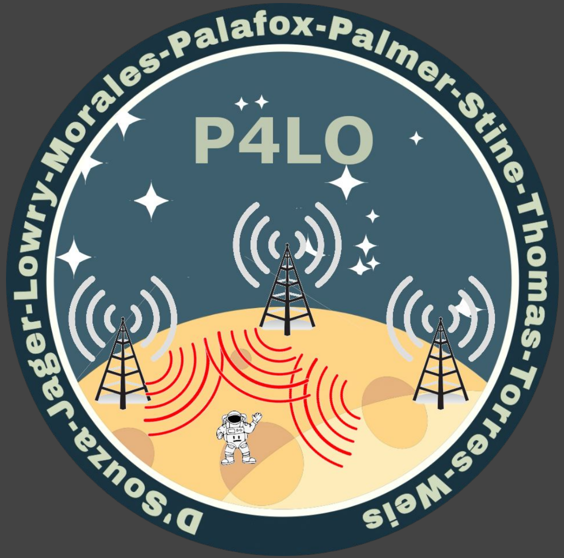
Preliminary Design Review

P4LO



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

Team Advisor: Dr. Jade Morton

Project Overview

Project Motivation

Mission Statement

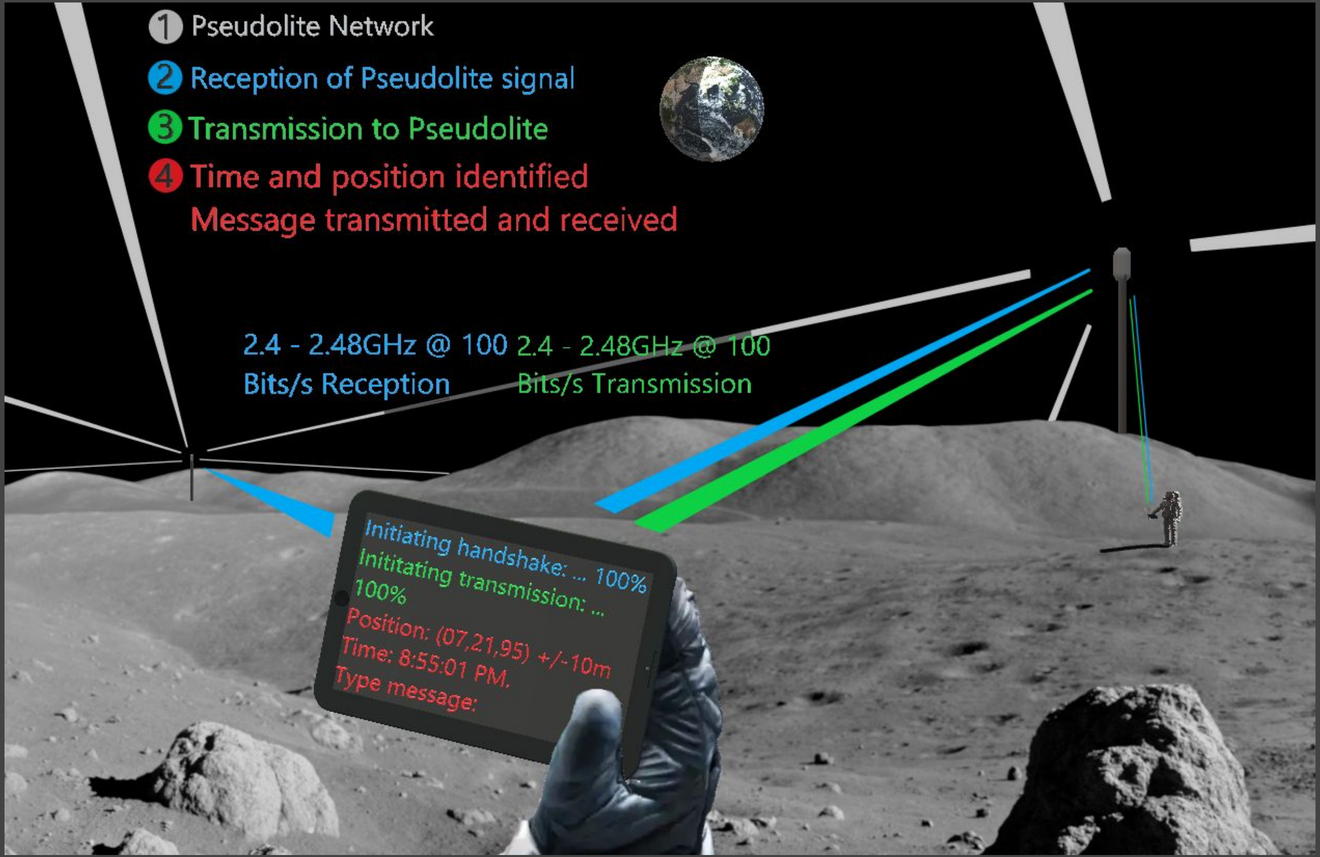
P4LO (**P**ositioning **For** **L**unar **O**perations) is a prototype network of software defined radios that demonstrates an architecture for the lunar communication and positioning system LunaNet.

Project Description

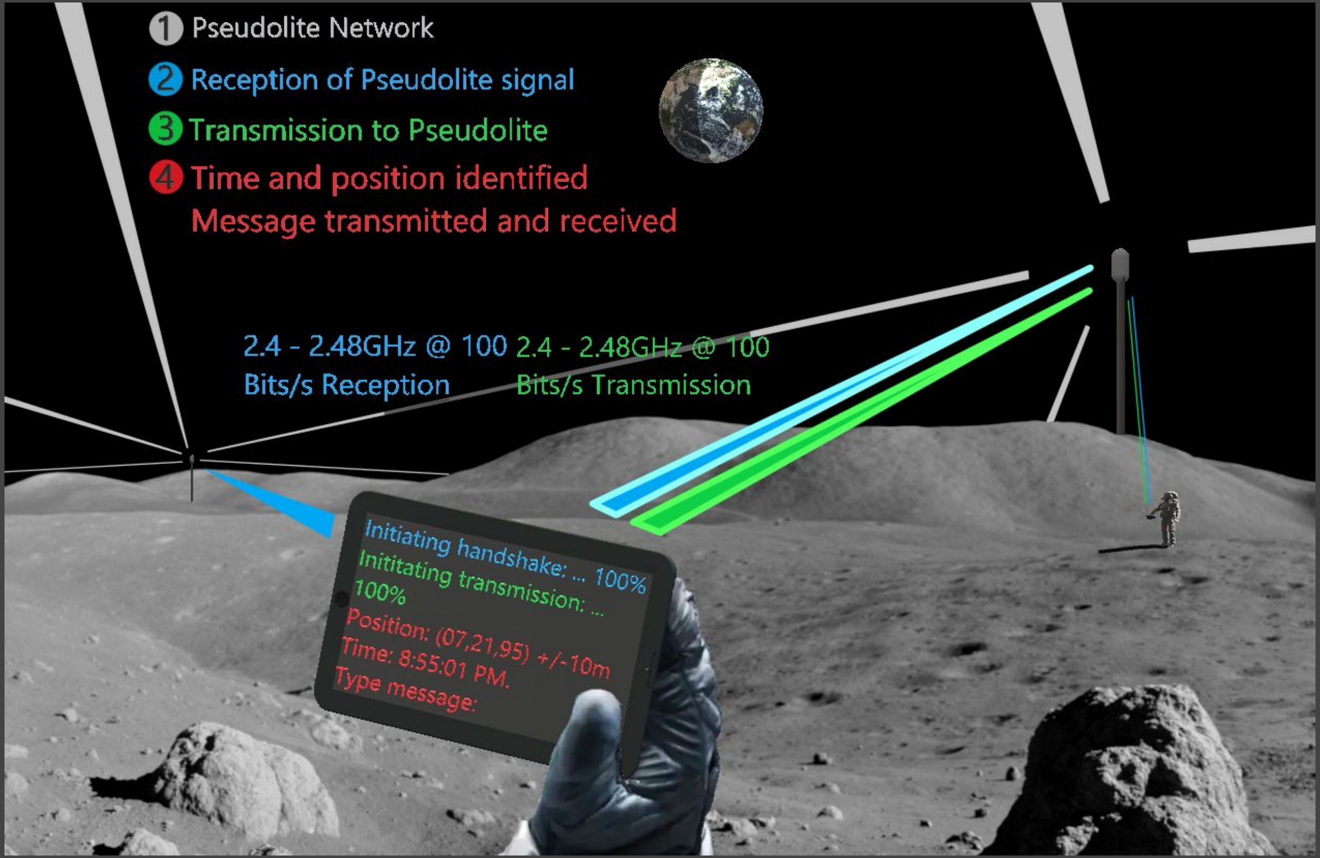
Develop a prototype to demonstrate positioning, timing, and communication systems feasible for use on the surface of the Moon

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

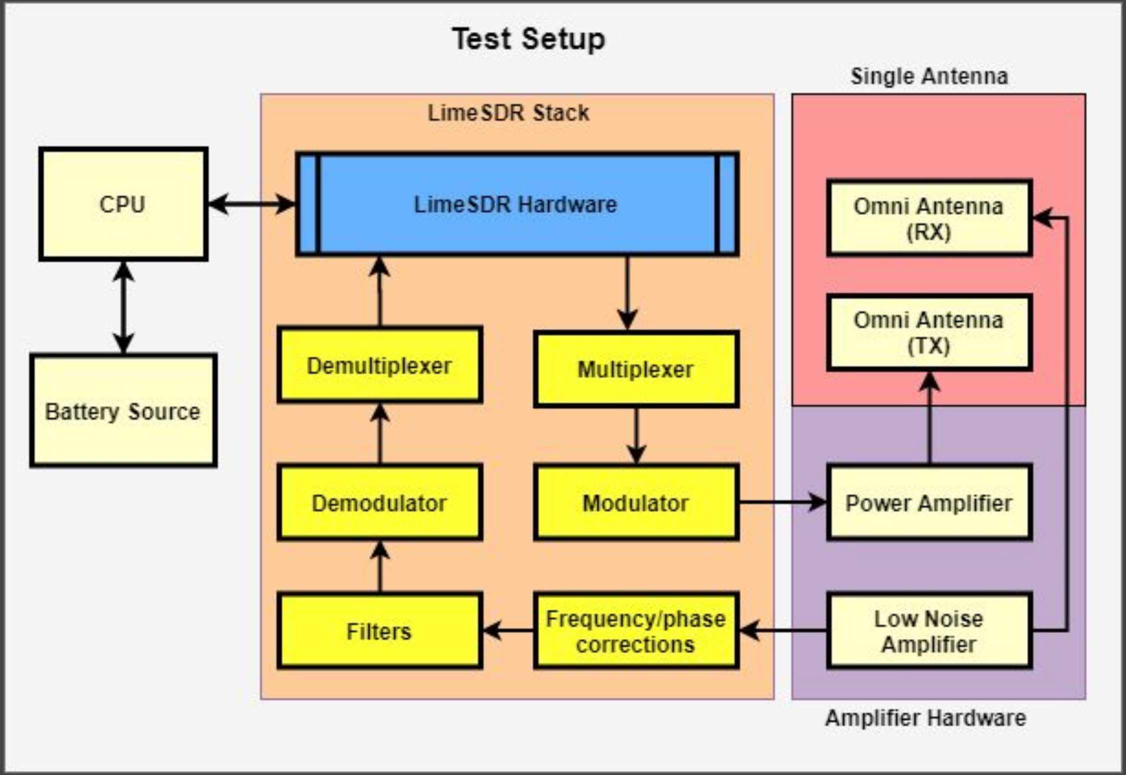
Concept Of Operations (CONOPS)



Concept Of Operations (CONOPS)



Functional Block Diagram



System Objectives

Functional Requirements

- **FR 1:** System must operate under a scalable Lunar Positioning Model
- **FR 2:** System will provide two-way SMS-like texting capabilities
- **FR 3:** System will provide architecture for navigation solutions to within 10 meter positioning accuracy, and 30 nanosecond 1-σ transfer time
- **FR 4:** System will transmit and receive data at 2.4 - 2.48 GHz
- **FR 5:** System framework must be extendable to 170 users communicating simultaneously
- **FR 6:** Systems communication link must have a channel bandwidth of no more than 1 MHz

Baseline Design

Critical Design Elements

Pseudolite Architecture

Communications Link

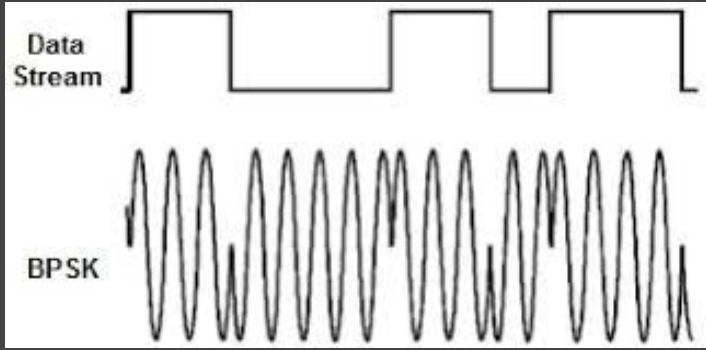
Antenna Type

LimeSDR

Pseudolite Architecture

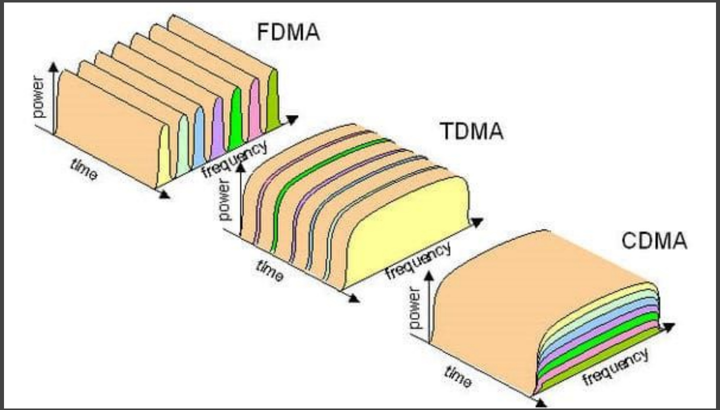
Link Baseline Design: Modulation

- Design Choice: Phase Shift Keying (PSK)
- 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

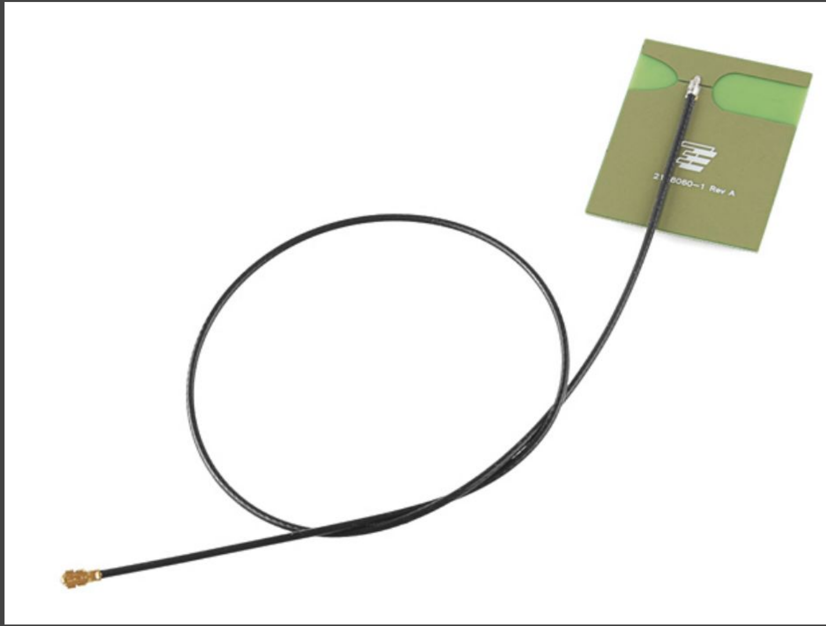


Link Baseline Design: Multiplexing

- 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



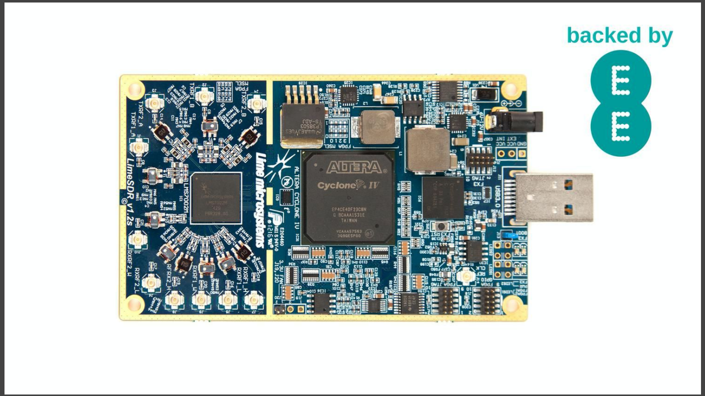
Antenna Type



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 (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

Evidence of Feasibility

Critical Project Elements

Positioning System

Communications

Antenna

SDR

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
- **DR 2.3.3** : Architecture must provide a Dilution of Precision (DOP) value below 5

Positioning System - Architecture

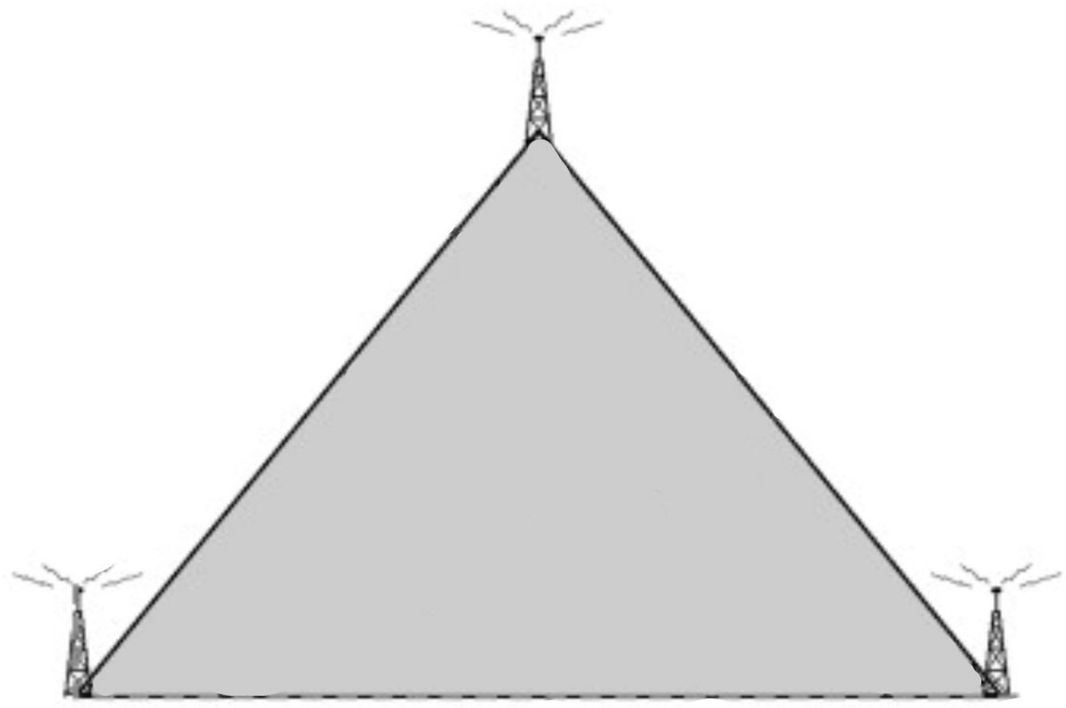
Possible Solutions

- Trilateration & Time of Arrival (TOA)
- Hyperbolic Positioning & Time Difference of Arrival (TDOA)
- Angle of Arrival (AOA)
- Received Signal Strength (RSS)
- Hybrid Method

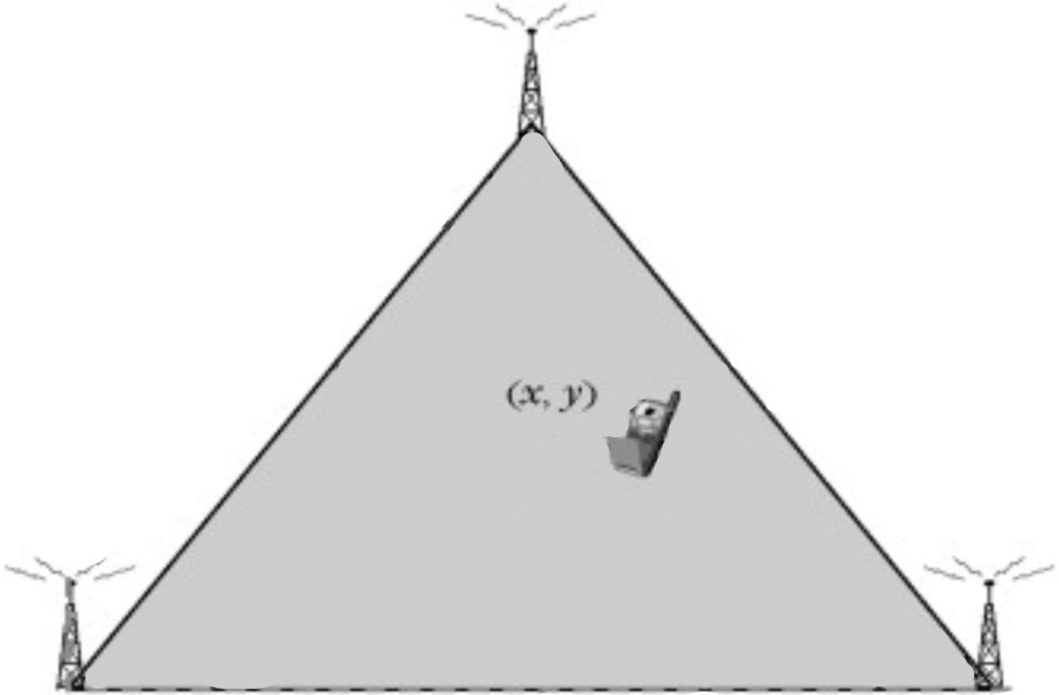
DR 2.3.2

FEASIBLE

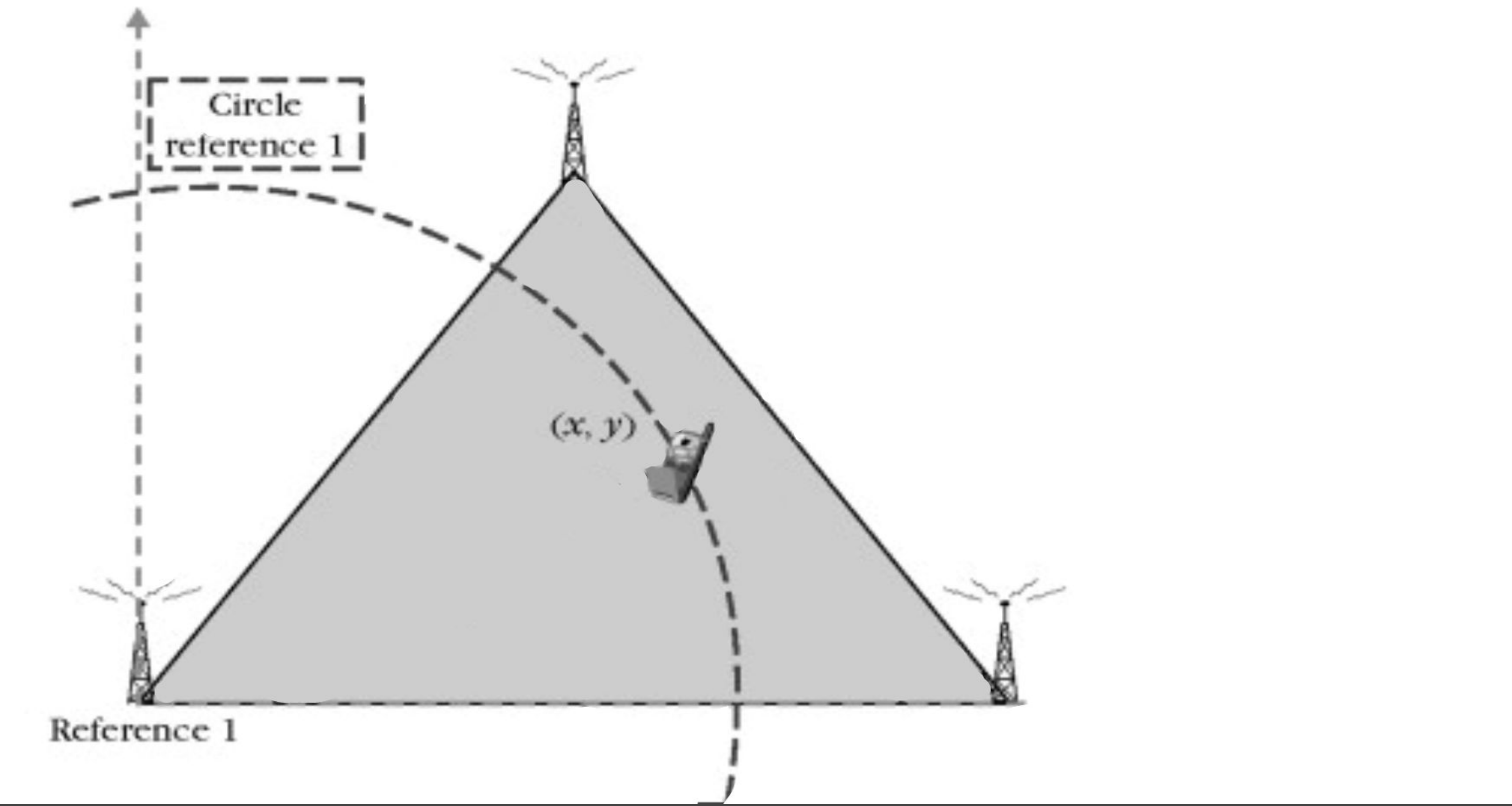
Positioning System - Architecture



Positioning System - Architecture



Positioning System - Architecture



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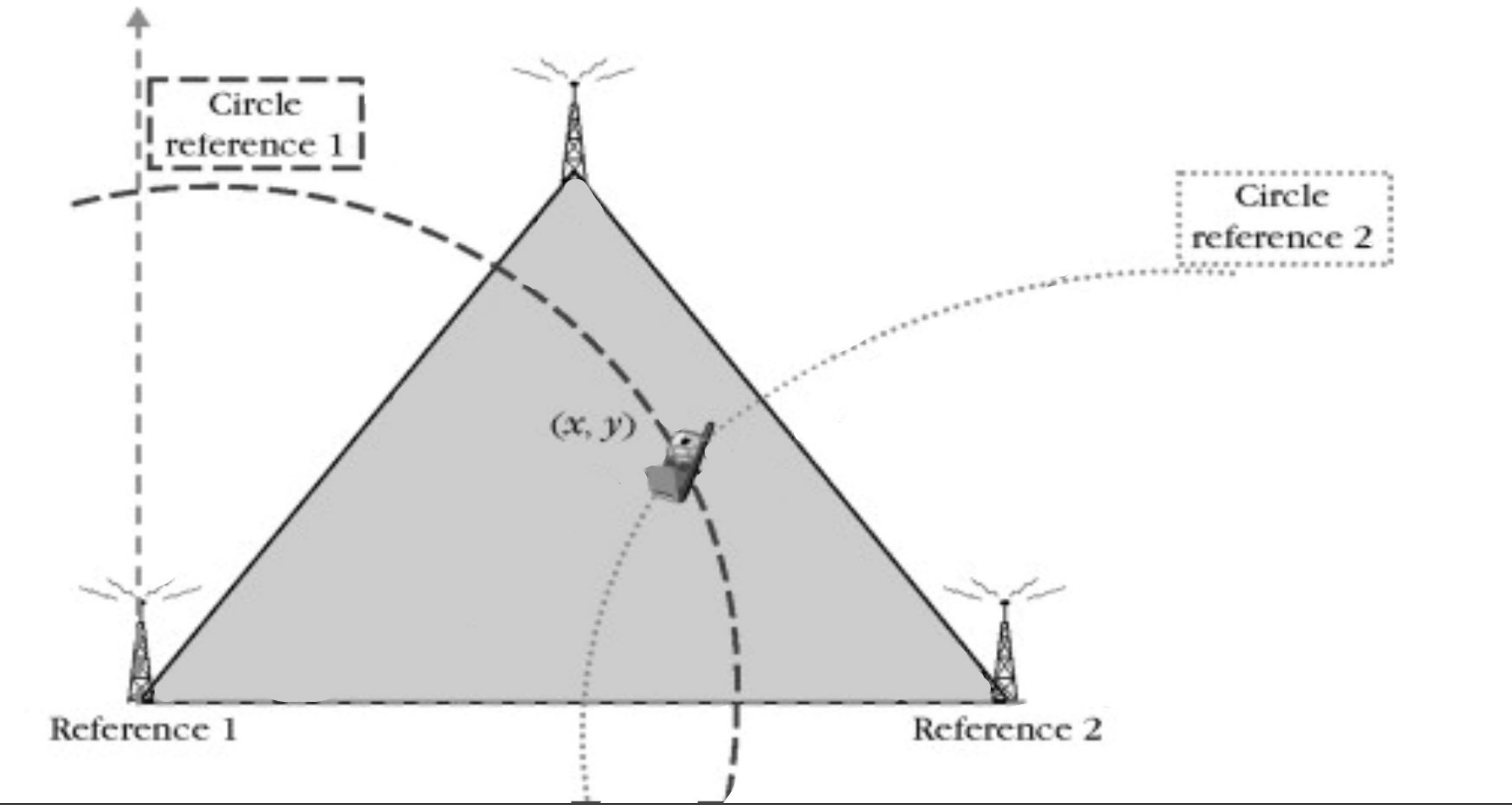

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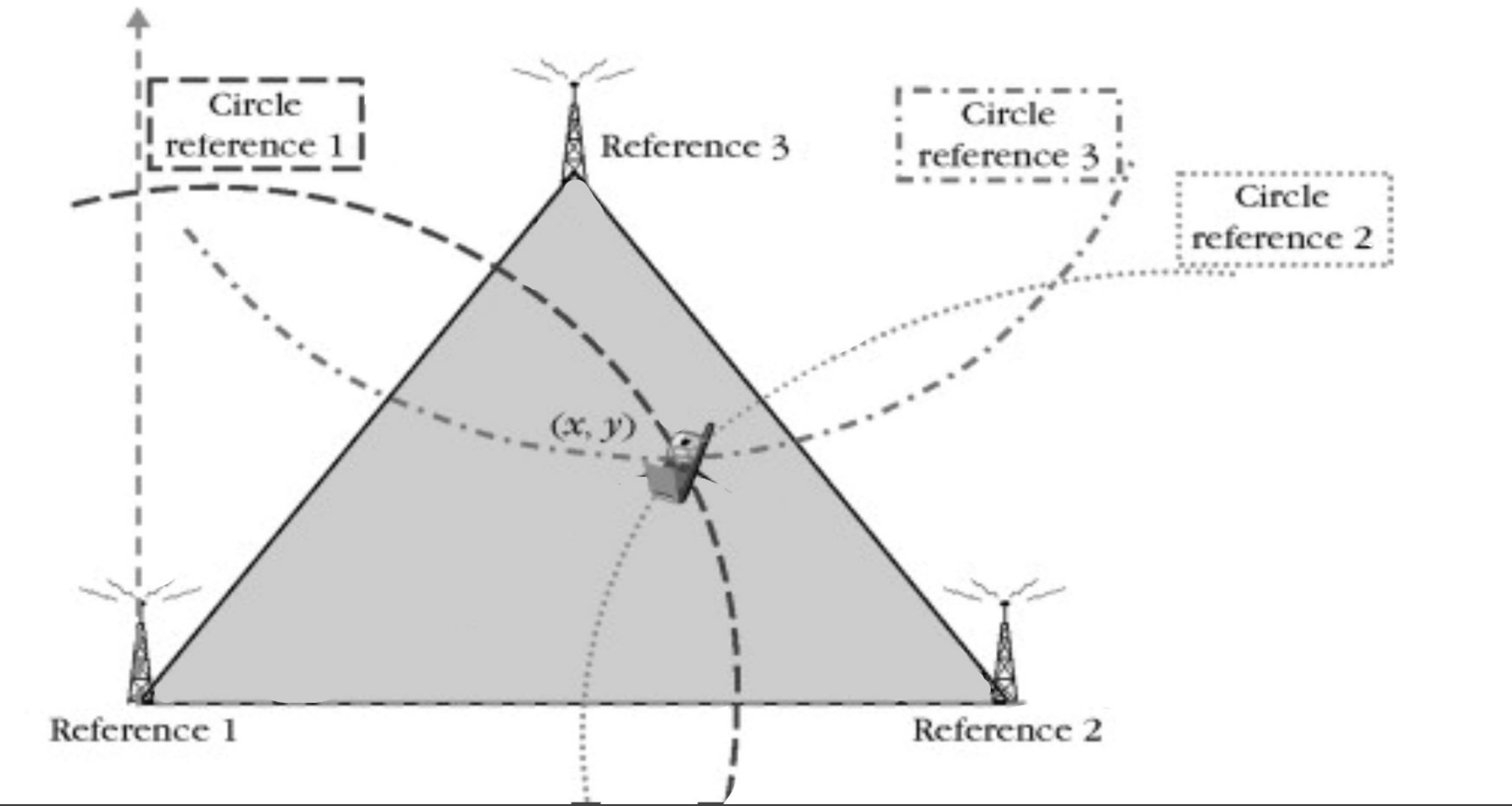

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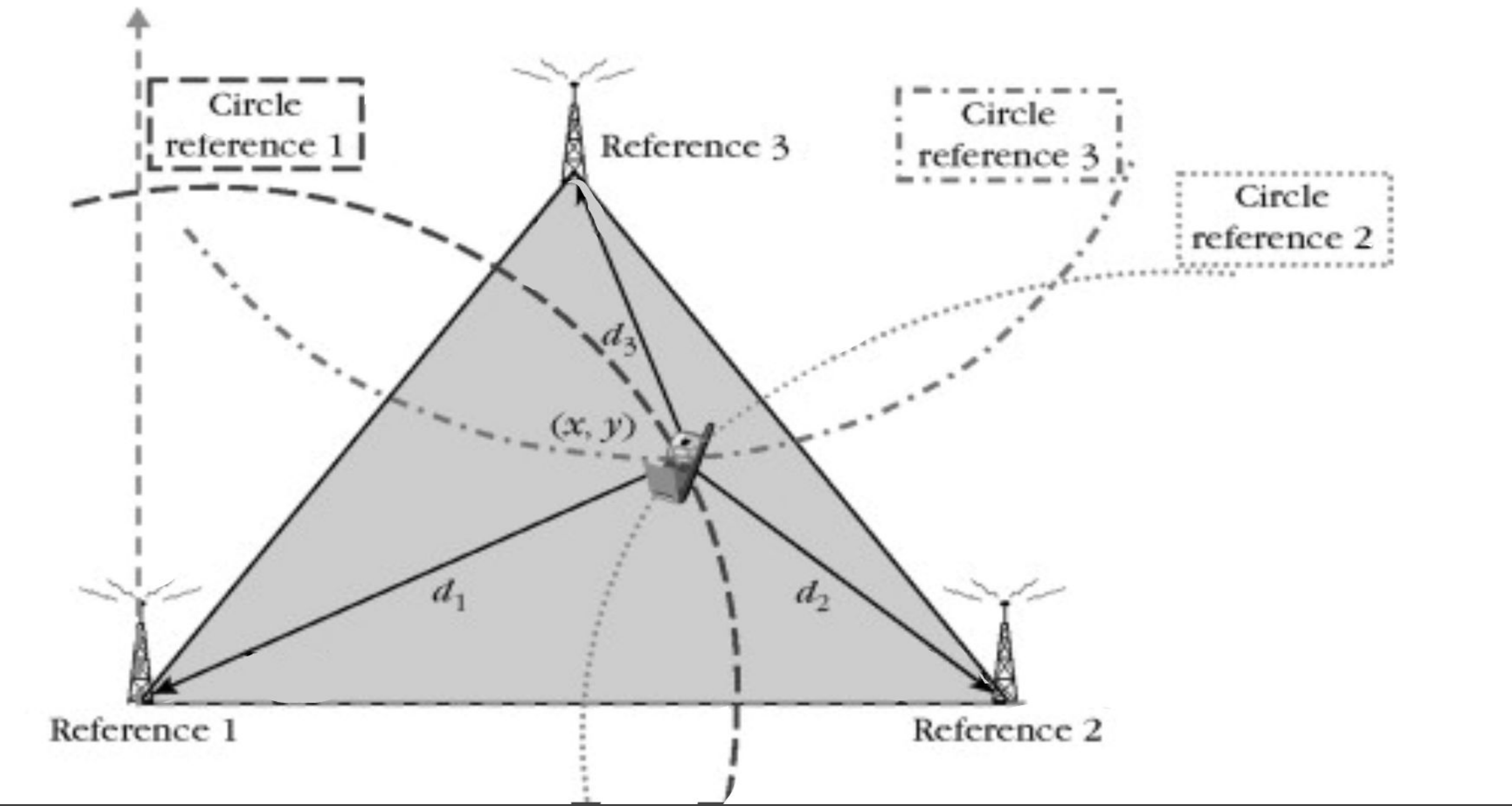
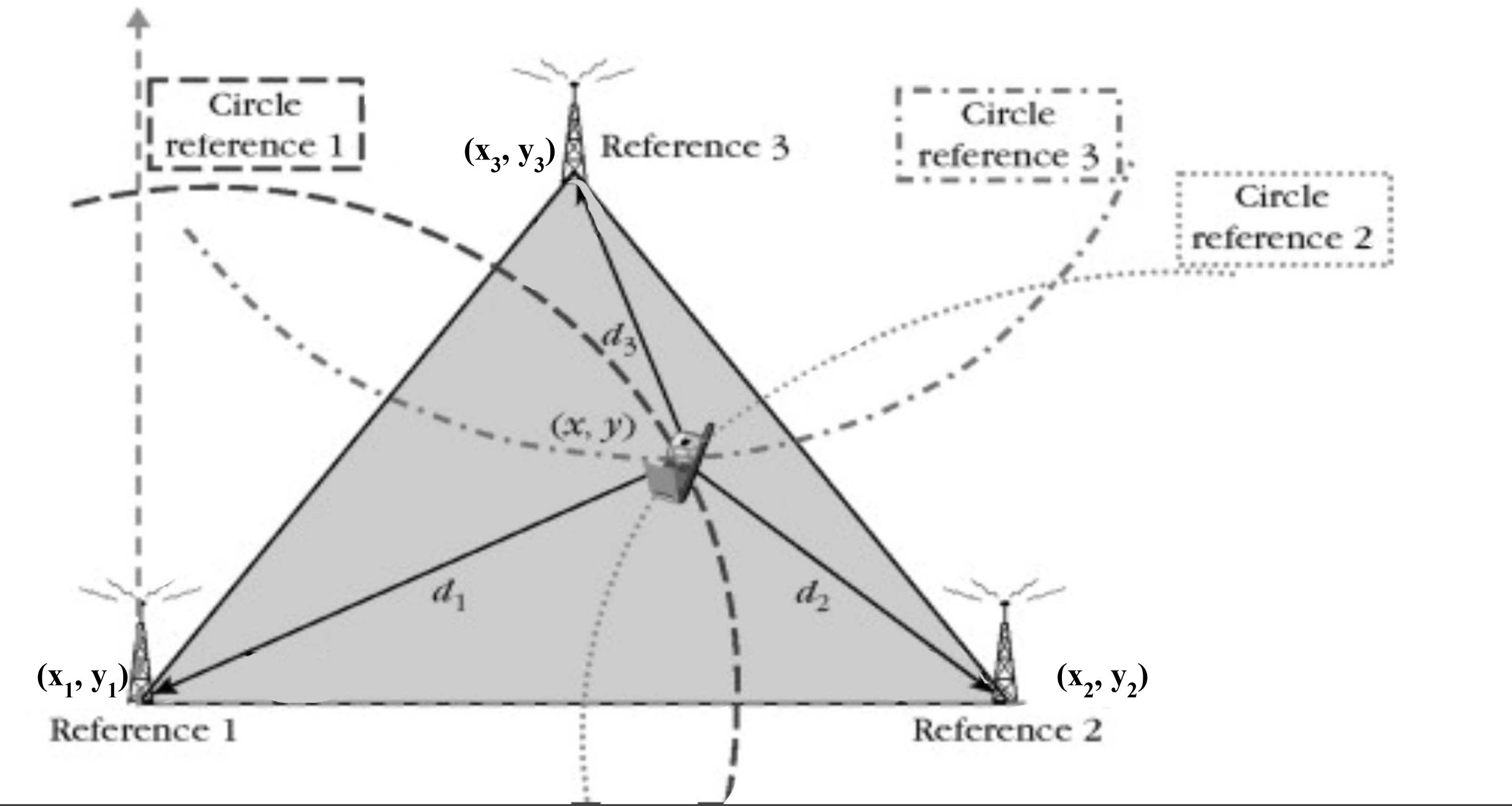
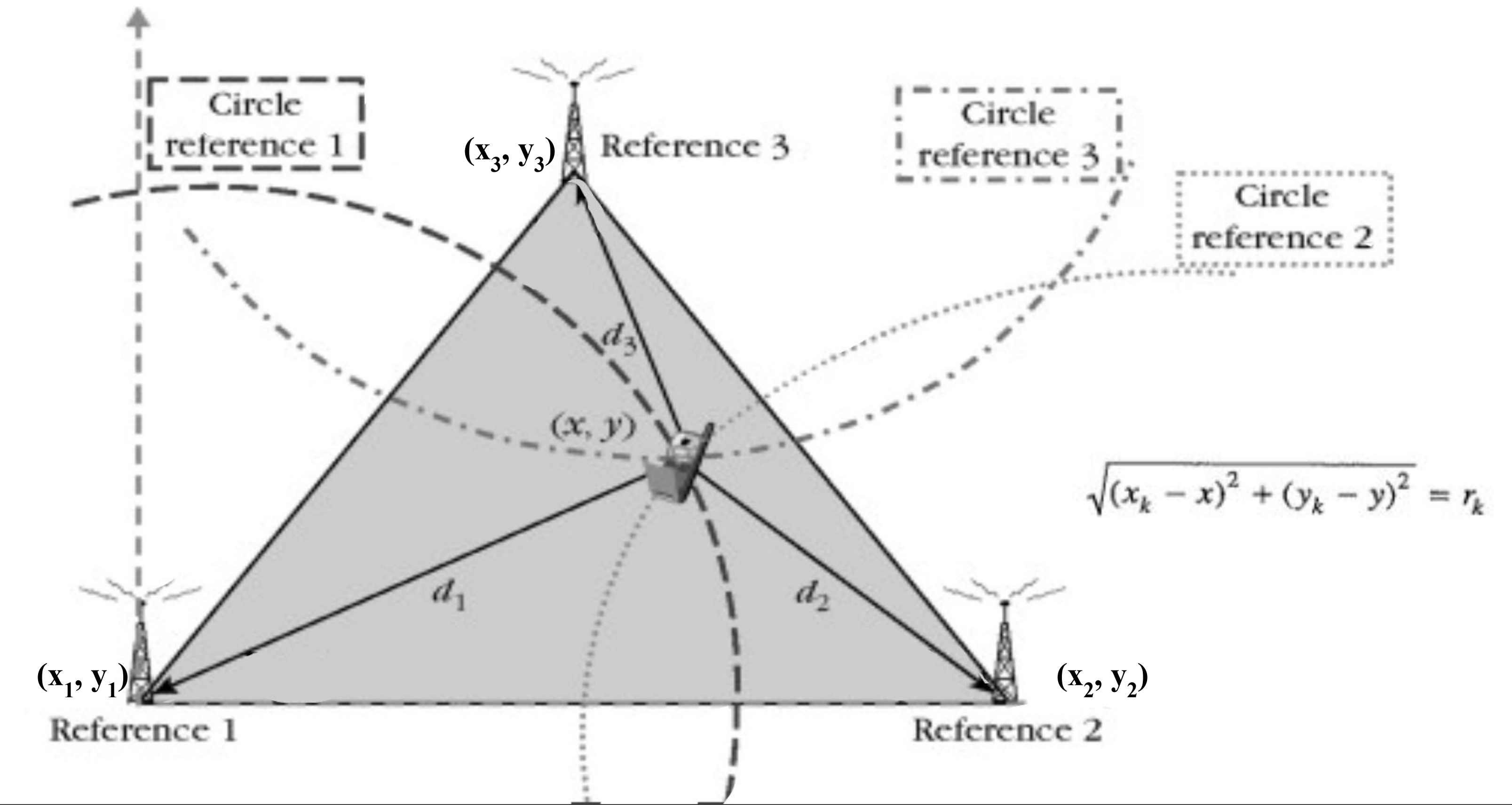


Positioning System - Architecture



Positioning System - Architecture



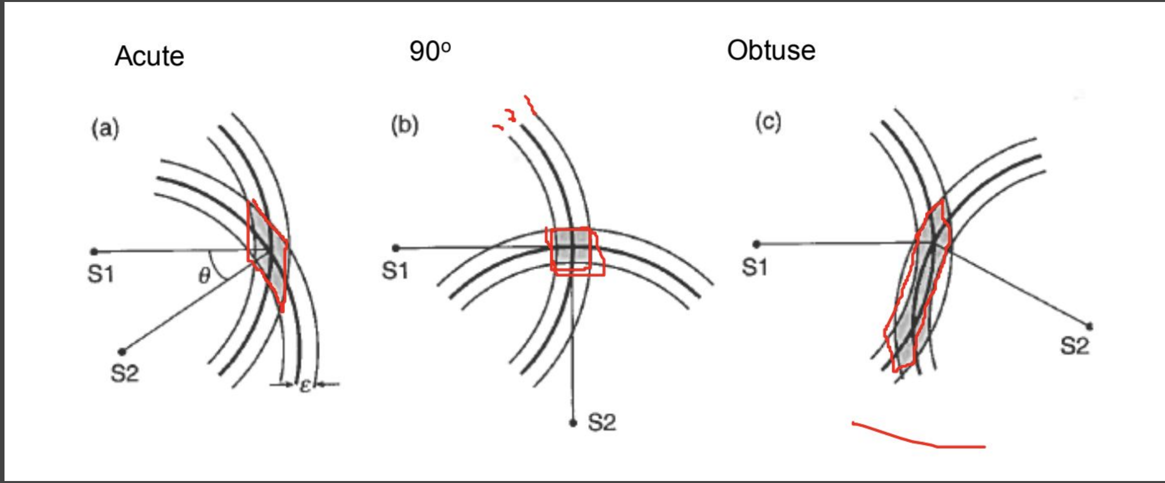
Positioning System - Error Sources

- Pseudolite locations (we'll assume we know these well)
- Multipath
  - Signal reflections off of features in the environment (rocks, solar panels, mountains, habitats, etc...)
- Receiver and Transmitter clock errors
  - One-way vs. two-way ranging
- Geometry of pseudolite configuration
  - HDOP

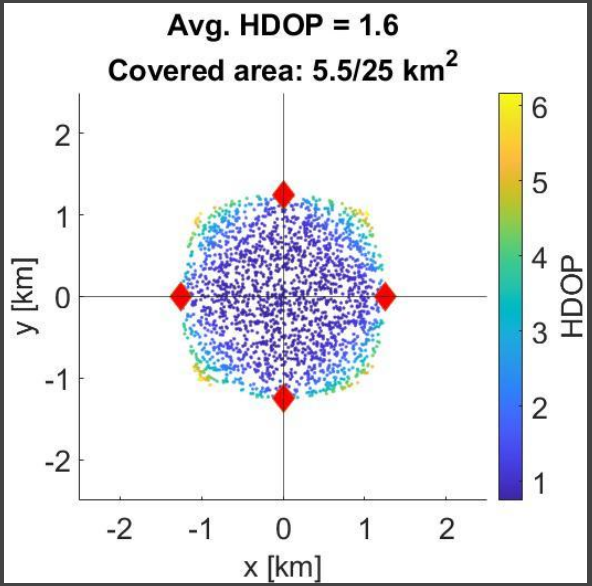
Positioning System - HDOP

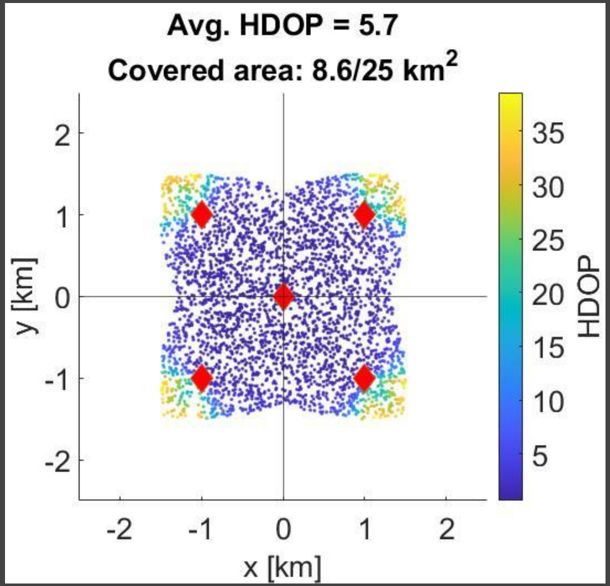
Horizontal **D**ilution **O**f **P**recision

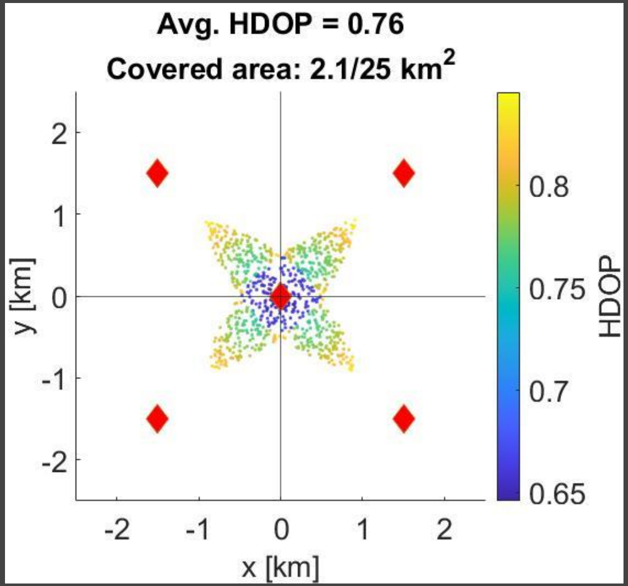
Definition: “Used to specify error propagation as a mathematical effect of navigation pseudolite geometry on positional measurement precision”.



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

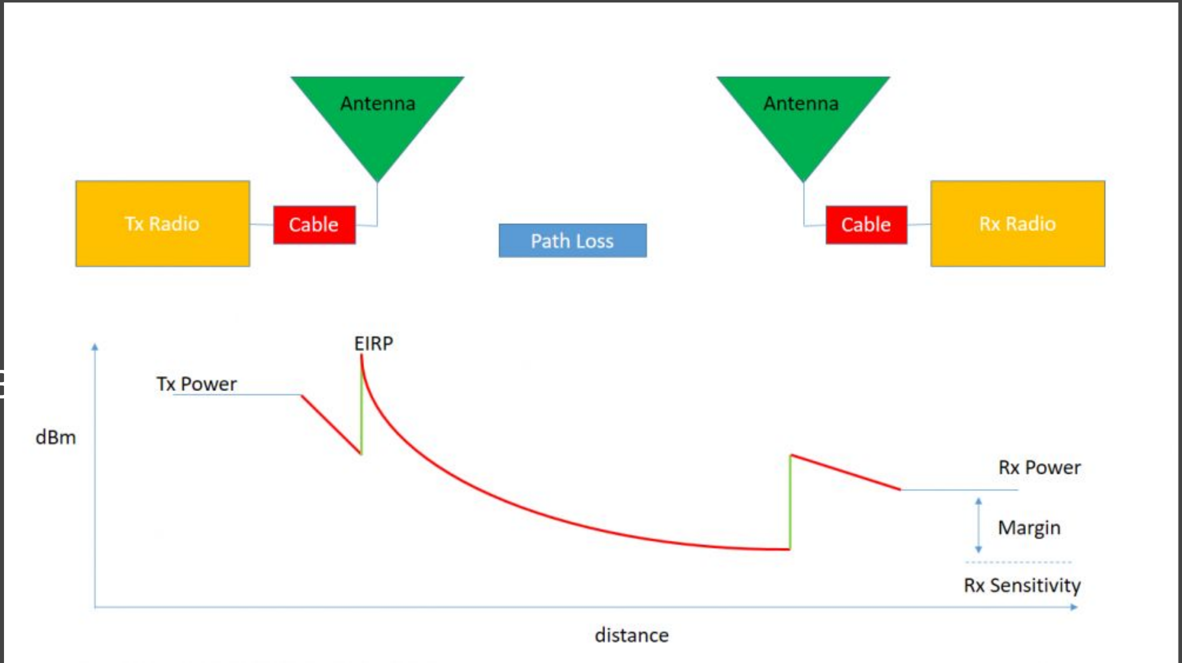
Communications - Link Budget

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

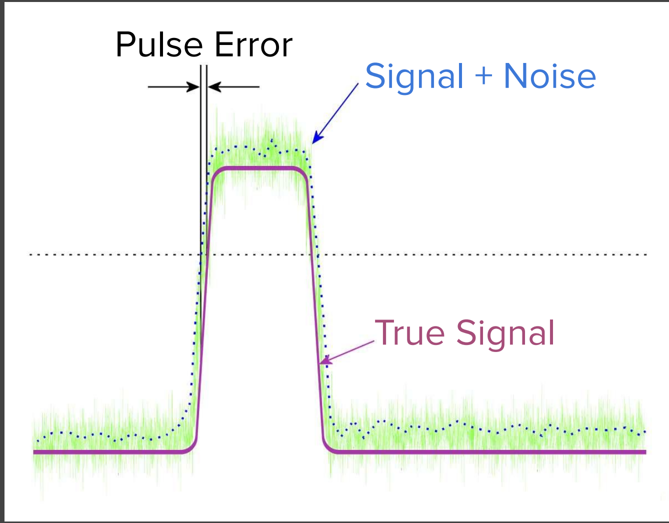


Minimum Ranging SNR

- 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

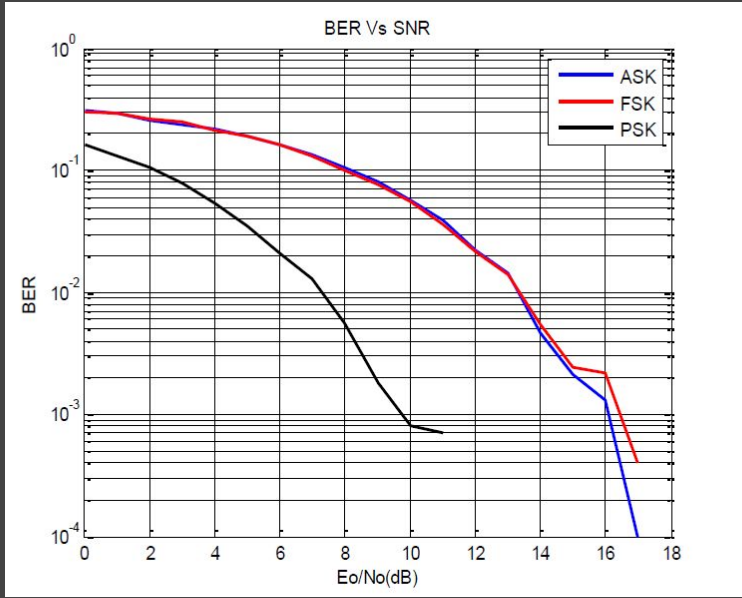


DR 3.1, FR7

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

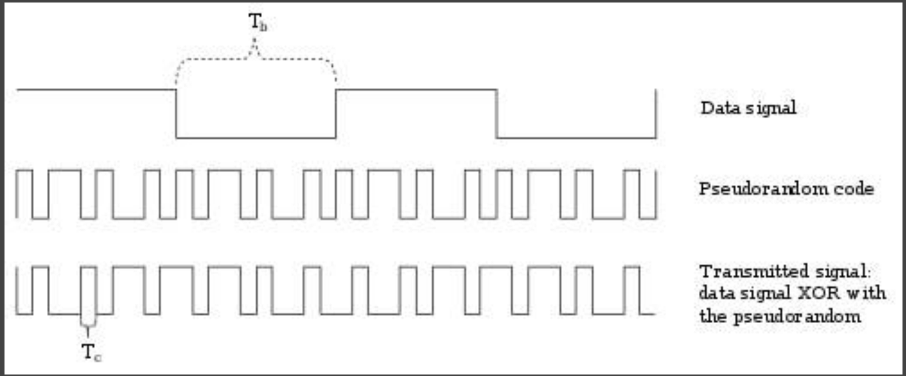


DR 2.1, 2.2, 3.1, FR4, 5, 7
SDR Compatibility

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.

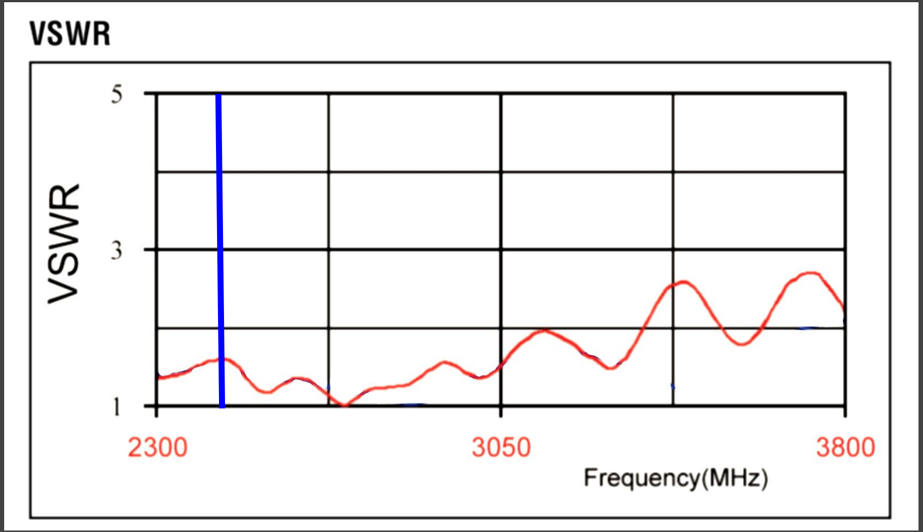
- DR 2.5.1 : Demonstrate downlink reception at a frequency range between 2.4-2.48 GHz

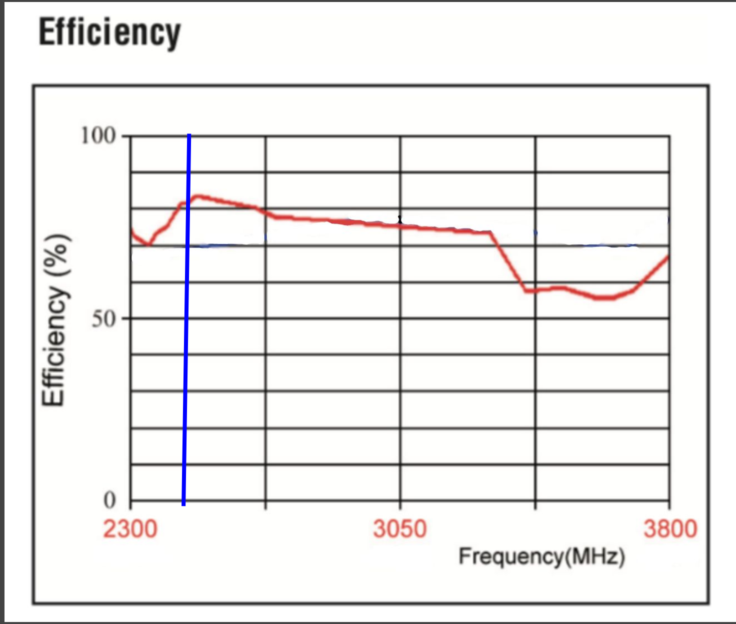
Antenna - Selection Analysis

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

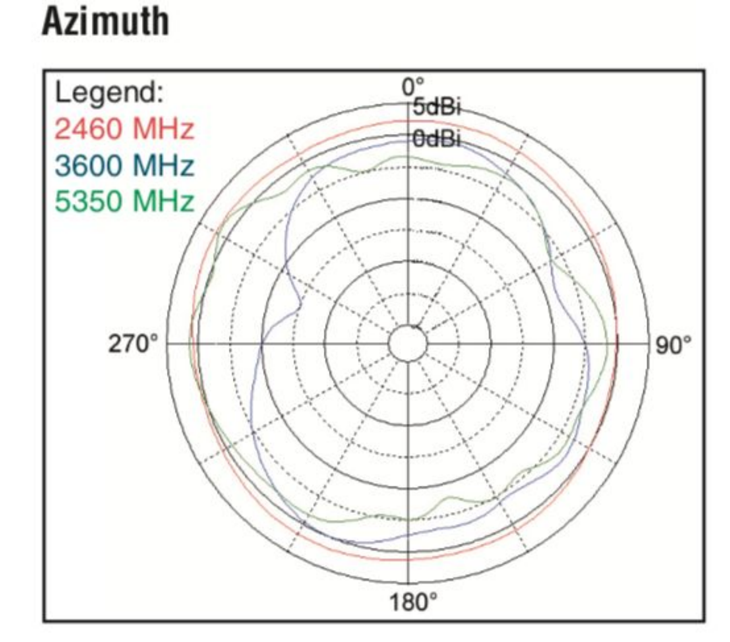


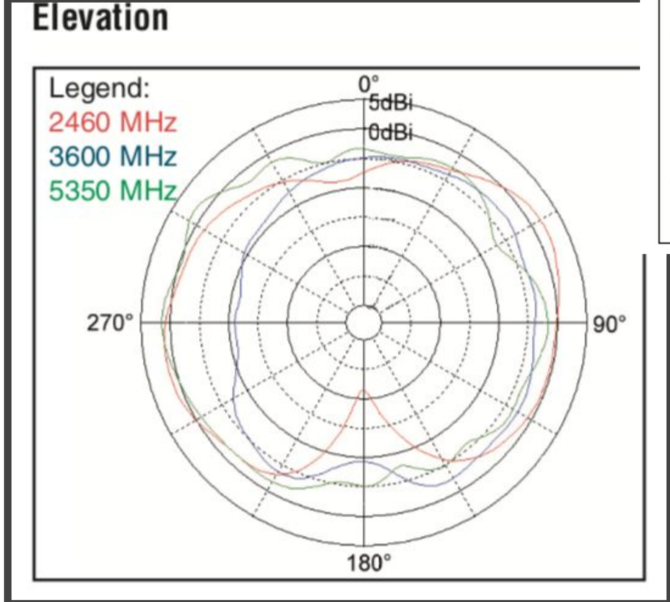


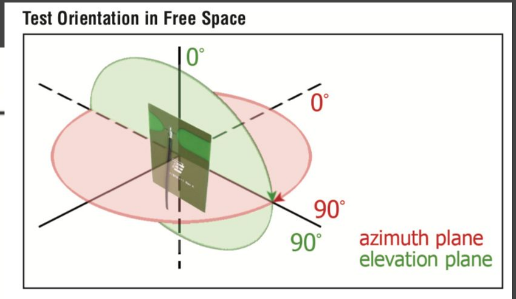
DR 2.4.1, 2.5.1

FEASIBLE

Antenna - Evidence of Feasibility



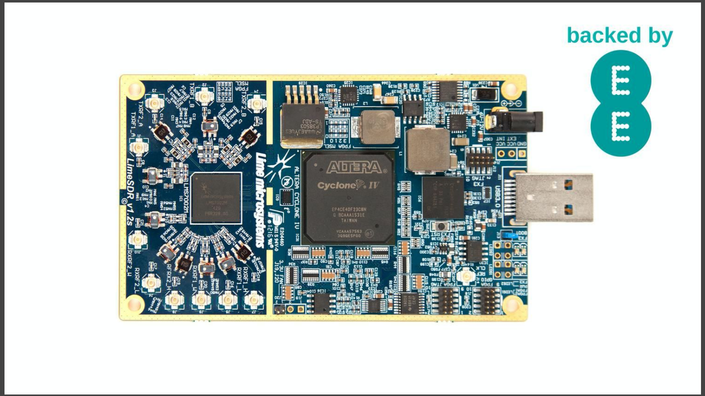




SDR - Requirements

- 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

SDR - Evidence of Feasibility on Hardware Side



- Cyclone IV Altera FPGA: Allows for iterative development and testing
- 4 Tx Channels (Transmission)
- 6 Rx Channels (Reception)
- 100kHz to 3.8GHz frequency range
- Works best with Linux based systems

Scalable LPS : FR 1	TX/RX at 2.49 GHz : FR 3
FEASIBLE	FEASIBLE

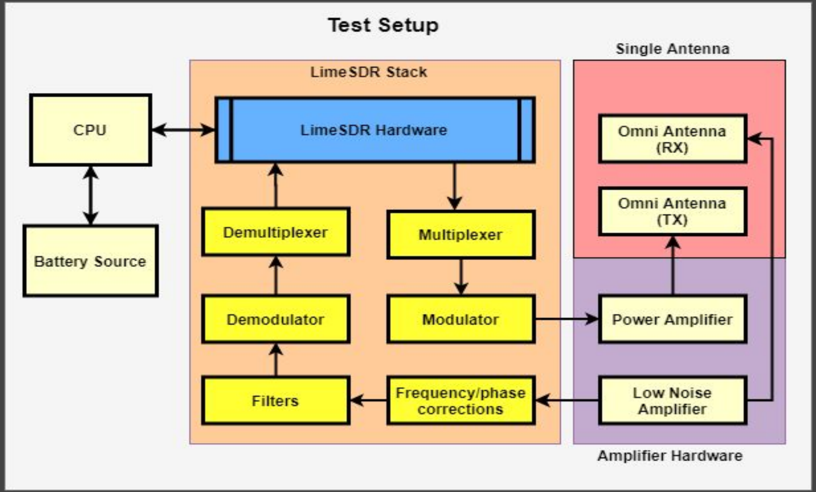
SDR - Evidence of Feasibility on Software Side

SMS-like TX/RX : FR 2

FEASIBLE

QPSK Modulation : FR 1

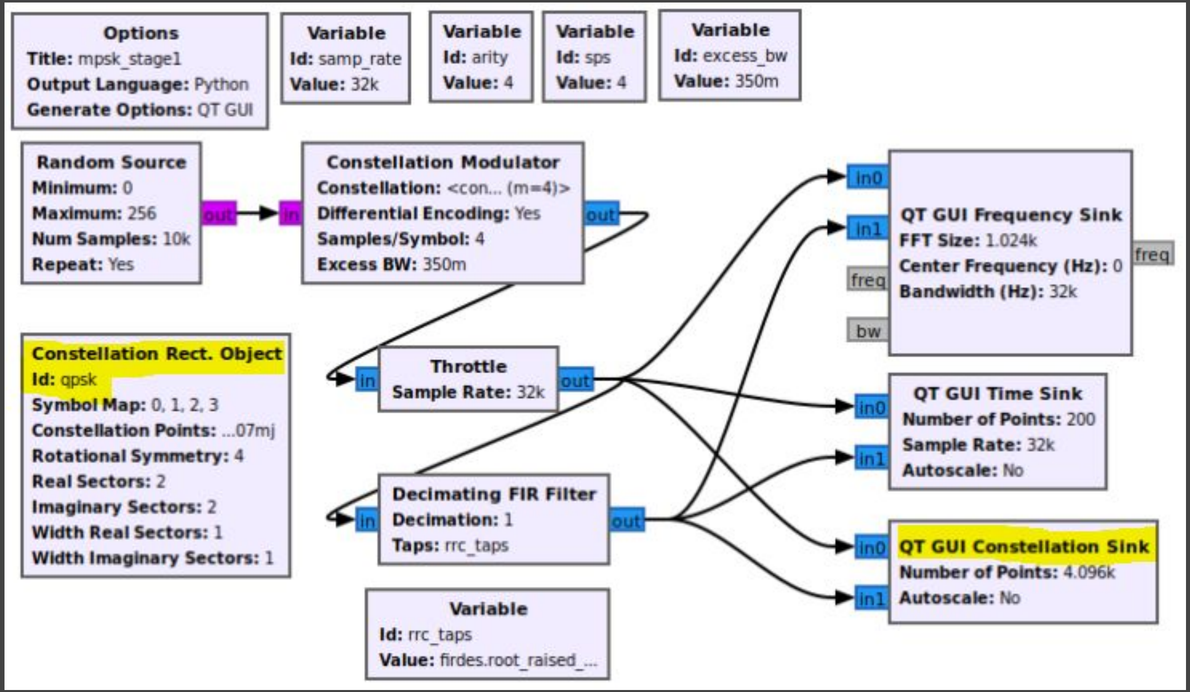
FEASIBLE



GNU Radio

- Transmission
  - QPSK Modulation
  - Multiplexer through gr-modtool
- Reception
  - Second order phase corrections using Costas Loop
  - QPSK Demodulation
  - Demultiplexer through gr-modtool

SDR - GNU Radio Flight Fidelity



GNU Radio can perform QPSK modulation and has a defined framework for implementation

This is an example of the flow graph framework for QPSK modulation through GNU Radio

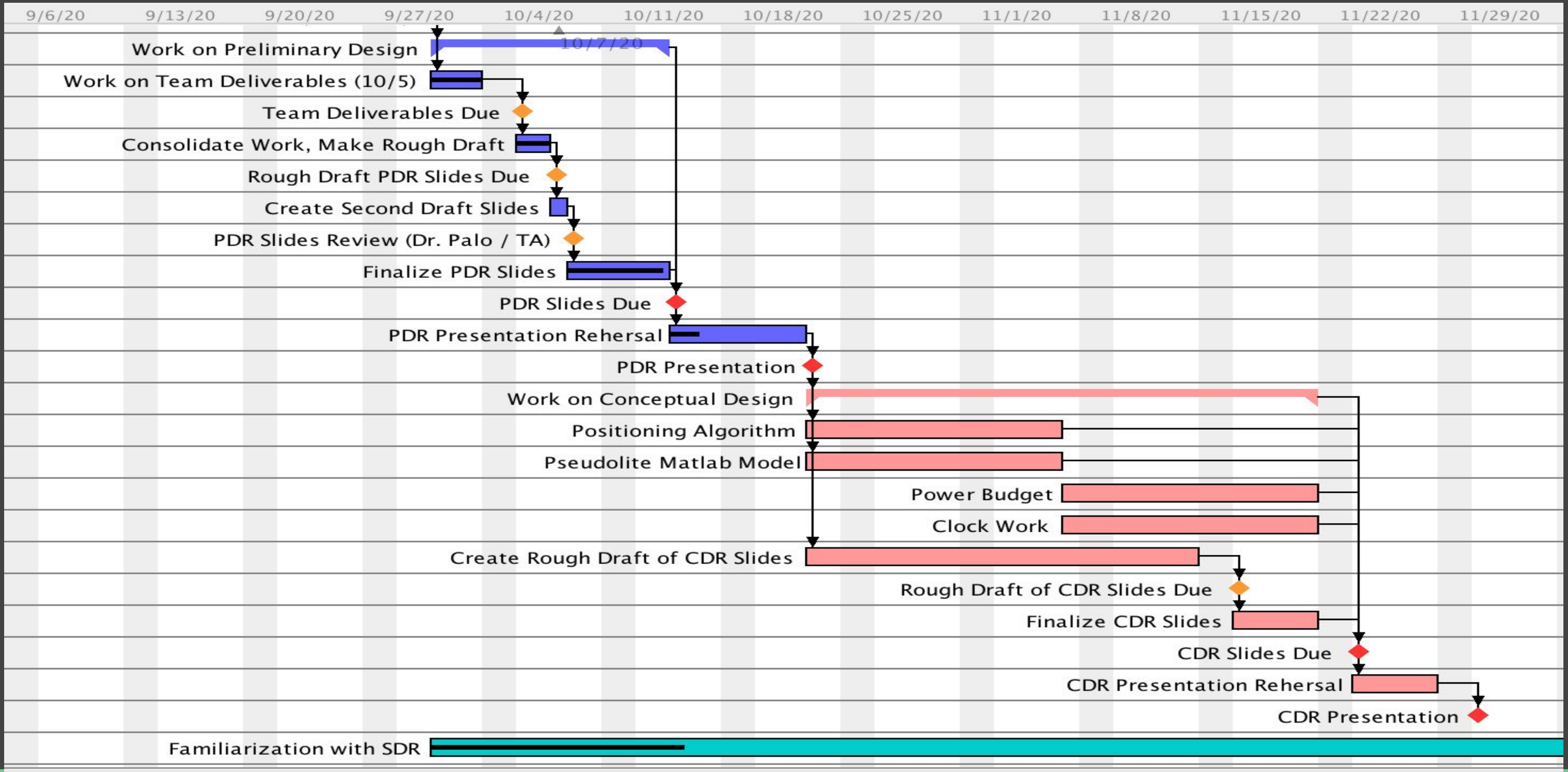
QPSK Modulation : FR 1

FEASIBLE

Software - Evidence of Feasibility

Design Requirement	How is it satisfied	Feasible?
2.1.3	GNU Radio supports LimeSDR	Feasible
2.2.1	Fulfills all elements of the LimeSDR stack through modulation/multiplexing/phase corrections	Feasible
2.4.1/2.5.1	LimeSDR and GNU radio support 100kHz-3.8GHz frequencies	Feasible

Schedule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10/25/20
11/1/20
11/8/20
11/15/20
11/22/20
11/29/20
10/7/20
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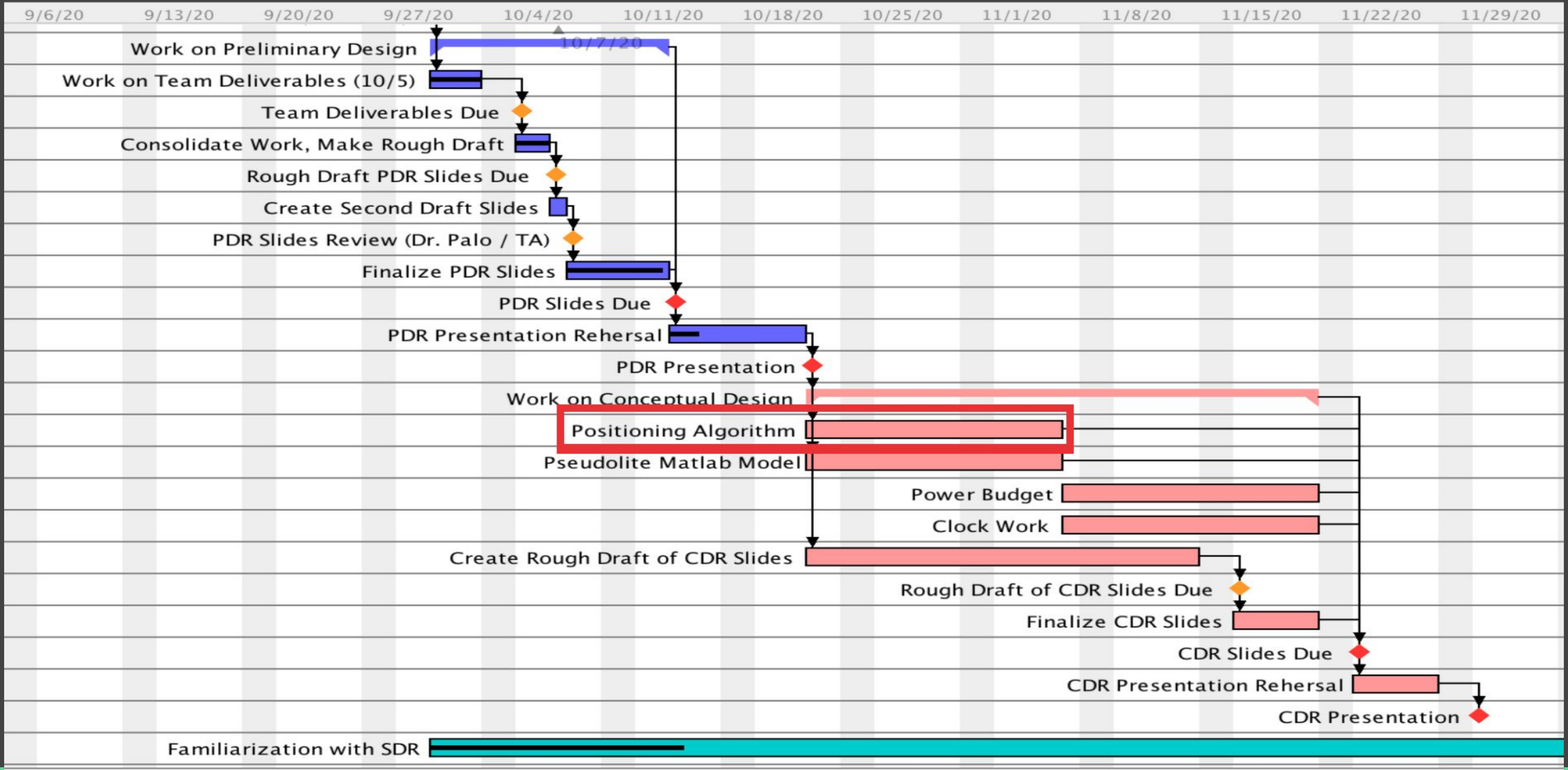
Work on Team Deliverables (10/5)
Team Deliverables Due
Consolidate Work, Make Rough Draft
Rough Draft PDR Slides Due
Create Second Draft Slides
PDR Slides Review (Dr. Palo / TA)
Finalize PDR Slides
PDR Slides Due
PDR Presentation Rehersal
PDR Presentation
Work on Conceptual Design
Positioning Algorithm
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
Familiarization with SDR

Project Overview | Baseline Design | Feasibility | Summary

Schedule



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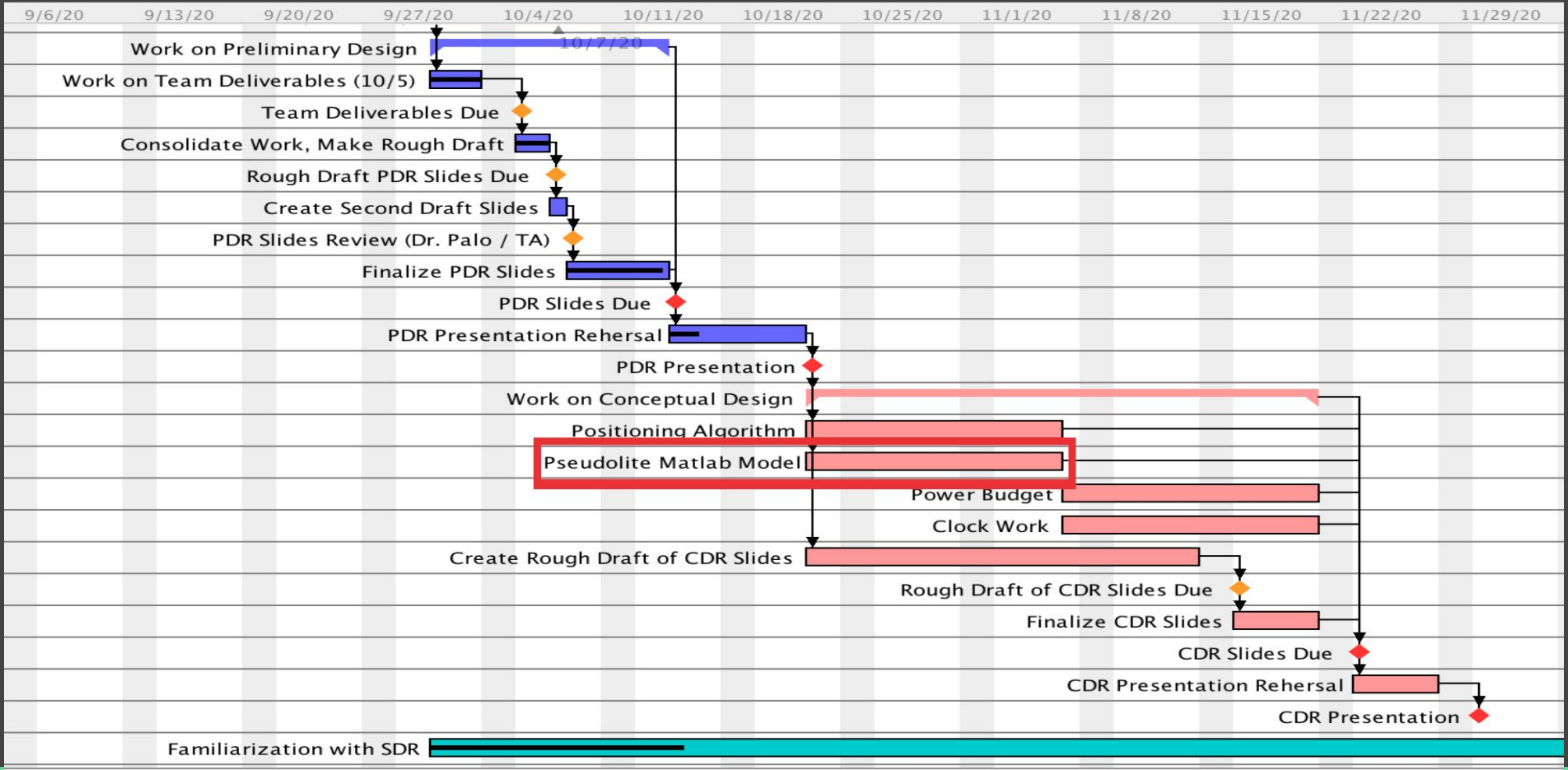
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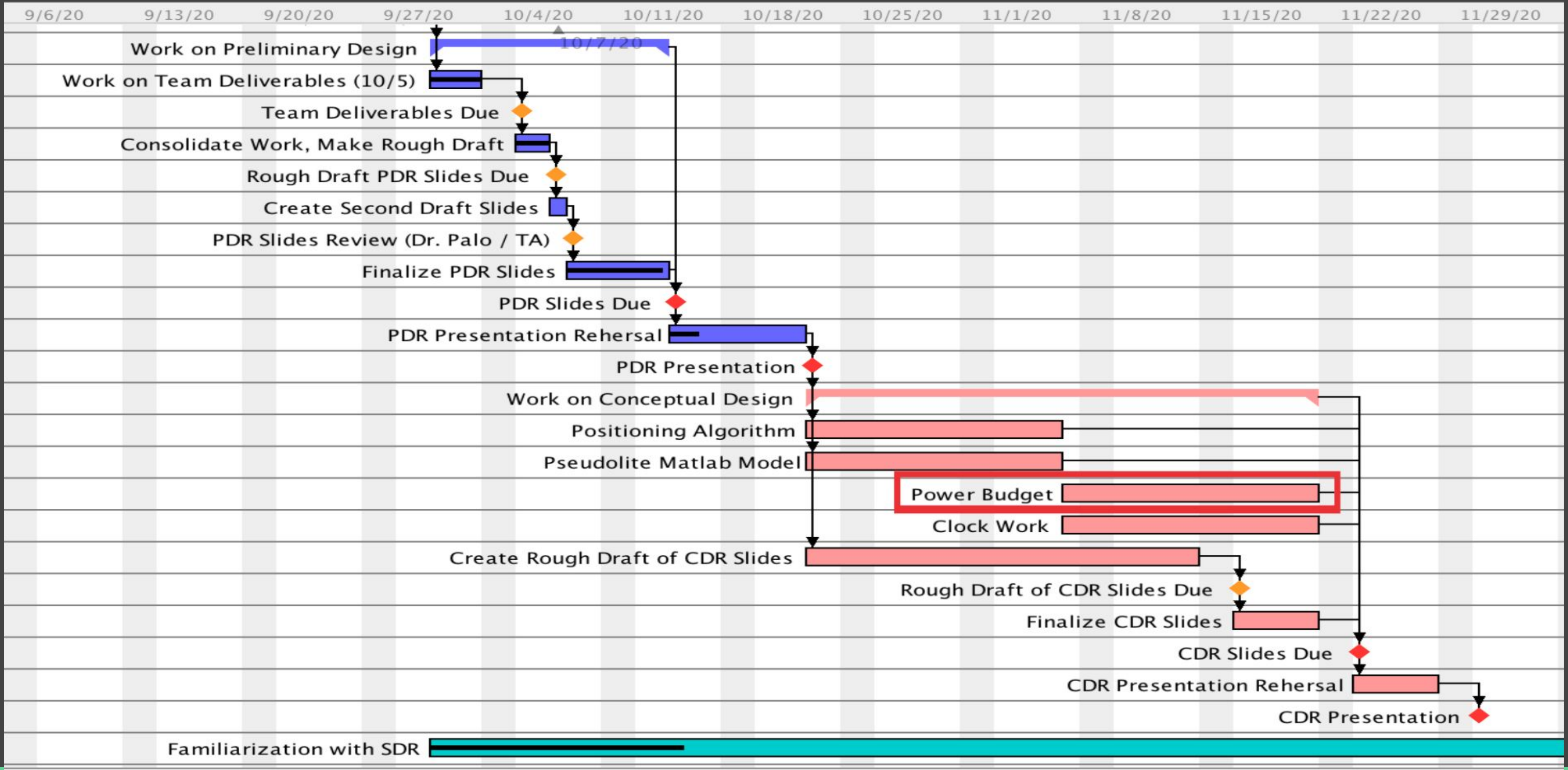

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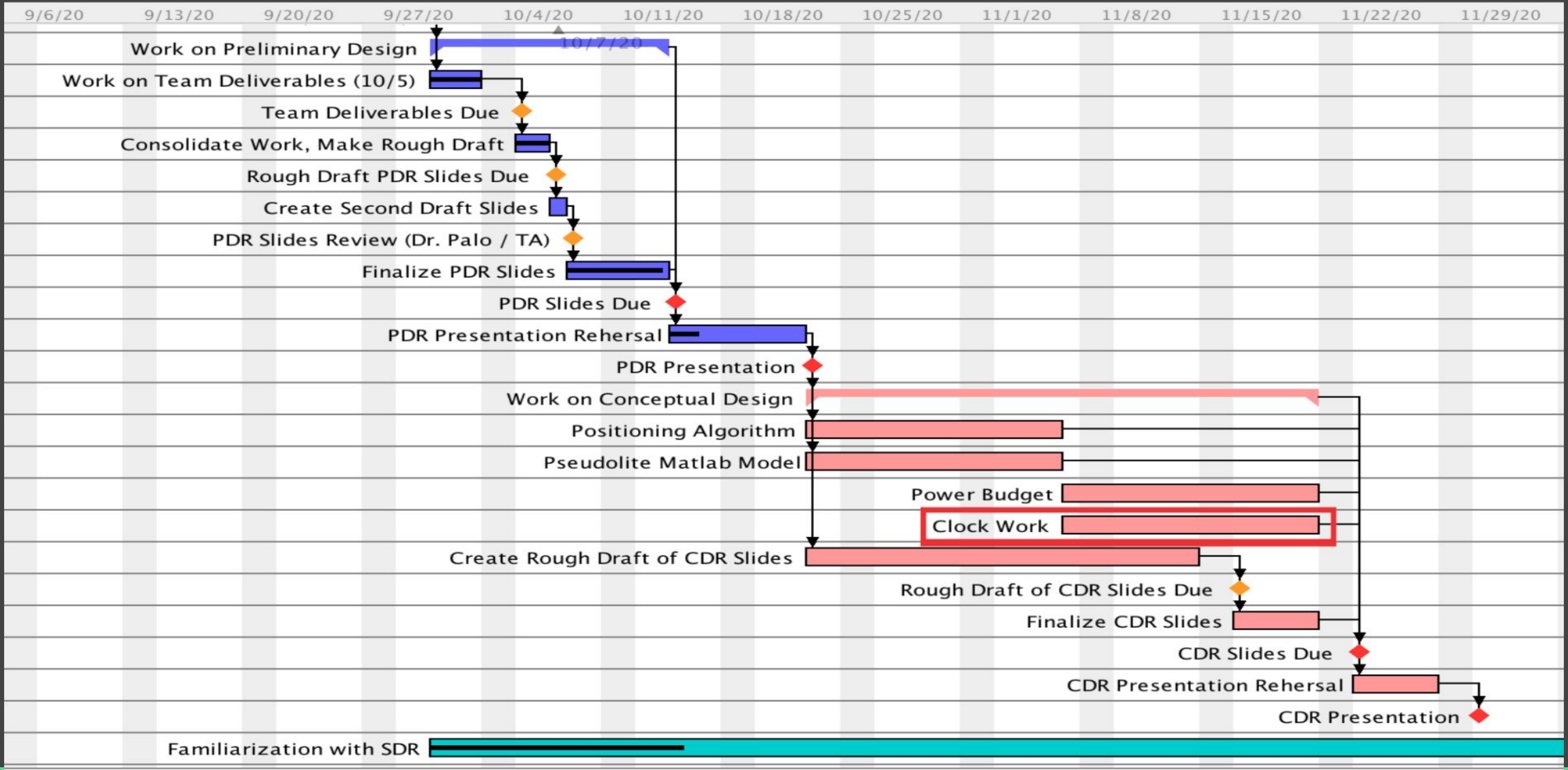
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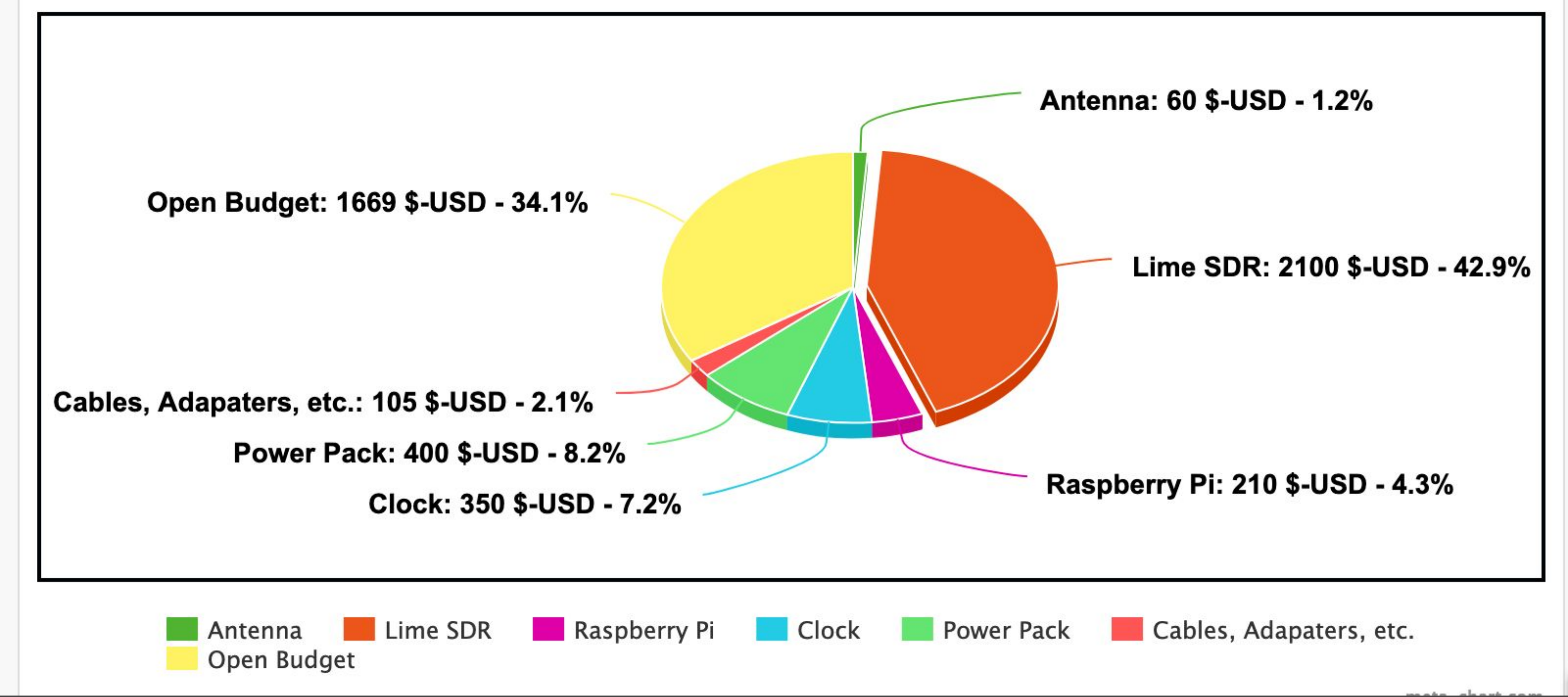
CDR Presentation
Familiarization with SDR

Budget

Feasible



Summary

Design Choices and Feasibility

- LimeSDR
- QPSK
- CDMA
- Lunar Pseudolite System Architecture
- Dual Band-TE Connectivity Antenna

Planned Work for Future

- Ranging and Clocks
  - Multiple Access Interference analysis for two-way ranging
- Improving on the LPS Model
  - Finalize and optimize Pseudolite Positioning Model
  - Trade study on positioning algorithms
- Power Budget
- Actual implementation of communication on the SDR
  - Get familiar with the LimeSDR this semester

References

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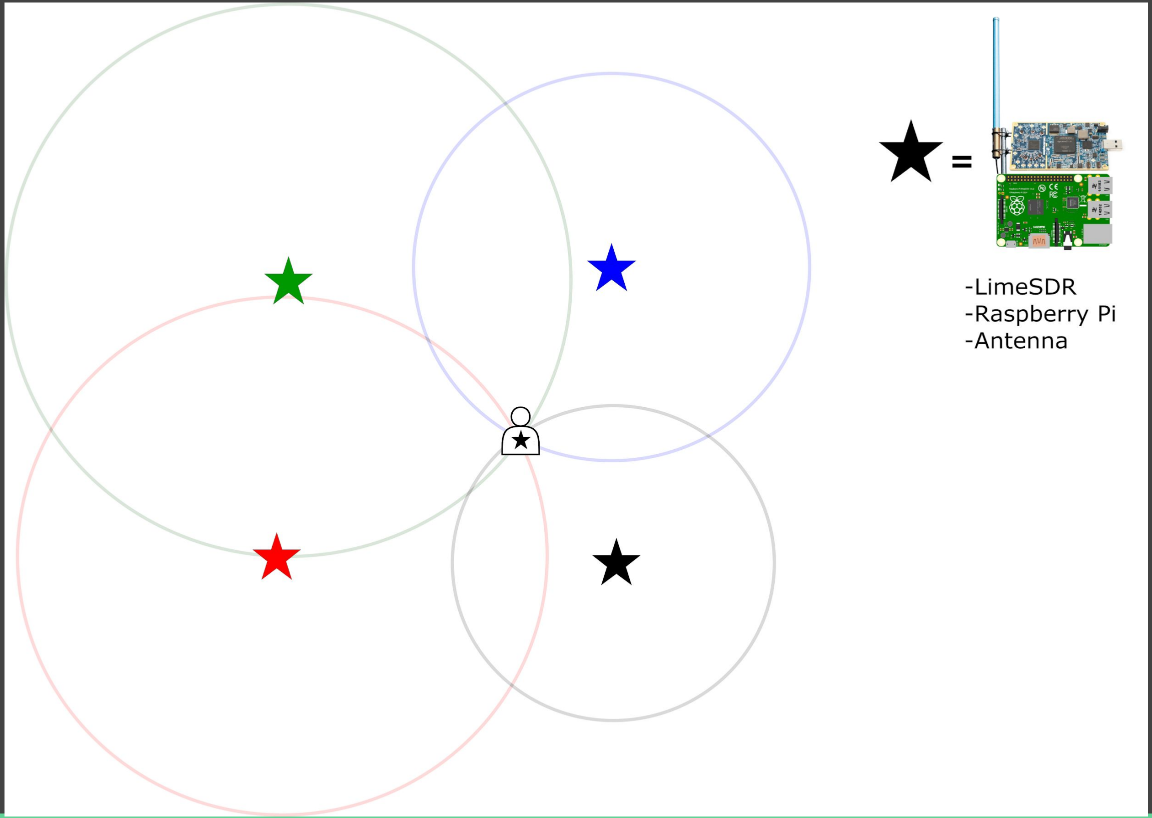
Questions

Backup Slides/ Question Support

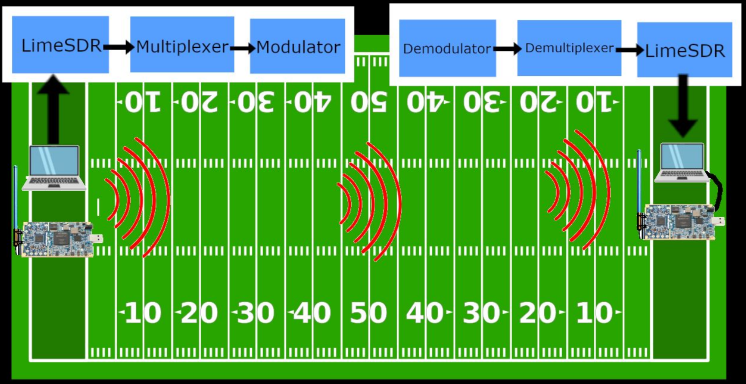
Testing


Wesley Foundation
Untd Methodist
Champions Center
Folsom Field
Stadium Building
Benson Earth Sciences
University of Colorado
Boulder Paul M. Rady...
Dept of Electrical,
Computer, and Energy...
Department of
Applied Mathematics at...
Department of
Computer Science
Business Field
Koelbel Building
University
of Colorado
Boulder
Duane Physics
and Astrophysics
Engineering
Quadrangle
Engebretson's
Quad
William M. White
Business Library
JILA
Baker Hall
ATLAS Institute,
University of Colorado...
University of
Colorado Art Museum
Unique exhibitions
& programming
Environmental
Design
Fiske Planetarium
3D

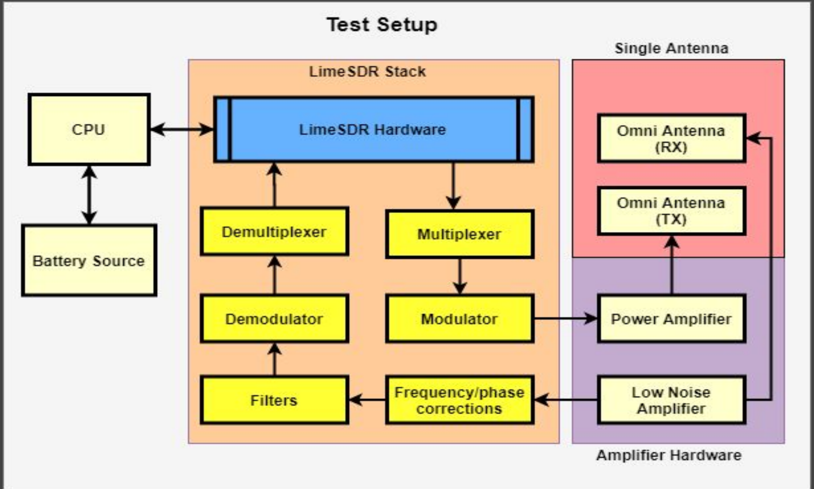
Testing Set-Up

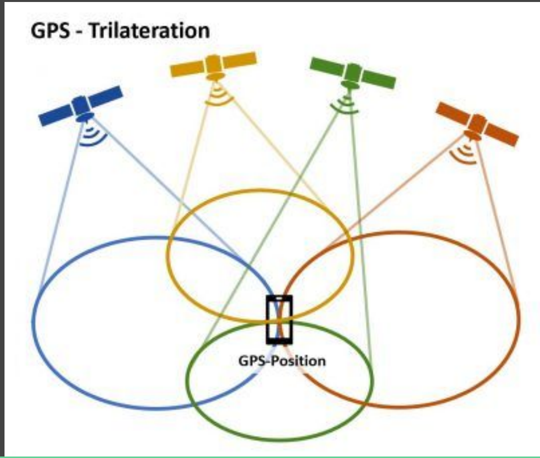


Critical Element 3



LEVEL 3 TEST SETUP





LPS

CPE 1: LPS - Parameters

Orbit 1 Parameters:

Altitude = 6000 km
Eccentricity = 0
Inclination = 80°
Ω = 0°
ω = 0°

3 satellites 120° out of phase (0°,120°,240°)

Orbit 2 Parameters:

Altitude = 6000 km
Eccentricity = 0
Inclination = 80°
Ω = 120°
ω = 0°

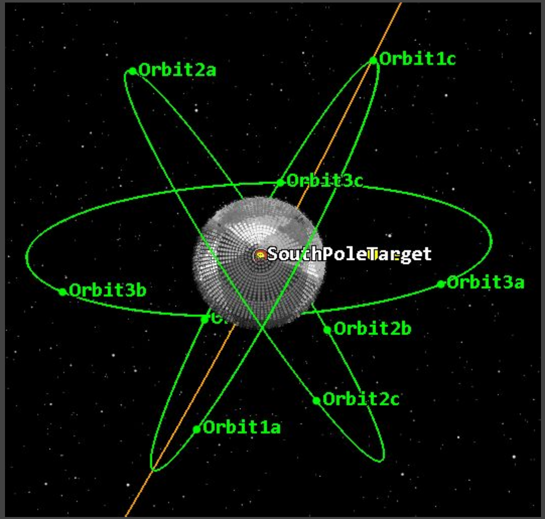
3 satellites 120° out of phase (40°,160°,280°)

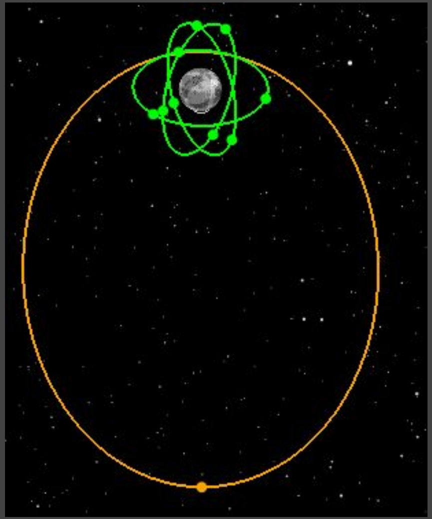
Orbit 3 Parameters:

Altitude = 6000 km
Eccentricity = 0
Inclination = 80°
Ω = 240°
ω = 0

3 satellites 120° out of phase (80°,200°,320°)

LPS - Orbital vs Pseudolite





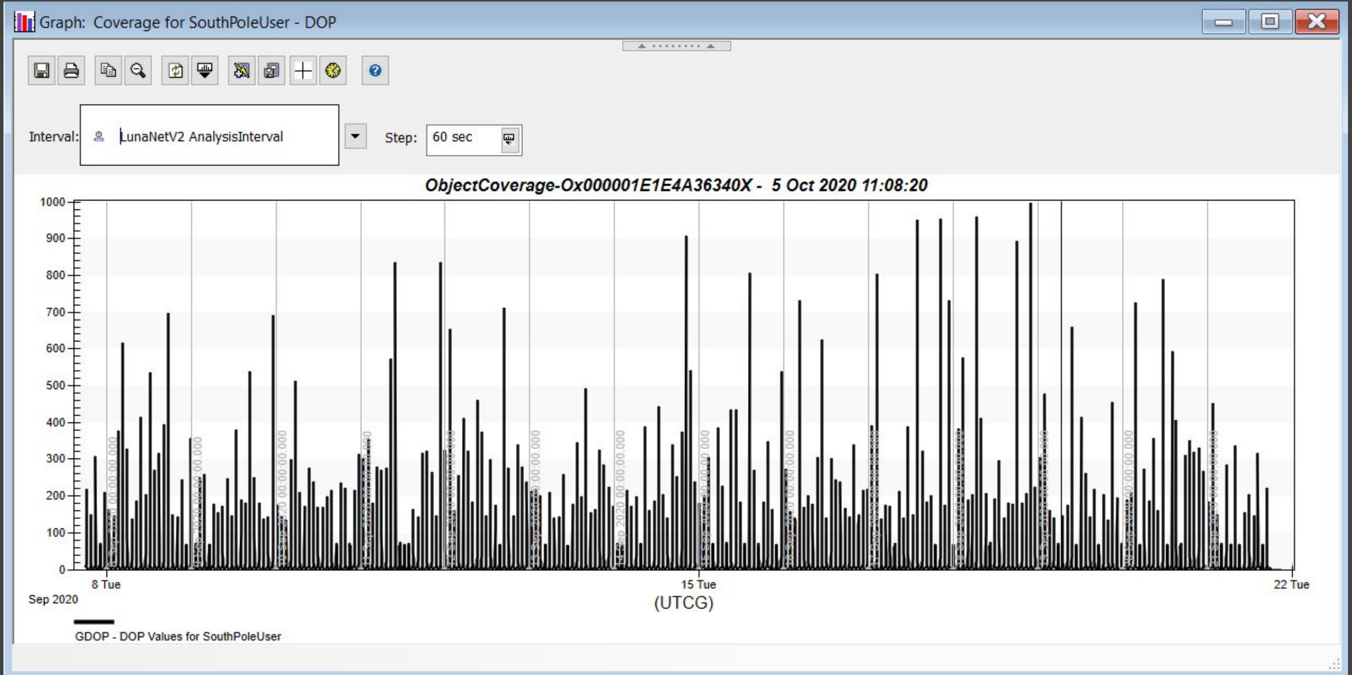
Customer Requirements:

- < 10 m positioning error
- 30 ns 1-sigma transfer time

Problems:

- Not enough satellites visible
- Insufficient coverage
- Unstable Orbits
- Large error in positioning

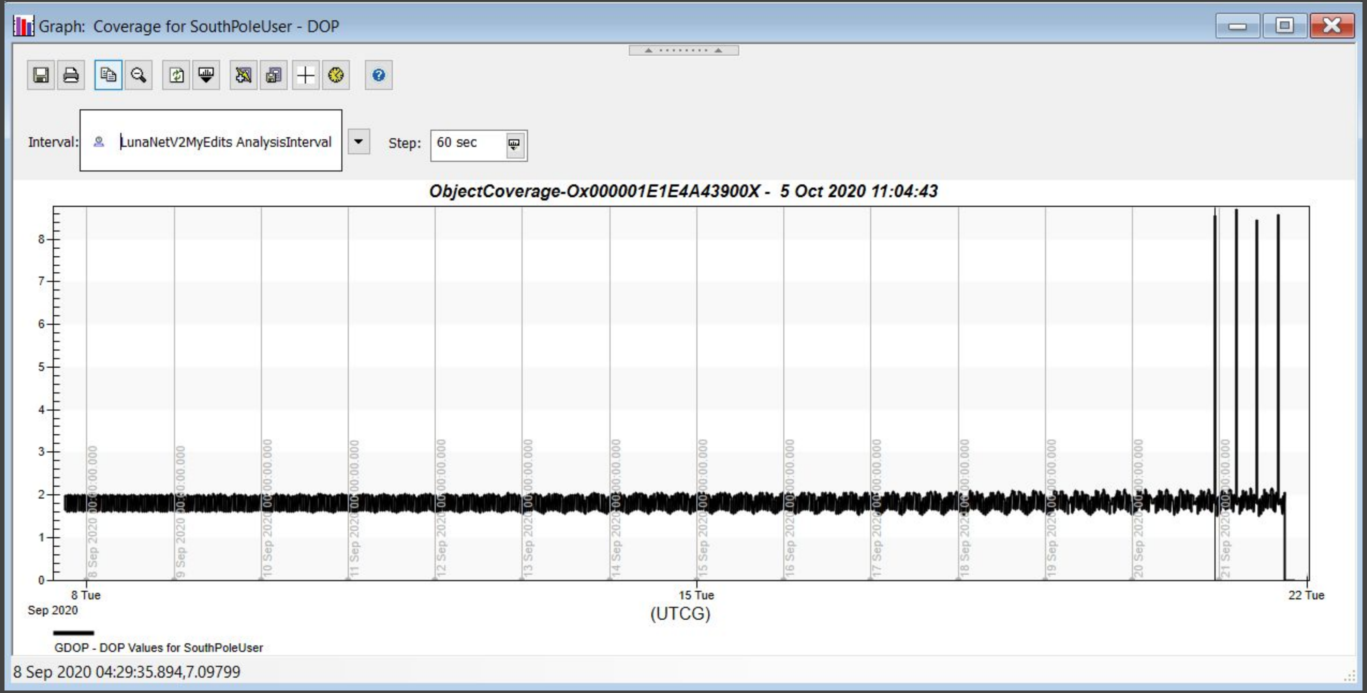
CPE 1: LPS - Error Analysis



Average GDOP: 24.047

Baseline Model GDOP Results

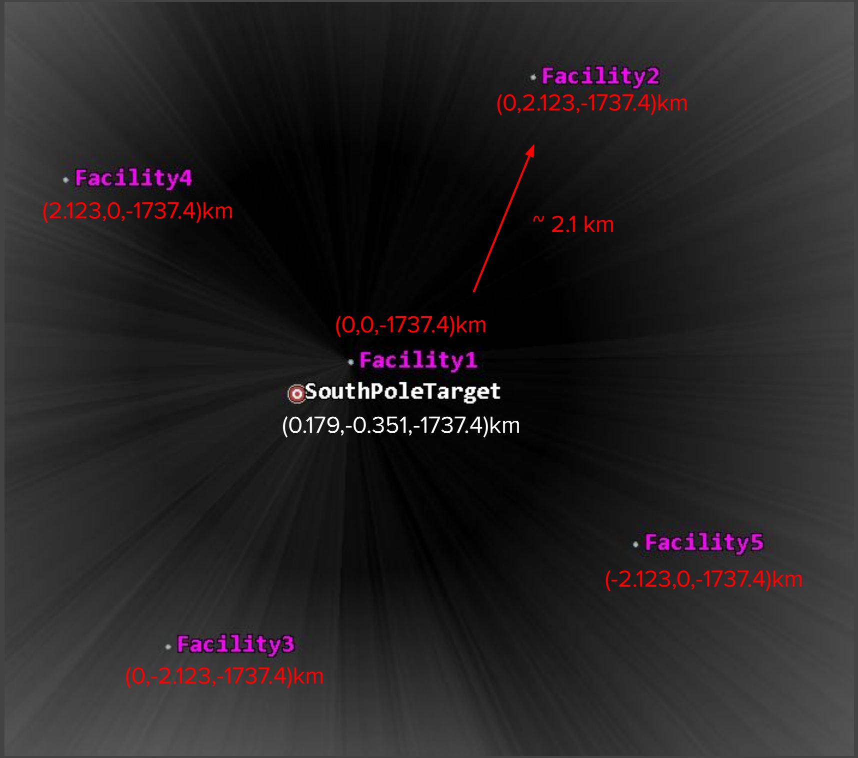
CPE 1: LPS - Error Analysis



Average GDOP: 1.979

Improved Baseline Model GDOP Results

Pseudolite Architecture on STK



Target Height: 2m

Facility Height: 5m

HDOP: 0.982037

Average Positioning: 4.910185 meters

LPS - Mathematical Computation of GDOP

As a first step in computing DOP, consider the unit vectors from the receiver to satellite i: $\left(\frac{(x_i - x)}{R_i}, \frac{(y_i - y)}{R_i}, \frac{(z_i - z)}{R_i}\right)$ where $R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$ and where x, y and z denote the position of the receiver and x_i, y_i and z_i denote the position of satellite i. Formulate the matrix, A, which (for 4 range measurement residual equations) is:

$$A = \begin{bmatrix} \frac{(x_1-x)}{R_1} & \frac{(y_1-y)}{R_1} & \frac{(z_1-z)}{R_1} & -1 \\ \frac{(x_2-x)}{R_2} & \frac{(y_2-y)}{R_2} & \frac{(z_2-z)}{R_2} & -1 \\ \frac{(x_3-x)}{R_3} & \frac{(y_3-y)}{R_3} & \frac{(z_3-z)}{R_3} & -1 \\ \frac{(x_4-x)}{R_4} & \frac{(y_4-y)}{R_4} & \frac{(z_4-z)}{R_4} & -1 \end{bmatrix}$$

$$Q = \left(A^T A\right)^{-1}$$

$$Q = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t^2 \end{bmatrix}$$

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

$$TDOP = \sqrt{\sigma_t^2}$$

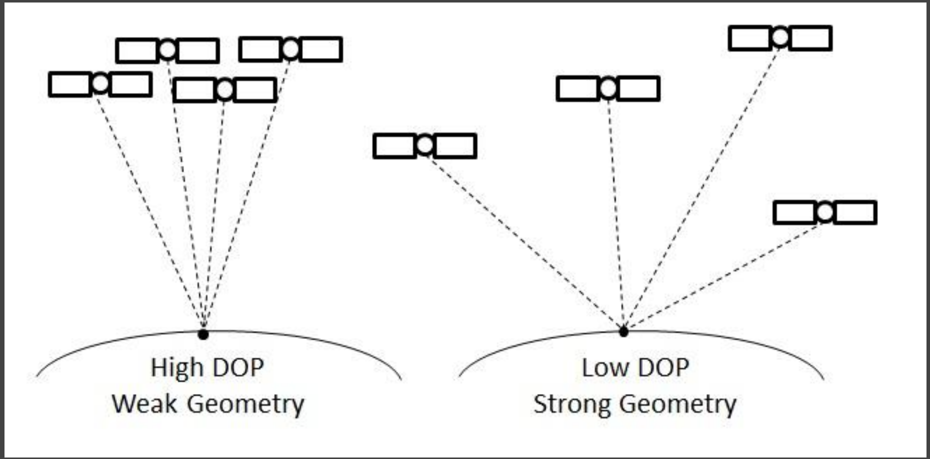
$$GDOP = \sqrt{PDOP^2 + TDOP^2}$$

Global Navigation Satellite System (GNSS) Basics

- A constellation of satellites constantly send out signals from space. By measuring how long these signals took to travel through space, we can determine how far they are.
    - These signals contain modulates data messages with the location of the satellite and corrections for the satellite clock.
- Through a process known as trilateration, receiver position can be determined.
- Four unknowns (x, y, z, and clock correction) which means we require at least 4 visible satellites.

GNSS: Error sources

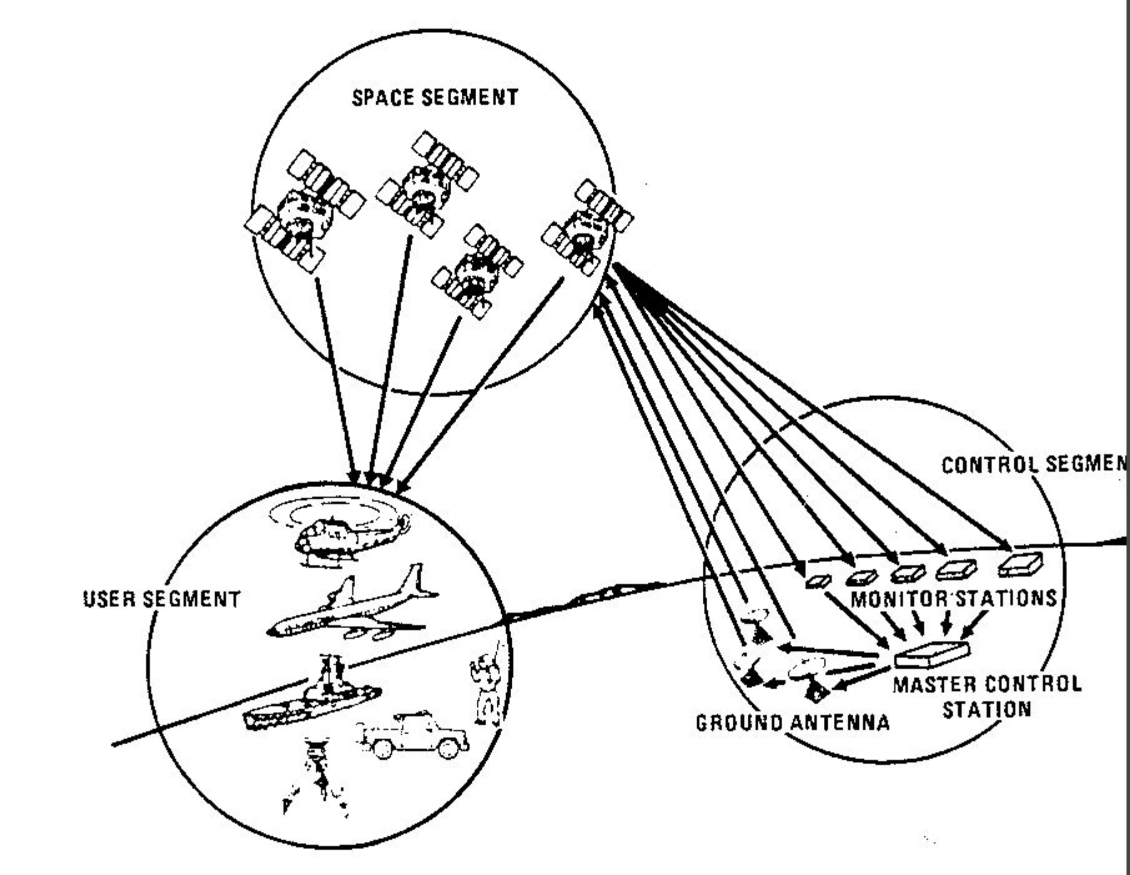
- Error sources can be divided into two categories:
  - Ranging error: signal quality, errors in transmitter location, environmental effects, receiver design, etc….
  - Geometry: Geometric Dilution of Precision (GDOP). Measures the quality of the geometric distribution of the satellites visible to the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



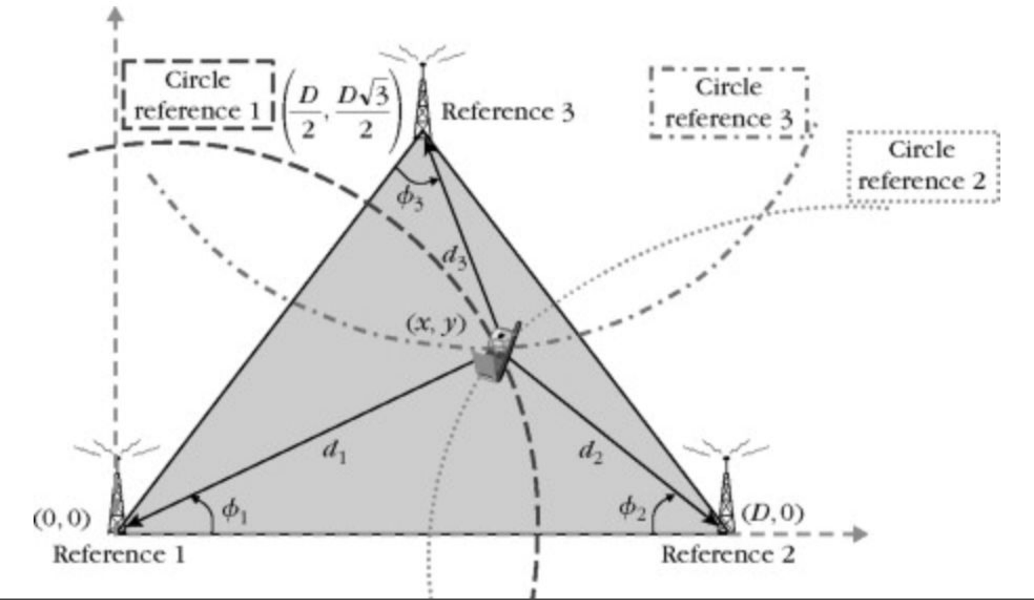
http://allaboutgps101.blogspot.com/2010/12/what-are-3-segments-of-gps-systems.html

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

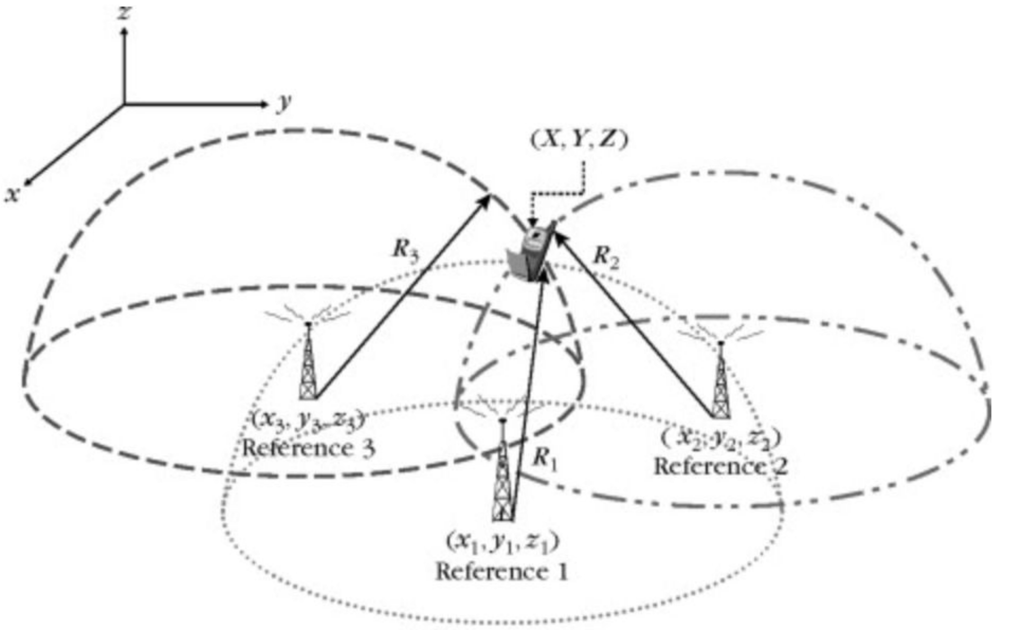
Time of Arrival (TOA)

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

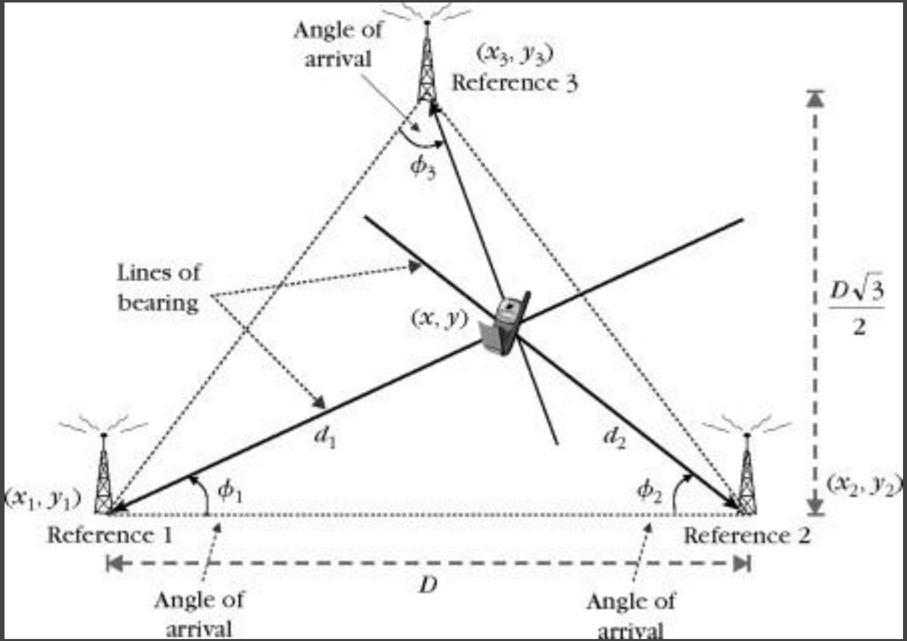
$$\begin{aligned} d_1^2 &= x^2 + y^2, \\ d_2^2 &= (x_2 - x)^2 + (y_2 - y)^2 = (D - x)^2 + y^2, \\ d_3^2 &= (x_3 - x)^2 + (y_3 - y)^2 = \tfrac{1}{2}(D - 2x)^2 + \left(D\sqrt{3} - 2y\right)^2. \end{aligned}$$

Time of Arrival (TOA)

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

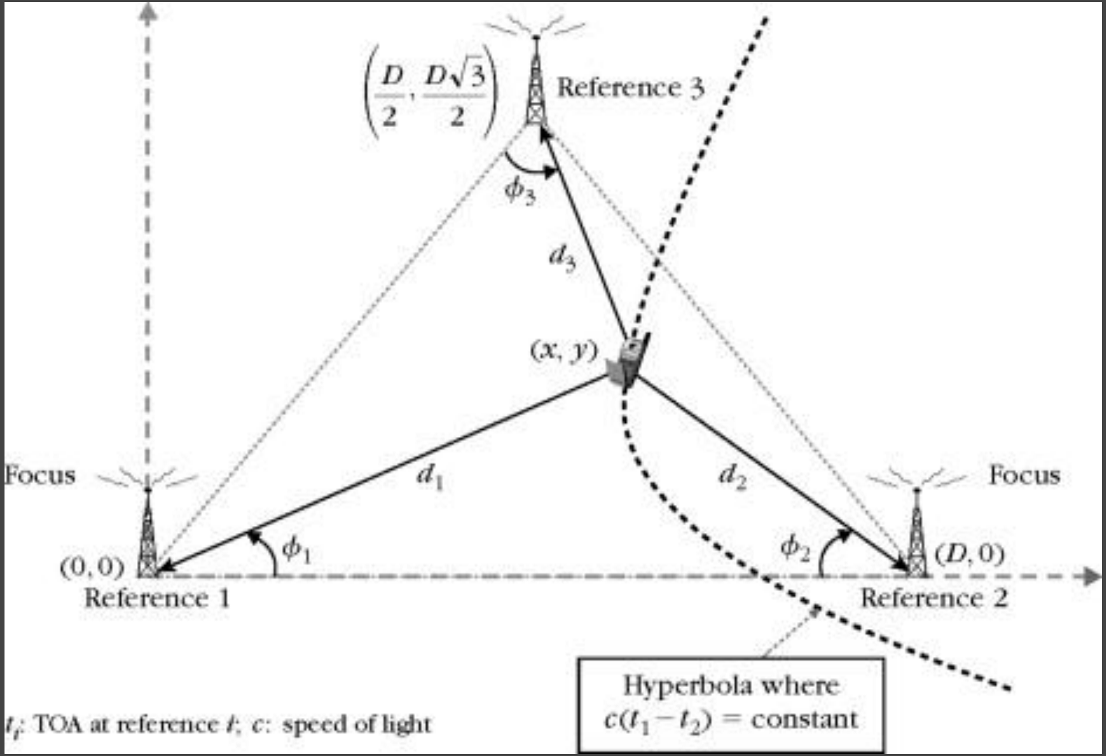


Angle of Arrival (AOA)



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

Time Difference of Arrival (TDOA)



Time Difference of Arrival (TDOA)

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

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

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

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

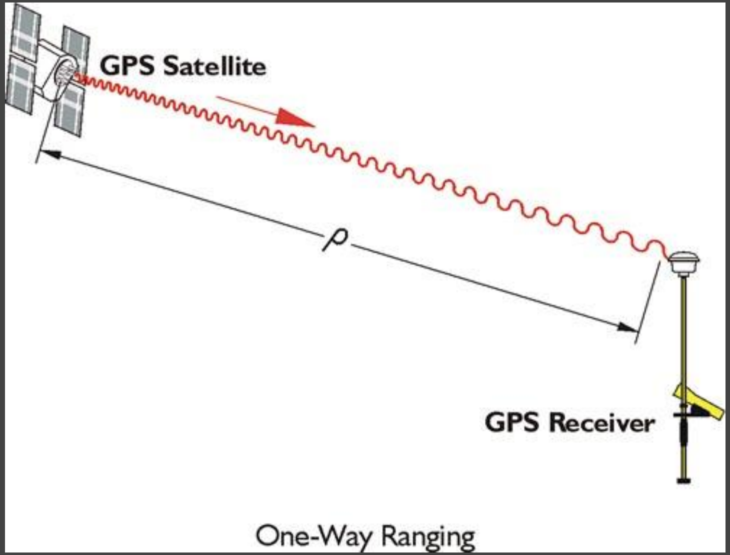
$$(d_{21}^2 - x_2^2 - y_2^2) + 2d_{21} d_1 = -2x_2 x - 2y_2 y,$$

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

Communications

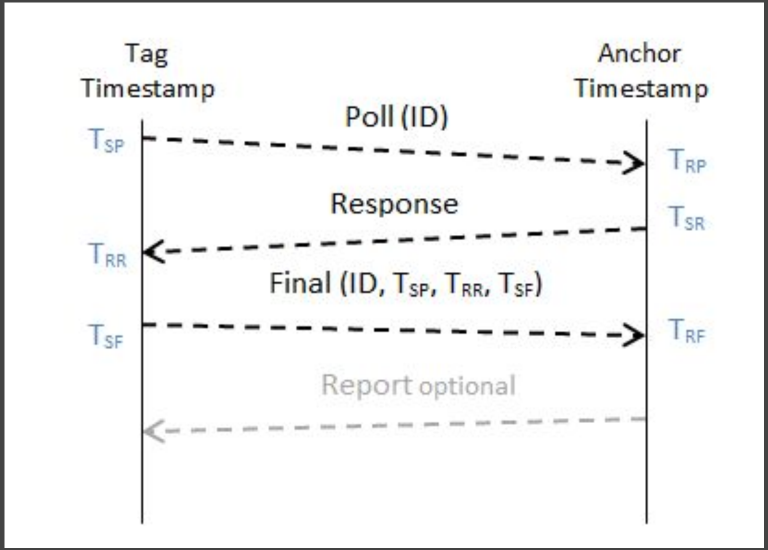
One way ranging

- 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

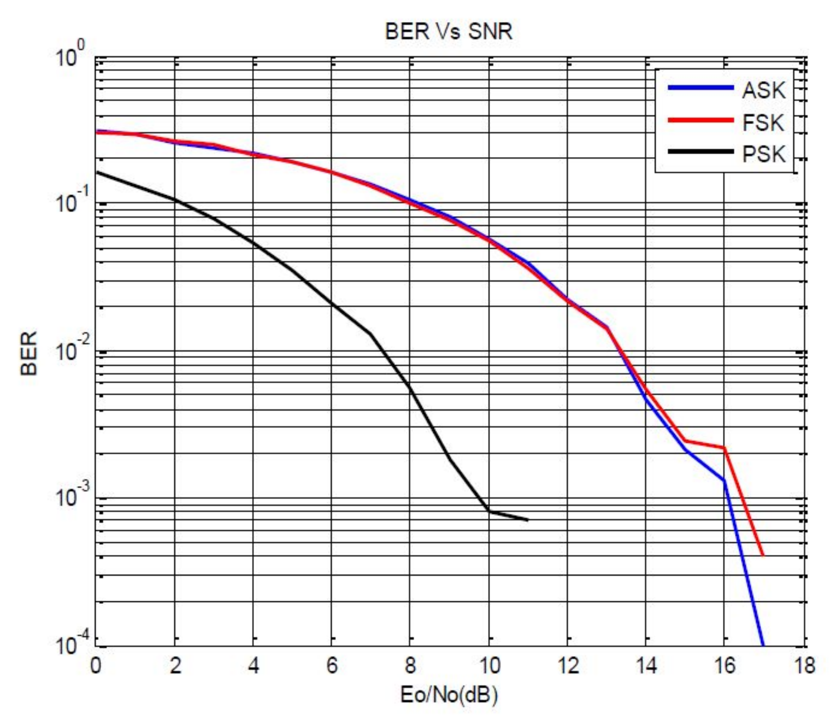
- Requires clocks on both ends but does need them to be synced up with each other.
- Receiver must transmit data BACK to the transmitter - multiple times.
- **Both the satellite and the receiver know the location of the satellite.**
- The energy and processing requirements are high due to the fast data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



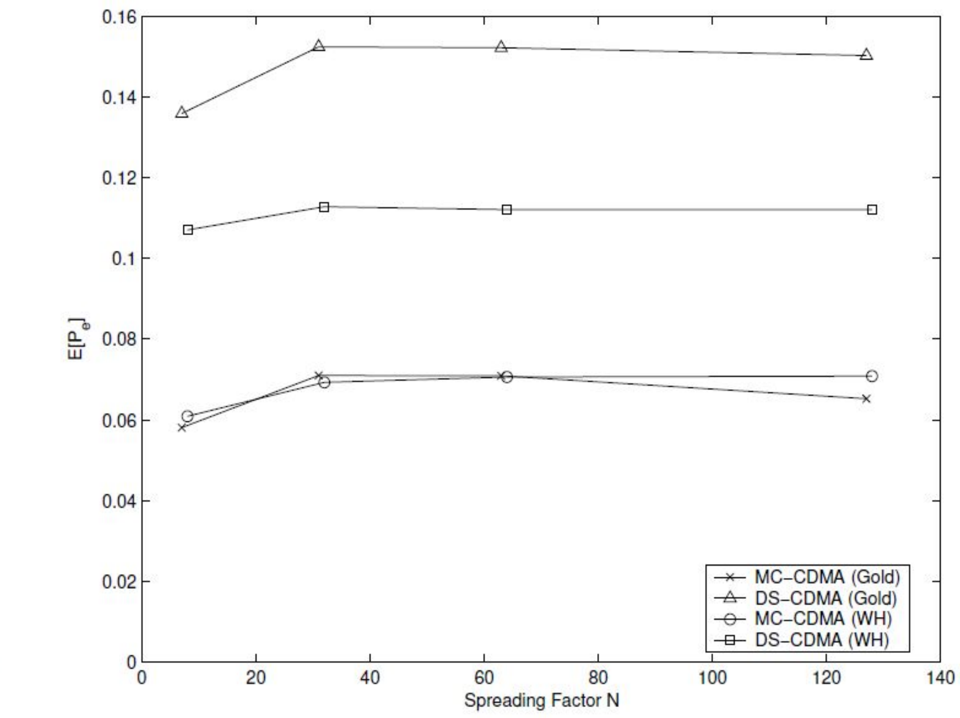
One way vs Two way ranging

	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

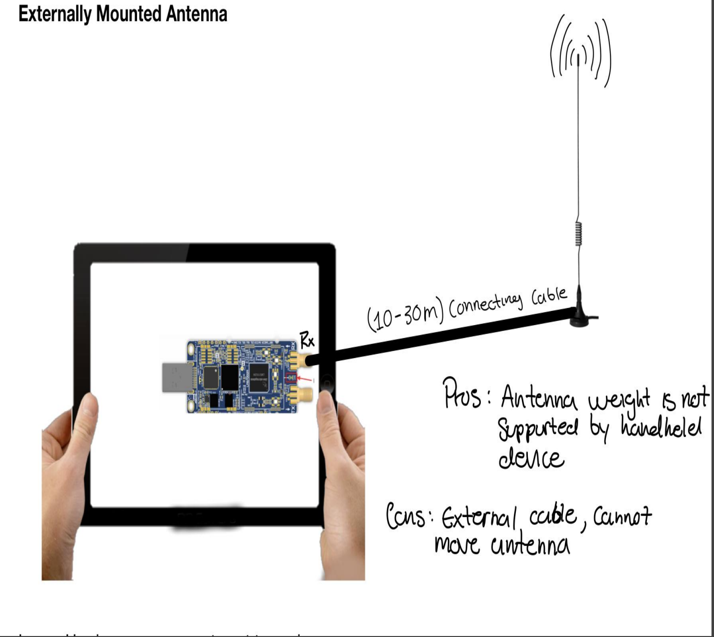
PARAMETER	UPLINK (Receiver to Satellite)	DOWNLINK (Satellite to Receiver)	UNITS	Symbol	Reference
Speed of Light	*3.0E+08*	*3.0E+08*	*m/s*	*C=λ*f*	*constant*
Frequency	*2.5*	*2.5*	*GHz*	*f*	*Input: system choice, X-band mil.com.sat.*
Wavelength	0.120	0.120	m	l	
Range	*10000*	*10000*	*km*	*R*	*Input: Geostationary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

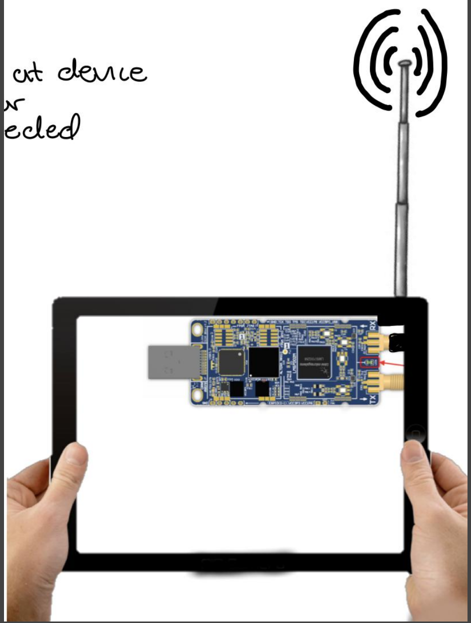
Satellite Link Budget 2

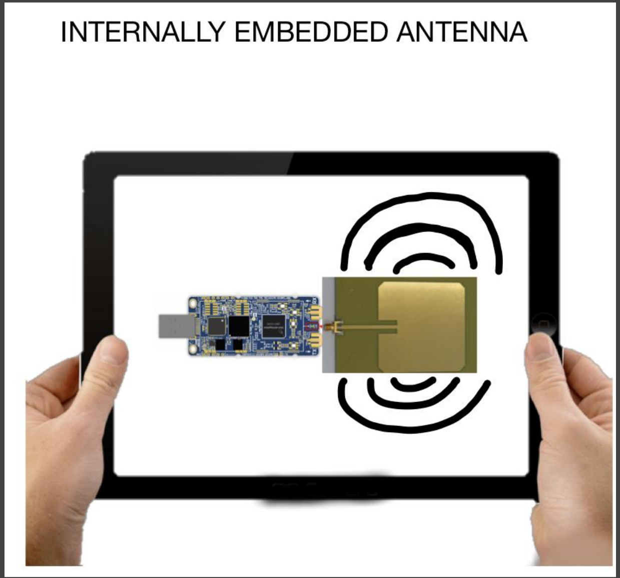
Transmitter Parameters:	Uplink	Downlink	Units	Symbol	Reference
Transmit Antenna Diameter	NA	NA	m	D	Switch Receive
Transmit Antenna Area	NA	NA	m^2	A	Switch Receive
Transmit Antenna Efficiency	NA	NA	[-]	h	Switch Receive
Transmit Antenna Effective Area	0.002	NA	m2	Ae	Switch Receive
Transmit Antenna Gain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

Antenna

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

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

$|\Gamma|$ = 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%