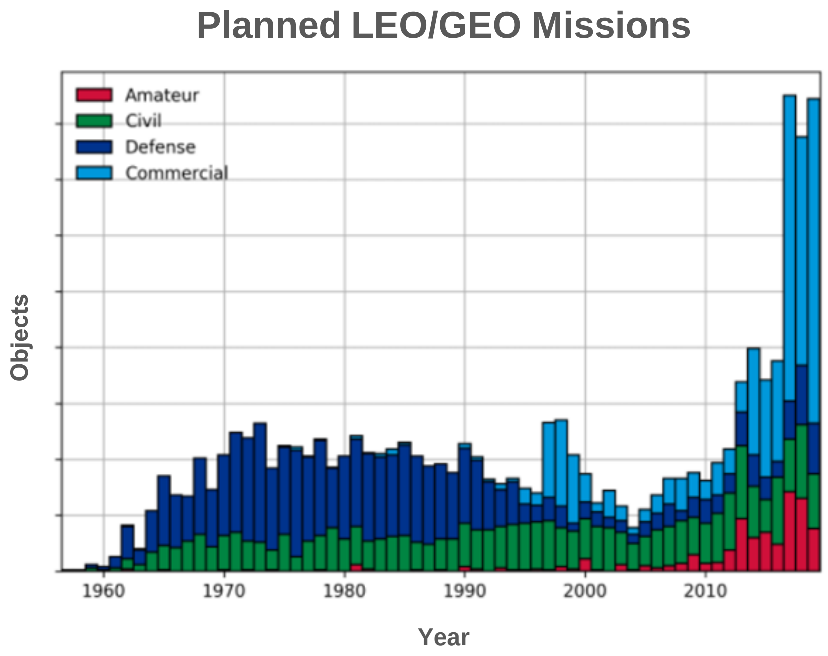
SpaceNet
Manufacturing Status Review

Spring 2021

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

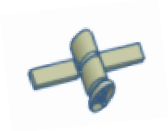
Four unit proof of concept proving hardware and software

This project will produce four functional ground units that can record UHF/L-Band satellite Quadrature signal (IQ) data

The recorded data will be used to produce both a position estimation and orbit estimate

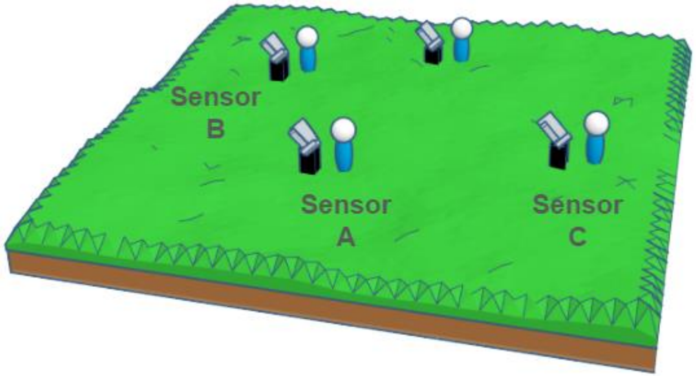
SpaceNet
Concept of Operations (CONOPS)

1. Sensors are temporarily deployed
2. Sensors synchronize to UTC time



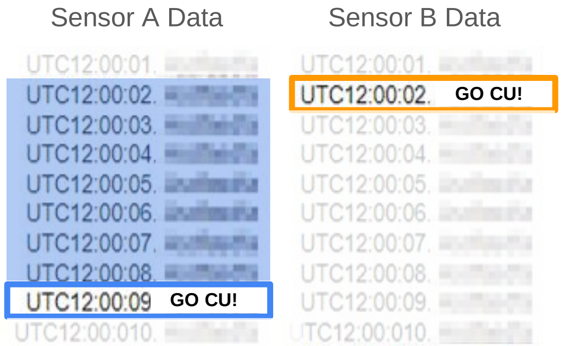
3. Satellite transmits during flyby

4. Transmissions are received by sensors



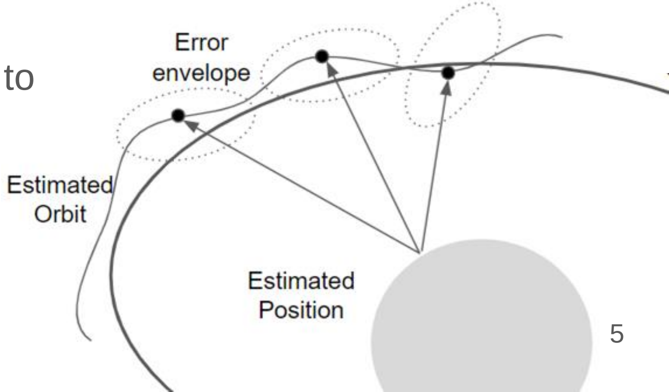
5. Transmissions are identified post test

6. Time delay of signal arrival is calculated from UTC time

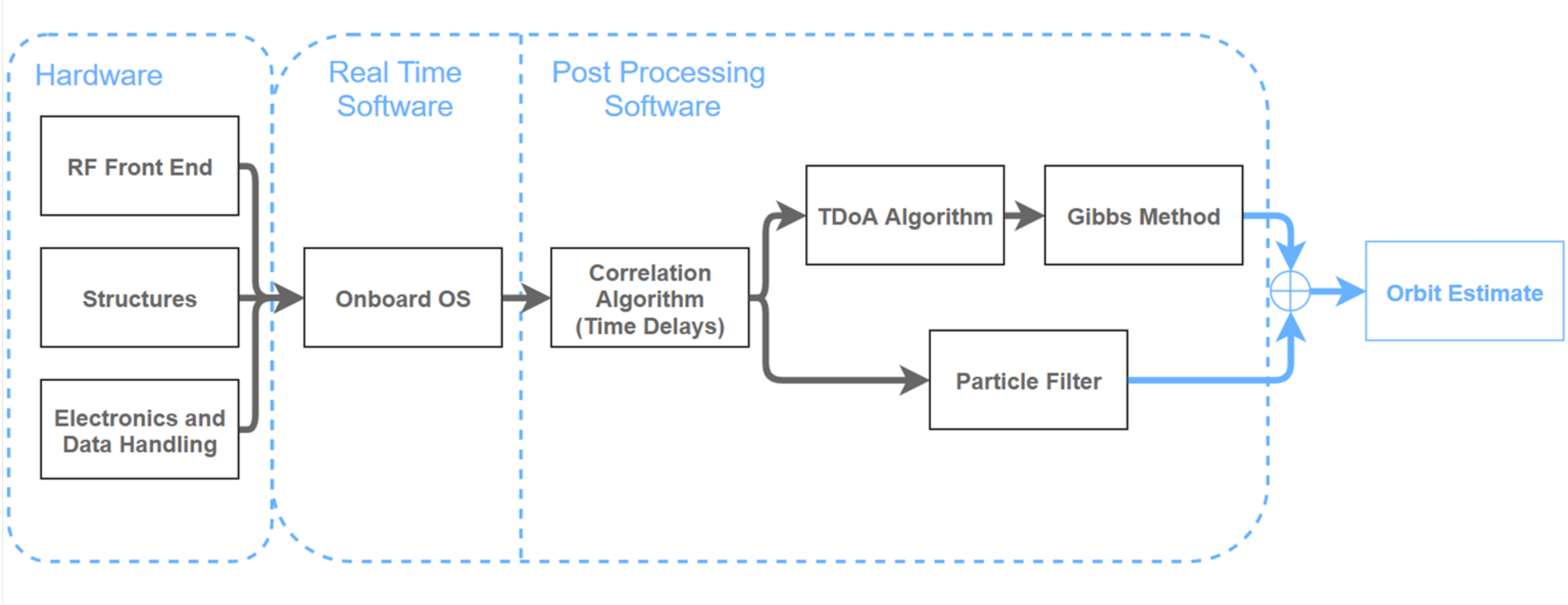


7. Time delay is used to estimate satellite position

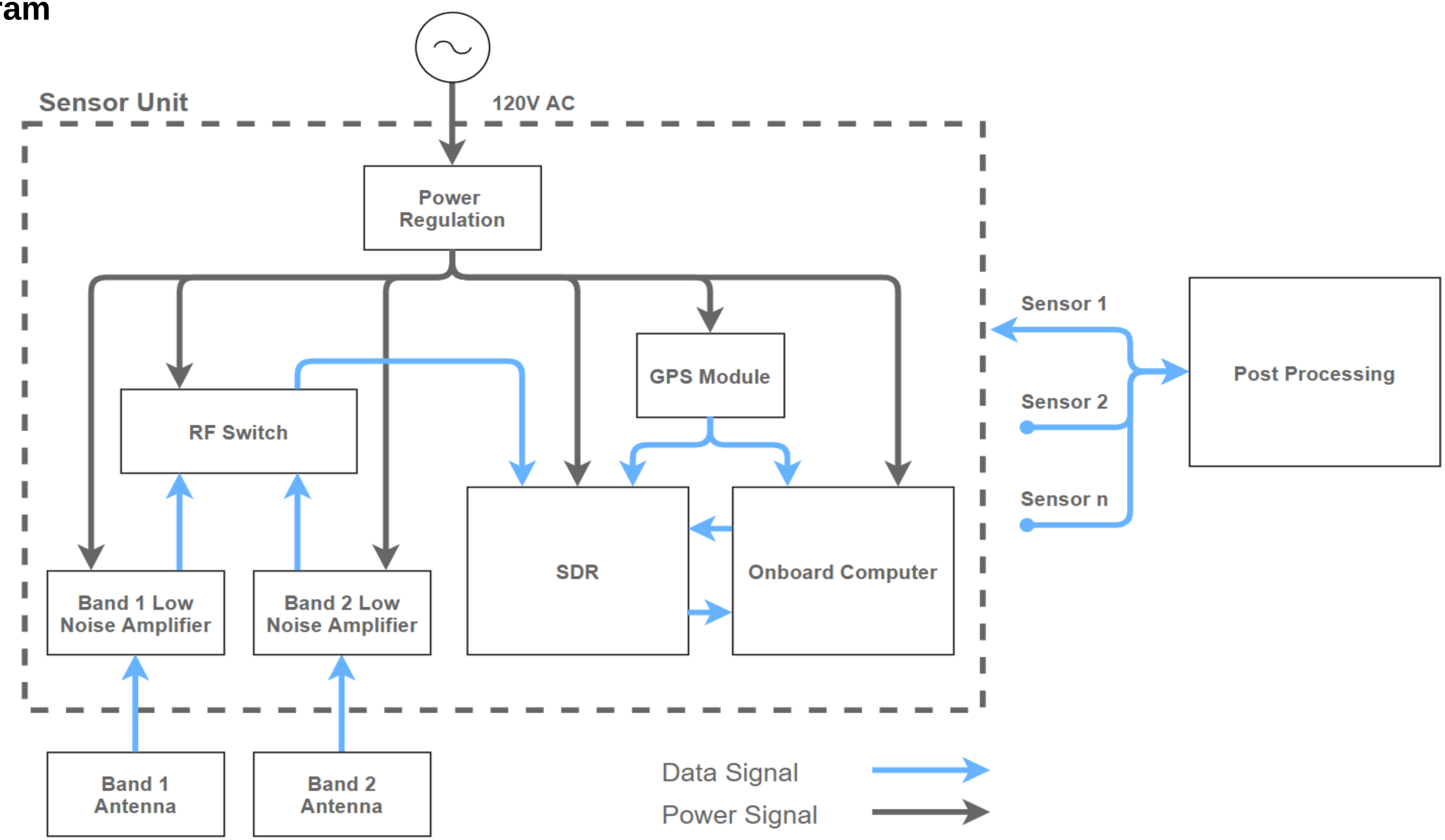
8. Position used to estimate orbit



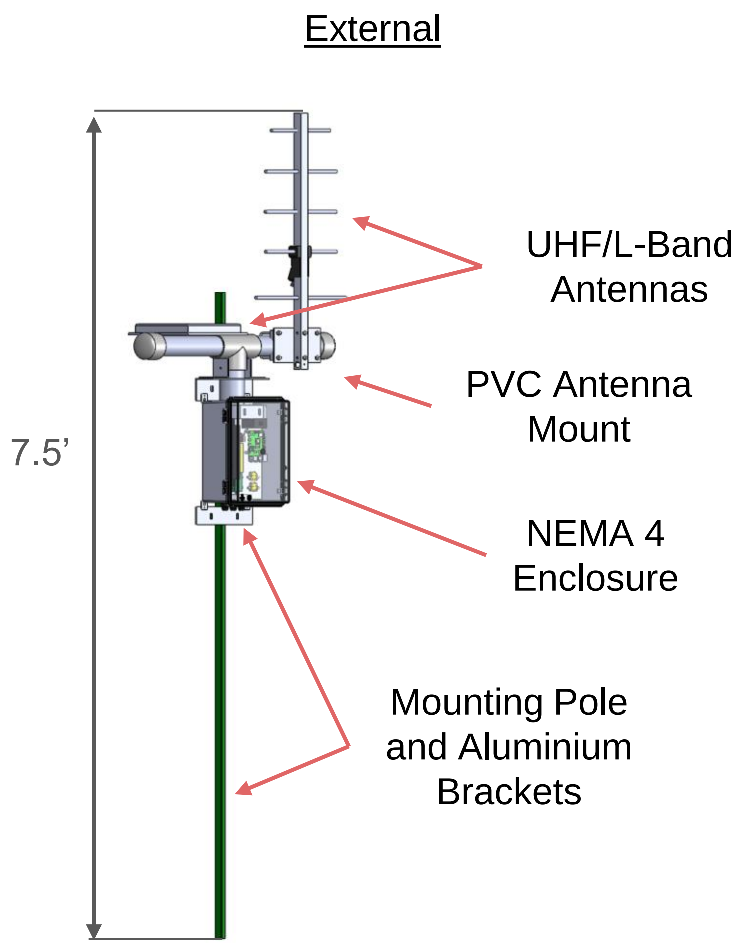
Conceptual Block Diagram

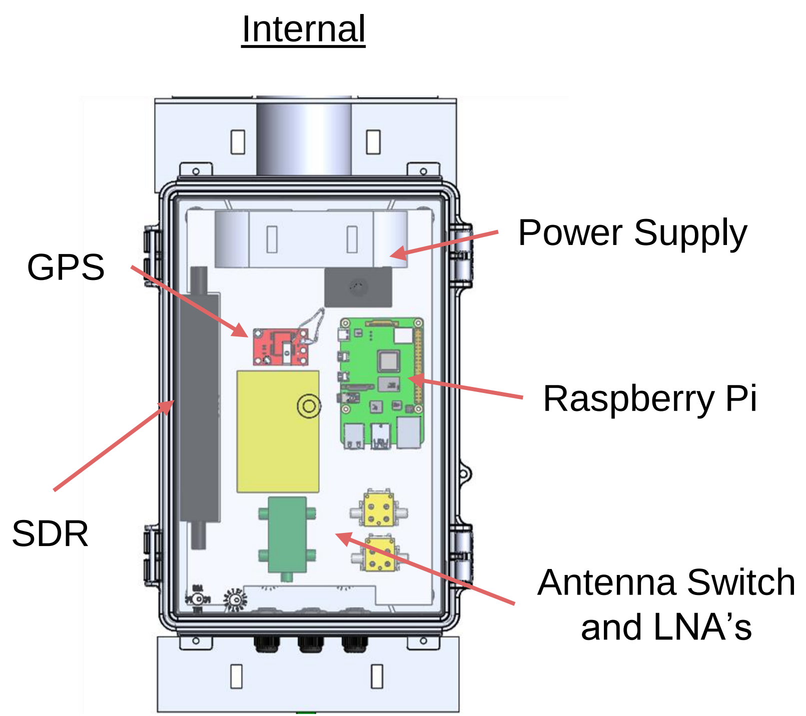


SpaceNet Functional Block Diagram



Baseline Design

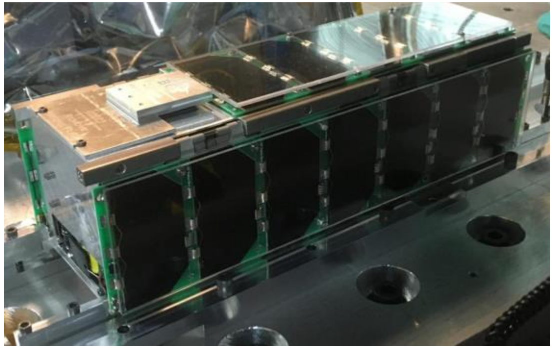




Satellite Targets

UHF Target: CSIM

The main target we will be using for this Frequency band is the CSIM Satellite operated locally here at CU Boulder



Operational characteristics:

- Fc = 437.25 MHz (Carrier)
- P = 5 W (Transmitted power)
- BW = 30 kHz (Beamwidth)
- DR = 9.6 kbps
- Demod = GMSK

L-Band Target: Iridium Next

Our primary target for this band is the Iridium NEXT Constellation.

Operation characteristics:

- Fc = 1616-1626.5 MHz (Carrier)
- P = 5 W (Transmitted power)
- BW = 30 kHz (Beamwidth)
- Possible data rates
  - Voice = 2.4kBps
  - Short Burst = 64 kBps

Critical Project Element	Why is This Critical?
Environmental Readiness	Testing time will be dictated by satellite’s orbital passes. The sensor unit must be ready to operate in rain, snow and the temperatures expected during spring semester in Boulder

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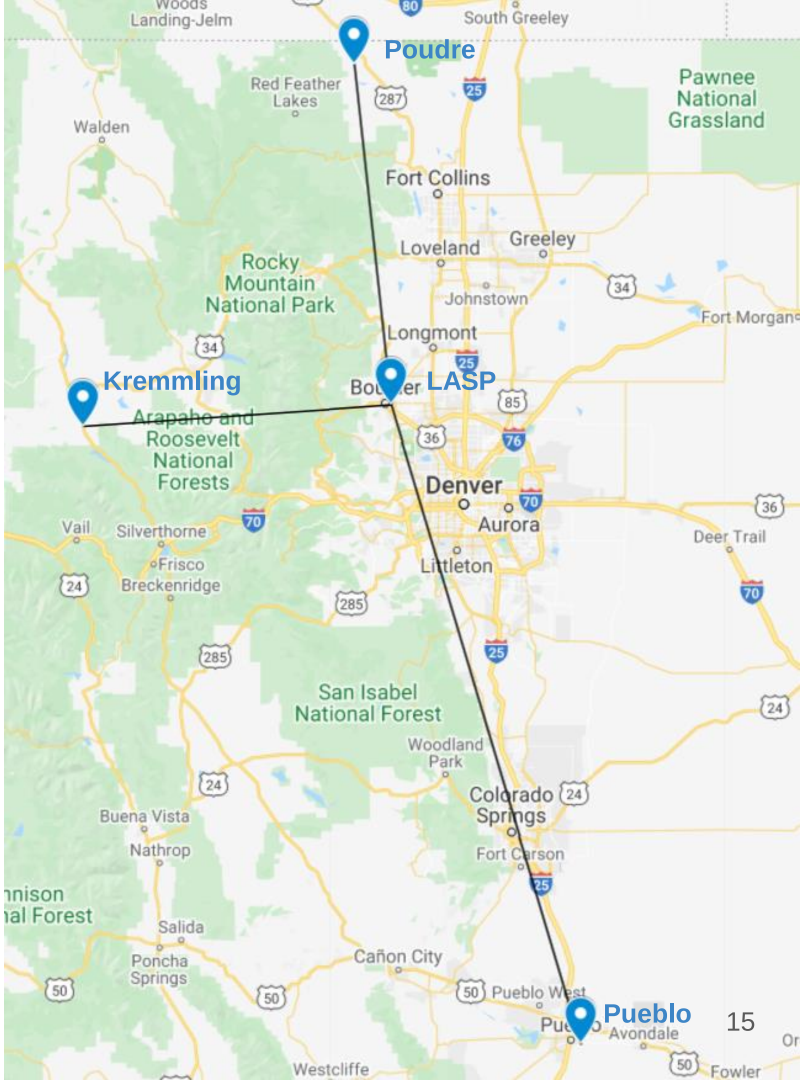
Position Vector Estimate using TDoA	Time Delay of Arrival(TDoA) ranging is used to produce the positional information required for orbital prediction
Orbital determination	Two methods: Gibbs and Particle Filter. Both produce orbital predictions that are the final product of the project

Location and Deployment?

- Is this wall powered and will you have access?
- Are the locations safe?

The units are wall powered and will be stationed with friends and family giving us access as needed

If willing friends and family can also handle data collection(changing SD cards) to reduce our travel time.



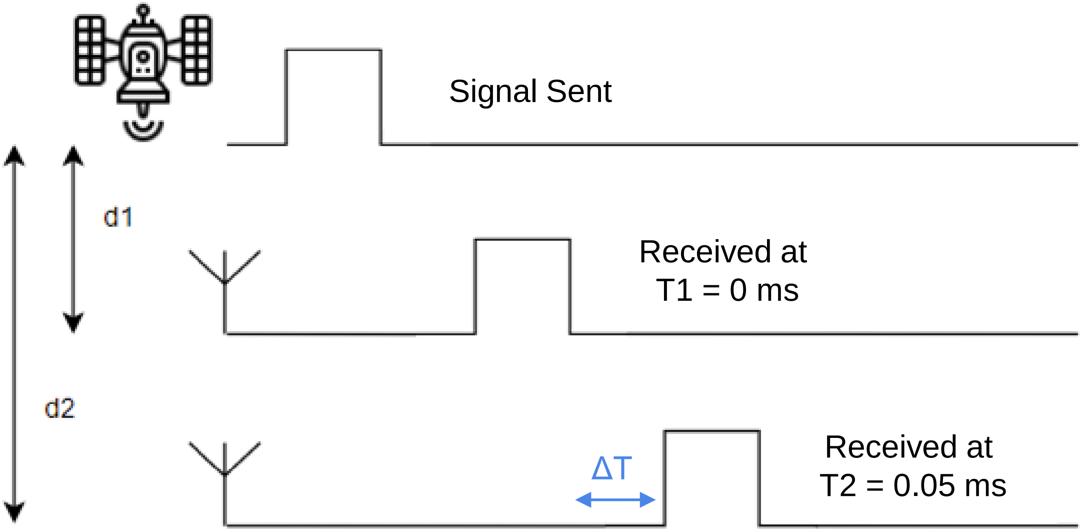
What is the systems time accuracy?

Timing Accuracy: The level of accuracy the system can measure time delay with

Depends on:

SDR Sample rate - how many samples the SDR takes (up to 20 Ms/sec)

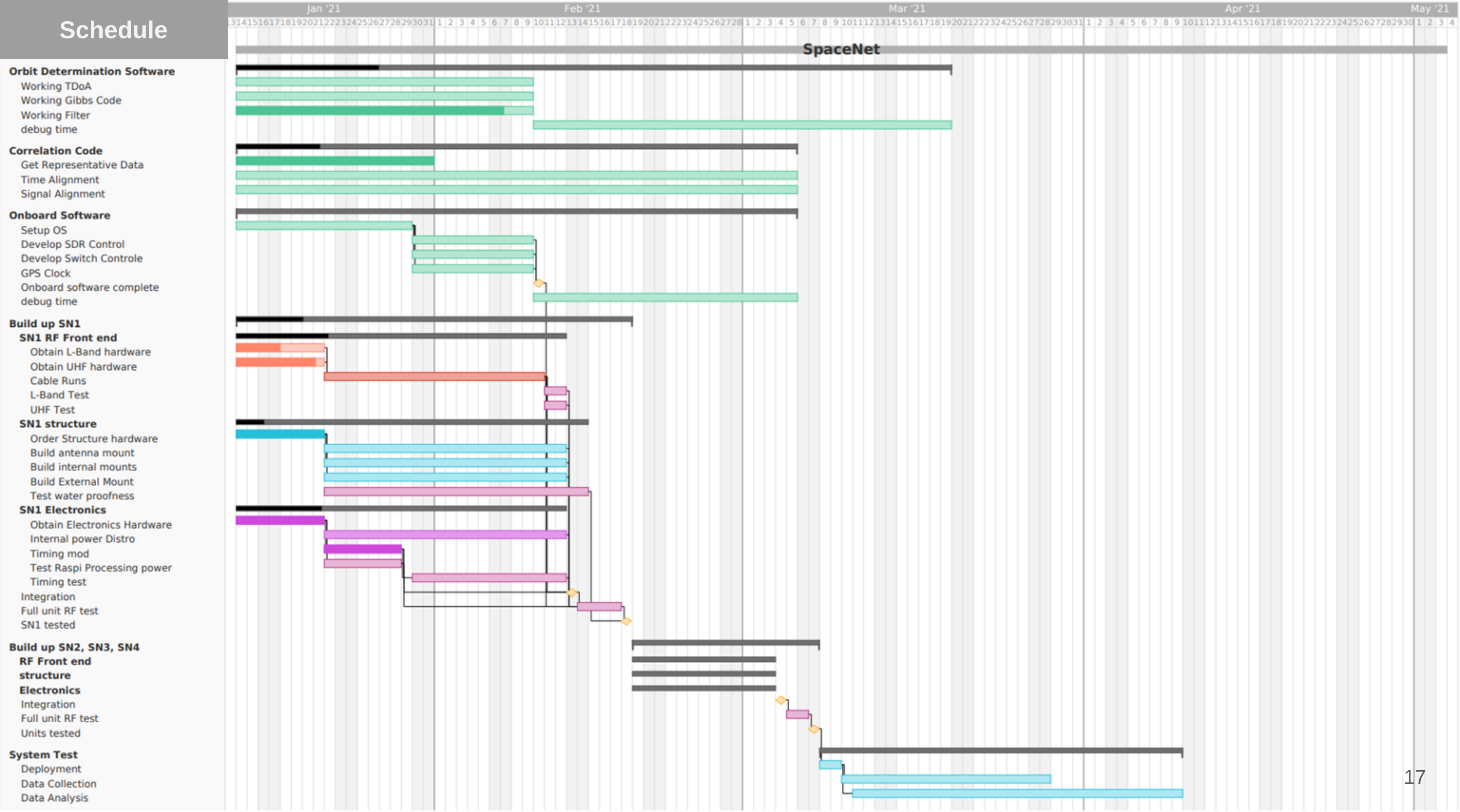
GPS Pulse Per Sec accuracy - How close the pulse period is to being exactly 1 second (+/- ns)



Time delay = T2-T1

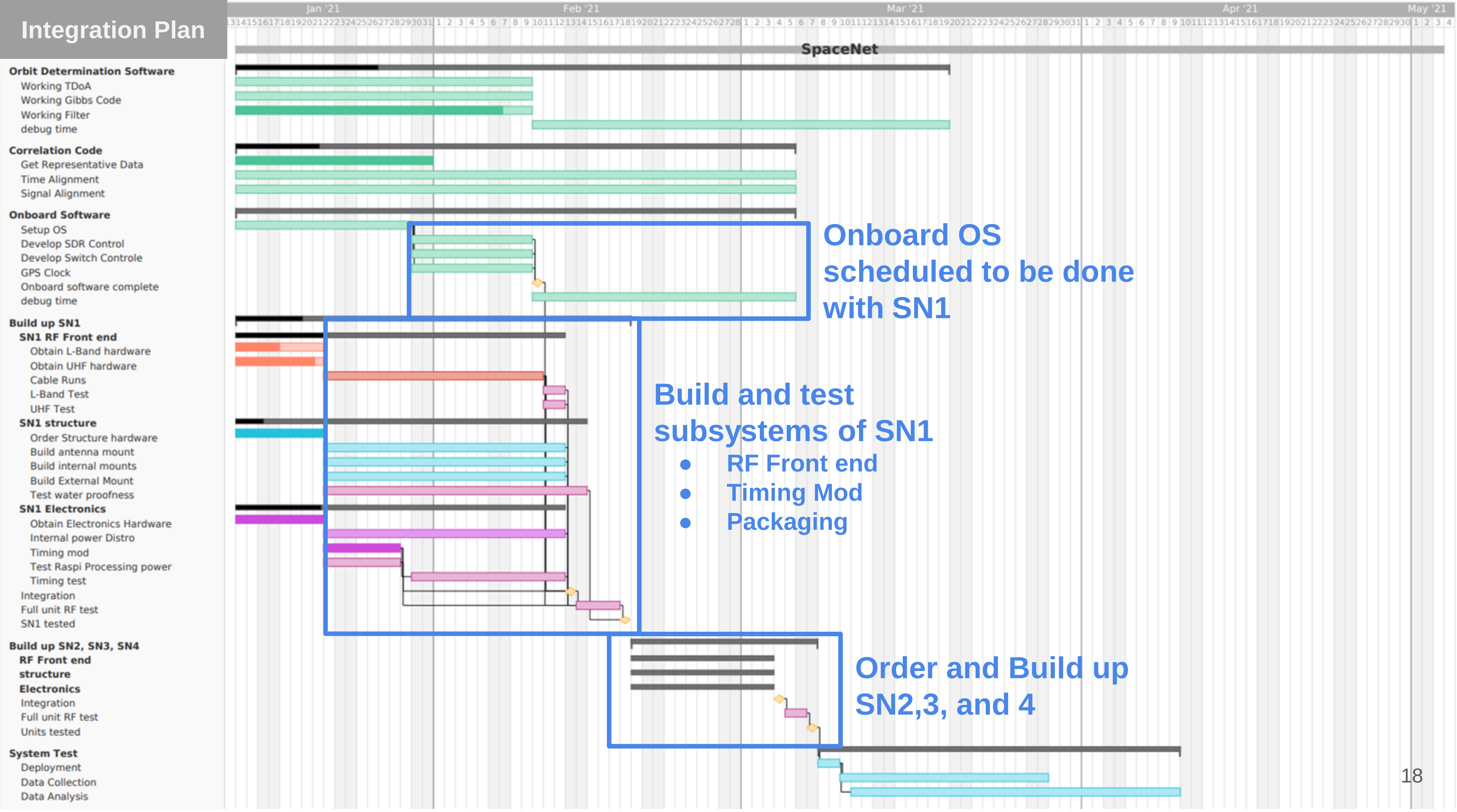
$\Delta T = 5*10^{-5}$ s

Schedule



Jan '21
Feb '21
Mar '21
Apr '21
May '21
SpaceNet
Orbit Determination Software
Working TDoA
Working Gibbs Code
Working Filter
debug time
Correlation Code
Get Representative Data
Time Alignment
Signal Alignment
Onboard Software
Setup OS
Develop SDR Control
Develop Switch Controle
GPS Clock
Onboard software complete
debug time
Build up SN1
SN1 RF Front end
Obtain L-Band hardware
Obtain UHF hardware
Cable Runs
L-Band Test
UHF Test
SN1 structure
Order Structure hardware
Build antenna mount
Build internal mounts
Build External Mount
Test water proofness
SN1 Electronics
Obtain Electronics Hardware
Internal power Distro
Timing mod
Test Raspi Processing power
Timing test
Integration
Full unit RF test
SN1 tested
Build up SN2, SN3, SN4
RF Front end
structure
Electronics
Integration
Full unit RF test
Units tested
System Test
Deployment
Data Collection
Data Analysis

Integration Plan



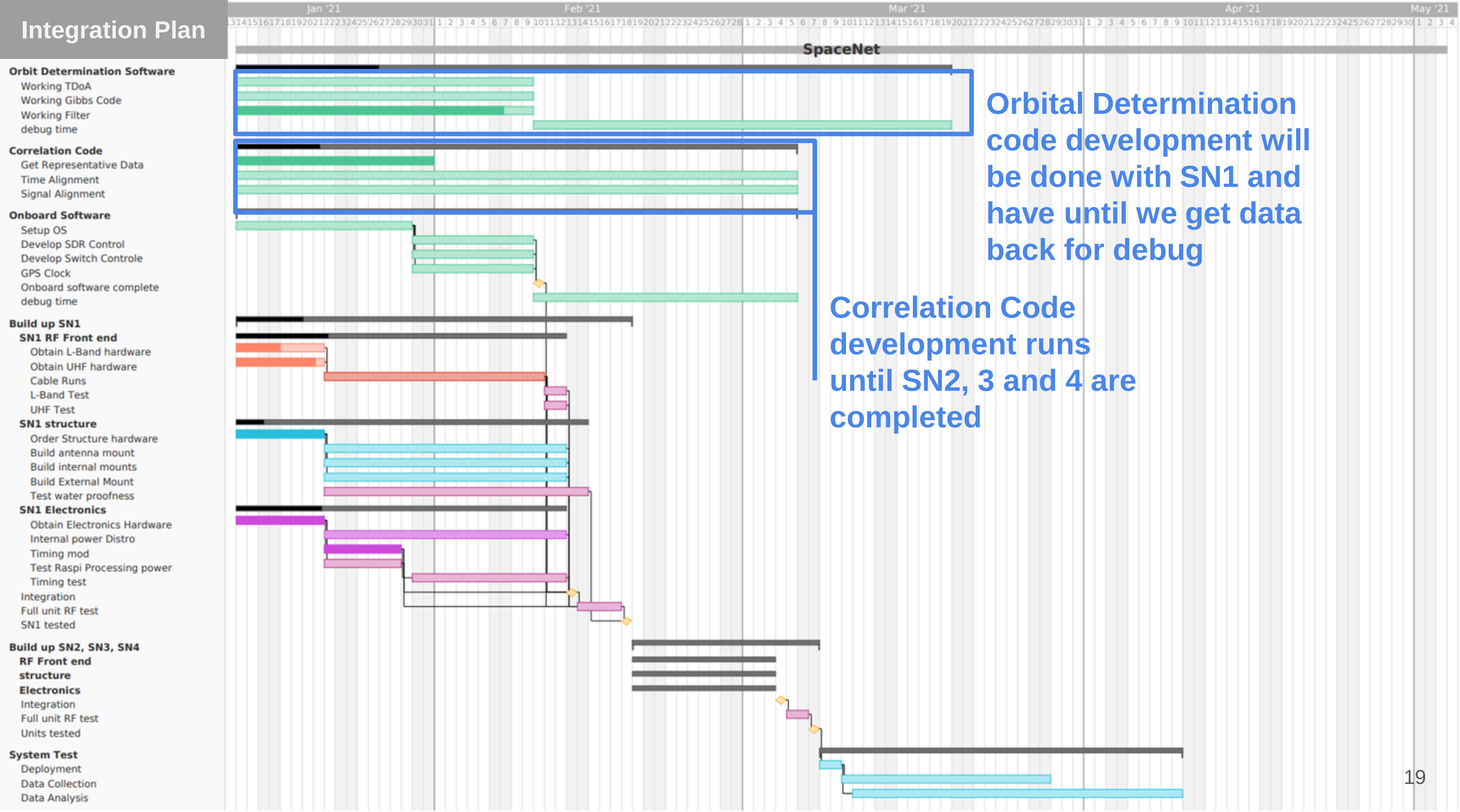
Onboard OS scheduled to be done with SN1

Build and test subsystems of SN1

- RF Front end
- Timing Mod
- Packaging

Order and Build up SN2,3, and 4

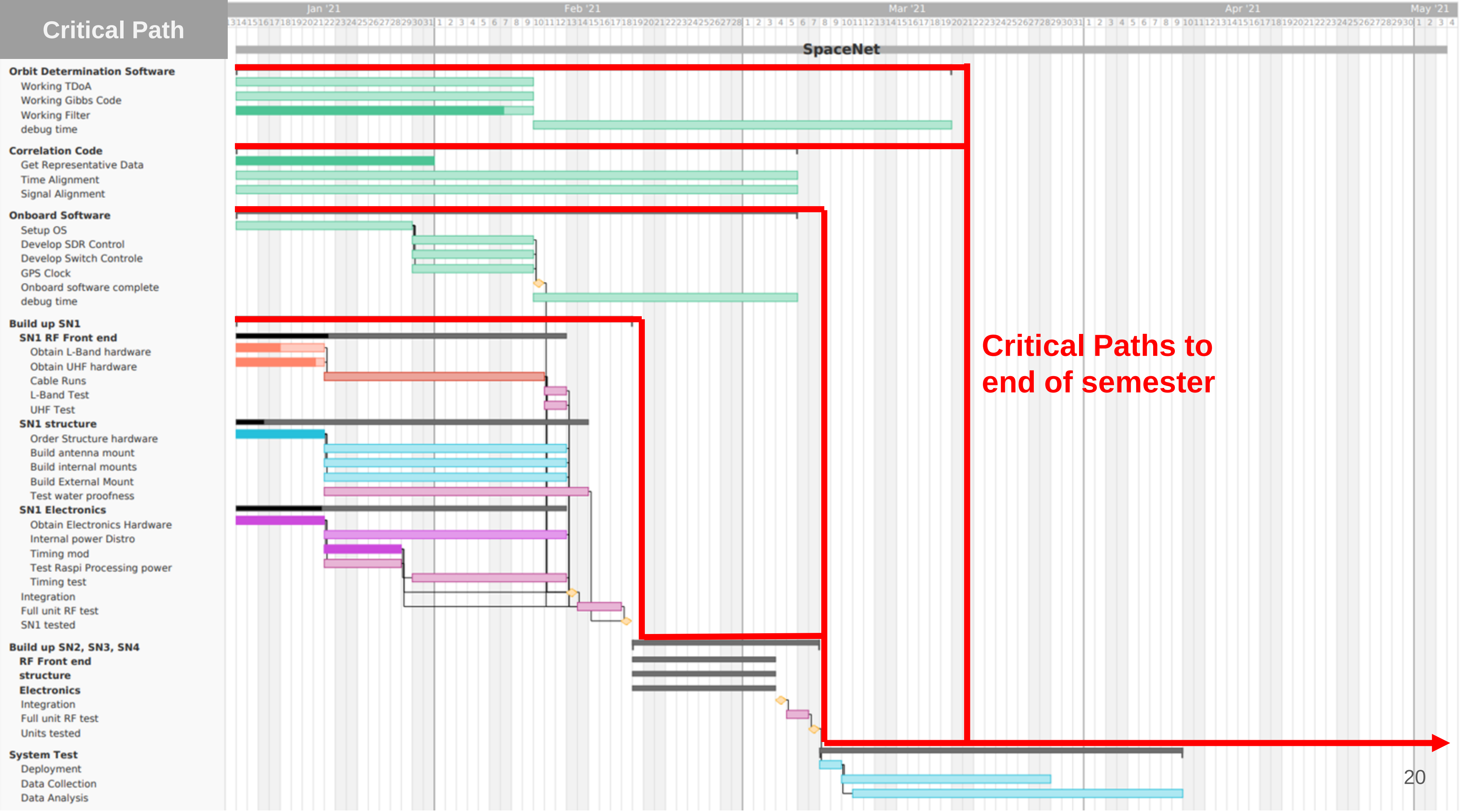
Integration Plan



Orbital Determination code development will be done with SN1 and have until we get data back for debug

Correlation Code development runs until SN2, 3 and 4 are completed

Critical Path



Manufacturing Tasks

Hardware:

Packaging

Timing

RF front end

Software:

Signal Cross-Correlation for TDoA

Particle Filter

Gibb’s Method

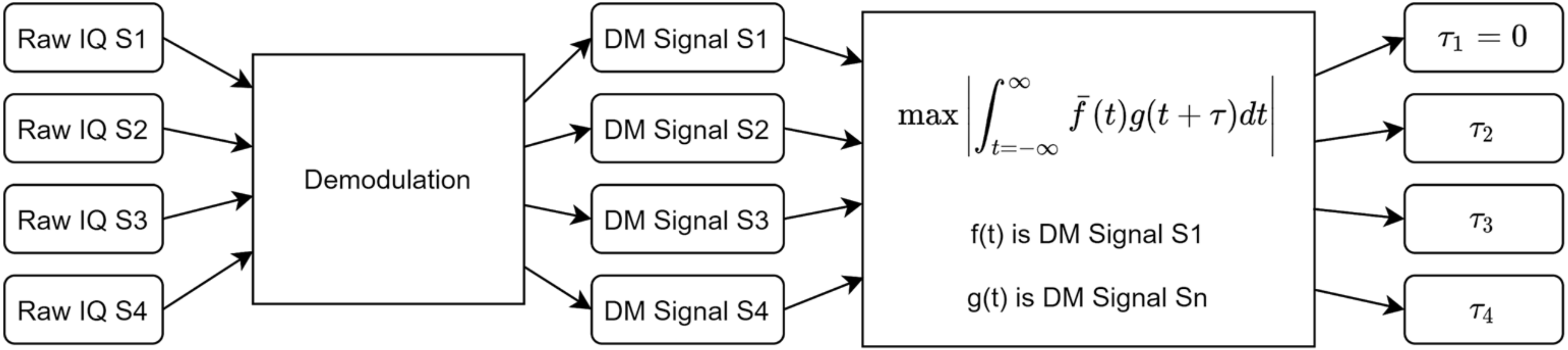
Onboard OS

Work Status:	Completion Date:
Open ⇓ In Progress ⇓ Testing ⇓ Done	Ahead of Schedule ⇓ On Time ⇓ Behind

Software: Signal Cross-Correlation for TDoA [In Progress]

Completed:
- Acquisition of representative Raw IQ
- Demodulated sample data

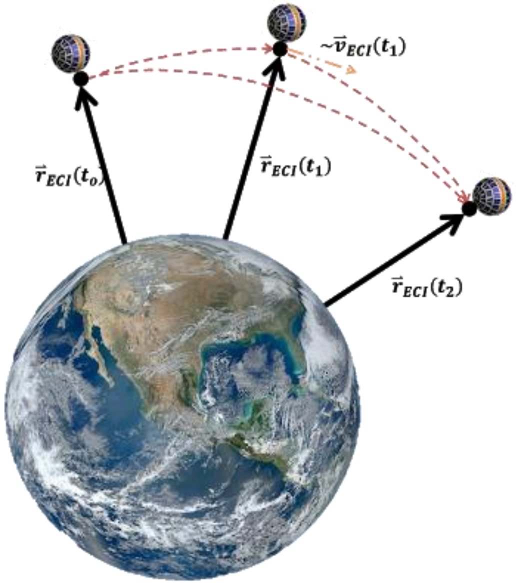
Remaining:
- Correlation peak finding MATLAB function
- Verification and qualification testing with actual data



Road Blocks:
- Specific demodulation parameters
- Realistic raw data (working on simulating)

Sched. Completion: 03/05/21
Est. Completion: 03/05/21
On Time

Software: Gibb's Method [Testing]

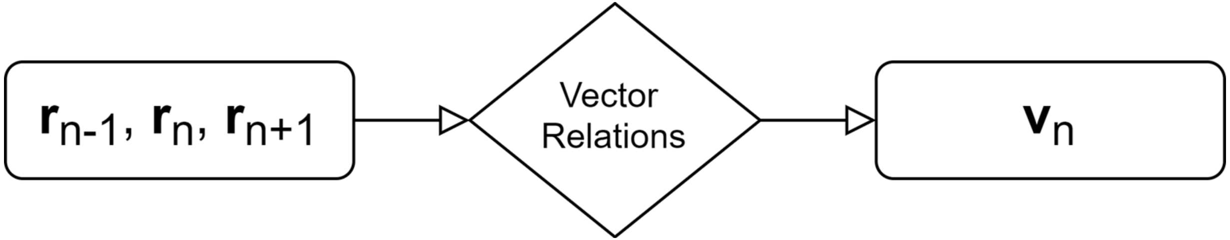


Inputs:

- Three time-sequential position vectors

Outputs:

- Velocity vector at the second time



Completed:

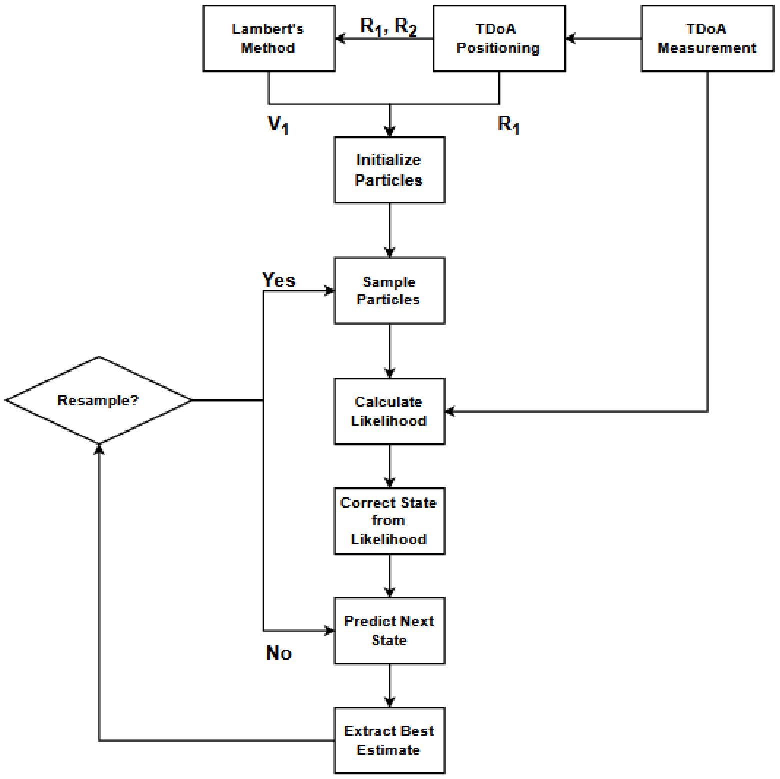
- Software Package (MATLAB function)

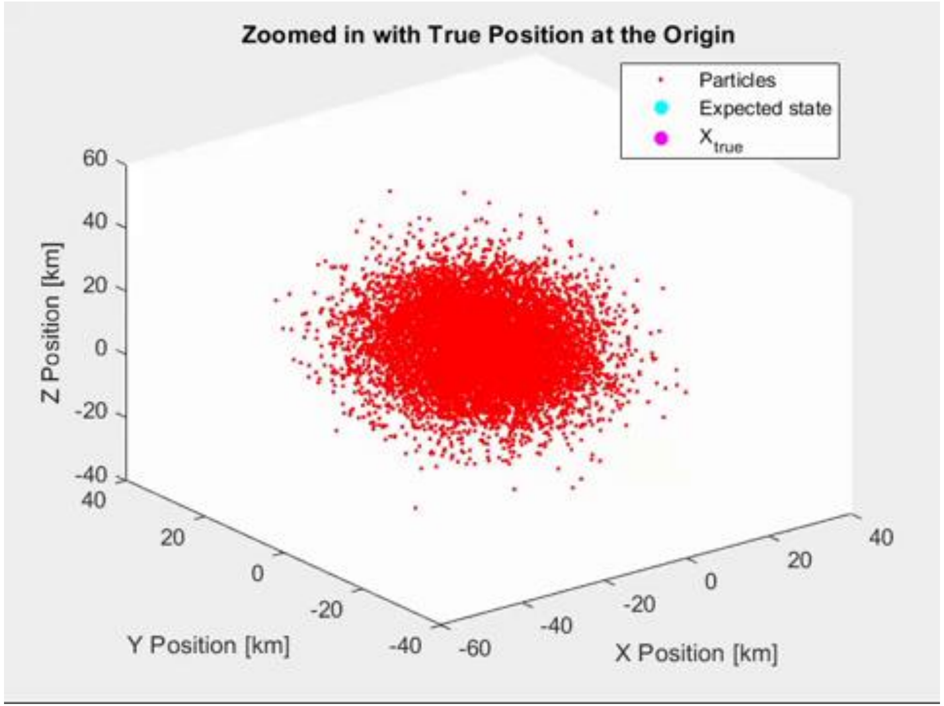
Remaining:

- Streamline post processing
- Verification and qualification testing with actual data

Sched. Completion: 02/09/21
Est. Completion: 02/01/21
Ahead of Schedule

Software: Particle Filter [Testing]





Software: Particle Filter [Testing]

Progress:

- Have an initial particle filter complete
- Needs to be tested with more STK simulated data

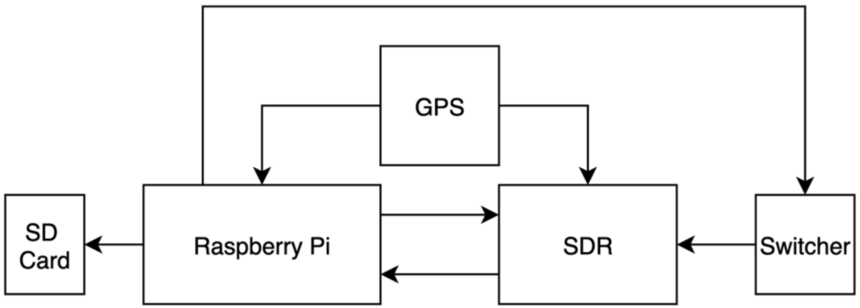
Concerns:

- Correlation data is far noisier than suspected
- Integration with the rest of software has yet to be started

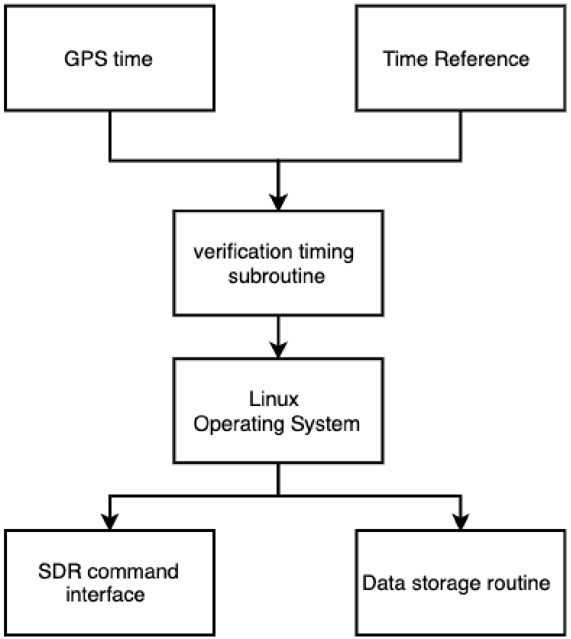
Sched. Completion: 02/09/21
Est. Completion: 01/26/21
Ahead of Schedule

Software: Onboard OS [In Progress]

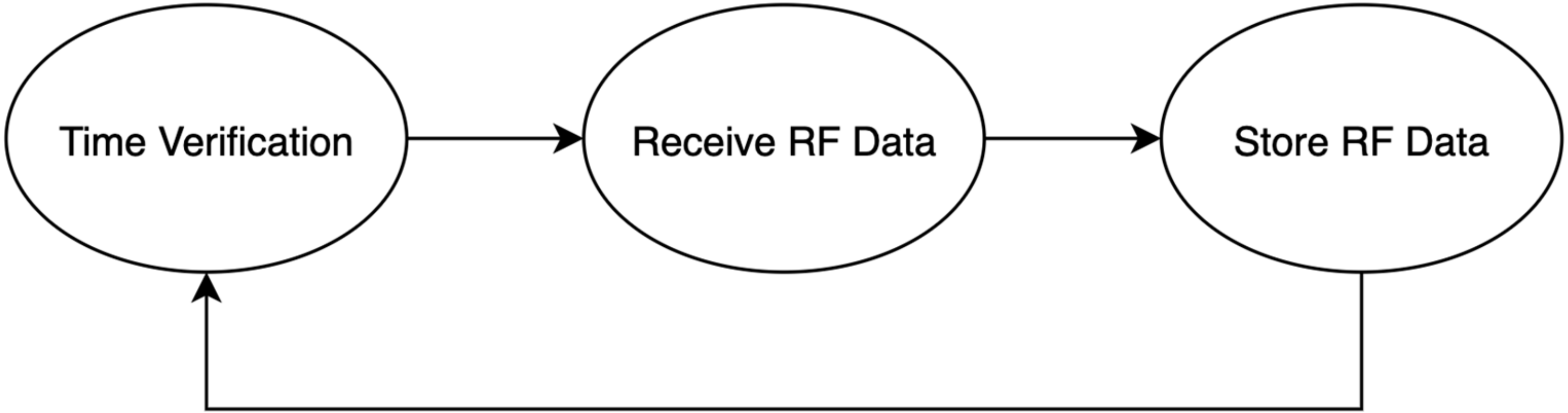
Hardware Block Diagram:



Software Block Diagram:



OnBoard OS: State Diagram



Compare GPS times to known flybys to determine when to start data collection.

Turn on the SDR.
Set frequency, bandwidth, and sampling rate.

Stop data acquisition and export data with necessary information. Time, Date, sample rate etc.

Software: Onboard OS [In Progress]

Progress:

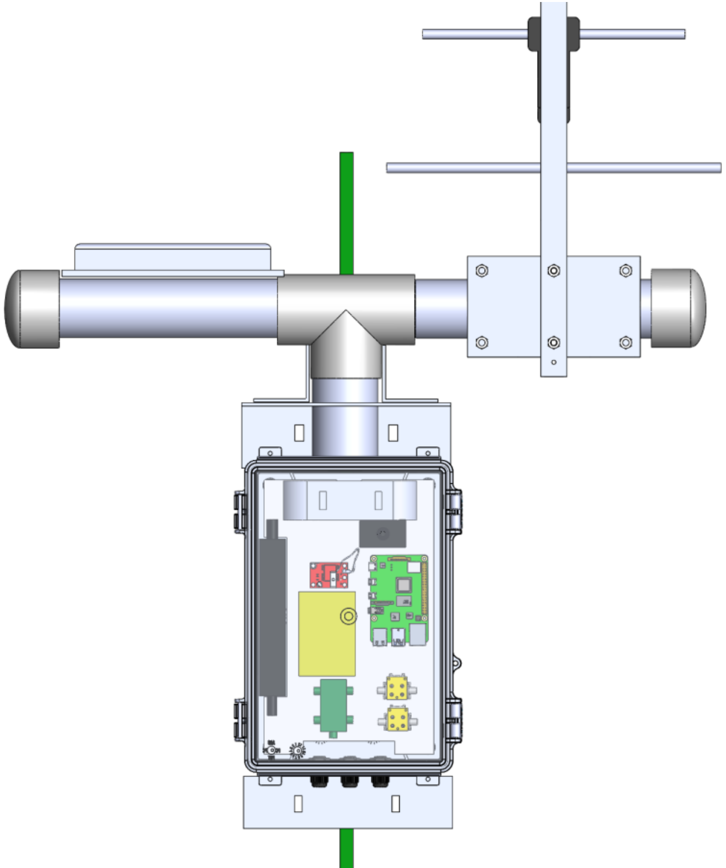
- All parts delivered for first unit
- Downloaded Software
- Begun programing/coding

Concerns:

- Learning curve
- Any debugging issues
- Hardware/Software compatibility issues

Sched. Completion: 03/05/21
Est. Completion: 02/16/21
Ahead of Schedule

Hardware: Packaging [In Progress]



Hardware: Packaging [In Progress]

Progress:

- Internal mount cut, drilled and installed
- Hardware checklist (what needs changed versus what is good)
- New component placement

Concerns:

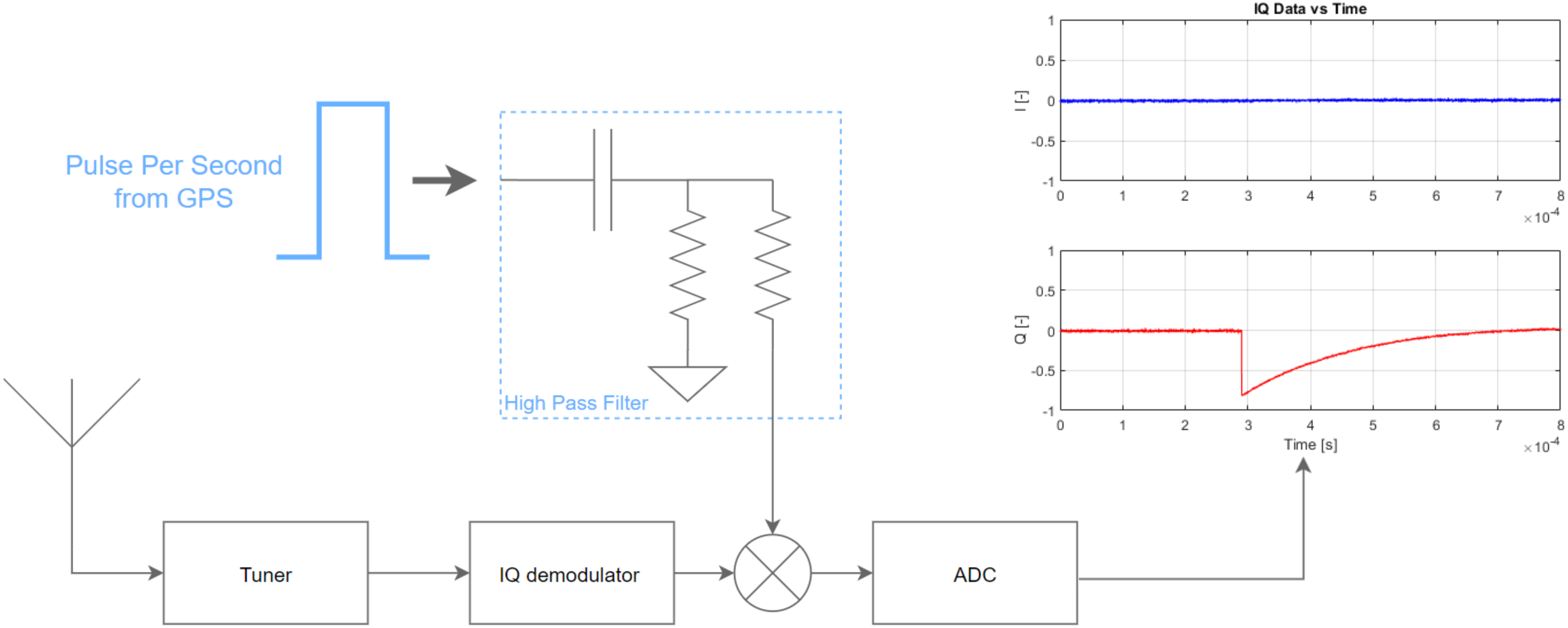
- None at the moment

To Do's:

- Determine finalized antenna mounting
- Update CAD based on component sizes/needs along with add mounting holes from components/box

Sched. Completion: 02/12/21
Est. Completion: 02/01/21
Ahead of Schedule

Hardware: Timing [Testing]



Hardware: Timing [Testing]

Progress:

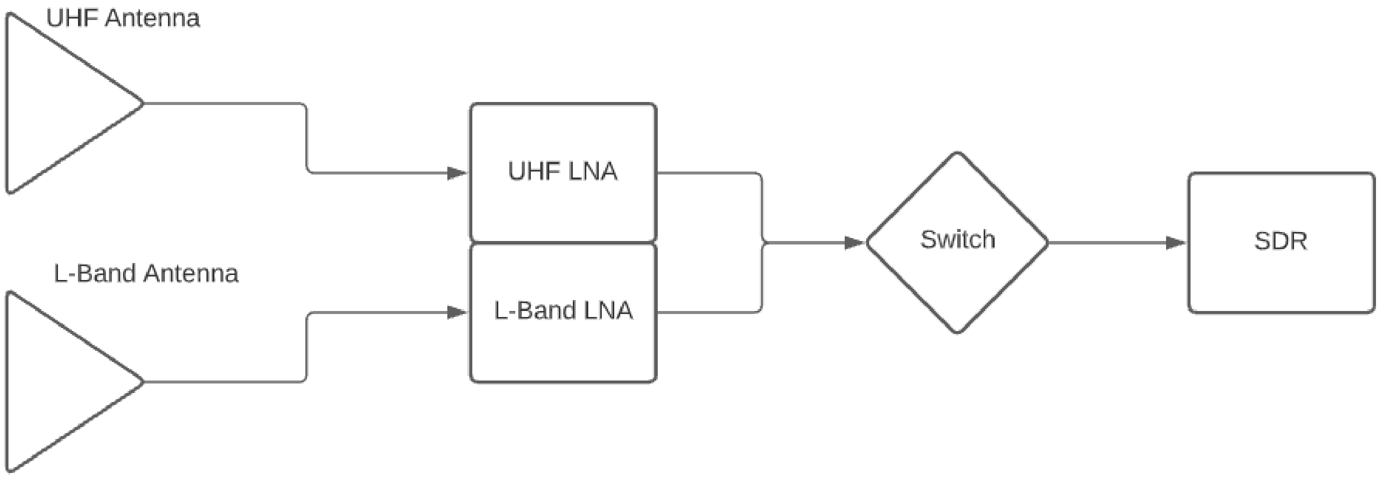
- Timing system works on HackRF at 10Ms/sec (100ns)
- Filter tuned to reduce number of data points modified

Concerns:

- Dropping samples at higher sampling rates (>10Ms/s)
- Debug is underway

Sched. Completion: 02/12/21
Est. Completion: 02/05/21
Ahead of Schedule

Hardware: RF Front end[In Progress]



Hardware: RF Front end[In Progress/ On Hold]

UHF [In Progress**]**
Analysis
- Link Budget has been verified and antenna has been ordered

Procurement
- Waiting for connectors

Assembly
- Waiting for connectors

L-band [On Hold**]**
Analysis
- Link Budget being verified
- New Satellite selection

Procurement
- Waiting on antenna
    - Backordered currently

Concerns:
Main concern is difficulty achieving proper downlink from L-Band satellites due to high data rate and packets, and order times due to part uniqueness

Sched. Completion: 02/12/21
Est. Completion: 02/25/21
Behind

Manufacturing Tasks

Hardware:

Packaging [In progress]

- Waiting for integration

Timing [Testing]

- debugging samples rates

RF front end [In progress/On Hold]

- Waiting on adapters
- Verify L-Band Link budget

Software:

Signal Cross-Correlation for TDoA [In progress]

Particle Filter [Testing]

- Test with more data

Gibb’s Method [Testing]

- Working on improvements

Onboard OS [In progress]

- Testing GPS and pi
- Testing SDR and pi

Budget

SpaceNet Unit 1

Group	Part	Status
Off the Shelf Electronics	Raspberry Pi 4 Model B (4 GB) HackRf One Electronic RF Logic Switch GPS Module	Received
RF Front End	UHF Antenna	Received
	UHF Low Noise Amplifier	Pending
	L-Band Low Noise Amplifier L-Band Antenna	Pending Decision
Hardware	WH-16 Hinged Nema Enclosure Miscellaneous Hardware Miscellaneous Electronics Hardware	Received

SpaceNet Units 2-4

Group	Part	Status
Off the Shelf Electronics	Raspberry Pi 4 Model B (4 GB) HackRf One Electronic RF Logic Switch GPS Module	Pending SN1 Testing
RF Front End	UHF Antenna UHF Low Noise Amplifier L-Band Low Noise Amplifier L-Band Antenna	Pending SN1 Testing
Hardware*	WH-16 Hinged Nema Enclosure Miscellaneous Hardware Miscellaneous Electronics Hardware	Pending SN1 Testing

*Some Hardware orders for SN1 include numbers required for all 4 units, i.e. bolts that come in packs of 50

Expenses To Date
$974.05

Remaining Expected Costs
$3,089.61

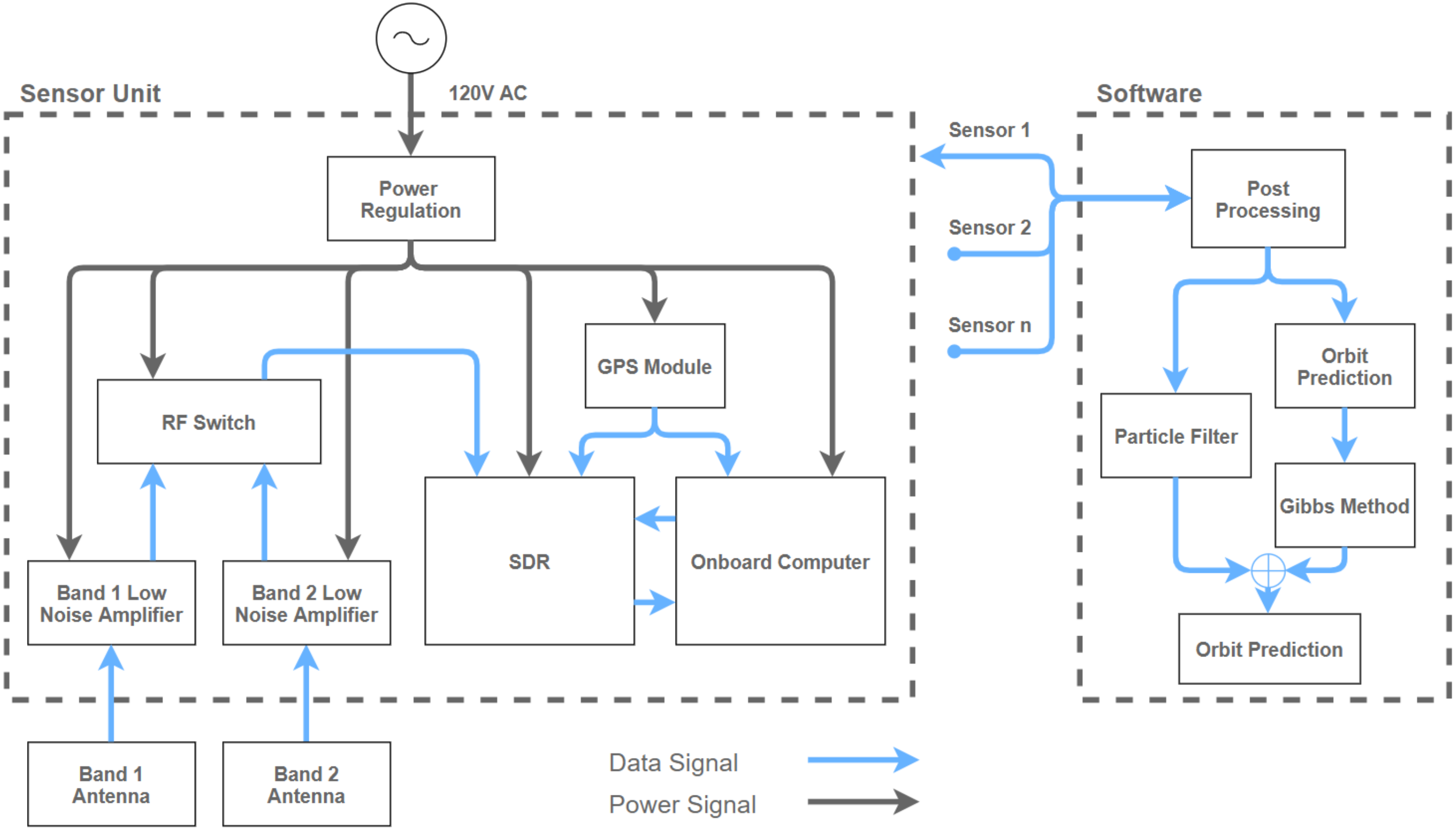
Remaining Development Budget
$936.34

Acknowledgements

- Dr. Francisco López Jiménez
- Martin Wilson (Raytheon)
- Mike Walker (Raytheon)
- Sheldon Clark (Raytheon)
- Mark Werremeyer (Raytheon)
- Dr. Zachary Sunberg

Backups

SpaceNet Functional Block Diagram



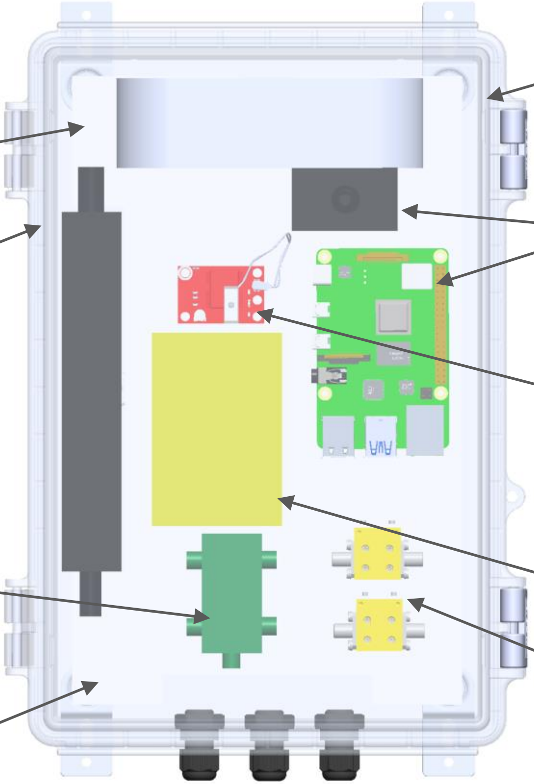
Baseline Sensor Unit Design

Power Strip
Used to distribute power to components within the box

HackRF One
SDR that will handle RF communications

Antenna Switcher
Used to switch between the antennas.

Internal Mounting Plate
Used to secure hardware within the box



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

Raspberry Pi 4 & Power Supply
On Board Computer for data collection and transfer

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

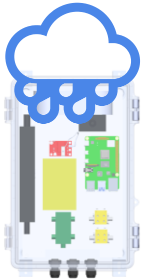
Power Regulator Board
Used to supply steady voltage too.. (add)

LNA’s
Used to improve G/T metric ensuring adequate reception of satellite transmission.

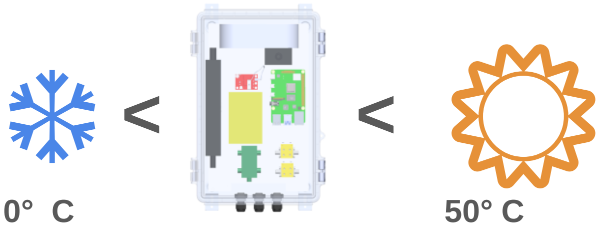
Hardware

Key Driving Requirements

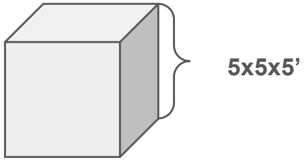
DR1.1.
The sensor unit packaging shall be able to maintain a dry environment in rain and snow

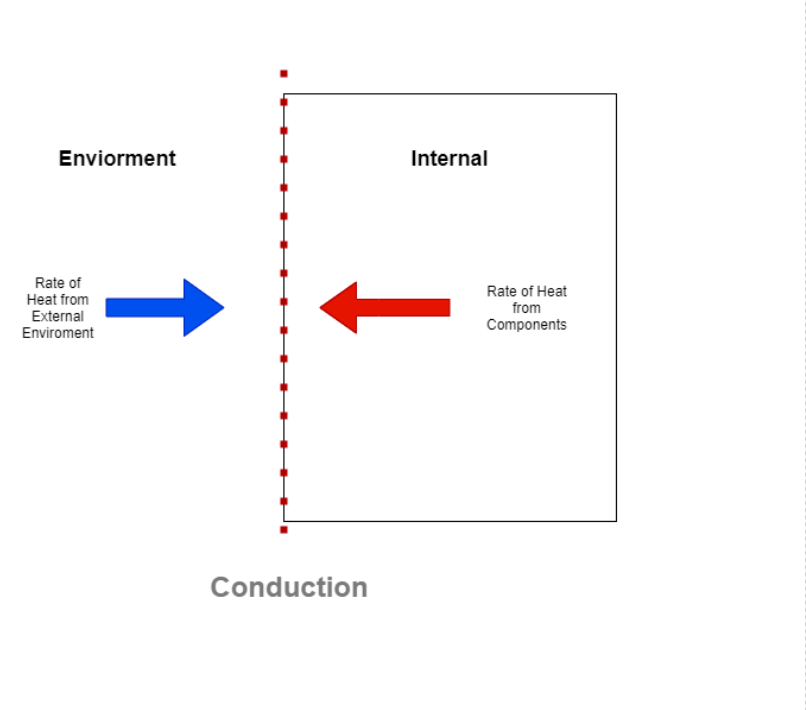


DR1.2.
The sensor unit packaging shall be capable of maintaining an internal operating temperature range of 0-50 degrees Celsius



DR2.2.
The deployed sensor unit and antenna shall fit within a 5x5x5’ space





Thermal Analysis Equations:

$$\dot{Q}_{components} = 19.8W$$

$$\dot{Q}_{conduction} = kA\frac{T_1 - T_2}{\Delta x}$$

$$\dot{E}_{gained} = \dot{E}_{lost}$$

$$\dot{Q}_{components} = \dot{Q}_{conduction}$$

$$\frac{\dot{Q}_{components} * \Delta x}{k} + T_2 = T_1$$

$$T_1 = Internal\ Temperature$$

$$T_2 = External\ Temperature$$

Results:

$Min\ Operating\ Temperature\ (COLD)$: 0℃

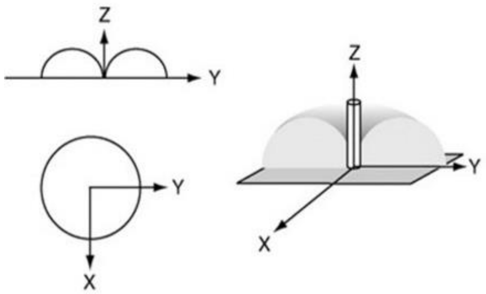
$$T_2 = -11℃$$

$Min\ Operating\ Temperature\ (HOT)$: 50℃

$$T_2 = 33℃$$

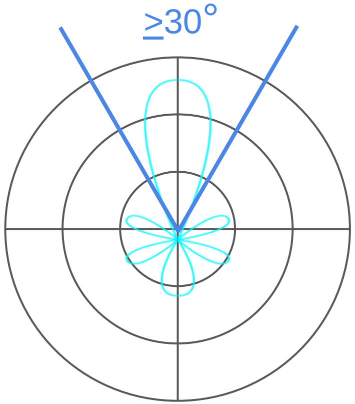
Key Driving Requirements

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



Linx Technologies

DR4.2.
Antenna(s) will have have minimum beamwidth of 30°



Key Driving Requirements

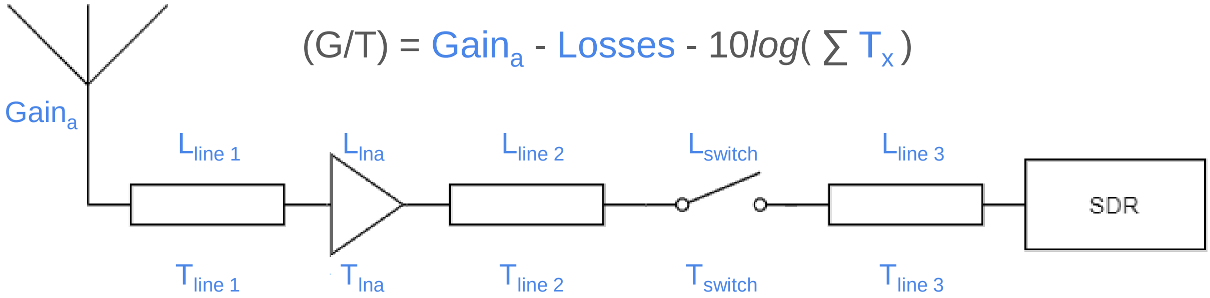
DR3.1.
Each sensor unit shall have a minimum UHF system noise temperature of -20dB/K with a target value of -15 dB/K

Overall UHF noise temperature
> -20 dB/k

DR3.2.
Each sensor unit shall have a minimum L-band system noise temperature of -17dB/K with a target value of -13 dB/K

Overall L-band noise temperature
> -17 dB/k

$$(G/T) = Gain_a - Losses - 10\,log(\sum T_x)$$



System Noise Temperature Results

UHF
Satellite Target: CSIM

Frequency: 437.25 MHz

Data Rate: 9.6kbps

Based on UHF/VHF hardware:

- $Gain_a$ = 9 dBi
- Losses = 1.76 dB
- Ts = 275 °K

Calculated G/T = -17.15 dB/K

> -20 dB/k

VHF
Satellite Target: Iridium NEXT

Frequency: 1616 MHz

Data Rate: 64kbps

Based on UHF/VHF hardware:

- $Gain_a$ = 9 dBi
- Losses = 1.76 dB
- Ts = 275 °K

Calculated G/T = -17.15 dB/K

> -20 dB/k

L-Band
Satellite Target: Iridium NEXT

Frequency: 1616 MHz

Data Rate: 64kbps

Based on L-band hardware:

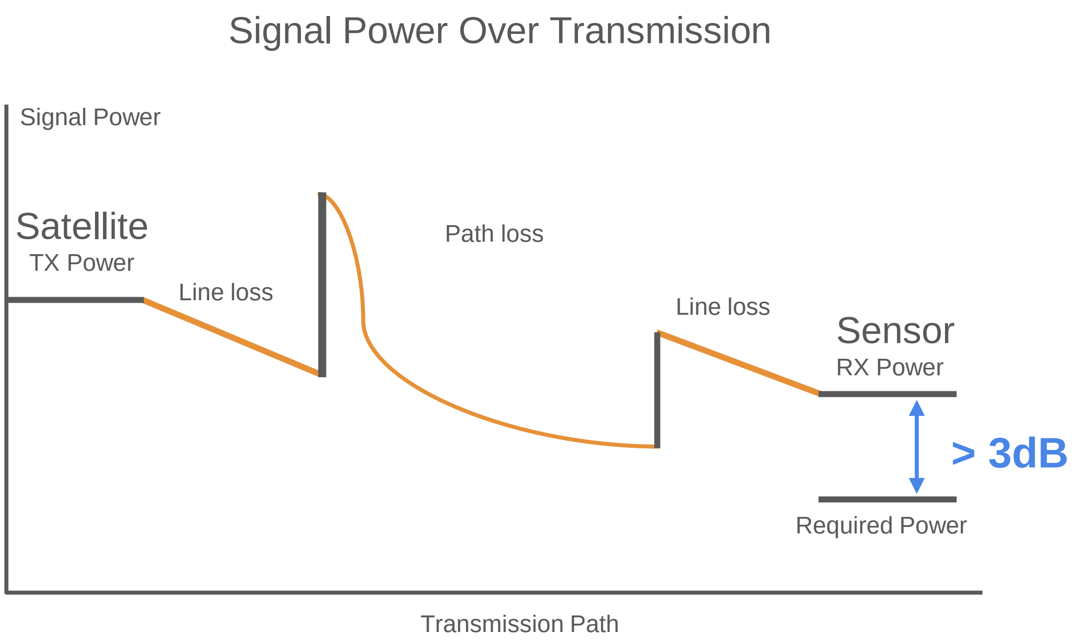
- $Gain_a$ = 8 dBi
- Losses = 1.76 dB
- Ts = 243 °K

Calculated G/T = -15.62 dB/K

> -17 dB/k

Key Driving Requirements

DR3.3./3.4.
Each sensor unit shall have a minimum UHF & L-Band link margin of 3dB



Link Margin Results

UHF

Satellite Target: CSIM

Frequency: 437.25 MHz

Data Rate: 9.6kbps

Calculated Link Margin = 20.5 dB

VHF

Satellite Target: AO-91 (RadFxSat / Fox-1B)

Frequency: 145 MHz

Data Rate: 9.6kbps

Calculated Link Margin = 11.2 dB

L-Band

Satellite Target: Iridium NEXT

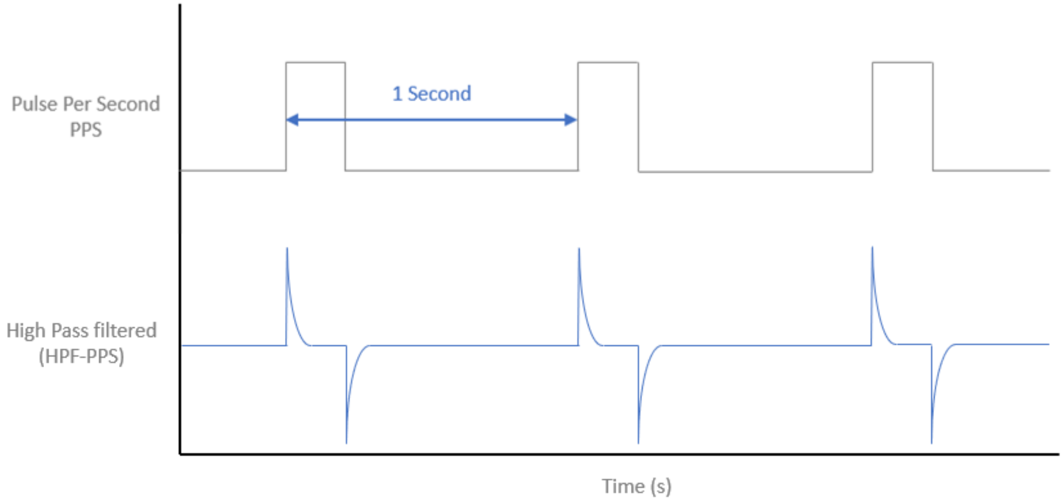
Frequency: 1616 MHz

Data Rate: 64kbps

Calculated Link Margin = 9.2 dB

Link margins for both UHF and L-band are > 3 dB based on our hardware selection, satellite characteristics, and expected atmospheric losses

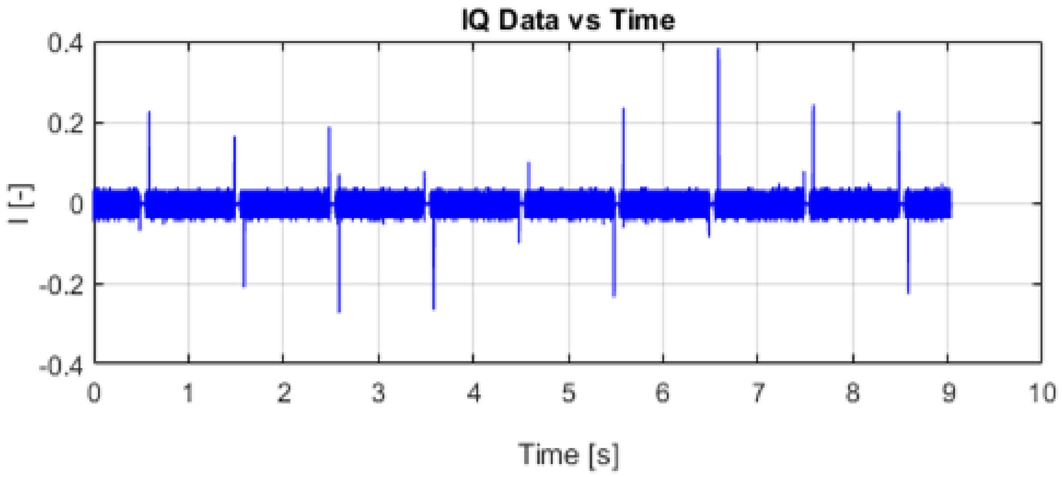
PPS is filtered to remove DC component



HackRF can record
20M samples per second

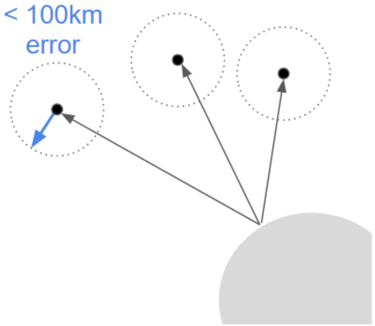
PPS can be aligned with
2 sample precision

~100ns alignment precision

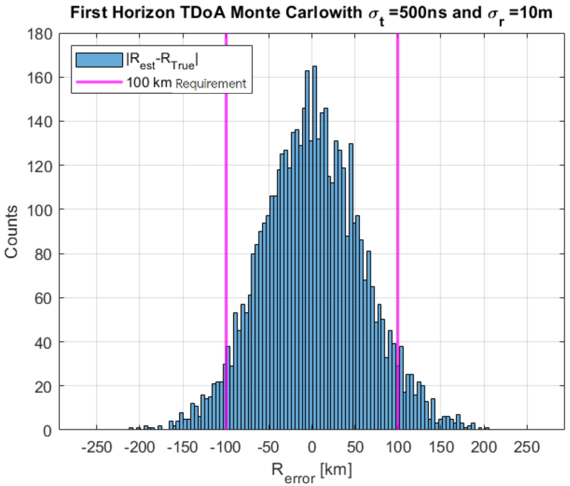


FR5. Recorded data can be used to produce an orbital position within 100km absolute error of a known satellite

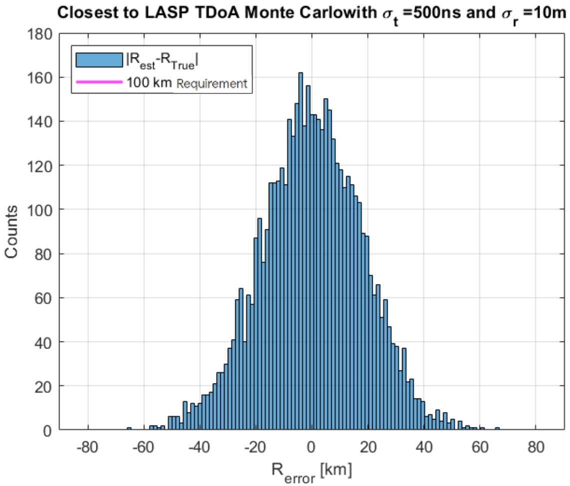
- Primary source of TDoA error is how accurately we can time stamp incoming signals for later post processing
- GPS provides time synchronizing pulse per second (pps) signal
- SDR needs to be capable of stamping pps timing signals onto input data and achieving data rate of 20MHz (50ns)
  - 500ns timestamp accuracy provides us a large timing margin



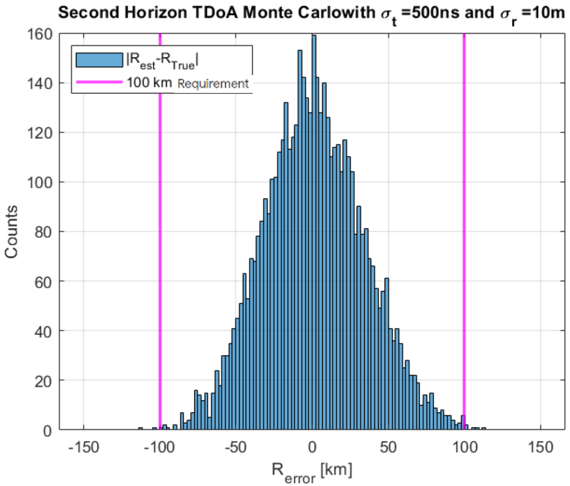
Error greater than 100km: 9.58%



Error greater than 100km: 0.38%

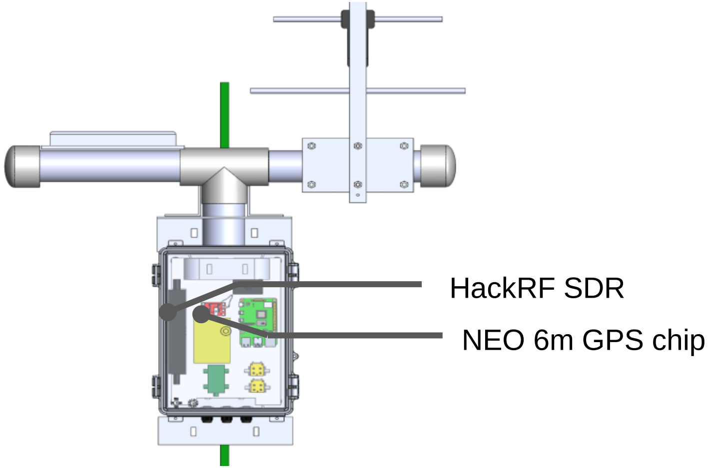


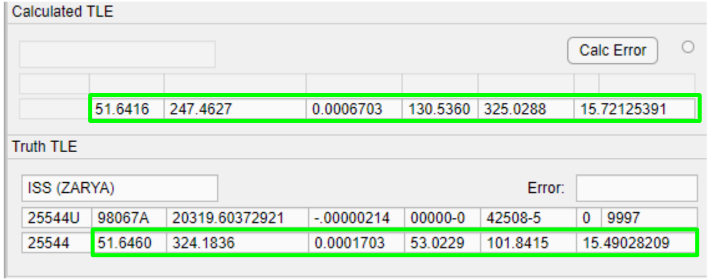
Error greater than 100km: 0.54%



FR6. A TLE will be calculated from a satellite passover. TLE will predict a future passover occurring within a day of TLE calculation. This prediction will include expected time to within ±45 minutes, azimuth start angle to within ±30º, and max elevation angle to within ±15º.

- In order to produce a TLE within the characteristics detailed by FR6, the TDoA accuracy requirement detailed in FR5 must also be satisfied. If the timing requirements for FR5 are met, the timing requirements for FR6 are also met. This means the design decisions driven by FR5 also satisfy our requirements for FR6.




Calculated TLE

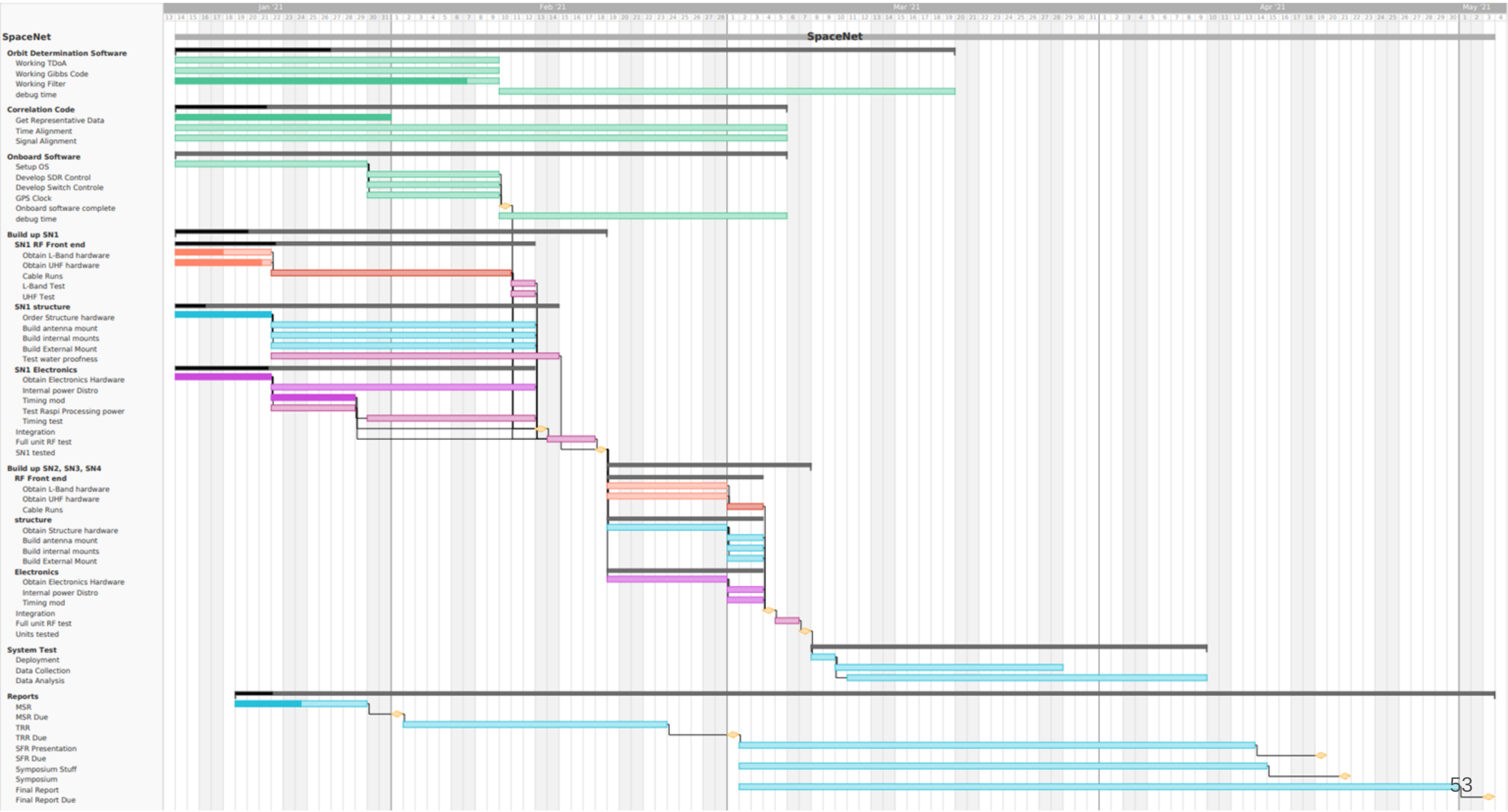
Calc Error

	51.6416	247.4627	0.0006703	130.5360	325.0288	15.72125391	

Truth TLE

ISS (ZARYA) Error:

25544U	98067A	20319.60372921	-.00000214	00000-0	42508-5	0	9997
25544	51.6460	324.1836	0.0001703	53.0229	101.8415	15.49028209	


Jan '21
Feb '21
Mar '21
Apr '21
May '21
SpaceNet
SpaceNet
Orbit Determination Software
Working TDoA
Working Gibbs Code
Working Filter
debug time
Correlation Code
Get Representative Data
Time Alignment
Signal Alignment
Onboard Software
Setup OS
Develop SDR Control
Develop Switch Controle
GPS Clock
Onboard software complete
debug time
Build up SN1
SN1 RF Front end
Obtain L-Band hardware
Obtain UHF hardware
Cable Runs
L-Band Test
UHF Test
SN1 structure
Order Structure hardware
Build antenna mount
Build internal mounts
Build External Mount
Test water proofness
SN1 Electronics
Obtain Electronics Hardware
Internal power Distro
Timing mod
Test Raspi Processing power
Timing test
Integration
Full unit RF test
SN1 tested
Build up SN2, SN3, SN4
RF Front end
Obtain L-Band hardware
Obtain UHF hardware
Cable Runs
structure
Obtain Structure hardware
Build antenna mount
Build internal mounts
Build External Mount
Electronics
Obtain Electronics Hardware
Internal power Distro
Timing mod
Integration
Full unit RF test
Units tested
System Test
Deployment
Data Collection
Data Analysis
Reports
MSR
MSR Due
TRR
TRR Due
SFR Presentation
SFR Due
Symposium Stuff
Symposium
Final Report
Final Report Due

Satellite Target Candidates

UHF Target: CSIM

The main target we will be using for this Frequency band is the CSIM Satellite operated locally here at CU Boulder

Operational characteristics:

- Fc = 437.25 MHz (Carrier)
- P = 5 W (Transmitted power)
- BW = 30 kHz (Beamwidth)
- DR = 9.6 kbps
- Demod = GMSK

L-Band Target: Iridium Next

Our primary target for this band is the Iridium NEXT Constellation.

Operation characteristics:

- Fc = 1616-1626.5 MHz (Carrier)
- P = 5 W (Transmitted power)
- BW = 30 kHz (Beamwidth)
- Possible data rates
  - Voice = 2.4kBps
  - Short Burst = 64 kBps

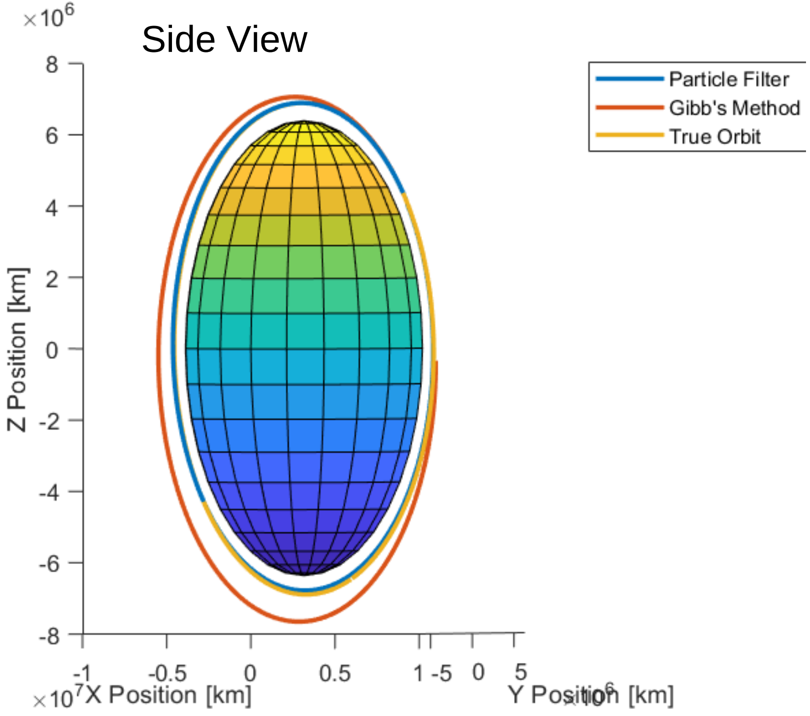
Backup L-Band Target

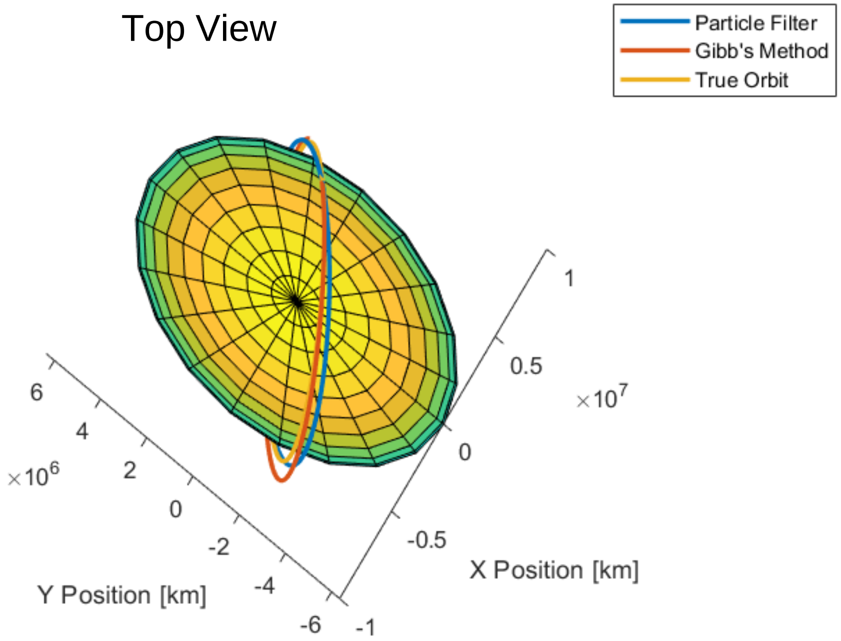
NOAA 15,18, or 19
All three of these are in Polar orbits

Operation characteristics respectively:

- Fc = 1702.5, 1707, 1698 MHz (Carrier)
- P = 6.35 W (Transmitted power)
- BW = 2.66 MHz (Beamwidth)
- DR = .665 Mbps
- Demod = BPSK or QPSK

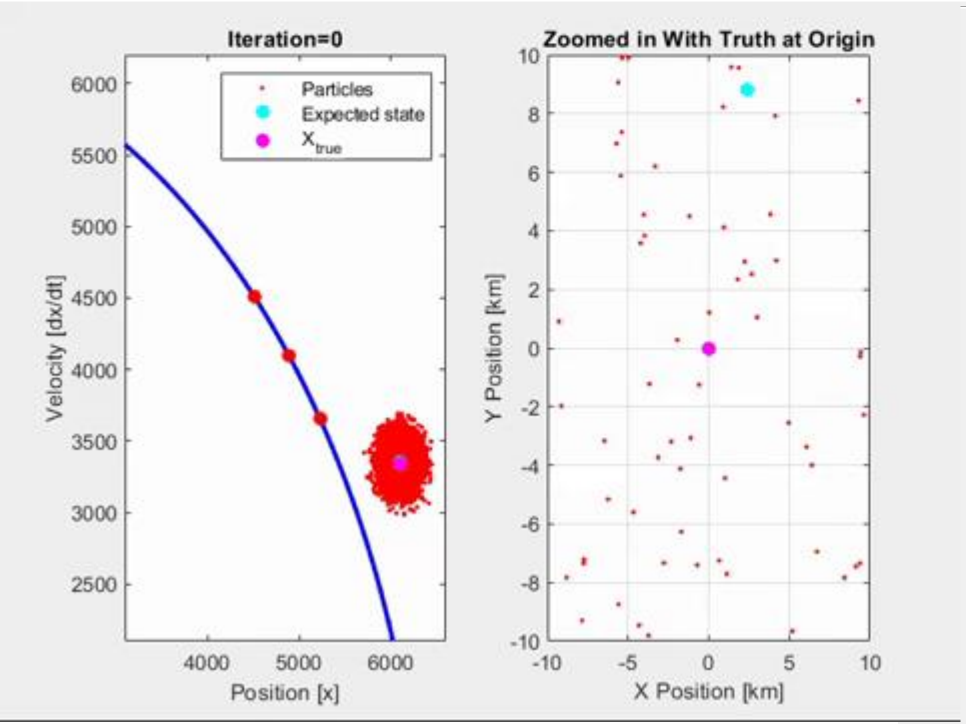
Orbital Partilce Filter One Orbit Comparisons

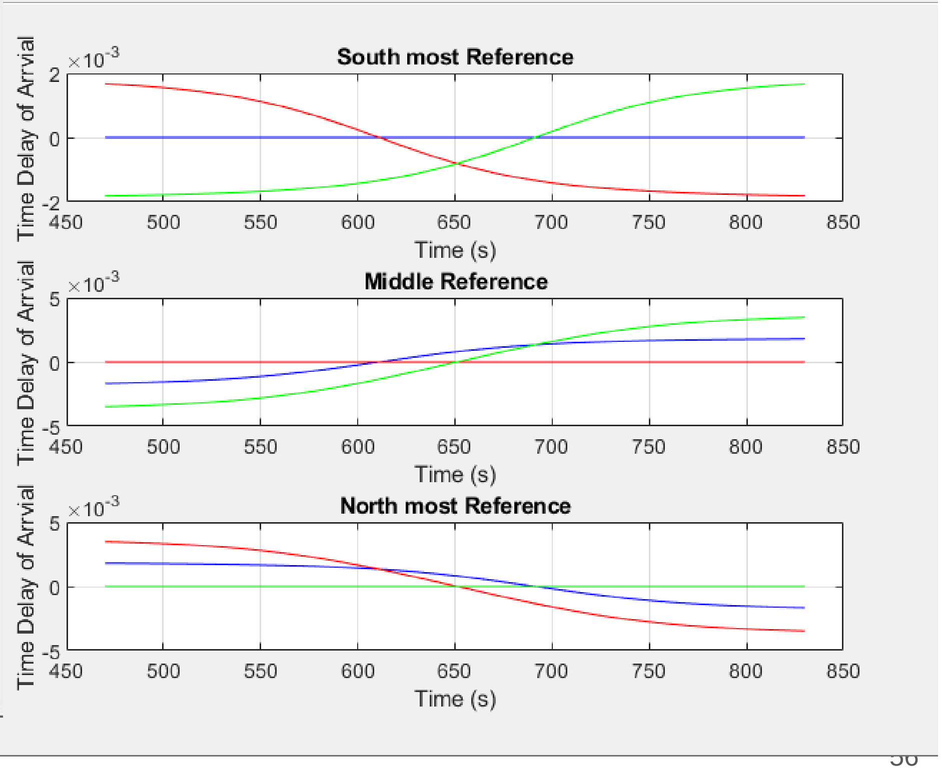




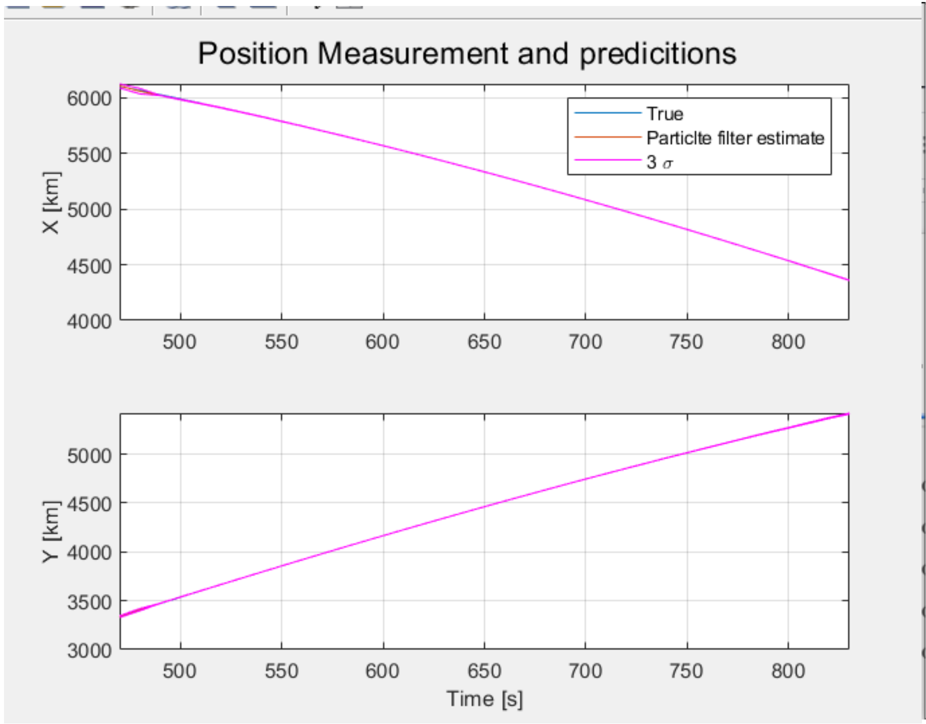
*Gibbs shown here DOES NOT have smoothing on TDoA Data

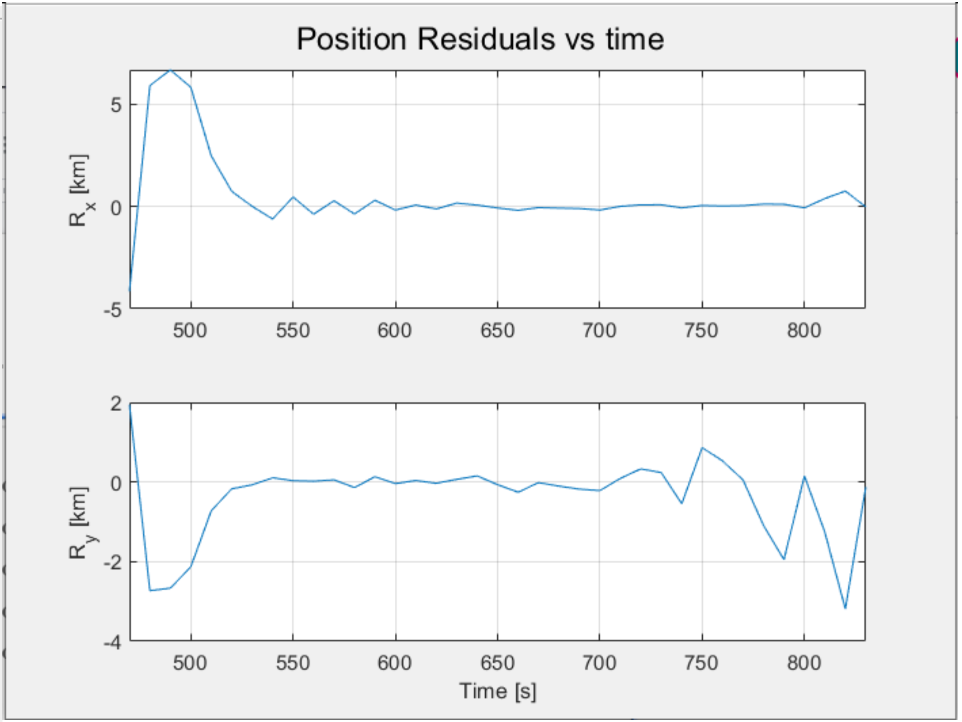
2D Particle Filter



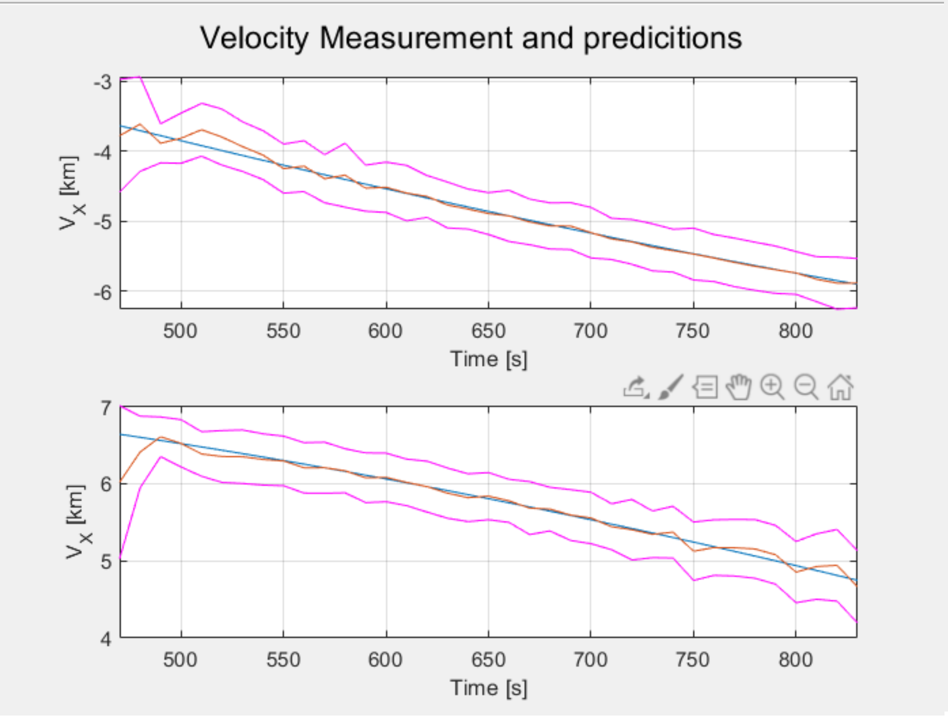


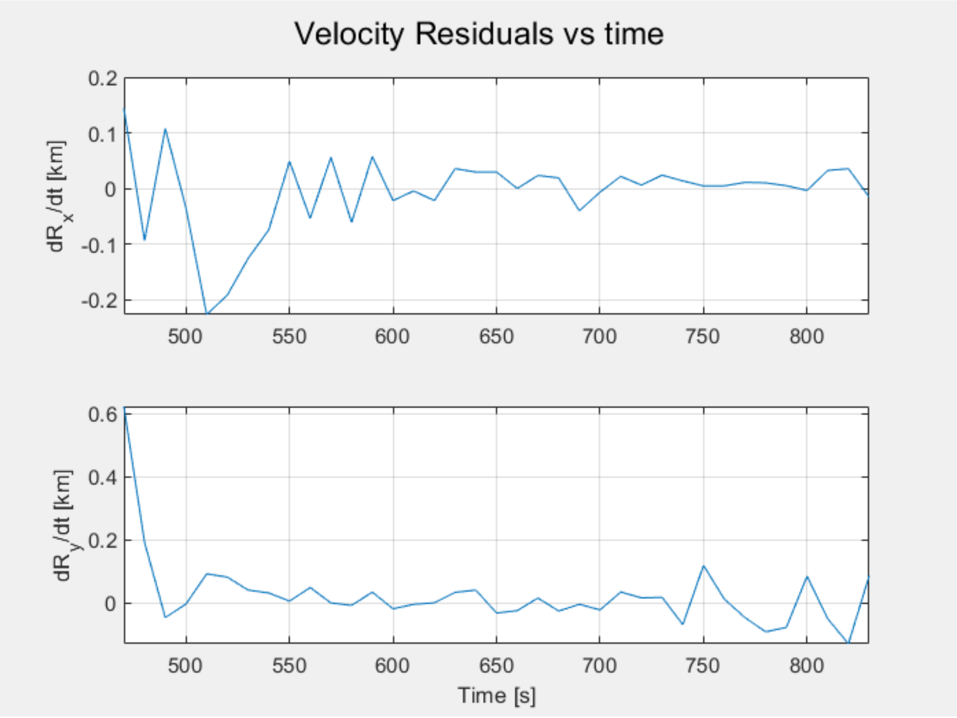
2D Particle Filter Position





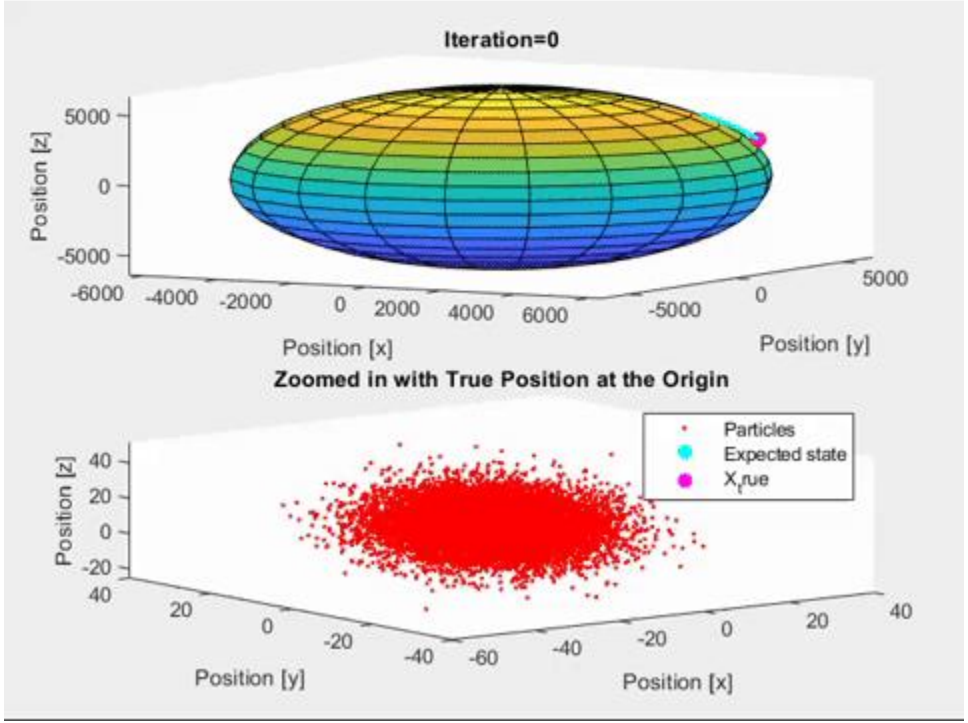
2D Particle Filter Position



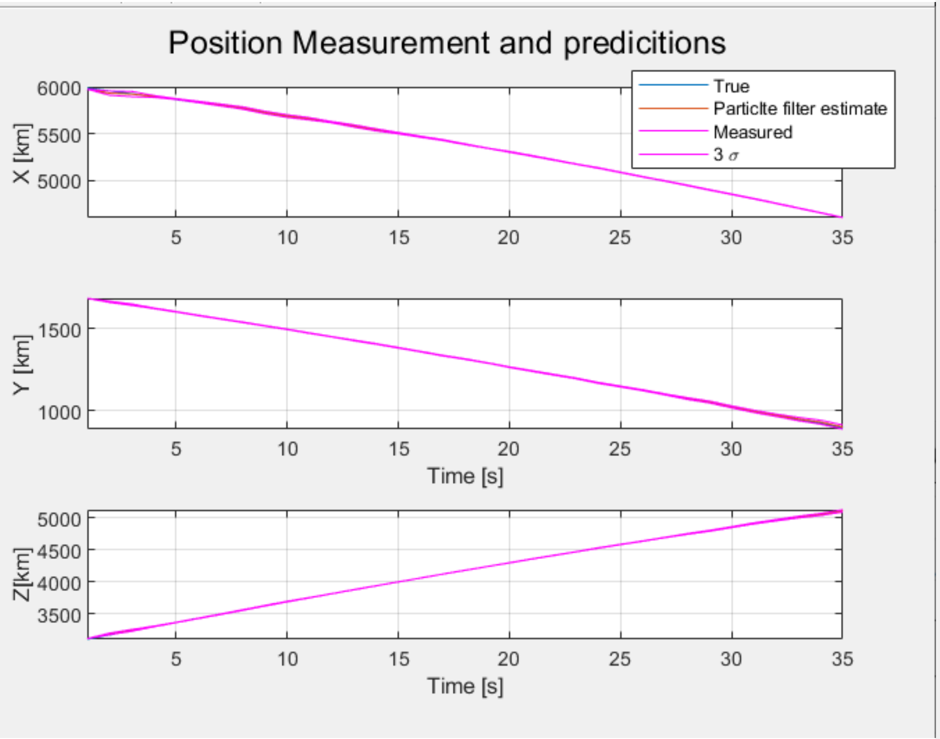


Particle Filter Verification

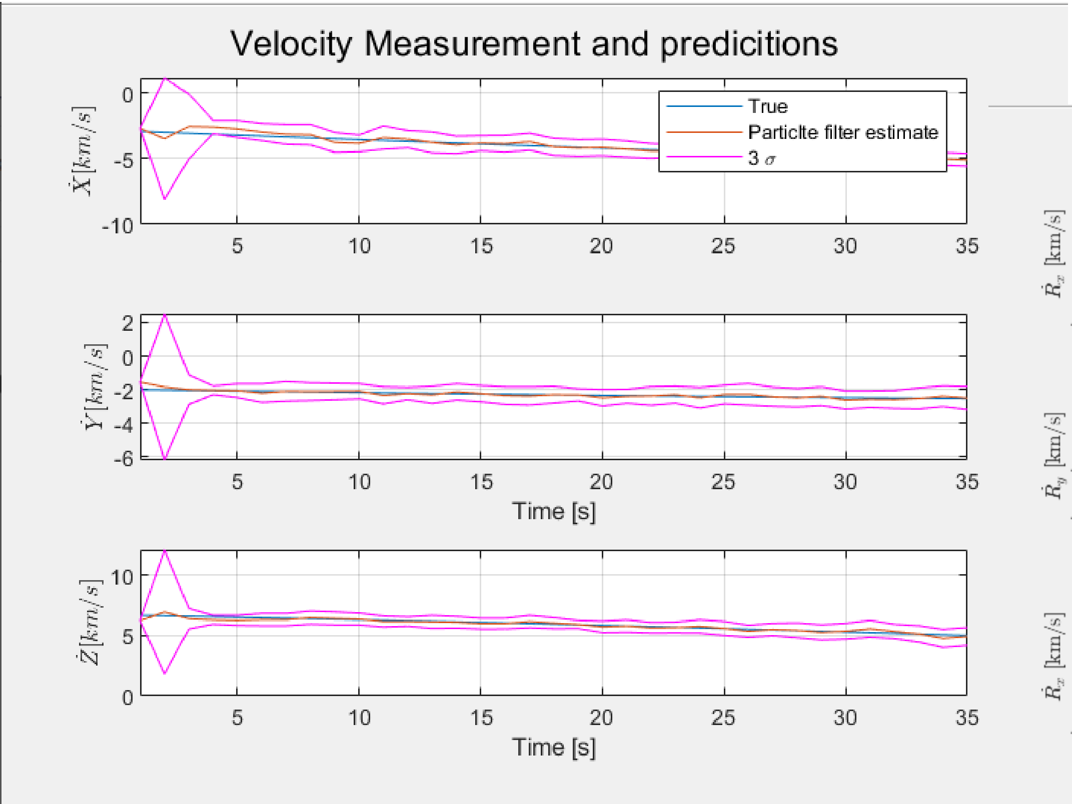
- New Range data will be generated in STK
- This will be used to create TDoA data
  - Add some noise
- See how well it predicts the orbit
- Compare to Gibb's and Lamberts

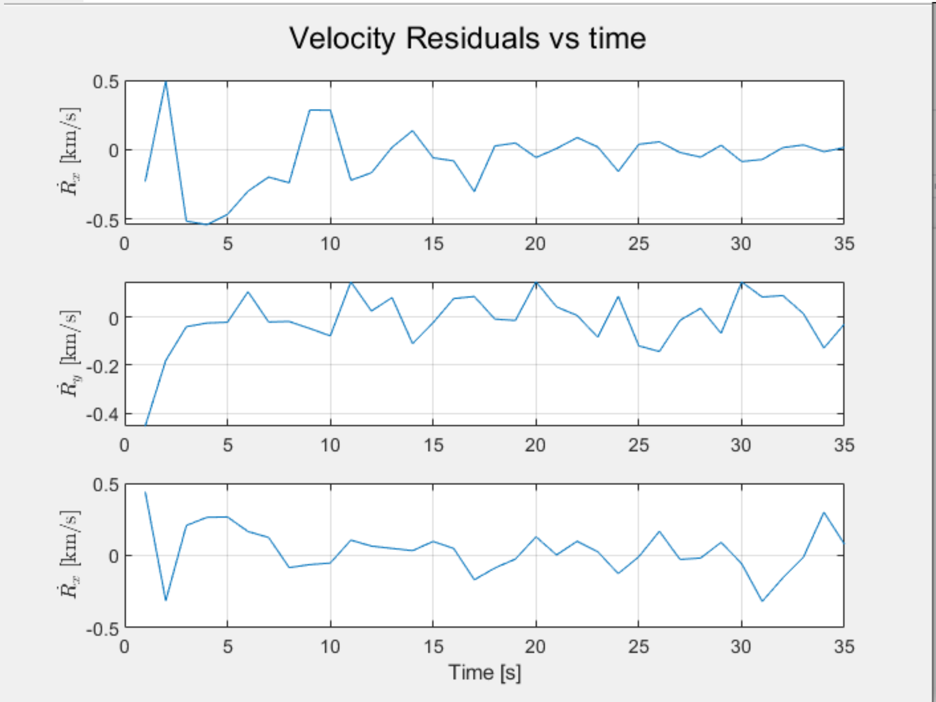


Particle Results: Position

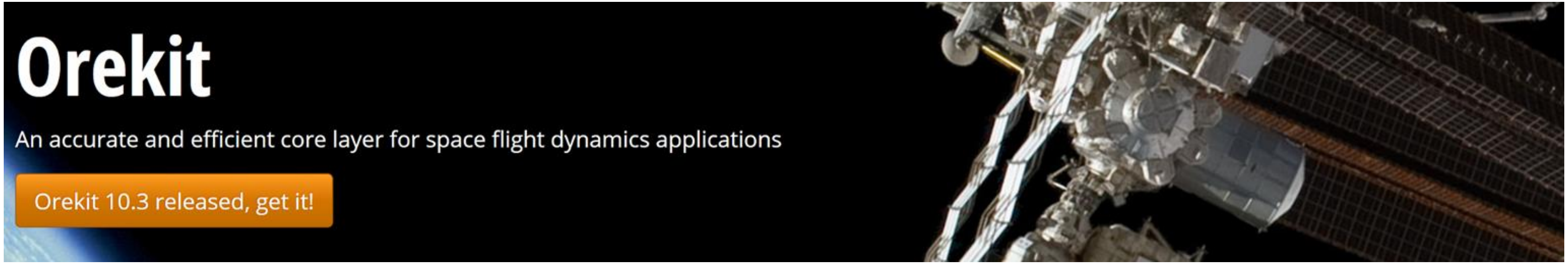


Particle Results: Velocity



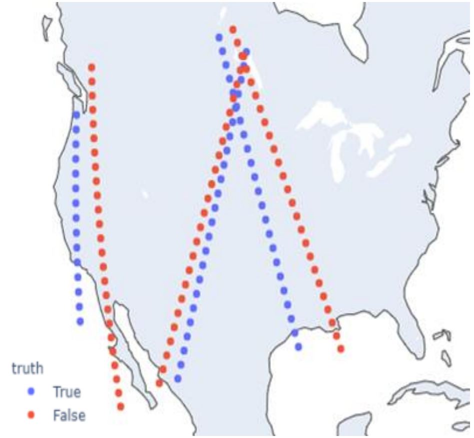


SGP4 Implementation: 1 of 2, Python Orekit Package

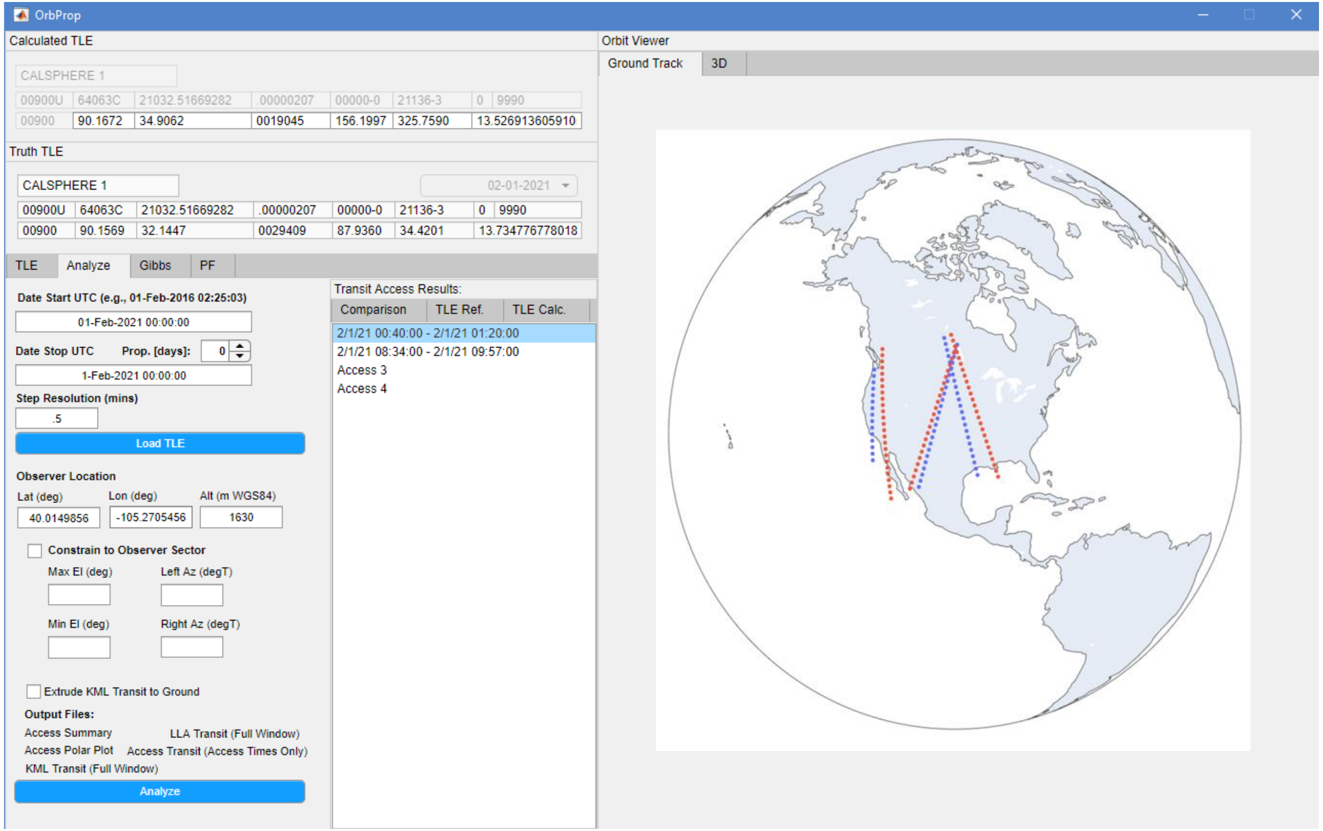


Simplified General Perturbations model 4(SGP4) includes the effects of drag and other orbital decay mechanisms for near earth objects with an orbital period less than 225 min.

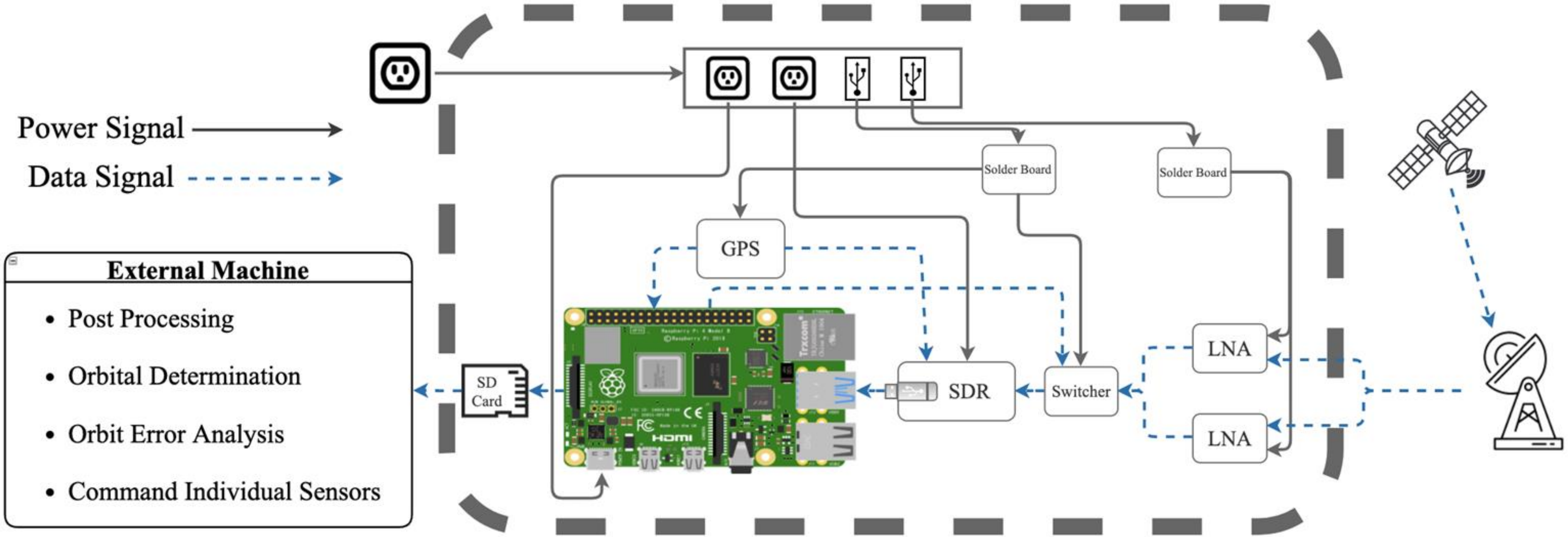
```
#CSIM-FD (Nov. 17, 2020) {CelesTrak}
tle_line1_1 = '1 43793U 18099AM  20322.77650623  .00000294  00000-0  31140-4 0  9996'
tle_line2_1 = '2 43793  97.6901  32.0620 0013721  41.5085 318.7175 14.96224559106613'

#CSIM-FD (Nov. 17, 2020) {Calculated from purturbed position data}
tle_line1_2 = '1 43793U 18099AM  20322.77650623  .00000294  00000-0  31140-4 0  9996'
tle_line2_2 = '2 43793  99.3581  44.5458 0288570  117.3180  15.5230 14.3573000106613'
```



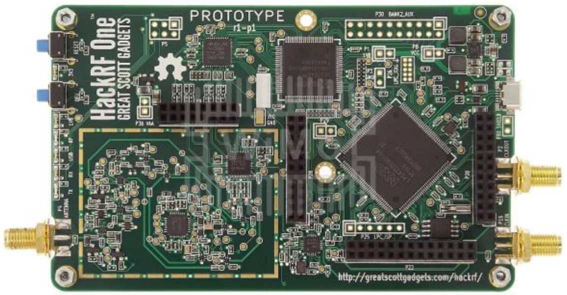
SGP4 Implementation: 1 of 2, Matlab App

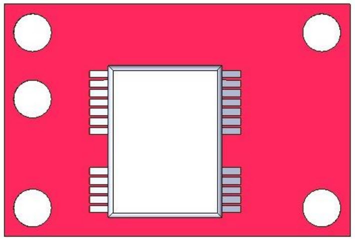


Power & Data Pipeline



Data Transfer Bottlenecks: SDR and GPS Module





<u>HackRF One</u>

The HackRF One is capable of receiving and transmitting on a frequency range of 1MHz to 6GHz with output power of 30 mW to 1 mW depending on the band.

<u>Ublox NEO 7M</u>

The maximum reference output clock per the data sheet is 10 MHz.

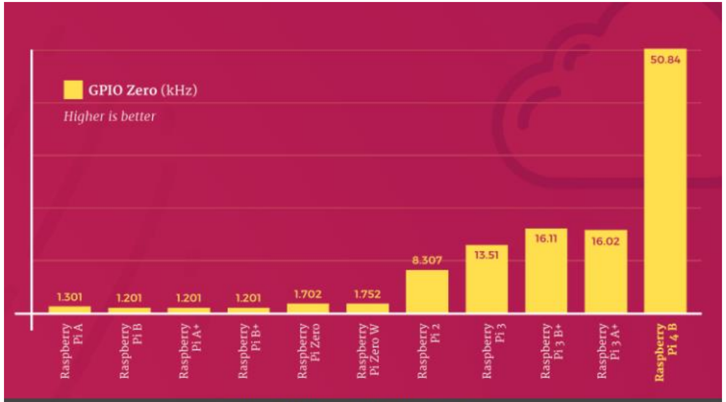
Has also been reported to be stable at 13 MHz.

Link

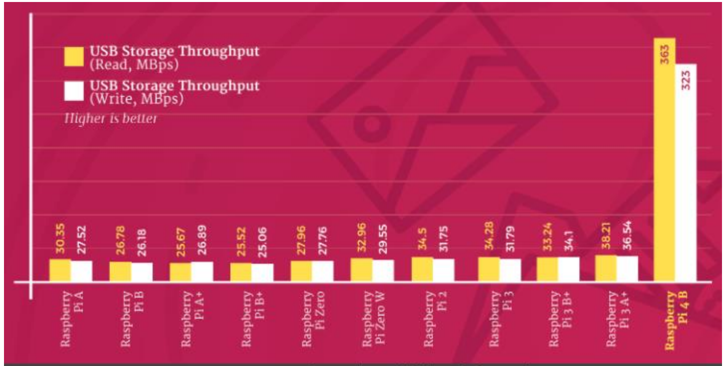
Data Transfer Bottlenecks: Raspberry Pi 4

- 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