Critical Design Review

P4LO

Positioning For Lunar Operations

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 (Positioning For Lunar Operations)** 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)

1. Pseudolite Network
2. Reception of Pseudolite signal
3. Transmission to Pseudolite
4. Time and position identified Message Transmitted and received

2.4 - 2.48GHz @ 100 Bits/s Reception
2.4 - 2.48GHz @ 100 Bits/s Transmission
Design Solution
Design Solution Set Up
Overall FBD

Signal From Pseudolite (2.48 GHz)

Pseudolite

Signal To Pseudolite (2.48 GHz)

Analog Down Conversion → Digital Down Conversion → Receive

Analog Up Conversion → Digital Up Conversion → Transmit

Coarse Acquisition → Reading Data (Comms)

Fine Acquisition/Tracking → Reading Data (Navigation)

Ranging Measurement

Code Generation Multiplexing

Positioning Solution (1.0 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”)

- **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

- Side length: 0.18 km
- Avg. HDOP = 1.3
- STD = 0.18
- Polygon Coverage: 0.013/0.014 km² (89%)

HDOP Distribution:
- HDOP Values
- Max. Allowable HDOP
Testing site: Foothills Park
Pseudolite Geometry: Specifics

Filter 3: Near-far problem

Filter 2: Only points within polygon

Yellow = valid location; Blue = invalid location
Near-Far Problem
Near-Far Problem

Acquisition Feasibility vs. Near-Far Interference

Side length: 0.18 km
Avg. HDOP = 1.3
STD = 0.18
Polygon Coverage: 0.013/0.014 km² (89%)
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

- 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
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:

  -> sudo add-apt-repository -y ppa:myriadrf/drivers
  -> sudo apt-get update
  -> sudo apt-get install limesuite lliblimesuite-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 --list="driver=lime"

Note: The Release version must be 3.8.2.0
  -> sudo add-apt-repository ppa:gnuradio/gnuradio-releases
  -> sudo apt-get update
  -> sudo apt-get 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.

[3.1] - 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.

```
ASEN_4018_SeniorProjects $ LimeUtil --find
  [LimeSDR=USB, media=USB 1.0, module=FX3, addr=1d50:6108, serial=0009072C0289300F]
```
Receive FBD

Signal From Pseudolite (2.48 GHz)

Signal Reception

Antenna Receives

Analog Down Conversion

Reference Oscillator

ADC

Digital Down Conversion

Channel 1

Coarse Acquisition

Tracking

Channel 2

Coarse Acquisition

Tracking

... ...

Channel n

Coarse Acquisition

Tracking

Comms Data

Comms

Navigation

Positioning Solution

Planning
Transmit FBD

Data Rate: 1 Kbps
Chipping Rate: 1.023 Mbps
Signal Transmitted to Pseudolite 2.4 GHz
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

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

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

**SEVERITY**
- CRITICAL
- EXTREME
- HIGH
- MEDIUM
- LOW

**Likelihood**
- 1
- 2
- 3
- 4
- 5
## Risk Mitigation Table

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Mitigation Effects

Mitigation

Severity

Overview Solution CPE DR Risk & M V&V Planning

Critical Mitigation

Comms-3

Comms-2

Comms-1

Soft-2

soft-1

Electr-1

Comms-3

Comms-2

Soft-1

Low

Medium

High

EXTREME

Critical

Comms-3

Comms-2

Soft-1

Low

Medium

High

EXTREME

CRITICAL
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
USB Connection sends .txt as bits to LimeSDR

Wired from TX to RX sending bits

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.

1. LimeSDR
2. Raspberry Pi
3. Battery Pack
4. Cut out for antenna
5. GPS Receiver/Clock
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

LimeSDR receives the
modulated signal and
demodulates using GNURadio
demodbox

GNURadio modbox modulates
bits using BPSK modulation
scheme

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

Dr. Scott Palo (Customer)  Sam D'Souza (Project Manager)  Jade Morton (Advisor)

Dawson Weis (Systems Engineer)

Ventura Morales (Finance)  Ruben Torres/Brendan Palmer (SDR)  Ian Thomas (Communications)  Fernando Palafox (Positioning)  Alex Lowry (Manufacturing/Integration)  Ponder Stine (Testing/Human Factors)

Ventura Morales  Dawson Weis  Alex Lowry
Dawson Weis  Sam D'Souza  Ventra Morales
Fernando Palafox  Nathan Jager  Nathan Jager
Alex Lowry  Ventura Morales  Brendan Palmer
Ruben Torres
Budget Pie Chart

- **Antenna's:** 24.75 $ - 0.5%
- **Power Pack's:** 125 $ - 2.5%
- **GPS Receiver's:** 525 $ - 10.5%
- **Clock's:** 300 $ - 6.0%
- **Raspberry Pi's:** 275 $ - 5.5%
- **Lime SDR's:** 1749.75 $ - 35.0%
- **Test Equipment:** 95 $ - 1.9%
- **Adapter's:** 75 $ - 1.5%

**Open Budget:** 1832 $ - 36.6%
Test Plan

<table>
<thead>
<tr>
<th>Testing Procedure</th>
<th>Date Scheduled</th>
<th>Location</th>
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<tbody>
<tr>
<td>Signal Reception Test</td>
<td>March 9th</td>
<td>Foothills Park</td>
</tr>
<tr>
<td>Modulation and Multiplexing Test</td>
<td>March 15th</td>
<td>Foothills Park</td>
</tr>
<tr>
<td>HDOP Test</td>
<td>March 23rd</td>
<td>Foothills Park</td>
</tr>
<tr>
<td>Full Scale Test</td>
<td>March 25th</td>
<td>Foothills Park</td>
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</table>
Questions?
Back Up Slides
## Expense Budget & Margin

### Team P4LO Budget

| Allowable Budget | $5,000.00 |

### Communications Hardware

<table>
<thead>
<tr>
<th>Item</th>
<th>Individual Cost</th>
<th># of Items</th>
<th>Subtotal Per Set</th>
<th>Supplier</th>
<th>Item Description</th>
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</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>$4.95</td>
<td>5</td>
<td>$24.75</td>
<td>SparkFun</td>
<td>2.4GHz Antenna - Adhesive (U.FL Connector)</td>
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<tr>
<td>Lime SDR</td>
<td>$349.95</td>
<td>5</td>
<td>$1,749.75</td>
<td>SparkFun</td>
<td></td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td>$55.00</td>
<td>5</td>
<td>$275.00</td>
<td>SparkFun</td>
<td>Raspberry Pi 4 Model B (4 GB)</td>
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<tr>
<td>Hardware Adaptors</td>
<td>$14.95</td>
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<td>SparkFun</td>
<td>Antenna Adapter Cable</td>
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<tr>
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<td>$25.00</td>
<td>5</td>
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<td>SparkFun</td>
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<tr>
<td>Clock's</td>
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<tr>
<td>GPS Receiver</td>
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<td>5</td>
<td>$525.00</td>
<td>Time Machines</td>
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<tr>
<td>Testing Tri-pods</td>
<td>$18.95</td>
<td>5</td>
<td>$94.75</td>
<td>Target</td>
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</table>

### 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Max Operating Power (Transmit)</th>
<th>Max Operating Power (Receive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LimeSDR</td>
<td>4.5W (More like 2mW)</td>
<td>NA</td>
</tr>
<tr>
<td>Antenna</td>
<td>NA</td>
<td>3.0W</td>
</tr>
<tr>
<td>Raspberry Pi</td>
<td>NA</td>
<td>3.5W</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.5W</strong></td>
<td><strong>6.5W</strong></td>
</tr>
<tr>
<td></td>
<td>or approx 2mW</td>
<td></td>
</tr>
</tbody>
</table>

Battery Pack Requirements for Testing: 7.5W
- Many options available to purchase
Back-Up Testing Area
Positioning System - HDOP

**Horizontal Dilution Of Precision**

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

![Diagram of Acute, 90°, and Obtuse angles between pseudolites S1 and S2](image-url)
Positioning System - Evidence of Feasibility

Avg. HDOP = 1.6
Covered area: 5.5/25 km²

Avg. HDOP = 5.7
Covered area: 8.6/25 km²

Avg. HDOP = 0.76
Covered area: 2.1/25 km²

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

Two Way Ranging: FR 6

Data signal

Pseudorandom code

Transmitted signal: data signal XOR with the pseudorandom
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)

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>PROS</th>
<th>CONS</th>
</tr>
</thead>
</table>
| 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.

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.
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)

\[
\begin{align*}
  d_1 &= c(t_1 - t_0) = \sqrt{x^2 + y^2} \\
  d_2 &= c(t_2 - t_0) = \sqrt{(D-x)^2 + y^2} \\
  d_3 &= c(t_3 - t_0) = \frac{1}{2} \sqrt{(D-2x)^2 + (D\sqrt{3}-2y)^2}
\end{align*}
\]

\(t_i\): TOA at reference \(i\); \(c\): speed of light
Time of Arrival (TOA)

\[ d_i = c(t_i - t_0), \]

\[ d_1^2 = x^2 + y^2, \]
\[ d_2^2 = (x_2 - x)^2 + (y_2 - y)^2 = (D - x)^2 + y^2, \]
\[ d_3^2 = (x_3 - x)^2 + (y_3 - y)^2 = \frac{1}{2} (D - 2x)^2 + (D\sqrt{3} - 2y)^2. \]
Time of Arrival (TOA)

\[ R_i^2 = (X - x_i)^2 + (Y - y_i)^2 + (Z - z_i)^2, \quad i = 1, 2, 3. \]
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)

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

\[ d_i = d_{ij} + d_j; \]

\[ d_2^2 = (d_{21} + d_1)^2 \]
\[ = (x_2 - x)^2 + (y_2 - y)^2 \]
\[ = x_2^2 - 2x_2 x + x^2 + y_2^2 - 2y_2 y + y^2 \]
\[ = x_2^2 - 2x_2 x + y_2^2 - 2y_2 y + d_1^2, \]

\[ d_1^2 = x^2 + y^2. \]

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

\[ (d_{31}^2 - x_3^2 - y_3^2) + 2d_{31} d_1 = -2x_3 x - 2y_3 y. \]
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.
<table>
<thead>
<tr>
<th></th>
<th>One way</th>
<th>Two way</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power required</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Position information</td>
<td>Only receiver</td>
<td>Both receive info</td>
</tr>
<tr>
<td>Clock synchronization</td>
<td>Required</td>
<td>Not required</td>
</tr>
</tbody>
</table>
Bit Error Rates of Modulation Schemes

Bharati et. al.

Carey et. al.
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UPLINK (Receiver to Satellite)</th>
<th>DOWNLINK (Satellite to Receiver)</th>
<th>UNITS</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of Light</td>
<td>3.08 x 10^8</td>
<td>3.08 x 10^8</td>
<td>m/s</td>
<td>c</td>
<td>constant</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.4</td>
<td>2.4</td>
<td>GHz</td>
<td>f</td>
<td>f</td>
</tr>
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<td>Wavelength</td>
<td>0.125</td>
<td>0.125</td>
<td>m</td>
<td>l</td>
<td>l</td>
</tr>
<tr>
<td>Range</td>
<td>10</td>
<td>10</td>
<td>km</td>
<td>R</td>
<td>R (GEO)</td>
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<tr>
<td>Boltzman's Constant</td>
<td>1.3803E-23</td>
<td>1.3803E-23</td>
<td>W/(K-H)</td>
<td>k</td>
<td>k</td>
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<table>
<thead>
<tr>
<th>Data Parameters</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Error Rate / Probability of Bit Error</td>
<td>10^-8</td>
<td>10^-8</td>
<td>&amp;</td>
<td>BE-P</td>
<td>BE-P</td>
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<tr>
<td>Data Coding Scheme</td>
<td>QPSK</td>
<td>QPSK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required Bit Energy to Noise Ratio</td>
<td>12</td>
<td>12</td>
<td>dB</td>
<td>Eb/No</td>
<td></td>
</tr>
<tr>
<td>Data Rate</td>
<td>1000</td>
<td>1000</td>
<td>bps (Hz)</td>
<td>R</td>
<td></td>
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<tr>
<td>Carrier to Noise Ratio Density</td>
<td>42.09</td>
<td>42.09</td>
<td>dB-Hz</td>
<td>CNR</td>
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<tr>
<td>Required Design Margin</td>
<td>6.00</td>
<td>6.00</td>
<td>dB</td>
<td>DMR</td>
<td></td>
</tr>
<tr>
<td>Minimum PRF/No</td>
<td>4.00</td>
<td>4.00</td>
<td>PRF/No</td>
<td></td>
<td></td>
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<table>
<thead>
<tr>
<th>Noise (applies to receiving elements)</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Receiving Antenna Noise Temperature</td>
<td>400</td>
<td>400</td>
<td>K</td>
<td>T_a</td>
<td>Lecture Pt. 2, Slide 13</td>
</tr>
<tr>
<td>Receiver Cable Loss</td>
<td>0.9</td>
<td>0.9</td>
<td>dB</td>
<td>L_c</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Receiver Noise Figure (based on receiver)</td>
<td>3.0</td>
<td>3.0</td>
<td>dB</td>
<td>N_f</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Receiver Noise Factor</td>
<td>2.9</td>
<td>2.9</td>
<td></td>
<td>F</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Receiver Noise Temperature</td>
<td>208.6</td>
<td>208.6</td>
<td>K</td>
<td>T_r</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Reference Temperature</td>
<td>290</td>
<td>290</td>
<td>K</td>
<td>T_o</td>
<td>Lecture Pt. 2, Slide 13</td>
</tr>
<tr>
<td>Receiver System Noise Temperature</td>
<td>580.32</td>
<td>580.32</td>
<td>K</td>
<td>T_s</td>
<td>Lecture Pt. 2, Slide 13</td>
</tr>
<tr>
<td>Receiver System Noise Power</td>
<td>-290.36</td>
<td>-290.36</td>
<td>dBW-Hz</td>
<td>N_e</td>
<td>Lecture Pt. 2, Slide 9</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Receiver Parameters:</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Receive Antenna Diameter</td>
<td>NA</td>
<td>NA</td>
<td>m</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Receive Antenna Area</td>
<td>NA</td>
<td>NA</td>
<td>m^2</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Receive Antenna Efficiency</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td>h</td>
<td></td>
</tr>
<tr>
<td>Receive Antenna Effective Area</td>
<td>NA</td>
<td>NA</td>
<td>m^2</td>
<td>A_e</td>
<td></td>
</tr>
<tr>
<td>Receive Antenna Gain</td>
<td>2.09</td>
<td>2.09</td>
<td></td>
<td>G_r</td>
<td>Lecture Pt. 1, Slide 14</td>
</tr>
<tr>
<td>Receive Antenna Beamwidth</td>
<td>180.0</td>
<td>180.0</td>
<td>degrees</td>
<td>D_e</td>
<td>Lecture Pt. 1, Slide 10</td>
</tr>
<tr>
<td>Receive Antenna Pointing Accuracy</td>
<td>0.0</td>
<td>0.0</td>
<td>degree</td>
<td>E_r</td>
<td>Lecture Pt. 1, Slide 10</td>
</tr>
<tr>
<td>Receive Antenna Pointing Loss</td>
<td>0.0</td>
<td>0.0</td>
<td>dB</td>
<td>L_r</td>
<td>SMAID 12-21</td>
</tr>
<tr>
<td>Receiver Figure of Merit</td>
<td>0.0</td>
<td>0.0</td>
<td>dB/K</td>
<td>D_r</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Receiver Figure of Merit</td>
<td>0.0</td>
<td>0.0</td>
<td>dB/K</td>
<td>D_r</td>
<td>Lecture Pt. 2, Slide 10</td>
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<table>
<thead>
<tr>
<th>Propagation Parameters:</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Loss</td>
<td>-120.05</td>
<td>-120.05</td>
<td>dB</td>
<td>L_s</td>
<td>Lecture Pt. 2, Slide 3</td>
</tr>
<tr>
<td>Atmospheric Attenuation (clear air)</td>
<td>0</td>
<td>0</td>
<td>dB</td>
<td>L_a</td>
<td>Lecture Pt. 2, Slide 7</td>
</tr>
<tr>
<td>Polariation Loss</td>
<td>0</td>
<td>0</td>
<td>dB</td>
<td>L_p</td>
<td>Lecture Pt. 2, Slide 7</td>
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</table>
## Pseudolite Link Budget 2

### Transmitter Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Antenna Diameter</td>
<td>NA</td>
<td>NA</td>
<td>m</td>
<td>D</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Area</td>
<td>NA</td>
<td>NA</td>
<td>m²</td>
<td>A</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Efficiency</td>
<td>NA</td>
<td>NA</td>
<td>[-]</td>
<td>h</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Effective Area</td>
<td>NA</td>
<td>NA</td>
<td>m²</td>
<td>Ae</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Gain</td>
<td>2.00</td>
<td>2.00</td>
<td>dBi</td>
<td>Gt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Beamwidth</td>
<td>180.00</td>
<td>180.00</td>
<td>degrees</td>
<td>qt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Pointing Accuracy</td>
<td>0.00</td>
<td>0.15</td>
<td>degrees</td>
<td>et</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Pointing Loss</td>
<td>0.00</td>
<td>0.00</td>
<td>dB</td>
<td>Lpt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Line Loss</td>
<td>-0.5</td>
<td>-0.5</td>
<td>dBi</td>
<td>Lt</td>
<td>Input: based on chosen cable/geometry</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>-27.0</td>
<td>-27.0</td>
<td>dBW</td>
<td>Pt</td>
<td>10*LOG10(Tx power)</td>
</tr>
<tr>
<td>Transmit Power, Linear</td>
<td>0.002</td>
<td>0.002</td>
<td>W</td>
<td>Ptl</td>
<td>Input: chosen transmitter</td>
</tr>
<tr>
<td>Effective Isotropic Radiated Power</td>
<td>-25.49</td>
<td>-25.49</td>
<td>dBW</td>
<td>EIRP</td>
<td>Sum of Power, Gain, and Losses in dB</td>
</tr>
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</table>

### Link Budget:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Isotropic Radiated Power</td>
<td>-25.49</td>
<td>-25.49</td>
<td>dBW</td>
<td>EIRP</td>
<td>From Above</td>
</tr>
<tr>
<td>Propagation Losses</td>
<td>-120.05</td>
<td>-120.05</td>
<td>dB</td>
<td>L</td>
<td>Sum of Losses</td>
</tr>
<tr>
<td>Receive System Gain</td>
<td>1.50</td>
<td>1.50</td>
<td>dB</td>
<td>Gr</td>
<td>Sum of antenna gain and system losses</td>
</tr>
<tr>
<td>Received Power</td>
<td>-144.04</td>
<td>-144.04</td>
<td>dBW</td>
<td>Pr</td>
<td>Sum of Power sent out minus losses</td>
</tr>
<tr>
<td>System Noise Power</td>
<td>-200.96</td>
<td>-200.96</td>
<td>dBW-Hz</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Carrier to Noise Ratio Density</td>
<td>56.93</td>
<td>56.93</td>
<td>dB-Hz</td>
<td>Pr/No</td>
<td></td>
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<tr>
<td>Minimum Pr/No</td>
<td>48.00</td>
<td>48.00</td>
<td>dB-Hz</td>
<td></td>
<td></td>
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<tr>
<td>Link Margin</td>
<td>8.93</td>
<td>8.93</td>
<td>dB</td>
<td></td>
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</table>
**Satellite Link Budget 1**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UPLINK (Receiver to Satellite)</th>
<th>DOWNLINK (Satellite to Receiver)</th>
<th>UNITS</th>
<th>SYMBOL</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of Light</td>
<td>3.0E+10</td>
<td>3.0E+08</td>
<td>m/s</td>
<td>c=1/f</td>
<td>constant</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.5</td>
<td>2.5</td>
<td>GHz</td>
<td>f</td>
<td>Input: system choice, X-band mil.com sat.</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.120</td>
<td>0.120</td>
<td>m</td>
<td>l</td>
<td>Input: satellite [km]</td>
</tr>
<tr>
<td>Range</td>
<td>10000</td>
<td>10000</td>
<td>km</td>
<td>R</td>
<td>Input: Geostationary Satellite [km]</td>
</tr>
<tr>
<td>Boltzmann’s Constant</td>
<td>1.386E-23</td>
<td>1.386E-23</td>
<td>(W/K.m)</td>
<td>k</td>
<td>constant</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Data Parameters</th>
<th>Uplink</th>
<th>Downlink</th>
<th>UNITS</th>
<th>SYMBOL</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit Error Rate/Probability of Bit Error</td>
<td>10^-6</td>
<td>10^-6</td>
<td>dB</td>
<td>Eb/No</td>
<td>Input: design requirement</td>
</tr>
<tr>
<td>Data Coding Scheme</td>
<td>QPSK</td>
<td>QPSK</td>
<td></td>
<td>E_v/2N_v</td>
<td>Input: chosen modulation (SMAD Tab. 13-10)</td>
</tr>
<tr>
<td>Required Bit Energy to Noise Ratio</td>
<td>11.0</td>
<td>12.0</td>
<td>dB</td>
<td>Eb/No</td>
<td>Lecture Pt. 2, Slide 15</td>
</tr>
<tr>
<td>Data Rate</td>
<td>1000</td>
<td>1000</td>
<td>bit/s (bit)</td>
<td>R</td>
<td>Input: based on mission / objective</td>
</tr>
<tr>
<td>Carrier to Noise Ratio Density</td>
<td>41.0</td>
<td>42.0</td>
<td>dB/Hz</td>
<td>Lr</td>
<td>Lecture Pt. 2, Slide 15</td>
</tr>
<tr>
<td>Required Margin</td>
<td>3.00</td>
<td>6.00</td>
<td>dB</td>
<td>Lr</td>
<td>Lecture Pt. 2, Slide 15</td>
</tr>
<tr>
<td>Minimum P/N0</td>
<td>44.00</td>
<td>48.00</td>
<td>dB/Hz</td>
<td>Lr</td>
<td>Lecture Pt. 2, Slide 15</td>
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<table>
<thead>
<tr>
<th>Noise (applicable to receiving elements)</th>
<th>Uplink</th>
<th>Downlink</th>
<th>UNITS</th>
<th>SYMBOL</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Receiving Antenna Noise Temperature</td>
<td>40.0</td>
<td>25.0</td>
<td>K</td>
<td>Ta</td>
<td>Lecture Pt. 2, Slide 13</td>
</tr>
<tr>
<td>Receiver Cable Loss</td>
<td>0.9</td>
<td>1.0</td>
<td>dB</td>
<td>Lc</td>
<td>SMAD Table 13-10</td>
</tr>
<tr>
<td>Receiver Noise Figure (based on receiver)</td>
<td>3.0</td>
<td>1.0</td>
<td>dB</td>
<td>NF</td>
<td>SMAD Table 13-10</td>
</tr>
<tr>
<td>Receiver Noise Factor</td>
<td>2.0</td>
<td>1.3</td>
<td>K</td>
<td>F</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Receiver Noise Temperature</td>
<td>288.5</td>
<td>75.1</td>
<td>K</td>
<td>Tr</td>
<td>Lecture Pt. 2, Slide 10</td>
</tr>
<tr>
<td>Reference Temperature</td>
<td>290</td>
<td>290</td>
<td>K</td>
<td>Tr</td>
<td>SMAD Eqn13-24</td>
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<tr>
<td>Receiver Antenna Noise Temperature</td>
<td>593.32</td>
<td>31.75</td>
<td>K</td>
<td>Ta</td>
<td>Lecture Pt. 2, Slide 13</td>
</tr>
<tr>
<td>Receiver Antenna Noise Power</td>
<td>-203.96</td>
<td>-219.58</td>
<td>dB/Hz</td>
<td>No</td>
<td>Lecture Pt. 2, Slide 9</td>
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<tr>
<th>Receiver Parameters:</th>
<th>Uplink</th>
<th>Downlink</th>
<th>UNITS</th>
<th>SYMBOL</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Receiver Antenna Diameter</td>
<td>NA</td>
<td>NA</td>
<td>m</td>
<td>D</td>
<td>Input given geometry from spacecraft</td>
</tr>
<tr>
<td>Receiver Antenna Area</td>
<td>NA</td>
<td>NA</td>
<td>m²</td>
<td>A</td>
<td>Geometry</td>
</tr>
<tr>
<td>Receiver Antenna Efficiency</td>
<td>NA</td>
<td>NA</td>
<td>W/m²</td>
<td>f</td>
<td>Input typical value</td>
</tr>
<tr>
<td>Receiver Antenna Effective Area</td>
<td>NA</td>
<td>0.002</td>
<td>m²/2</td>
<td>A_e</td>
<td>Efficiency area</td>
</tr>
<tr>
<td>Receiver Antenna Gain</td>
<td>29.00</td>
<td>2.38</td>
<td>dB</td>
<td>Gr</td>
<td>Lecture Pt. 1, Slide 14</td>
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<tr>
<td>Receiver Antenna Elevation</td>
<td>20.0</td>
<td>190.0</td>
<td>deg</td>
<td>Fr</td>
<td>Lecture Pt. 1, Slide 16</td>
</tr>
<tr>
<td>Receiver Antenna Pointing Accuracy</td>
<td>0.2</td>
<td>0</td>
<td>deg</td>
<td>Fr</td>
<td>Input: pointing accuracy for chosen system</td>
</tr>
<tr>
<td>Receiver Antenna Pointing Loss</td>
<td>0.00</td>
<td>0</td>
<td>dB</td>
<td>BN</td>
<td>SMAD 13-21</td>
</tr>
<tr>
<td>Receiver Cable Loss (w/o noise)</td>
<td>0.5</td>
<td>0.5</td>
<td>dB</td>
<td>Lr</td>
<td>Input typical value</td>
</tr>
<tr>
<td>Receiver Figure of Merit</td>
<td>0.00</td>
<td>0.00</td>
<td>dB</td>
<td>Lr</td>
<td>Input typical value</td>
</tr>
<tr>
<td>Propagation Parameters:</td>
<td>Uplink</td>
<td>Downlink</td>
<td>UNITS</td>
<td>SYMBOL</td>
<td>Reference</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------</td>
<td>----------</td>
<td>-------</td>
<td>--------</td>
<td>-----------</td>
</tr>
<tr>
<td>Space Loss</td>
<td>-10.37</td>
<td>-10.37</td>
<td>dB</td>
<td>Ls</td>
<td>Lecture Pt. 2, Slide 3</td>
</tr>
<tr>
<td>Atmospheric Attenuation (clear air)</td>
<td>0</td>
<td>0</td>
<td>dB</td>
<td>Ls</td>
<td>Lecture Pt. 2, Slide 7</td>
</tr>
<tr>
<td>Polarization Loss</td>
<td>0</td>
<td>0</td>
<td>dB</td>
<td>Lp</td>
<td>Lecture Pt. 2, Slide 7</td>
</tr>
</tbody>
</table>

Note: All units and symbols are meaningful in the context of satellite link budget calculations.
### Satellite Link Budget 2

<table>
<thead>
<tr>
<th>Transmitter Parameters:</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Antenna Diameter</td>
<td>NA</td>
<td>NA</td>
<td>m</td>
<td>D</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Area</td>
<td>NA</td>
<td>NA</td>
<td>m²</td>
<td>A</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Efficiency</td>
<td>NA</td>
<td>NA</td>
<td>[-]</td>
<td>h</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Effective Area</td>
<td>0.002</td>
<td>NA</td>
<td>m²</td>
<td>Ae</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Gain</td>
<td>2.38</td>
<td>20.00</td>
<td>dB</td>
<td>Gt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Beamwidth</td>
<td>180.00</td>
<td>20.00</td>
<td>degrees</td>
<td>qt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Pointing Accuracy</td>
<td>0.00</td>
<td>0.15</td>
<td>degrees</td>
<td>et</td>
<td>Switch Receive</td>
</tr>
<tr>
<td>Transmit Antenna Pointing Loss</td>
<td>0.00</td>
<td>0.00</td>
<td>dB</td>
<td>Lpt</td>
<td>Switch Receive</td>
</tr>
<tr>
<td><strong>Transmit Line Loss</strong></td>
<td>-0.5</td>
<td>-0.5</td>
<td>dB</td>
<td>Lt</td>
<td>Input, based on chosen cable/geometry</td>
</tr>
<tr>
<td><strong>Transmit Power</strong></td>
<td>3.0</td>
<td>14.1</td>
<td>dBW</td>
<td>Pt</td>
<td>10*LOG10(Transmit power)</td>
</tr>
<tr>
<td><strong>Transmit Power, Linear</strong></td>
<td>2.0</td>
<td>25.6</td>
<td>W</td>
<td></td>
<td>Input, chosen transmitter</td>
</tr>
<tr>
<td>Effective Isotropic Radiated Power</td>
<td>4.89</td>
<td>33.58</td>
<td>dBW</td>
<td>EIRP</td>
<td>Sum of Power, Gain, and Losses in dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link Budget:</th>
<th>Uplink</th>
<th>Downlink</th>
<th>Units</th>
<th>Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Isotropic Radiated Power</td>
<td>4.89</td>
<td>33.58</td>
<td>dBW</td>
<td>EIRP</td>
<td>From Above</td>
</tr>
<tr>
<td>Propagation Losses</td>
<td>-180.37</td>
<td>-180.37</td>
<td>dB</td>
<td>L</td>
<td>Sum of Losses</td>
</tr>
<tr>
<td>Receive System Gain</td>
<td>19.50</td>
<td>1.88</td>
<td>dB</td>
<td>Gr</td>
<td>Sum of antenna gain and system losses</td>
</tr>
<tr>
<td>Received Power</td>
<td>-155.97</td>
<td>-144.90</td>
<td>dBW</td>
<td>Pr</td>
<td>Sum of Power sent out minus losses</td>
</tr>
<tr>
<td>System Noise Power</td>
<td>-200.96</td>
<td>-213.58</td>
<td>dBW-Hz</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Carrier to Noise Ratio Density</td>
<td>44.95</td>
<td>69.68</td>
<td>dB-Hz</td>
<td>Pr/No</td>
<td></td>
</tr>
<tr>
<td>Minimum Pr/No</td>
<td>44.00</td>
<td>43.00</td>
<td>dB-Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td>0.99</td>
<td>20.68</td>
<td>dB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CDMA Signal Acquisition

Cross Correlation between Data and Code, No Noise

Cross Correlation between Data and Code, 10 Extra Users
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

Pros: Antenna weight is not supported by handheld device
Cons: External cable, cannot move antenna

(10-30m) Connecting Cable

INTERNALLY EMBEDDED ANTENNA

at device selected
VSWR Equations

\[ V_{SWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \frac{V_{\text{max}}}{V_{\text{min}}} \]

= Absolute Reflection Coefficient
<table>
<thead>
<tr>
<th>Antenna Model</th>
<th>Antenna Type</th>
<th>Antenna Design Configuration</th>
<th>Gain (dBI)</th>
<th>Bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE Connectivity Antenna</td>
<td>Omnidirectional-DualBand</td>
<td>Embedded</td>
<td>2</td>
<td>2.4-3.8 GHz, 5.150-5.870 GHz</td>
</tr>
<tr>
<td>Laird-MAF94051</td>
<td>External Dual-Band Omnidirectional</td>
<td>Attached</td>
<td>2</td>
<td>2.4-2.5</td>
</tr>
<tr>
<td>Laird OC24006H</td>
<td>Omnidirectional/horizontally polarized</td>
<td>External</td>
<td>6</td>
<td>2.4-2.5</td>
</tr>
<tr>
<td>Argain-N2420M</td>
<td>Single Band embedded</td>
<td>Embedded</td>
<td>2.81</td>
<td>2.4-2.49</td>
</tr>
</tbody>
</table>
### Table 2. Antenna and other characteristics

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

\[ A_e = \frac{c^2}{f^2} \times \frac{10^{G (dB)/10}}{4\pi} \]
<table>
<thead>
<tr>
<th>Metric</th>
<th>High Score (3)</th>
<th>Medium Score (2)</th>
<th>Low Score (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Effectiveness</td>
<td>low cost for a high performance and capabilities (price&lt;5)</td>
<td>The antenna has an average cost for its capabilities (5-30)</td>
<td>The antenna has a high cost for its capabilities (Over 30)</td>
</tr>
<tr>
<td>Weight</td>
<td>The antenna is very light (Under 50 grams)</td>
<td>The antenna has a medium weight (from 50-200 grams)</td>
<td>The antennas has a high weight value (over 200 grams)</td>
</tr>
<tr>
<td>Compatibility</td>
<td>The antenna can easily connect to the SDR, The user has no issues when using the antenna</td>
<td>The antenna is compatible with the sdr without any extra hardware but needs intervention for it to start working</td>
<td>The antenna is not compatible with the sdr without any extra hardware and needs intervention for it to start functioning</td>
</tr>
<tr>
<td>Performance/Specs</td>
<td>Omnidirectional, Operates in designated frequency, high bandwidth, good materials, Large Effective Area, etc.</td>
<td>The antenna has all the required specs but does not have good materials or other hardware constraints</td>
<td>The antenna doesn't satisfy all the needed requirements</td>
</tr>
</tbody>
</table>
Antenna Trade Study BU-Slides (Table 4)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weighting</th>
<th>Antenna #1</th>
<th>Antenna #2</th>
<th>Antenna #3</th>
<th>Antenna #4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TE  Laird-1</td>
<td>Laird-2</td>
<td>Laird-2</td>
<td>Argain</td>
</tr>
<tr>
<td>Cost</td>
<td>0.15</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Weight</td>
<td>0.30</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Compatibility</td>
<td>0.15</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Performance/Specs</td>
<td>0.40</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total Score</td>
<td>100%</td>
<td>100%</td>
<td>80%</td>
<td>65%</td>
<td>90%</td>
</tr>
</tbody>
</table>