Critical Design Review

P4LO

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

Team Advisor: Dr. Jade Morton

Agenda

1. Project Overview/Objectives
2. Design Solution (Solution)
3. Critical Project Elements (CPE)
4. Design Requirements (DR)
5. Project Risks/Mitigation (Risk)
6. Verification & Validation (VV)
7. Project Planning

Project Overview

Project Motivation

Mission Statement

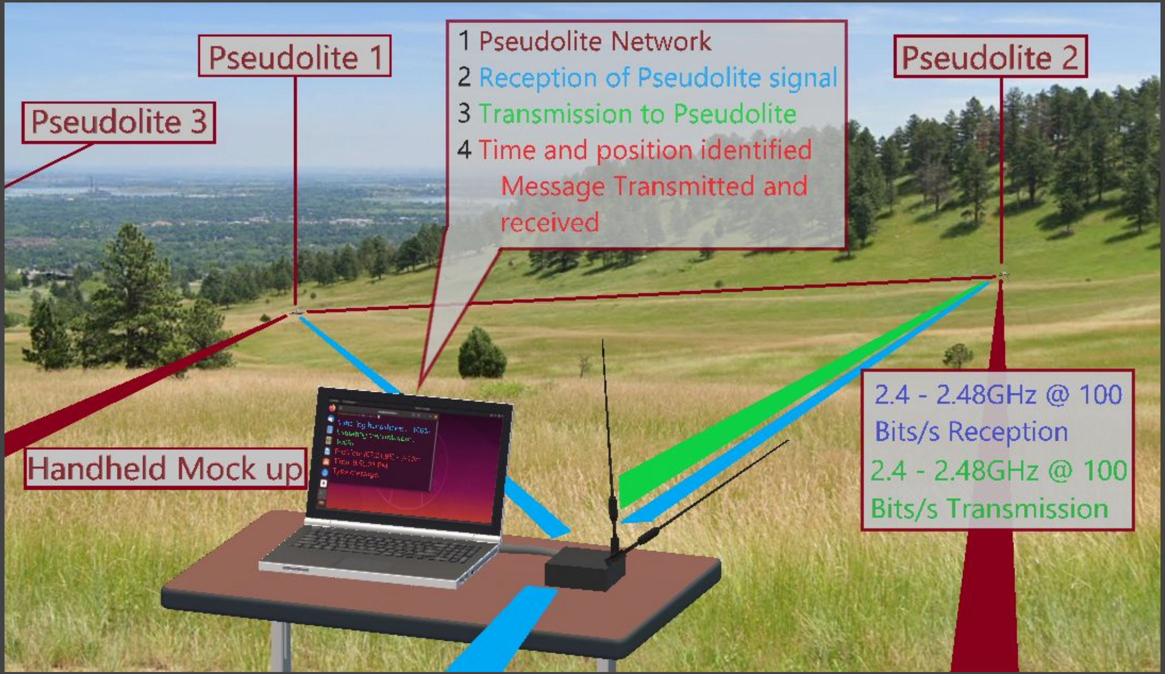
P4LO (**P**ositioning **For** **L**unar **O**perations) is a prototype network of software defined radios that demonstrates an architecture for the lunar communication and positioning system LunaNet.

Project Description

Develop a prototype to demonstrate positioning, timing, and communication systems feasible for use on the surface of the Moon

- Lunar Positioning System (LPS)
- Communications
- Risk Reduction for Future JPL/LunaNet Projects

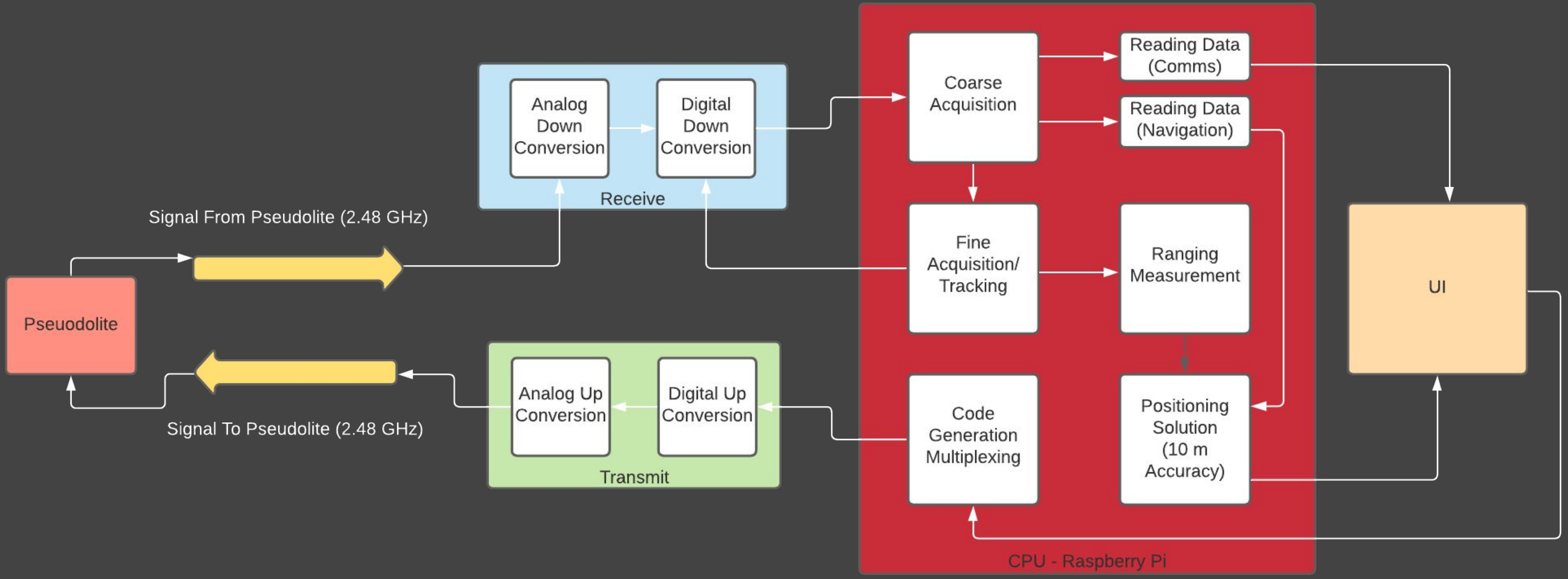
Concept Of Operations (CONOPS)



Design Solution

Design Solution Set Up

Overall FBD


Analog
Down
Conversion
Digital
Down
Conversion
Receive
Signal From Pseudolite (2.48 GHz)
Pseudodolite
Signal To Pseudolite (2.48 GHz)
Analog Up
Conversion
Digital Up
Conversion
Transmit
Coarse
Acquisition
Reading Data
(Comms)
Reading Data
(Navigation)
Fine
Acquisition/
Tracking
Ranging
Measurement
Code
Generation
Multiplexing
Positioning
Solution
(10 m
Accuracy)
CPU - Raspberry Pi
UI

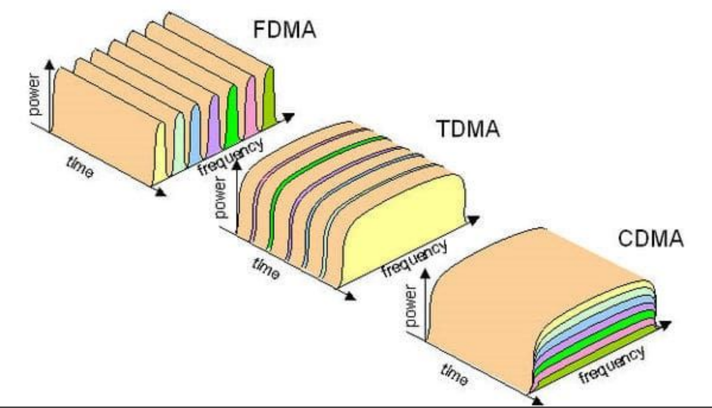
Critical Project Elements

Critical Project Elements

- Positioning System
- Communications
- Antenna
- SDR
- One-Way Ranging

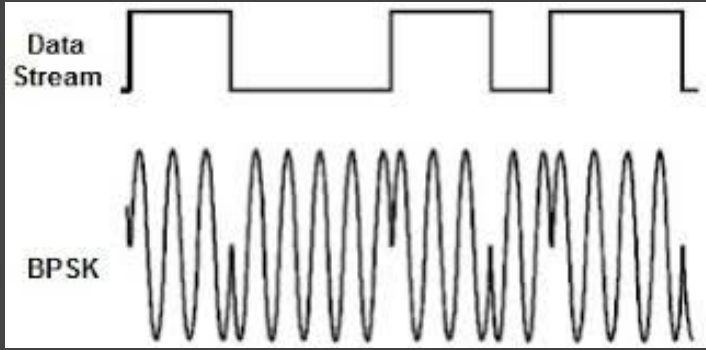
Link Design: Multiplexing

- Design Choice: 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
  - GPS uses CDMA
- Specification:
  - 1023 bit Gold Code PRN chipping code
  - 1.023 MHz chipping rate
  - 1 ms code period (same as data rate)

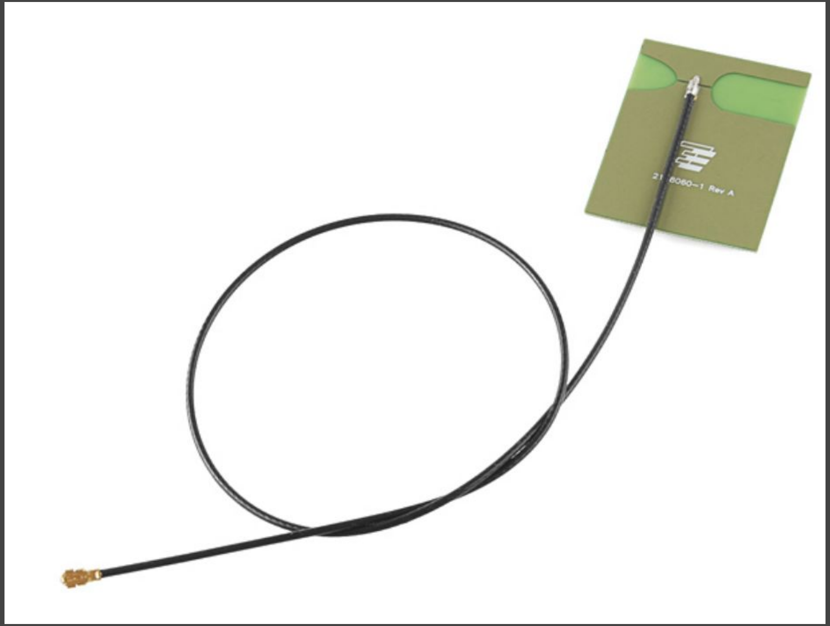


Link Design: Modulation

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



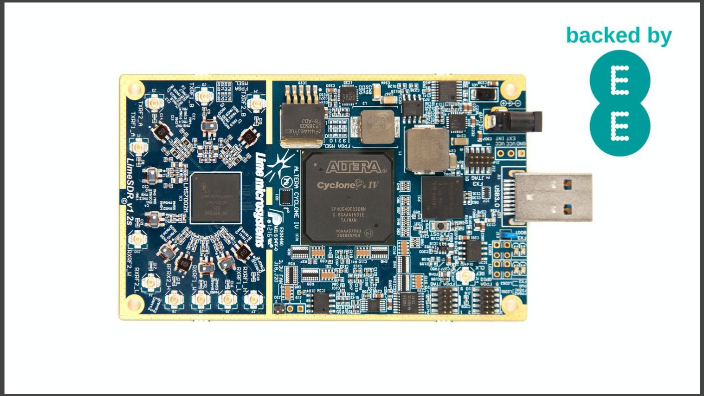
Antenna Type



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

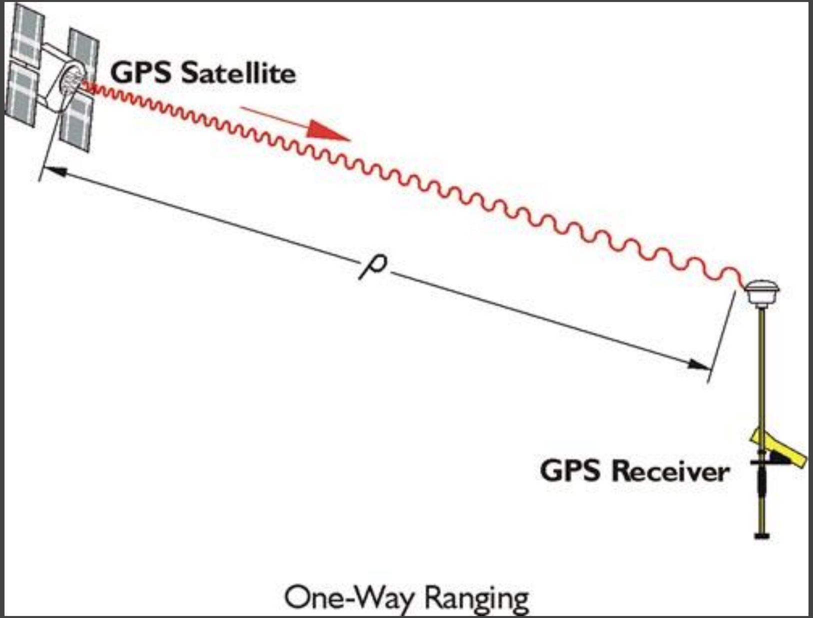
LimeSDR (SDR - “Software Defined Radio”)



GNURadio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

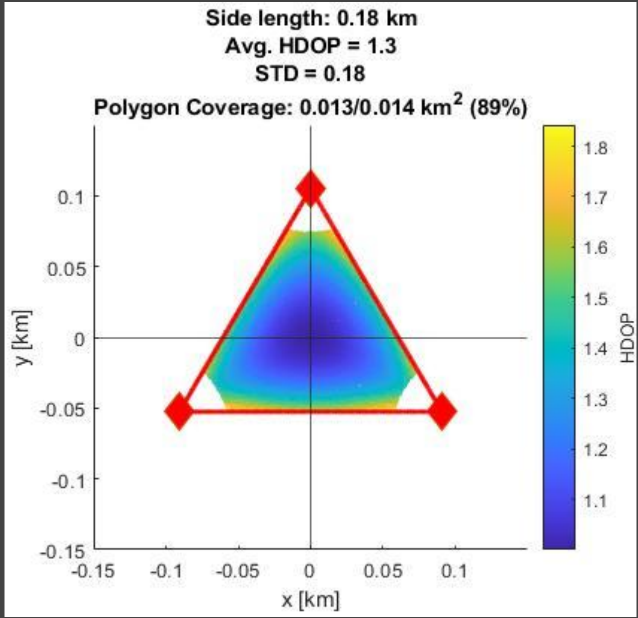
- LimeSDR (Hardware)
  - Customer requirement
  - Reception and Transmission of signal
  - Ability to work with modulator/demodulator software packages
  - Functions at 2.4-2.48 GHz
- GNU Radio (Software)
  - Suggested by customer
  - Able to implement all communication schemes and all frequency ranges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

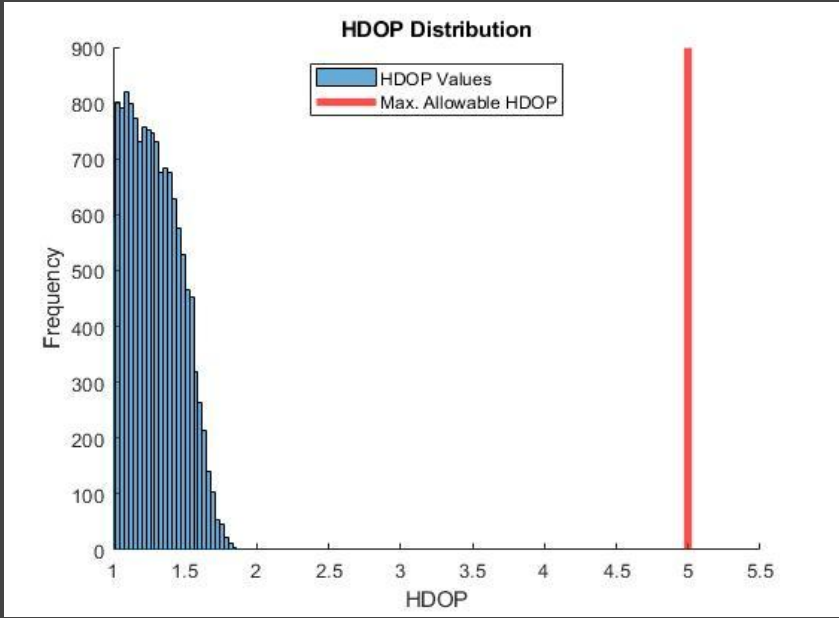
One Way Ranging



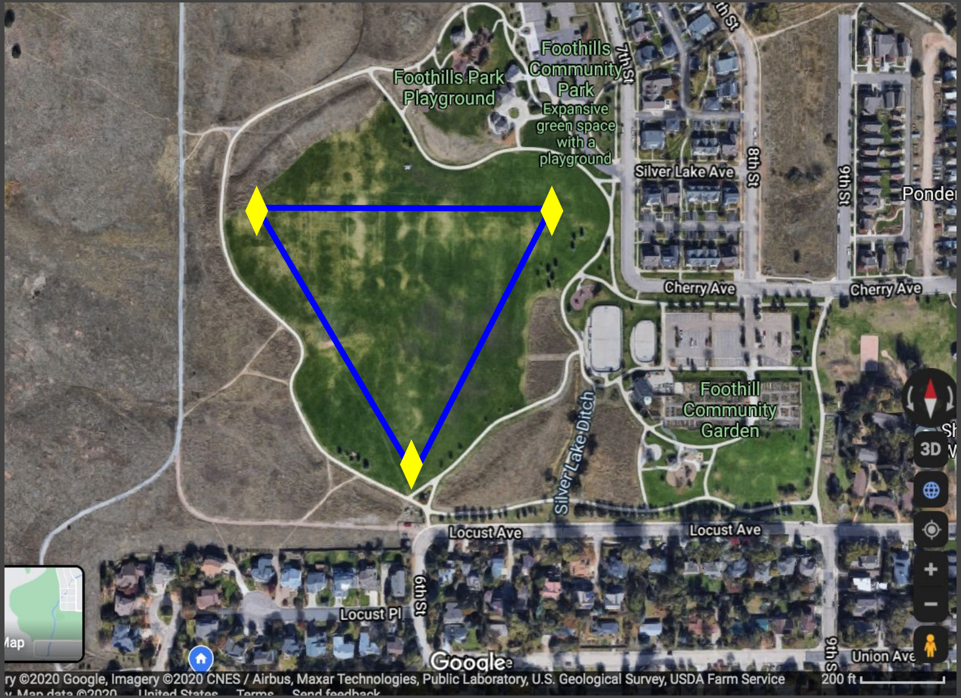
Design Requirements

Pseudolite Geometry

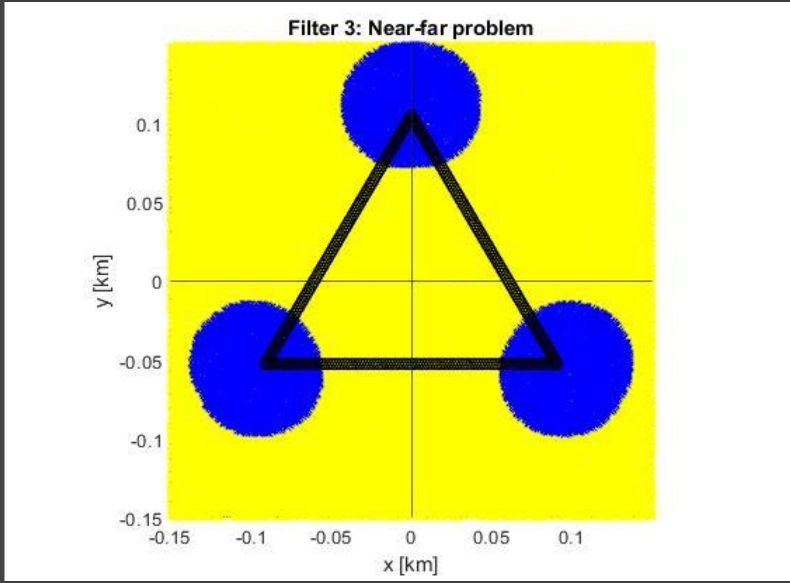


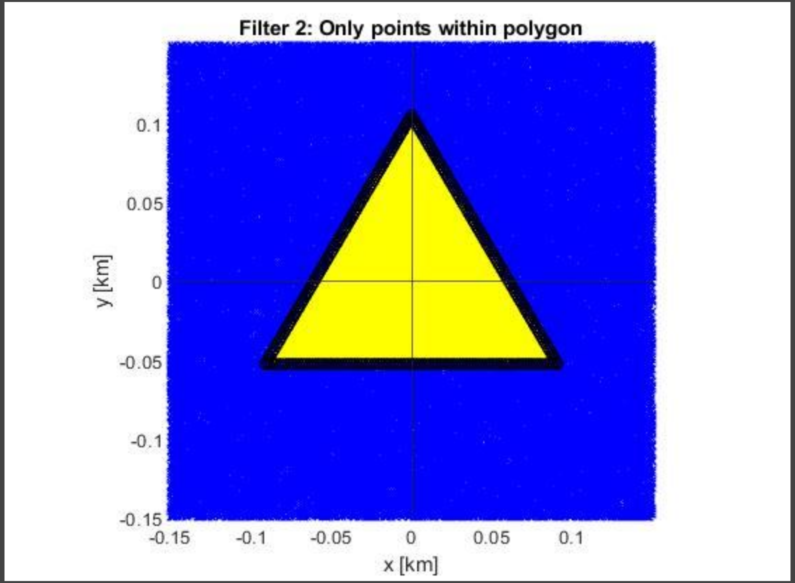


Testing site: Foothills Park



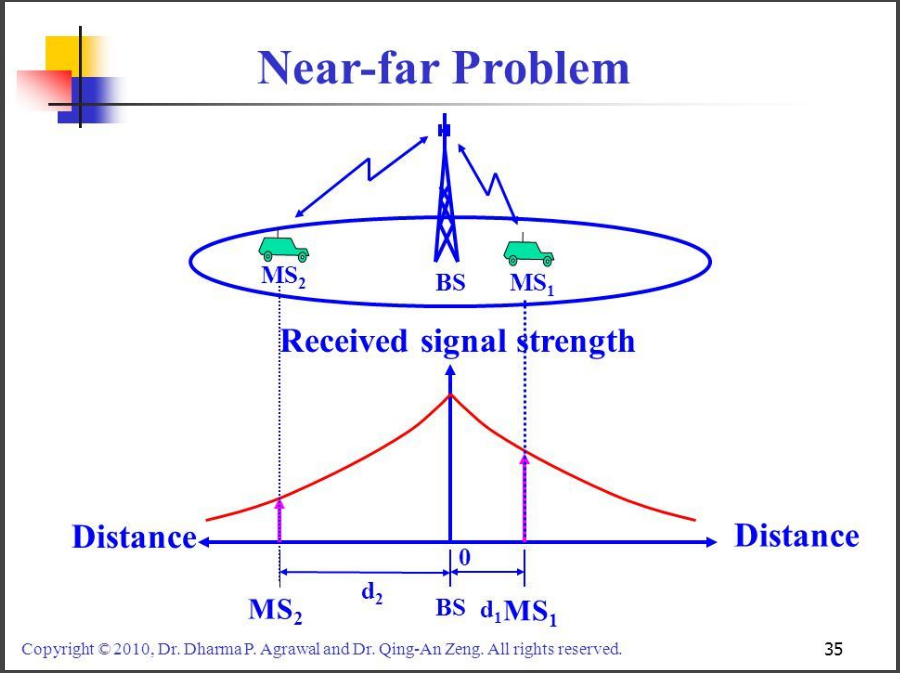
Pseudolite Geometry: Specifics



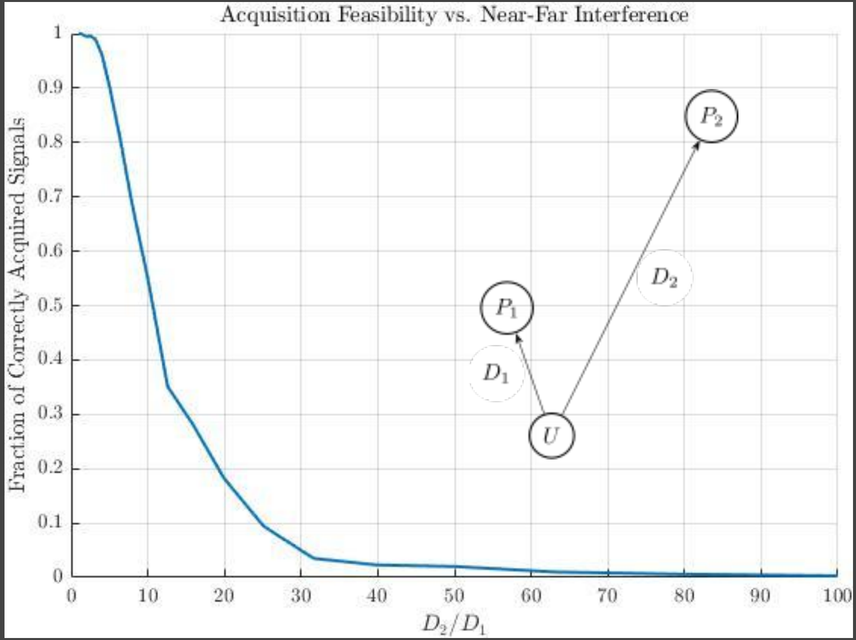


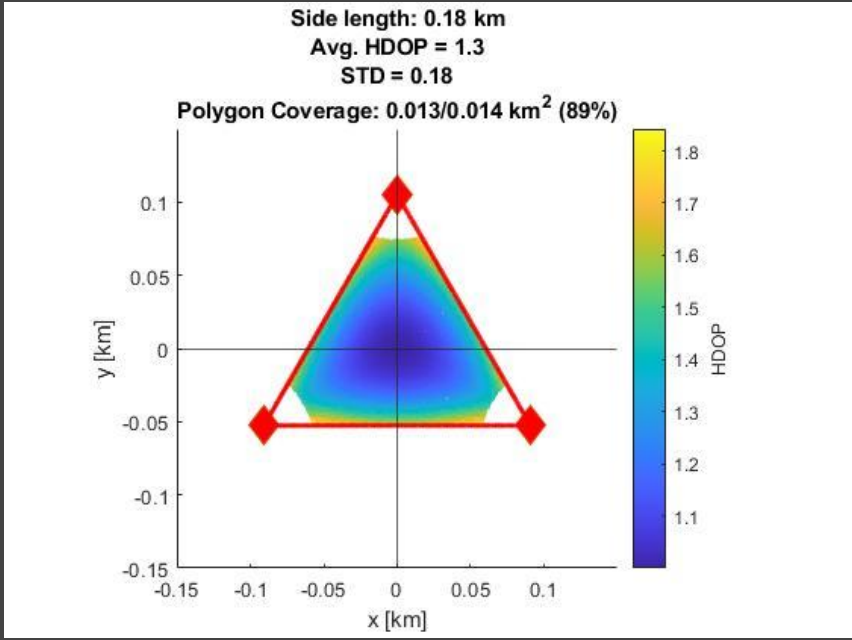
Yellow = valid location; Blue = invalid location

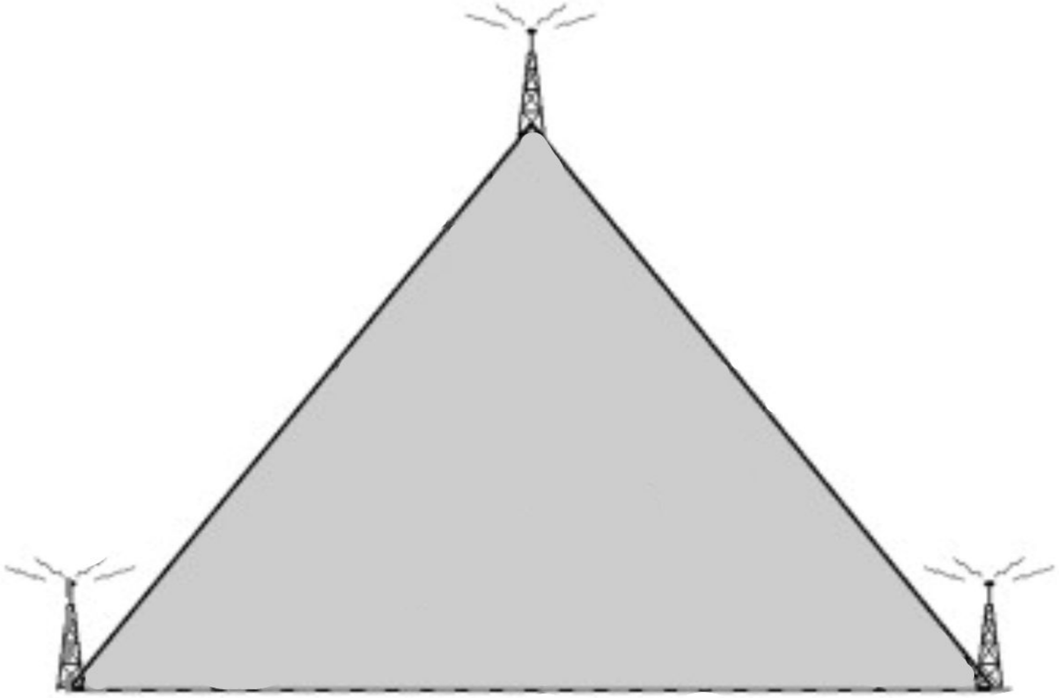
Near-Far Problem

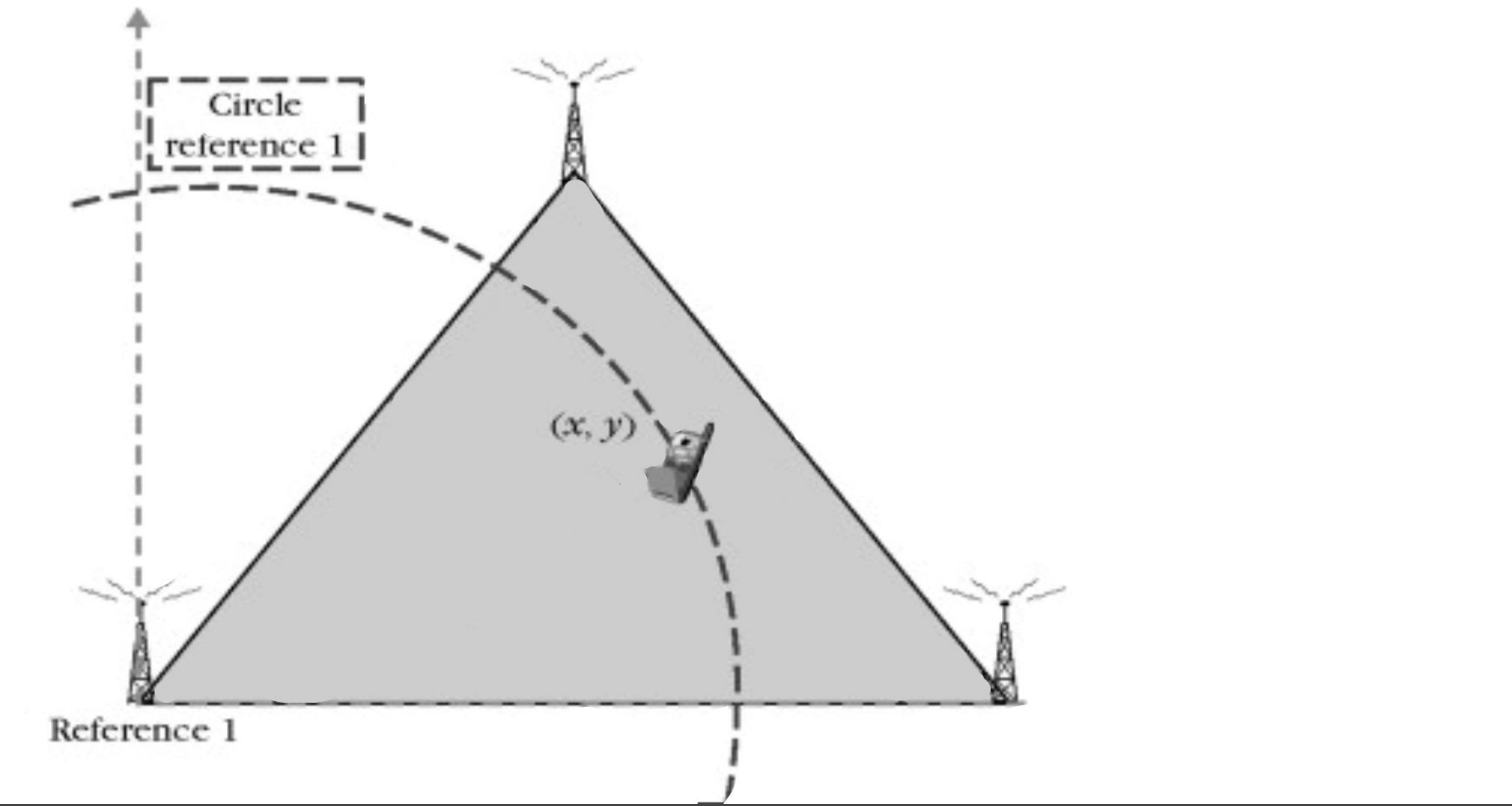


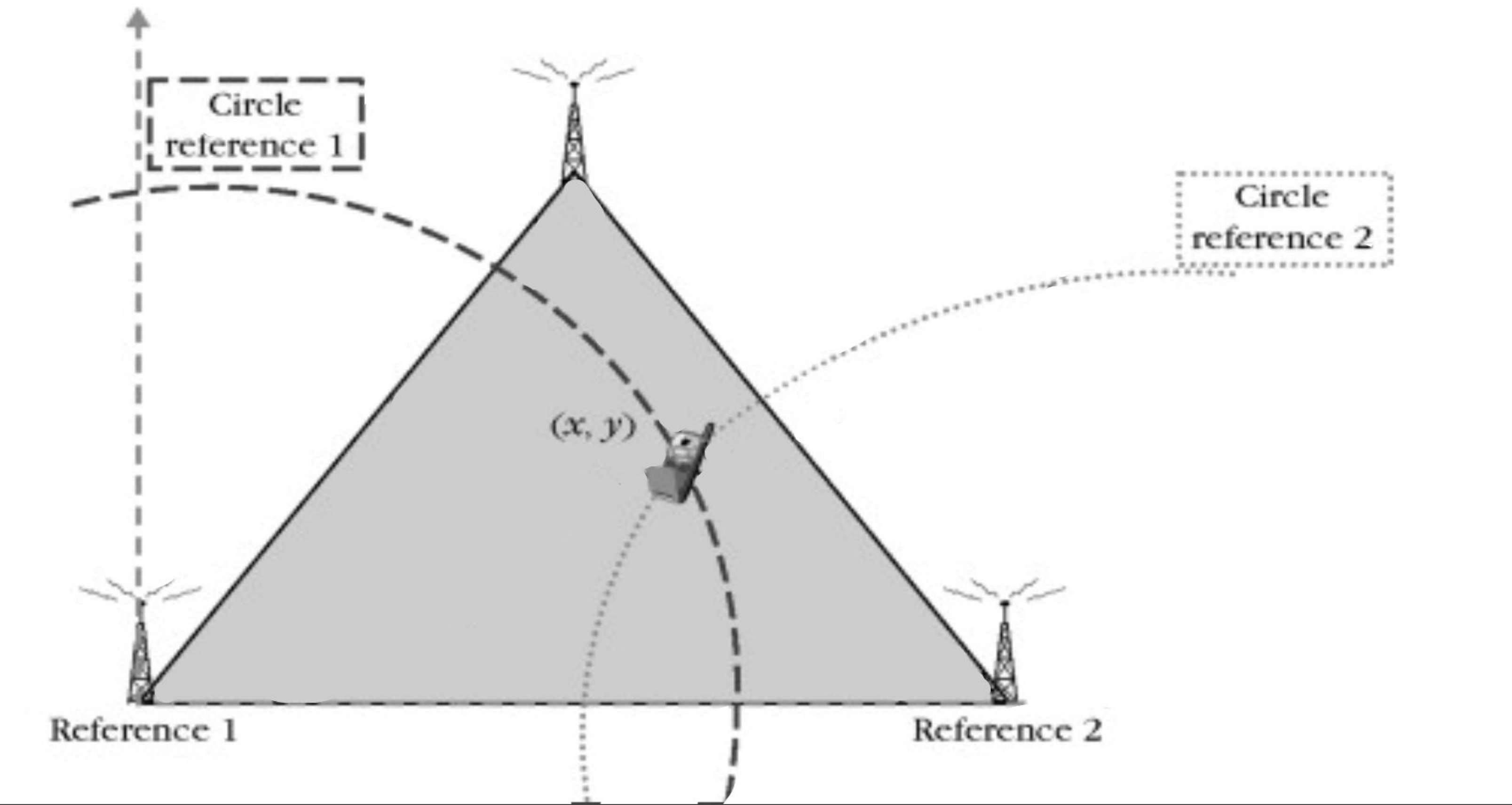
Near-Far Problem

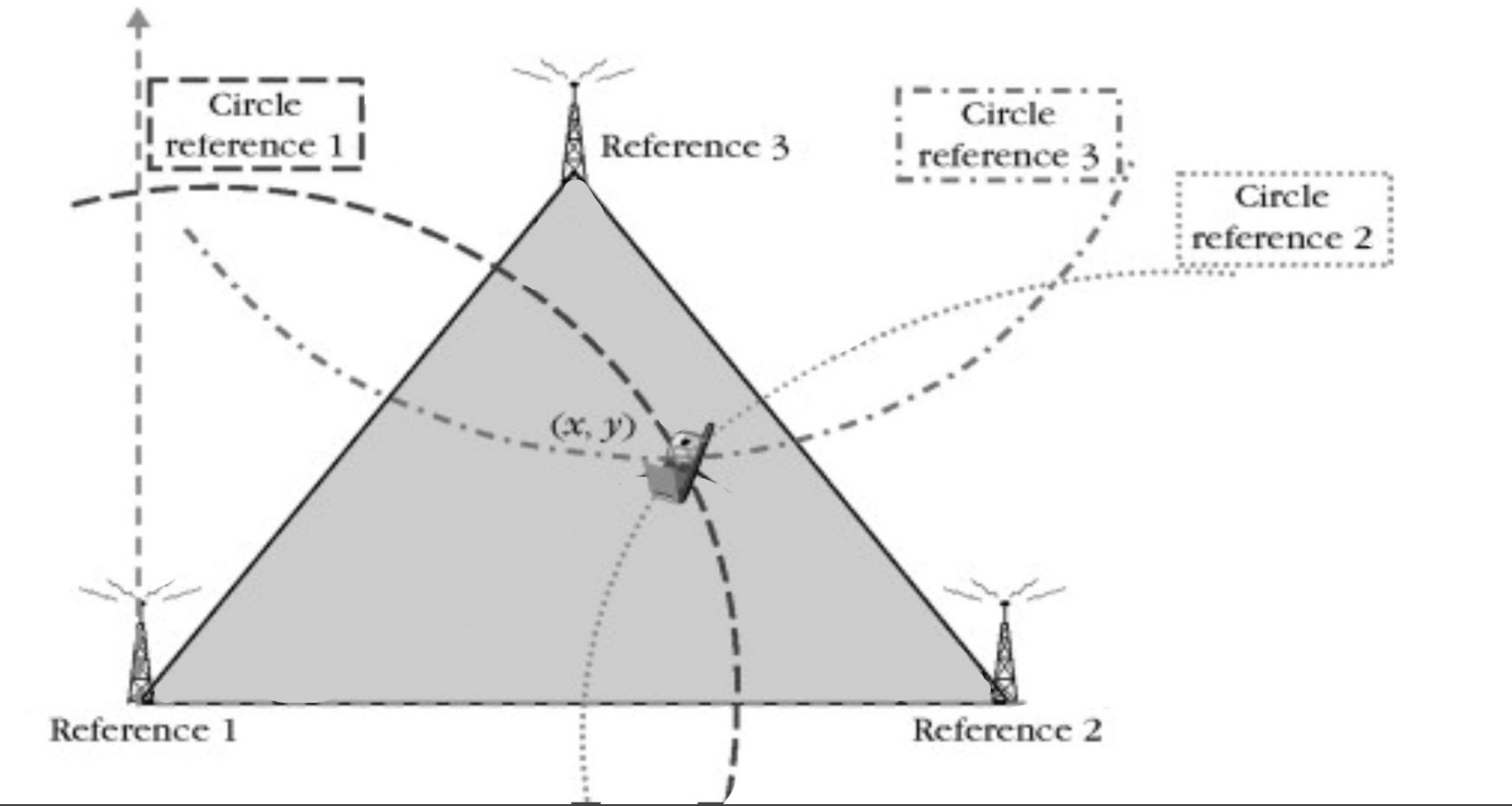







Circle
reference 1
(x, y)
Reference 1


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

Clocks

- All clocks must be within **30 ns (FR3)** of each other **for the duration of a test (2 hr)**.*
- On-board clock (TCXO) drifts at an average of 0.05 ns, every second.
- In order to save the **complexity** and **cost** of outfitting all pseudolites with expensive clocks that won't drift during our test, we'll take advantage of GPS.
- We will keep the pseudolite (SDR Lime) clocks **GPS-disciplined**:
  - GPS receiver computes pseudolite position and clock bias from GPS time. Use this clock bias to keep pseudolite clock synced with GPS time.
- **Expected accuracy: 5-10ns.**

*due to the use of one-way ranging

Clocks (cont.)

- The previous slides show how **pseudolite geometry** composed of a **0.18km equilateral triangle** + **GPS-disciplined clocks** satisfy functional requirement 3 and its corresponding design requirements:

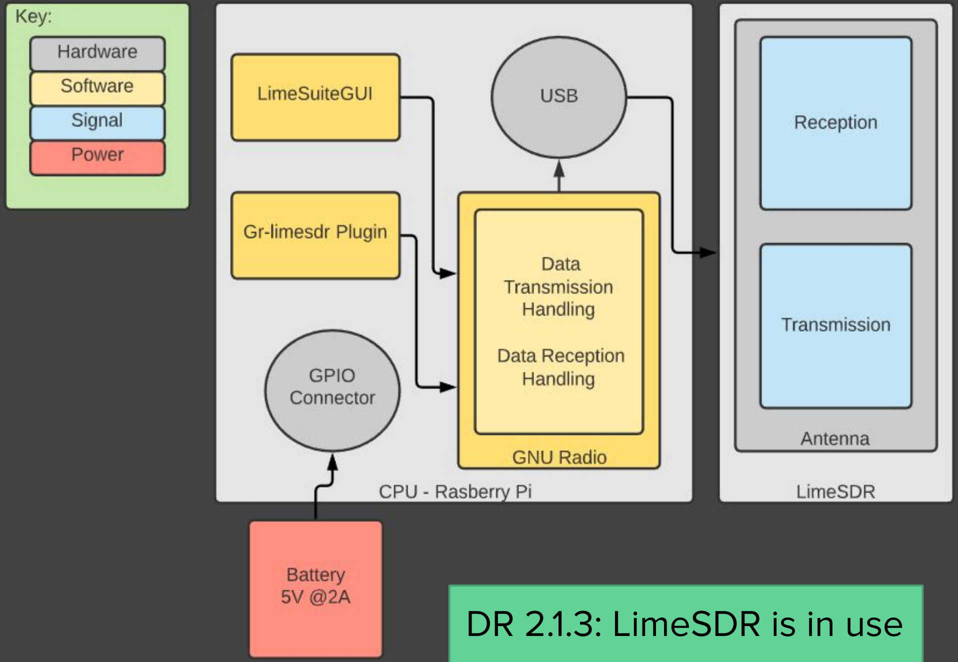
  FR3: The system will be able to provide an architecture for a navigation solution with a 10 meter position accuracy and a 30 nanosecond 1-σ transfer time

  - **DR 2.3.2** : Provide LPS coverage to the Moon's South Pole
  - **DR 2.3.3** : Architecture must provide a Dilution of Precision (DOP) value below 5

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

Pseudolite Electronic Configuration



DR 2.1.3: LimeSDR is in use

- 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?

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.

For Example:

[1] - LimeSuite 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"

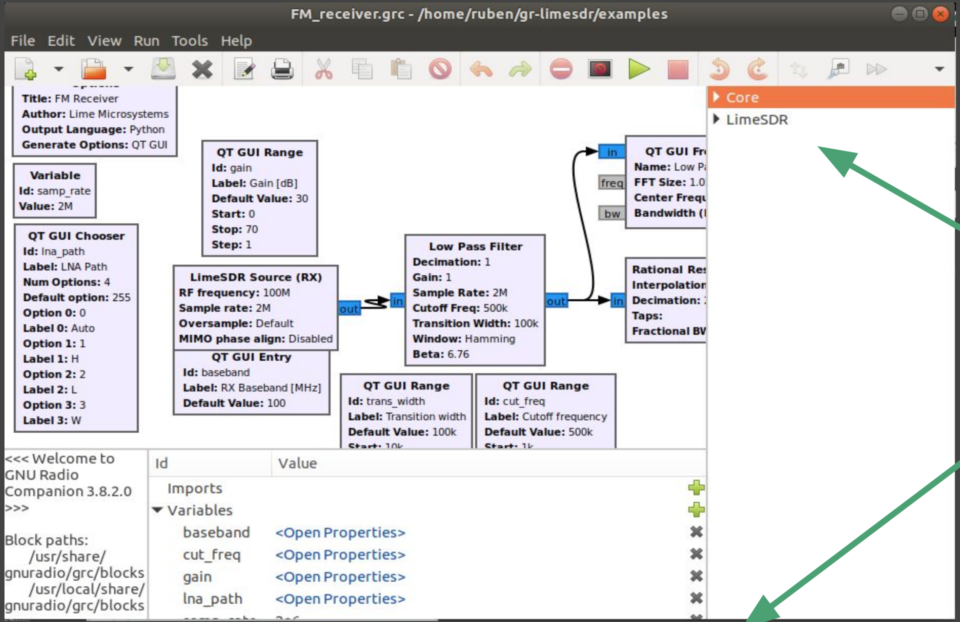
[2] - GNU Radio Installation: (PPA Installation)
Note: The Release version must be 3.8.2.0
-> sudo add-apt-repository ppa:gnuradio/gnuradio-releases
-> sudo apt-get update
-> sudo apt install gnuradio
To optimize GNU Radio kernel usage type:
-> volk_profile
To Open GNU Radio GUI:
-> gnuradio-companion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

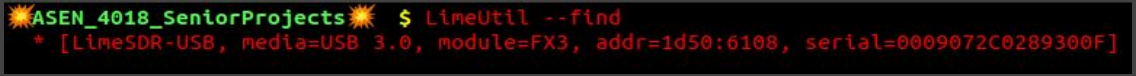
Gr-LimeSDR Installation Process

The current issue is with the gr-limesdr plugin package.

[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





- Environment is in beginning stages still.
- 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 LimeSuite

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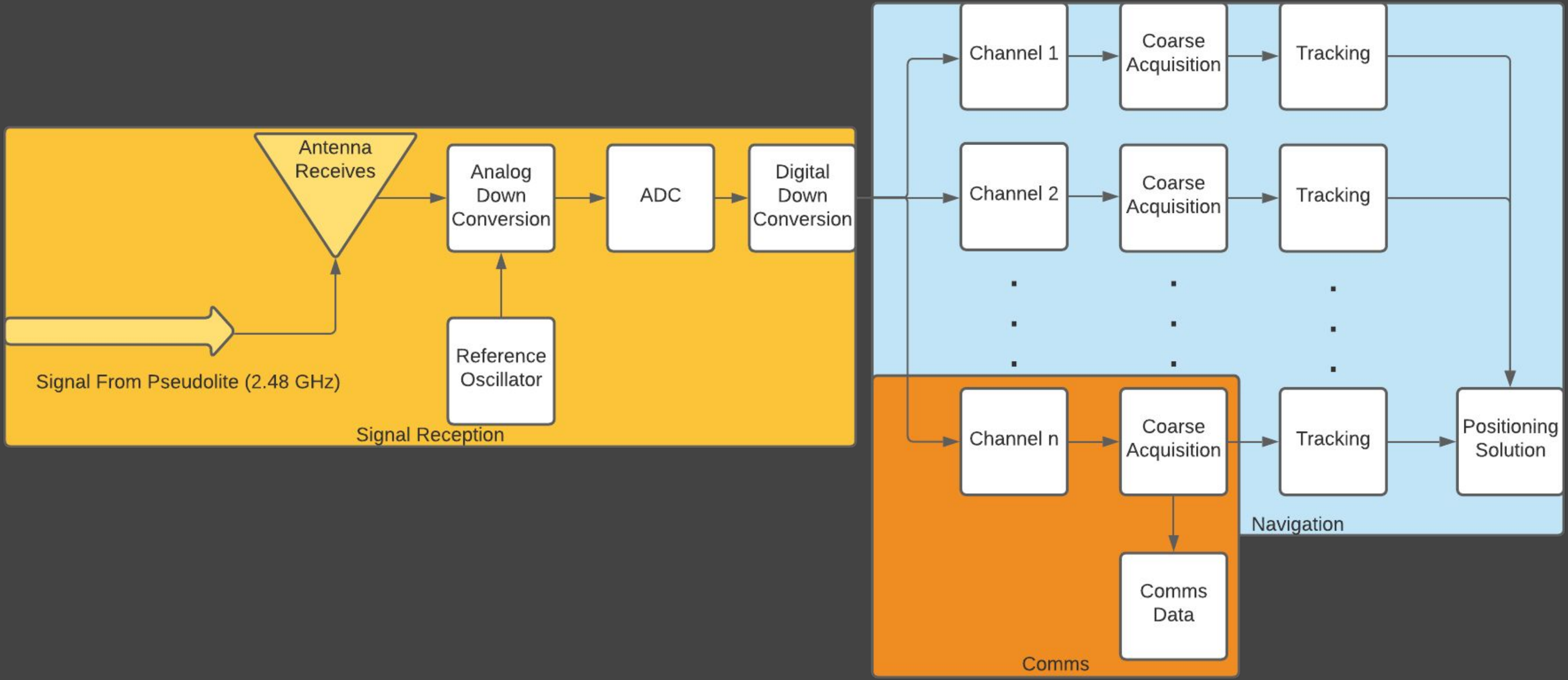
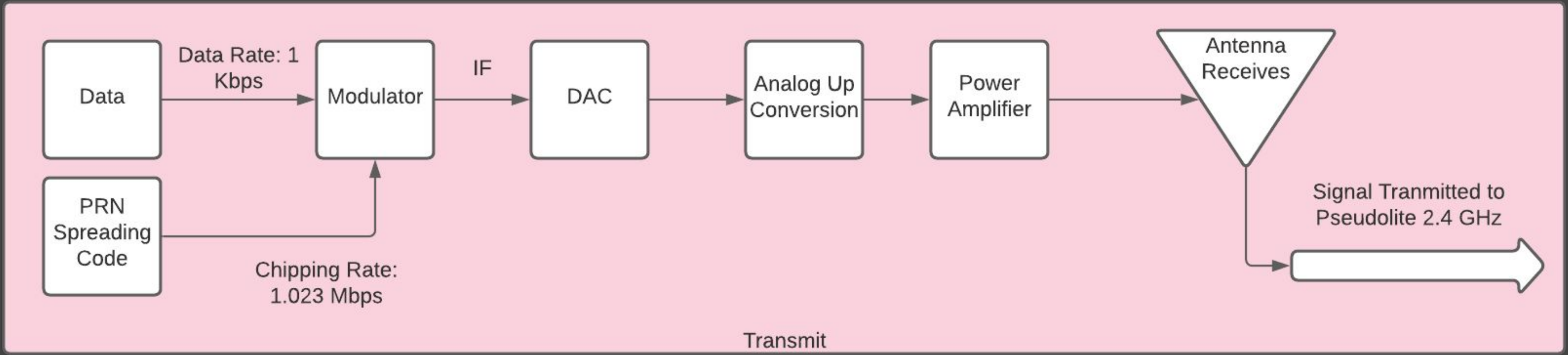
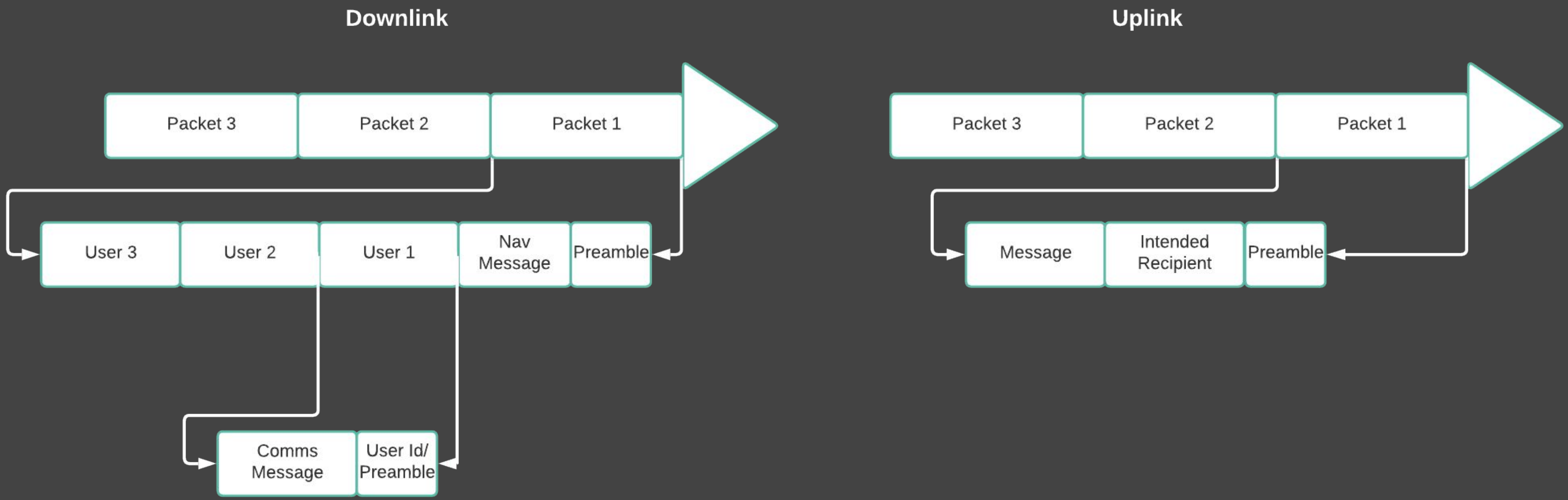
Receive FBD


Antenna Receives
Analog Down Conversion
ADC
Digital Down Conversion
Reference Oscillator
Signal From Pseudolite (2.48 GHz)
Signal Reception
Channel 1
Coarse Acquisition
Tracking
Channel 2
Coarse Acquisition
Tracking
Channel n
Coarse Acquisition
Tracking
Positioning Solution
Navigation
Comms Data
Comms

Transmit FBD



Signal FBD


Downlink
Packet 3
Packet 2
Packet 1
User 3
User 2
User 1
Nav Message
Preamble
Comms Message
User Id/ Preamble
Uplink
Packet 3
Packet 2
Packet 1
Message
Intended Recipient
Preamble

Project Risks and Mitigation

Risk Control Log

Risk ID	Description	Likelihood	Severity	Total
Comms-1	Multiple User Communicating	4	5	9
Comms-2	Signal Interference in testing environment	4	3	7
Soft-1	Team inexperience handling new software. GNU Radio for example	3	4	7
Soft-2	Lime-SDR, Raspberry pi, and other hardware components not communicating correctly	2	3	4
Electr-1	Time Synchronization between pseudolites	3	5	8
Comms-3	Near-Far Problem: difficulty to hear weak-far signals from strong-close signal sources	4	5	9
Logistics-1	Hardware/Electronics don’t arrive on time which sets back schedule of overall project	2	5	7

Risk Matrix

LOW RISK	Acceptable
MEDIUM RISK	Requires monitoring
HIGH RISK	Moderate Mitigation
EXTREME RISK	Immediate Mitigation
CRITICAL	Unacceptable Risk

SEVERITY

Likelihood

Likelihood \ Severity	1	2	3	4	5
1	LOW				MEDIUM
2			MEDIUM Soft-2		HIGH Logistics-1
3				Soft-1	EXTREME Electr-1
4	MEDIUM		Comms-2		Comms-1 Comms -3
5		HIGH	EXTREME		Critic al

Risk Mitigation Table

Risk ID	Description	Likelihood	Severity	Total
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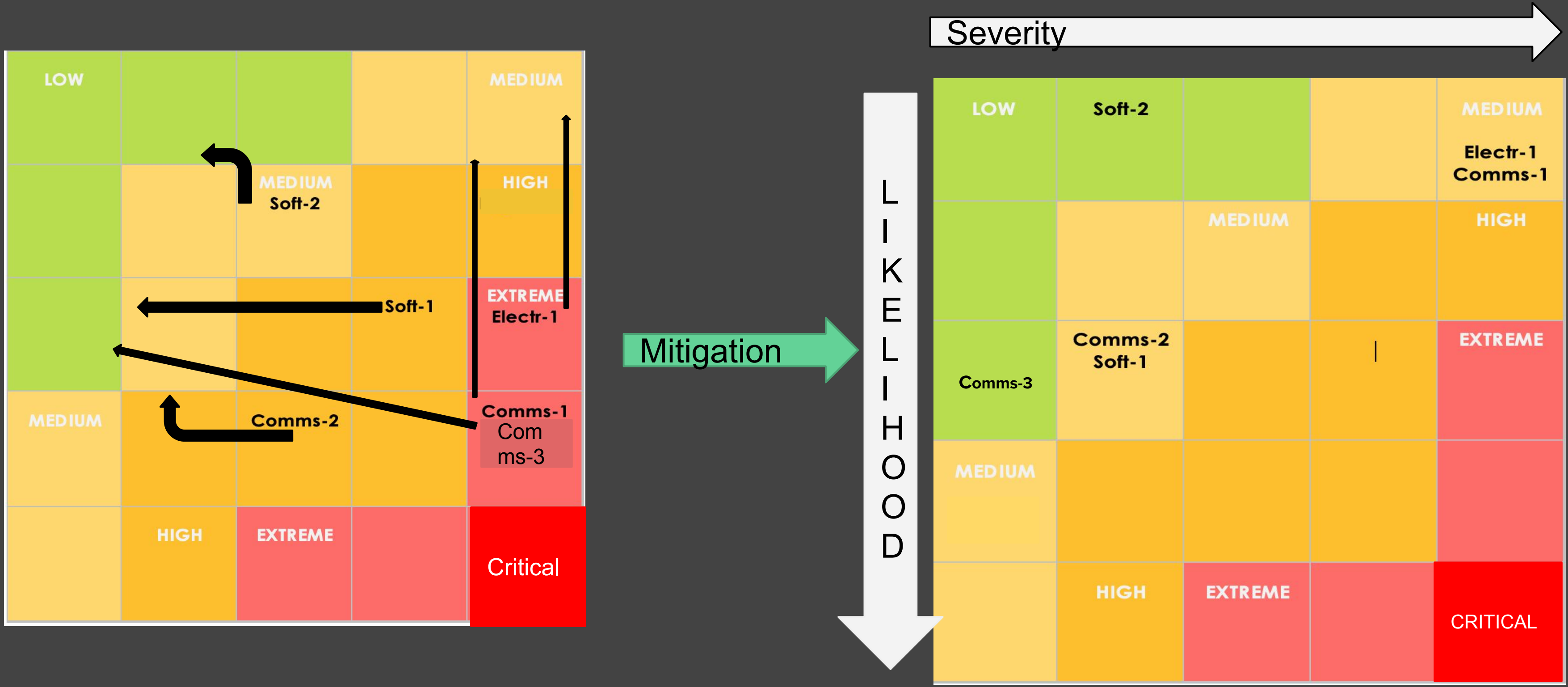
Mitigation Effects

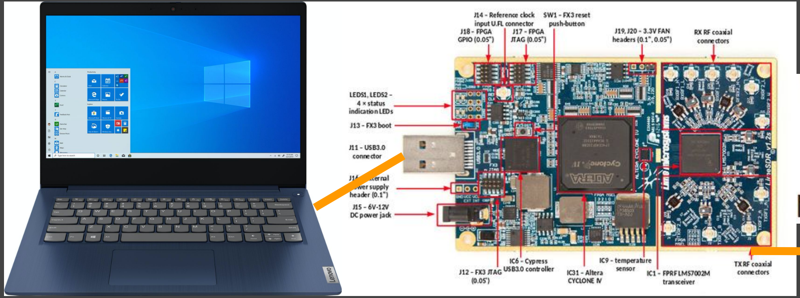


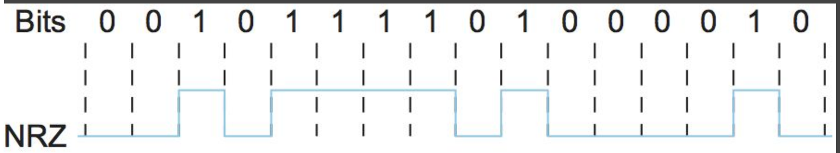
Verification and Validation

Signal Reception

LimeSDR demonstrates reception signal through USB connection

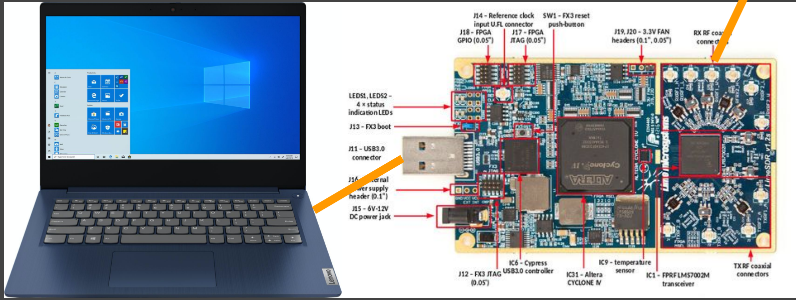
- Laptop running GNU radio creates signal and sends to LimeSDR
  - Create 100 bit .txt file to use as transmission signal
  - Send bits to LimeSDR using USB connection
- Verify receipt of signal to the LimeSDR
  - Create .txt file from bits and compare sent and received signal





Wired from TX to RX sending bits

USB Connection sends .txt as bits to LimeSDR

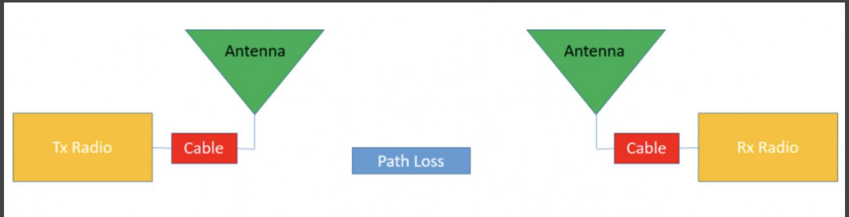


Bits converted to .txt and compared to initial file

Antenna test

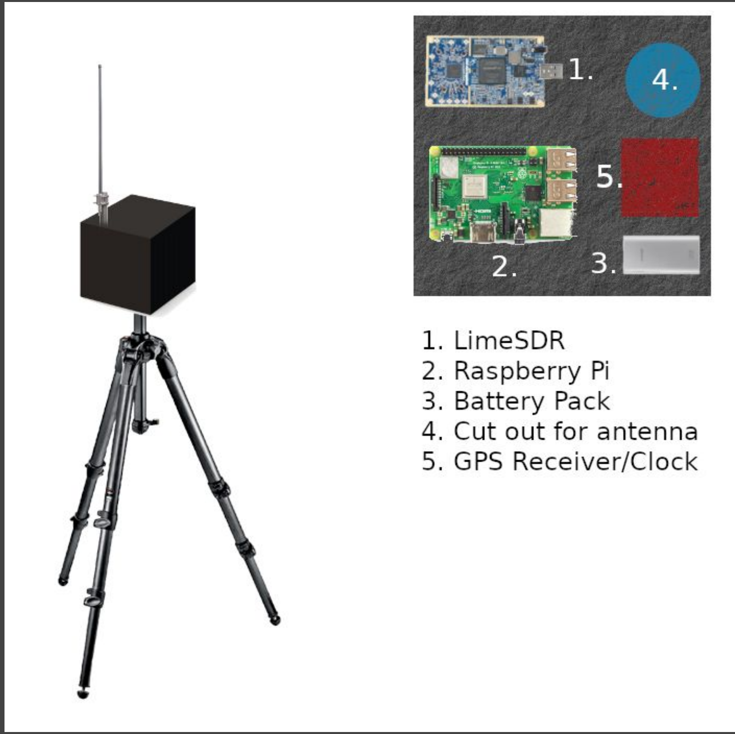
Demonstrate that the antennas used can supply the proper gain for the design

- 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



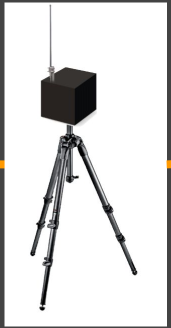
Each transmitter and receiver will feature a 3D printed casing for the electronics that will hold the LimeSDR, Raspberry Pi, a battery pack, and space for wiring and a connection to the antenna. The electronics casing will be thread-mounted to a camera tripod.

Modulation Scheme

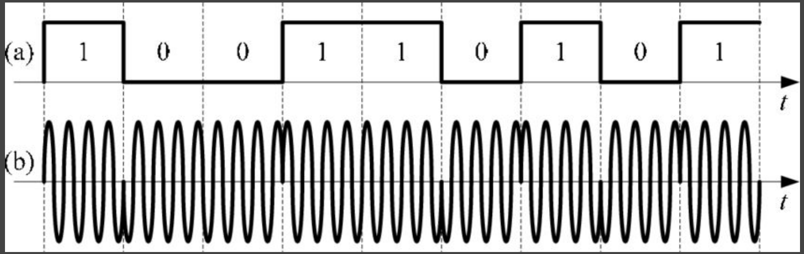
LimeSDR receiver positioned 100m away from LimeSDR transmitter

- Transmitter modulates 100 bit .txt file to 2.49 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

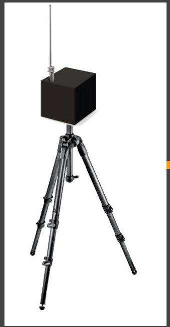
Using Laptop and GNURadio send .txt file to LimeSDR



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

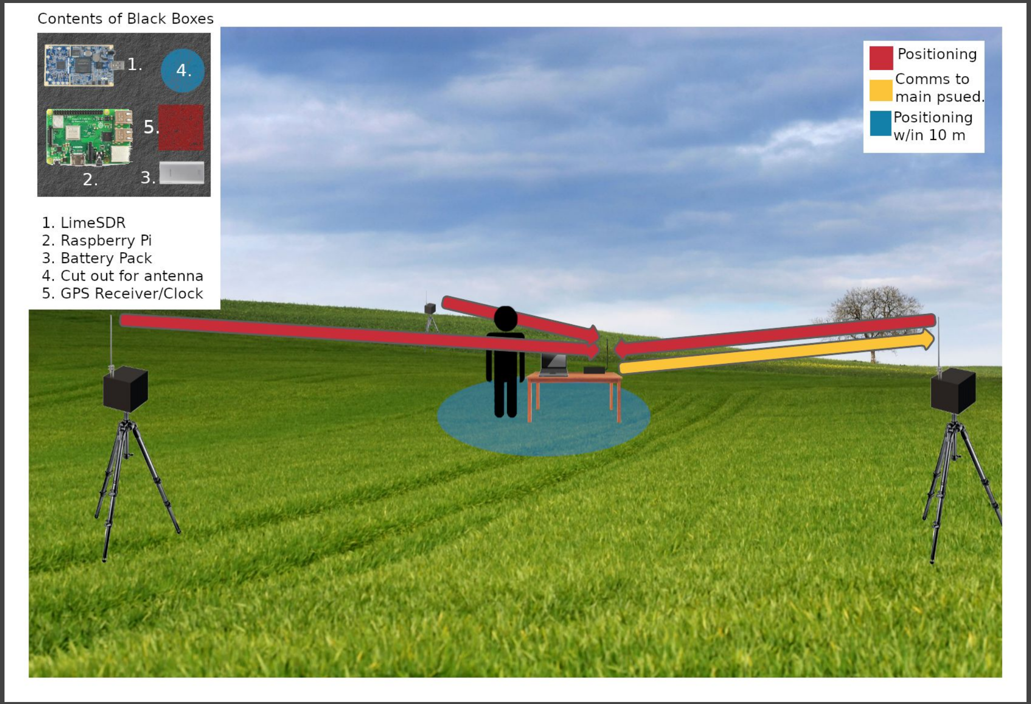
- 3 transmitters generate and transmit signals of different 100 bit .txt files
  - For each file, send preamble and .txt file using GNU radio PSK modulator
- LimeSDR receiver positioned 100m away receives the signals and listens for specific preamble
  - Based on desired preamble, receiver demodulates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

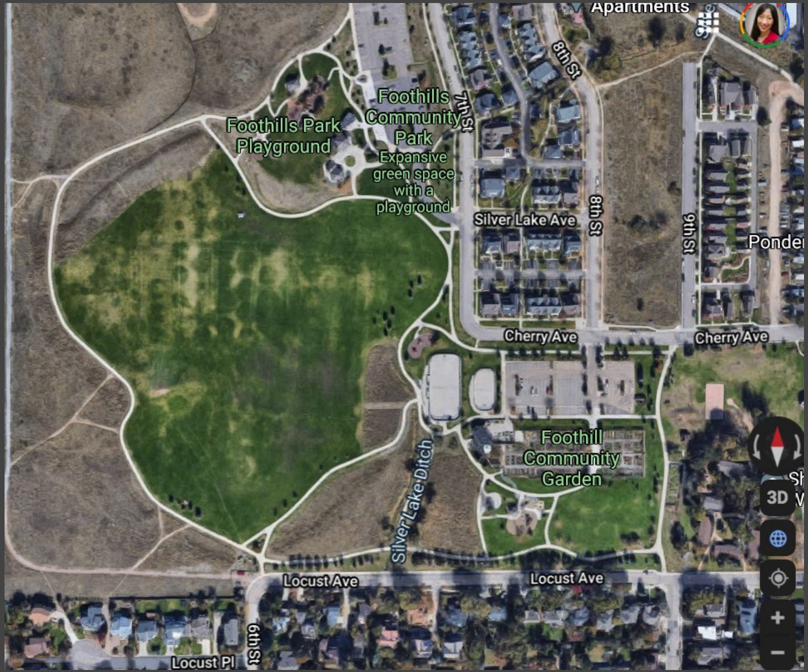
HDOP and Positioning Accuracy

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



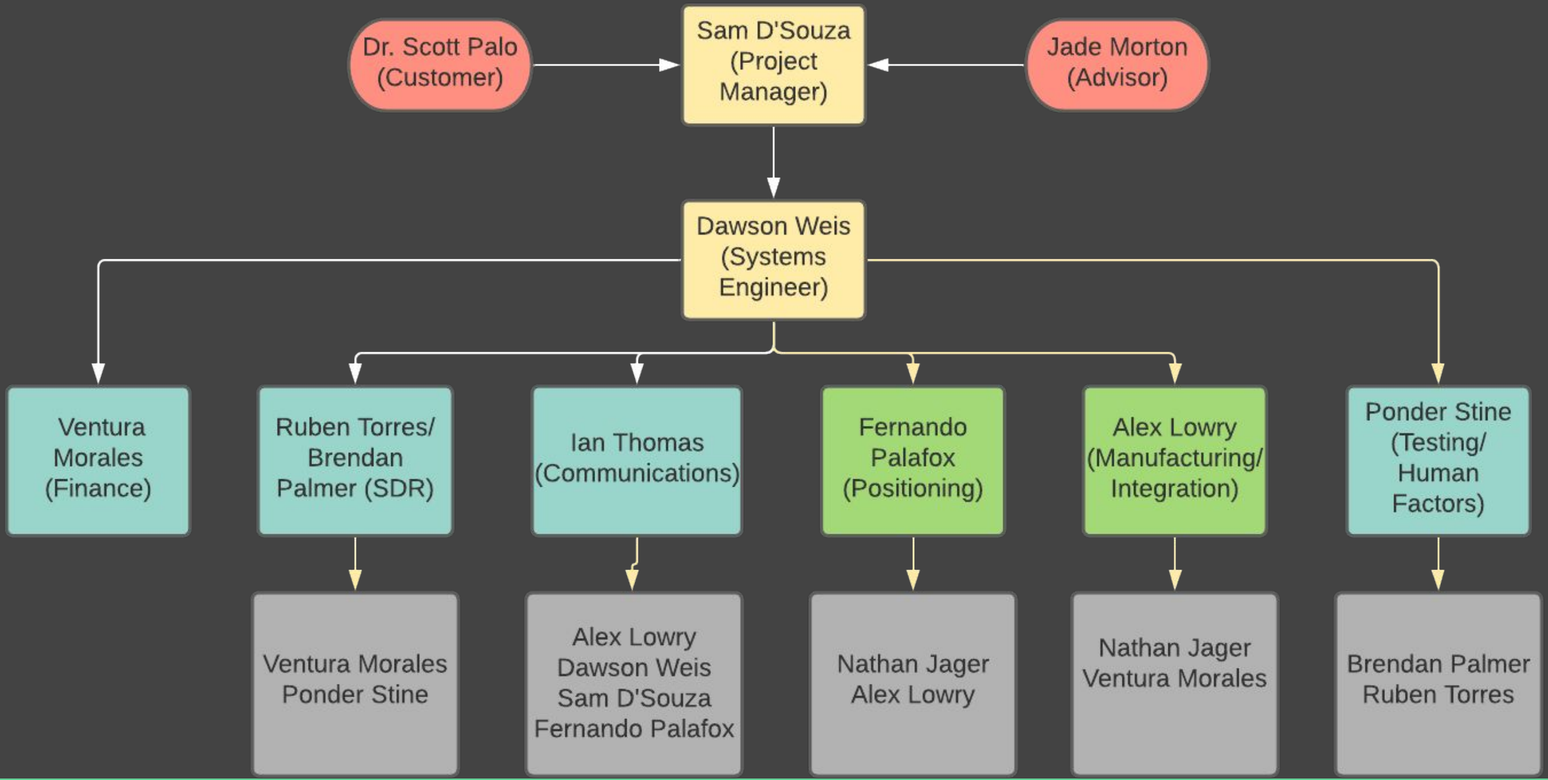


Test Checklist

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

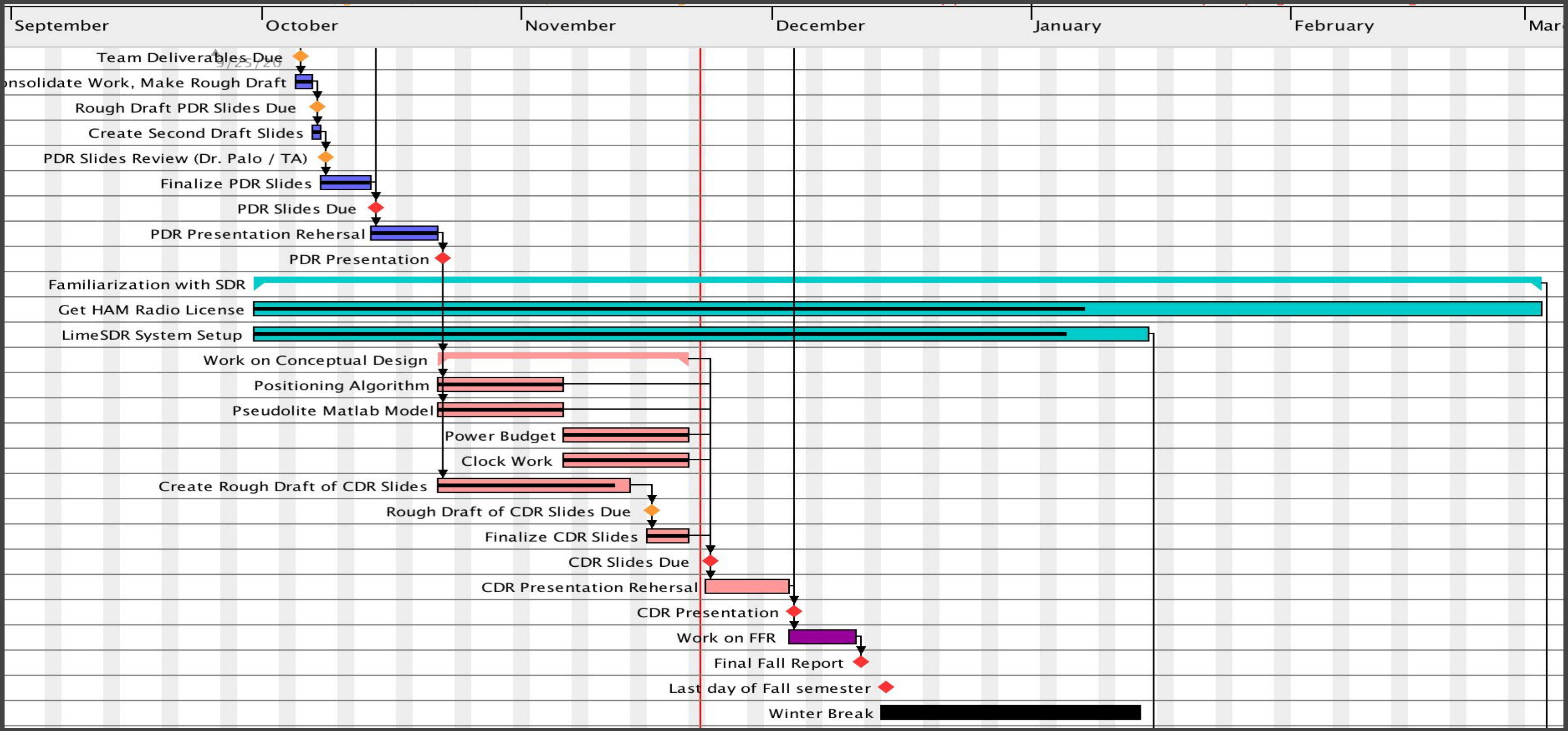
Project Planning

Organizational Chart



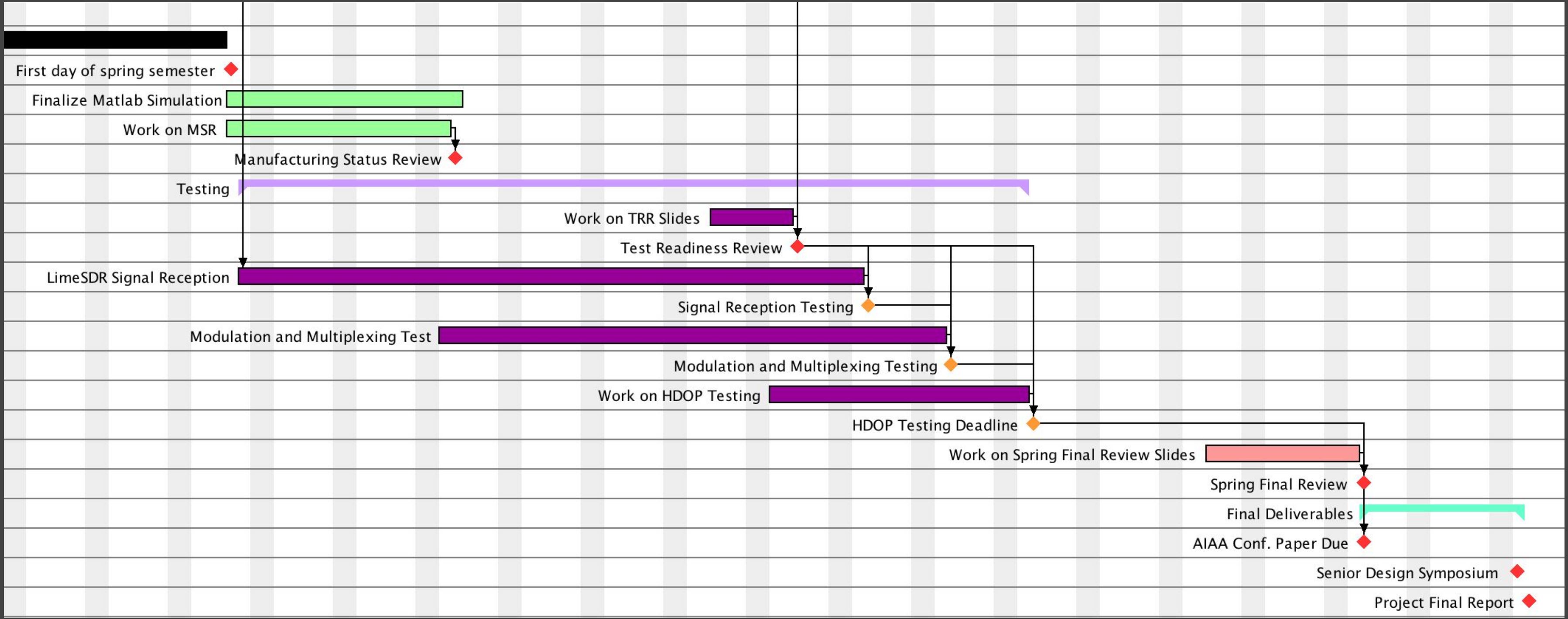
Work Breakdown Structure (WBS)

Work Plan

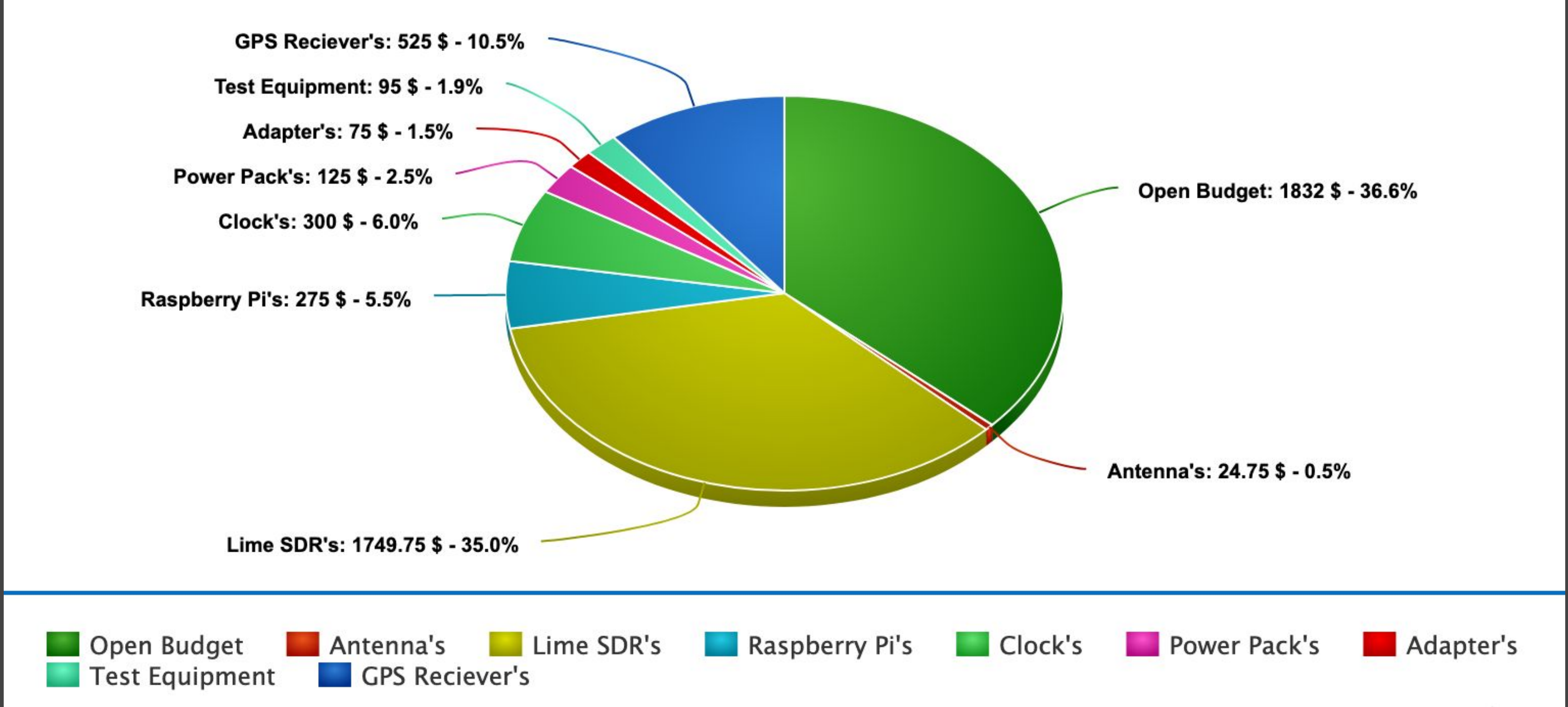


September
October
November
December
January
February
Mar
Team Deliverables Due
9/23/20
onsolidate Work, Make Rough Draft
Rough Draft PDR Slides Due
Create Second Draft Slides
PDR Slides Review (Dr. Palo / TA)
Finalize PDR Slides
PDR Slides Due
PDR Presentation Rehersal
PDR Presentation
Familiarization 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


First day of spring semester
Finalize Matlab Simulation
Work on MSR
Manufacturing Status Review
Testing
Work on TRR Slides
Test Readiness Review
LimeSDR Signal Reception
Signal Reception Testing
Modulation and Multiplexing Test
Modulation and Multiplexing Testing
Work on HDOP Testing
HDOP Testing Deadline
Work on Spring Final Review Slides
Spring Final Review
Final Deliverables
AIAA Conf. Paper Due
Senior Design Symposium
Project Final Report

Budget Pie Chart



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

Questions?

Back Up Slides

Expense Budget & Margin

Team P4LO Budget					
Allowable Budget	$5,000.00				
Communications Hardware					
Item	Individual Cost	# of Items	Subtotal Per Set	Supplier	Item Description
Antenna	$4.95	5	$24.75	SparkFun	2.4GHz Antenna - Adhesive (U.FL Connector)
Lime SDR	$349.95	5	$1,749.75	SparkFun	
Raspberry Pi	$55.00	5	$275.00	SparkFun	Raspberry Pi 4 Model B (4 GB)
Hardware Adapators	$14.95	5	$74.75	SparkFun	Antenna Adapter Cable
Power Pack	$25.00	5	$125.00	SparkFun	
Clock's	$59.95	5	$299.75	TBA	
GPS Reciever	$105.00	5	$525.00	Time Machines	
Testing Tri-pods	$18.95	5	$94.75	Target	
Budget Balance					
Sub-total Balance	$3,168.75				
Sales Tax Total	$253.50				
Total Cost	$3,422.25				
Budget Balance	$1,577.75				

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 Requirements for Testing: 7.5W

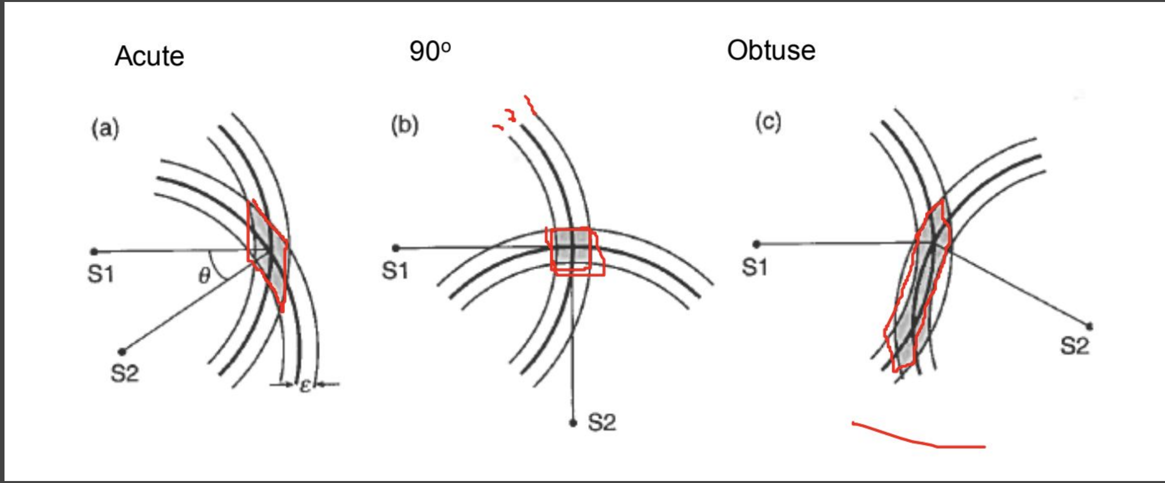
- Many options available to purchase

Back-Up Testing Area

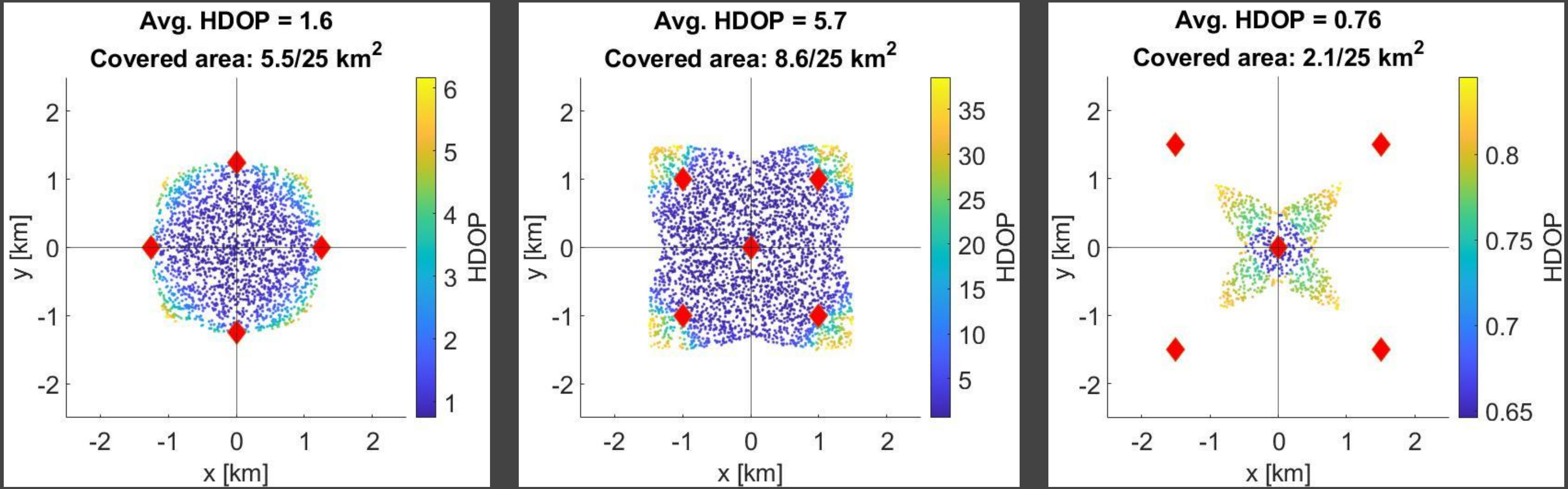
Positioning System - HDOP

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”.



Positioning System - Evidence of Feasibility



DR 2.3.3

FEASIBLE

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

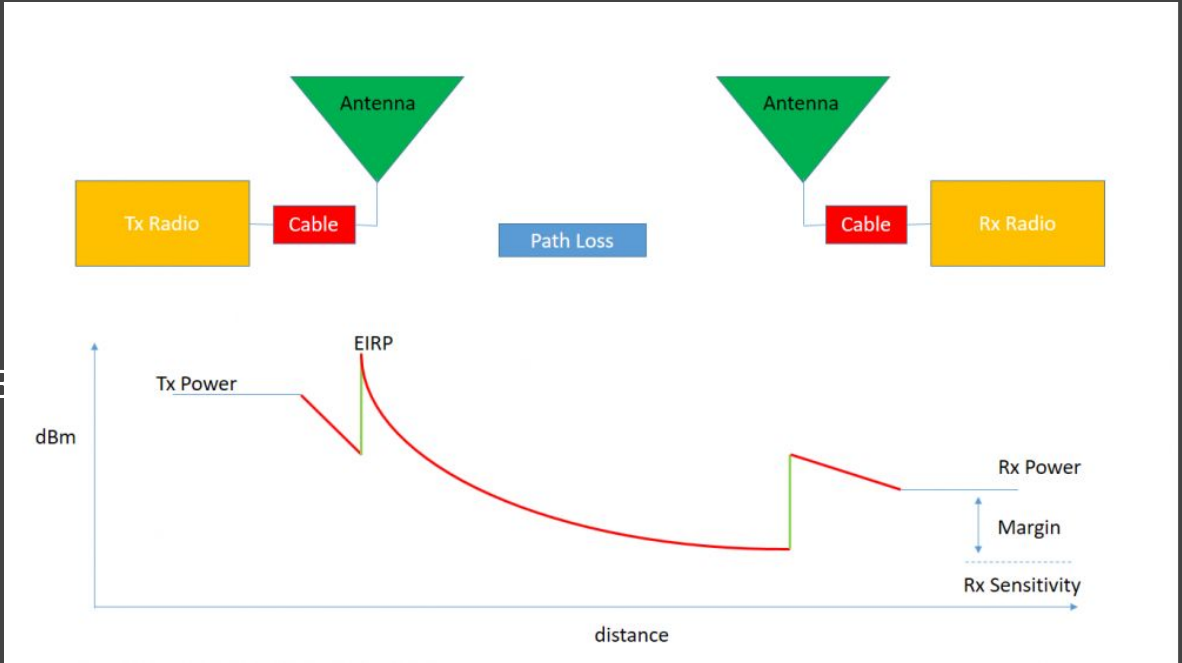
FR 6: The architecture must be extendable to 170 simultaneous users

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

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

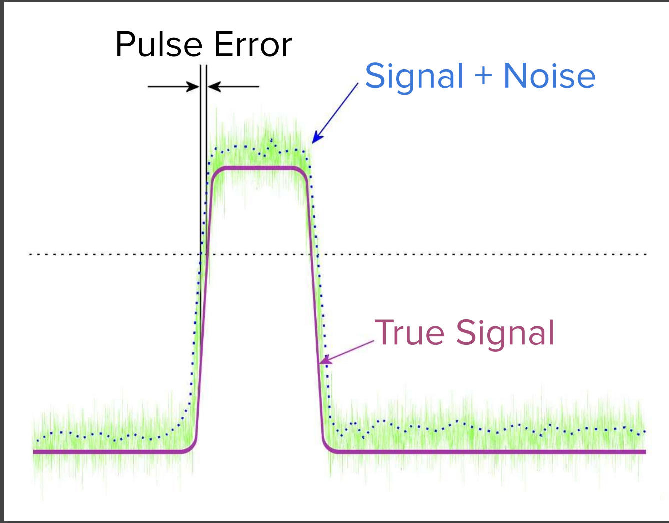
FEASIBLE

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

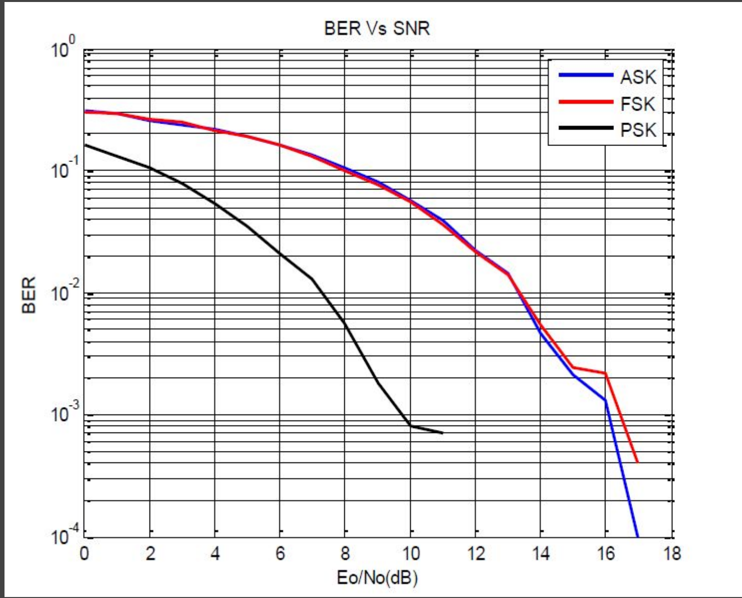


DR 3.1, FR7

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

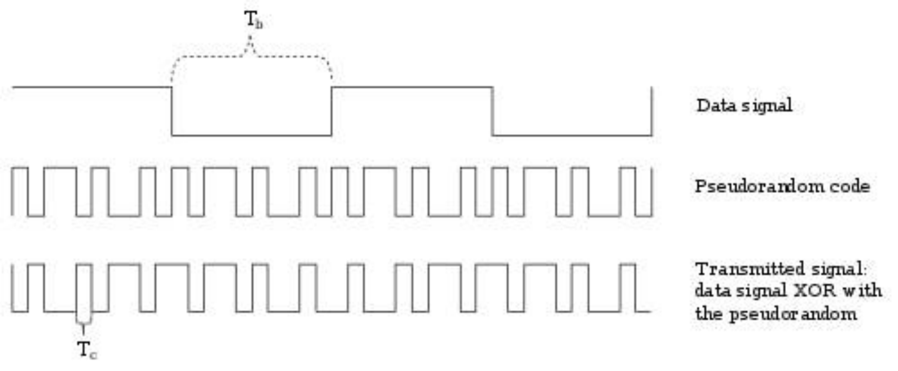


DR 2.1, 2.2, 3.1, FR4, 5, 7
SDR Compatibility

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

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.

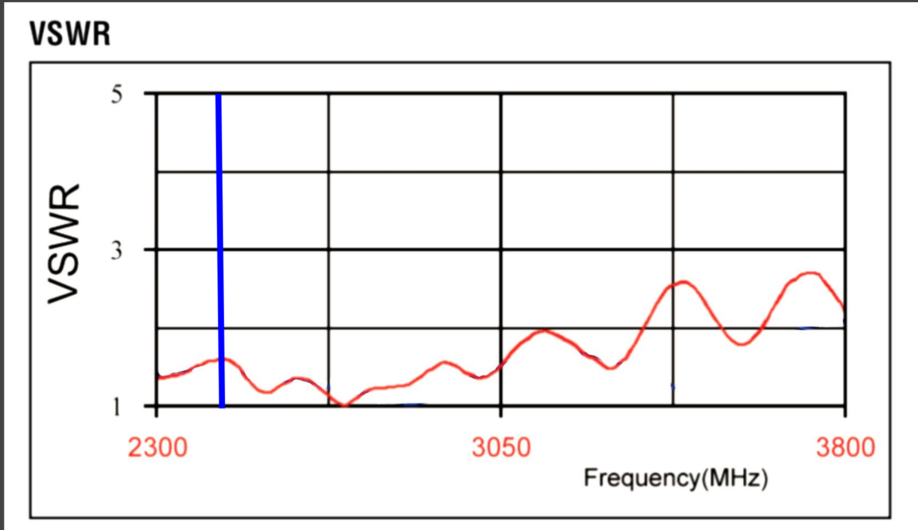
- DR 2.5.1 : Demonstrate downlink reception at a frequency range between 2.4-2.48 GHz

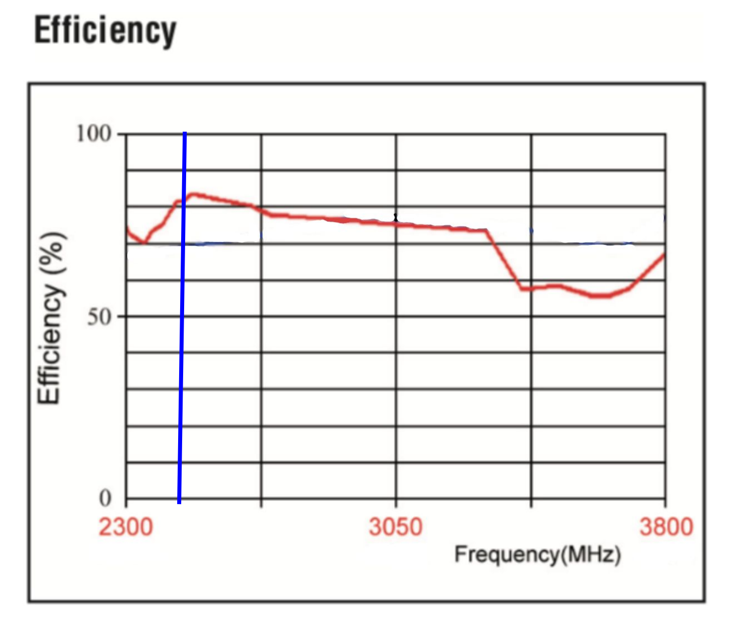
Antenna - Selection Analysis

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

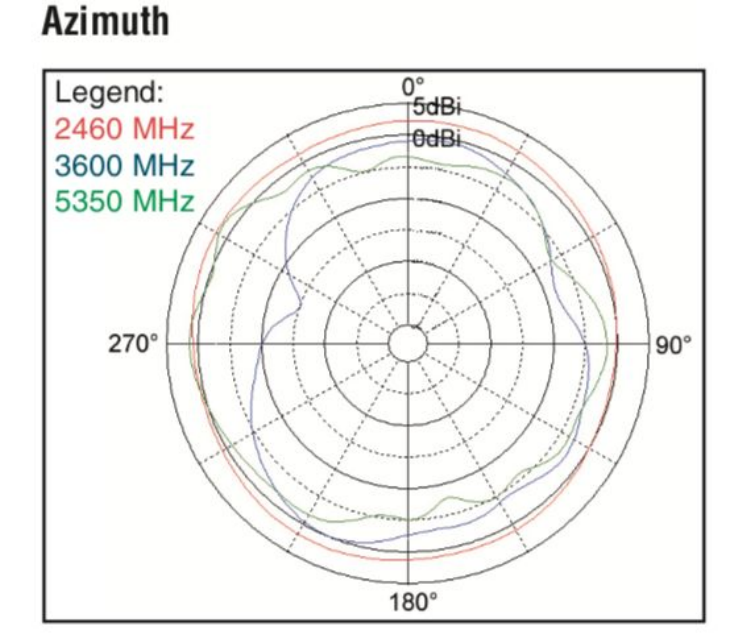


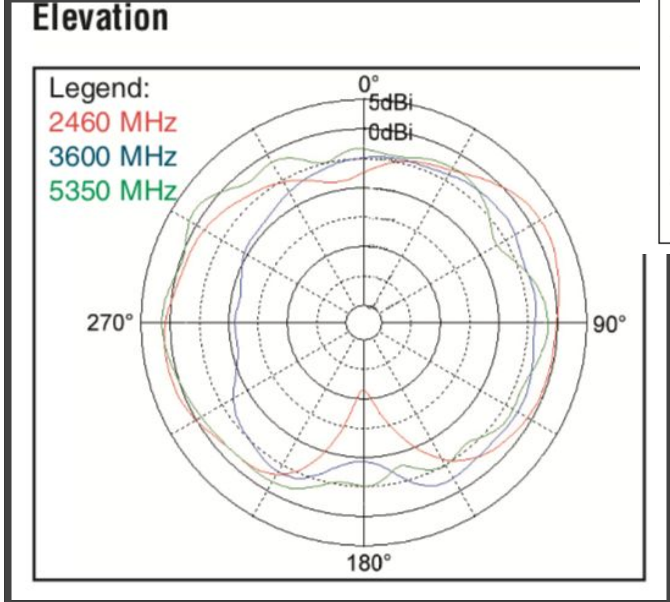


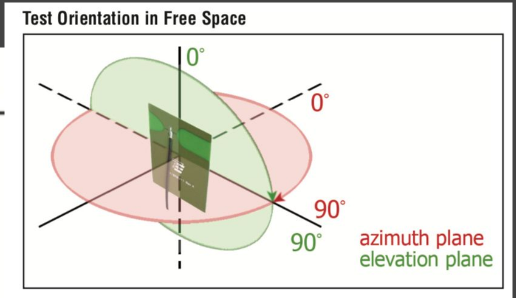
DR 2.4.1, 2.5.1

FEASIBLE

Antenna - Evidence of Feasibility

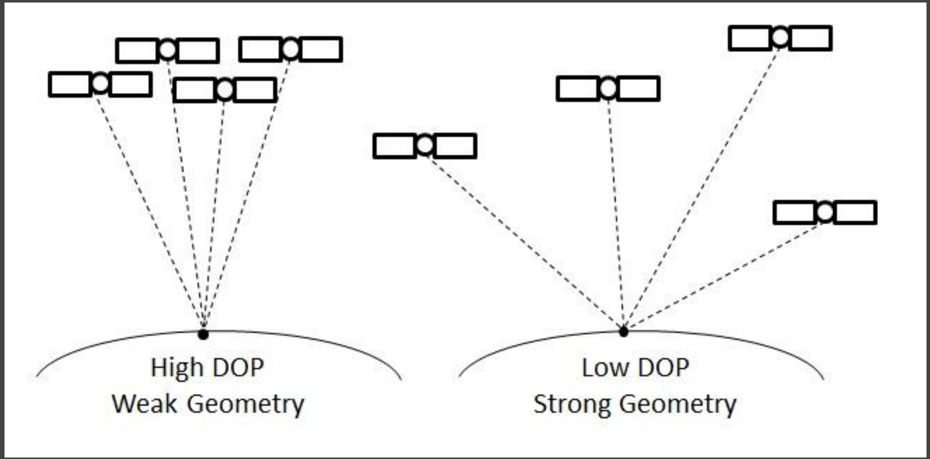






GNSS: Error sources

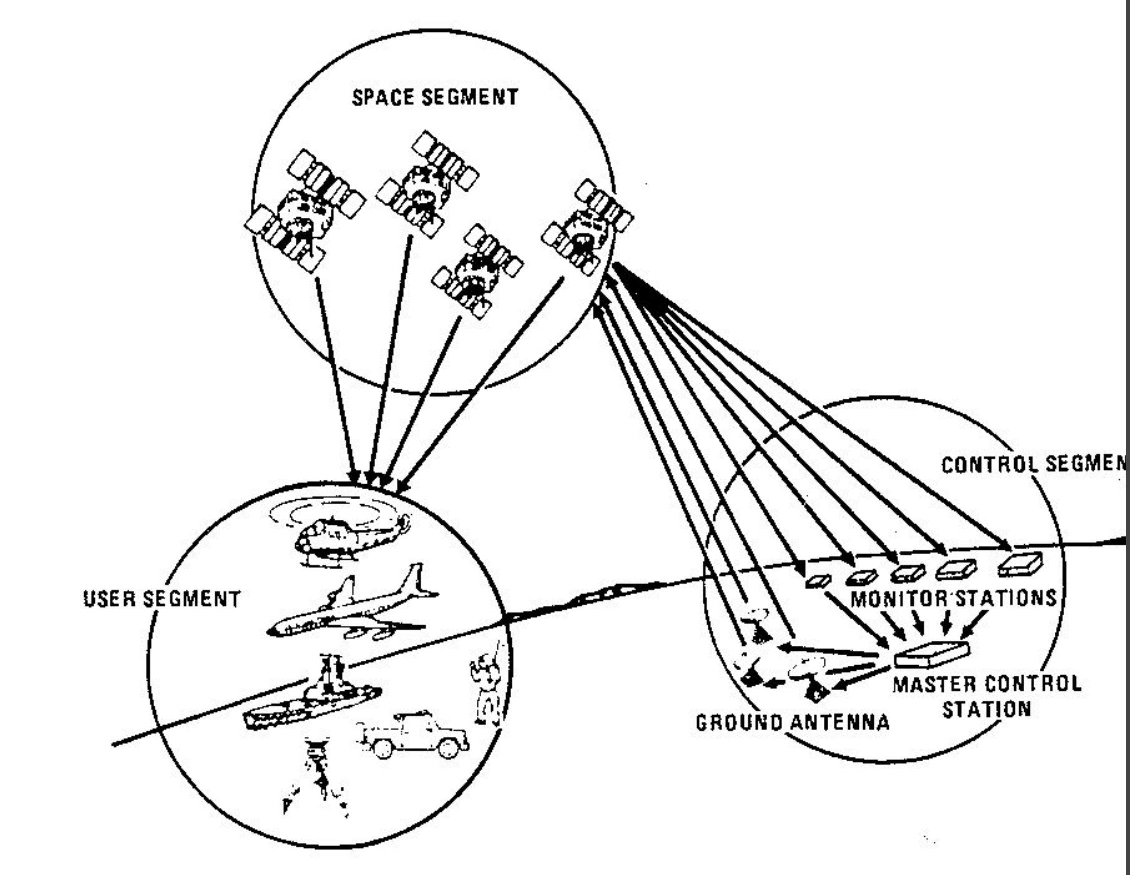
- Error sources can be divided into two categories:
  - Ranging error: signal quality, errors in transmitter location, environmental effects, receiver design, etc….
  - Geometry: Geometric Dilution of Precision (GDOP). Measures the quality of the geometric distribution of the satellites visible to the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



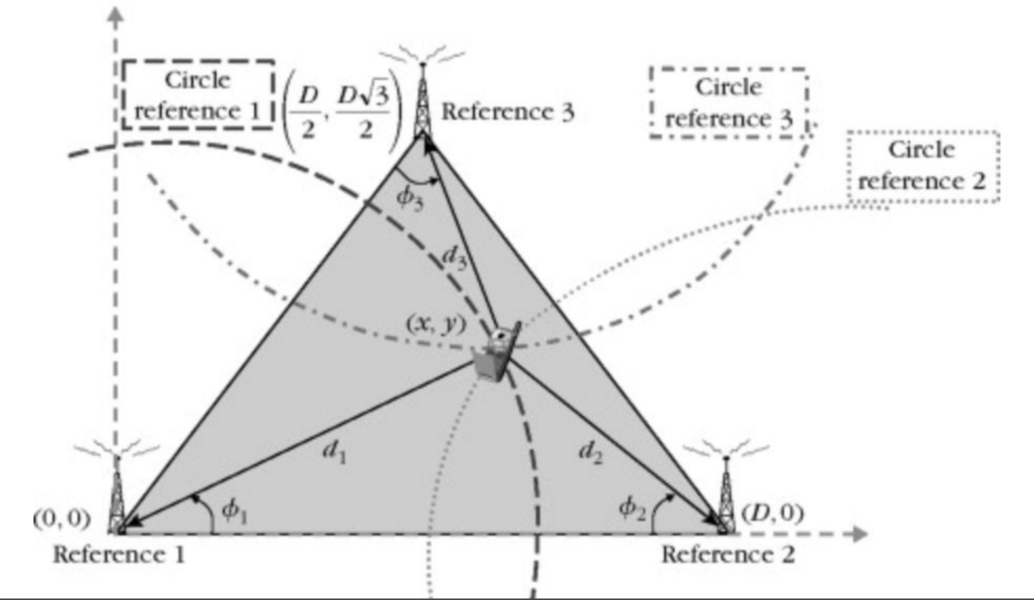
http://allaboutgps101.blogspot.com/2010/12/what-are-3-segments-of-gps-systems.html

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
-

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

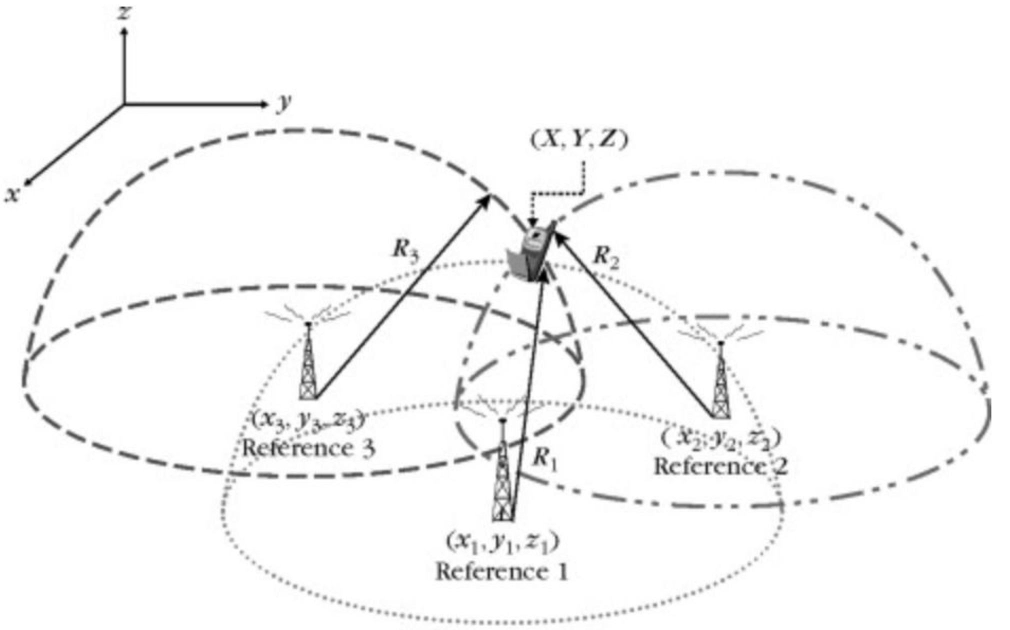
Time of Arrival (TOA)

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

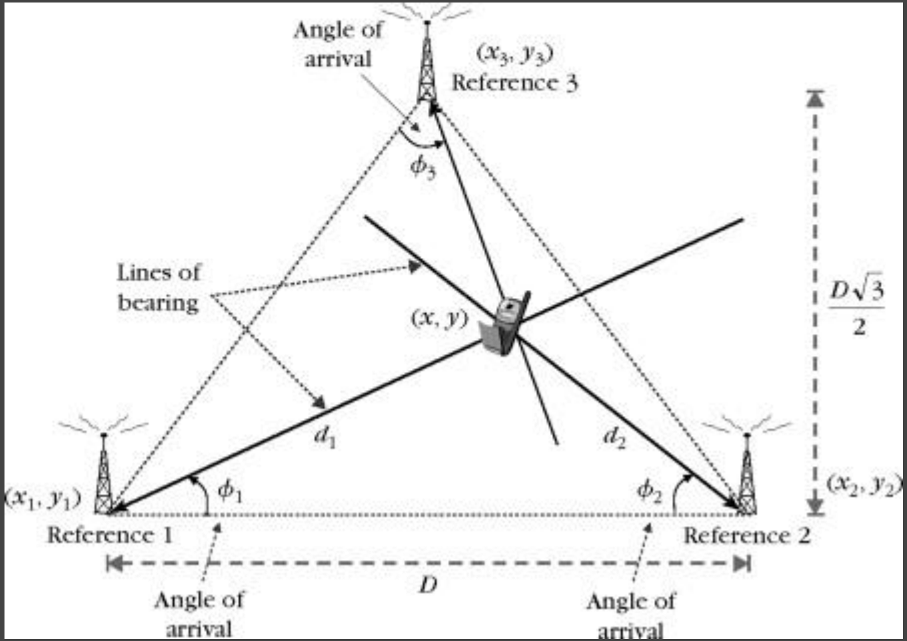
$$d_1^2 = x^2 + y^2,$$
$$d_2^2 = (x_2 - x)^2 + (y_2 - y)^2 = (D - x)^2 + y^2,$$
$$d_3^2 = (x_3 - x)^2 + (y_3 - y)^2 = \tfrac{1}{2}(D - 2x)^2 + \left(D\sqrt{3} - 2y\right)^2.$$

Time of Arrival (TOA)

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

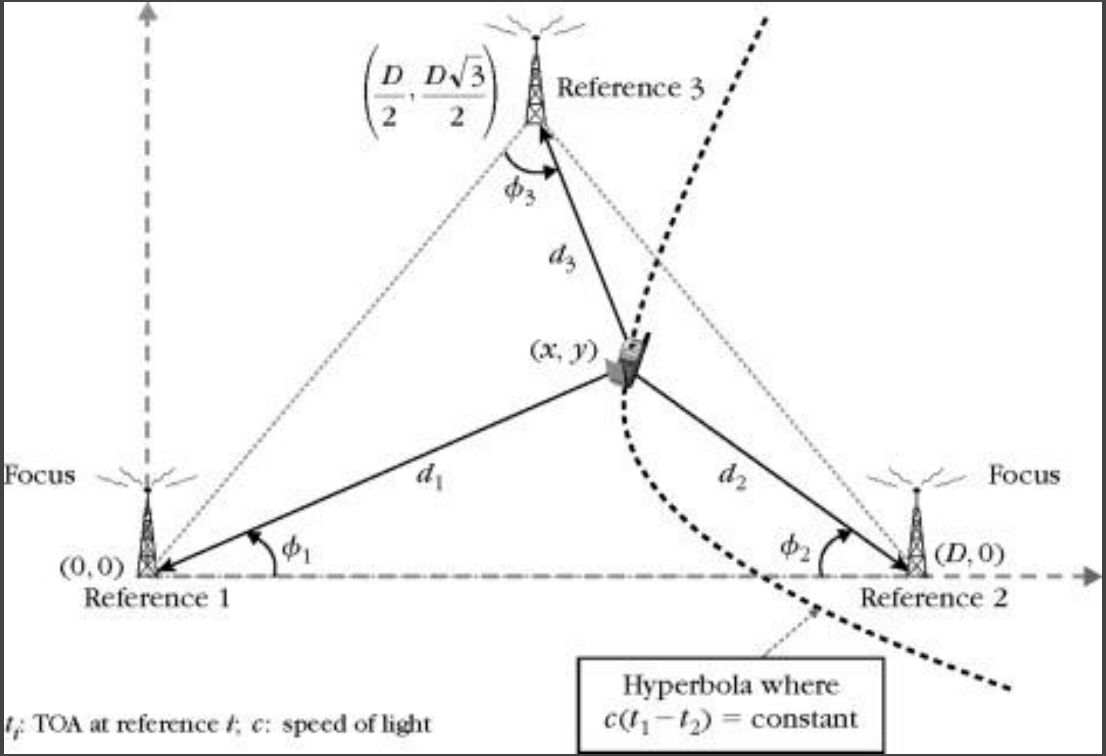


Angle of Arrival (AOA)



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

Time Difference of Arrival (TDOA)



Time Difference of Arrival (TDOA)

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

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

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

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

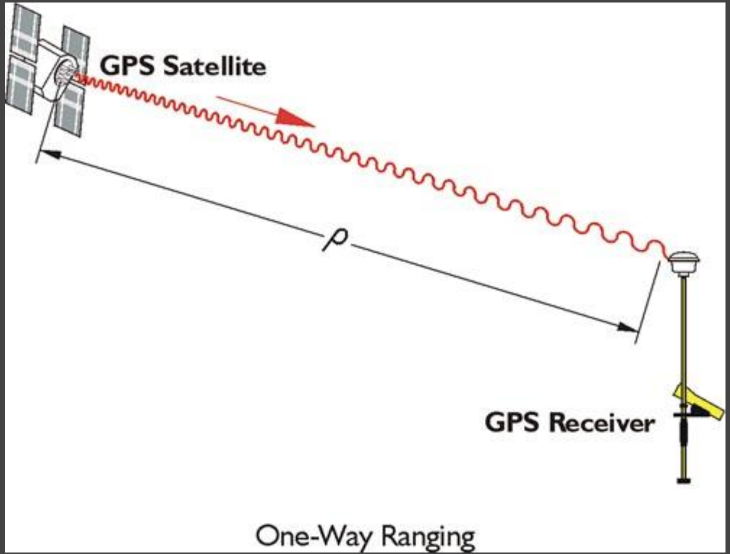
$$(d_{21}^2 - x_2^2 - y_2^2) + 2d_{21}d_1 = -2x_2x - 2y_2y,$$

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

Communications

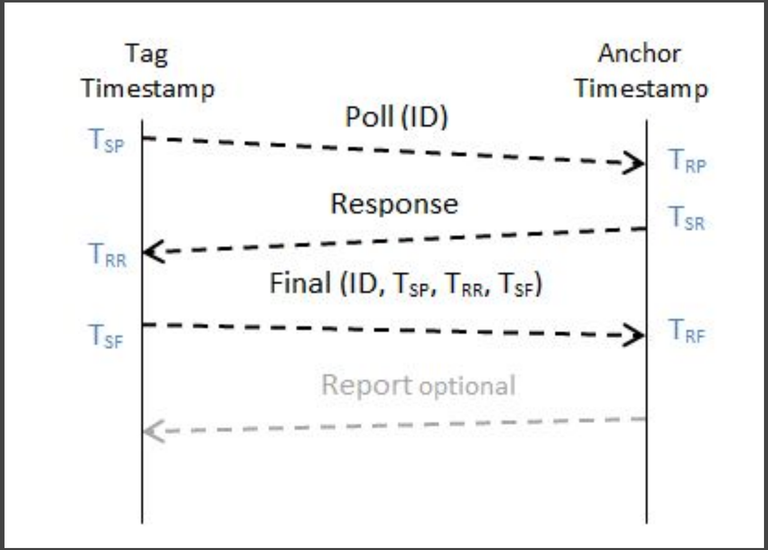
One way ranging

- 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

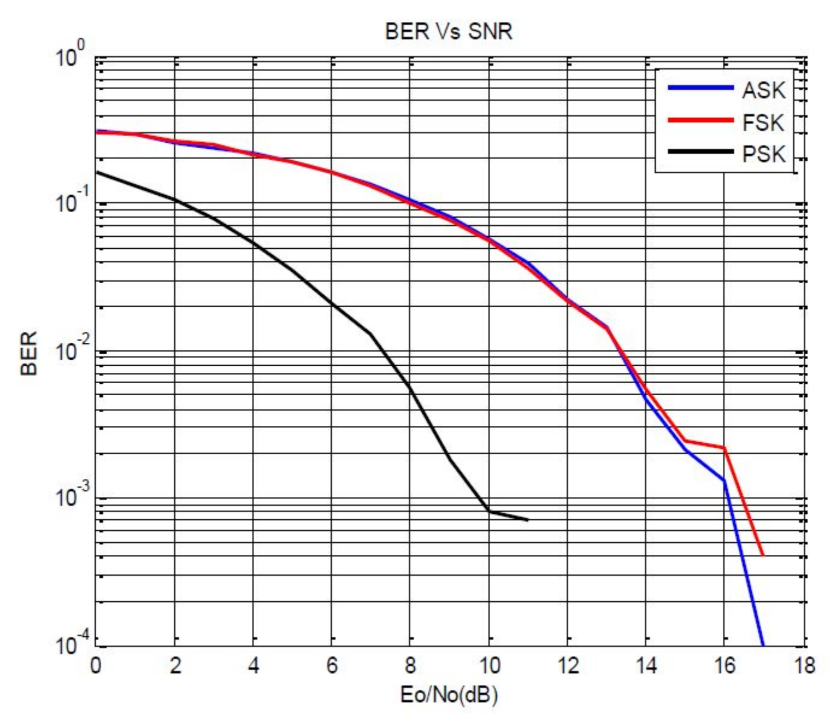
- Requires clocks on both ends but does need them to be synced up with each other.
- Receiver must transmit data BACK to the transmitter - multiple times.
- **Both the satellite and the receiver know the location of the satellite.**
- The energy and processing requirements are high due to the fast data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



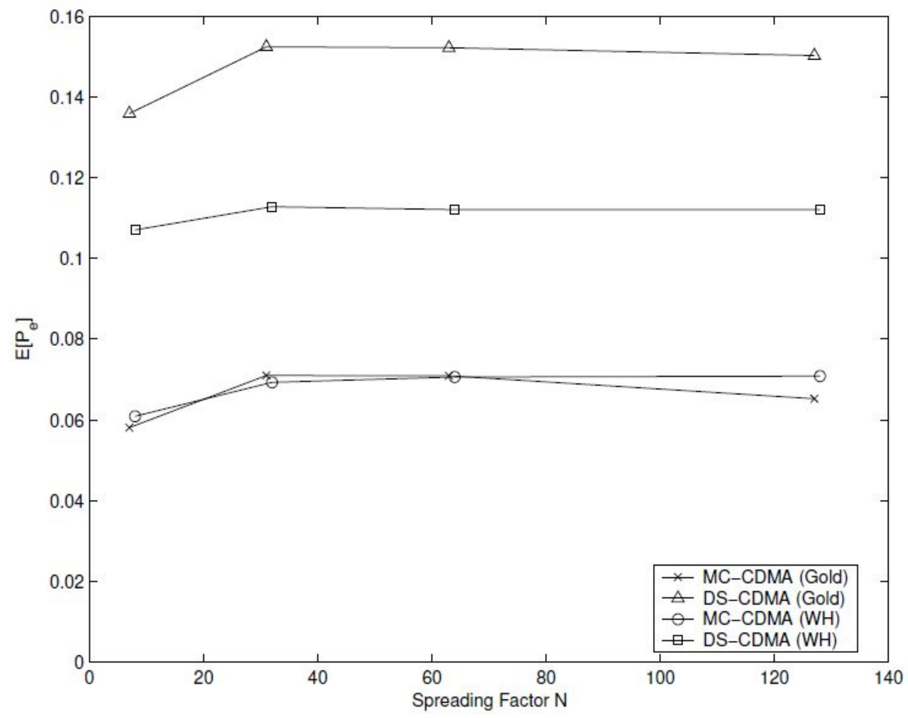
One way vs Two way ranging

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

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**		

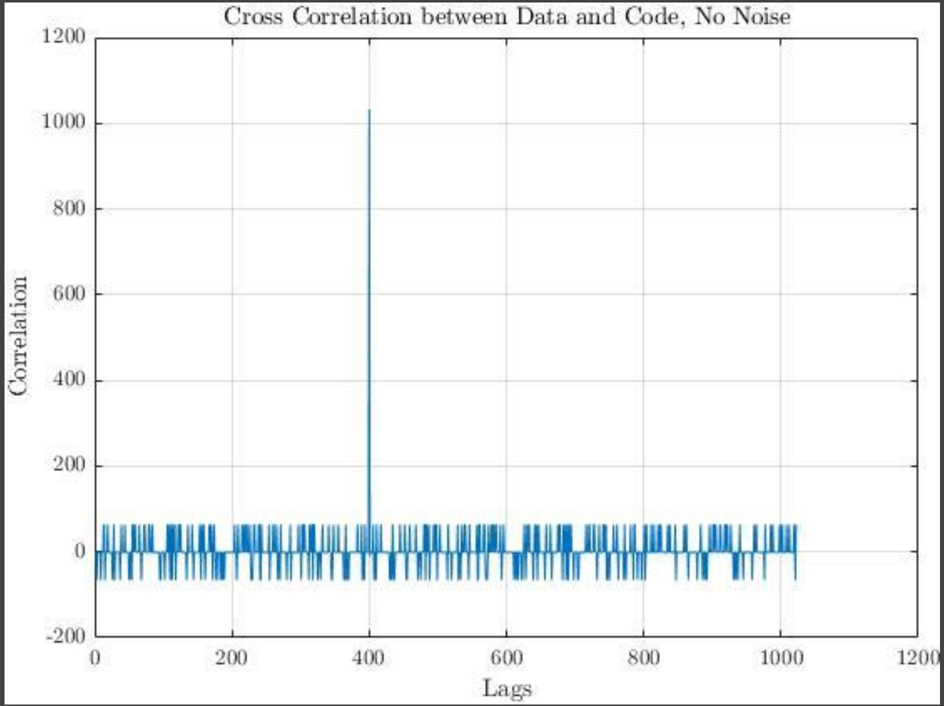
Satellite Link Budget 1

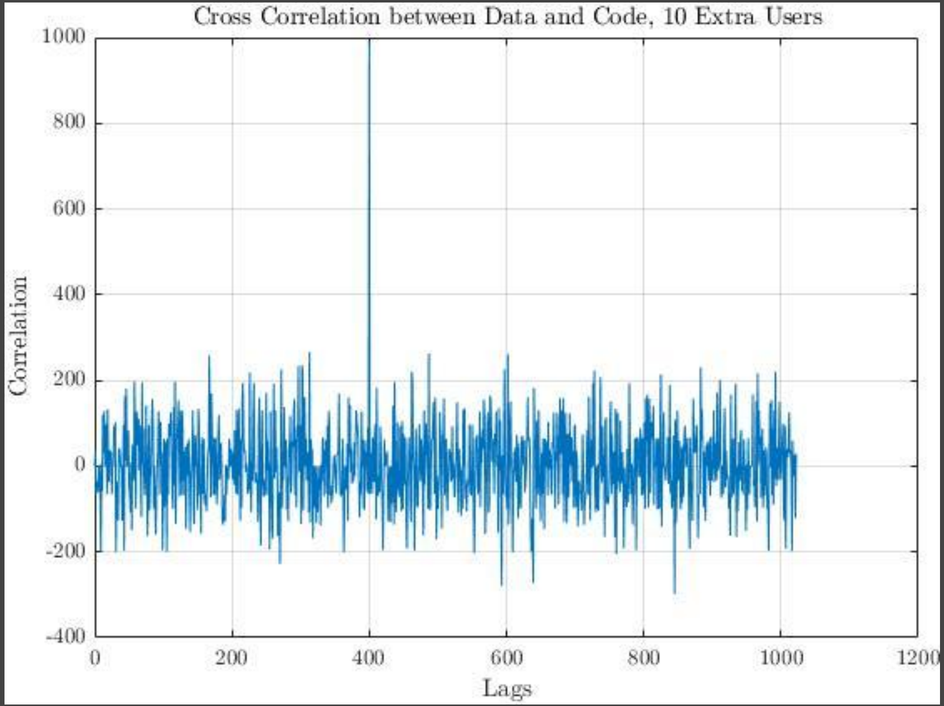
PARAMETER	UPLINK (Receiver to Satellite)	DOWNLINK (Satellite to Receiver)	UNITS	Symbol	Reference
Speed of Light	*3.0E+08*	*3.0E+08*	*m/s*	*C=λ*f*	*constant*
Frequency	*2.5*	*2.5*	*GHz*	*f*	*Input: system choice, X-band mil.com.sat.*
Wavelength	0.120	0.120	m	l	
Range	*10000*	*10000*	*km*	*R*	*Input: Geostationary 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

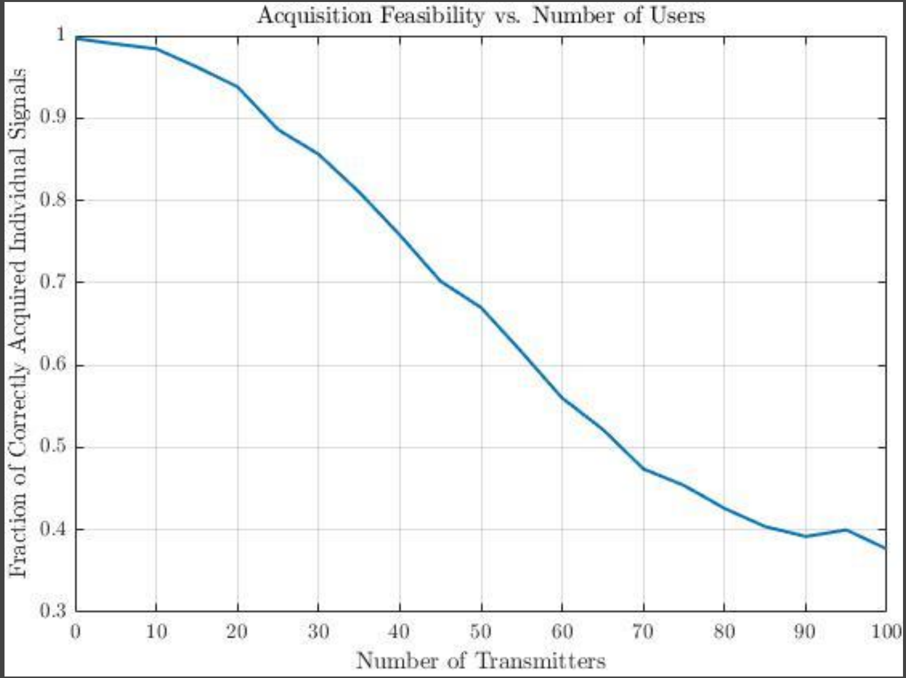
Transmitter Parameters:	Uplink	Downlink	Units	Symbol	Reference
Transmit Antenna Diameter	NA	NA	m	D	Switch Receive
Transmit Antenna Area	NA	NA	m^2	A	Switch Receive
Transmit Antenna Efficiency	NA	NA	[-]	h	Switch Receive
Transmit Antenna Effective Area	0.002	NA	m2	Ae	Switch Receive
Transmit Antenna Gain	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





Multiple Access Interference



Antenna

Antenna Design Requirements

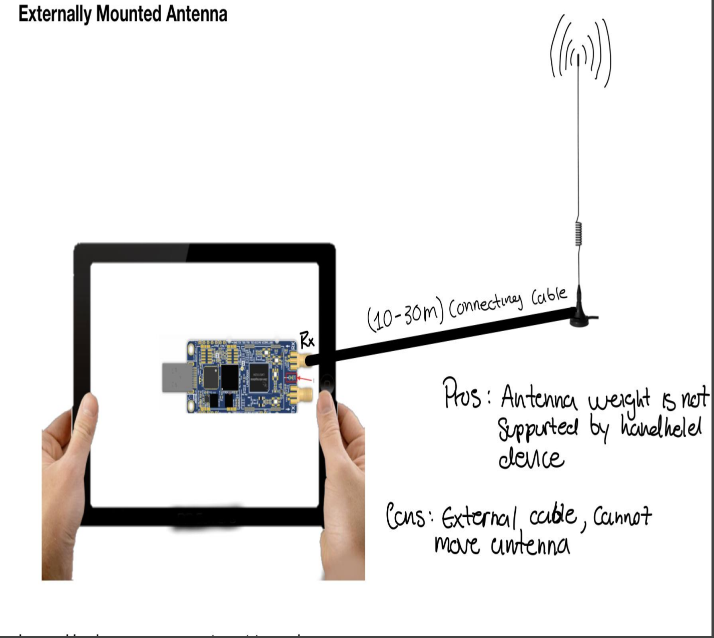
FR4: The system will transmit data on the S-Band frequency.

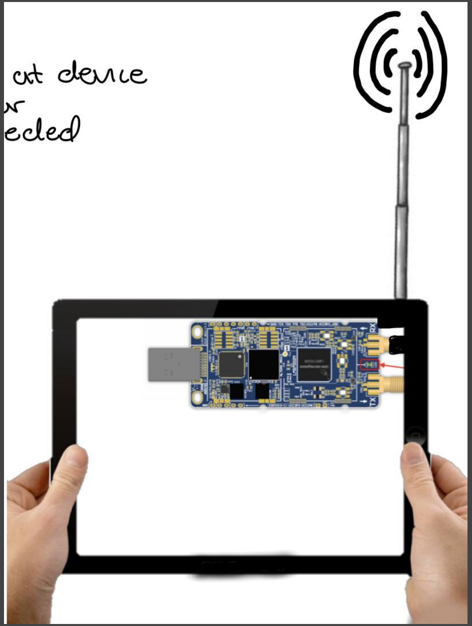
- DR 2.4.1 : Demonstrate uplink transmission at a frequency range between 2.4-2.48 GHz

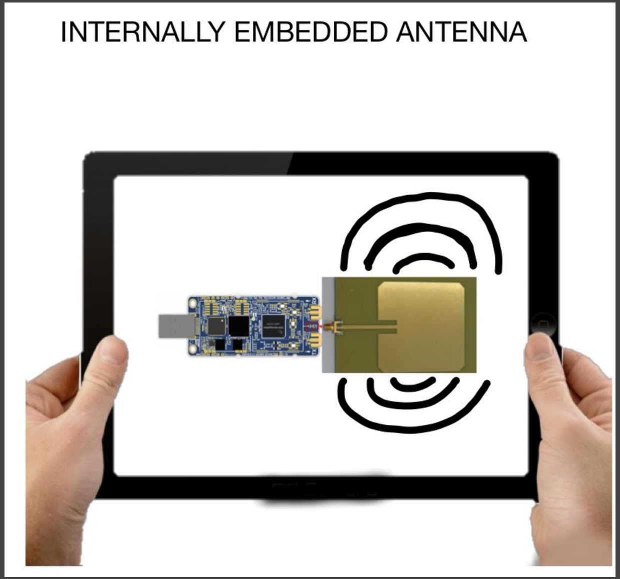
FR5: The system will receive data on the S-Band frequency.

- 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


ct device
ected


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%