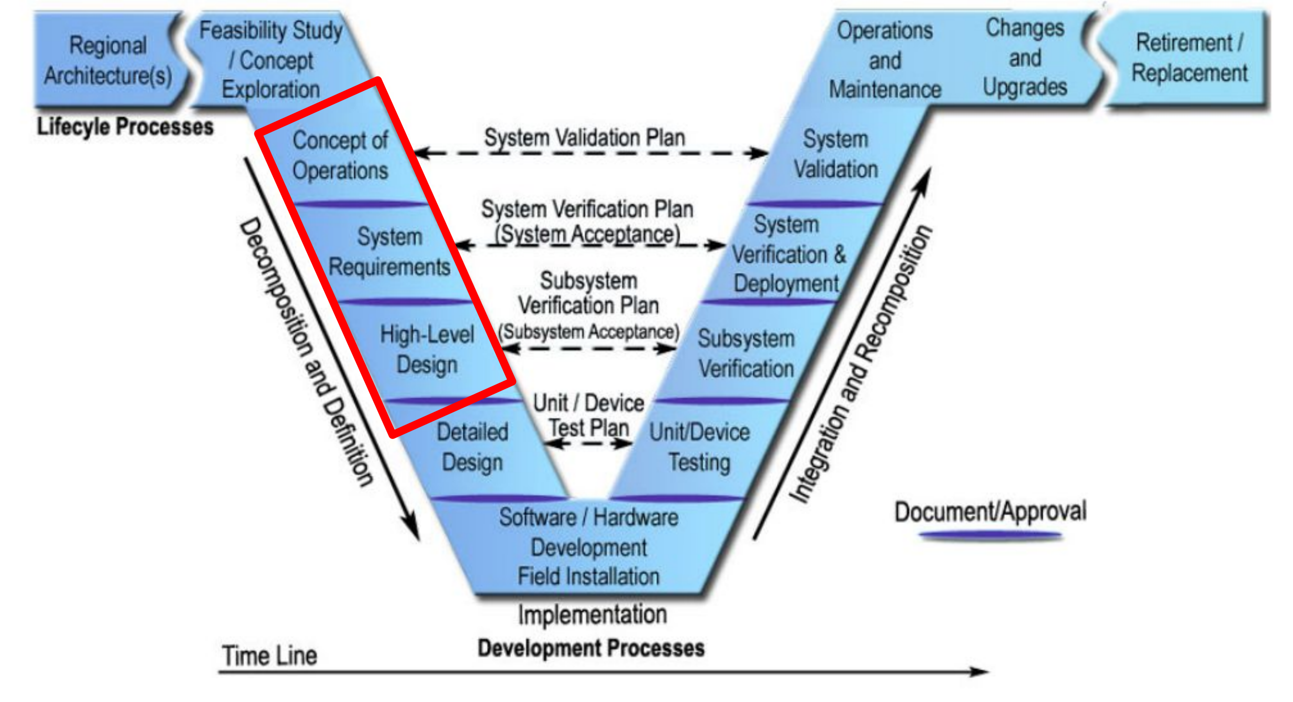
Systems Engineering

Approach - Initial Problem Statement



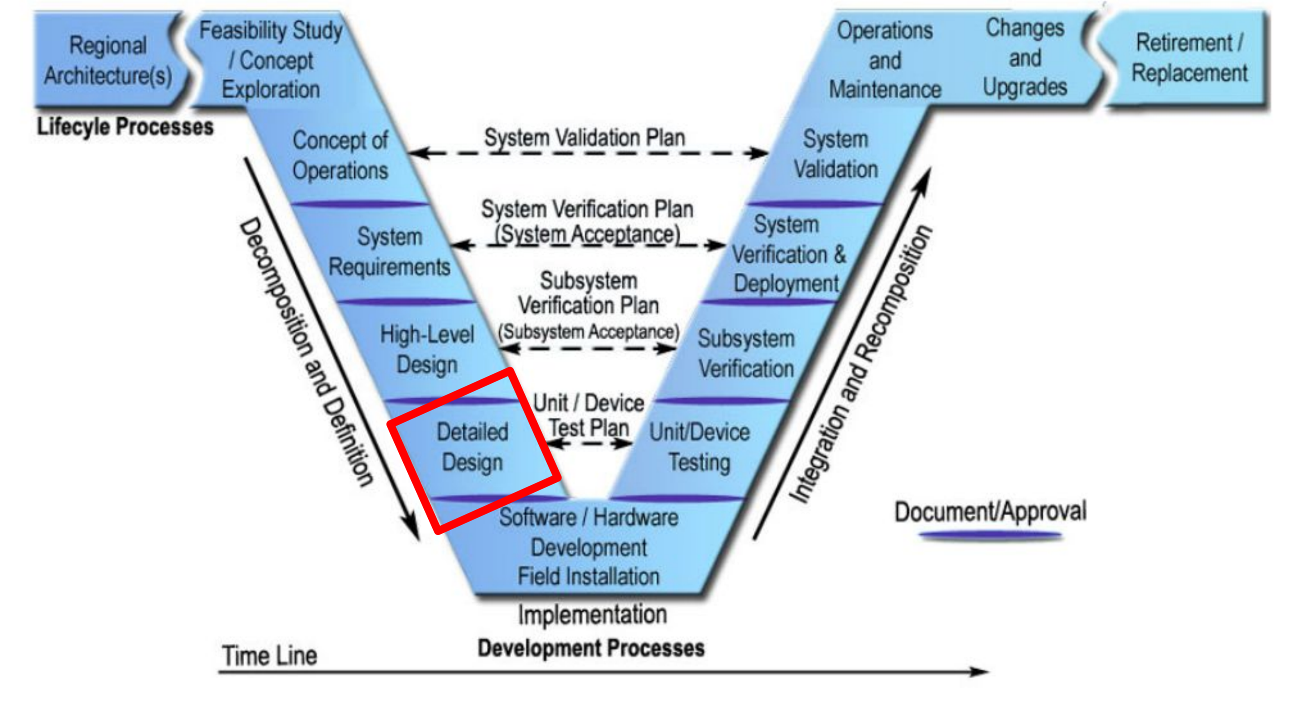
- Lunar Communications and Positioning
- Narrowing Possibilities
- Feasibility Analysis
  - Risk Reduction
- Building Initial CONOPS

Approach - Refining the Design



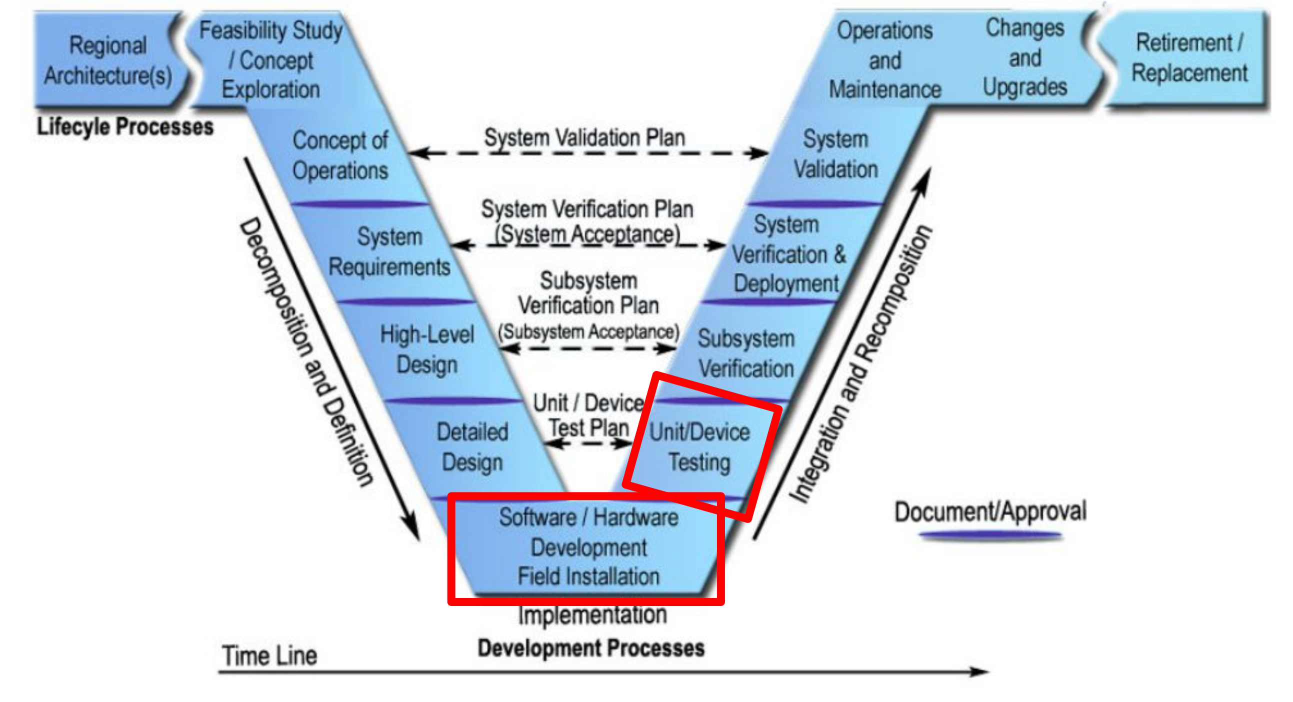
- Pseudolite Network
  - Refined CONOPS
- Derive Functional Requirements
  - Construct DR's
- Outline necessary hardware
  - SDR, Antenna, power, etc

Approach - Finalizing Design



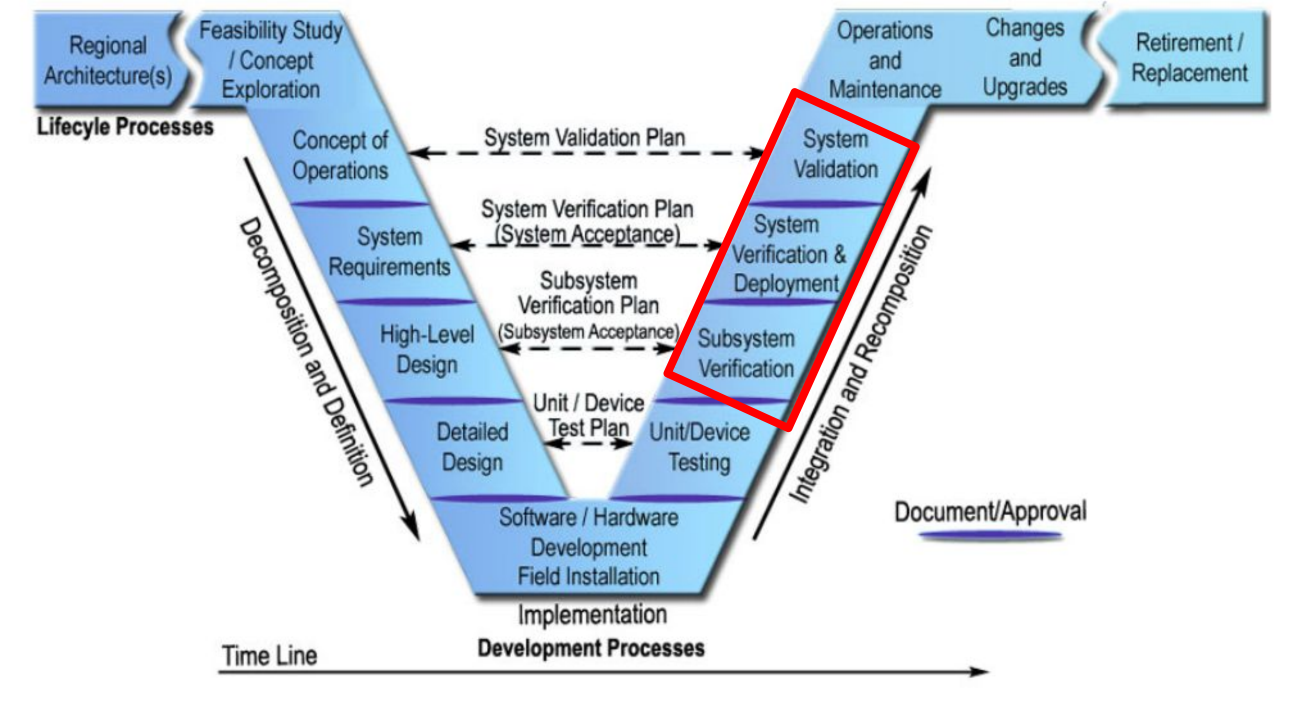
- Trade different aspects of project
  - Software and hardware
- Development of ICD's in the form of FBD's
- Create testing plan for all aspects of project

Approach - Testing Hardware



- Get SSD's and GNU Radio set up
- Purchase and receive hardware
- Verify hardware functionality
    - Basic signal transmission and reception

Approach - Full Scale Testing



- Test different subsystems
  - Clock Override
  - Acquisition
- Build pseudolites
- Combine subsystems into overall system
- Does system meet requirements?

Main Issues Encountered

- Difficulty acquiring signals consistently at distances >100 m
    - Antenna/amplifying capabilities limited transmission power
    - Hardware did not meet expected performance
- Significant electrical engineering expertise required
    - CS knowledge
    - RF knowledge
    - Positioning Systems
- COVID
    - Delays in hardware shipping
    - Testing and scheduling
        - Difficulties in scheduling face-to-face meetings
        - Weather, suitable locations, hardware, etc...

Key Lessons Learned (Systems)

- LunaNet Risk Mitigation
  - Thorough link budget estimation is required
    - Antenna
    - Amplifiers
    - Radio performance
  - Pseudolite synchronization capabilities
  - Hardware interfacing difficulties
- Design space flexibility
  - Altered requirements may change design path
- Field test efficiency
  - Field tests require proper planning and execution
  - Experience in running efficient field tests

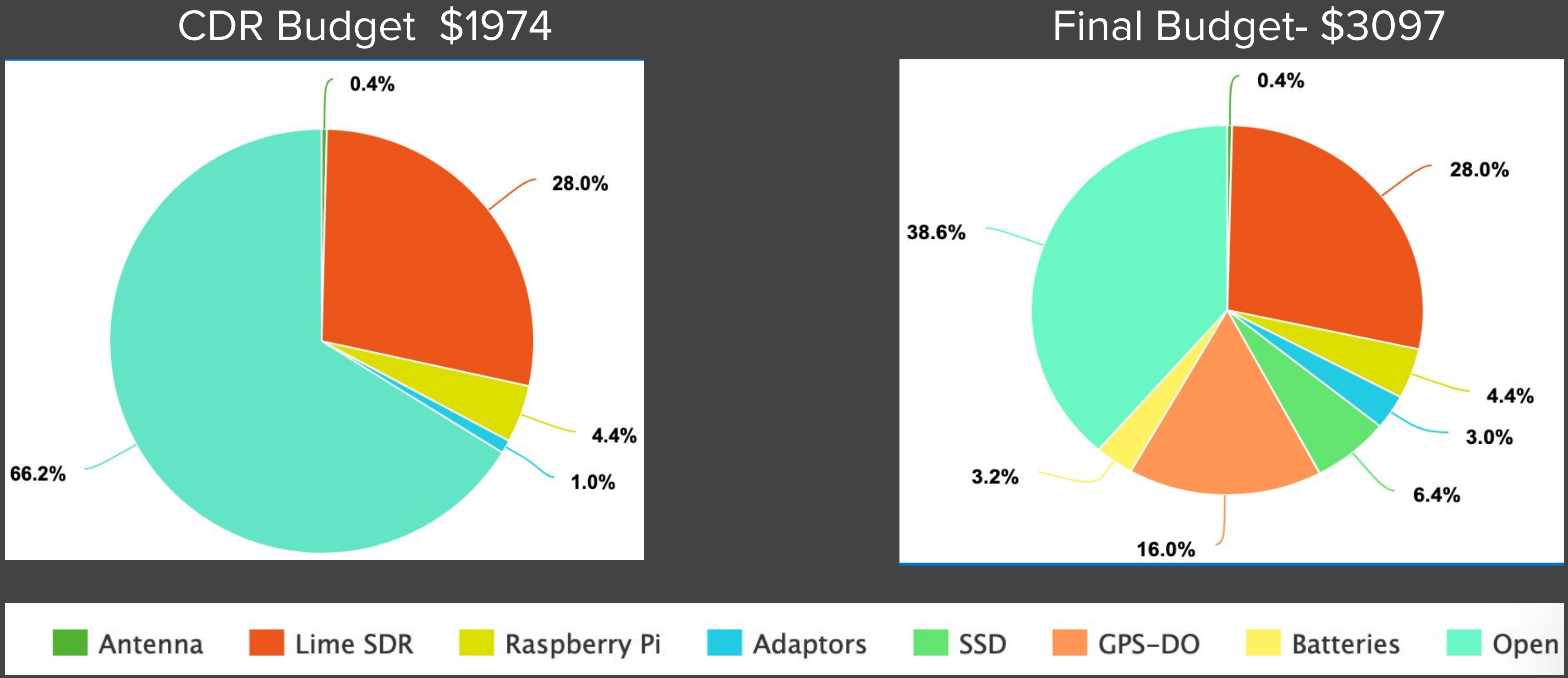
Project Management

Project Management

	Successes
1	Great team chemistry
2	Team understanding of PNT Technologies
3	Hands on experience with SDR's
4	Team experience with GNU Radio

	Challenges
1	Steep Learning Curve
2	Risk Profile Estimation
3	Limited Link Budget Calculations
4	Hardware Interfacing Difficulties

Cost Plan Comparison



Hardware Addition Justification Post-CDR

Component	Purpose	Dollar Increase	Budget Percentage Increase
GPSDO's	Increase transmitter/receiver clock stability	$800	16%
SSD's	Store data, boot programs like GNU Radio through Ubuntu	$320	6.5%
Power Packs	Extend to outside testing for pseudolites (power GPS-DO, LimeSDR,etc)	$160	3.2%
Extra Adaptors	USB-Extender cables and adaptors for pseudolites (needed for accommodating pseudolite housing)	$150	3.9%

Cost to Customer

Labor Hours	**2230**
Labor Rate*	**$31.25**
Labor Costs	**$69,687.5**
Overhead (200%)	**$139,375**
Materials	**$3097**
Total Cost	**$142,472**

*Assumes yearly salary of $65,000 for 2080 hours of work

Acknowledgements

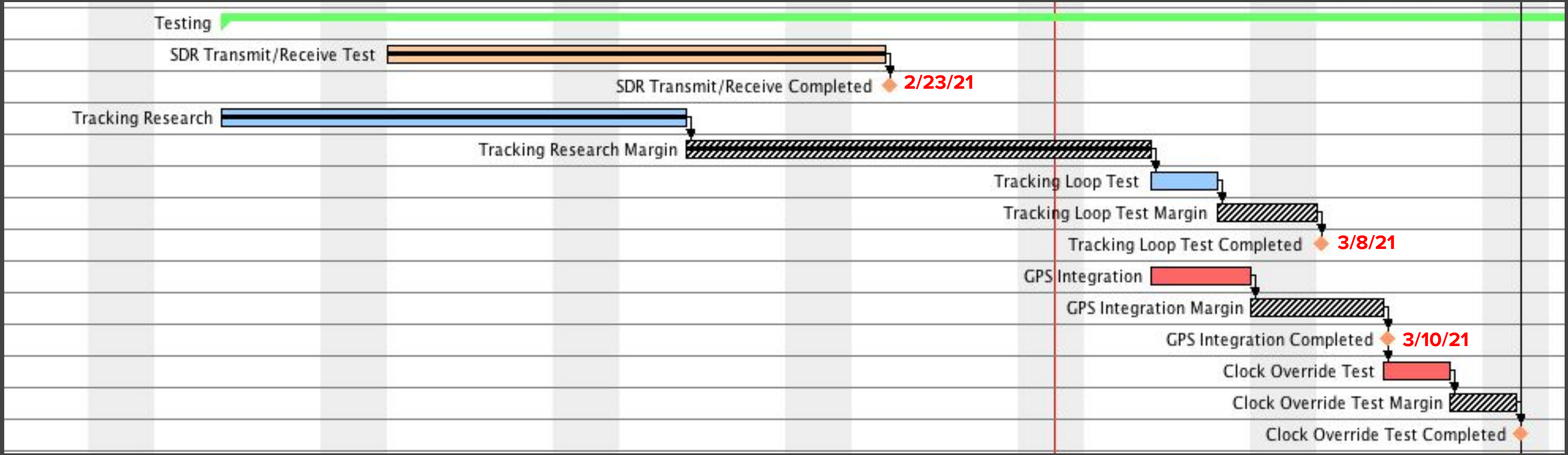
- Dr. Jade Morton
- Dr. Scott Palo
- Dr. Dennis Akos
- Dr. Nicholas Rainville
- Sr. Instr. Trudy Schwartz
- Steve Taylor
- Dr. Kathryn Wingate
- Brian Breitsch
- Lara Buri
- Prof. John Mah

Questions?

Backup Slides

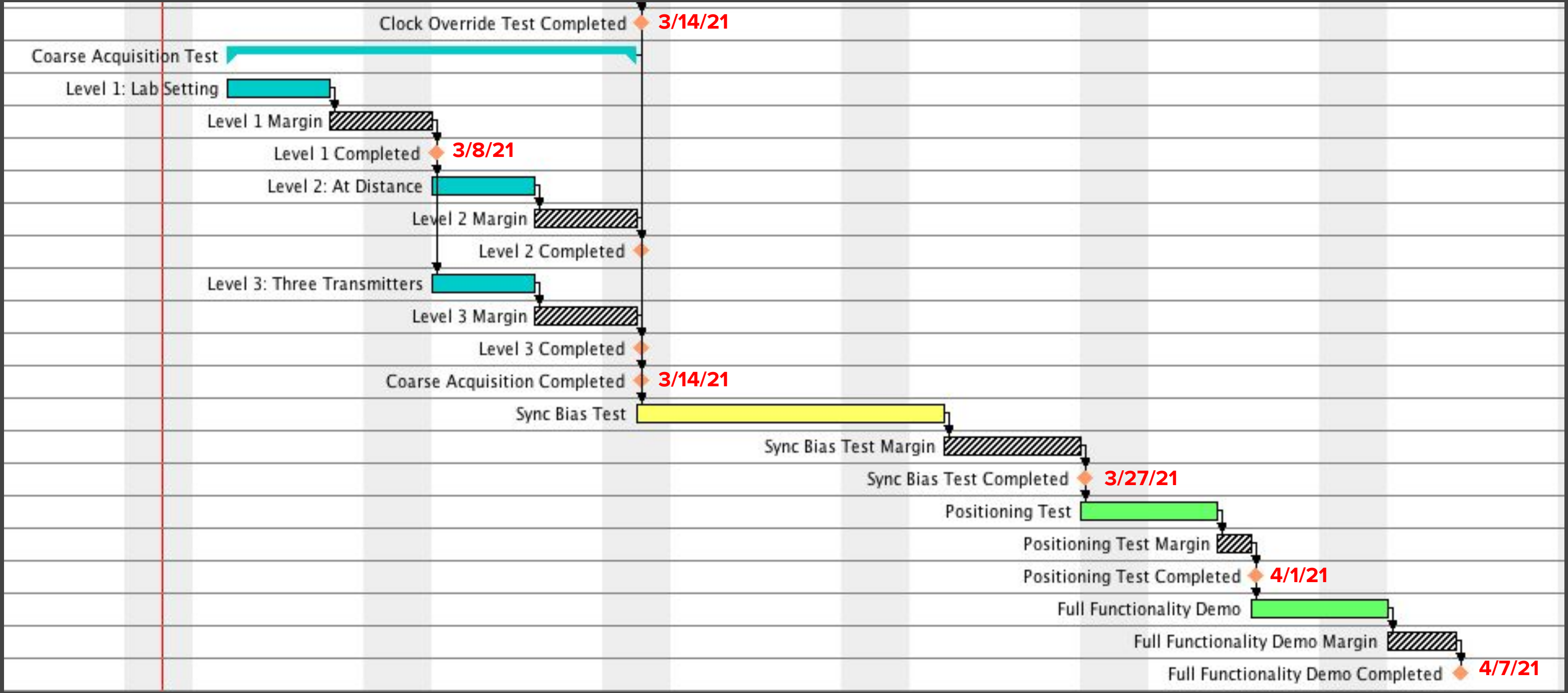
Budget

Schedule



Testing
SDR Transmit/Receive Test
SDR Transmit/Receive Completed
2/23/21
Tracking Research
Tracking Research Margin
Tracking Loop Test
Tracking Loop Test Margin
Tracking Loop Test Completed
3/8/21
GPS Integration
GPS Integration Margin
GPS Integration Completed
3/10/21
Clock Override Test
Clock Override Test Margin
Clock Override Test Completed

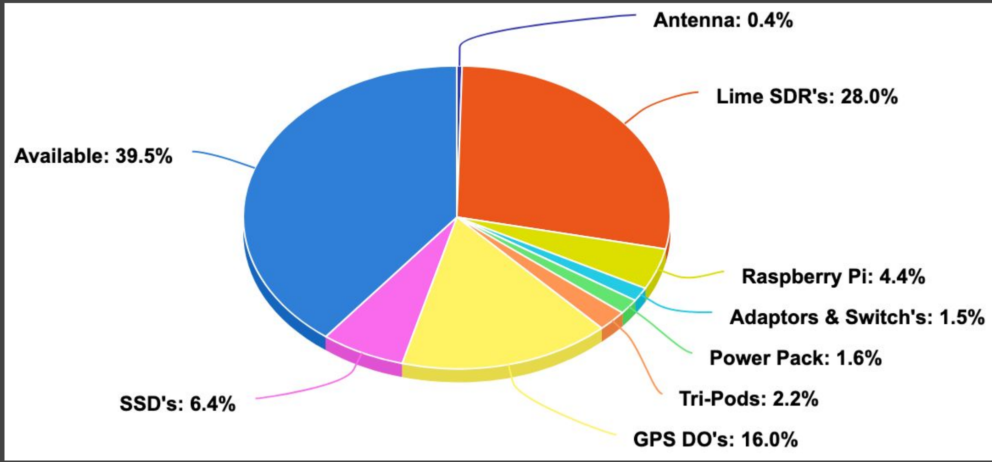
Schedule



Clock Override Test Completed
3/14/21
Coarse Acquisition Test
Level 1: Lab Setting
Level 1 Margin
Level 1 Completed
3/8/21
Level 2: At Distance
Level 2 Margin
Level 2 Completed
Level 3: Three Transmitters
Level 3 Margin
Level 3 Completed
Coarse Acquisition Completed
3/14/21
Sync Bias Test
Sync Bias Test Margin
Sync Bias Test Completed
3/27/21
Positioning Test
Positioning Test Margin
Positioning Test Completed
4/1/21
Full Functionality Demo
Full Functionality Demo Margin
Full Functionality Demo Completed
4/7/21

Cost Plan & Margin

Group	Cost (USD)
Dual TE Connectivity Antennas (4)	$19.80
Lime SDR's (4)	$1,399.80
Raspberry Pi (4)	$220.00
Adapters & Connectors (4 Sets)	$74.65
Miadi Portable Charger (Power Pack) (4)	$79.96
5 Feet Tripods (4)	$111.96
GPS Disciplined Oscillator (4)	$769.53
Samsung External SSD 500Gb(4)	$319.96
Budget Status	
Projected Purchases Total	$3026.12
Current Up to date Purchase Amount Total	$2862.19
Available Amount / Percentage	$1973.68 ~ 39.48%



Major Item List & Status

Item	Status
Dual Band TE Connectivity Antenna (4)	In Possession (4)
Lime SDR's (4)	In Possession (4)
Laptops (4)	In Possession (4) Team Member Laptops
GPS Disciplined Oscillator (4)	Shipped From China (4) Max ETA (3/1)
Samsung External SSD 500Gb(4)	In Possession (4)

Obstacles: P-card access, Shipping Logistics & Chinese New Years Celebration

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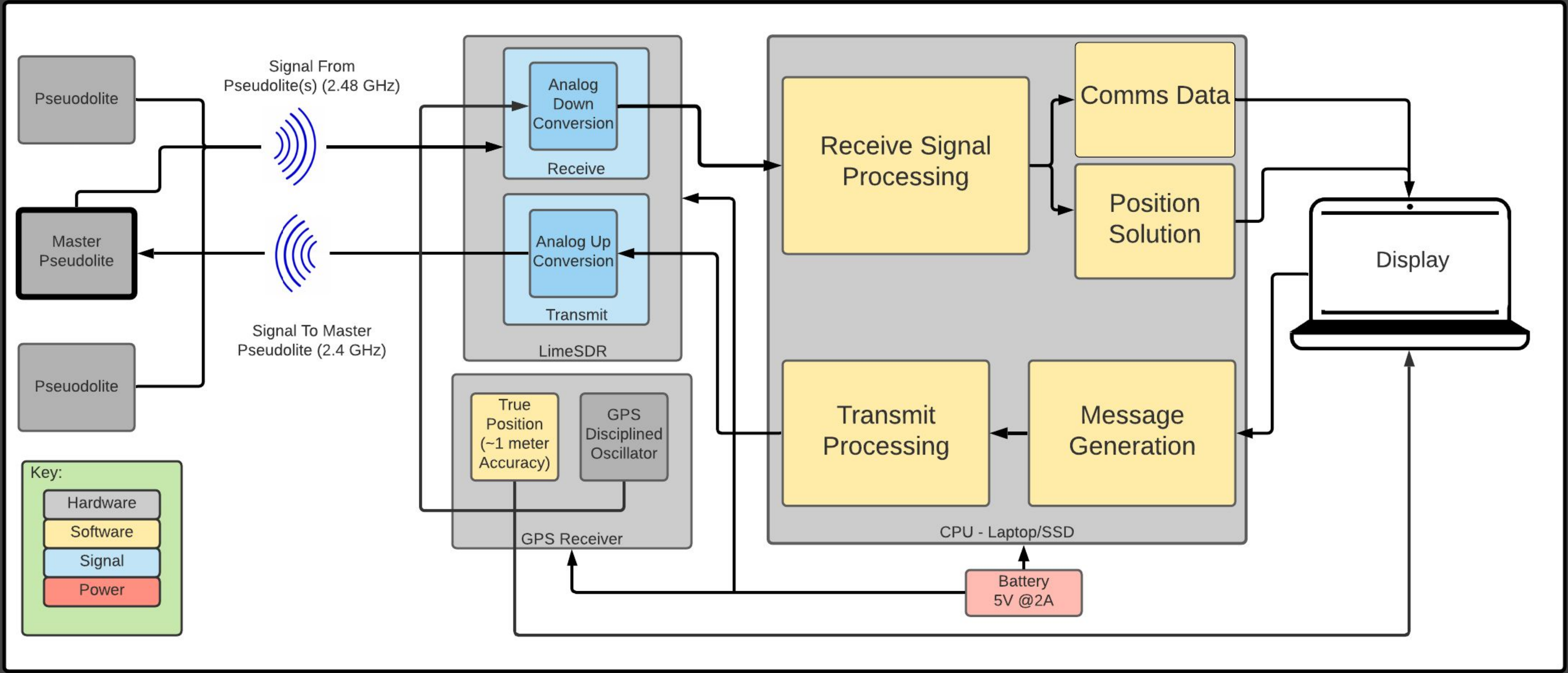
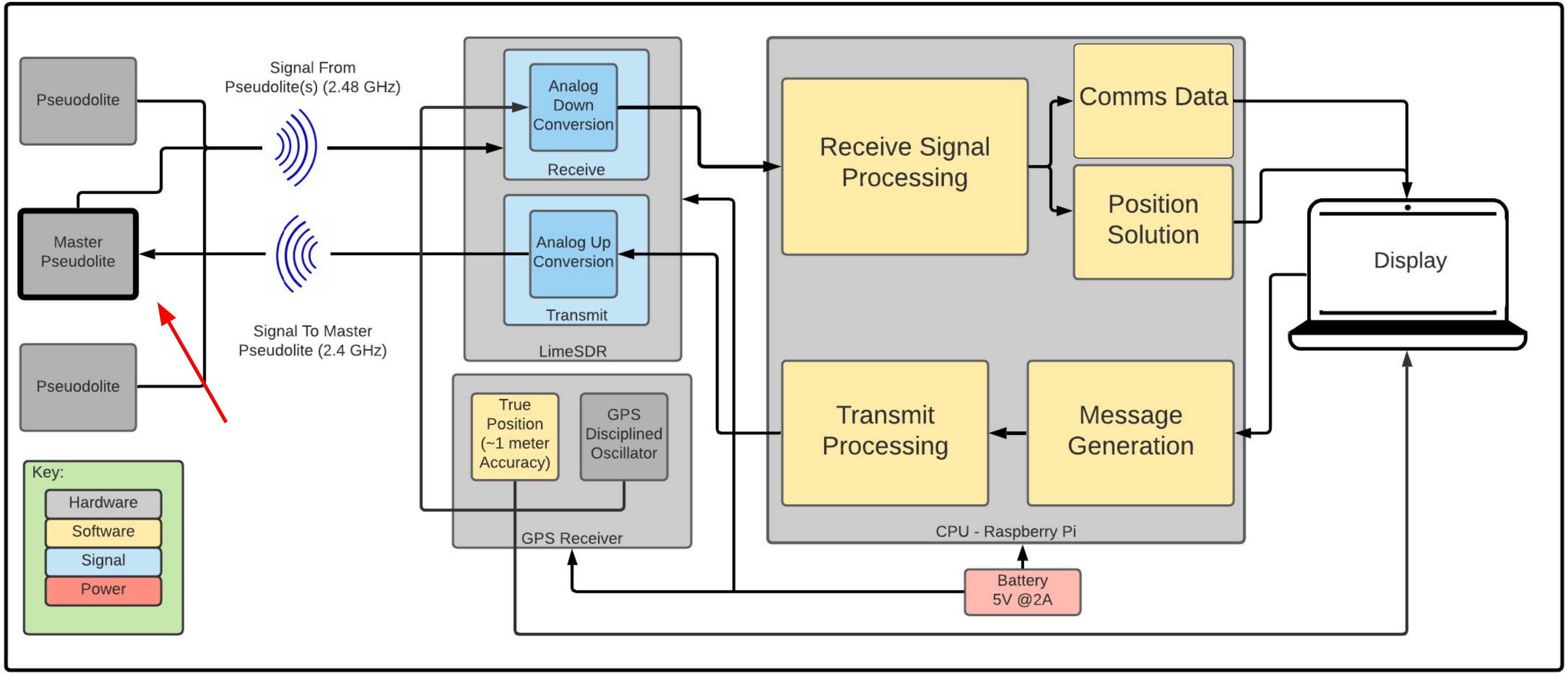
Intro/Overview

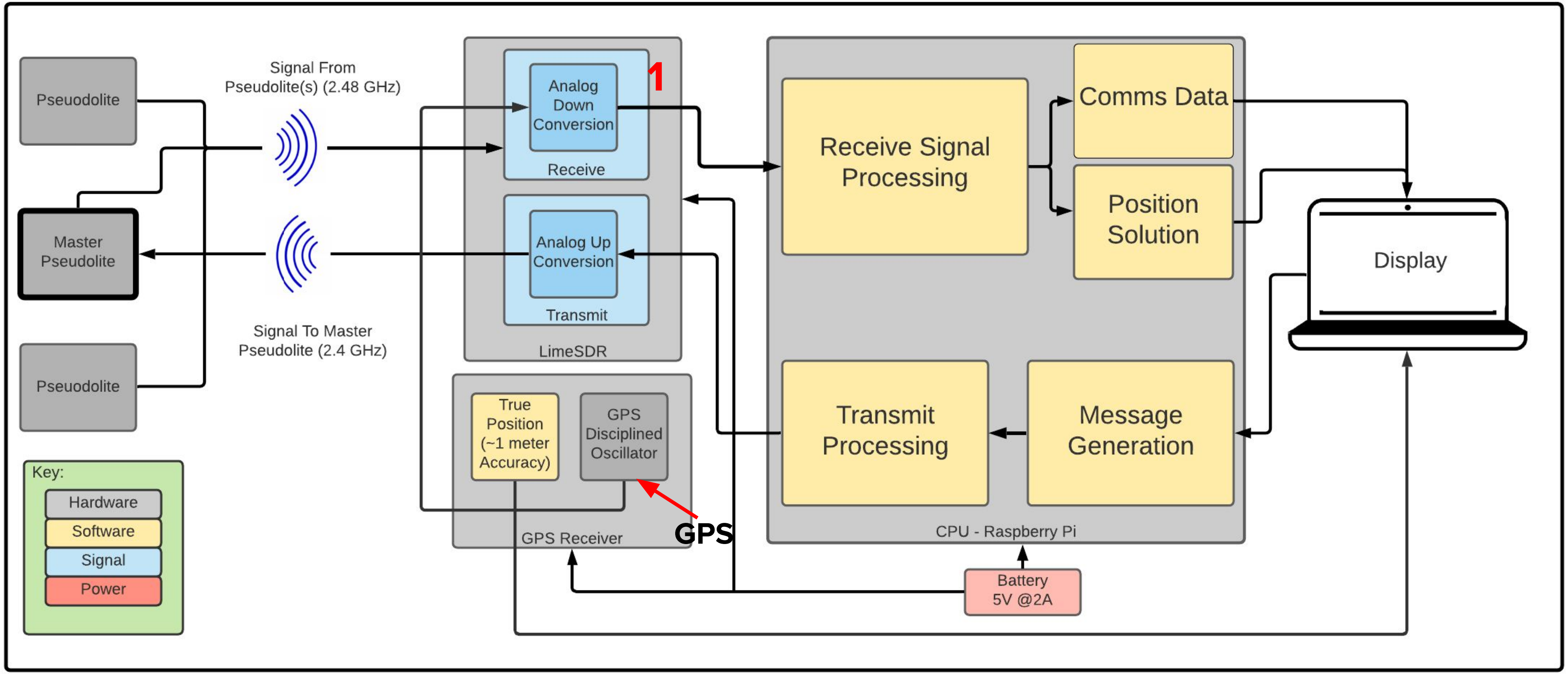
Overall FBD


Pseudolite
Signal From
Pseudolite(s) (2.48 GHz)
Master
Pseudolite
Signal To Master
Pseudolite (2.4 GHz)
Pseudolite
Analog
Down
Conversion
Receive
Analog Up
Conversion
Transmit
LimeSDR
True
Position
(~1 meter
Accuracy)
GPS
Disciplined
Oscillator
GPS Receiver
Receive Signal
Processing
Comms Data
Position
Solution
Transmit
Processing
Message
Generation
CPU - Laptop/SSD
Display
Battery
5V @2A
Key:
Hardware
Software
Signal
Power

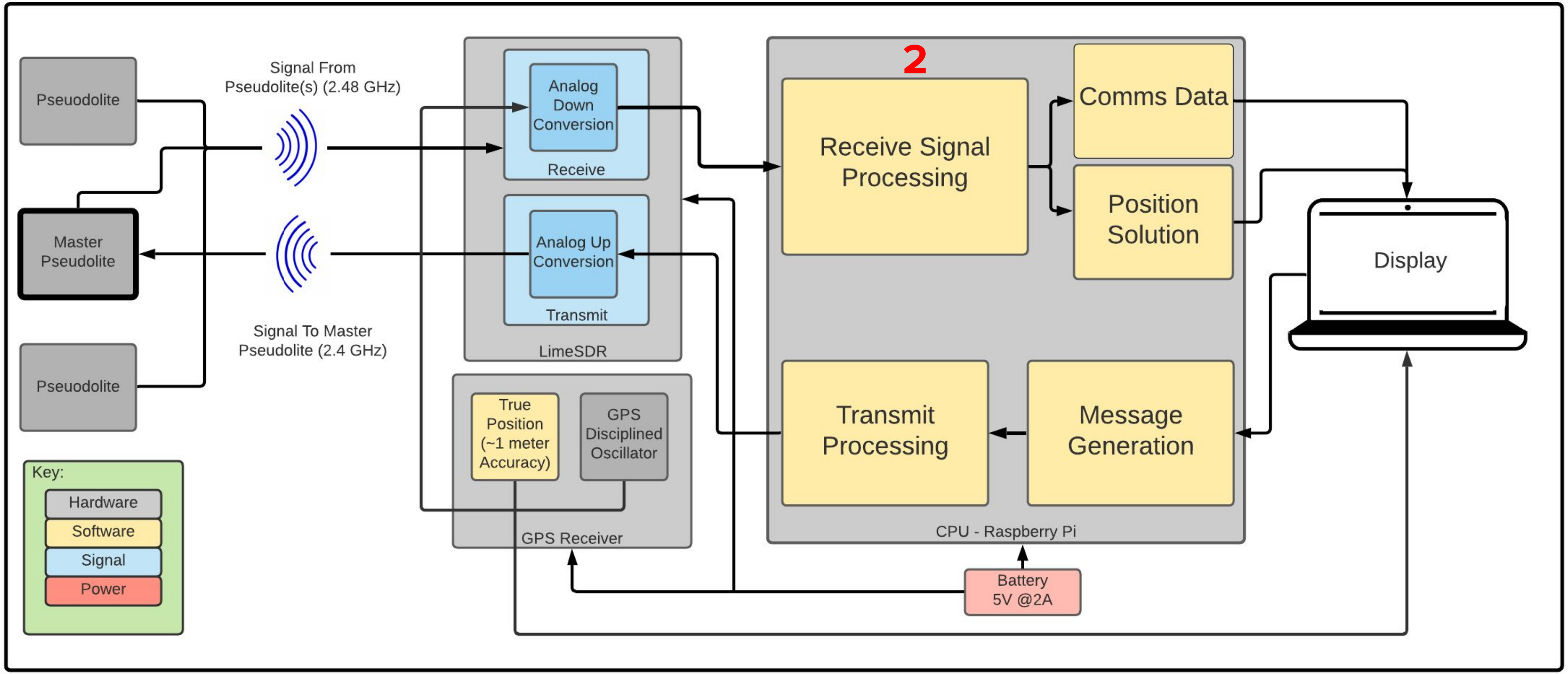
Overall FBD


Pseudodolite
Signal From
Pseudolite(s) (2.48 GHz)
Analog
Down
Conversion
Receive
Analog Up
Conversion
Transmit
LimeSDR
Master
Pseudolite
Signal To Master
Pseudolite (2.4 GHz)
Pseudodolite
True
Position
(~1 meter
Accuracy)
GPS
Disciplined
Oscillator
GPS Receiver
Receive Signal
Processing
Comms Data
Position
Solution
Transmit
Processing
Message
Generation
CPU - Raspberry Pi
Display
Battery
5V @2A
Key:
Hardware
Software
Signal
Power

Overall FBD


Pseudolite
Signal From Pseudolite(s) (2.48 GHz)
Master Pseudolite
Signal To Master Pseudolite (2.4 GHz)
Pseudolite
Key:
Hardware
Software
Signal
Power
Analog Down Conversion
Receive
1
Analog Up Conversion
Transmit
LimeSDR
True Position (~1 meter Accuracy)
GPS Disciplined Oscillator
GPS Receiver
GPS
Receive Signal Processing
Comms Data
Position Solution
Transmit Processing
Message Generation
CPU - Raspberry Pi
Battery 5V @2A
Display

Overall FBD


2
Pseudodolite
Signal From
Pseudolite(s) (2.48 GHz)
Master
Pseudolite
Signal To Master
Pseudolite (2.4 GHz)
Pseudodolite
Analog
Down
Conversion
Receive
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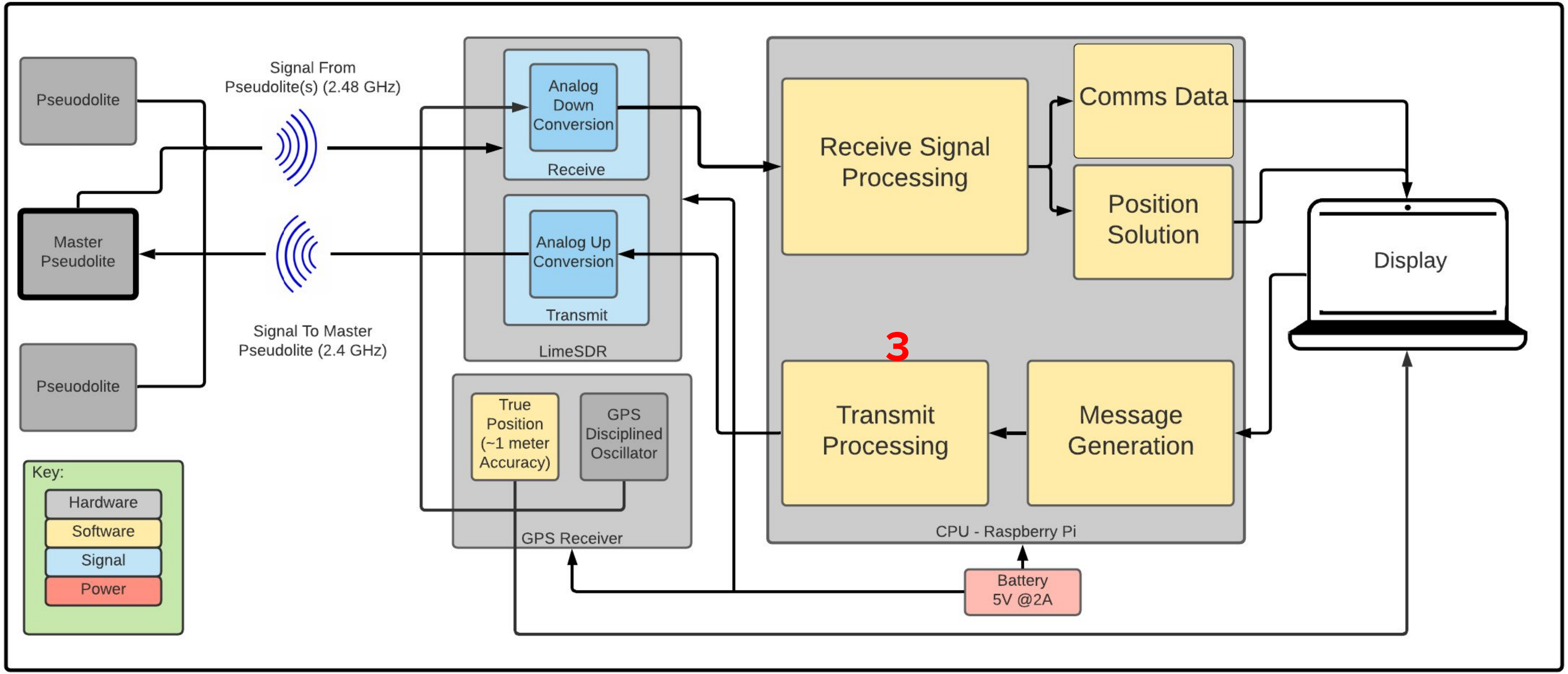
Overall FBD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Message
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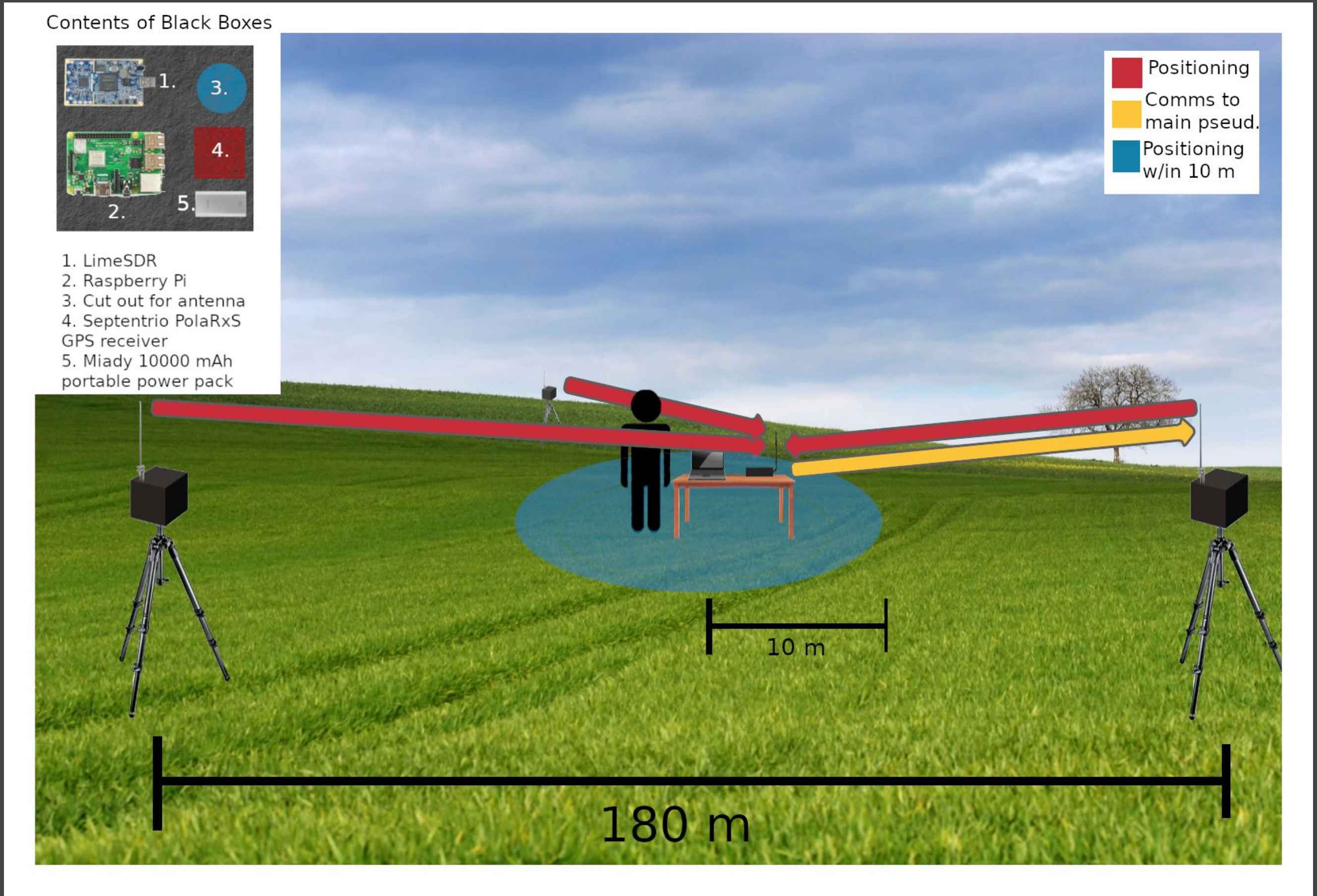
CPU - Raspberry Pi
Display
Battery
5V @2A
Key:
Hardware
Software
Signal
Power

Scaled Down Testing (Placeholder Title)

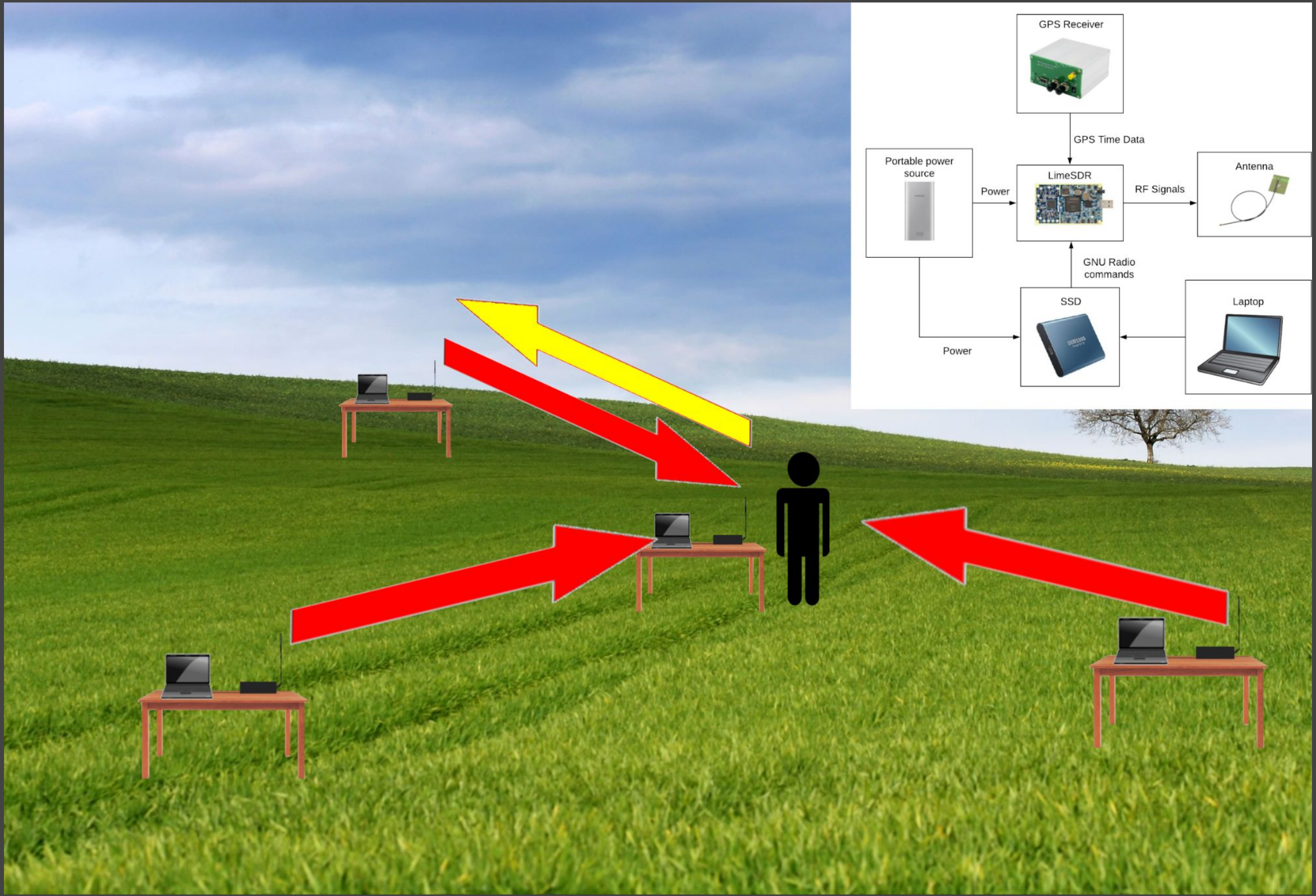
- Scale from 2.4 km to 0.18 km dist. between transmitters
- Assume 2D (only x and y, no height)
- Transmitting on Earth is at least as complicated as on the Moon
    - Atmospheric losses
    - RF Interference
    - Man-made structures/materials interfering
- Not testing environmental constraints

A scaled-down test in Boulder, CO is still able to validate the design for use on the lunar surface

Design Solution Set Up



Design Solution Set Up



Critical Project Elements

Critical Project Element	Design Solution
Positioning System	One-Way Pseudolite Ranging
Antenna	Dual Band TE-Connectivity Antenna
Communication	BPSK Modulation | CDMA Multiplexing
Software Defined Radio	LimeSDR
Clock	Septentrio PolaRxS - GPS Receiver
CPU	Raspberry Pi

Software Overview

GNU Radio

- Reference oscillator integration
- Signal reception and transmission
  - Modulation
  - Multiplexing
  - Up/Down Conversion
  - Acquisition
  - Tracking

Matlab

- Packet Creation
- Positioning algorithm
- For simulation
  - Modulation
  - Multiplexing
  - Up/Down Conversion
  - Acquisition
  - Tracking

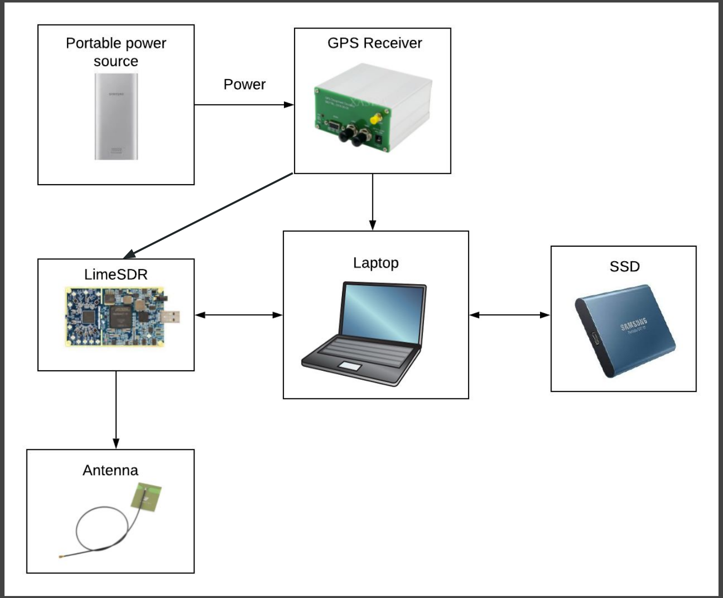
LimeSDR

- Overwrite clock with reference oscillator
- Integrate antenna

Team Created
Open Source Edited
Outside Leveraged

What is a Pseudolite?

- A portable ground station
  - Transmits positioning messages
  - Receives user communication messages



Pseudolite Hardware Block Diagram

Positioning Test

- Design:
  - Hardware: Pseudolites, User system
  - Software: Positioning Algorithm
- Test:
  - **Feed range measurements into positioning algorithm.** Determine the position of the user to sub 10m accuracy at testing location
- Status:
  - Positioning algorithm ready to go
  - Need previous tests to be completed first
  - Pseudolites need to be setup

$$\begin{bmatrix} \delta\hat{\mathbf{x}} \\ \delta\hat{b} \end{bmatrix} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\delta\boldsymbol{\rho}$$

G = *Geometry Matrix*

$$A = \begin{bmatrix} -\frac{x^{(1)}-x_0}{R_0^{(1)}} & -\frac{y^{(1)}-y_0}{R_0^{(1)}} & -\frac{z^{(1)}-z_0}{R_0^{(1)}} & 1 \\ -\frac{x^{(2)}-x_0}{R_0^{(2)}} & -\frac{y^{(2)}-y_0}{R_0^{(2)}} & -\frac{z^{(2)}-z_0}{R_0^{(2)}} & 1 \\ -\frac{x^{(3)}-x_0}{R_0^{(3)}} & -\frac{y^{(3)}-y_0}{R_0^{(3)}} & -\frac{z^{(3)}-z_0}{R_0^{(3)}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -\frac{x^{(m)}-x_0}{R_0^{(m)}} & -\frac{y^{(m)}-y_0}{R_0^{(m)}} & -\frac{z^{(m)}-z_0}{R_0^{(m)}} & 1 \end{bmatrix}$$

$$\delta\boldsymbol{\rho} = G\begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix}$$

Test Site Images

Manufacturing Slides

Changes since CDR

- Signal Reception: SSD + Laptops instead of Raspberry Pi
  - Due to computation restrictions, boot Linux off external SSDs connected to laptops for additional speed and memory
- Signal Transmission: Pseudolites equipped with a reference oscillator
  - GPS disciplined oscillator (GPSDO)
  - Parts have been selected and ordered.

Customer Value Proposition

- Develop testing scenario
  - Testing out a **scaled down version** of the system
  - What it takes to test the system
  - What works, what doesn't
- Develop/Integrate hardware & software
  - LimeSDR (Radio)
    - Performance metrics
    - External clock integration
  - GNU Radio v3.8 (Software)
    - Performance
    - Interfacing with LimeSDR

Manufacturing Overview

Purchase

- LimeSDR
- Reference Oscillator
- Antenna
- SSD
- Tripod

Integrate

- Pseudolite electronics
  - Antenna
  - GNU Radio
  - Laptop
- Pseudolite clock
  - Override internal clock
- Calibrate system

Develop / Manufacture

- GNU Radio script
- Communications Protocol
- Positioning Algorithm
- Pseudolite Housing

Manufacturing Overview

Purchase

- LimeSDR
- Reference Oscillator
- Antenna
- SSD
- Tripod

Integrate

- Pseudolite electronics
  - Antenna
  - GNU Radio
  - Laptop
- **Pseudolite clock**
  - **Override internal clock**
- **Calibrate system**

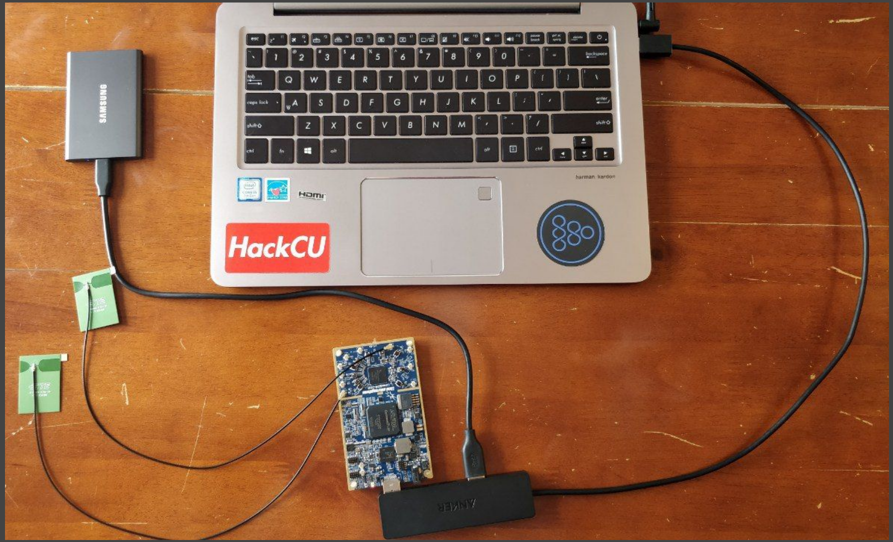
Develop / Manufacture

- GNU Radio script
- **Communications Protocol**
- **Positioning Algorithm**
- Pseudolite Housing

Integrate: Pseudolite Electronics

Task: Send and receive test signals using pseudolite electronics

- GNU Radio 3.8 (Software)
- Ubuntu Linux booted on a Samsung T7 500 GB External SSD
    - Running GNURadio
    - 1 GBps read/write
- Dual Band TE Connectivity Patch Antennas
- LimeSDR USB 3.0
- ASUS Zenbook (Core i5 @ 3.5 GHz)
- Write samples to file



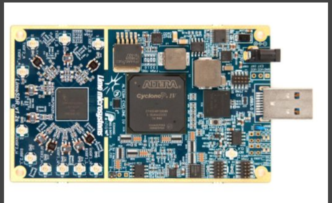
Status: **Done**

Integrate: Pseudolite Clock

Task: Override internal LimeSDR clock in each pseudolite

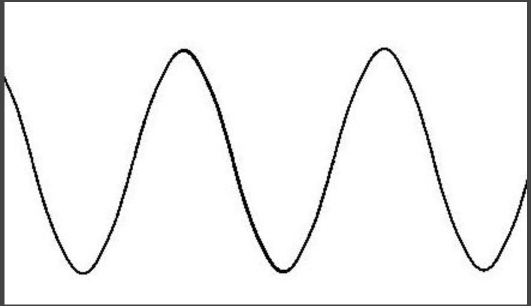
- **Synchronize** all pseudolites in order to get **accurate** range measurements.
- Provide a more **stable** oscillator for higher quality transmitting and receiving.
- Using a GPS-disciplined oscillator (GPSDO)

Status: Shipping (ETA: 2/5/21)


LimeSDR

+

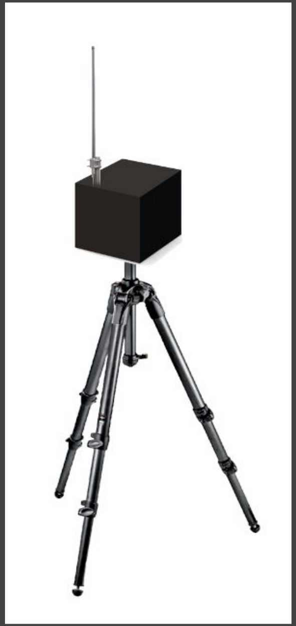

GPSDO



Integrate: Calibrate System

Task: Measure and calibrate for total system bias (Pseudolite + GPSDO) when transmitting

Status: **Waiting** for overall system integration

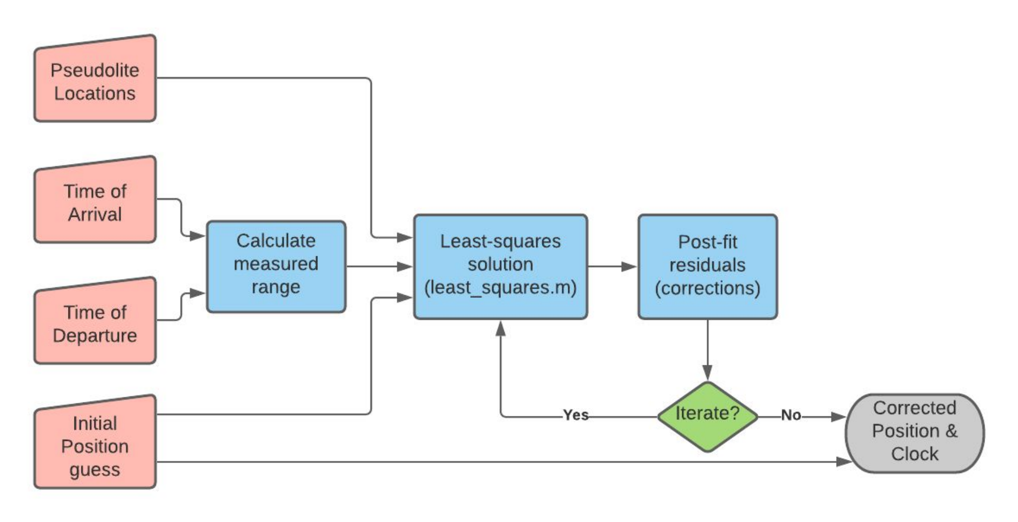


Develop: Positioning Algorithm

Task: Develop code to process received samples and then compu position.

Status:

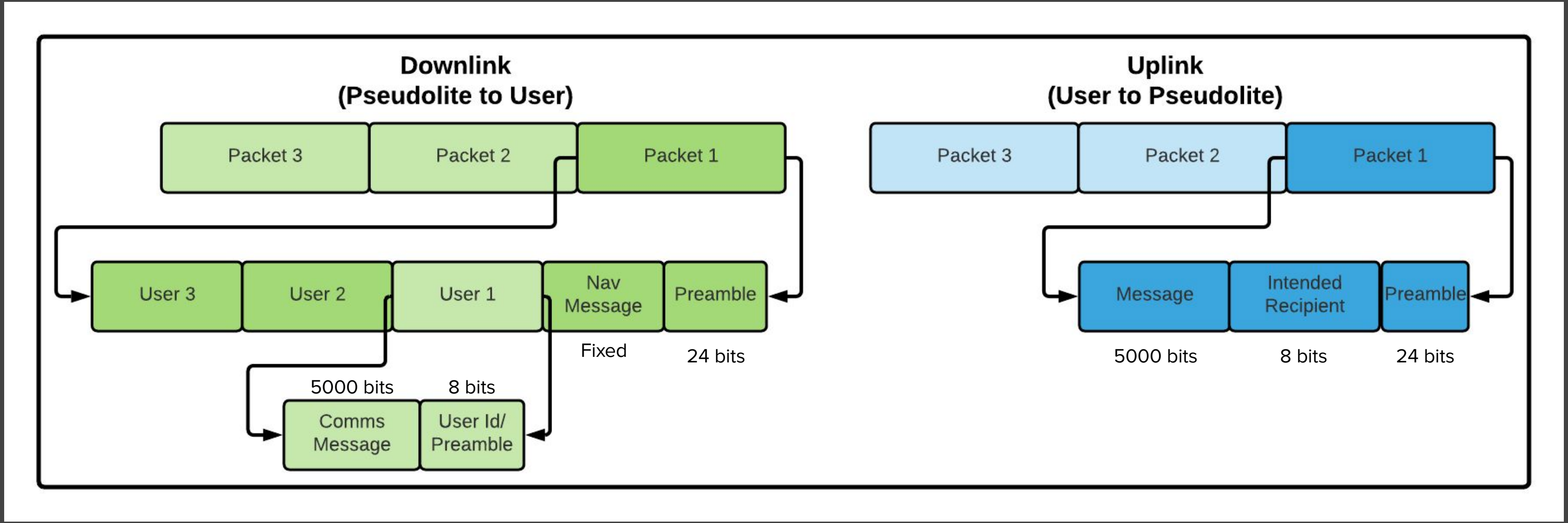
- Signal processing script **in progress**
- Positioning script **done**



Positioning Script Block Diagram

Develop: Communications Protocol

Task: Format communication data into packets
Status: Done

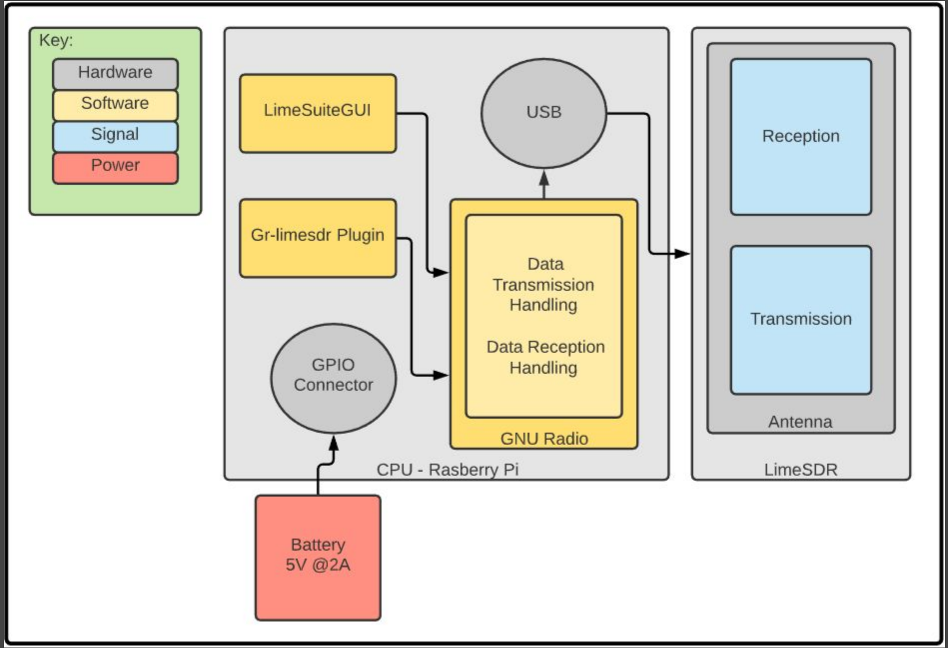


CDR Status Update

- GNU Radio system setup
- Signal detection between two transmitters
- Measured signal interference at testing location
- Preliminary CAD Housing Model Done
- Selected Referenced Oscillator

Hardware

Pseudolite Electronic Configuration

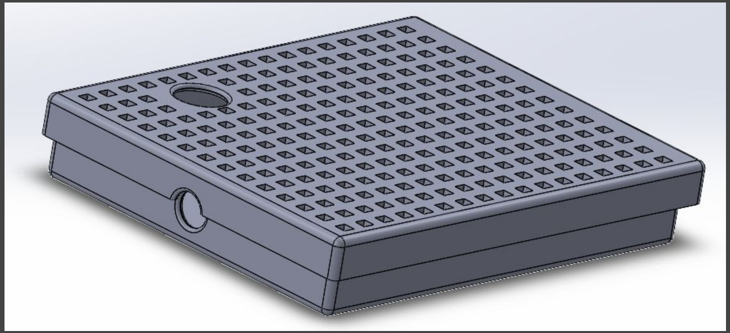


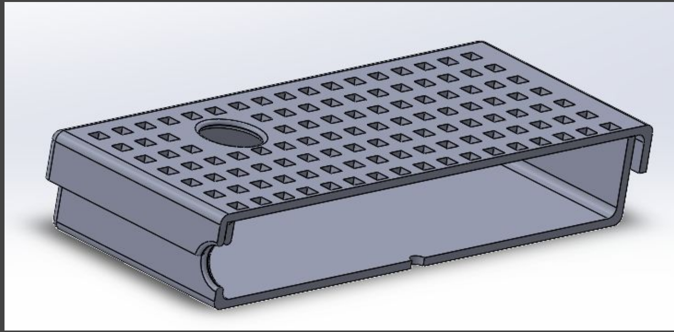
- Electronic/Hardware functional block diagram.
  - DR 2.1.3: The system will operate using the LimeSDR electronics device
- The LimeSDR combined with the GNU Radio software package.
  - FR1: The system must operate under a scalable LPS model
- How is this scalable?

DR 2.1.3: LimeSDR is in use

Mechanical Hardware Integration - CAD

- CAD model of case for holding the limeSDR, GPS, power supply, and Raspberry Pi
- Holes for cable, antenna, and ventilation.
- To do: get a tripod so that the model can be made to attach

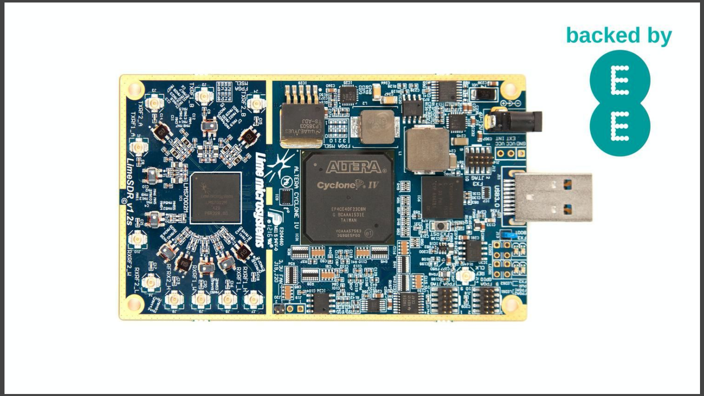




SDR - Requirements

- FR1: The system must operate under a scalable LPS model
  - DR 2.1.3: The system will operate using the LimeSDR electronics device
- FR2: Demonstrate SMS-like communication
  - DR 2.2.1: Device must demonstrate wireless transmission and reception of data
- FR 4: System will transmit and receive data between (2.4 - 2.48 GHz)
  - DR 2.4.1: Demonstrate uplink transmission at 2.4-2.48 GHz
  - DR 2.5.1: Demonstrate downlink transmission at 2.4-2.48 GHz

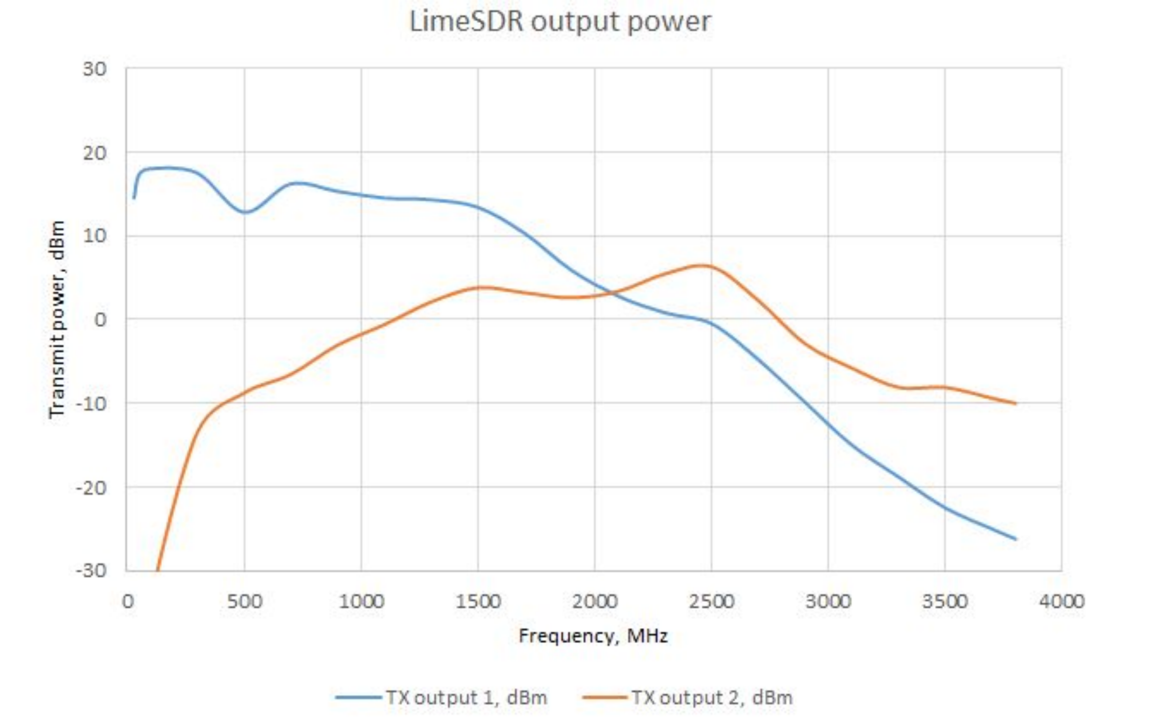
LimeSDR (SDR - “Software Defined Radio”)



- LimeSDR (Hardware)
  - Customer requirement
  - Reception and Transmission of signal
  - Ability to work with modulator/demodulator software packages
  - Functions at 2.4-2.48 GHz
- GNU Radio (Software)
  - Suggested by customer
  - Able to implement all communication schemes and all frequency ranges
  - Able to do simulation and testing

GNURadio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

LimeSDR Output Power



Antenna - Requirements

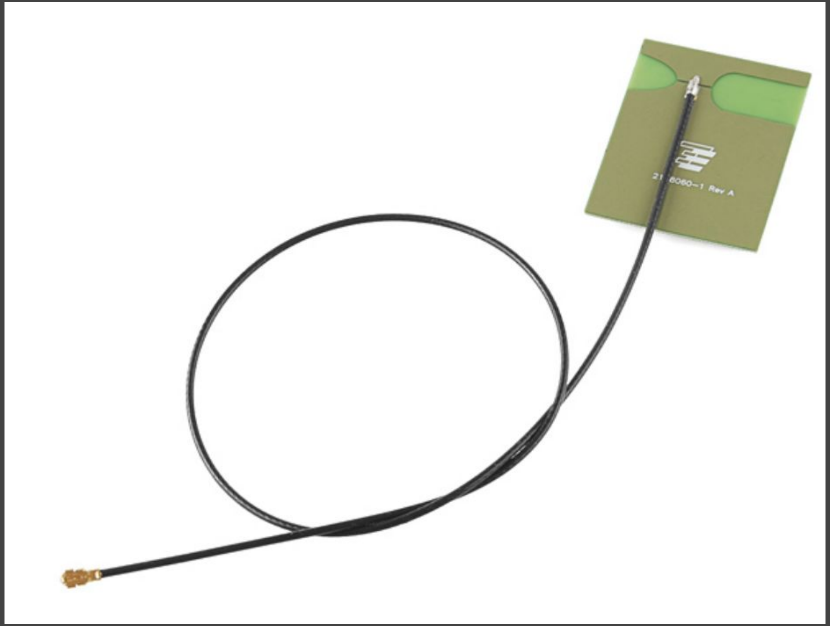
FR4: The system will transmit data on the S-Band frequency.

- DR 2.4.1 : Demonstrate uplink transmission at a frequency range between 2.4-2.48 GHz

FR5: The system will receive data on the S-Band frequency.

- DR 2.5.1 : Demonstrate downlink reception at a frequency range between 2.4-2.48 GHz

Dual Band-TE Connectivity Antenna



Dual Band-TE Connectivity

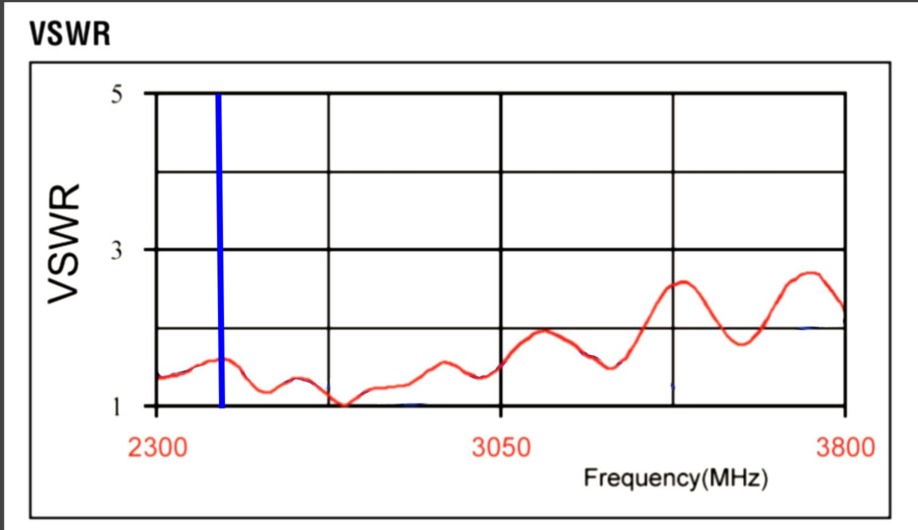
- Peak Gain 2dBi
- Embedded Antenna Style
- Freq Range: 2.4-3.8GHz
- Low Weight (<3.3gram)
- Low Cost (5 USD)
- Voltage Standing Wave Ratio (VSWR) - MAX 3:1

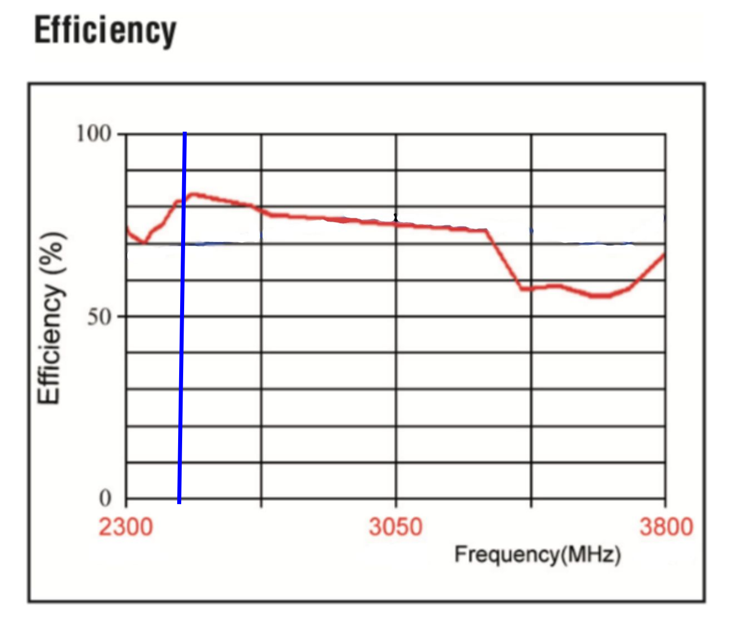
Antenna - Selection Analysis

Customer Requirement: S-Band (due to radio silent far side of the moon)

Frequency Range	PROS	CONS
S- Band: (2-4 GHz)	• Previous communication satellites (NASA) • Unlicensed bandwidth (2.4-2.483 GHz) good for testing • Low Cost system	• Large amount of interference (Many devices at this bandwidth) • Mainly used for large antennas (transmission)

Antenna - Evidence of Feasibility

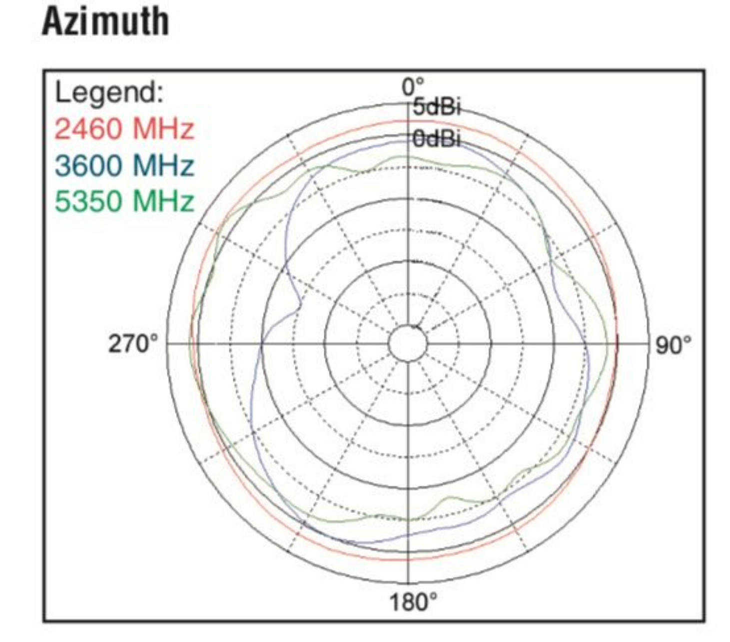


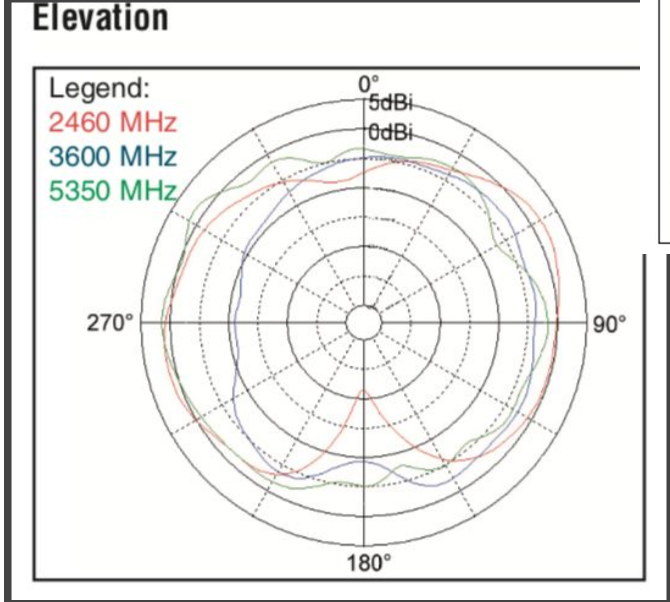


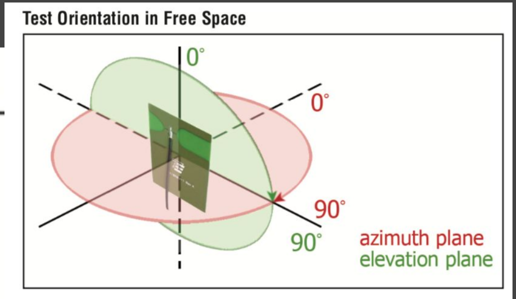
DR 2.4.1, 2.5.1

FEASIBLE

Antenna - Evidence of Feasibility







Antenna Design Requirements

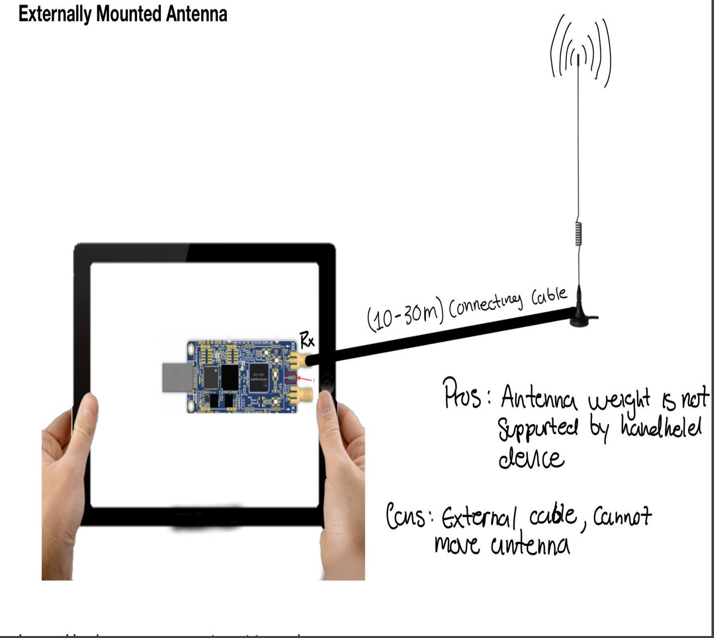
FR4: The system will transmit data on the S-Band frequency.

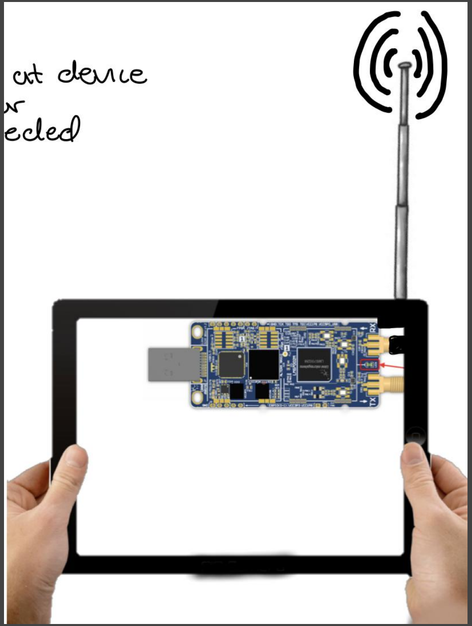
- DR 2.4.1 : Demonstrate uplink transmission at a frequency range between 2.4-2.48 GHz

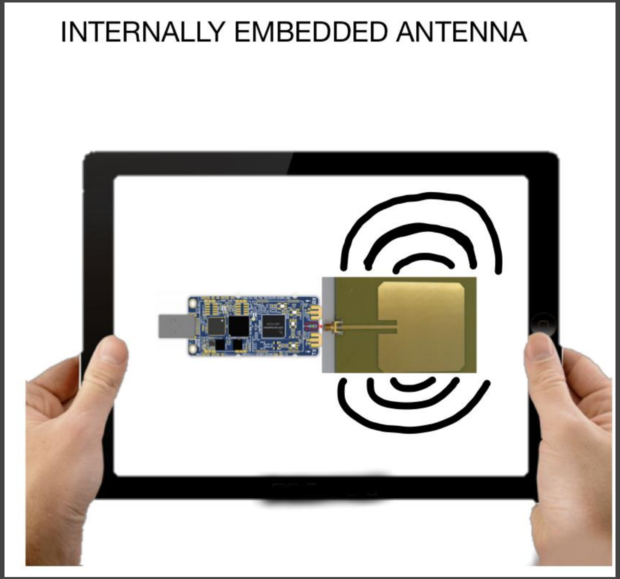
FR5: The system will receive data on the S-Band frequency.

- DR 2.5.1 : Demonstrate downlink reception at a frequency range between 2.4-2.48 GHz

Antenna


Externally Mounted Antenna
(10-30m) Connecting Cable
Rx
Pros: Antenna weight is not supported by handheld device
Cons: External cable, cannot move antenna




INTERNALLY EMBEDDED ANTENNA

VSWR Equations

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{V_{\text{max}}}{V_{\text{min}}}$$

$|\Gamma|$ = Absolute Reflection Coefficient

Antenna Tradestudy BU-Slides (Table 1)

Table1.Antenna Options with performance characteristics

Antenna Model	Antenna Type	Antenna Design Configuration	Gain (dBi)	Bandwidth(GHz)
TE Connectivity Antenna	Omnidirectional-DualBand	Embedded	2	2.4-3.8 GHz, 5.150-5.870 GHz
Laird-MAF94051	External Dual-Band Omnidirectional	Attached	2	2.4-2.5
Laird OC24006H	Omnidirectional/ horizontally polarized	External	6	2.4-2.5
Argain-N2420M	Single Band embedded	Embedded	2.81	2.4-2.49

Antenna Tradestudy BU-Slides (Table 2)

Table2.Antenna and other characteristics

Antenna Model	Weight (grams)	Unit-Cost (USD Currency)	Connector Type	Effective Area (Ae) or Effective Antenna Aperture (m^2)
TE Connectivity	3.3	4.79	Cable-Side Entry	0.001828
Laird-MAF94051	113.4	7.64	RP SMA Connector with 90 degree elbow	0.001814
Laird OC24006H	260	50.20	N-Female	0.004556
Argain-N2420M	0.5	1.80	IPEX/MHF/U FL	0.002186

Antenna Tradestudy BU (Effective Area Equations)

$$A_e = \frac{\lambda^2}{4\pi} G = \frac{c^2}{f^2} \times \frac{G}{4\pi}$$

Eq#1 is assuming Linear Gain and Eq#2 Assuming dB Gain

$$A_e = \frac{c^2}{f^2} \times \frac{10^{\frac{G\,(dB)}{10}}}{4\pi}$$

Table3. Point Matrix Criteria

Metric	High Score (3)	Medium Score(2)	Low Score(1)
Cost Effectiveness	low cost for a high performance and capabilities (price<5)	The antenna has an average cost for its capabilities(5-30)	The antenna has a high cost for its capabilities (Over 30)
Weight	The antenna is very light (Under 50 grams)	The antenna has a medium weight (from 50-200grams)	The antennas has a high weight value (over 200 grams)
Compatibility	The antenna can easily connect to the SDR, The user has no issues when using the antenna	The antenna is compatible with the sdr without any extra hardware but needs intervention for it to start working	The antenna is not compatible with the sdr without any extra hardware and needs intervention for it to start functioning
Performance/Specs	Omnidirectional, Operates in designated frequency, high bandwidth, good materials, Large Effective Area,etc.	The antenna has all the required specs but does not have good materials or other hardware constraints	The antenna doesn't satisfy all the needed requirements

Antenna TradeStudy BU-Slides (Table 4)

Metric	Weighting	Antenna #1 TE	Antenna #2 Laird-1	Antenna #3 Laird-2	Antenna #4 Argain
Cost	0.15	3	2	1	3
Weight	0.30	3	2	1	3
Compatibility	0.15	3	3	2	3
Performance/Specs	0.40	3	3	3	2
Total Score	100%	100%	80%	65%	90%

Power Budget

Component	Max Operating Power (Transmit)	Max Operating Power (Receive)
LimeSDR	4.5W (More like 2mW)	NA
Antenna	NA	3.0W
Raspberry Pi	NA	3.5W
Total	4.5W	6.5W
	or approx 2mW	

Battery Pack: Miady

- 5V 2A spread evenly from two outputs

Power Pack (Selected Battery)

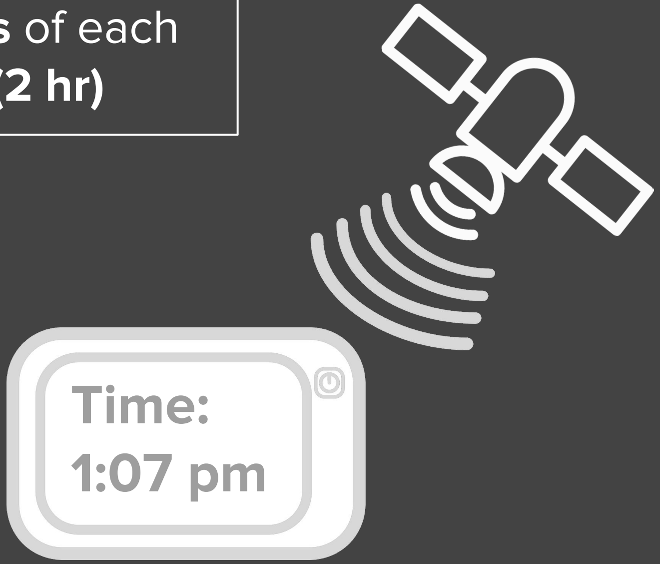
Miady 10000mAh Dual USB Portable Charger

Scaling and Power

- Scaling
  - In the real-life application of this project we will use 2.4km side-lengths for the pseudolite geometry
    - Calculated using the horizon of the Moon.
    - Would also need to take into account any terrain on the Moon.
  - **Scaled down geometry** was created for **practical** reasons.
- Power
  - Current testing power is **2 mW** which is **more than enough** (even for a pseudolite configuration with 2.4km side-lengths)
  - As part of our testing we will **vary transmit power** and plot ranging accuracy vs. SNR in order to determine the **optimal transmit power.**

Pseudolite Clocks

FR3: All clocks must be within **30 ns** of each other **for the duration of a test (2 hr)**



- On-board Clock (TCXO): Drifts on average 0.05ns every second
- Pseudolite Clocks: **GPS Disciplined**
  - Using clock bias to keep pseudolite clock synced
  - Reduces jitter
  - Septentrio PolaRxS
- **Expected Accuracy: 0.5 ns**

Navigation

Positioning System Requirements

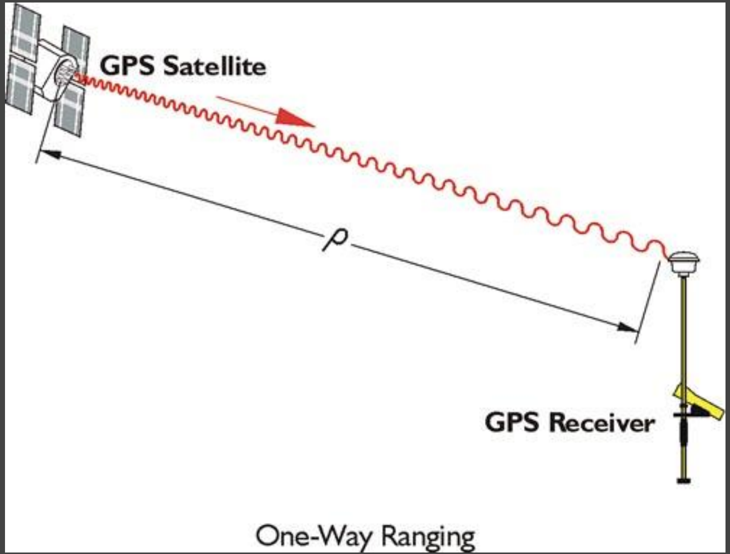
FR3: The system will be able to provide an architecture for a navigation solution with a 10 meter position accuracy and a 30 nanosecond 1-σ transfer time

- **DR 2.3.2** : Provide LPS coverage to the Moon's South Pole

Solution: Pseudolite geometry composed of a 0.18km equilateral triangle + GPS-disciplined clocks

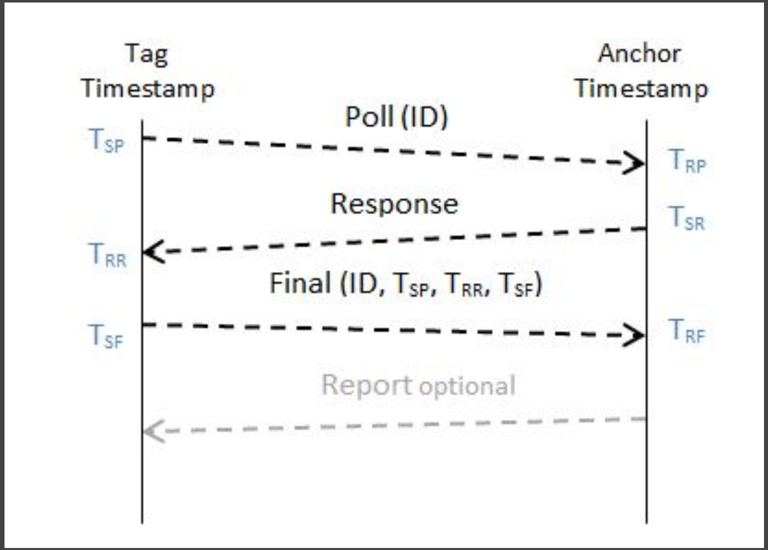
One way ranging

- Requires accurate clocks on both ends to determine the distance based on time differences.
- Lots of research/documentation available supporting the algorithms and systems.
- Only satellite transmits.
- The energy and time required is low due to only one transmission of data.



Two way ranging

- Requires clocks on both ends but does need them to be synced up with each other.
- Receiver must transmit data BACK to the transmitter - multiple times.
- **Both the satellite and the receiver know the location of the satellite.**
- The energy and processing requirements are high due to the fast data transmission requirements.



One way vs Two way ranging

	One way	Two way
Power required	Low	High
Position information	Only receiver	Both receive info
Clock synchronization	Required	Not required

Positioning Algorithm: Least-Squares Solution

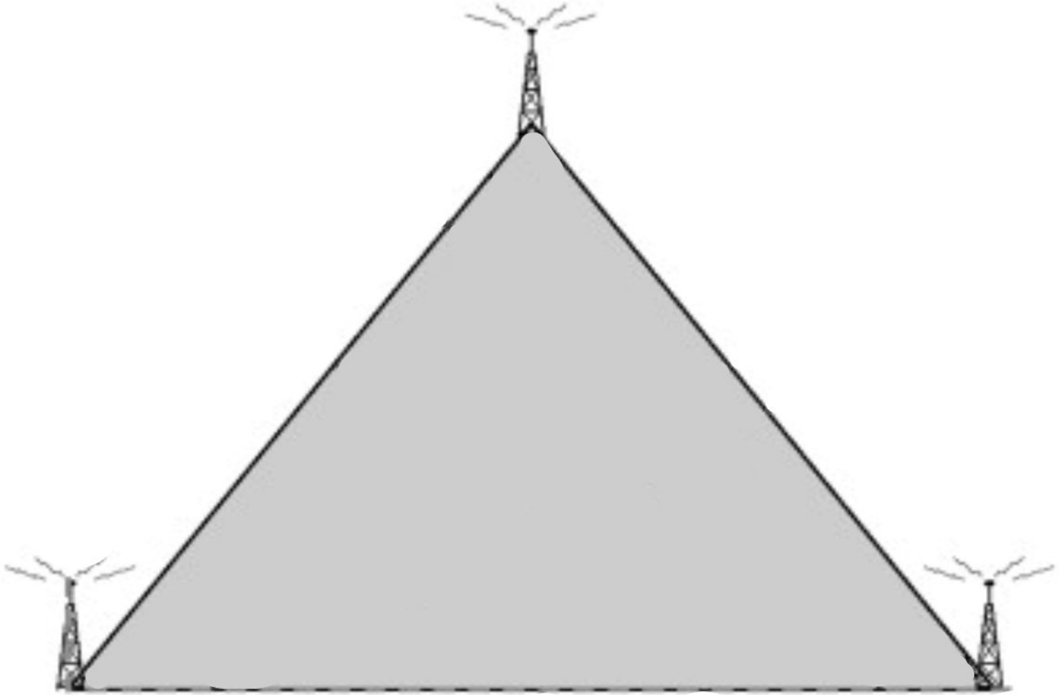
- Reason for using least-squares method
- Position Guess and corrections

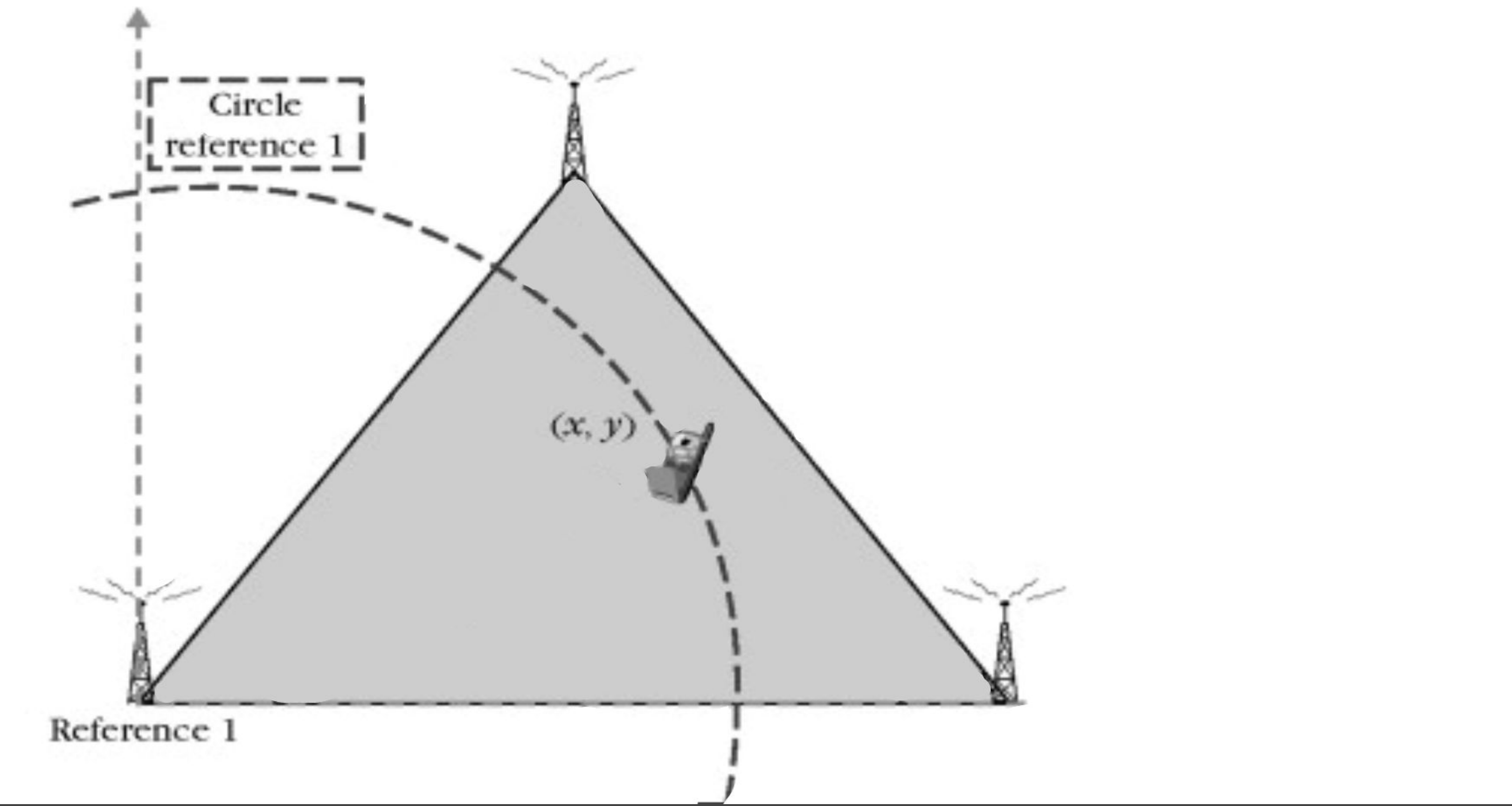
G = $A = \begin{bmatrix} -\frac{x^{(1)} - x_0}{R_0^{(1)}} & -\frac{y^{(1)} - y_0}{R_0^{(1)}} & -\frac{z^{(1)} - z_0}{R_0^{(1)}} & 1 \\ -\frac{x^{(2)} - x_0}{R_0^{(2)}} & -\frac{y^{(2)} - y_0}{R_0^{(2)}} & -\frac{z^{(2)} - z_0}{R_0^{(2)}} & 1 \\ -\frac{x^{(3)} - x_0}{R_0^{(3)}} & -\frac{y^{(3)} - y_0}{R_0^{(3)}} & -\frac{z^{(3)} - z_0}{R_0^{(3)}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -\frac{x^{(m)} - x_0}{R_0^{(m)}} & -\frac{y^{(m)} - y_0}{R_0^{(m)}} & -\frac{z^{(m)} - z_0}{R_0^{(m)}} & 1 \end{bmatrix}$

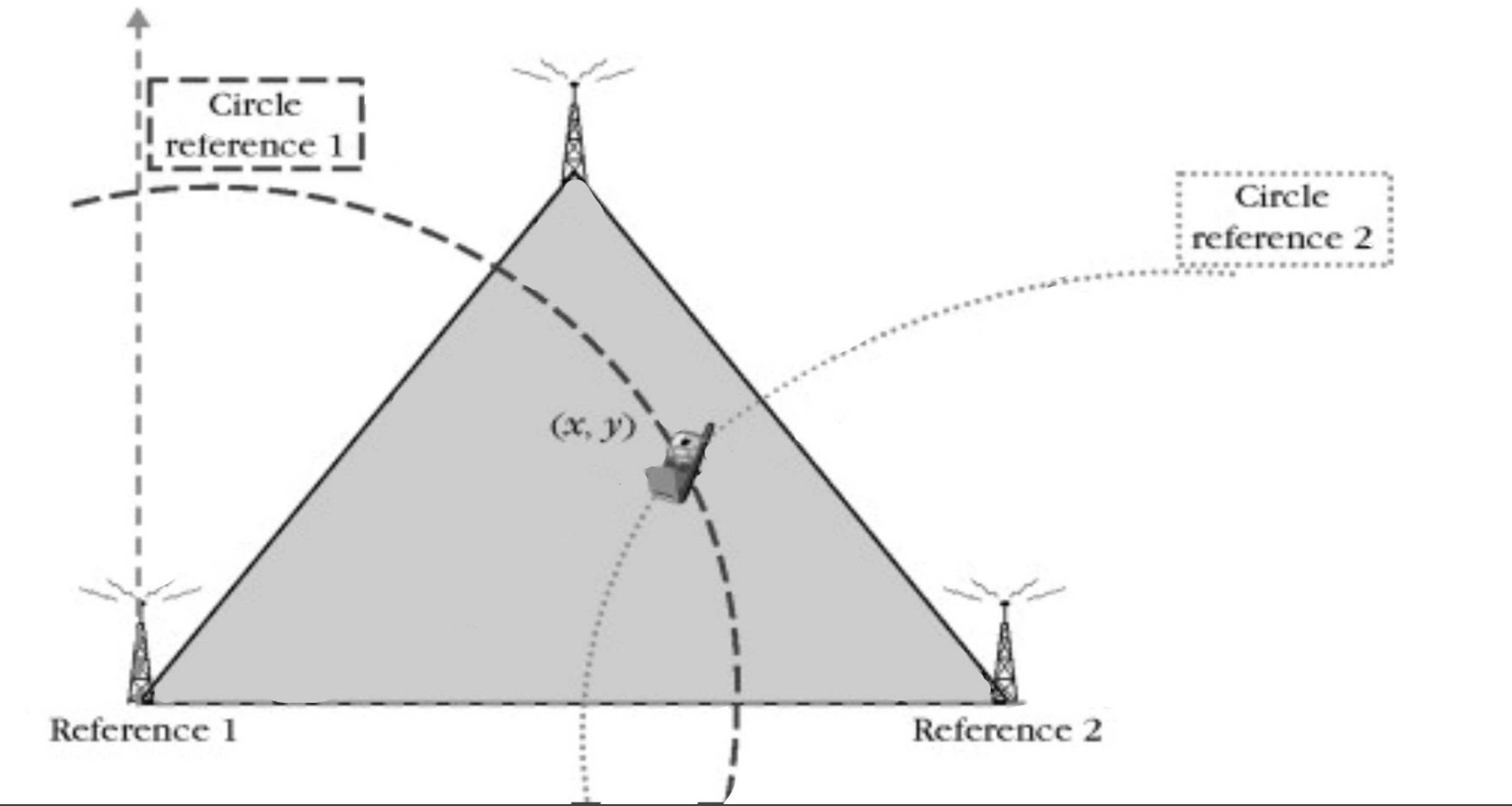
Geometry Matrix

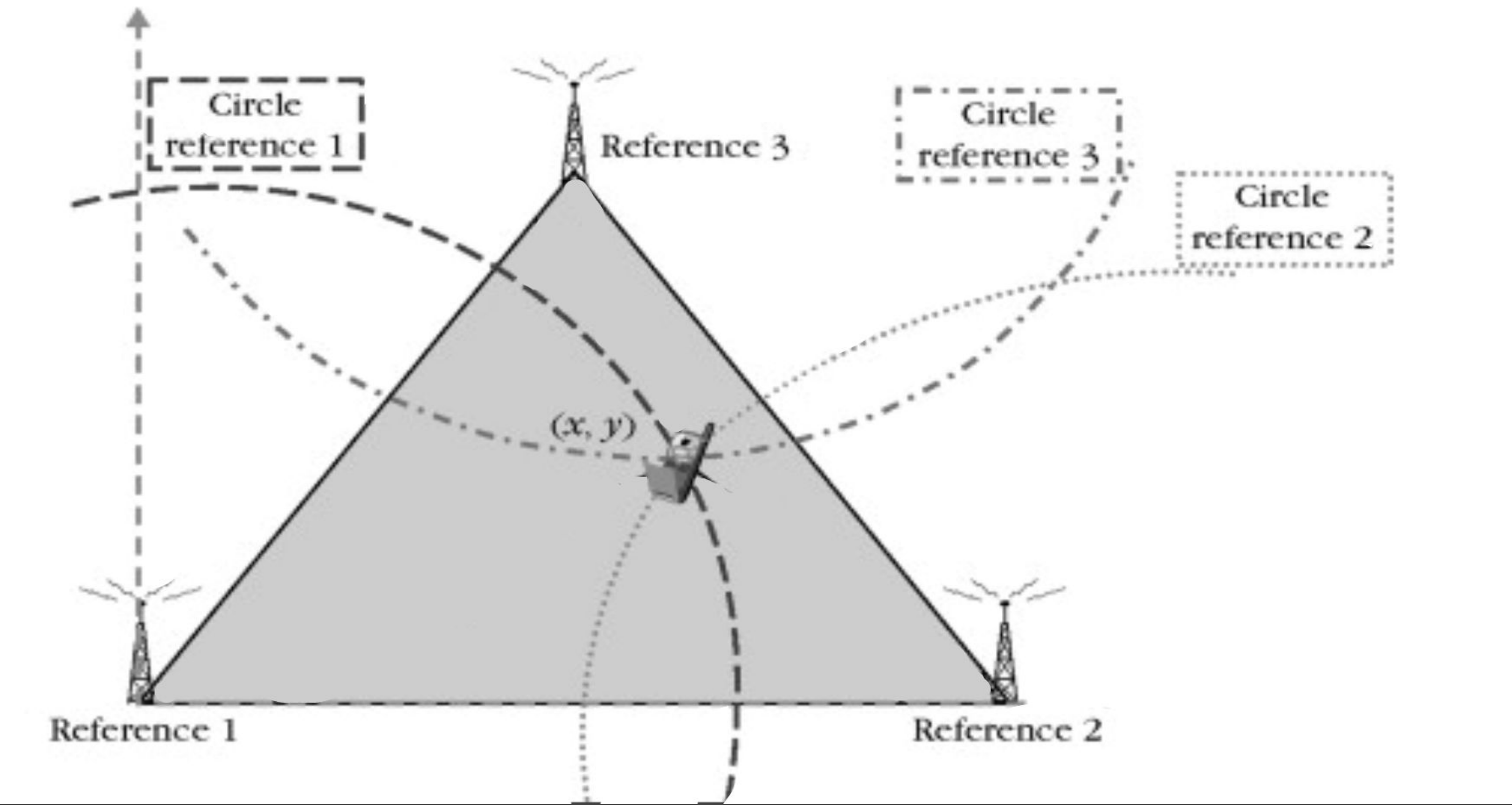
$$\delta\boldsymbol{\rho} = G \begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix}$$

$$\begin{bmatrix} \delta\hat{\mathbf{x}} \\ \delta\hat{b} \end{bmatrix} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\delta\boldsymbol{\rho}$$




Circle
reference 1
(x, y)
Reference 1


Circle
reference 1
Circle
reference 2
(x, y)
Reference 1
Reference 2

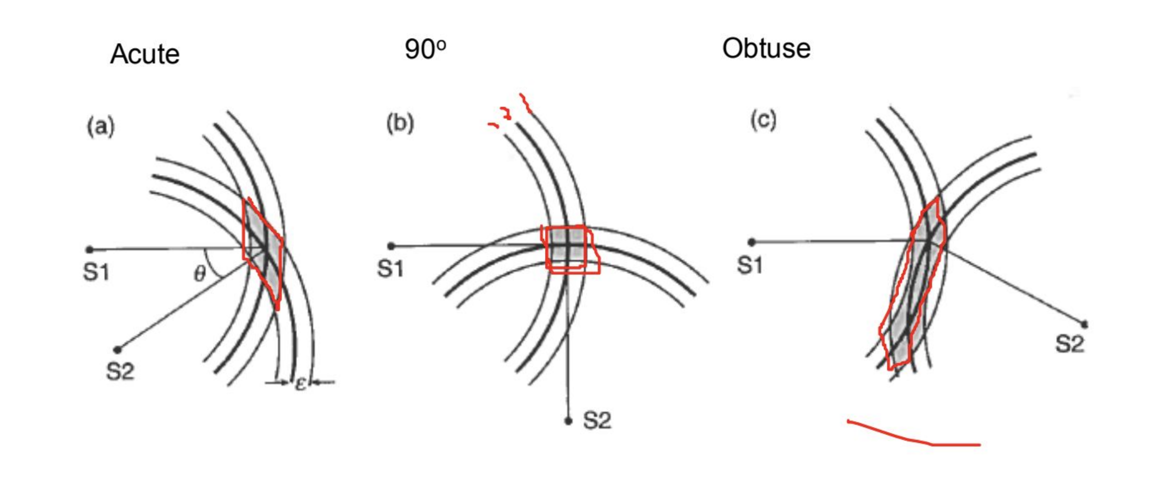


Circle reference 1
Reference 3
Circle reference 3
Circle reference 2
(x, y)
Reference 1
Reference 2

Positioning System - HDOP

Horizontal **D**ilution **O**f **P**recision

Definition: “Used to specify error propagation as a mathematical effect of navigation pseudolite geometry on positional measurement precision”.



$$\text{RMS horizontal error} = \sqrt{\sigma_E^2 + \sigma_N^2} = \sigma \cdot \text{HDOP} \quad (6.2$$

$$\text{RMS vertical error} = \sigma_U = \sigma \cdot \text{VDOP} \quad (6.2$$

$$\text{RMS 3-D error} = \sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_U^2} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = \sigma \cdot \text{PDOP} \quad (6.2$$

Positioning System - HDOP

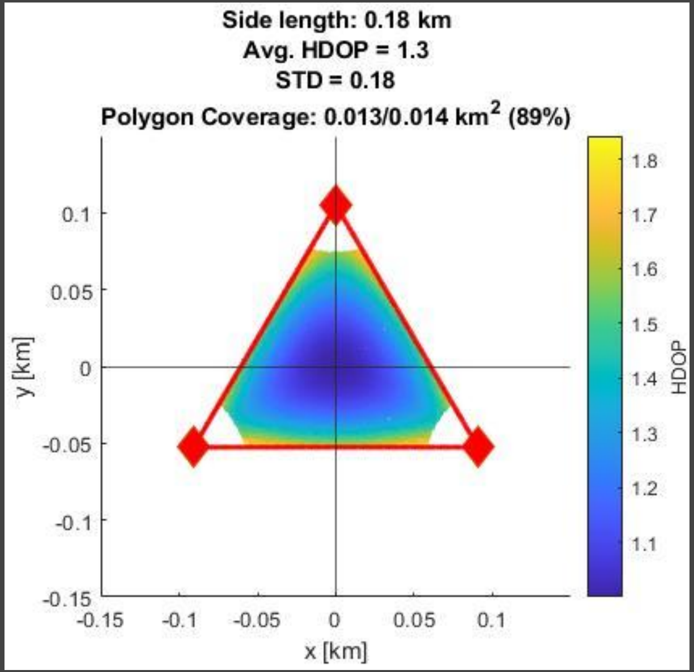
The DOPs provide a simple characterization of the user-satellite geometry. The more favorable the geometry, the lower the DOP. The lower the DOP and σ, the better the quality of the position estimate, in general. If a receiver is limited in the number of satellites it can track simultaneously, the user pays a price with larger rms position error due to higher DOP values.

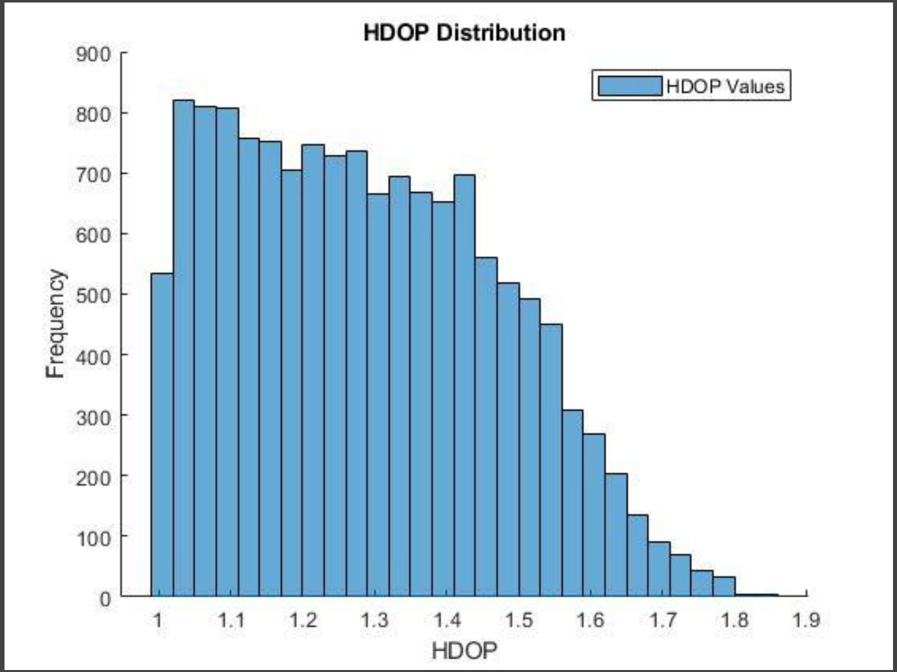
$$\text{RMS horizontal error} = \sqrt{\sigma_E^2 + \sigma_N^2} = \sigma \cdot \text{HDOP} \qquad (6.27a)$$

$$\text{RMS vertical error} = \sigma_U = \sigma \cdot \text{VDOP} \qquad (6.27b)$$

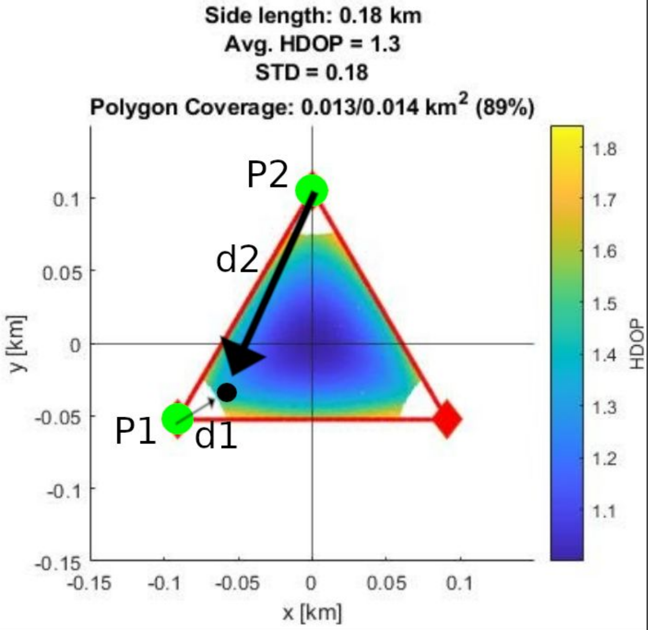
$$\text{RMS 3-D error} = \sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_U^2} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = \sigma \cdot \text{PDOP} \qquad (6.27c)$$

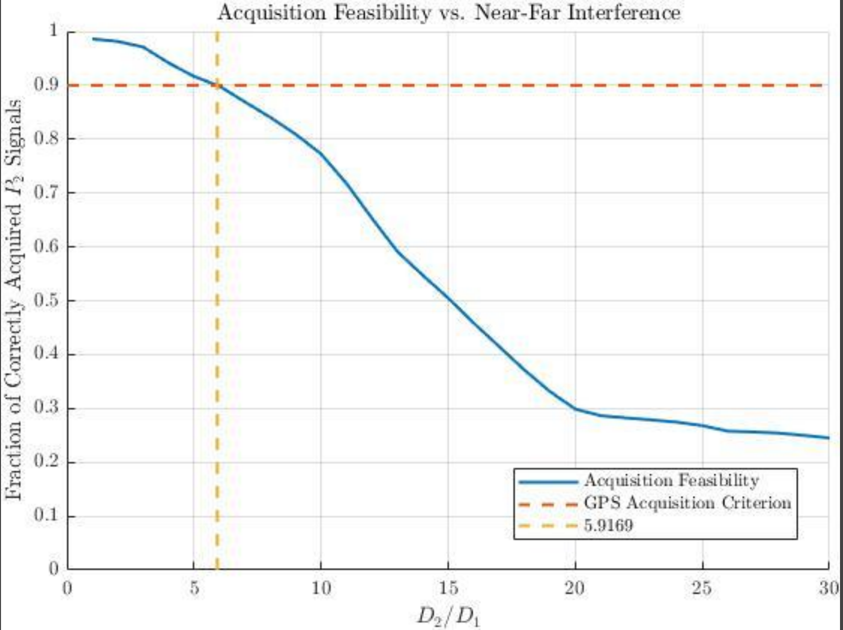
Pseudolite Geometry



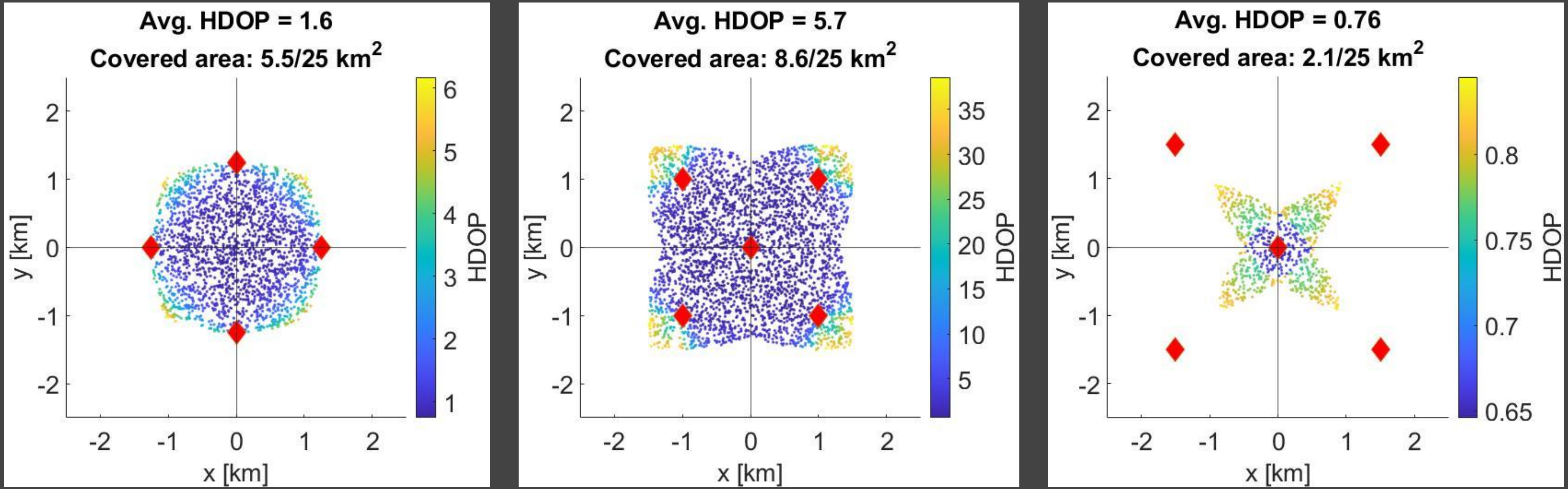


Near-Far Problem



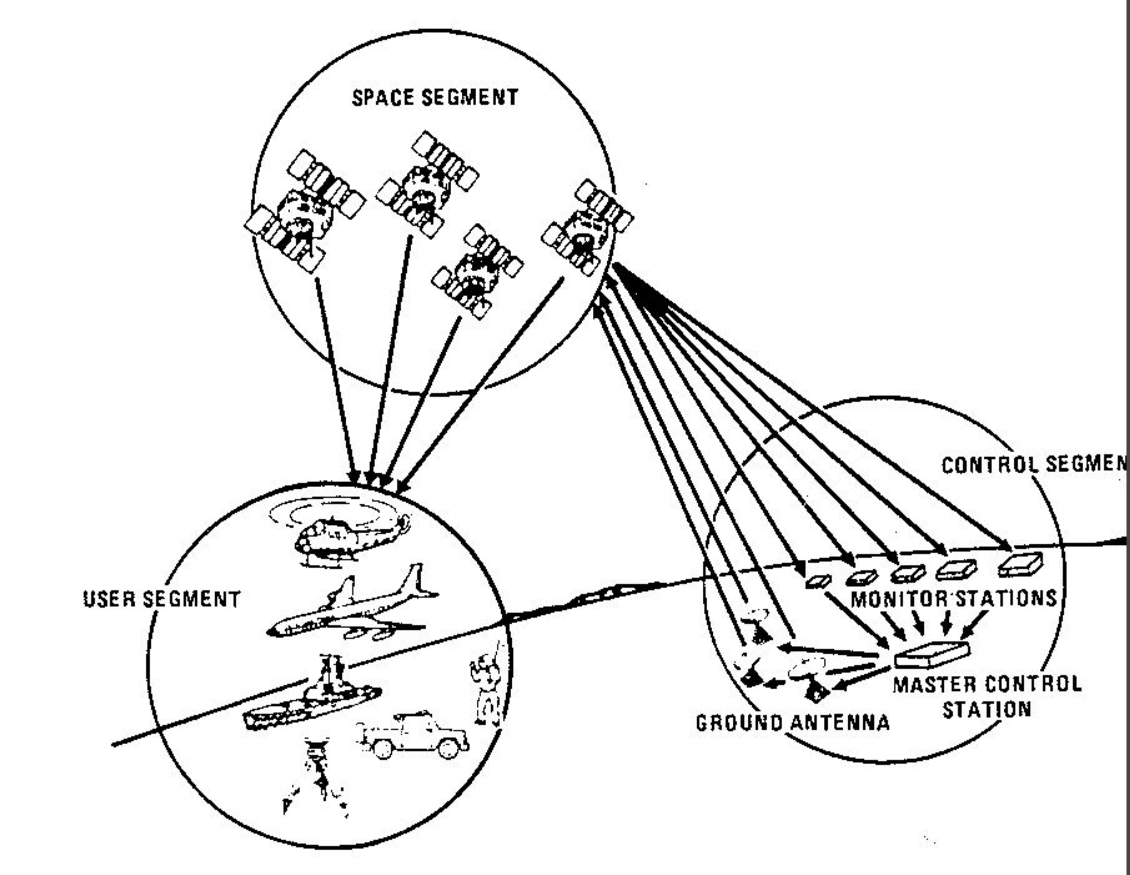


Positioning System - Evidence of Feasibility



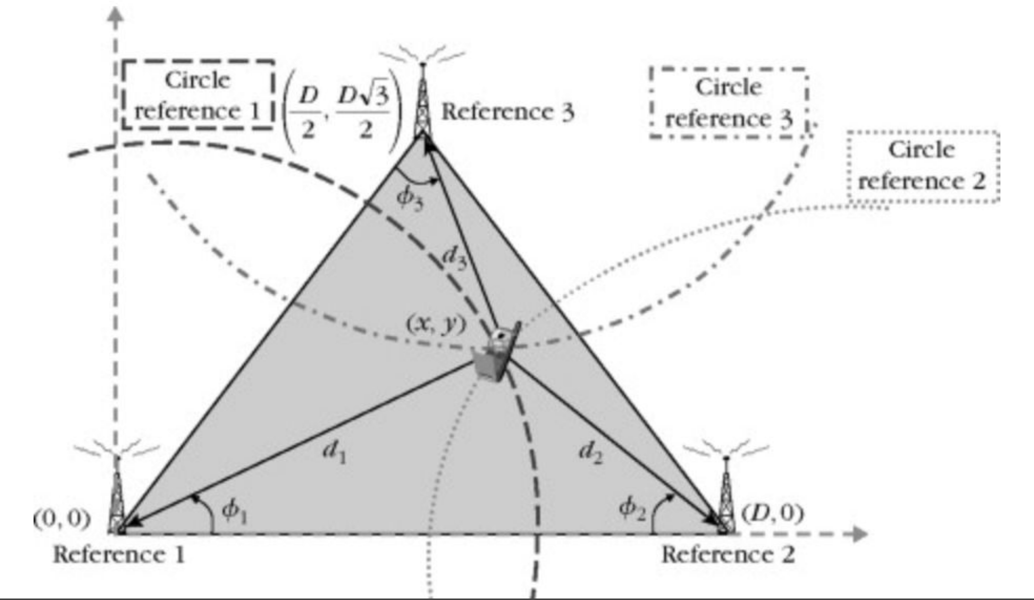
DR 2.3.3

FEASIBLE



http://allaboutgps101.blogspot.com/2010/12/what-are-3-segments-of-gps-systems.html

Time of Arrival (TOA)



$$d_1 = c(t_1 - t_0) = \sqrt{x^2 + y^2}$$

$$d_2 = c(t_2 - t_0) = \sqrt{(D - x)^2 + y^2}$$

$$d_3 = c(t_3 - t_0) = \frac{1}{2}\sqrt{(D - 2x)^2 + \left(D\sqrt{3} - 2y\right)^2}$$

t_i: TOA at reference i; c: speed of light

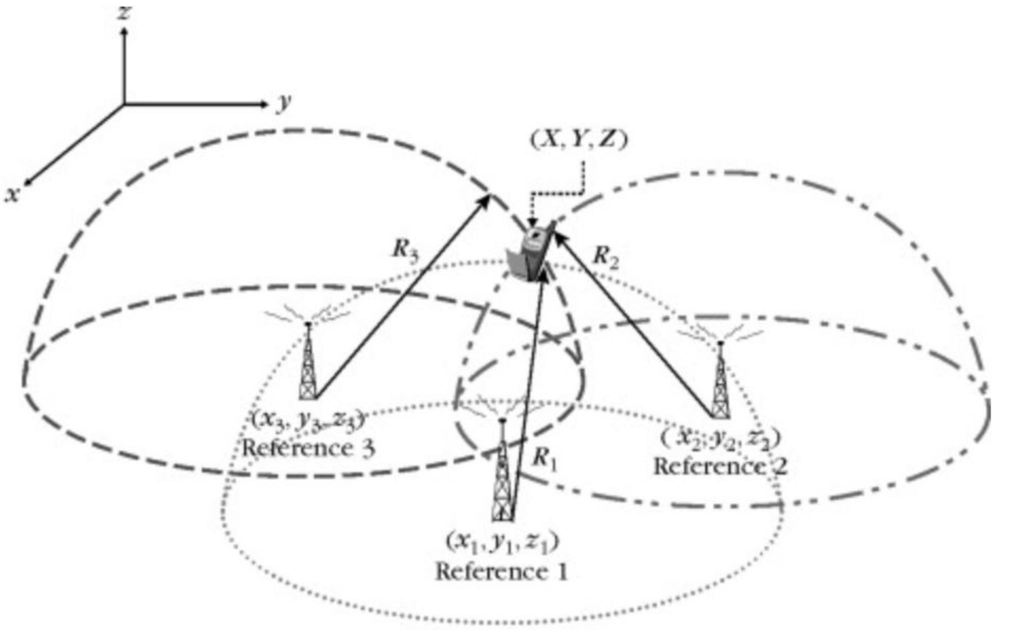
Time of Arrival (TOA)

$$d_i = c(t_i - t_0),$$

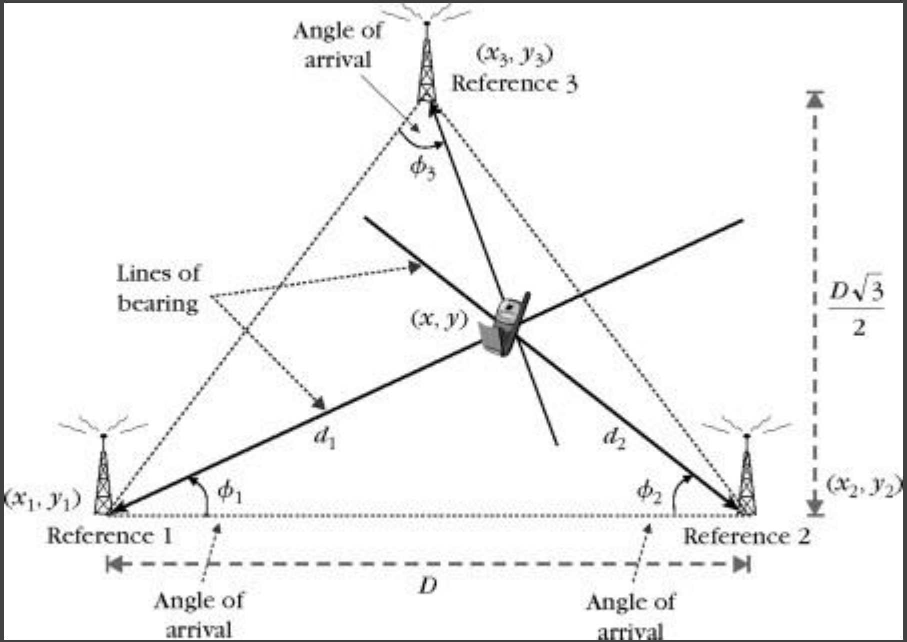
$$d_1^2 = x^2 + y^2,$$
$$d_2^2 = (x_2 - x)^2 + (y_2 - y)^2 = (D - x)^2 + y^2,$$
$$d_3^2 = (x_3 - x)^2 + (y_3 - y)^2 = \tfrac{1}{2}(D - 2x)^2 + \left(D\sqrt{3} - 2y\right)^2.$$

Time of Arrival (TOA)

$$R_i^2 = (X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2, i = 1, 2, 3.$$

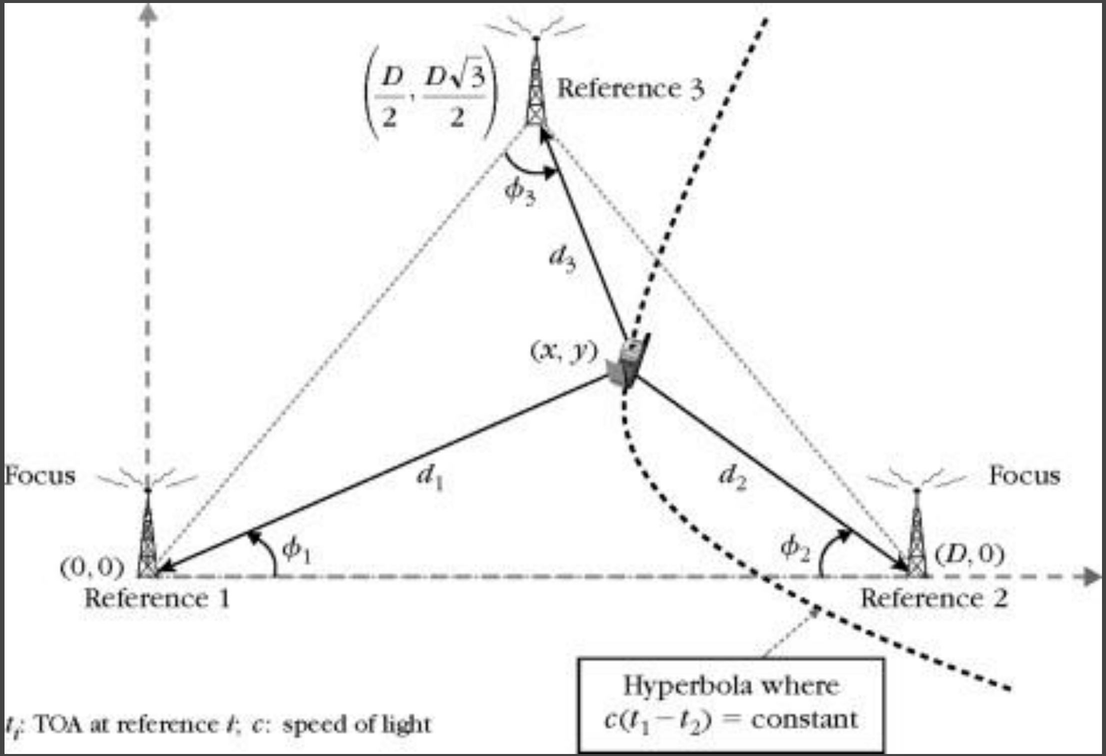


Angle of Arrival (AOA)



$$x = d_i \cos(\phi_i) + x_i\,,$$
$$y = d_i \sin(\phi_i) + y_i\,, i = 1, 2, 3.$$

Time Difference of Arrival (TDOA)



Time Difference of Arrival (TDOA)

$$d_{ij} = d_i - d_j = c(t_i - t_o) - c(t_j - t_o) = c(t_i - t_j), i = 1, 2, 3, j = 1, 2, 3, i \neq j.$$

$$d_i = d_{ij} + d_j;$$

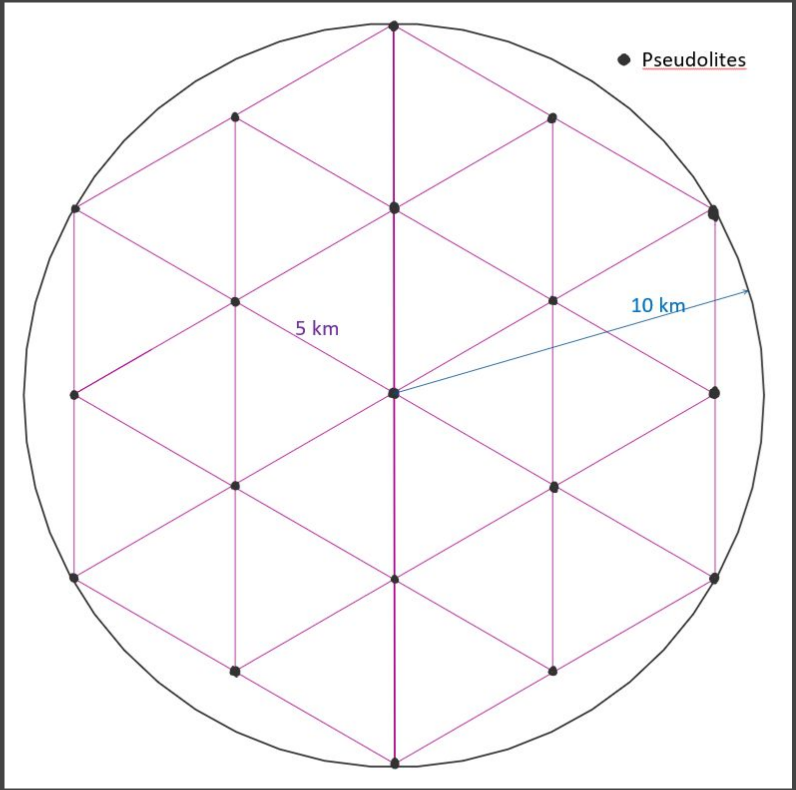
$$\begin{aligned} d_2^2 &= (d_{21} + d_1)^2 \\ &= (x_2 - x)^2 + (y_2 - y)^2 \\ &= x_2^2 - 2x_2x + x^2 + y_2^2 - 2y_2y + y^2 \\ &= x_2^2 - 2x_2x + y_2^2 - 2y_2y + d_1^2, \end{aligned}$$

$$d_1^2 = x^2 + y^2.$$

$$(d_{21}^2 - x_2^2 - y_2^2) + 2d_{21}d_1 = -2x_2x - 2y_2y,$$

$$(d_{31}^2 - x_3^2 - y_3^2) + 2d_{31}d_1 = -2x_3x - 2y_3y.$$

Lunar Pseudolite Geometry

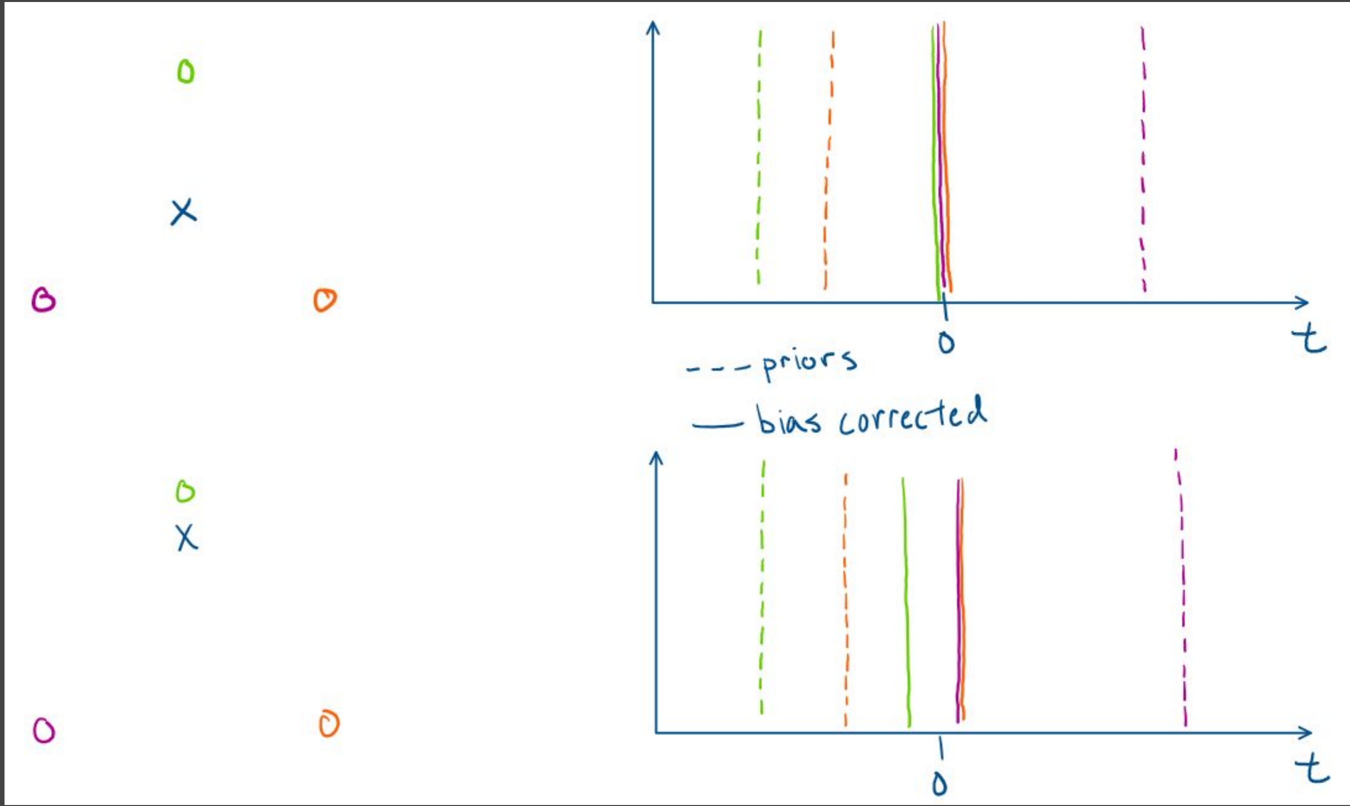


Positioning Solution

Tentative Trade/Analysis Aspects

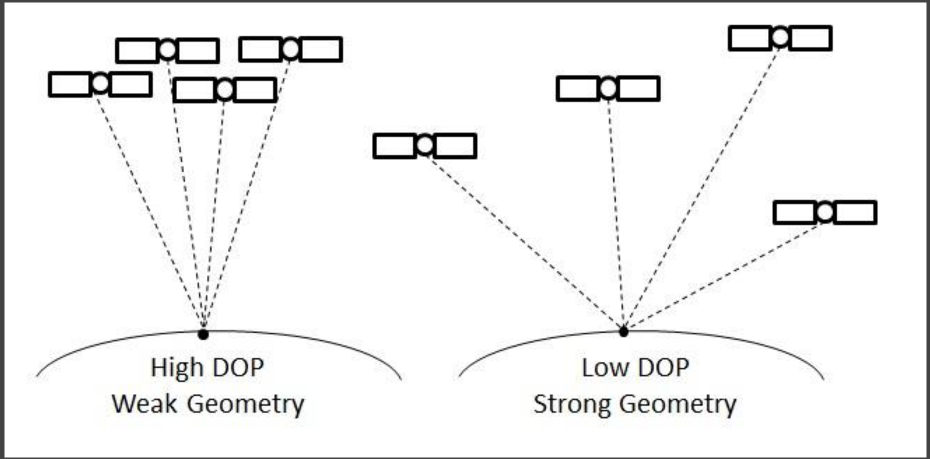
- Will we need accurate clocks
- How complicated the positioning algorithm will be / is it feasible for us to implement
- Antenna requirements
- Near Far problem
-

Basic Positioning System



GNSS: Error sources

- Error sources can be divided into two categories:
  - Ranging error: signal quality, errors in transmitter location, environmental effects, receiver design, etc.…
  - Geometry: Geometric Dilution of Precision (GDOP). Measures the quality of the geometric distribution of the satellites visible to the receiver.



https://www.polyu.edu.hk/proj/gef/index.php/glossary/dilution-of-precision/

GNSS: Architecture

- 3 segments:
  - Ground control segment
    - Provides satellites with ephemeris data and almanac
    - Provides clock-correction factors and data on atmospheric effects
    - Keeps satellites “in check”
  - Space segment
    - Satellites which send out coded ranging signals, ephemerides, correction parameters and almanac.
  - User segment
    - Receiver (which in the case of this project, can also transmit SMS messages)
    - Acquires and track satellite signals.
    - Computes position solution.
    - For this project, THIS is the segment we’ll be working with. All other segments will be assumed as working.

Comms

Communications - Requirements

FR 2: The prototype will provide two-way SMS-like messaging

- **DR 2.1:** Device must have wireless transmission and reception of data
- **DR 2.2:** Communication data rate must be at least 200 bits/s

FR 3: The prototype will provide path to navigation solution with 10 meter positioning accuracy and 30 nanosecond 1-sigma transfer time

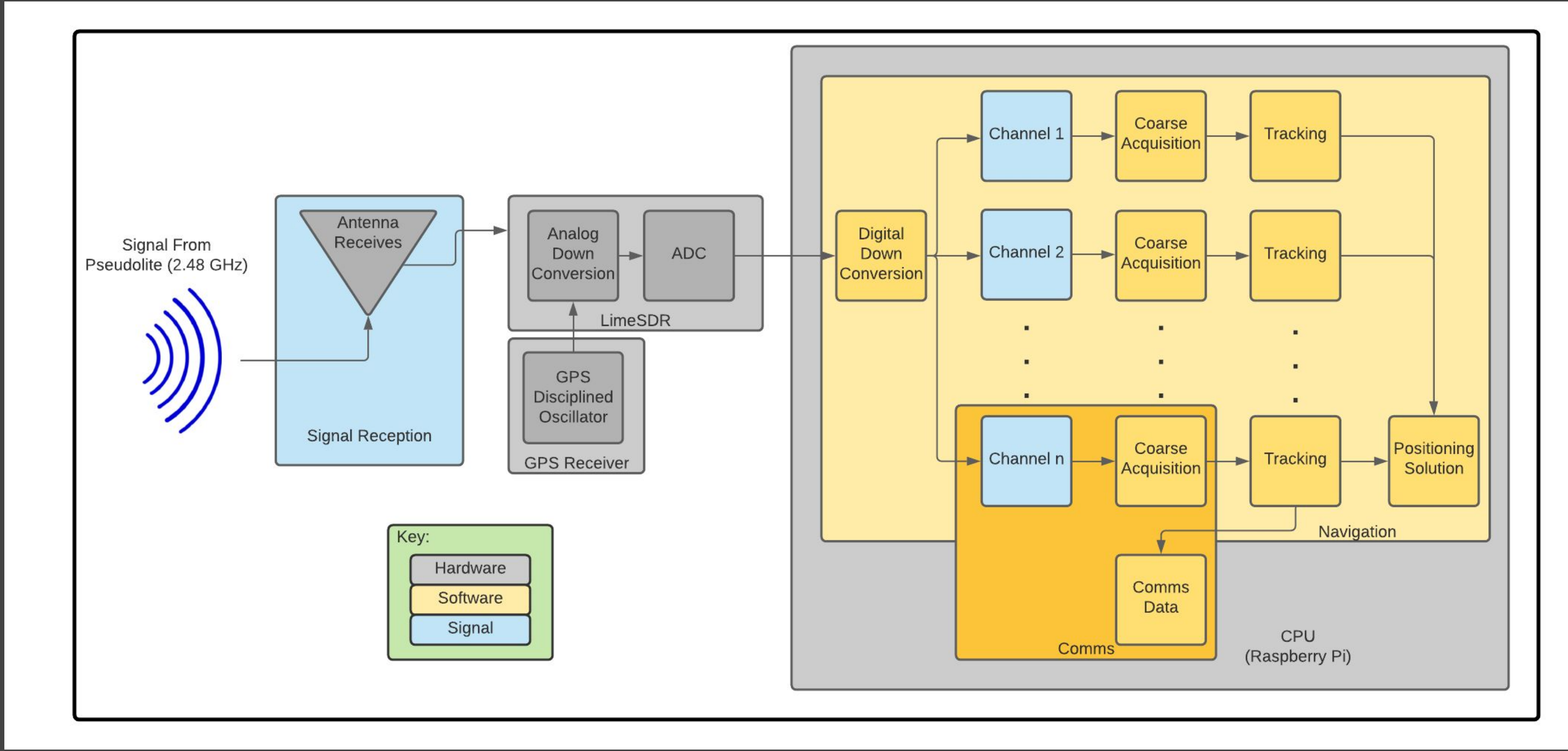
- **DR 3.1**: Receiver Signal to Noise Ratio must be at least 20 dB

FR 4/5: The communication link must operate at 2.4-2.48 GHz

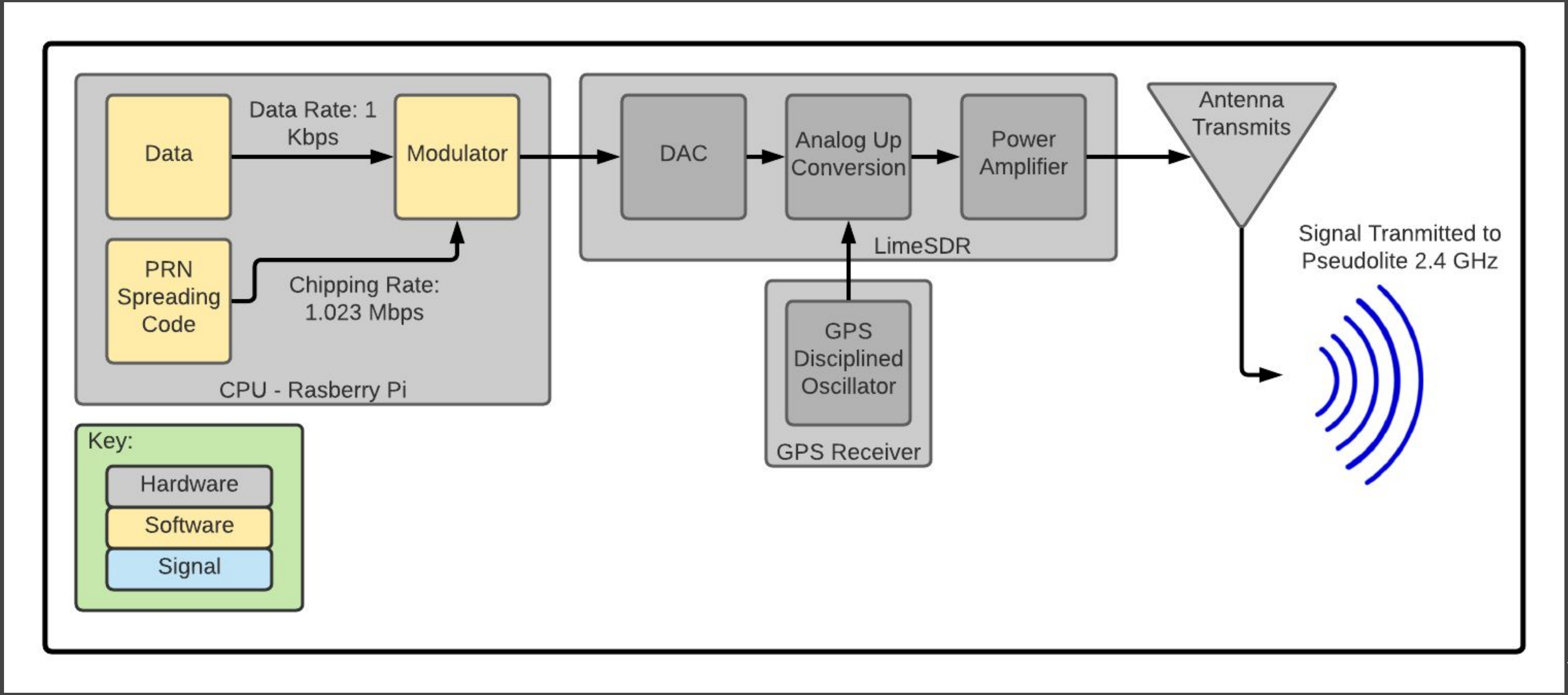
FR 6: The architecture must be extendable to 170 simultaneous users

FR 7: The communication link must have 3 dB channel bandwidth of 1 MHz

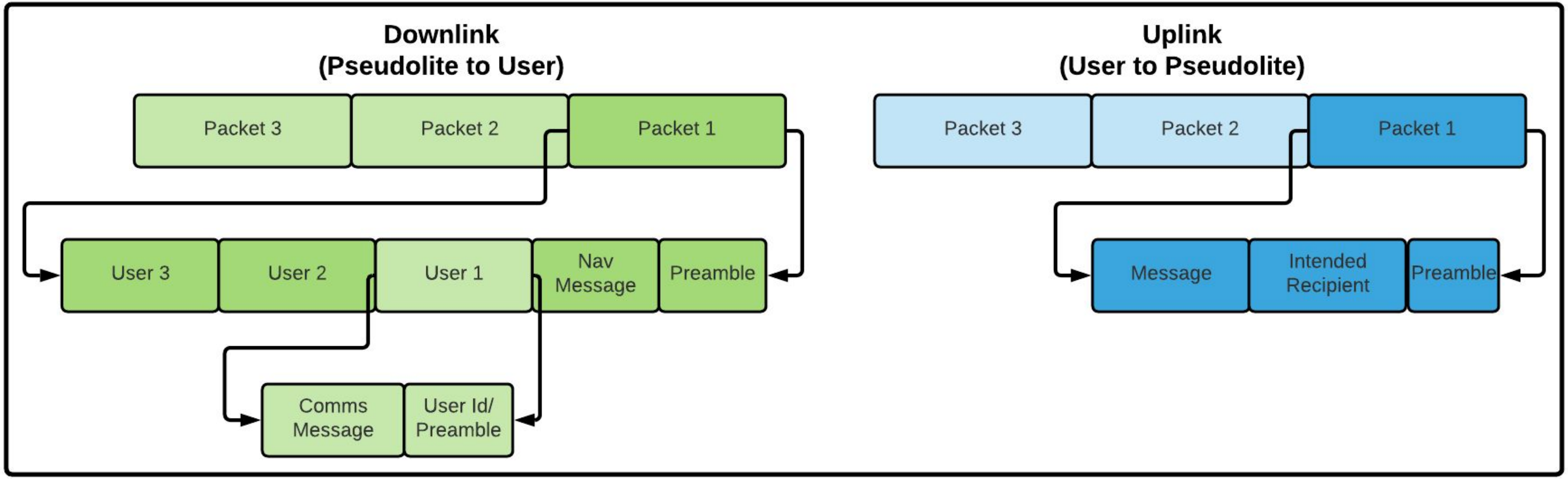
Receive FBD


Signal From
Pseudolite (2.48 GHz)
Antenna
Receives
Signal Reception
Analog
Down
Conversion
ADC
LimeSDR
GPS
Disciplined
Oscillator
GPS Receiver
Digital
Down
Conversion
Channel 1
Coarse
Acquisition
Tracking
Channel 2
Coarse
Acquisition
Tracking
Channel n
Coarse
Acquisition
Tracking
Positioning
Solution
Navigation
Comms
Data
Comms
CPU
(Raspberry Pi)
Key:
Hardware
Software
Signal

Transmit FBD

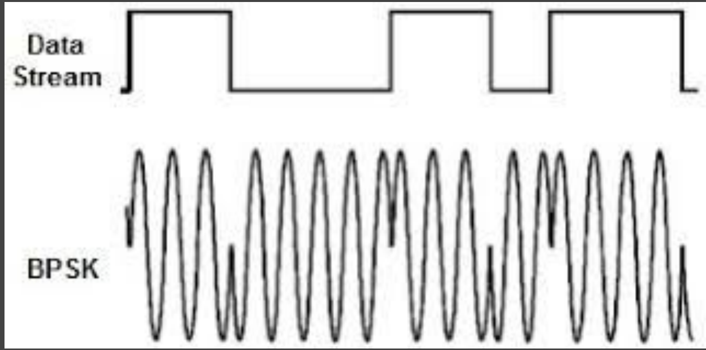


Signal FBD


Downlink
(Pseudolite to User)
Packet 3
Packet 2
Packet 1
User 3
User 2
User 1
Nav Message
Preamble
Comms Message
User Id/ Preamble
Uplink
(User to Pseudolite)
Packet 3
Packet 2
Packet 1
Message
Intended Recipient
Preamble

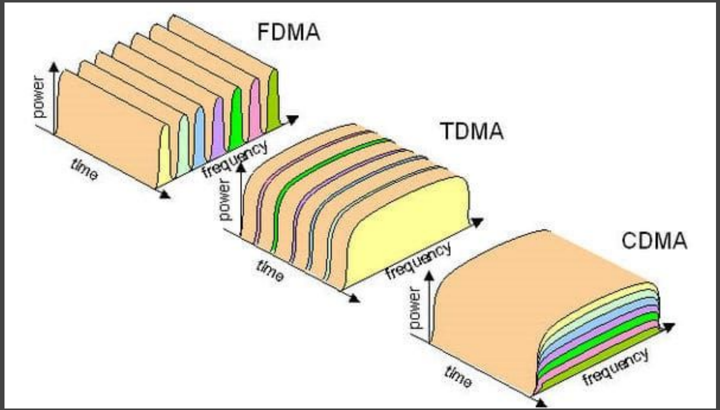
Link Design: Modulation

- Design Choice: Binary Phase Shift Keying (BPSK)
- Reasoning:
  - Low bit error rate (BER)
  - Low complexity
  - Able to use carrier phase to get even more precise signal time of arrival
  - Currently used in GPS implementations



Link Design: Multiplexing

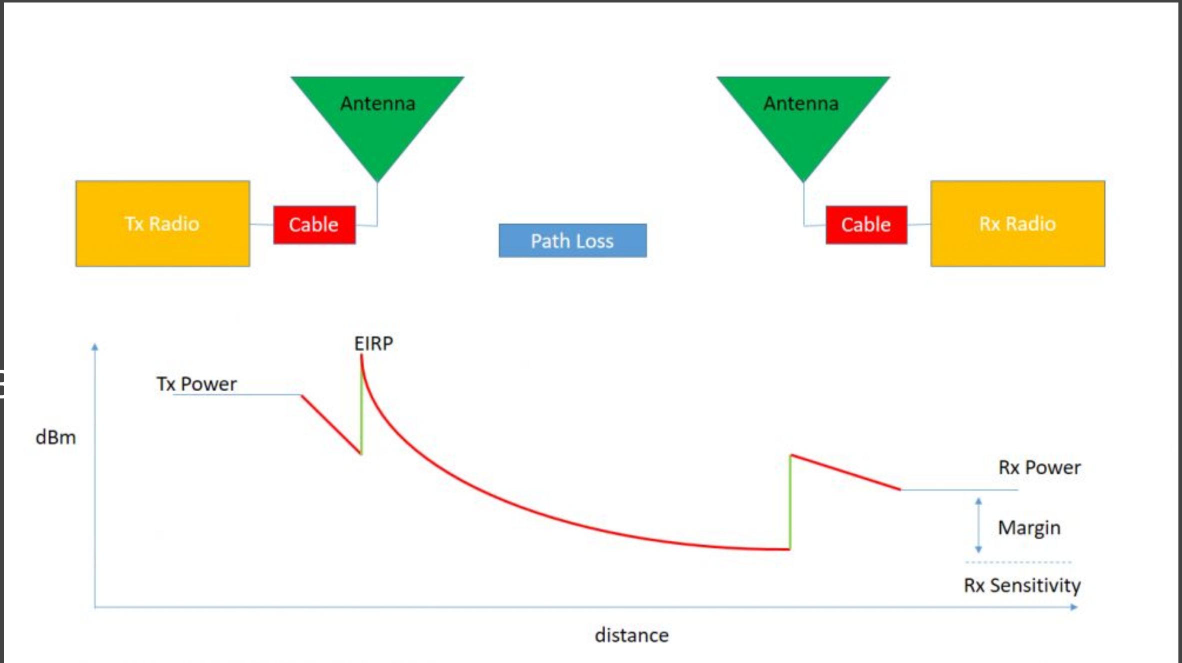
- Design: Code Division Multiple Access
- Reasoning:
  - Able to use phase of spreading code to calculate time of arrival (TOA)
  - Single Frequency
  - Asynchronous CDMA
  - Low cross-interference
- Specification (Design Solution):
  - 1023 bit Gold Code PRN chipping code
  - 1.023 MHz chipping rate
  - 1 ms code period (same as data rate)



Communications - Link Budget

Link Budget (Single User):

- Data Rate: 1 kbps
- Frequency: 2.4 GHz
- Modulation: BPSK
- Distance: 10 km
- Transmit Power: 2 mW
- Minimum Receive SNR: -12 dB
  - BER: 10^{-8}, Eb/N0: 12 dB
- Link Margin: 9 dB



DR 2.1, 2.2, FR4, FR 5

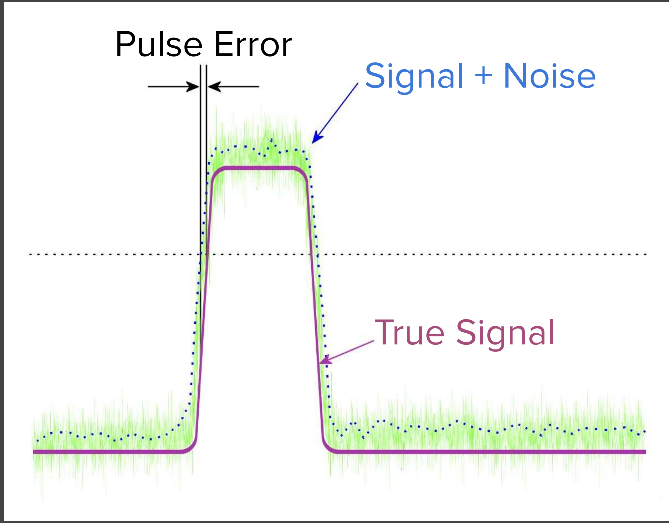
FEASIBLE

Minimum Ranging SNR

- FR 3: System will provide path to a position to 10 m accuracy (30 ns transfer time)
  - DR 3.1: Received SNR (Signal-to-Noise Ratio) must be at least 20 dB from following formula

$$\delta R = \frac{c_0}{2B\sqrt{2SNR}}$$

- FR 7: Link must operate at 1 MHz bandwidth
- Link Budget operates on a 48 dB-Hz minimum C/N_0

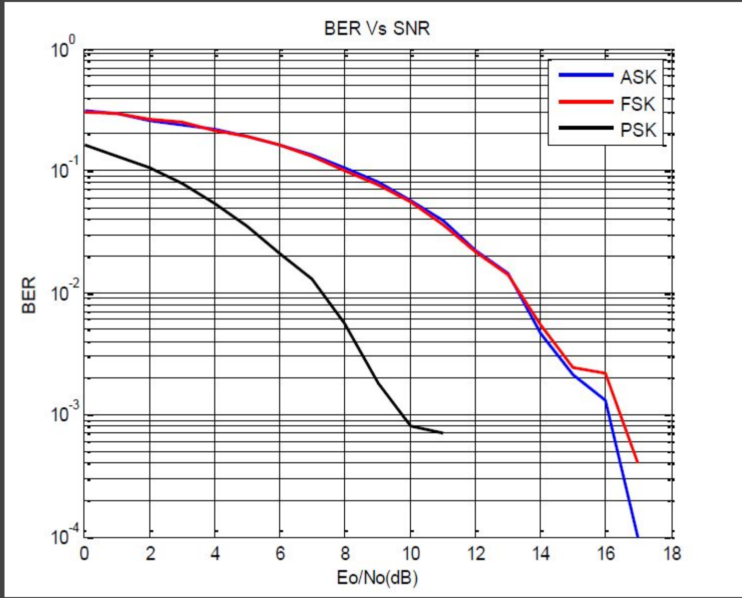


DR 3.1, FR7

FEASIBLE

Modulation: Phase Shift Keying

- Modulation Scheme must be compatible with SDR
    - Compatible with LimeSDR
    - Compatible with GNU Radio
- Low Bit Error Rate
- Single Frequency
- Use carrier phase for additional position accuracy
- GPS uses Phase Shift Keying

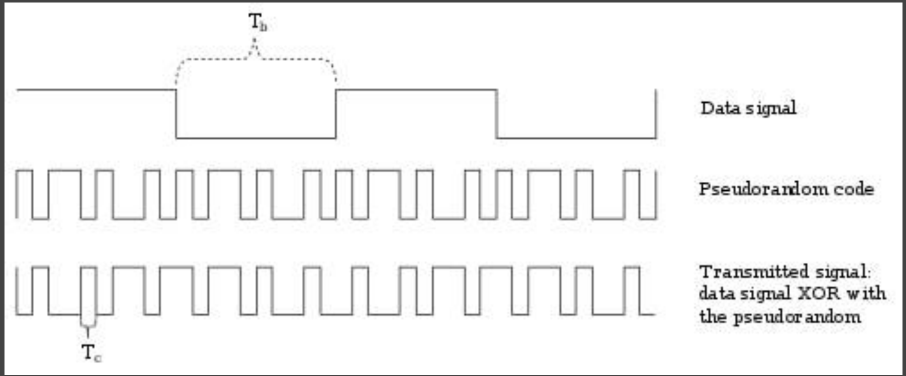


DR 2.1, 2.2, 3.1, FR4, 5, 7
SDR Compatibility

FEASIBLE

Multiplexing: CDMA

- CDMA used in GPS
- CDMA code rate relates to first level of position accuracy
- CDMA can operate on single frequency
- Receiver can receive multiple signals simultaneously
- CDMA with 1023 bit chip code:
  - One way ranging: more end users overall, more precise timing requirements
  - Two way ranging: each user contributes to multiple access interference



One Way Ranging: FR 6

MORE ANALYSIS

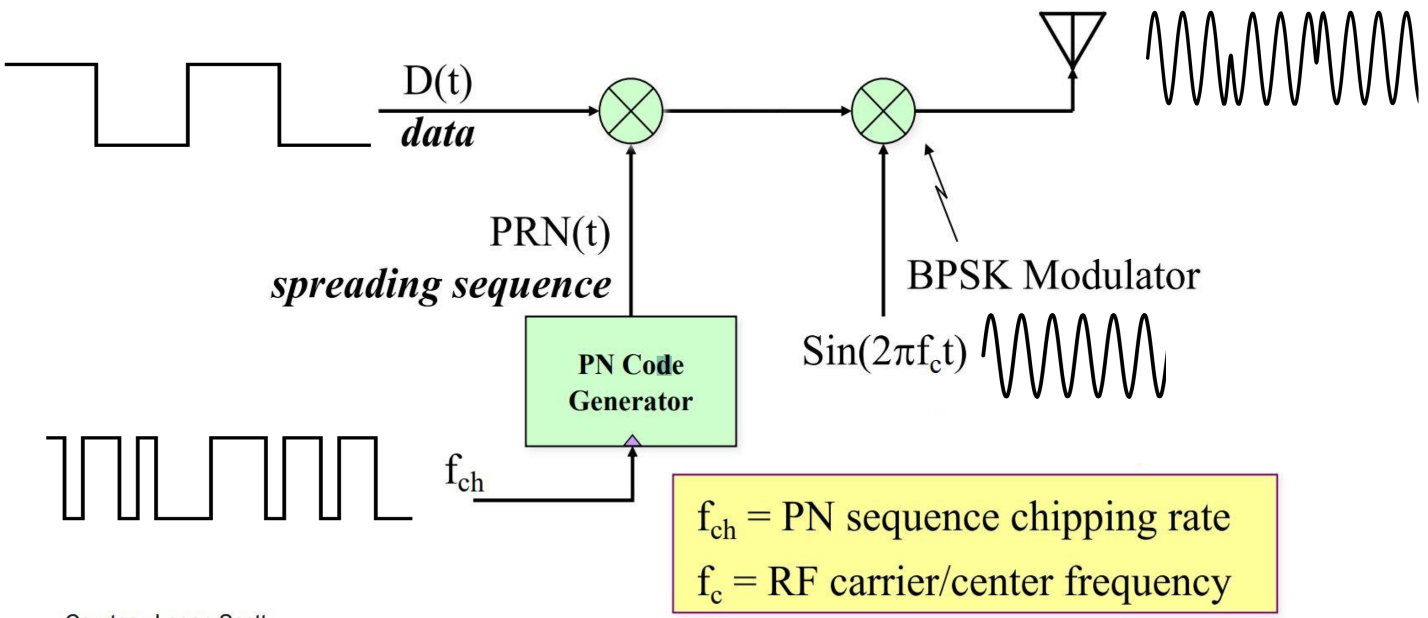
Two Way Ranging: FR 6

MORE ANALYSIS

DR 2.1, 3.1, FR 4, 5, 7

FEASIBLE

Signal Generation



Courtesy Logan Scott

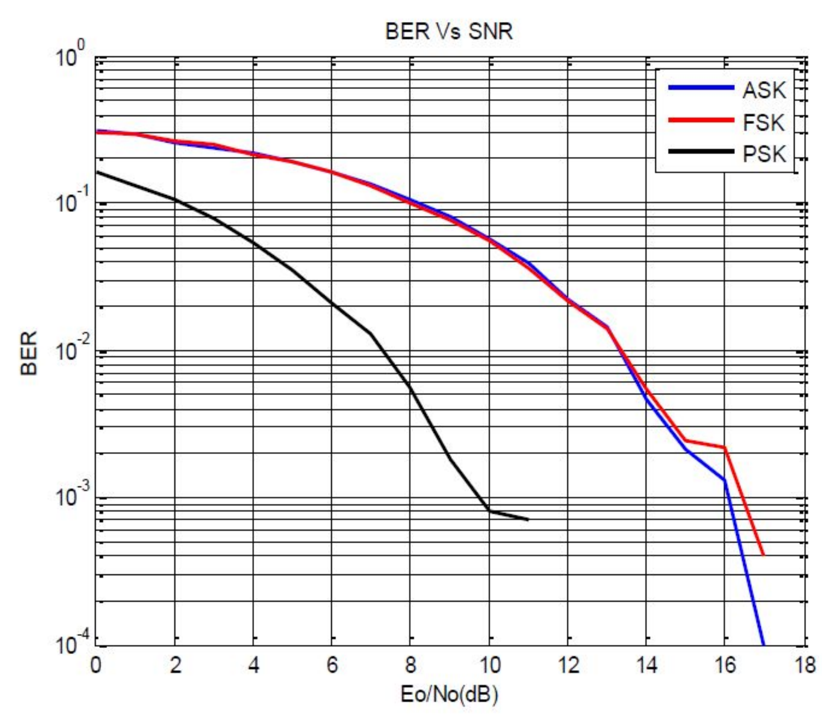
Downlink Packet Breakdown

- Preamble
  - Unique 24 bit code sequence to allow for signal correlation
- Navigation Message
  - Element of set bit length providing timing for positioning algorithm
- User ID
  - 8 bit element containing a unique user identification sequence for each user to identify intended recipient
  - Designed to accommodate 30 user requirement
- Communications Message
  - 5000 bit text communication element broken into 8 bit characters
  - Message will be appended with ‘ ‘(space) buffers to maintain constant size

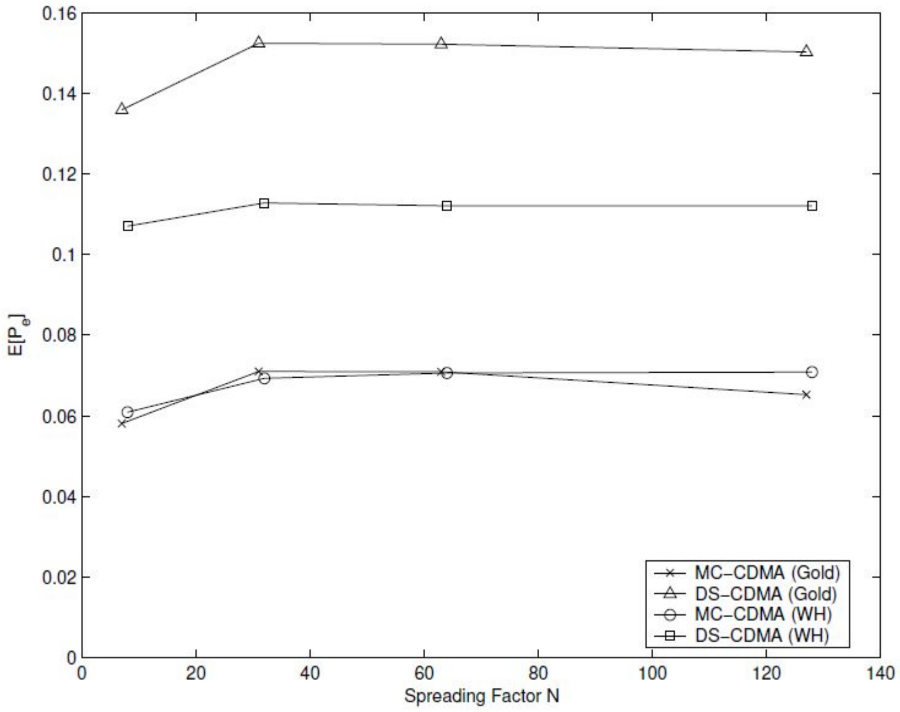
Uplink Breakdown

- Preamble
  - Unique 24 bit code sequence to allow for signal correlation
- User Identification
  - 8 bit element containing a unique user identification sequence for each user to identify transmitting user
  - Designed to accommodate 30 user requirement
- Communications Message
  - 5000 bit text communication element broken into 8 bit characters
  - Message will be appended with ‘ ‘(space) buffers to maintain constant size

Bit Error Rates of Modulation Schemes



Bharati et. al.



Carey et. al.

Pseudolite Link Budget 1

PARAMETER	UPLINK (Receiver to Satellite)	DOWNLINK (Satellite to Receiver)	UNITS	Symbol	Reference
Speed of Light	*3.0E+08*	*3.0E+08*	*m/s*	*C=λ*f*	*constant*
Frequency	*2.4*	*2.4*	*GHz*	*f*	*Input: system choice, X-band mil.com.sat.*
Wavelength	0.125	0.125	m	l	
Range	*10*	*10*	*km*	*R*	*Input: Geostationary Satellite [km]*
Boltzman's Constant	*1.380E-23*	*1.380E-23*	*W/(Hz-K)*	*k*	*constant*
Data Parameters	Uplink	Downlink	Units	Symbol	Reference
Bit Error Rate / Probablility of Bit Error	*10-8*	*10-8*	*[-]*	*BER*	*Input: design requirement*
Data Coding Scheme	*QPSK*	*QPSK*			*Input: chosen modulation (SMAD Tab.13-10)*
Required Bit Energy to Noise Ratio	12	12.0	dB	Eb/No	Lecture Pt. 2, Slide 15
Data Rate	*1000*	*1,000*	*bps (Hz)*	*R*	*Input: based on mission / objective*
Carrier to Noise Ratio Density	42.00	42.00	dB-Hz	Pr/No	Lecture Pt. 2, Slide 15
Required Design Margin	*6.00*	*6.00*	*dB*		*Input: design rule (Hoffmann chap. 9.4.4)*
Minimum Pr/No	**48.00**	**48.00**	**dB-Hz**		
Noise (applies to receiving elements)	Uplink	Downlink	Units	Symbol	Reference
Receiving Antenna Noise Temperature	400	400	K	Ta	Lecture Pt. 2, Slide 13
Receiver Cable Loss	*0.9*	*0.9*	*dB*	*Lc*	*SMAD Table 13-10*
Receiver Noise Figure (based on receiver)	*3.0*	*3.0*	*dB*	*NF*	*SMAD Table 13-10*
Receiver Noise Factor	2.0	2.0	[-]	F	Lecture Pt. 2, Slide 10
Receiver Noise Temperature	288.6	288.6	K	Tr	Lecture Pt. 2, Slide 10
Reference Temperature	*290*	*290*	*K*	*To*	*SMAD Eqn13-24*
Receiver System Noise Temperature	580.32	580.32	K	Ts	Lecture Pt 2, Slide 13
Receiver System Noise Power	-200.96	-200.96	dBW-Hz	No	Lecture Pt 2, Slide 9
Receiver Parameters:	Uplink	Downlink	Units	Symbol	Reference
Receive Antenna Diameter	*NA*	*NA*	*m*	*D*	*Input: given geometry from spacecraft*
Receive Antenna Area	NA	NA	m^2	A	Geometry
Receive Antenna Efficiency	*NA*	*NA*	*[-]*	*h*	*Input: typical value*
Receive Antenna Effective Area	NA	NA	m^2	Ae	efficiency * area
Receive Antenna Gain	2.00	2.00	ower Ratio	Gr	Lecture Pt 1, Slide 14
Receive Antenna Beamwidth	180.0	180.0	Degrees	qr	Lecture Pt 1, Slide 16
Receive Antenna Pointing Accuracy	*0.0*	*0*	*degrees*	*er*	*Input: pointing error e for chosen system*
Receive Antenna Pointing Loss	0.00	0.00	dB	Lpr	SMAD 13-21
Receiver Cable Loss (see noise)	*-0.5*	*-0.5*	*dB*	*Lc*	*Input: typical value*
Receiver Figure of Merit	0.00	0.00	dB/K	FOM	
Propagation Parameters:	Uplink	Downlink	Units	Symbol	Reference
Space Loss	-120.05	-120.05	dB	Ls	Lecture Pt 2, Slide 3
Atmospheric Attenuation (clear air)	0	0	dB	La	Lecture Pt 2, Slide 7
Polarization Loss	*0*	*0*	*dB*	*Lp*	*Input: typical value*

Pseudolite Link Budget 2

Transmitter Parameters:	Uplink	Downlink	Units	Symbol	Reference
Transmit Antenna Diameter	NA	NA	m	D	Switch Receive
Transmit Antenna Area	NA	NA	m^2	A	Switch Receive
Transmit Antenna Efficiency	NA	NA	[-]	h	Switch Receive
Transmit Antenna Effective Area	NA	NA	m2	Ae	Switch Receive
Transmit Antenna Gain	2.00	2.00	dBi	Gt	Switch Receive
Transmit Antenna Beamwidth	180.00	180.00	degrees	qt	Switch Receive
Transmit Antenna Pointing Accuracy	0.00	0.15	degrees	et	Switch Receive
Transmit Antenna Pointing Loss	0.00	0.00	dB	Lpt	Switch Receive
Transmit Line Loss	*-0.5*	*-0.5*	*dB*	*Lt*	*Input: based on chosen cable/geometry*
Transmit Power	-27.0	-27.0	dBW	Pt	10*LOG10(Transmit power)
Tramsmit Power, Linear	*0.002*	*0.002*	*W*		*Input: chosen transmitter*
Effective Isotropic Radiated Power	-25.49	-25.49	dBW	EIRP	Sum of Power, Gain, and Losses in dB
Link Budget:	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Effective Isotropic Radiated Power	-25.49	-25.49	dBW	EIRP	From Above
Propagation Losses	-120.05	-120.05	dB	L	Sum of Losses
Receive System Gain	1.50	1.50	dB	Gr	Sum of antenna gain and system losses
Received Power	-144.04	-144.04	dBW	Pr	Sum of Power sent out minus losses
System Noise Power	-200.96	-200.96	dBW-Hz	No	
Carrier to Noise Ratio Density	56.93	56.93	dB-Hz	Pr/No	
Minimum Pr/No	48.00	48.00	dB-Hz		
Link Margin	**8.93**	**8.93**	**dB**		

Satellite Link Budget 1

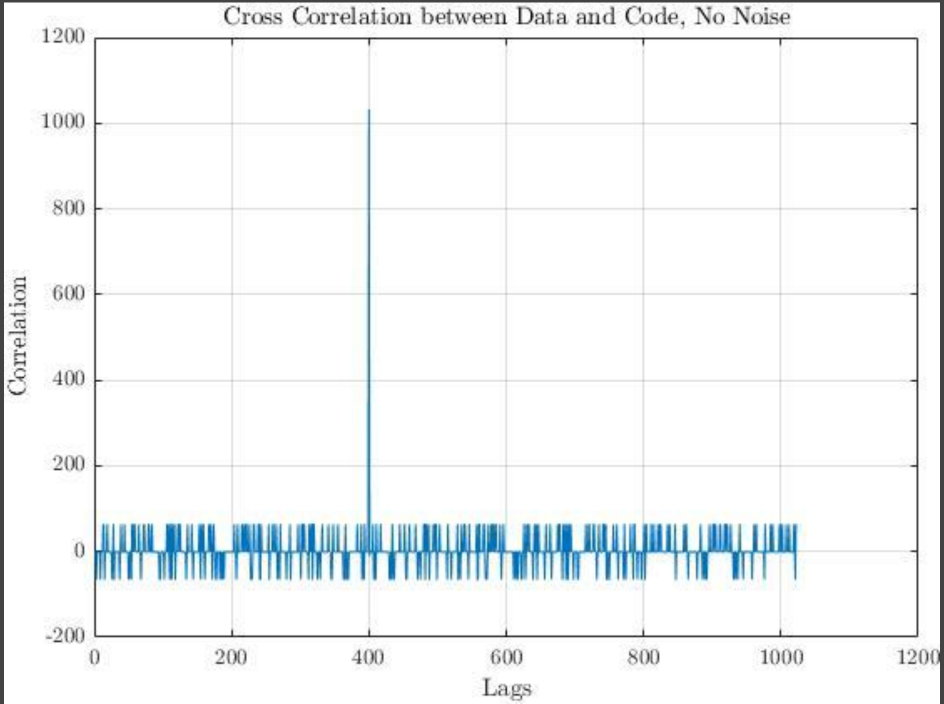
PARAMETER	UPLINK (Receiver to Satellite)	DOWNLINK (Satellite to Receiver)	UNITS	Symbol	Reference
Speed of Light	*3.0E+08*	*3.0E+08*	*m/s*	*C=λ*f*	*constant*
Frequency	*2.5*	*2.5*	*GHz*	*f*	*Input: system choice, X-band mil.com.sat.*
Wavelength	0.120	0.120	m	l	
Range	*10000*	*10000*	*km*	*R*	*Input: Geostationary Satellite [km]*
Boltzman's Constant	*1.380E-23*	*1.380E-23*	*W/(Hz-K)*	*k*	*constant*
Data Parameters	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Bit Error Rate / Probablility of Bit Error	*10-6*	*10-6*	*[-]*	*BER*	*Input: design requirement*
Data Coding Scheme	*QPSK*	*QPSK*			*Input: chosen modulation (SMAD Tab.13-10)*
Required Bit Energy to Noise Ratio	11	12.0	dB	Eb/No	Lecture Pt. 2, Slide 15
Data Rate	*1000*	*1,000*	*bps (Hz)*	*R*	*Input: based on mission / objective*
Carrier to Noise Ratio Density	41.00	42.00	dB-Hz	Pr/No	Lecture Pt. 2, Slide 15
Required Design Margin	*3.00*	*6.00*	*dB*		*Input: design rule (Hoffmann chap. 9.4.4)*
Minimum Pr/No	**44.00**	**48.00**	**dB-Hz**		
Noise (applies to receiving elements)	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Receiving Antenna Noise Temperature	400	25	K	Ta	Lecture Pt. 2, Slide 13
Receiver Cable Loss	*0.9*	*0.9*	*dB*	*Lc*	*SMAD Table 13-10*
Receiver Noise Figure (based on receiver)	*3.0*	*1.0*	*dB*	*NF*	*SMAD Table 13-10*
Receiver Noise Factor	2.0	1.3	[-]	F	Lecture Pt. 2, Slide 10
Receiver Noise Temperature	288.6	75.1	K	Tr	Lecture Pt. 2, Slide 10
Reference Temperature	*290*	*290*	*K*	*To*	*SMAD Eqn13-24*
Receiver System Noise Temperature	580.32	31.75	K	Ts	Lecture Pt 2, Slide 13
Receiver System Noise Power	-200.96	-213.58	dBW-Hz	No	Lecture Pt 2, Slide 9
Receiver Parameters:	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Receive Antenna Diameter	NA	NA	*m*	*D*	*Input: given geometry from spacecraft*
Receive Antenna Area	NA	NA	m^2	A	Geometry
Receive Antenna Efficiency	*NA*	*NA*	*[-]*	*h*	*Input: typical value*
Receive Antenna Effective Area	NA	0.002	m^2	Ae	efficiency * area
Receive Antenna Gain	20.00	2.38	ower Ratio	Gr	Lecture Pt 1, Slide 14
Receive Antenna Beamwidth	20.0	180.0	Degrees	qr	Lecture Pt 1, Slide 16
Receive Antenna Pointing Accuracy	*0.2*	*0*	*degrees*	*er*	*Input: pointing error e for chosen system*
Receive Antenna Pointing Loss	0.00	0.00	dB	Lpr	SMAD 13-21
Receiver Cable Loss (see noise)	*-0.5*	*-0.5*	*dB*	*Lc*	*Input: typical value*
Receiver Figure of Merit	0.03	0.08	dB/K	FOM	
Propagation Parameters:	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Space Loss	-180.37	-180.37	dB	Ls	Lecture Pt 2, Slide 3
Atmospheric Attenuation (clear air)	0	0	dB	La	Lecture Pt 2, Slide 7
Polarization Loss	*0*	*0*	*dB*	*Lp*	*Input: typical value*

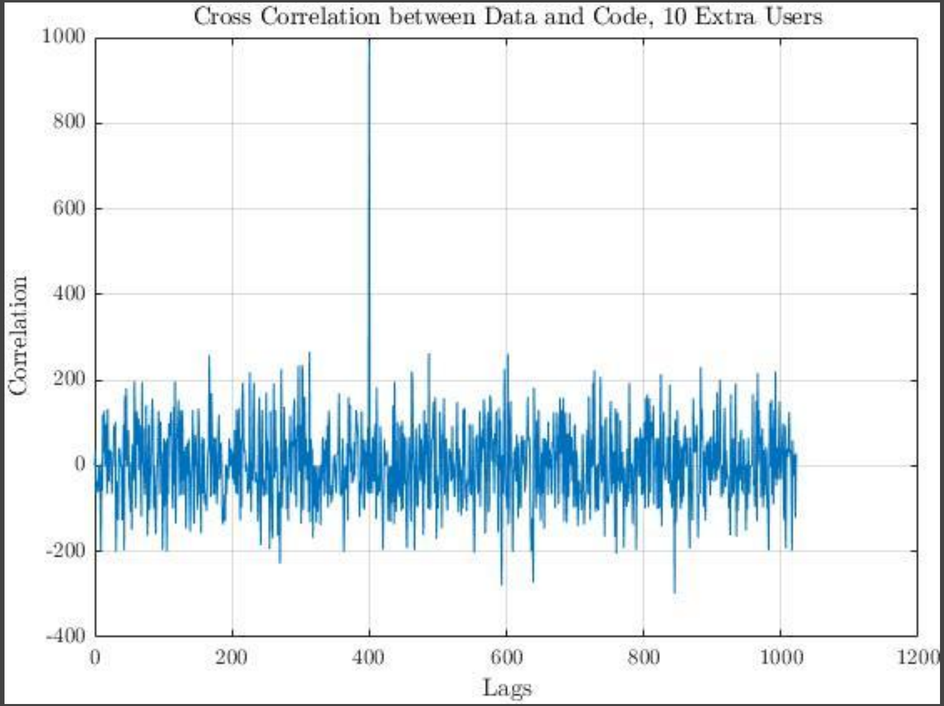
Satellite Link Budget 2

Transmitter Parameters:	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Transmit Antenna Diameter	NA	NA	m	D	Switch Receive
Transmit Antenna Area	NA	NA	m^2	A	Switch Receive
Transmit Antenna Efficiency	NA	NA	[-]	h	Switch Receive
Transmit Antenna Effective Area	0.002	NA	m2	Ae	Switch Receive
Transmit Antenna Gain	2.38	20.00	dBi	Gt	Switch Receive
Transmit Antenna Beamwidth	180.00	20.00	degrees	qt	Switch Receive
Transmit Antenna Pointing Accuracy	0.00	0.15	degrees	et	Switch Receive
Transmit Antenna Pointing Loss	0.00	0.00	dB	Lpt	Switch Receive
Transmit Line Loss	*-0.5*	*-0.5*	*dB*	*Lt*	*Input: based on chosen cable/geometry*
Transmit Power	3.0	14.1	dBW	Pt	10*LOG10(Transmit power)
Tramsmit Power, Linear	*2*	*25.6*	*W*		*Input: chosen transmitter*
Effective Isotropic Radiated Power	4.89	33.58	dBW	EIRP	Sum of Power, Gain, and Losses in dB

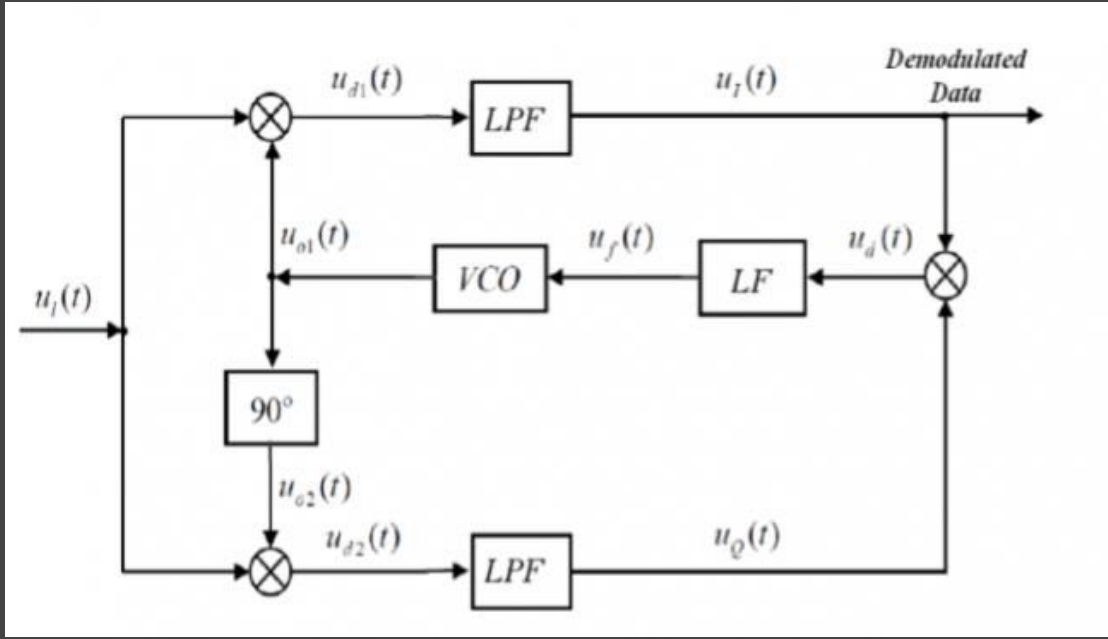
Link Budget:	*Uplink*	*Downlink*	*Units*	*Symbol*	*Reference*
Effective Isotropic Radiated Power	4.89	33.58	dBW	EIRP	From Above
Propagation Losses	-180.37	-180.37	dB	L	Sum of Losses
Receive System Gain	19.50	1.88	dB	Gr	Sum of antenna gain and system losses
Received Power	-155.97	-144.90	dBW	Pr	Sum of Power sent out minus losses
System Noise Power	-200.96	-213.58	dBW-Hz	No	
Carrier to Noise Ratio Density	44.99	68.68	dB-Hz	Pr/No	
Minimum Pr/No	44.00	48.00	dB-Hz		
Link Margin	**0.99**	**20.68**	**dB**		

CDMA Signal Acquisition

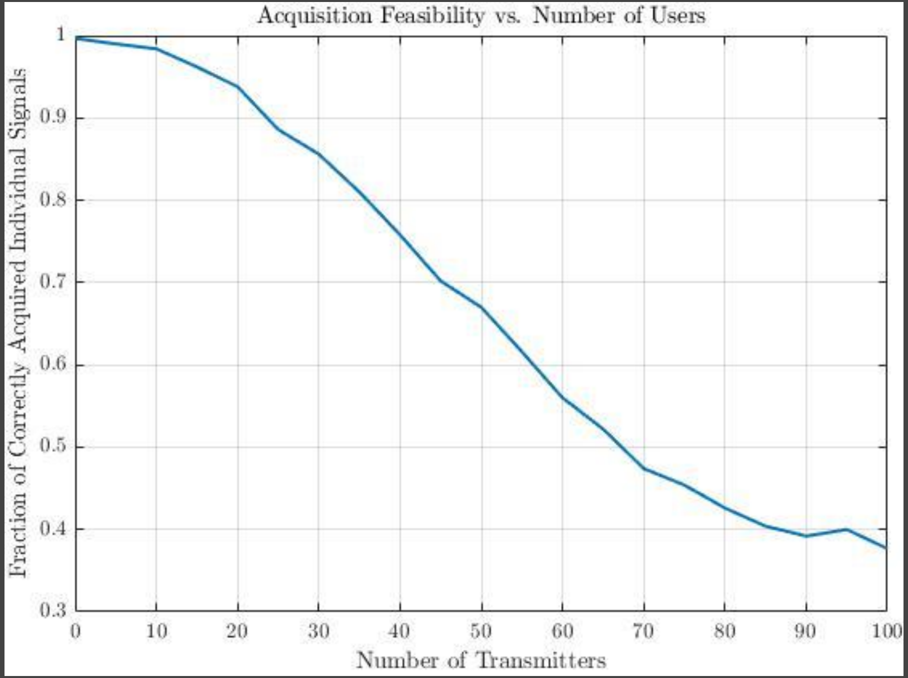




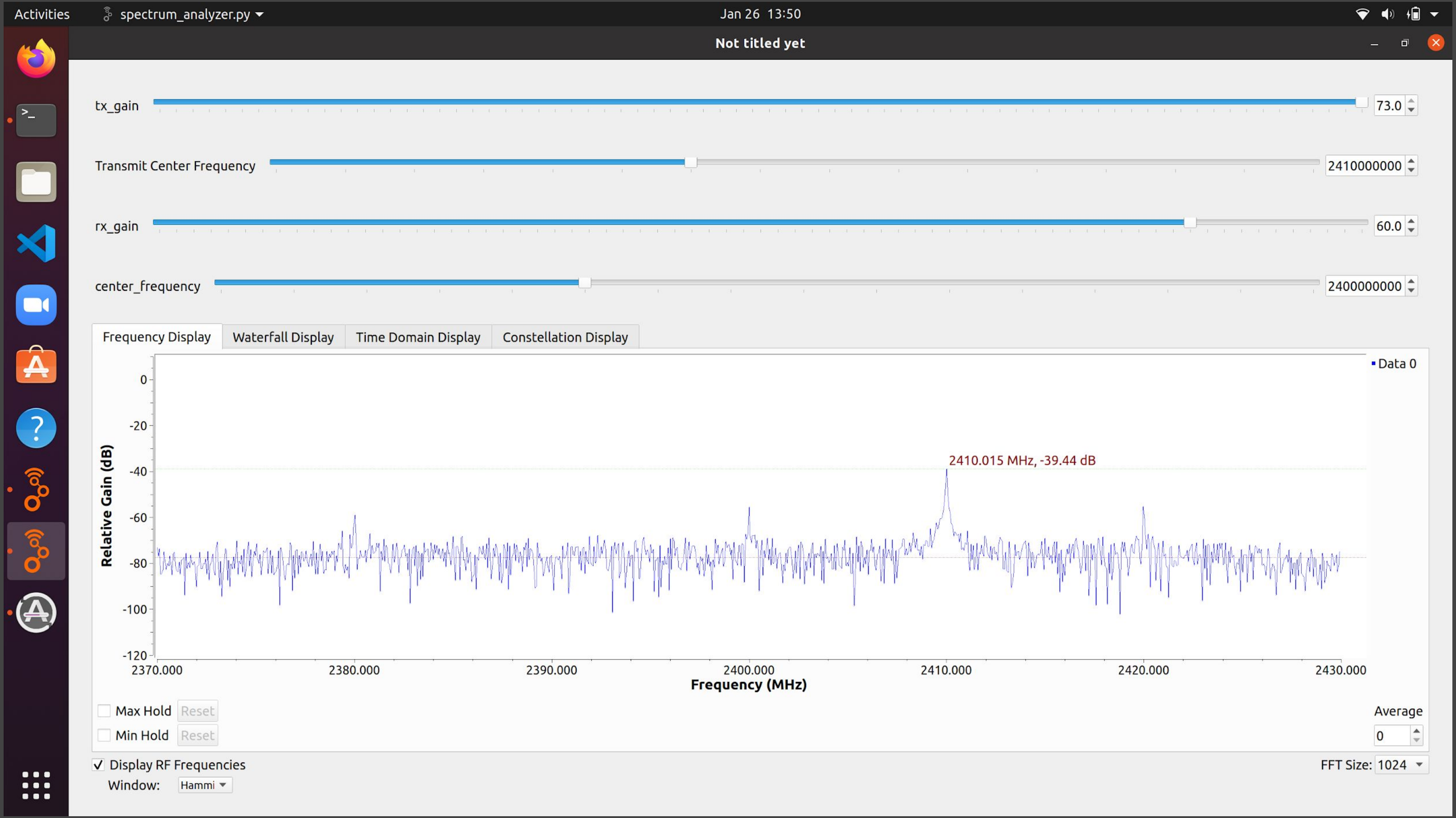
Simple Tracking Loop (Costas Loop)



Multiple Access Interference

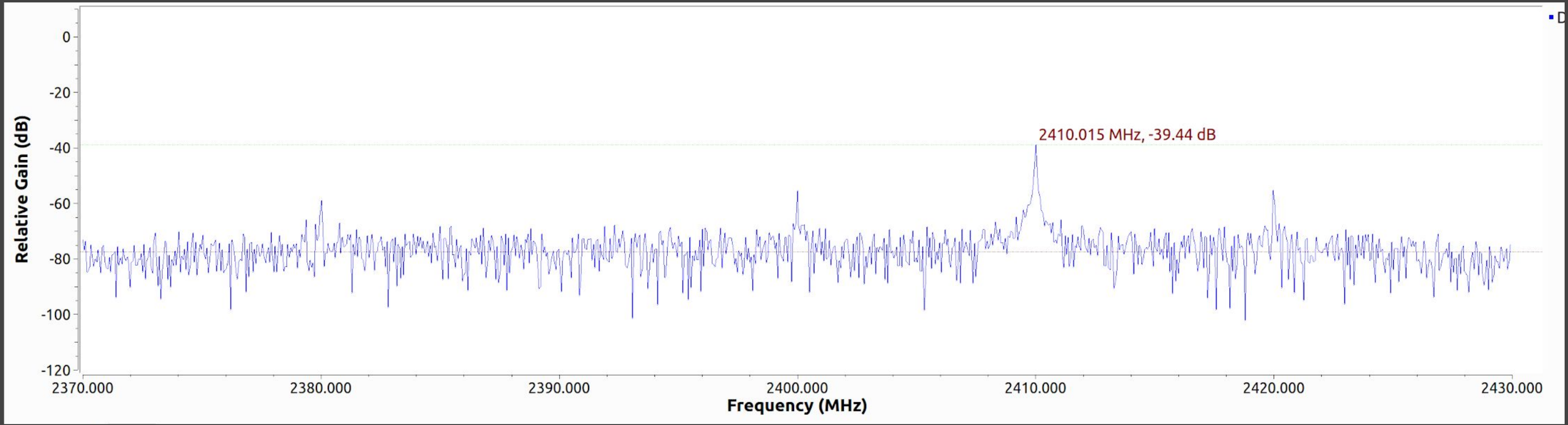


LimeSDR Hardware/Software Validation



Signal Interference (Simple Tranceiver)

- Preliminary interference and verification test resulted in positive results.
- Single tone SNR:
  - At 1 foot separation 40dB
  - At 590 feet (180 Meters) -15dB (Extrapolation)



Downlink Packet Breakdown

- Preamble
  - Unique 24 bit code sequence to allow for signal correlation
- Navigation Message
  - Element of set bit length providing timing for positioning algorithm
- User ID
  - 8 bit element containing a unique user identification sequence for each user to identify intended recipient
  - Designed to accommodate 30 user requirement
- Communications Message
  - 5000 bit text communication element broken into 8 bit characters
  - Message will be appended with ‘ ‘(space) buffers to maintain constant size

Uplink Breakdown

- Preamble
  - Unique 24 bit code sequence to allow for signal correlation
- User Identification
  - 8 bit element containing a unique user identification sequence for each user to identify transmitting user
  - Designed to accommodate 30 user requirement
- Communications Message
  - 5000 bit text communication element broken into 8 bit characters
  - Message will be appended with ‘ ‘(space) buffers to maintain constant size

Gr-LimeSDR Installation Process

The goal is to create a universal installation script, which a person could run on a Linux terminal and have access to a LimeSDR Development Environment.

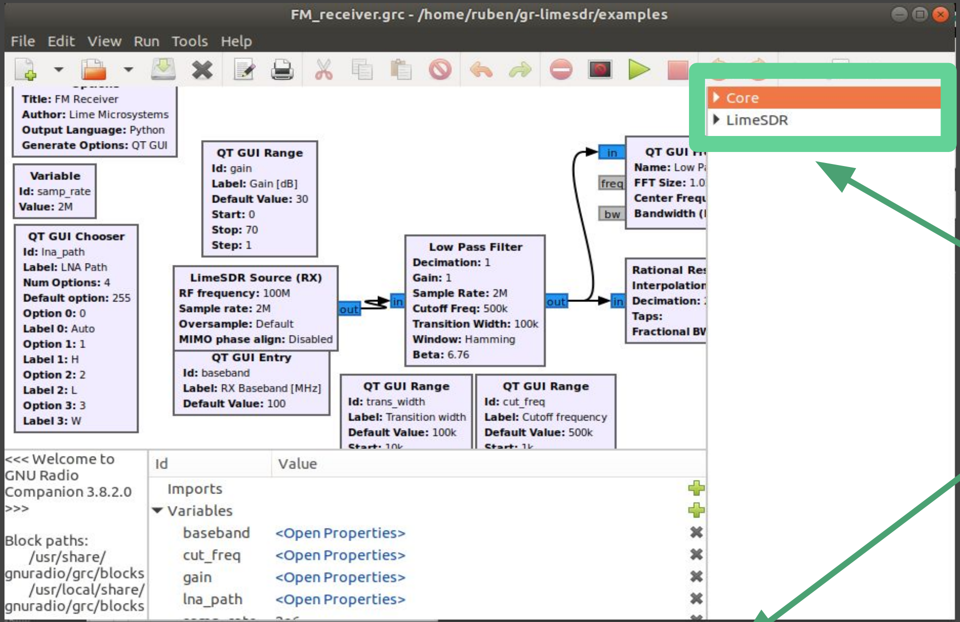
Gr-LimeSDR Installation Process

Integrating gr-limesdr plugin package.

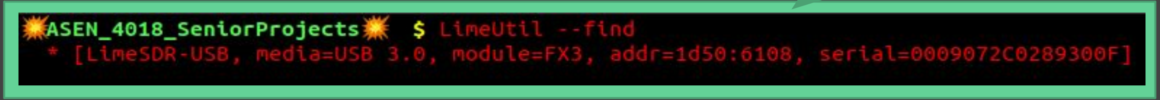
Example script:

[3] - **Gr-limeSDR Plugin Installation**: (Source Code Installation)
[3.1] - Installing Dependencies:
-> sudo apt-get install libboost-all-dev swig
Just in case:
-> sudo apt-get install gnuradio-dev
[3.2] - Building gr-limesdr from source: (Only for GNU Radio 3.8!)
-> git clone https://github.com/myriadrf/gr-limesdr
-> cd gr-limesdr
-> git checkout gr-3.8
-> mkdir build
-> cd build
-> cmake ..
-> make
-> sudo make install
-> sudo ldconfig

Gr-LimeSDR Development Environment



- We have a head start in the environment setup!
- We can also verify that the GNU Radio communicates with the Gr-LimeSDR plugin
- We can already verify the LimeSDR communicates with the given software via the LimeSuiteGUI



Gr-LimeSDR Installation Process

The goal is to create a universal installation script, which a person could run on a Linux terminal and have access to a LimeSDR Development Environment.

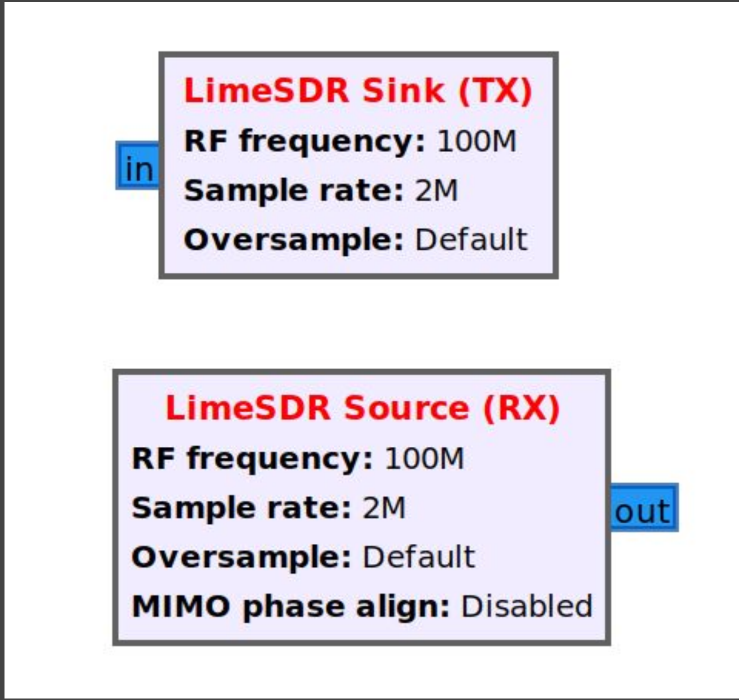
Example script:

[1] - **LimeSuiteGUI Installation**: (PPA Installation)
-> sudo add-apt-repository -y ppa:myriadrf/drivers
-> sudo apt-get update
-> sudo apt-get install limesuite liblimesuite-dev limesuite-udev limesuite-images
-> sudo apt-get install soapysdr-tools soapysdr-module-lms7
To open the LimeSuiteGUI simply type the command:
-> LimeSuiteGUI
To close, simply close the window.
If you have access to the LimeSDR, you can verify the GUI can talk to it by typing the command:
-> SoapySDRUtil --find="driver=lime"

[2] - **GNU Radio Installation**: (PPA Installation)
Note: The Release version must be 3.8.2.0
-> sudo add-apt-repository ppa:gnuradio/gnuradio-releases
-> sudo apt-get update
-> sudo apt install gnuradio
To optimize GNU Radio kernel usage type:
-> volk_profile
To Open GNU Radio GUI:
-> gnuradio-companion
To close, simply close window.

Integration: LimeSDR + GNU Radio

- gr-limesdr plugin for GNURadio
  - Provides LimeSDR Transmit and Receive blocks
    - Can specify Rx/Tx channels for multiple antennas
- Automatically finds the LimeSDR
- Configurable via .ini file
- These blocks feed samples into the well documented GNURadio sample stream



Project Risks and Mitigation

Risk Identification

Risk ID	Description	Likelihood	Consequence
COM-3	Near-Far problem: Difficulty to hear weak-far signals from strong-close signal sources	4	5
ELE-1	Time synchronization between pseudolite and GPS receiver	3	5
SOF-1	Team inexperience handling new software. For example, GNU radio	3	4
COM-2	Signal Interference in testing environment	4	3
SOF-2	Lime-SDR, Raspberry Pi, and other hardware components not communicating correctly	2	5
COM-1	Multiple User Communicating	5	2
LOG-1	Hardware/Electronics don’t arrive on time which sets back schedule of overall project	2	4

Risk Matrix

Risk ID	Description
COM-3	Near-Far problem: Difficulty to hear weak-far signals from strong-close signal sources
ELE-1	Time synchronization between pseudolite and GPS receiver
SOF-1	Team inexperience handling new software. For example, GNU radio
COM-2	Signal Interference in testing environment
SOF-2	Lime-SDR, Raspberry Pi, and other hardware components not communicating correctly
COM-1	Multiple User Communicating
LOG-1	Hardware/Electronics don’t arrive on time which sets back schedule of overall project

Legend

LOW RISK	Acceptable
LOW-MED RISK	Low Risk
MEDIUM RISK	Requires Monitoring
MED-HIGH RISK	Moderate Mitigation
HIGH-RISK	Immediate Mitigation
CRITICAL RISK	Unacceptable Risk

Likelihood / Consequence

Likelihood \ Consequence	1	2	3	4	5
5		COM-1		COM-3	
4			COM-2		
3				SOF-1	ELE-1
2				LOG-1	SOF-2
1					

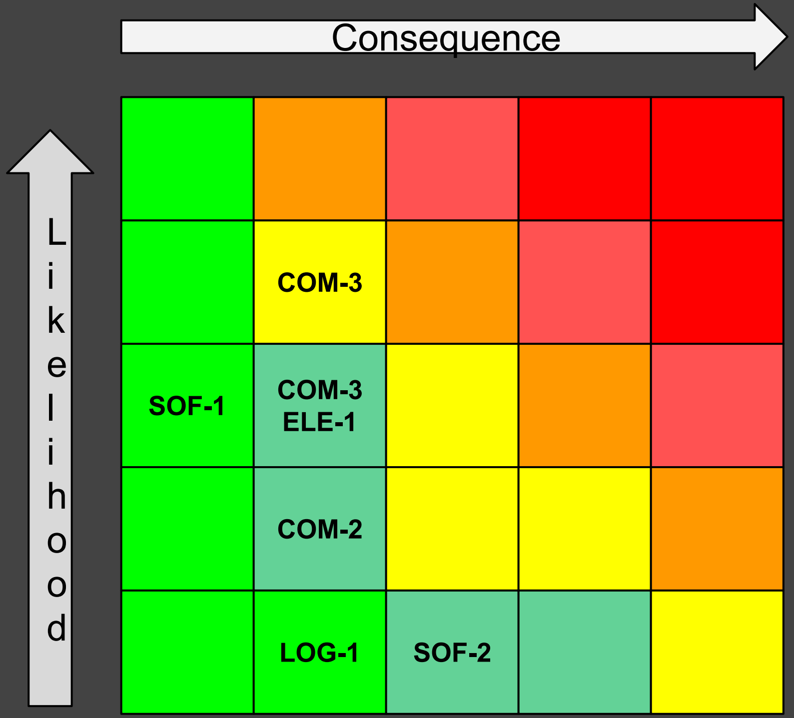
Risk Mitigation Table

Risk ID	Description	Mitigation Approach
COM-3	Near-Far problem: Difficulty to hear weak-far signals from strong-close signal sources	• Test within pseudolite geometry boundaries • Automatic gain control
ELE-1	Time synchronization between pseudolite and GPS receiver	Conduct initial test to verify limeSDR clock override with Septentrio PolaRxS GPS reciever.
SOF-1	Team inexperience handling new software. For example, GNU radio	• Fall semester early development • Online tutorials, device users manual • External Resources: Dr Akos, Dr Rainville, Steve Taylor, Sam Holt
COM-2	Signal Interference in testing environment	Change testing area to back up location (Platteville), change testing time to reduce interference (overnight)
SOF-2	Lime-SDR, Raspberry Pi, and other hardware components not communicating correctly	• Fall semester early development. • Refer to overall block diagram, • Dive into specific functional block diagrams and debug issues (divide and conquer).
COM-1	Multiple User Communicating	Design an optimal CDMA code for each user
LOG-1	Hardware/Electronics don't arrive on time which sets back schedule of overall project	Change provider of electronics to avoid schedule variance (Amazon, SparkFun, BestBuy,etc)

Mitigation Effects

Risk ID	Description
COM-3	Near-Far problem: Difficulty to hear weak-far signals from strong-close signal sources
ELE-1	Time synchronization between pseudolite and GPS receiver
SOF-1	Team inexperience handling new software. For example, GNU radio
COM-2	Signal Interference in testing environment
SOF-2	Lime-SDR, Raspberry Pi, and other hardware components not communicating correctly
COM-1	Multiple User Communicating
LOG-1	Hardware/Electronics don't arrive on time which sets back schedule of overall project

Post Mitigation

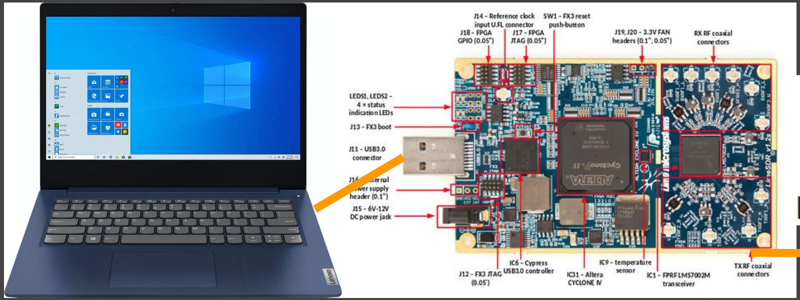


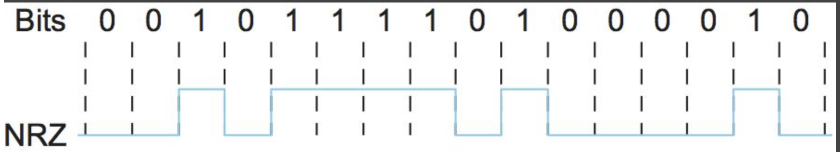
Verification and Validation

Signal Reception

LimeSDR demonstrates reception signal through wired connection

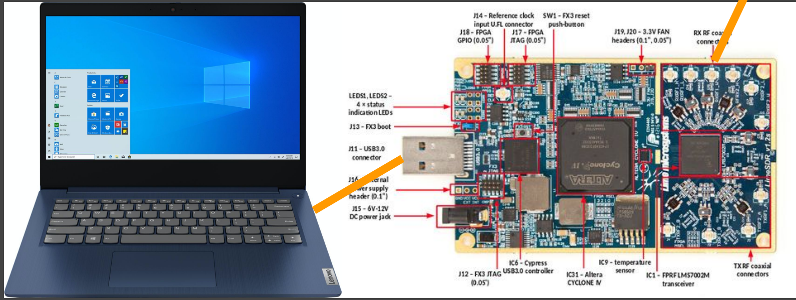
- Laptop running GNU radio creates signal and sends to LimeSDR
  - Create 100 bit .txt file to use as transmission signal
  - Send bits to LimeSDR using USB connection
- Verify receipt of signal to the LimeSDR
  - Create .txt file from bits and compare sent and received signal





Wired from TX to RX sending bits

USB Connection sends .txt as bits to LimeSDR

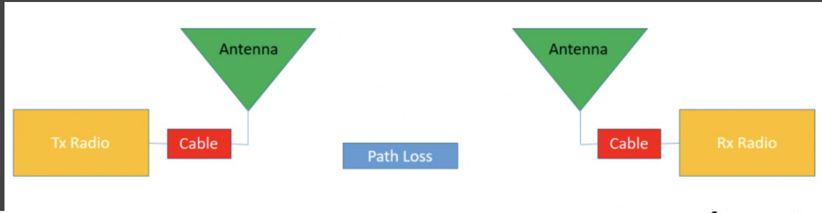


Bits converted to .txt and compared to initial file

Antenna test

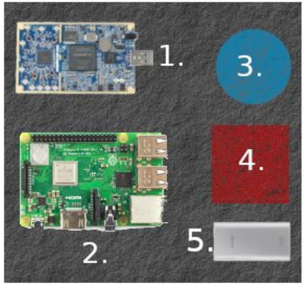
Demonstrate that the antennas used can supply the proper gain for the design

- Measure loss between a two radio/antenna setup running multiple trials at various distances
- Use least squares calculate the gain of the antennas(they are the same)



$$PL = G_1 + G_2 + 20\log\left(\frac{\lambda}{4\pi R}\right)$$

Transmitter/Receiver Set up



1. LimeSDR
2. Raspberry Pi
3. Cut out for antenna
4. Septentrio PolaRxS GPS receiver
5. Miady 10000 mAh portable power pack

Each transmitter and receiver will feature a casing for the electronics that will hold the LimeSDR, Raspberry Pi, a battery pack, and space for wiring and a connection to the antenna. The electronics casing will be thread-mounted to a camera tripod.

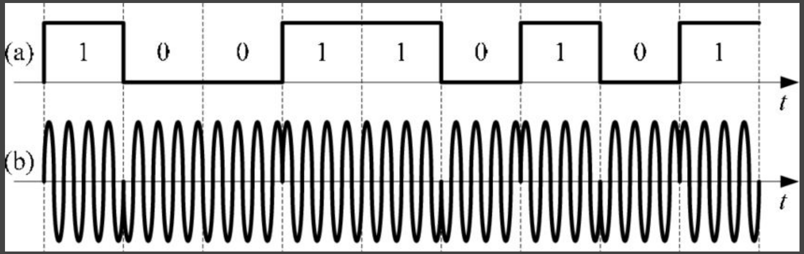
Modulation Scheme

LimeSDR receiver positioned 100m away from LimeSDR transmitter

- Transmitter modulates 100 bit .txt file to 2.48 GHz carrier frequency using GNU Radio PSK modulator
- LimeSDR receiver receives signal and demodulates it using GNU radio PSK demodulator
- Signal is re-output as .txt file and compared to initial file

Using Laptop and GNURadio send .txt file to LimeSDR

GNURadio modbox modulates bits using BPSK modulation scheme



LimeSDR receives the modulated signal and demodulates using GNURadio demodbox

Bits are converted to .txt file and compared to original .txt

Multiplexing and Wireless Transmission

Receiver can distinguish CDMA codes and process the desired signal

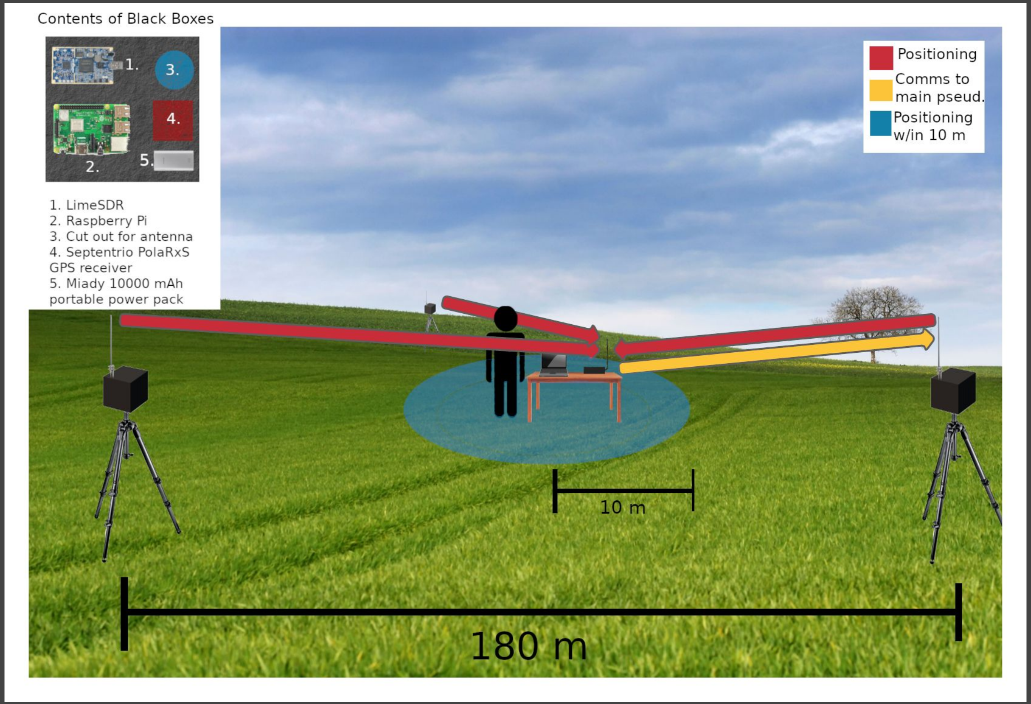
- 3 transmitters generate and transmit signals of different 100 bit .txt files
  - For each file, send preamble and .txt file using GNU radio PSK modulator
- LimeSDR receiver positioned 100m away receives the signals and listens for specific preamble
  - Based on desired preamble, receiver demodulates and converts desired signal to .txt
- Received .txt file is compared to original 3 to verify proper signal was processed

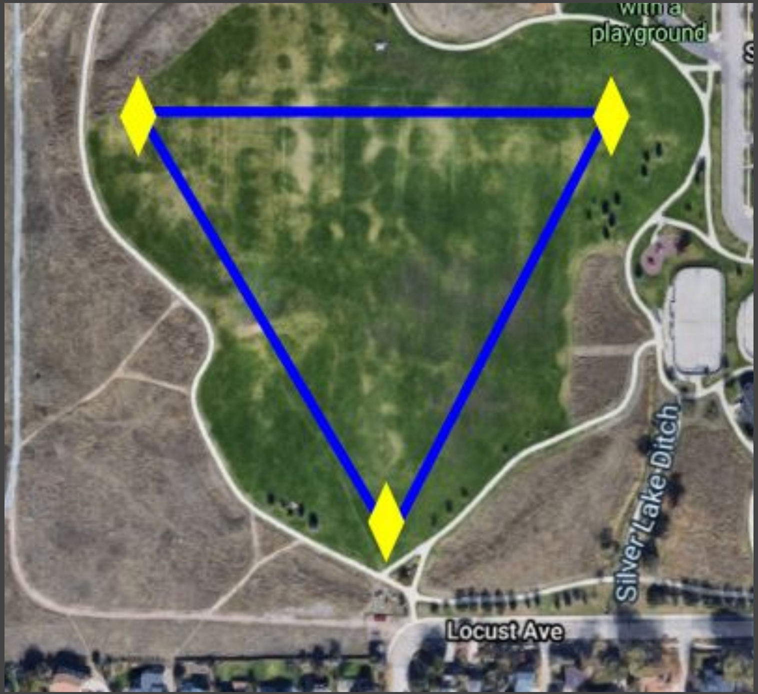
HDOP and Positioning Accuracy

LimeSDR demonstrate positioning accuracy within 10 m

- Have 3 transmitting set ups spaced out in an equilateral triangle
  - GNU radio with a LimeSDR and an antenna on a tripod
- Have a receiver set up in sensitive areas inside the triangle of transmitters:center of triangle, close to corner(near far problem)
- Receive signals from the transmitter stations to calculate position of receiver
- Verify that receiver position calculated from transmitters is within 10 m of expected position (from GPS)

Multiplexing & HDOP Test Setup

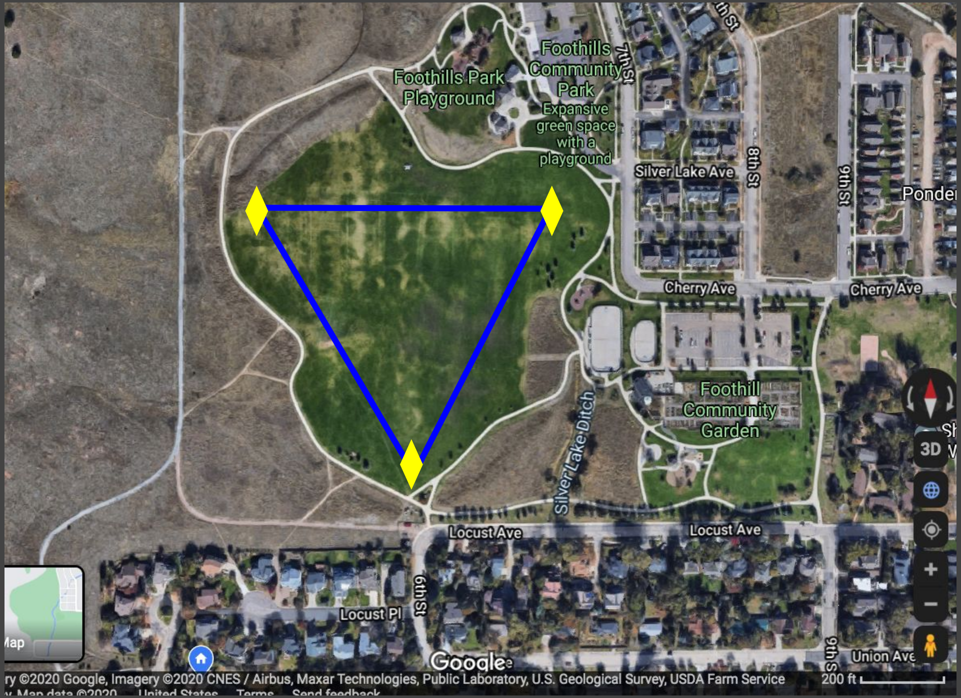




Test Checklist

1. Walk transmitters to their positions
2. Sync transmitters and receiver with GPS
   a. Sync up clocks to GPS (as well as to each other)
   b. Record “true” position of each transmitter and receiver
3. Verify all stations ready
4. Run communications/positioning test

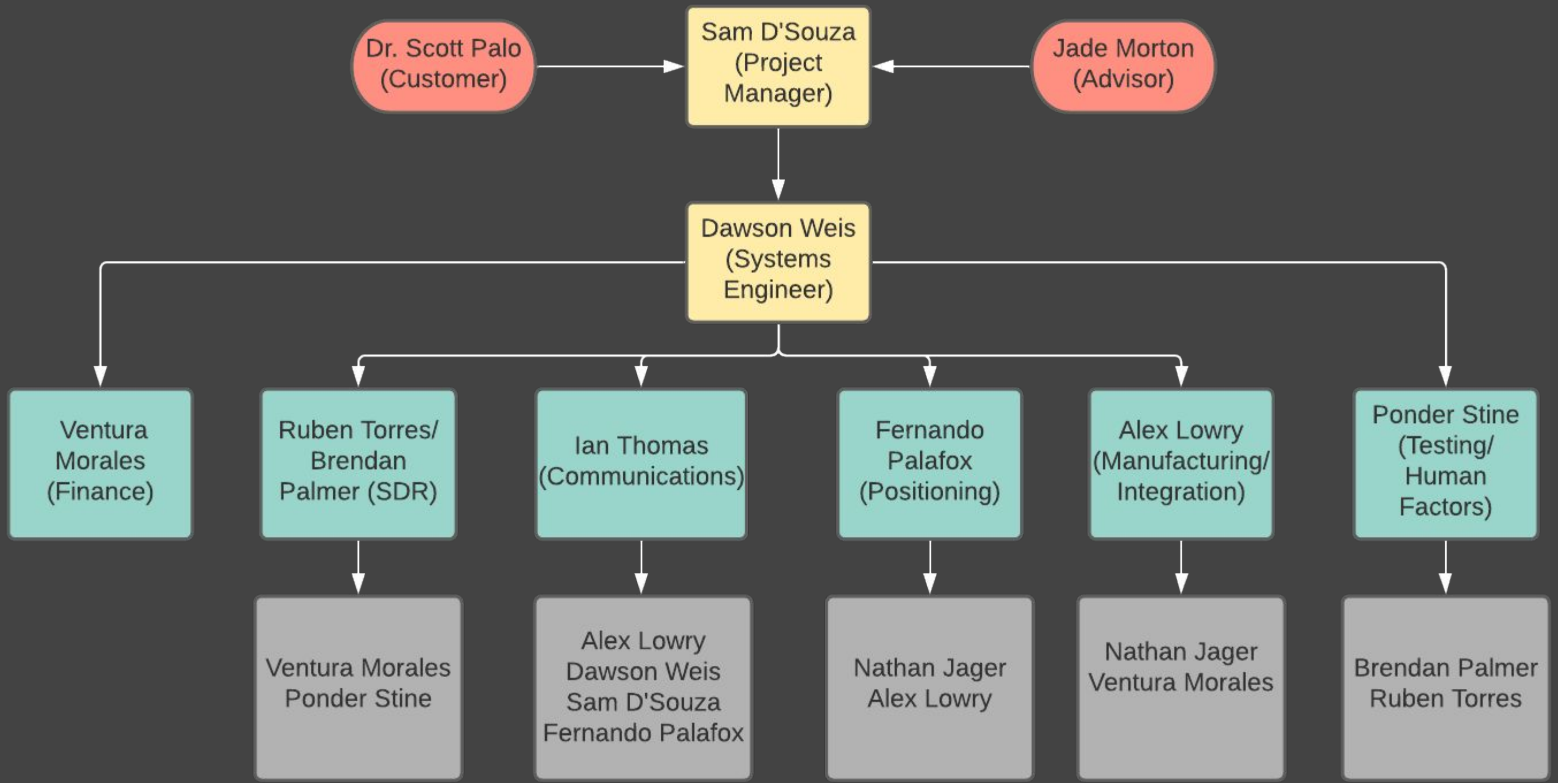
Testing site: Foothills Park

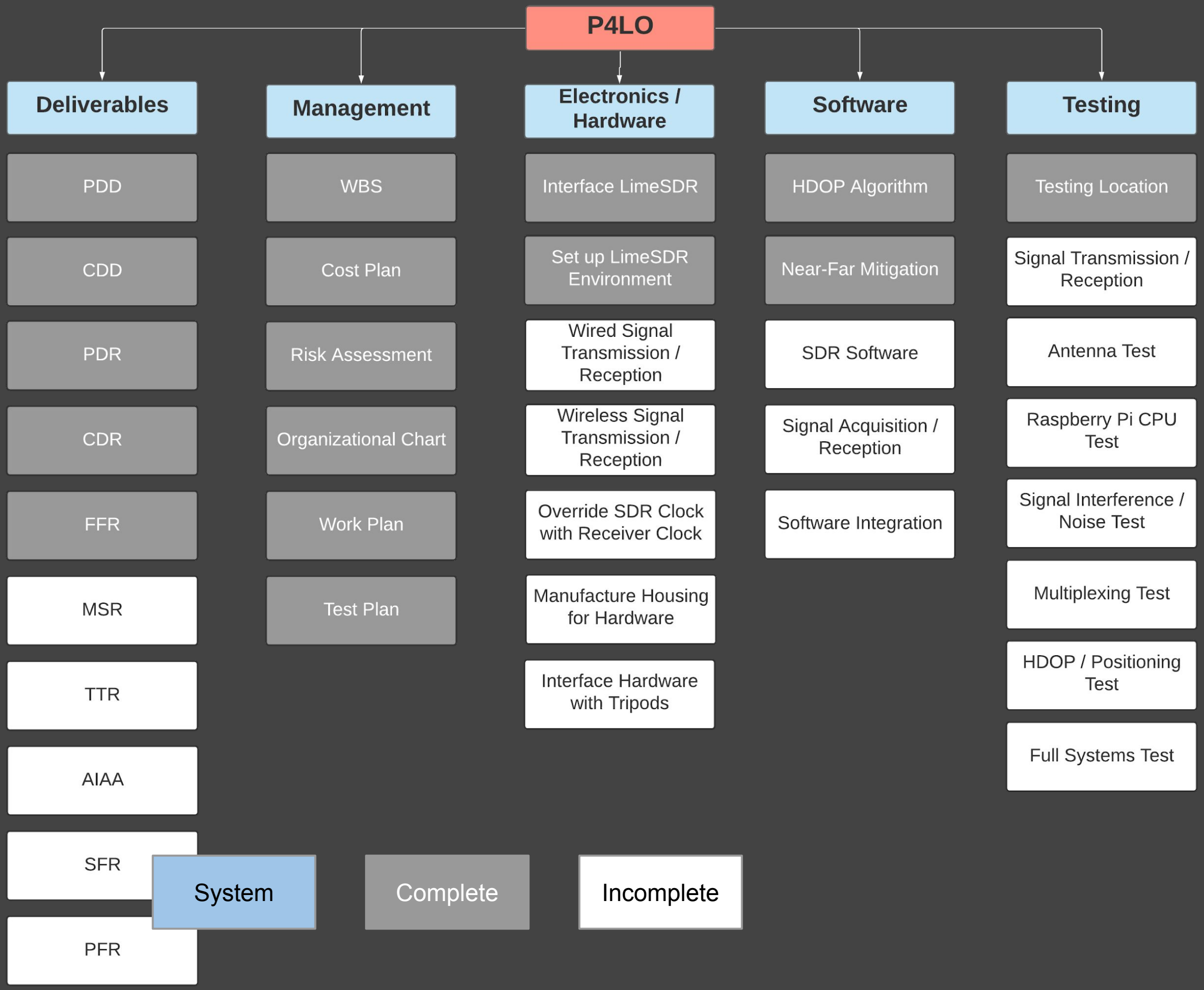


Back-Up Testing Area

Project Planning

Organizational Chart




P4LO
Deliverables
PDD
CDD
PDR
CDR
FFR
MSR
TTR
AIAA
SFR
PFR
Management
WBS
Cost Plan
Risk Assessment
Organizational Chart
Work Plan
Test Plan
Electronics / Hardware
Interface LimeSDR
Set up LimeSDR Environment
Wired Signal Transmission / Reception
Wireless Signal Transmission / Reception
Override SDR Clock with Receiver Clock
Manufacture Housing for Hardware
Interface Hardware with Tripods
Software
HDOP Algorithm
Near-Far Mitigation
SDR Software
Signal Acquisition / Reception
Software Integration
Testing
Testing Location
Signal Transmission / Reception
Antenna Test
Raspberry Pi CPU Test
Signal Interference / Noise Test
Multiplexing Test
HDOP / Positioning Test
Full Systems Test
System
Complete
Incomplete

Work Breakdown Structure (WBS)

P4LO

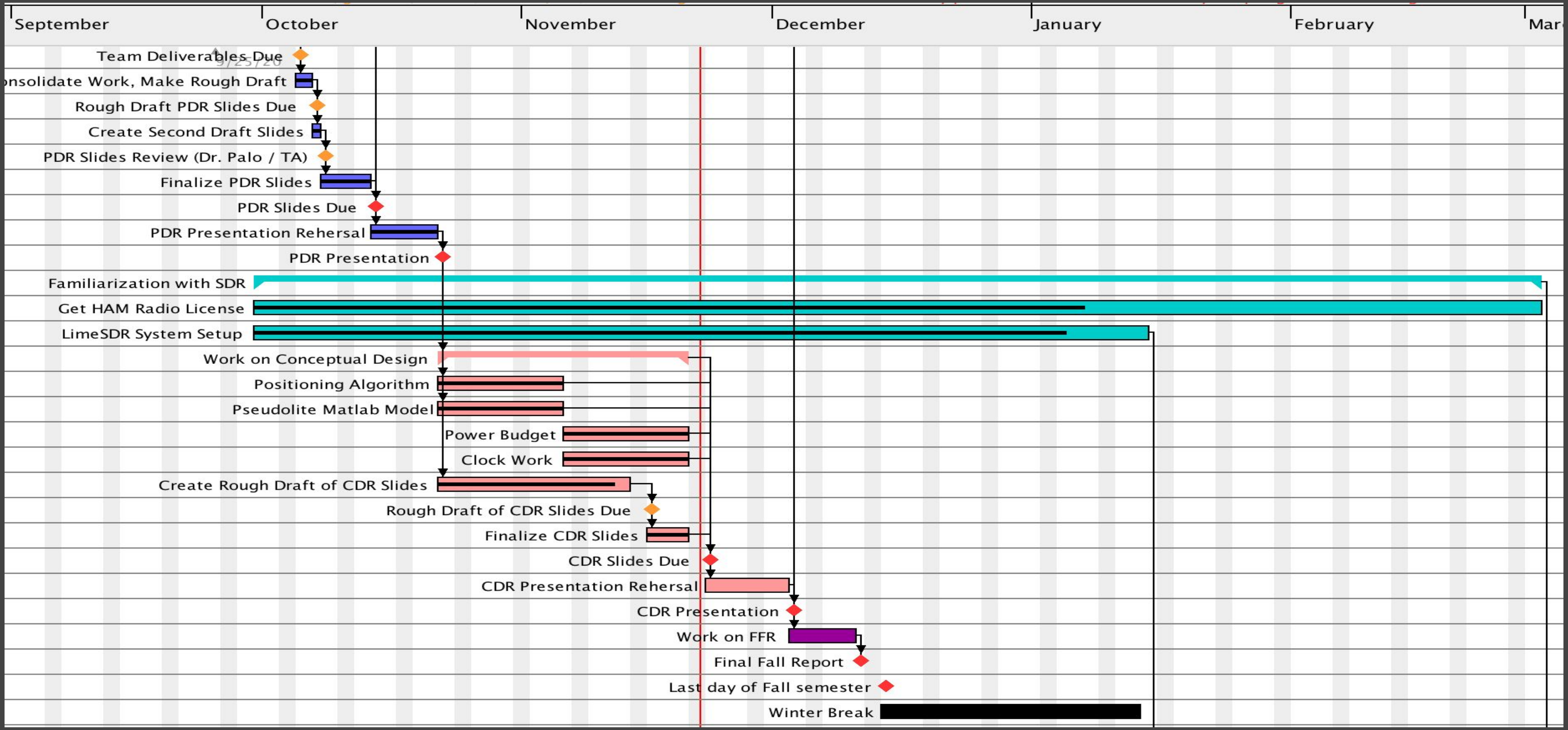
Deliverables	Management	Electronics / Hardware	Software	Testing
PDD	WBS	Interface LimeSDR	HDOP Algorithm	Testing Location
CDD	Cost Plan	Set up LimeSDR Environment	Near-Far Mitigation	Signal Transmission / Recpetion
PDR	Risk Assessment	Wired Signal Transmission / Reception	SDR Software	Antenna Test
CDR	Organizational Chart	Wireless Signal Transmission / Reception	Signal Acquisition / Reception	Multiplexing Test
FFR	Work Plan	Override SDR Clock with Receiver Clock	Software Integration	HDOP / Positioning Test
MSR	Test Plan	Manufacture Housing for Hardware		Full Systems Test
TTR		Interface Hardware with Tripods		
AIAA				
SFR				
PFR				

System

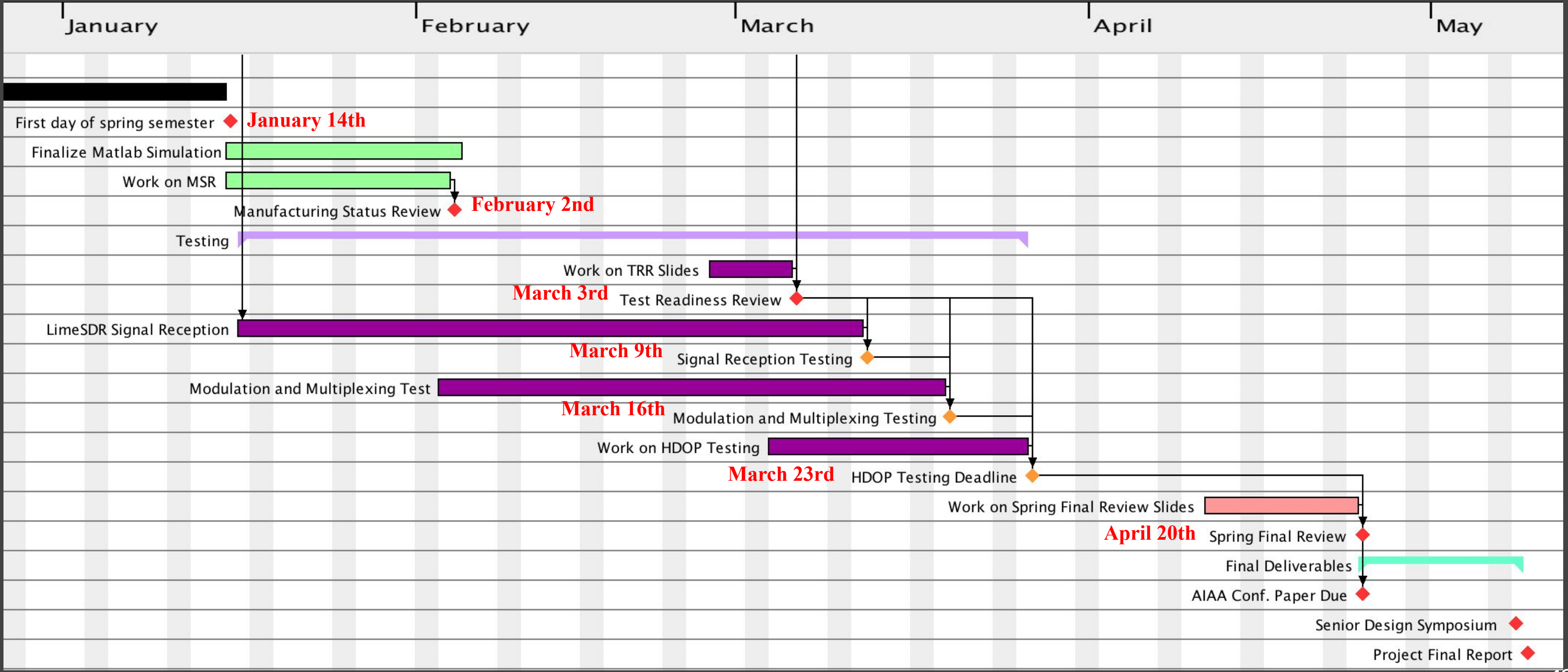
Complete

Incomplete

Work Plan


September
October
November
December
January
February
Mar
Team Deliverables Due
onsolidate Work, Make Rough Draft
Rough Draft PDR Slides Due
Create Second Draft Slides
PDR Slides Review (Dr. Palo / TA)
Finalize PDR Slides
PDR Slides Due
PDR Presentation Rehersal
PDR Presentation
Familiarization with SDR
Get HAM Radio License
LimeSDR System Setup
Work on Conceptual Design
Positioning Algorithm
Pseudolite Matlab Model
Power Budget
Clock Work
Create Rough Draft of CDR Slides
Rough Draft of CDR Slides Due
Finalize CDR Slides
CDR Slides Due
CDR Presentation Rehersal
CDR Presentation
Work on FFR
Final Fall Report
Last day of Fall semester
Winter Break

Work Plan

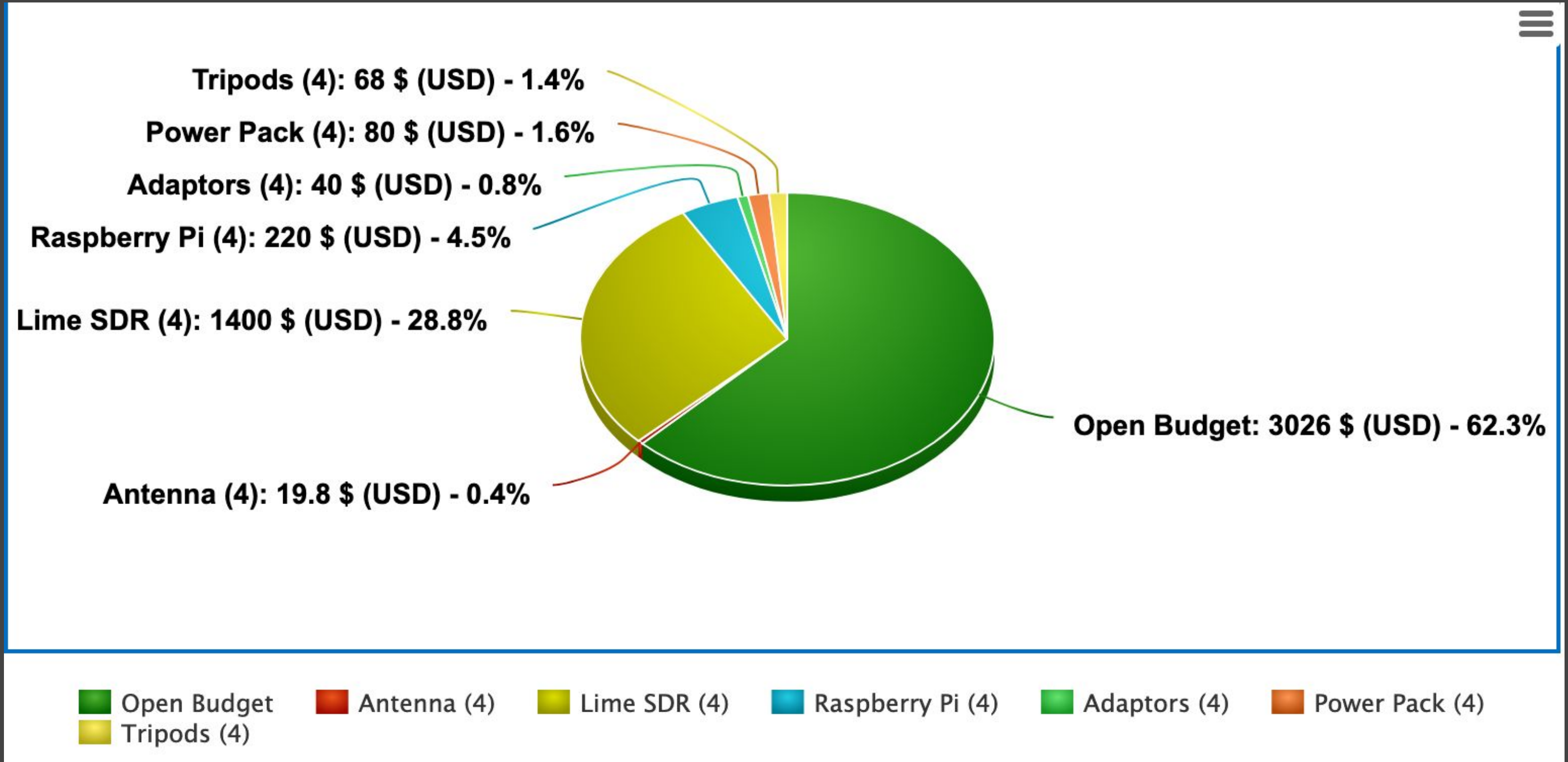

January
February
March
April
May
[redacted]
First day of spring semester
January 14th
Finalize Matlab Simulation
Work on MSR
Manufacturing Status Review
February 2nd
Testing
Work on TRR Slides
March 3rd
Test Readiness Review
LimeSDR Signal Reception
March 9th
Signal Reception Testing
Modulation and Multiplexing Test
March 16th
Modulation and Multiplexing Testing
Work on HDOP Testing
March 23rd
HDOP Testing Deadline
Work on Spring Final Review Slides
April 20th
Spring Final Review
Final Deliverables
AIAA Conf. Paper Due
Senior Design Symposium
Project Final Report

Test Plan

Testing Procedure	Date Scheduled	Location
Signal Reception Test	March 9th	Foothills Park
Modulation and Multiplexing Test	March 15th	Foothills Park
HDOP Test	March 23rd	Foothills Park
Full Scale Test	March 25th	Foothills Park

Budget

Budget Pie Chart



Expense Budget & Margin

Team P4LO Budget					
Allowable Budget	$5,000.00				
Communications Hardware					
Item	Individual Cost	# of Items	Subtotal Per Set	Supplier	Item Link
Antenna	$4.95	4	$19.80	SparkFun	https://www.sparkfun.com/products/11320
Lime SDR	$349.95	4	$1,399.80	SparkFun	https://www.sparkfun.com/products/15027
Raspberry Pi	$55.00	4	$220.00	SparkFun	https://www.sparkfun.com/products/15447
Hardware Adapators	$9.95	4	$39.80	SparkFun	https://www.sparkfun.com/products/9145
Power Pack	$19.99	4	$79.96	Amazon	https://www.amazon.com/Miady-10000mAh-Portabl
Testing Tripods (6ft)	$16.99	4	$67.96		https://www.continentalphoto.com/itemdetails.asp?r
Budget Balance					
Sub-total Balance	$1,827.32				
Sales Tax Total	$146.19				
Total Cost	$1,973.51				
Budget Balance	$3,026.49				

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