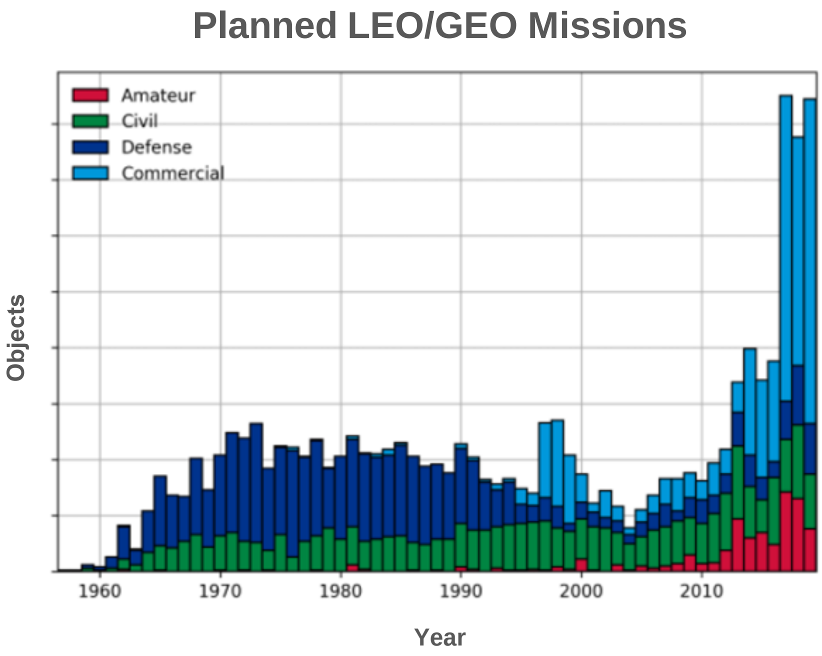
SpaceNet
Preliminary Design Review

Spring 2020

Raytheon Technologies + University of Colorado Boulder



Plot from the ESA space debris portal
https://sdup.esoc.esa.int/discosweb/statistics/

Increasing number of objects in Low Earth Orbit (LEO)

- CubeSats
- Commercial Constellations (Starlink, OneWeb)
- Debris

High fidelity phased-array sensors are limited

- Expensive
- Limited field of view
- Can only focus on a single object at a given time
- Time consuming to build and operate

What is SpaceNet?

A **Low-Cost** network of **Software Defined Radio(SDR)** equipt ground stations for monitoring LEO space domain

This type of network could be used to monitor LEO space domain relieving high fidelity sensors

The system would produce two-line element sets(TLE) that could be compared to expected orbits to determine if something is out of place

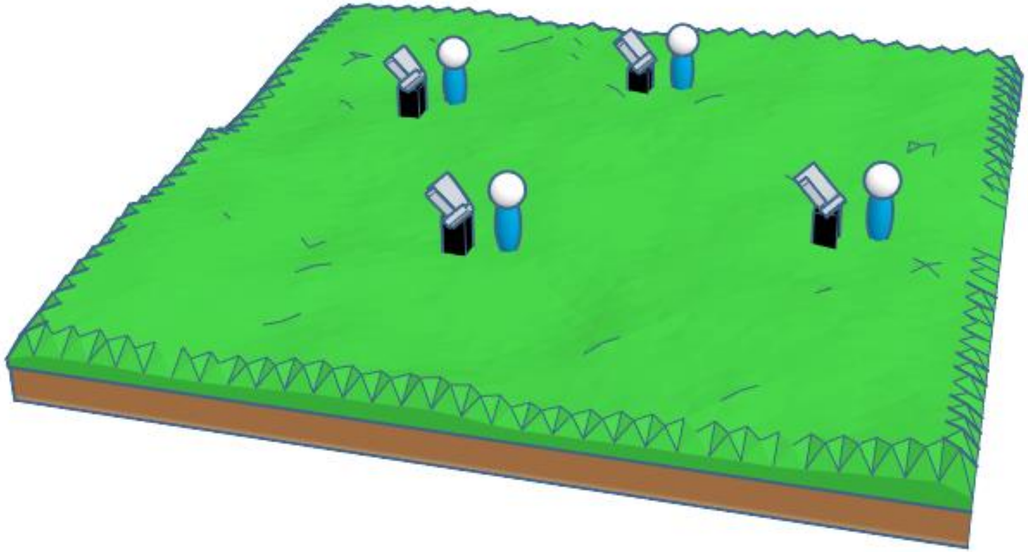
This Project

4 unit proof of concept for this type of low-cost, low-fidelity ground station network

This project will produce 4 functional ground units that can record UHF/L-Band satellite Quadrature signal (IQ) data from 2 target satellites

The recorded data will be used to produce both a orbital position estimation and Two-line element set.

SpaceNet
Concept of Operations (CONOPS)

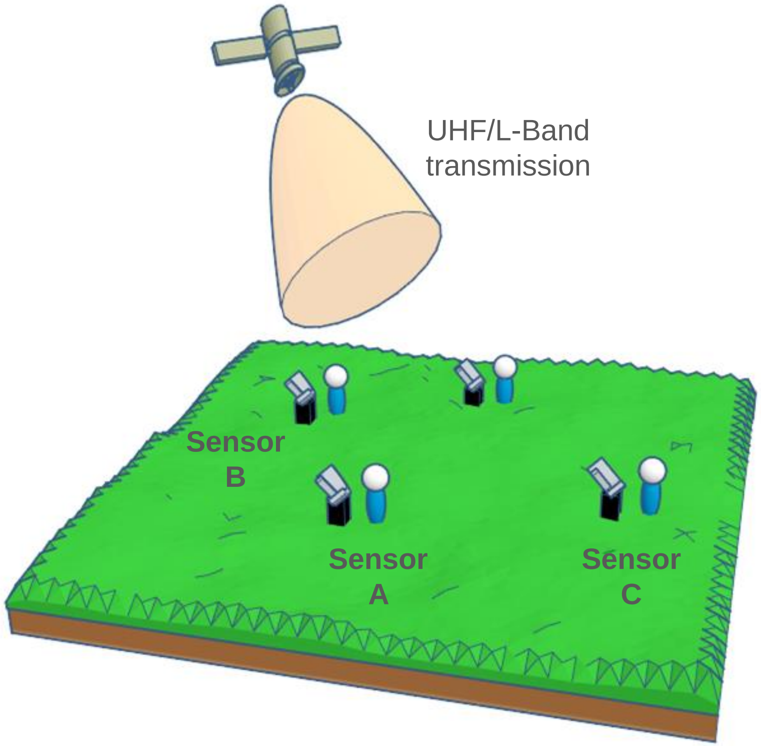


1. Sensor units are deployed and automatically achieve GPS time synchronization

1. Sensor unit SDRs are tuned to target satellite frequencies

1. Units automatically start IQ data collection simultaneously based on target satellite's know orbit and expected pass over

SpaceNet
Concept of Operations (CONOPS)



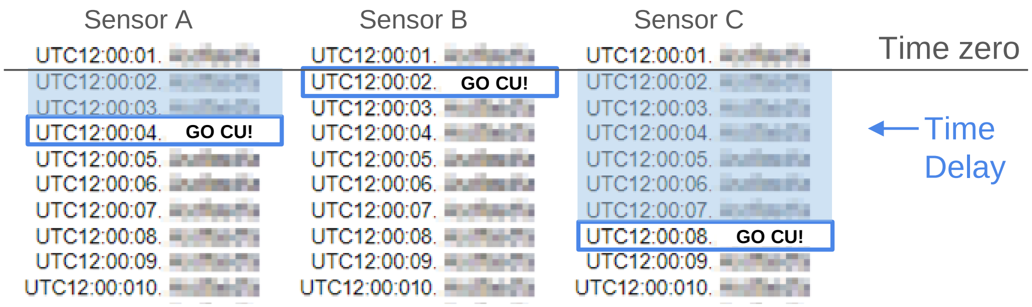
4. Target satellites emit a UHF/L-Band transmission on known frequencies

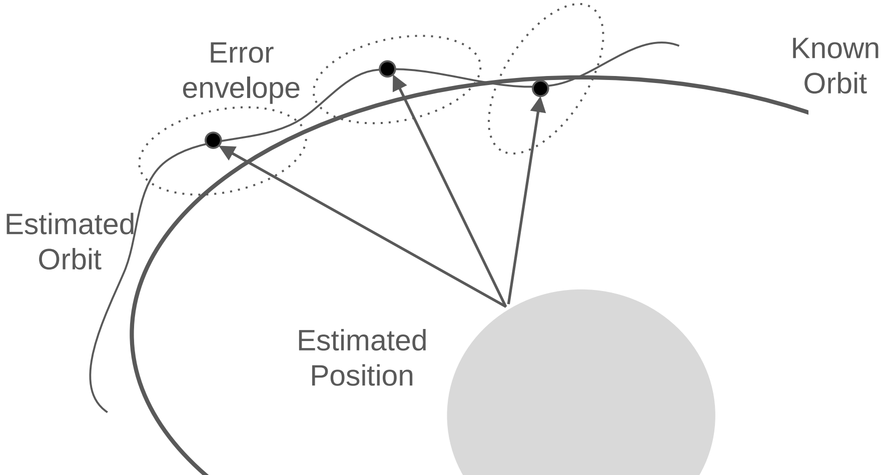
4. Sensor units receive the same UHF/L-band transmission at various local times due to their relative distances to the satellite

Sensor A	Sensor B	Sensor C
UTC12:00:01.	UTC12:00:01.	UTC12:00:01.
UTC12:00:02.	UTC12:00:02. GO CU!	UTC12:00:02.
UTC12:00:03.	UTC12:00:03.	UTC12:00:03.
UTC12:00:04. GO CU!	UTC12:00:04.	UTC12:00:04.
UTC12:00:05.	UTC12:00:05.	UTC12:00:05.
UTC12:00:06.	UTC12:00:06.	UTC12:00:06.
UTC12:00:07.	UTC12:00:07.	UTC12:00:07.
UTC12:00:08.	UTC12:00:08.	UTC12:00:08. GO CU!
UTC12:00:09.	UTC12:00:09.	UTC12:00:09.
UTC12:00:010.	UTC12:00:010.	UTC12:00:010.

4. IQ data is stored locally. The local data can be compiled into a central database after testing

SpaceNet
Concept of Operations (CONOPS)

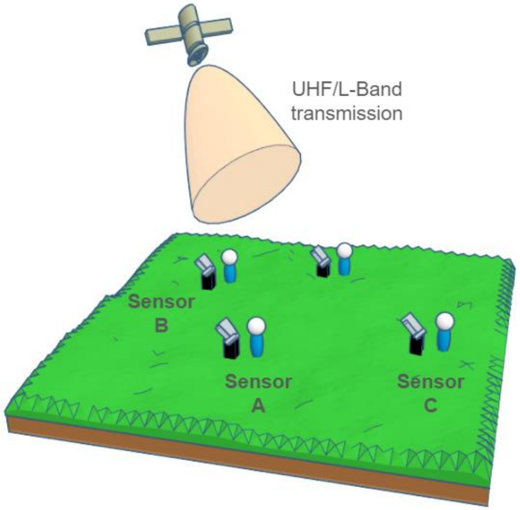


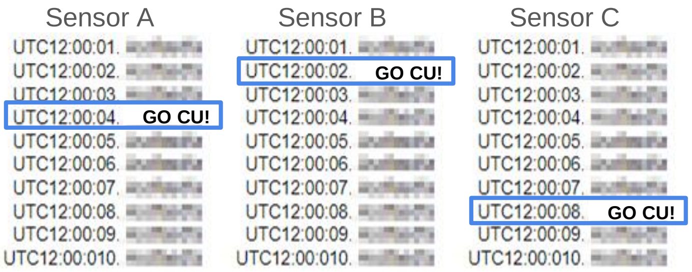


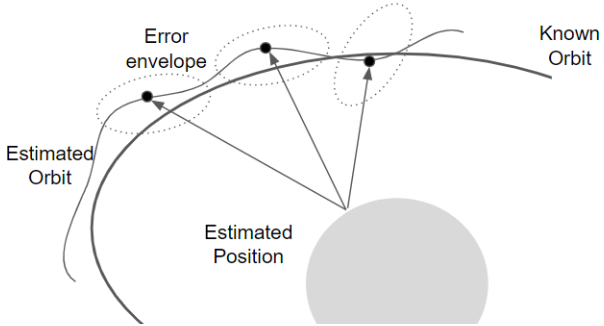
7. The compiled data can be parsed on a central machine to produce a orbital position via TDoA and a TLE

7. The estimated position and TLE can be compared to the know orbits for verification

SpaceNet
Concept of Operations (CONOPS)







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4. Target satellites emit a UHF/L-Band transmission on known frequencies

4. Sensor units receive the same UHF/L-band transmission at various local times due to their relative distances to the satellite

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7. The estimated position and TLE can be compared to the know orbits for verification

Functional System Requirements

FR1. The sensor units shall be weather resistant and capable of nominal operation outdoors for 24 continuous hours.

FR2. The sensor units shall be transportable and deployable by a single individual

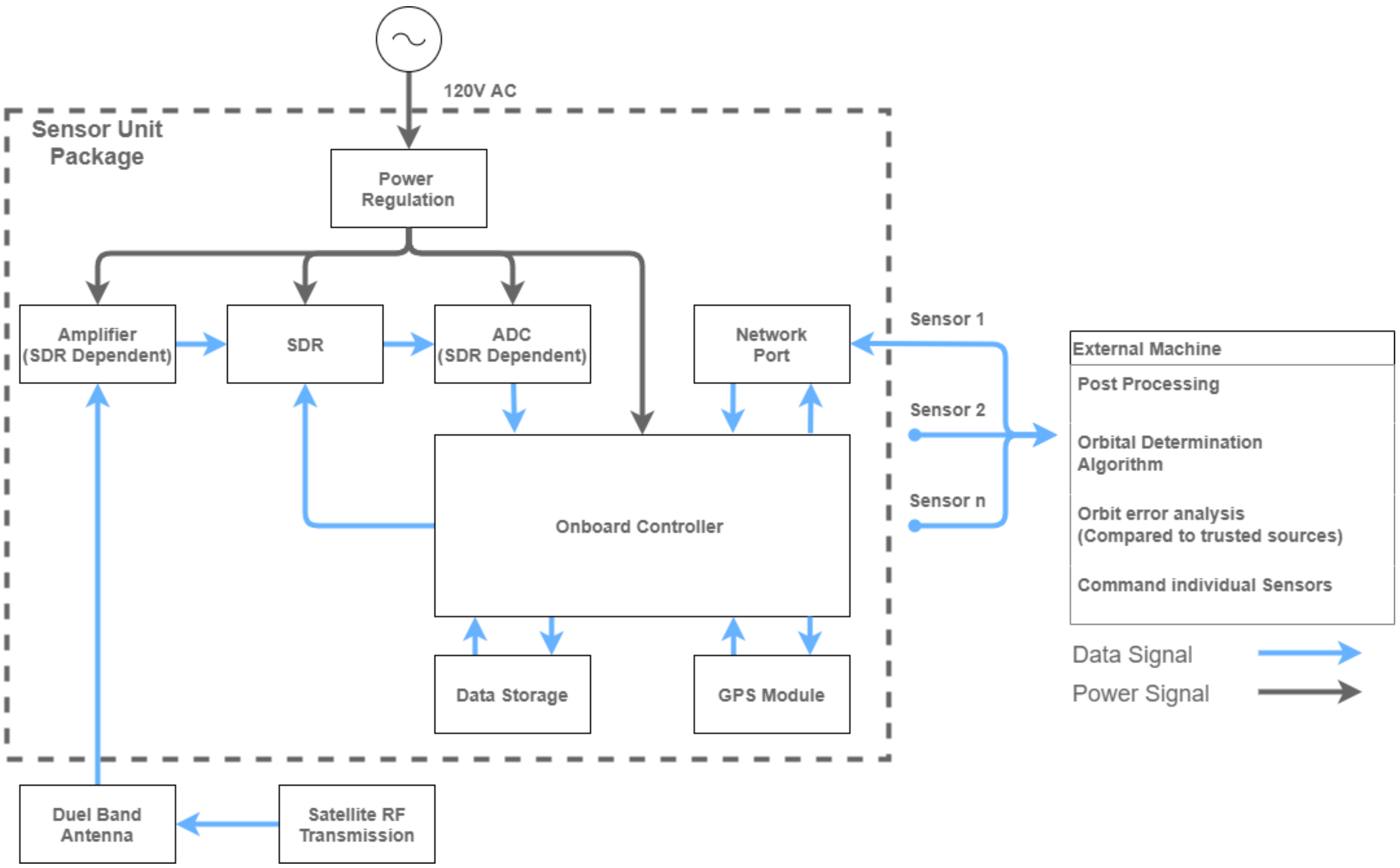
FR3. Each sensor unit will be capable of receiving RF signals from both UHF and L band ranges

FR4. The RF system will be capable of obtaining RF lock such that lock is achieved by at least 3 units at a time

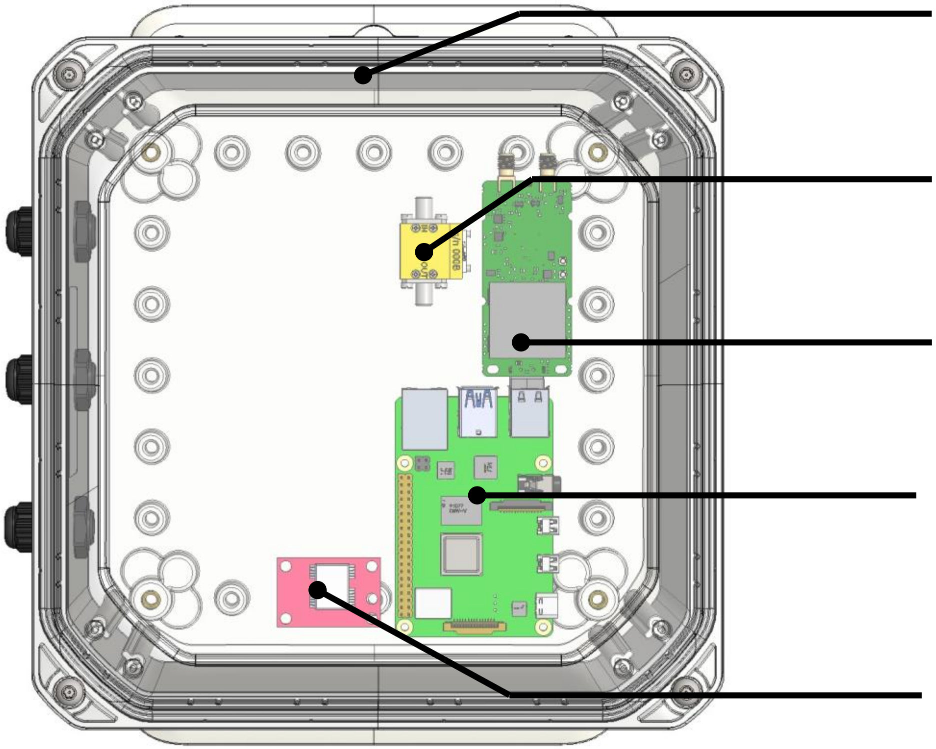
FR5. Recorded data can be used to produce a orbital position within 10km absolute error of a know satellite

FR6. Recorded data can be used to produce a two line element prediction of a know satellite candidate to within 25% error of a known good TLE set

FR7. The sensor unit shall be easily accessible and easy to manufacture


120V AC
Sensor Unit Package
Power Regulation
Amplifier (SDR Dependent)
SDR
ADC (SDR Dependent)
Network Port
Onboard Controller
Data Storage
GPS Module
Duel Band Antenna
Satellite RF Transmission
Sensor 1
Sensor 2
Sensor n
External Machine
Post Processing
Orbital Determination Algorithm
Orbit error analysis (Compared to trusted sources)
Command individual Sensors
Data Signal
Power Signal

Baseline Sensor Unit Design



Nema 4 Enclosure
Rated housing ensures component protection. Clear top enables GPS lock

LNA
Used to improve G/T metric ensuring adequate reception of satellite transmission

LimeSDR Mini
SDR that will handle RF communications

Raspberry Pi 4
On Board Computer for data collection and transfer

Neo-7M GPS Breakout Board
Used to synchronize data timestamps

Feasibility Concerns

Critical Project Element	Feasibility Concern
UHF and L-Band Link Budget	Given the baseline hardware choices will the system be able to meet the G/T requirement and provide adequate link margin for signal demodulation.
RF Front-End	Driven by link budget are the required gains and filter performance necessary to close the link budget physically attainable.
Orbital Position Estimate using TDoA	Time Delay of Arrival(TDoA) will be the primary method for finding the position of the satellite and requires a specific threshold of timing data and precision.
Timing and Hardware Limitations	Driven by TDoA, the hardware will need to achieve the prior timing requirement based on TDoA analysis and within hardware capabilities.
Orbital determination	Is there a viable method to produce a TLE set from the collected data?

UHF and L-Band Link Budget

Given the baseline hardware choices will the system be able to meet the G/T requirement and provide adequate link margin for signal demodulation.

Communication Flowdown

Link Budget

Noise temperature Feasibility

Does the selected hardware meet the system noise requirements

→

Link Margin Feasibility

With the expected G/T and satellite candidates can the communication link be closed

→

RF Front-End Feasibility

Can the required antenna/LNA/filters be built or bought

Communication Flowdown

Noise temperature Feasibility

Does the selected hardware meet the system noise requirements

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Link Margin Feasibility

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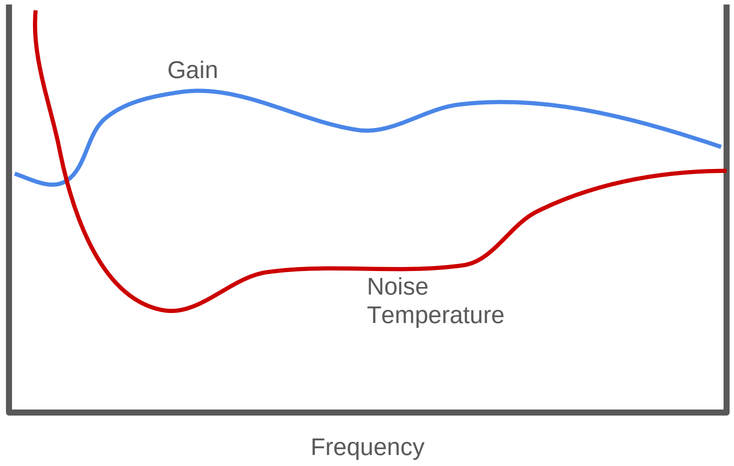
RF Front-End Feasibility

Can the required antenna/LNA/filters be built or bought

Antenna Gain to Noise Temperature (G/T)

G/T quantifies the system noise and fluctuates with frequency



Baseline design must meet the following G/T requirements:

Band	Target G/T [dB/K]	Allowable G/T [dB/K]
Band A: UHF (DR 3.1)	-15	-20
Band B: L-Band (DR 3.2)	-13	-17

G/T is defined as:

$$\frac{G}{T} = G_a - L - 10log(T_s)$$

Where:

- Ga is the antenna gain
- L is the line loss (UHF:1.8dB, L-Band:1.8dB)
- Ts is system noise temperature (UHF:305K, L-Band:170K)

Antenna Gains required to validate G/T analysis:

Band	Gain for Target G/T [dBi]	Gain for Allowable G/T [dBi]
Band A: UHF (DR 3.1)	11.6	6.6
Band B: L-Band (DR 3.2)	11.1	7.1

Communication Flowdown

Noise temperature Feasibility

Does the selected hardware meet the system noise requirements

Feasible

→

Link Margin Feasibility

With the expected G/T and satellite candidates can the communication link be closed

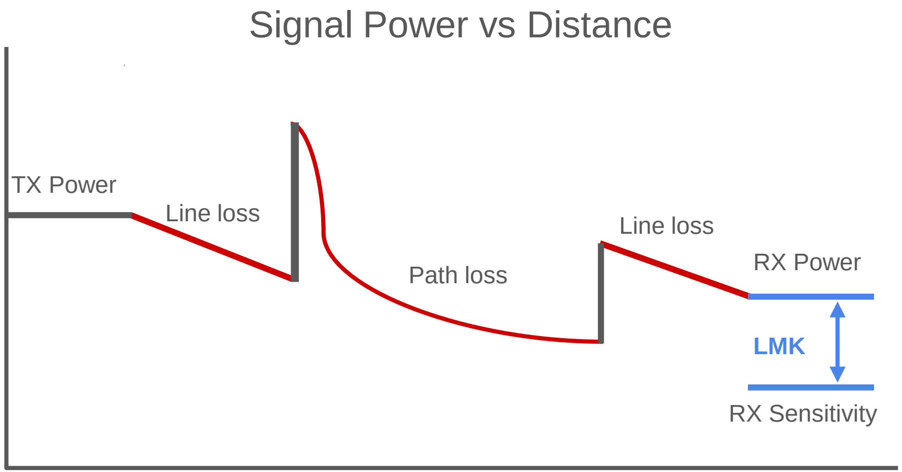
→

RF Front-End Feasibility

Can the required antenna/LNA/filters be built or bought

Link-Margin(LMK)

LMK is the difference between received power and the receiver's sensitivity.



Baseline design must meet the following LMK requirements:

Requirement	Target margin [dB]	Allowable margin [dB]
Band A: UHF (DR 3.3)	5	3
Band B: L-Band (DR 3.4)	5	3

Link-Margin is derived: $LMK = \frac{E_b}{N_0} - \frac{E_b}{N_0}|_{min}$

Where: $\frac{E_b}{N_0} = ISL + \frac{G}{T} - L_{pointing} - K_B(dB) - Z$

- ISL is the Isotropic Signal Level at the ground station(UHF:143.8dBW L-Band:-154.2dBW
- G/T is the same a prior calculated G/T(UHF:-20dB/K, L-Band:-17dB/K)
- Lpointing is the pointing loss of the antenna(UHF:9.5dB, L-band: 9.5dB)
- KB is Boltzmann Constant(-228.6dW/K/Hz)
- Z is the data rate(UHF:9.7kbps, L-band:2.4kbps)
- Eb/No|min is the required signal to noise ratio to detect the modulation technique(UHF:8.4dB, L-band:15.7dB)

Link margins based on G/T values:

Requirement	Calculated margin w/ target antenna gain [dB]	Calculated margin w/ min req antenna gain [dB]
Band A: UHF (DR 3.3)	11.9	7.5
Band B: L-Band (DR 3.4)	9.1	5.5

Link closes for both UHF and L-band given both target and min required antenna gain

Link Budget with baseline hardware is feasible

RF Front-End Feasibility

Driven by link budget are the required gains and filter performance necessary to close the link budget physically attainable.

Communication Flowdown

Noise temperature Feasibility

Does the selected hardware meet the system noise requirements

Feasible

→

Link Margin Feasibility

With the expected G/T and satellite candidates can the communication link be closed

Feasible

→

RF Front-End Feasibility

Can the required antenna/LNA/filters be built or bought

The RF Front-End must satisfy the following:

UHF Antenna Gain

≥ 6.6 dBi

L-Band Antenna Gain

≥ 7.1 dBi

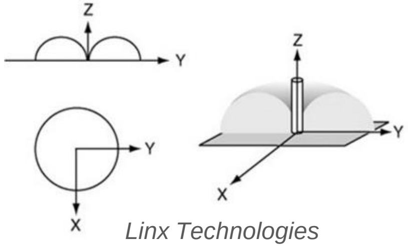
UHF LNA Gain

≥ 24 dB

L-Band LNA Gain ≥ 14dB

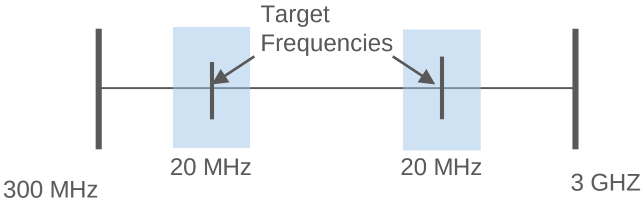
Required to validate link-budget analysis

DR4.1.
Antenna(s) will have have 360° azimuth field of view

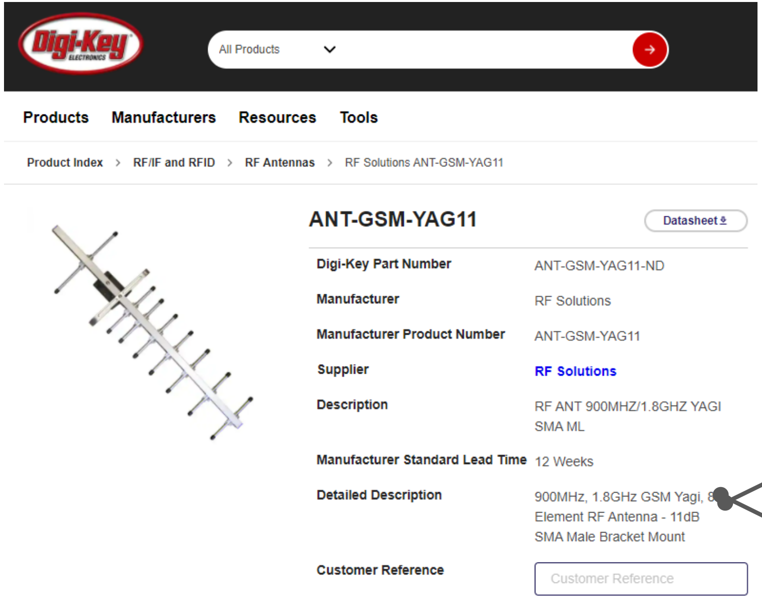


Linx Technologies

DR3.6./DR3.7.
Antenna(s) will cover +/- 10MHz of the target frequencies



Required to satisfy system requirements

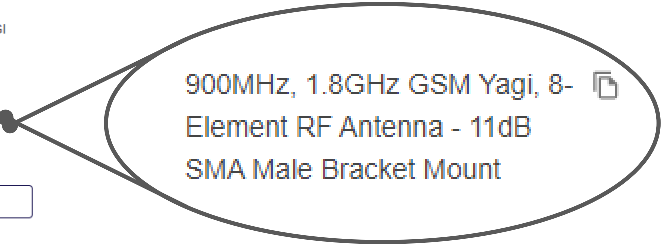


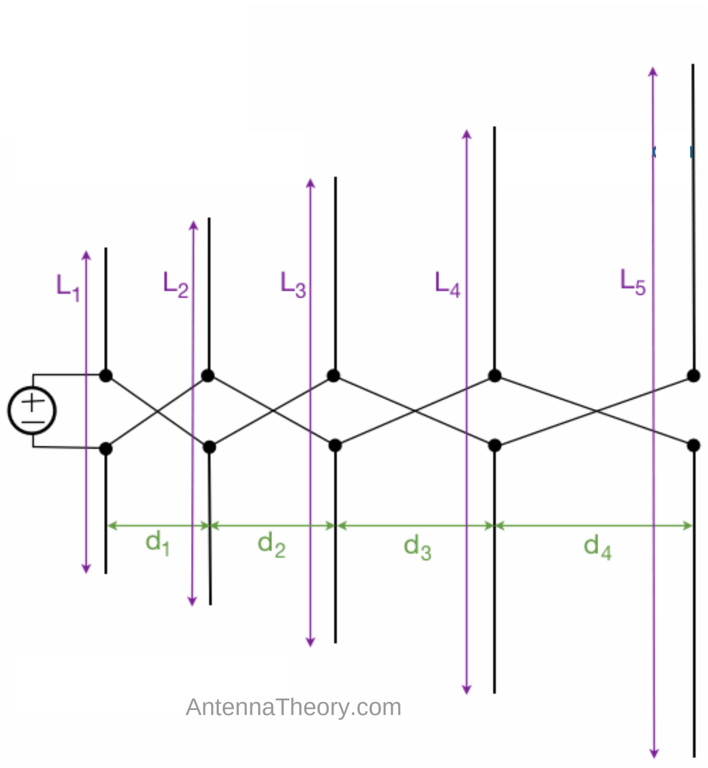
Method 1: Store Bought

Two antennas could be purchased, one for each band

Antennas could be paired with a RF switch

Feasible





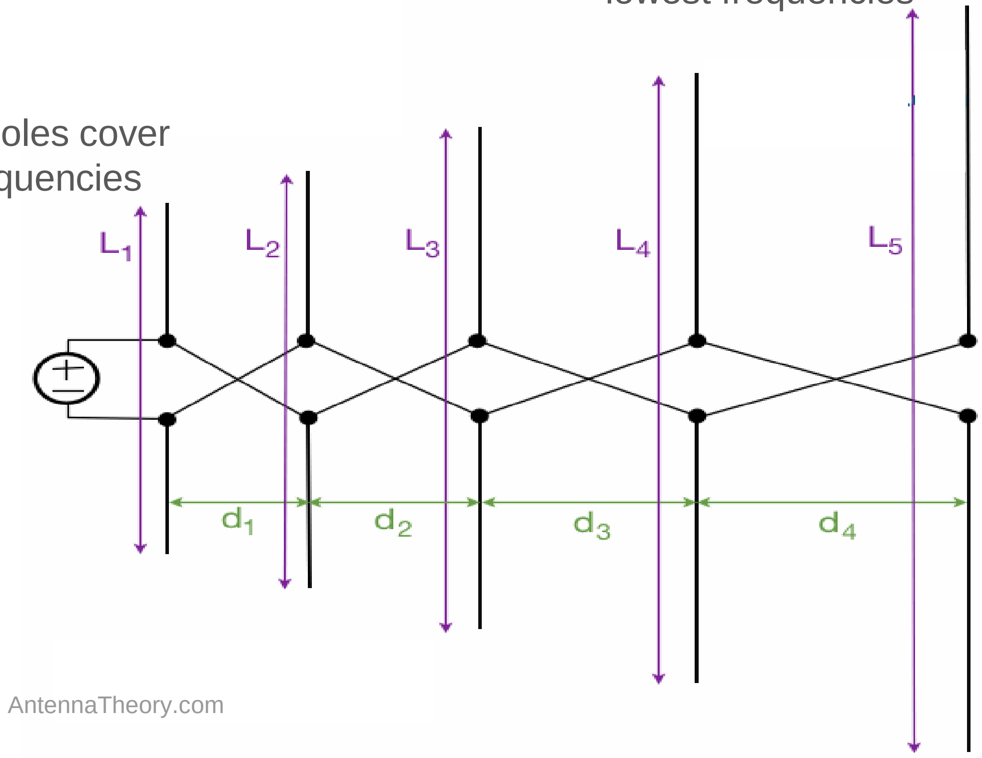
Method 2: Built in house

LPA Wideband antenna

Single antenna could potentially cover both bands

Longest dipoles cover
lowest frequencies

Shortest dipoles cover
Highest frequencies

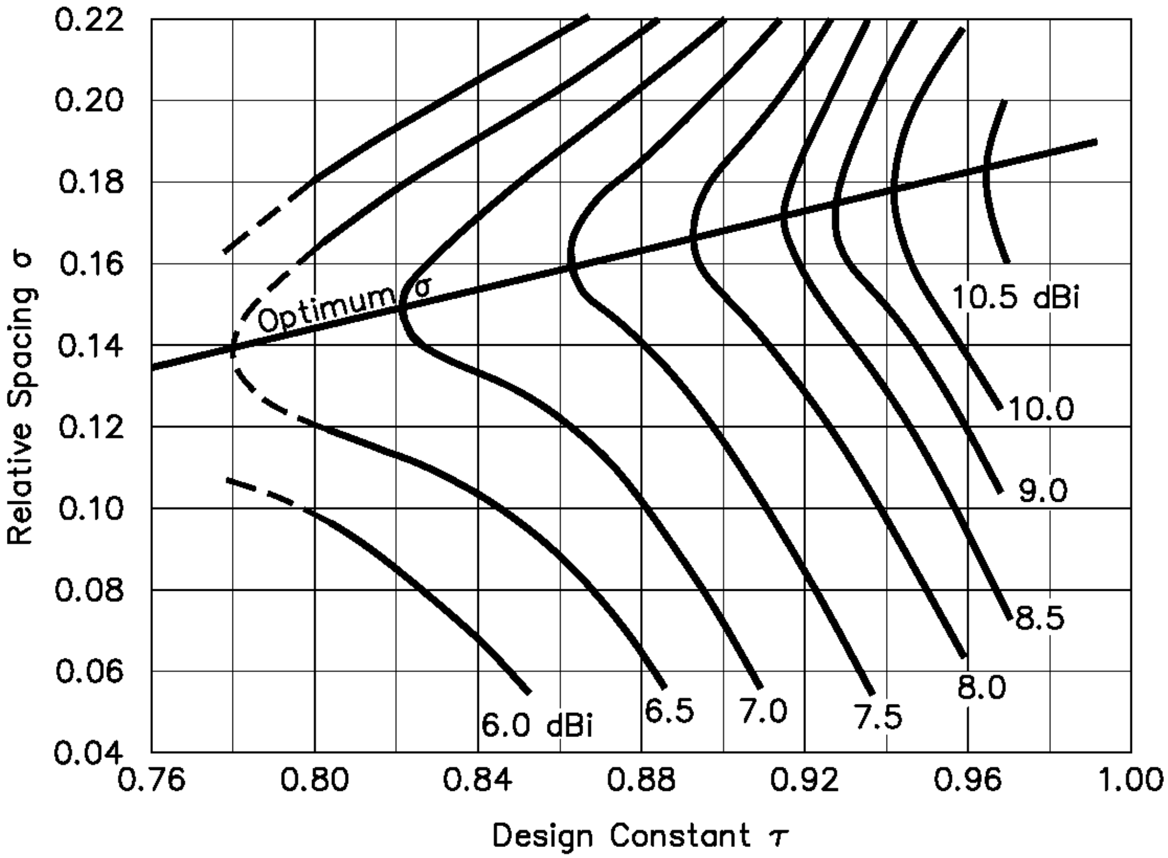


$$L_{dipole} = \frac{468}{f}$$

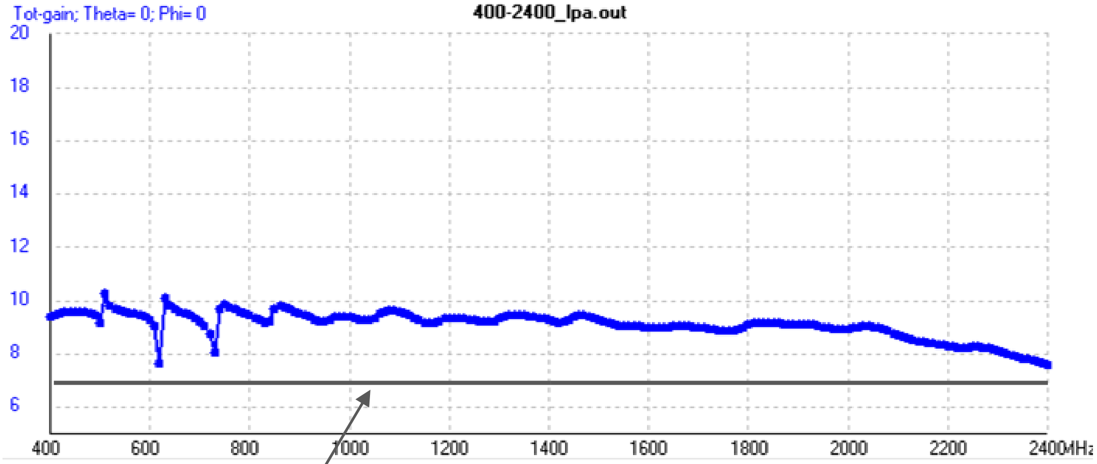
Poles are distributed based on **τ**:

$$\frac{L_{n+1}}{L_n} = \frac{d_{n+1}}{d_n} = \tau$$

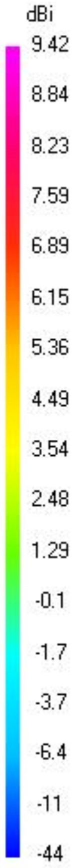
τ is optimized based on desired length and gain



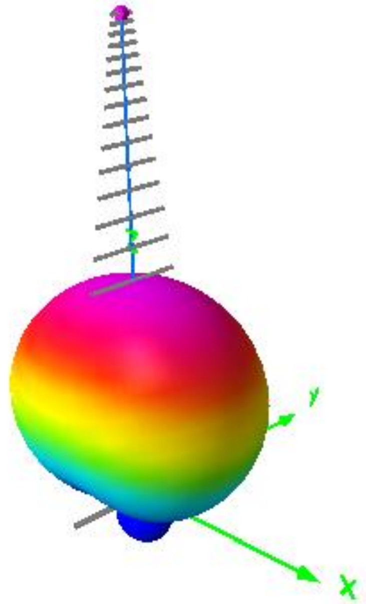
400 MHz - 2.4 GHz
20 element, 3.3ft LPA
Modeled using LPCAD



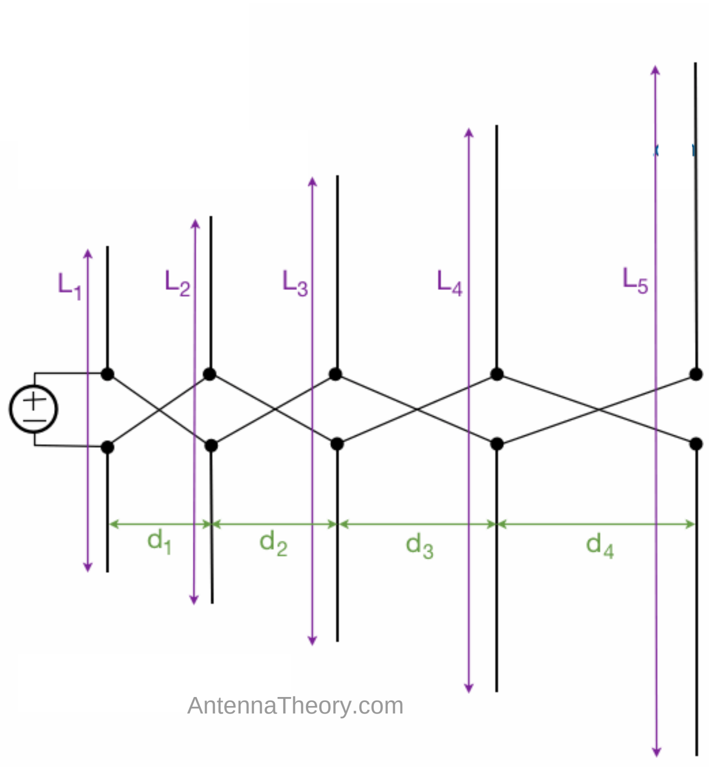
Gain required for G/T and Link Budget



Smallest element: 2”
Largest element: 14”



Antenna feasibility



Method 2: Built in house

Example: LPA Wideband antenna

Single antenna could potentially cover both bands

Feasible

Link-Budget Flowdown

Noise temperature Feasibility

Does the selected hardware meet the system noise requirements

Feasible

→

Link Margin Feasibility

With the expected G/T and satellite candidates can the communication link be closed

Feasible

→

RF Front-End Feasibility

Can the required antenna/LNA/filters be built or bought

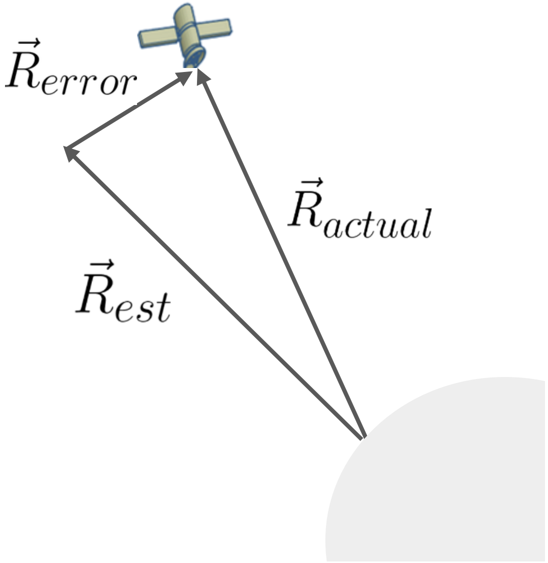
Feasible

Orbital Position estimation using TDoA

Time Delay of Arrival(TDoA) will be the primary method for finding the position of the satellite and requires a specific threshold of timing data and precision.

Orbital Position Estimate using TDoA

$$\vec{R}_{error} = \vec{R}_{actual} - \vec{R}_{est}$$



FR5 Recorded data can be used to produce a orbital position within 10km absolute error of a know satellite candidate

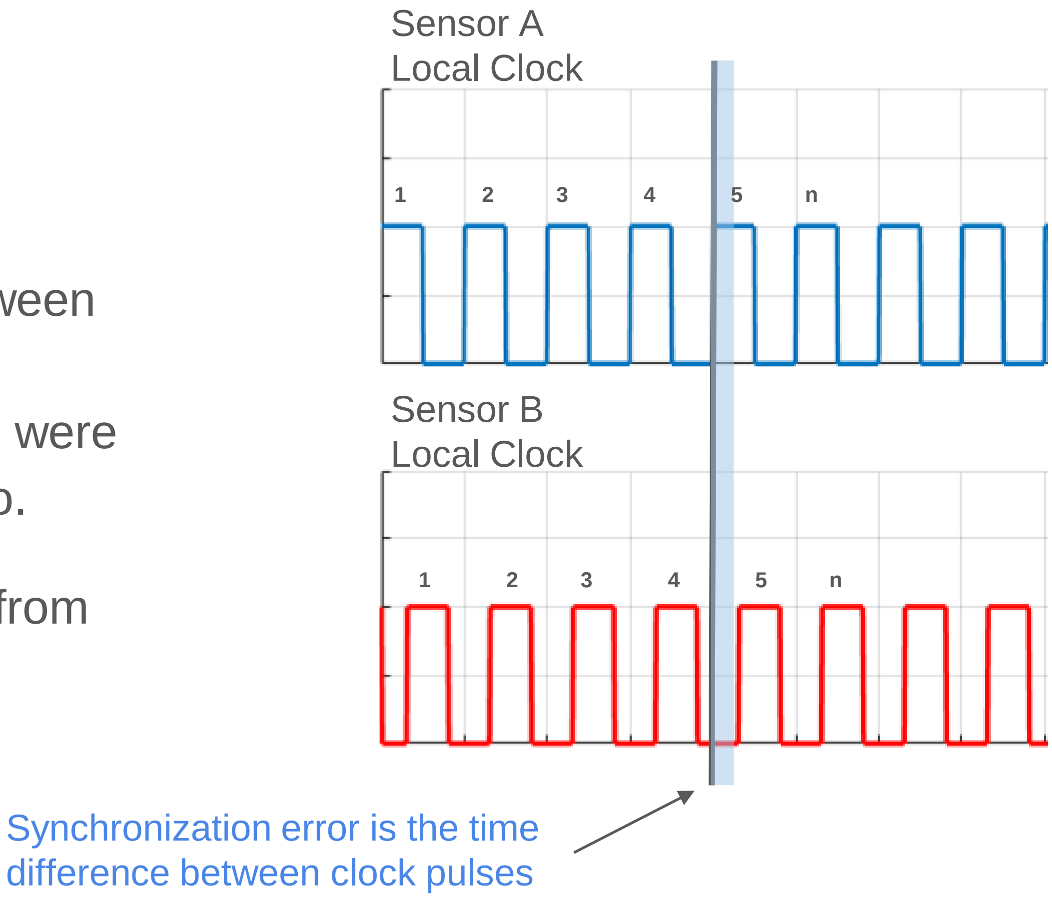
TDoA position estimate depends on two variables:

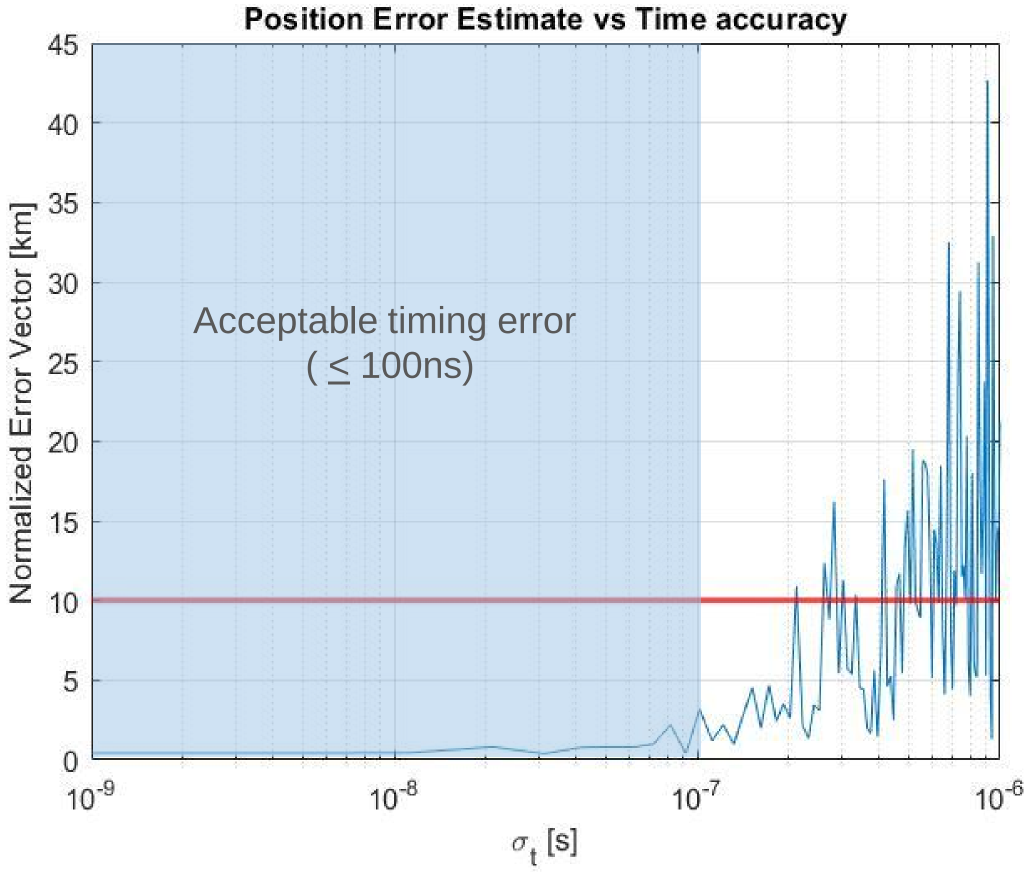
1. Accuracy of Clock Synchronization
2. Distance between Sensor units

Timing Accuracy

To determine the relationship between orbital position error and time synchronization error sensor units were modeled at all corners of Colorado.

Synchronization error was varied from 1 nanosecond - 1 microsecond



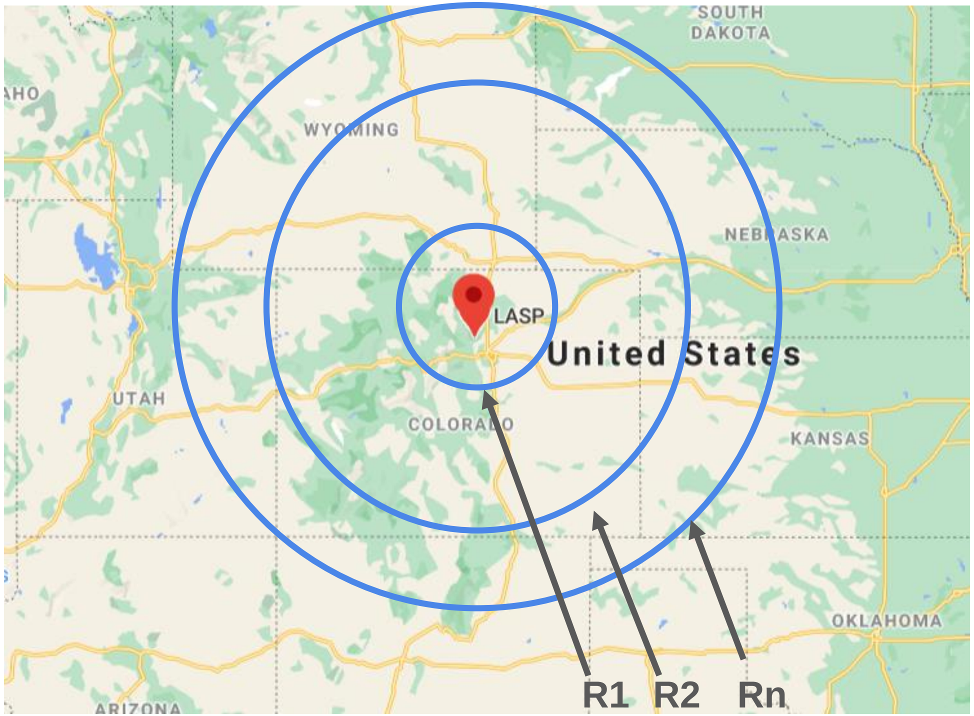


As time synchronization error increased positional error increased

To reach 10 km requirement consistently, timing synchronization error must be ≤ 100ns.

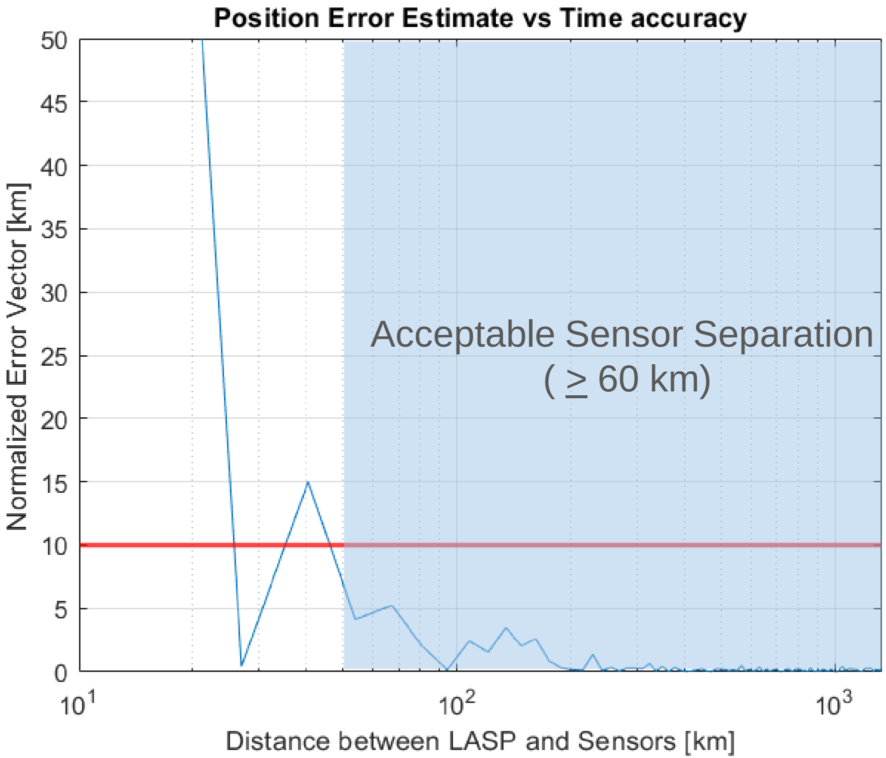
≤ 100ns is **feasible**

Sensor Separation



Separation affects time delay of arrival for each sensor.

The sensors were placed on circles of radius Rn at cardinal directions(North, East, South, West).



As sensor unit separation increase, positional error decreases.

To reach the 10 km requirement, the sensor must be placed on a circle with radius 60 km

60km separation is **feasible**

Timing and Hardware Limitations

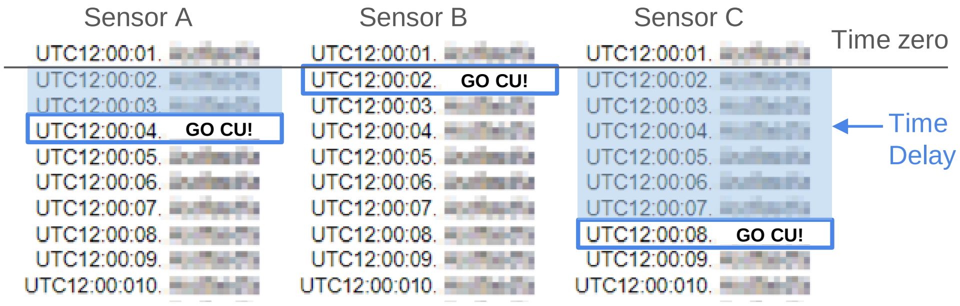
Driven by TDoA, the hardware will need to achieve the prior timing requirement based on TDoA analysis and within hardware capabilities.

Methods of Synchronization

Method 1.

Synchronized clock sources apply local timestamps to IQ data.

The first occurance of the expected transmission is treated as time zero



Method 2.

Reference signal from known source is used to align IQ data

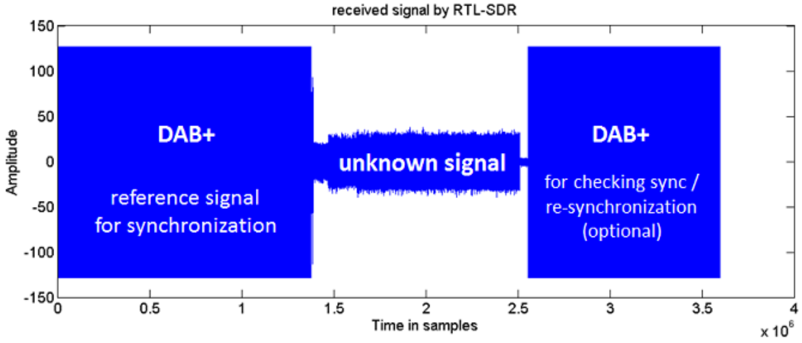
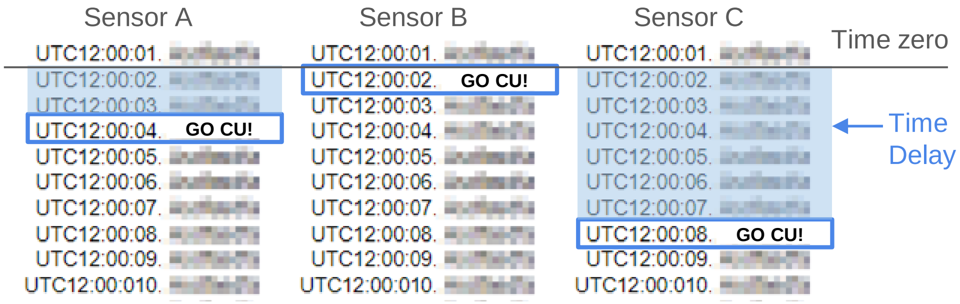


Image from: http://www.panoradio-sdr.de/tdoa-transmitter-localization-with-rtl-sdrs/

Methods of Synchronization

Method 1.

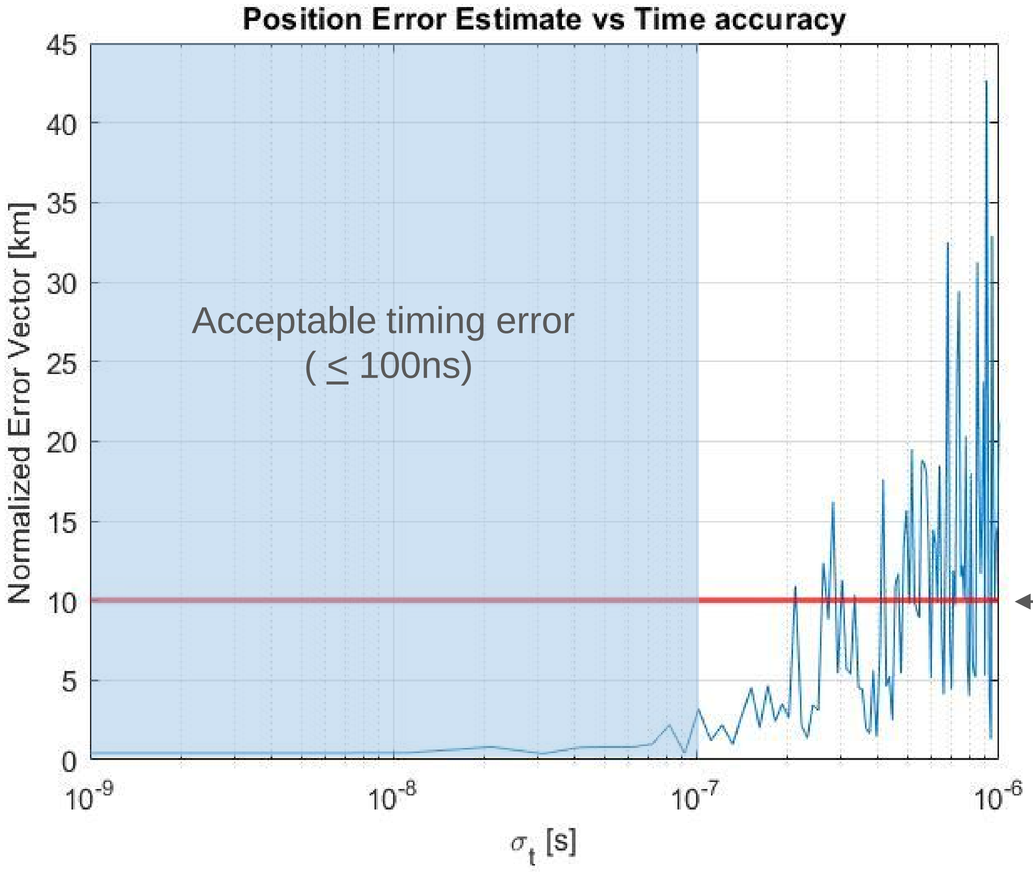
Use synchronized clock sources across all units to apply local timestamps to the RF data as it is received by the SDR. The first occurance of the expected transmission is treated as time zero



Method 2.

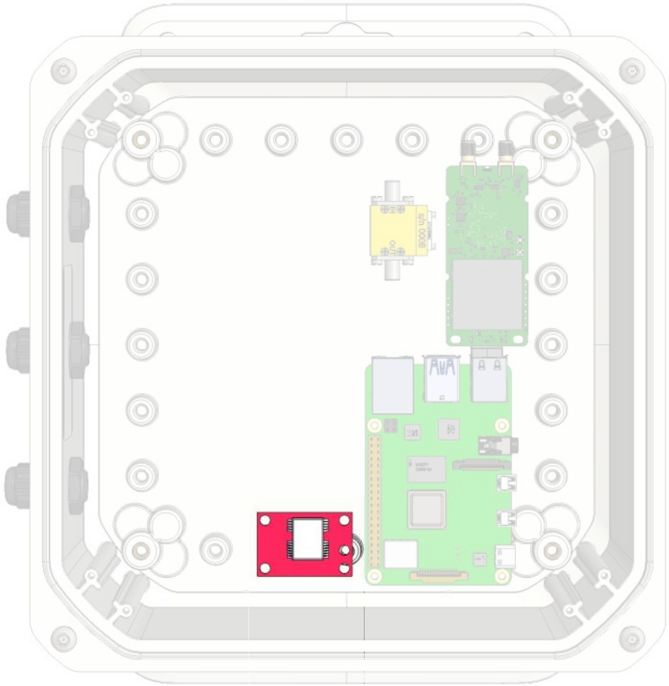
Use a reference signal that is being transmitted from a know location. This known pattern and expected delay can be used to align the data post testing.

Image from: http://www.panoradio-sdr.de/tdoa-transmitter-localization-with-rtl-sdrs/



From TDoA analysis timing error must be ≤100 nanoseconds

FR5. Recorded data can be used to produce a orbital position within 10km absolute error of a know satellite candidate



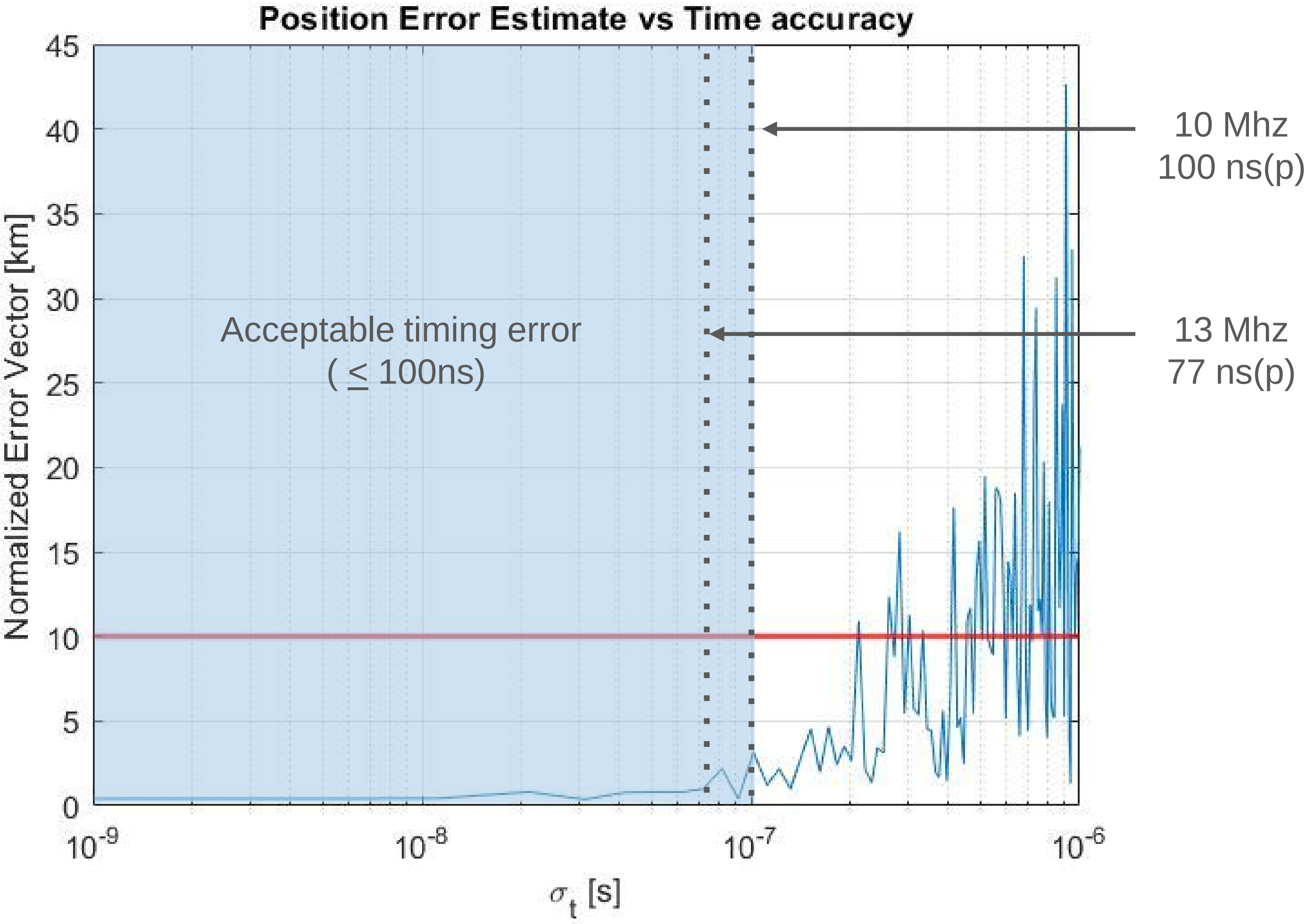
NEO-7m GPS Clock for Sync

Rated for reference clock of 10 MHz

Unrated for reference clock of 13 MHz

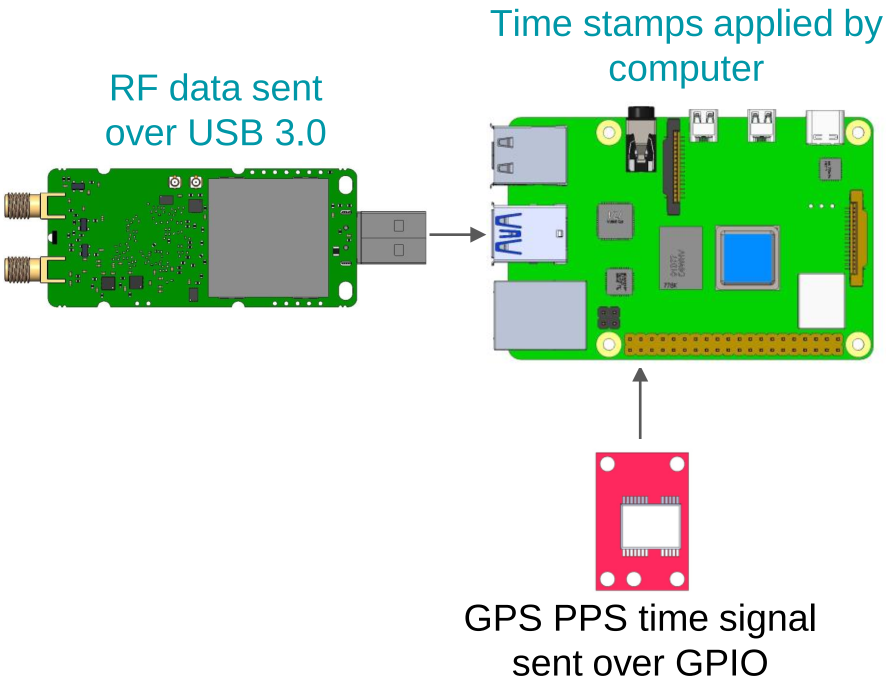
10 MHz → 100 nanoSecond(p)

13 MHz → ~77 nanoSeconds(p)



Position Error Estimate vs Time accuracy
Normalized Error Vector [km]
45
40
35
30
25
20
15
10
5
0
10^-9
10^-8
10^-7
10^-6
σ_t [s]
Acceptable timing error
(≤ 100ns)
10 Mhz
100 ns(p)
13 Mhz
77 ns(p)

Original Pipeline



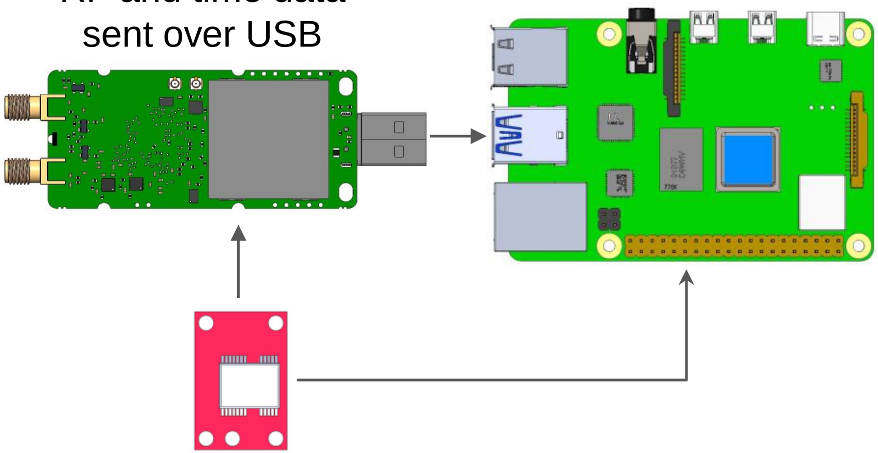
The GPS PPS signal and RF IQ data are recorded separately and paired up by the computer

Not Feasible

- USB protocol will induce some unknown error.
- This error could theoretically be predicted and **reduced** but will require extensive research into the Pi 4’s 500+ page data sheet.

New Pipeline

RF and time data
sent over USB



GPS PPS time signal
injected into SDR and
Onboard computer

GPS PPS signal is used to synchronize the sampling rate of the SDRs across all units.

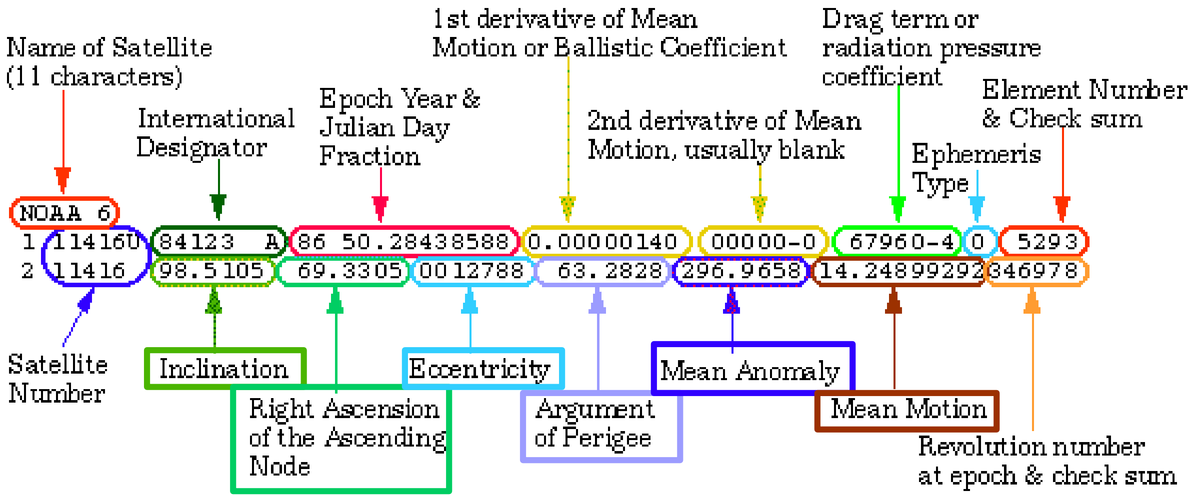
~~Not Feasible~~ Feasible

- Time delay can be extracted from known PPS sample rate
- Avoids USB protocol

Orbital Determination

Is there a viable method to produce a TLE set from the collected data?

Two Line Element (TLE)



Keplerian Elements:

- Inclination (i) [deg]
- RAAN (Ω) [deg]
- Eccentricity (e) [~]
- Arg. of Perigee (ω) [deg]
- Mean Anomaly (M) [deg]
- Mean Motion (n) [rev/day]

Image from: https://spaceflight.nasa.gov/realdata/sightings/SSapplications/Post/JavaSSOP/SSOP_Help/tle_def.html

Orbital Determination Methods

Method 1. *Radio Frequency Satellite Tracking (STRF)*

[Radio Frequency Satellite Tracking (STRF): Software]

This toolkit uses RF recordings to extract frequency measurements that give Doppler curves. These are then used to perform TLE matching and optimization for satellite identification and orbit determination.

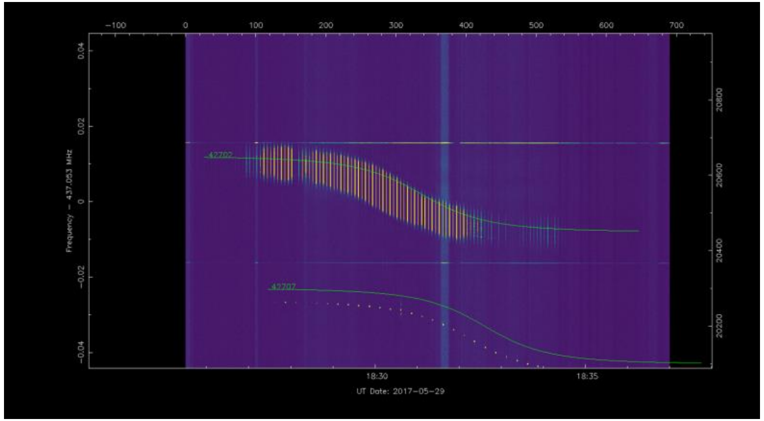


Image from: https://destevez.net/2019/01/an-strf-crash-course/

Method 2. *Gibb's Method*

[Gibb's Method Approach]

Using multiple position measurements of the target satellite from TDoA, a velocity vector is found. This along with its corresponding position vector can then be used to compute the orbital elements of the satellite.

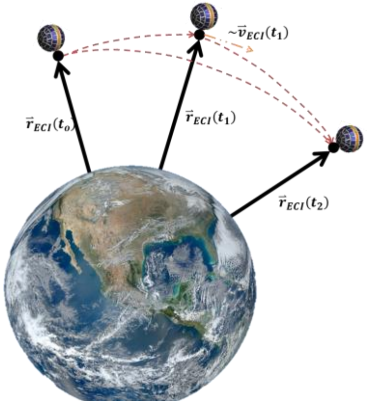
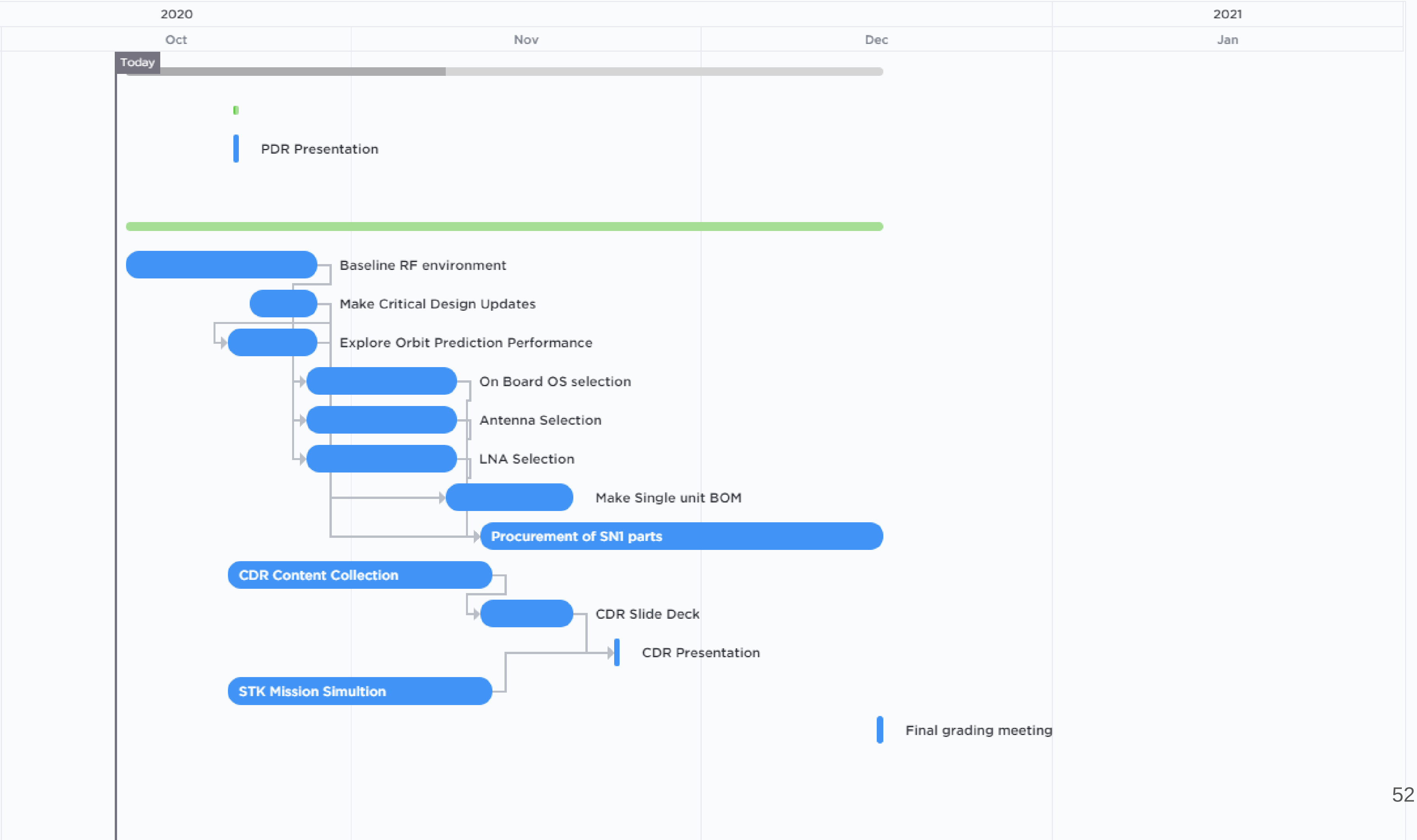


Image from: https://sites.google.com/site/asen5050kemble/gibbs-method-orbit-determination

Recap

Critical Project Element	Feasibility Results
UHF and L-Band Link Budget	**Feasible**, The G/T requirement for the system can be met through a combination of LNA and antenna gain. Given these restriction the Link-margin requirement can still be satisfied.
RF Front-End	**Feasible**, The antenna gain, LNA and RF system requirements can all be fulfilled in a number of ways either through off the shelf or theoretically in-house built components
Orbital Position Estimate using TDoA	**Feasible,** TDoA will a position within the required error bounds given we can achieve a time resolution and that the units can be space out over 100 kilometers apart
Timing and Hardware Limitations	**Feasible,** Given the new pipeline method there should be no hardware bottlenecks. As long as the GPS can produce a 10MHz > reference signal the required timing can be achieved
Orbital determination	**Feasible,** Determination methods such as STRF and Gibbs method should be able to identify the satellite and produce a TLE.


2020
2021
Oct
Nov
Dec
Jan
Today
PDR Presentation
Baseline RF environment
Make Critical Design Updates
Explore Orbit Prediction Performance
On Board OS selection
Antenna Selection
LNA Selection
Make Single unit BOM
Procurement of SN1 parts
CDR Content Collection
CDR Slide Deck
CDR Presentation
STK Mission Simultion
Final grading meeting

Backup Slides

Baseline Satellite Choices

CSIM

The first of the LASP payloads is the CSIM cubesat. It will be measuring the wavelengths from the sun from the near-ultraviolet to the near infrared – a wavelength range encompassing 96% of the total output of the sun. It's a 6U cubesat that will measure solar spectral irradiance (SSI) to understand how solar variability impacts the Earth's climate and to validate climate model sensitivities.
spaceflight.com

- UHF 437.35 MHZ
- GMSK Modulation
- 2.7kbps
- Sun-Synchronous Orbit (575km)

Iridium-169

The Iridium satellite constellation provides L band voice and data information coverage to satellite phones, pagers and integrated transceivers over the entire Earth surface. Iridium Communications owns and operates the constellation, additionally selling equipment and access to its services.
Wikipedia

- L-Band 1626 MHz
- QPSK Modulation
- 2.4kbps
- 7.0 Watt Transmitter
- Sun-Synchronous Orbit (770km)

UHF System Noise Temperature

$$T_s = aT_a + (1 - a)T_o + T_{LNA} + T_{ComRcvr}/(G_{LNA}/L_D)$$

Cable/Guide Type:			Belden 9913 cable	
Cable/Guide Loss/meter:	0.092	dB (at freq.)	437.5	MHz
Line A Loss:		LA =	0.046	dB
Line B Loss:		LB =	0.0092	dB
Line C Loss:		LC =	0.0092	dB
Bandpass Filter Insertion Loss:		LBPF =	1.5	dB
Insertion Loss of Other In-Line Devices		Lother =	0.0	dB
No. of In-Line Connectors:	4	X 0.05 dB/con.=	0.2	dB
Other In-Line Device Type:			none	
Total In-Line Losses from Antenna to LNA:			1.76	dB
Transmission Line Coefficient:		a =	0.6661	
Antenna or "Sky" Temperatu	NOTE:	Ta =	191.016239	K
Ground Station Feedline Temperature:		To =	290	K
LNA Temperature:		TLNA =	43	K
LNA Gain:	22.4 dB	GLNA =	172.7	
Cable/Waveguide D Length:	NOTE:		0.1	meteres
Cable/Waveguide D Type:			Belden 9913 cable	
Cable/Waveguide D Loss/meter:			0.092	dB/m
Cable/Waveguide D Loss:			0.0	dB
Communications Receiver Front End Temperatu		TComRcvr =	1000	K
System Noise Temperature:		Ts =	273	K

Ground Station, Antenna or Sky Noise Temperature Calculation Tool:

Galactic Noise Component:			
	Receiver Frequency:	437.5	MHz
	Coldest Galactic Noise Temp	20	K
	Warmest Galactic Noise Ter	84	K
Terrestrial Noise Component:			
	Receiver Bandwidth:	30.0	KHz
NOTE:	Estimated or Measured Noise Leve	-132.4	dBm
	Noise Source Effective Temperatu	139	K
Minimum Sky Noise Temp:		159	K
Maximum Sky Noise Temp:		223	K

https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/

UHFG/T and Link Margin

Isotropic Signal Level at Ground Station:	-143.8	dBW	This is the signal level received at the Earth in the vacinity of the ground station using an omnidirectional antenna.
Ground Station (EbNo Method):			
------- Eb/No Method -------			
Ground Station Antenna Pointing Loss:	9.5	dB	This value is transferred from "Antenna Pointing Losses" W/S, Cell [K102]
Ground Station Antenna Gain:	11.0	dBi	This value is selected at "Antenna Gain" W/S, Cell [E58]
Ground Station Total Transmission Line Losses:	1.8	dB	This value is transferred from the "Receivers" W/S, Cell [J123]
Ground Station Effective Noise Temperature:	273	K	This value is calculated in the "Receivers" W/S and Transferred from Cell [J138]
Ground Station Figure of Merrit (G/T):	-15.1	dB/K	G/T = Ga-Ltl-10log(Ts). This is the uptimate measure of the receiver's performance.
G.S. Signal-to-Noise Power Density (S/No):	60.2	dBHz	Boltzman's Constant: -228.6 dBW/K/Hz
System Desired Data Rate:	9700	bps	Operator selects this value. Be Careful! This is the data rate, not the symbol rate.
In dBHz:	39.9	dBHz	This is simply = 10log(R); R= data rate
Telemetry System Eb/No for the Downlink:	20.3	dB	
Demodulation Method Seleted:	GMSK		Values selected in "Modulation-Demodulation W/S, Cell [E30]
Forward Error Correction Coding Used:	None		Value selected in "Modulation-Demodulation" W/S, also Cell [E30]
System Allowed or Specified Bit-Error-Rate:	1.0E-04		The selected value is transferred from the "Modulation-Demodulation W/S, Cells [E33:E50]
Demodulator Implementation Loss:	0.0	dB	This value is transferred from the "Modulation-Demodulation W/S, Cell[E52]
Telemetry System Required Eb/No:	8.4	dB	The selected value is transferred from the "Modulation-Demodulation W/S, Cells [F33:F50]
Eb/No Threshold:	8.4	dB	This is the result of the "Modulation-Demodulation" W/S and is transferred from Cell [H32]
System Link Margin:	11.9	dB	

https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/

L-Band System Noise Temperature

Line A Loss:	L_A =	0.046	dB
Line B Loss:	L_B =	0.0092	dB
Line C Loss:	L_C =	0.0092	dB
Bandpass Filter Insertion Loss:	L_{BPF} =	1.5	dB
Insertion Loss of Other In-Line Devices	L_{other} =	0.0	dB
No. of In-Line Connectors: 4	X 0.05 dB/con.=	0.2	dB
Other In-Line Device Type:		none	
Total In-Line Losses from Antenna to LNA:		1.76	dB
Transmission Line Coefficient:	a =	0.6661	
Antenna or "Sky" Temperatu NOTE:	T_a =	4.91862292	K
Ground Station Feedline Temperature:	T_o =	290	K
LNA Temperature:	T_{LNA} =	29.4	K
LNA Gain: 14.0 dB	G_{LNA} =	25.1	
Cable/Waveguide D Length: NOTE:		0.1	meteres
Cable/Waveguide D Type:		Belden 9913 cable	
Cable/Waveguide D Loss/meter:		0.092	dB/m
Cable/Waveguide D Loss:		0.0	dB
Communications Receiver Front End Temperatu	$T_{ComRcvr}$ =	1000	K
System Noise Temperature:	T_s =	169	K

Ground Station, Antenna or Sky Noise Temperature Calculation Tool:

Galactic Noise Component:		
Receiver Frequency:	1702.5	MHz
Coldest Galactic Noise Temp	3	K
Warmest Galactic Noise Ter	5	K
Terrestrial Noise Component:		
Receiver Bandwidth:	4000.0	KHz
NOTE: Estimated or Measured Noise Leve	-132.4	dBm
Noise Source Effective Temperatu	1	K
Minimum Sky Noise Temp:	4	K
Maximum Sky Noise Temp:	6	K

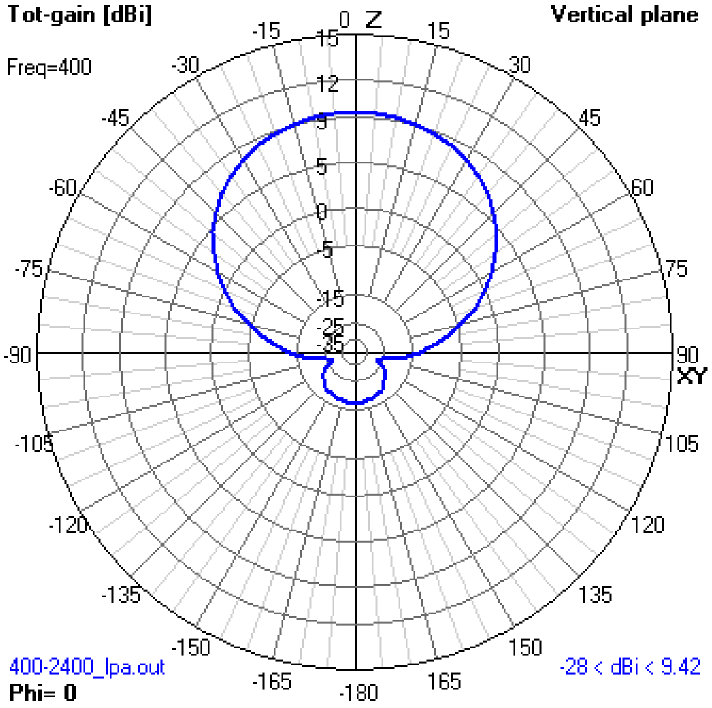
https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/

L-Band: G/T and Link Margin

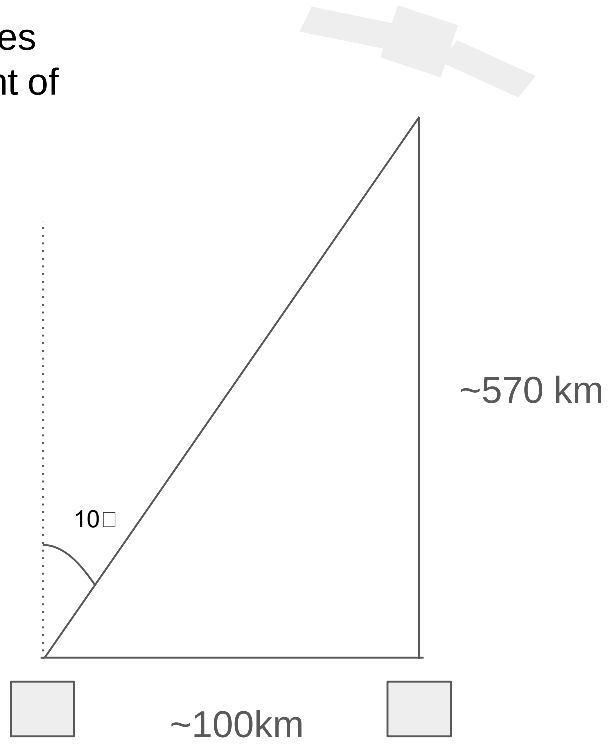
Rain Loss:	0.0	dB	This value should be estimated by the link model operator and place into Cell [D16]
Isotropic Signal Level at Ground Station:	-154.2	dBW	This is the signal level received at the Earth in the vacinity of the ground station using an omnidirectional antenna.
Ground Station (EbNo Method):			
------- Eb/No Method -------			
Ground Station Antenna Pointing Loss:	9.5	dB	This value is transferred from "Antenna Pointing Losses" W/S, Cell [K102]
Ground Station Antenna Gain:	11.1	dBi	This value is selected at "Antenna Gain" W/S, Cell [E58]
Ground Station Total Transmission Line Losses:	1.8	dB	This value is transferred from the "Receivers" W/S, Cell [J123]
Ground Station Effective Noise Temperature:	166	K	This value is calculated in the "Receivers" W/S and Transferred from Cell [J138]
Ground Station Figure of Merrit (G/T):	-12.9	dB/K	G/T = Ga-Ltl-10log(Ts). This is the uptimate measure of the receiver's performance.
G.S. Signal-to-Noise Power Density (S/No):	52.0	dBHz	Boltzman's Constant: -228.6 dBW/K/Hz
System Desired Data Rate:	2400	bps	Operator selects this value. Be Careful! This is the data rate, not the symbol rate.
In dBHz:	33.8	dBHz	This is simply = 10log(R); R= data rate
Telemetry System Eb/No for the Downlink:	18.2	dB	
Demodulation Method Seleted:	**User Defined**		Values selected in "Modulation-Demodulation W/S, Cell [E30]
Forward Error Correction Coding Used:	**None**		Value selected in "Modulation-Demodulation" W/S, also Cell [E30]
System Allowed or Specified Bit-Error-Rate:	1.0E-06		The selected value is transferred from the "Modulation-Demodulation W/S, Cells [E33:E50]
Demodulator Implementation Loss:		dB	This value is transferred from the "Modulation-Demodulation W/S, Cell[E52]
Telemetry System Required Eb/No:	9.1	dB	The selected value is transferred from the "Modulation-Demodulation W/S, Cells [F33:F50]
Eb/No Threshold:	9.1	dB	This is the result of the "Modulation-Demodulation" W/S and is transferred from Cell [H32]
System Link Margin:	9.1	dB	

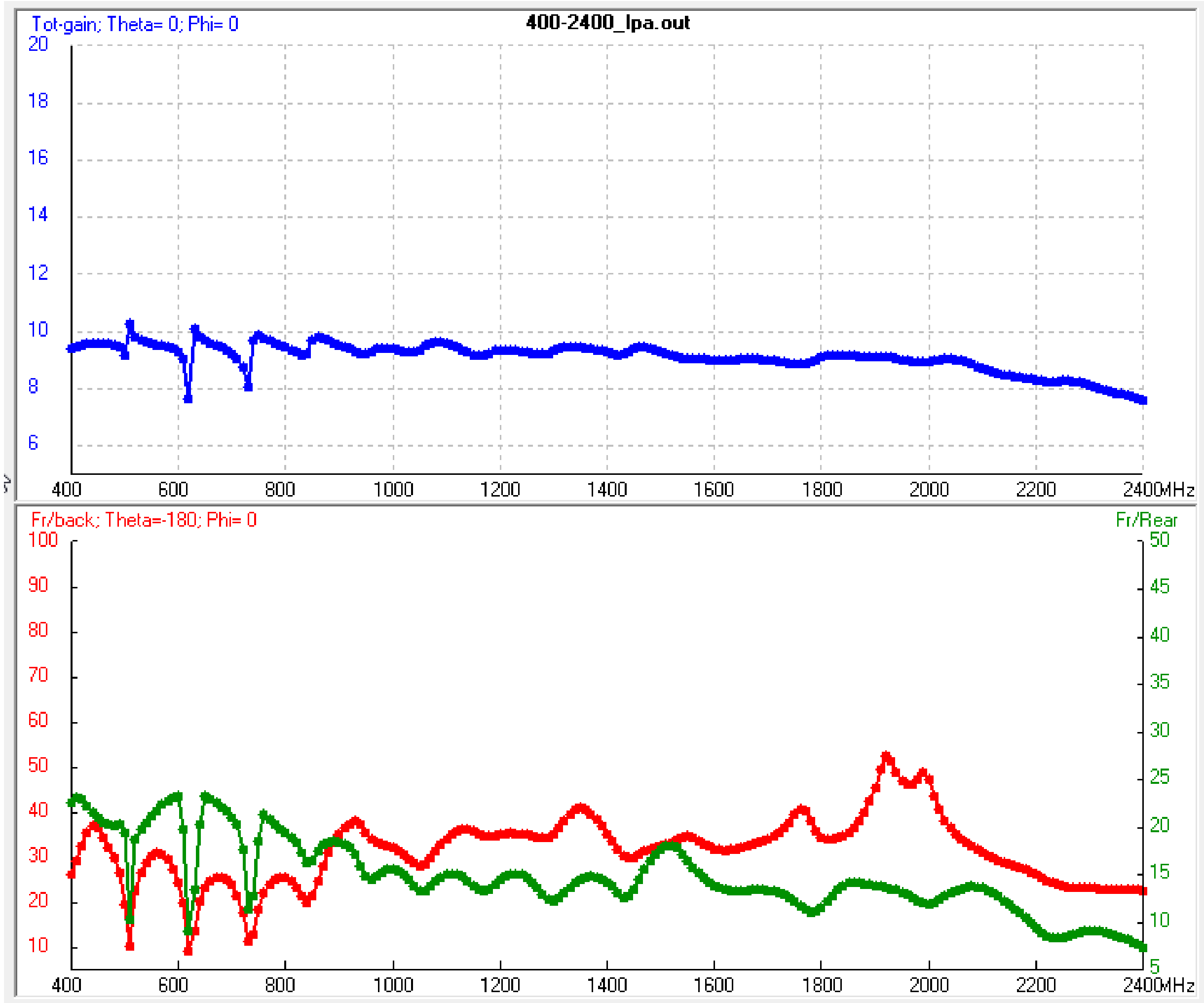
https://www.amsat.org/tools-for-calculating-spacecraft-communications-link-budgets-and-other-design-issues/

Minimum required FOV



TDoA study drives FOV requirement of 20°





Tot-gain; Theta= 0; Phi= 0
400-2400_lpa.out
20
18
16
14
12
10
8
6
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400MHz
Fr/back; Theta=-180; Phi= 0
Fr/Rear
100
90
80
70
60
50
40
30
20
10
50
45
40
35
30
25
20
15
10
5
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400MHz

LNA options

UHF: 22.372dB Gain, NF 0.6dB

RFMD
rfmd.com

SPF5189Z

50 MHz to 4000 MHz, GaAs pHEMT LOW NOISE MMIC AMPLIFIER

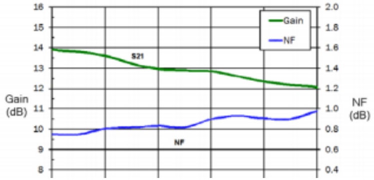
Product Description

The SPF5189Z is a high performance pHEMT MMIC LNA designed for operation from 50 MHz to 4000 MHz. The on-chip active bias network provides stable current over temperature and process threshold voltage variations. The SPF5189Z offers ultra-low noise figure and high linearity performance in a gain block configuration. Its single-supply operation and integrated matching networks make implementation remarkably simple. A high maximum input power specification make it ideal for high dynamic range receivers.

Optimum Technology Matching® Applied

- ☐ GaAs HBT
- ☐ GaAs MESFET
- ☐ InGaP HBT
- ☐ SiGe BiCMOS
- ☐ Si BiCMOS
- ☐ SiGe HBT
- ✓ GaAs pHEMT
- ☐ Si CMOS
- ☐ Si BJT

Gain and NF versus Frequency



Features

- Ultra-Low Noise Figure=0.60 dB at 900 MHz
- Gain=18.7 dB at 900 MHz
- High Linearity: OIP_3=39.5 dBm at 1960 MHz
- P_{1dB}=22.7 dBm at 1960 MHz
- Single-Supply Operation: 5V at I_{DQ}=90 mA
- Flexible Biasing Options: 3V to 5V, Adjustable Current
- Broadband Internal Matching

Applications

- Cellular, PCS, W-CDMA, ISM, WiMAX Receivers
- PA Driver Amplifier

L-Band: 14.0dB Gain, NF 0.4dB

Ultra Low Noise, High IP3

Monolithic Amplifier **PMA2-33LN+**

50Ω 0.4 to 3.0 GHz

2mm x 2mm

The Big Deal

- Ultra Low Noise Figure, 0.38 dB
- High Gain, High IP3
- Small Size, 2 x 2 x 1mm

Key Features

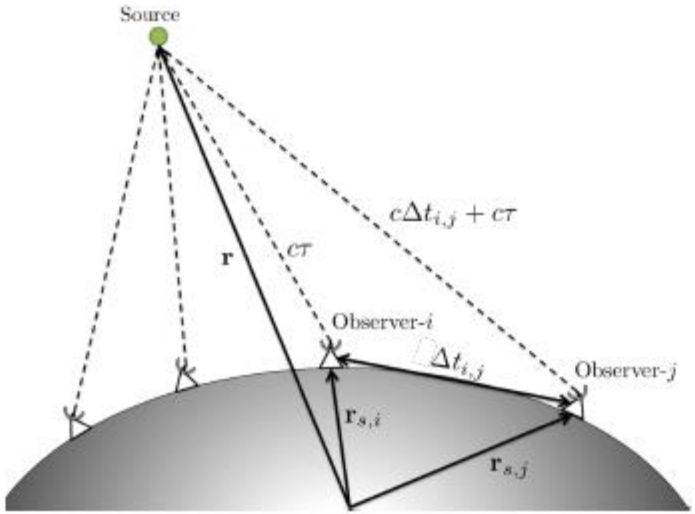
Feature	Advantages
Ultra Low Noise, 0.38 dB at 0.9 GHz	Enables lower system noise figure performance.
High IP3, • +34 dBm at 0.9 GHz and • +39 dBm at 3 GHz	Combination of low noise and high IP3 makes this MMIC amplifier ideal for use in low noise receiver front end (RFE) as it gives the user advantages of sensitivity & two-tone IM performance at both ends of the dynamic range.

Orbital Position Estimation with TDoA

Derivation:

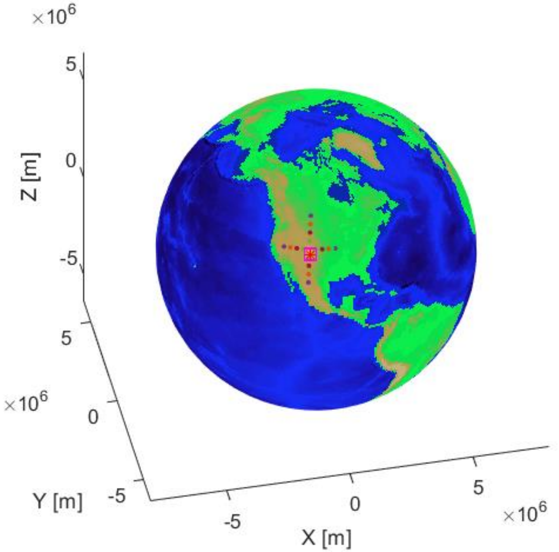
$$c\tau = \|\mathbf{r}_{s,1} - \mathbf{r}\|$$
$$p_2 + c\tau = \|\mathbf{r}_{s,2} - \mathbf{r}\|$$
$$p_3 + c\tau = \|\mathbf{r}_{s,3} - \mathbf{r}\|$$
$$p_4 + c\tau = \|\mathbf{r}_{s,4} - \mathbf{r}\|$$

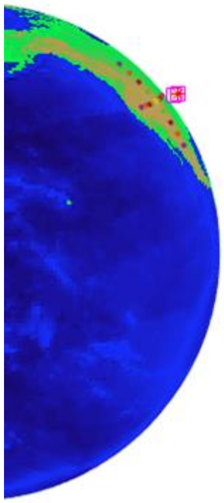
Where: $p_i = c\Delta t_{1,i}$



“UNCUED SATELLITE INITIAL ORBIT DETERMINATION USING SIGNALS OF OPPORTUNITY” Johnny L. Worthy III, Marcus J. Holzingery

Orbital Position Estimation with TDoA





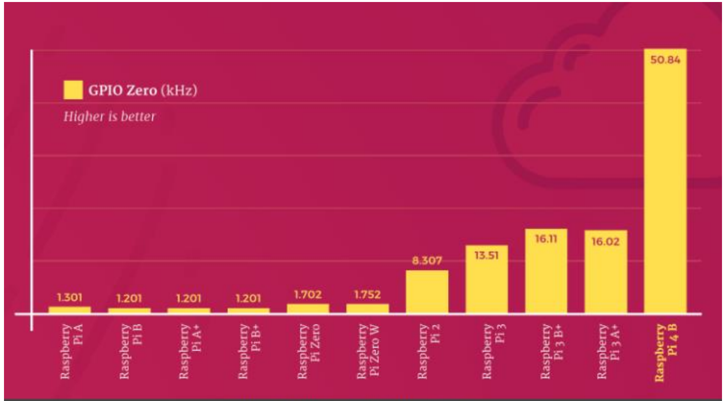
- Time accuracy of 30ns
- Position accuracy of 1m
- Satellite location of R =[-1381.1, -5289.2, 4283.7] km in ECEF

"UNCUED SATELLITE INITIAL ORBIT DETERMINATION USING SIGNALS OF OPPORTUNITY" Johnny L. Worthy III, Marcus J. Holzingery

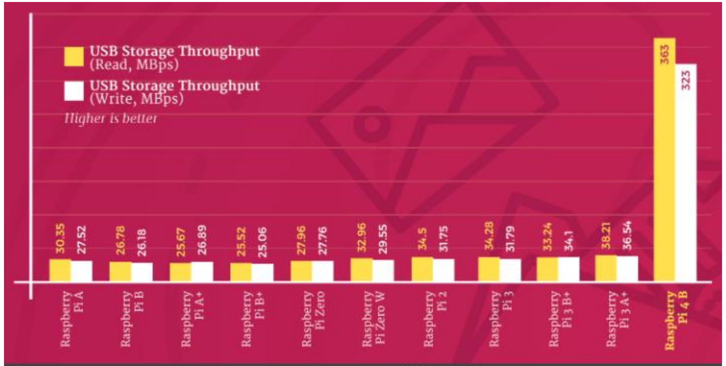
Data Transfer Bottlenecks: Raspberry Pi 4

- The rate at which the Pi 4 can transfer data through its GPIO ports is heavily controlled by the programming language, and by the interrupt configuration used
  - Python (upper right figure)
    - Typically ~ 50 kHz
  - C
    - Typically ~ 131 MHz

- The rate at which the Pi 4 can transfer data through its USB 3.0 ports is comparatively shown in the bottom right figure
  - Read: 363 MBps
  - Write: 323 MBps



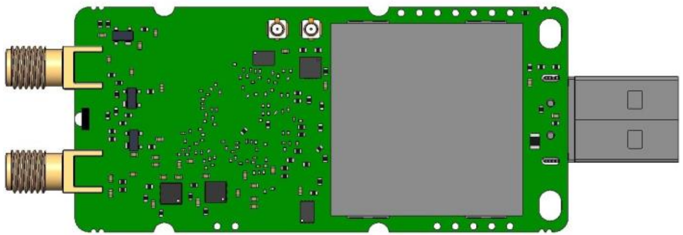
Python GPIO Zero (higher is better)



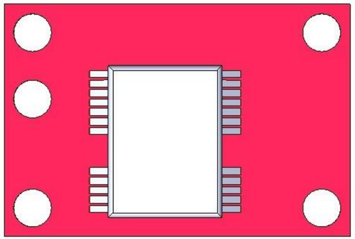
USB storage throughput (higher is better)

Link

Data Transfer Bottlenecks



LimeSDR mini
Max data output of 30.72 MHz using its on chip VCTCXO (Voltage Controlled Temperature Compensated Crystal Oscillator).

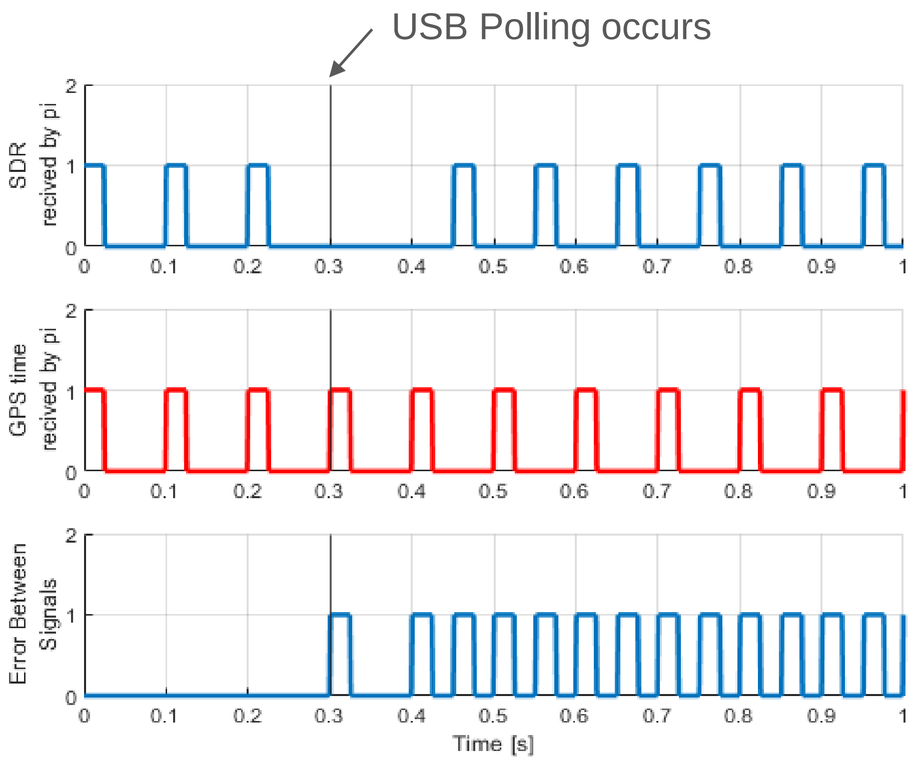


Ublox NEO 7M
The maximum reference output clock per the data sheet is 10 MHz

Has been reported stable at 13 MHz

Link

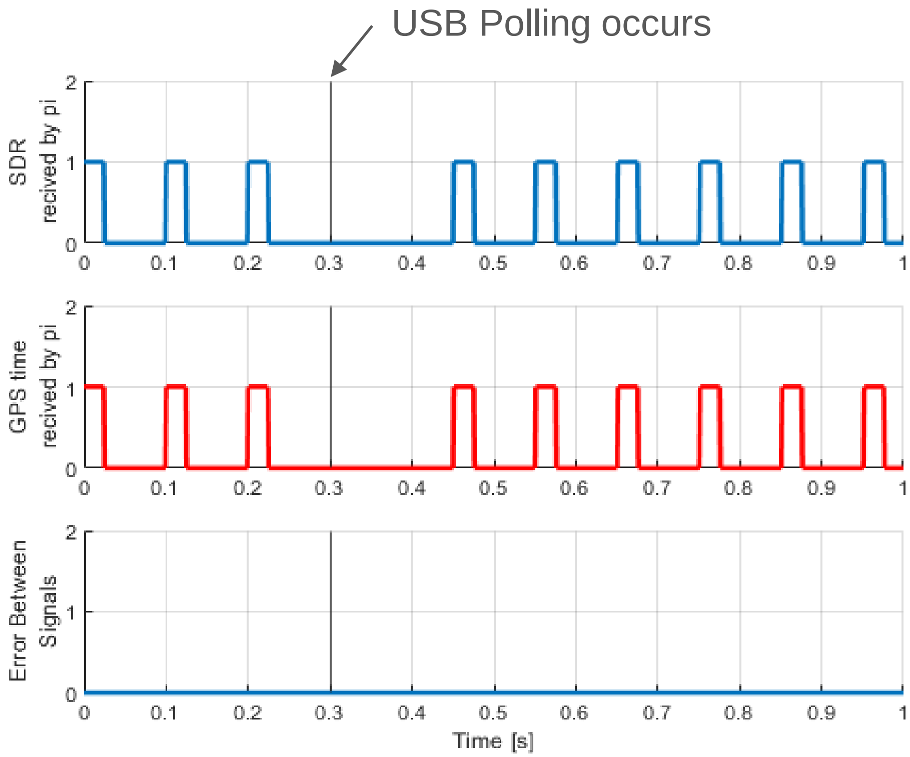
Original Pipeline



This graphic doesn't tell the whole story but is useful for visualizing the error

The “lag” due to polling will be different in each unit depending on the state of the bus registers

New Pipeline



Even if the received signals lag due to USB polling in real time all units continue to remain synchronized as they sample based on the GPS signal

Antenna params for sim

```
Enter Lowest Frequency (MHz):
 Enter Frequency greater than 1 MHz.
Enter Lowest Frequency (MHz):400
Enter Highest Frequency (MHz):2400
Enter rear-element diameter (inches):.5
Do you wish to base design on TAU and SIGMA? (Y/N) n
Do you wish to evaluate a known design? (Y/N) n

The design will be based on the specified number of elements
and the boom length.
Enter number of elements:20
Enter boomlength in inches: (Enter 0 to use Feet) 40
TAU = 0.90
Initial Spacing D(1) =   4.702 inches
Longest Element L(1) =  14.465 inches
SIGMA = 0.16
Approx. Gain =  8 dBi (  5.85 dBd )
Front-to-Back =  13 to  19 dB

PRESS ENTER TO CONTINUE:_
```

Radio Frequency Satellite Tracking (STRF): Software

- Open source, Linux based software satellite tracking solution
- Can be run local on one sensor

Input:

IQ data from SDR

STRF:

- Resources
  - TLE Database
  - Doppler shift Database
- Processing
  - Converts IQ data to doppler shift
  - Matches to recorded doppler shift to database

Outputs:

- Matched TLE from IQ data
- Doppler curve from IQ data

Gibb's Method Approach

TDoA → $\mathbf{r}_{n-1}$, $\mathbf{r}_n$, $\mathbf{r}_{n+1}$ (for given time n)

↳ Gibb's Method (Alg. 5.1) → $\mathbf{v}_n$

Now with $\mathbf{r}_n$ and $\mathbf{v}_n$ can back out orbital elements (Alg. 4.2)

↳ can get (h, i, Ω, e, ω, ν) → want for TLE (i, Ω, e, ω, M, n)

Can use:

$$E = 2\arctan\left(\sqrt{\frac{1-e}{1+e}}\tan\left(\frac{\nu}{2}\right)\right) \qquad M = E - e\sin(E)$$

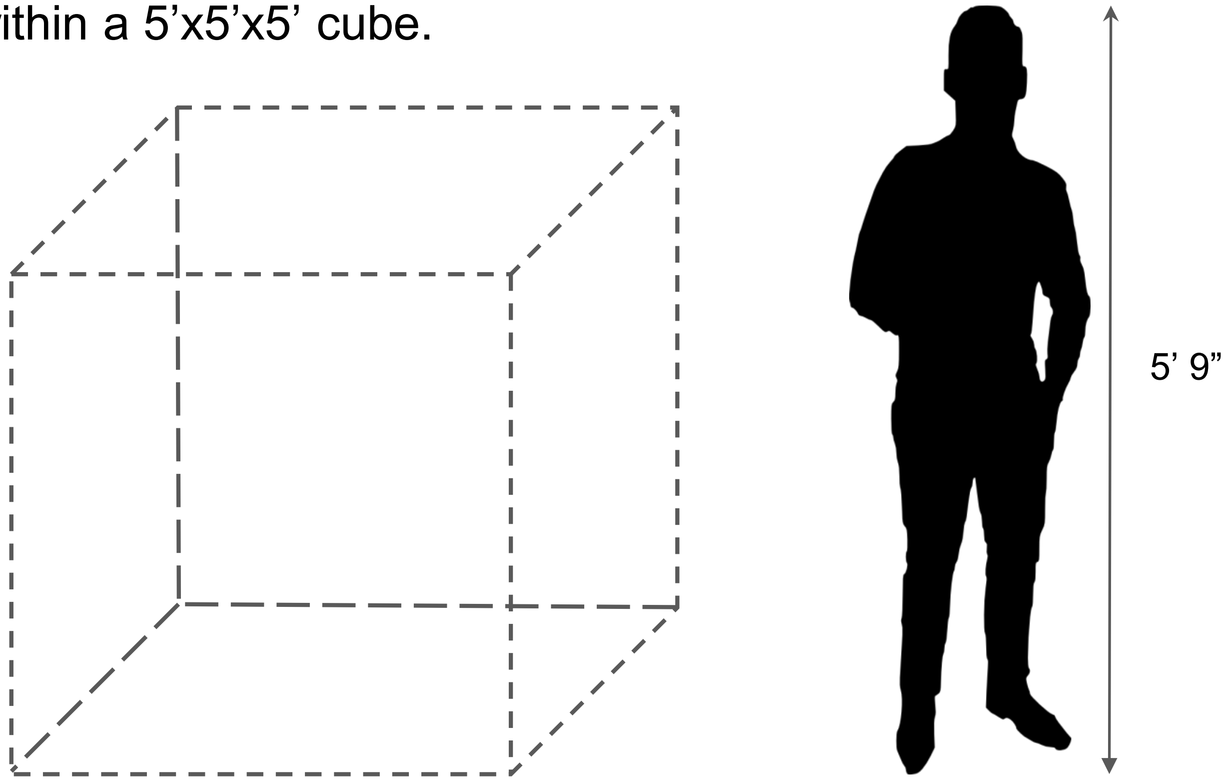
$$\frac{\mu^2(1-e^2)^{3/2}}{h^3} = \frac{2\pi}{T} \implies T = \frac{2\pi h^3}{\mu^2(1-e^2)^{3/2}}$$

$$n = \frac{2\pi}{T} \implies n = \frac{2\pi\mu^2(1-e^2)^{3/2}}{2\pi h^3} \implies n = \frac{\mu^2(1-e^2)^{3/2}}{h^3}$$

Size Feasibility

Baseline design fits within a 5’x5’x5’ cube.

FR2, DR2.1



Durability Concerns

Weather Resistance

Testing will occur outside on a fixed schedule due to the satellites orbit.

The electronics must be protected from rain and snow

FR1, DR1.1, DR1.3

Thermal Control

The electronic components and internal storage have a limited range of operating temperatures.

The electronics must stay within 5 - 50 ℃ for a 24 hour test day

FR1, DR1.2

Weather Resistance

A NEMA 4 rated enclosure

- Ensures internals are protected from water/snow, and suitable for outdoor conditions

- Using NEMA 4 rated components ensures weather resistance (FR1, DR1.4)

Table of outdoor Rated Enclosures

Provides a Degree of Protection Against the Following Conditions	Type of Enclosure									
	3	3X	3R	3RX	3S	3SX	4	4X	6	6P
Access to Hazardous Parts	X	X	X	X	X	X	X	X	X	X
Ingress of Solid Foreign Objects (Falling Dirt)	X	X	X	X	X	X	X	X	X	X
Ingress of Water (Dripping and Light Splashing)	X	X	X	X	X	X	X	X	X	X
Ingress of Water (Rain, Snow, and Sleet)	X	X	X	X	X	X	X	X	X	X
Sleet (Operating mechanisms work with ice)	-	-	-	-	X	X	-	-	-	-
Ingress of Solid Foreign Objects (Windblown Dust, Lint, Fibers, and Flyings)	X	X	-	-	X	X	X	X	X	X
Ingress of Water (Hosedown and Splashing Water)	-	-	-	-	-	-	X	X	X	X
Corrosive Agents	-	X	-	X	-	X	-	X	-	X
Ingress of Water (Occasional Temporary Submersion)	-	-	-	-	-	-	-	-	X	X
Ingress of Water (Occasional Prolonged Submersion)	-	-	-	-	-	-	-	-	-	X

https://certifigroup.com/weekly-whitepaper/nema-enclosure-rating-chart/

Thermal Control

Maximum recorded temperature in Colorado: 46°C

Minimum recorded temperature in Denver: -32°C

Area of lid: ~0.04 m^2

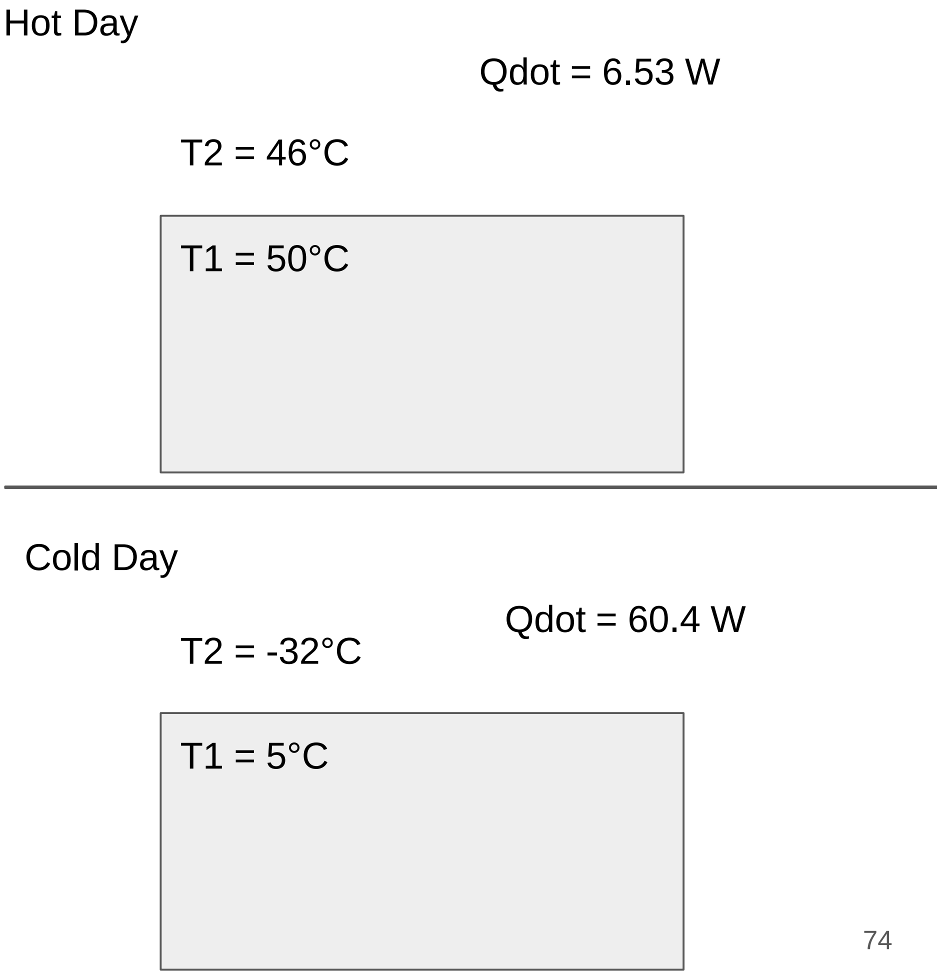
Thermal conductivity of polycarbonate: ~0.2

Thickness of lid: ~4.9mm

Assuming only conduction on hottest and coldest days

Conclusions:

- May need heater for coldest day
- Electronics will not overheat even on hottest day



Cost Feasibility

Per Unit Part Costs:

- Raspberry Pi 4 Model B(8GB) - $75
- LimeSDR mini - $175
- Acrobotic NEO-6M breakout board - $14.95
- Case Plus Hardware - $70
- Antenna - Max ~$200 (4 Yagi Antennas per unit)
- LNA - Max ~$50
- BandPass Filter - Max ~$50
- Misc Cables - $20
- Total: $654.95

Four Unit Suite Cost: $2619.8