SpaceNet
Test Readiness Review

Spring 2021

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Raytheon Technologies + University of Colorado Boulder

What is SpaceNet?

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

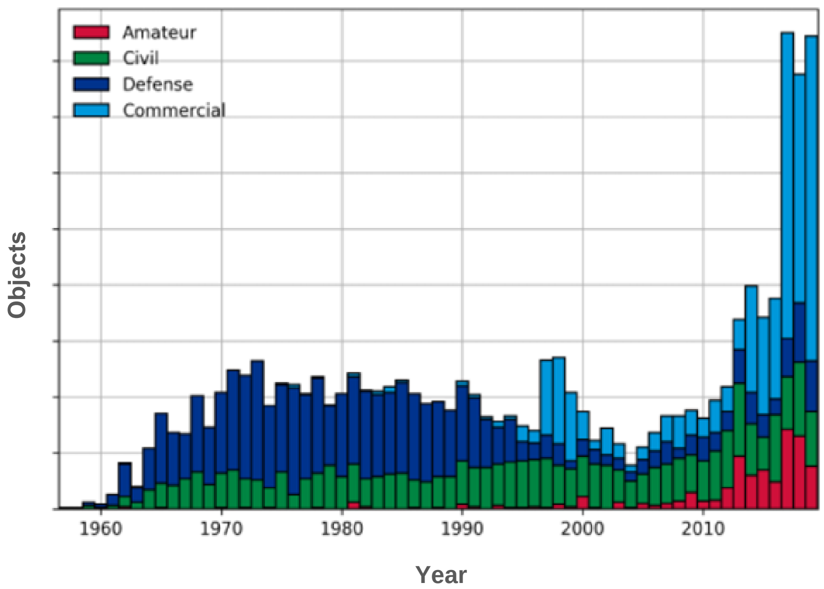
This Project

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

Planned LEO/GEO Missions



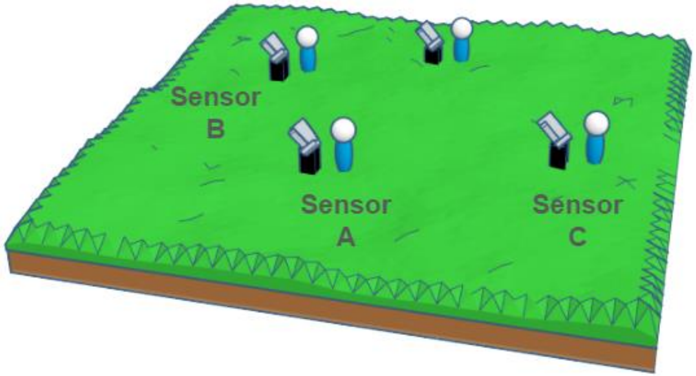
Plot from the ESA space debris portal https://sdup.esoc.esa.int/discosweb/statistics/

SpaceNet
Concept of Operations (CONOPS)

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

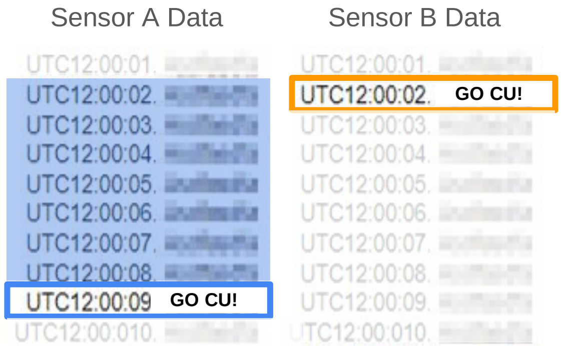
3. Satellite transmits during flyby

4. Transmissions are received by sensors



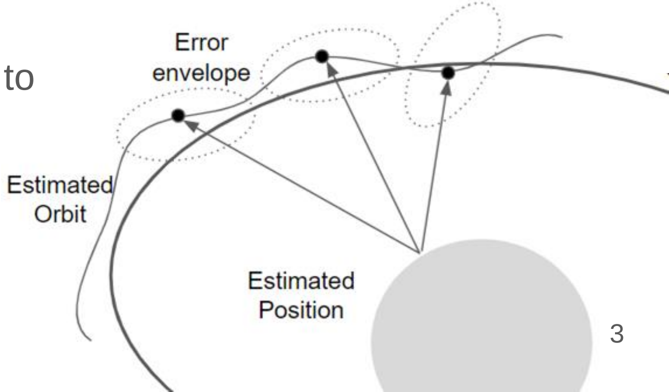
5. Transmissions are identified post test

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

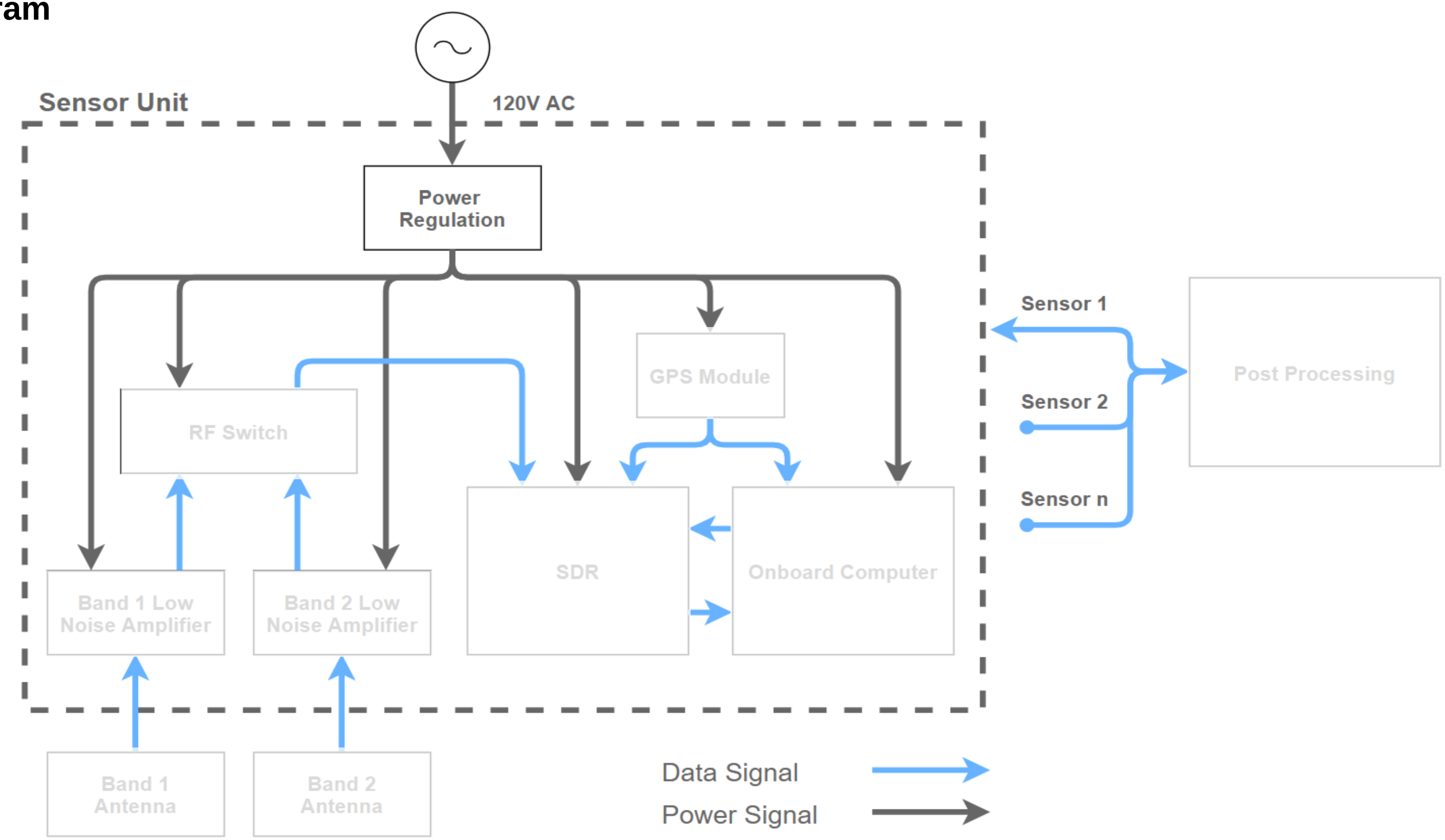


7. Time delay is used to estimate satellite position

8. Position used to estimate orbit

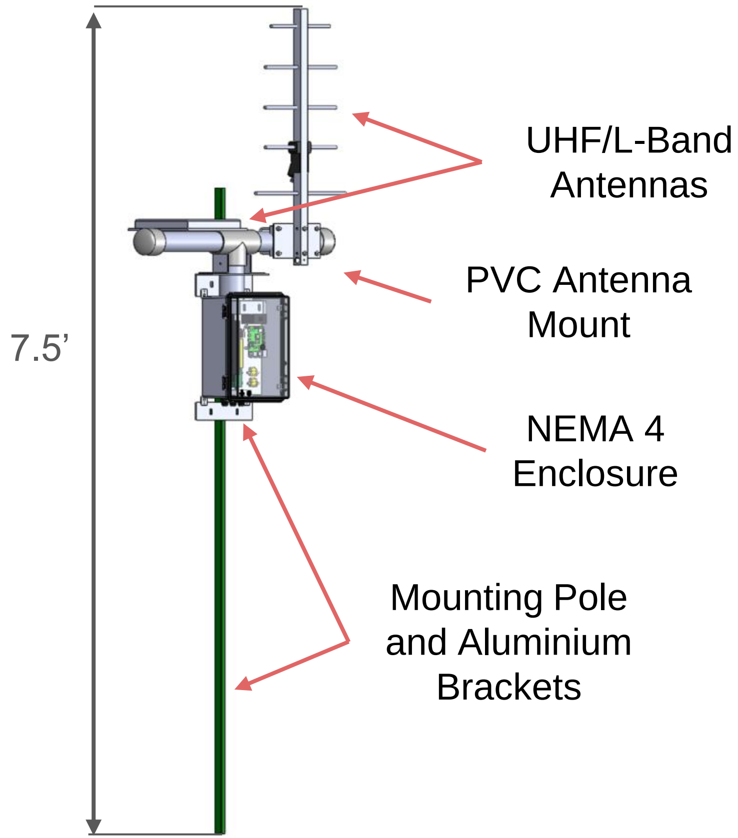


SpaceNet Functional Block Diagram

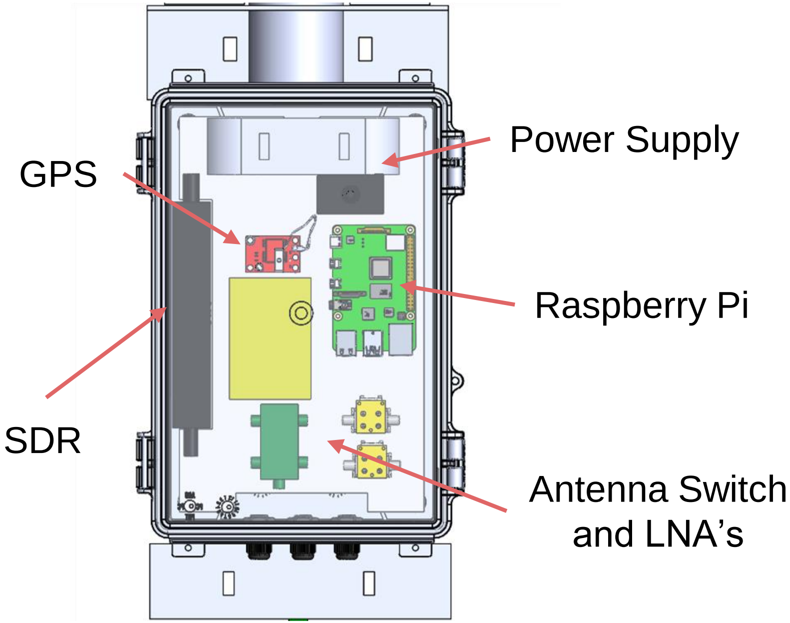


Baseline Design

External



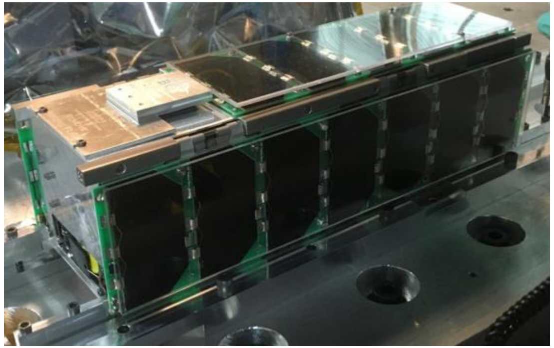
Internal



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

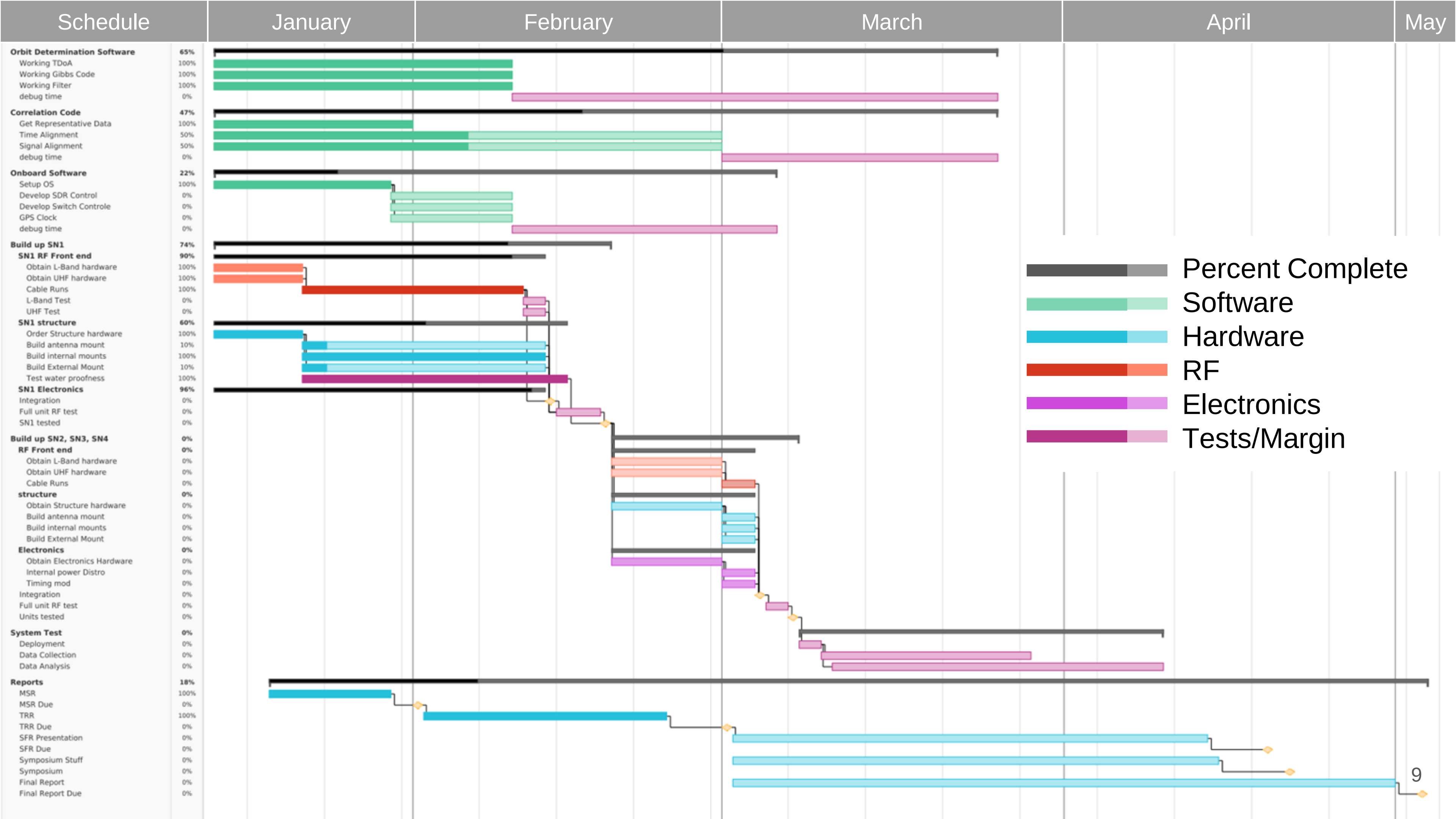
Our primary target for this band is the Iridium NEXT Constellation.

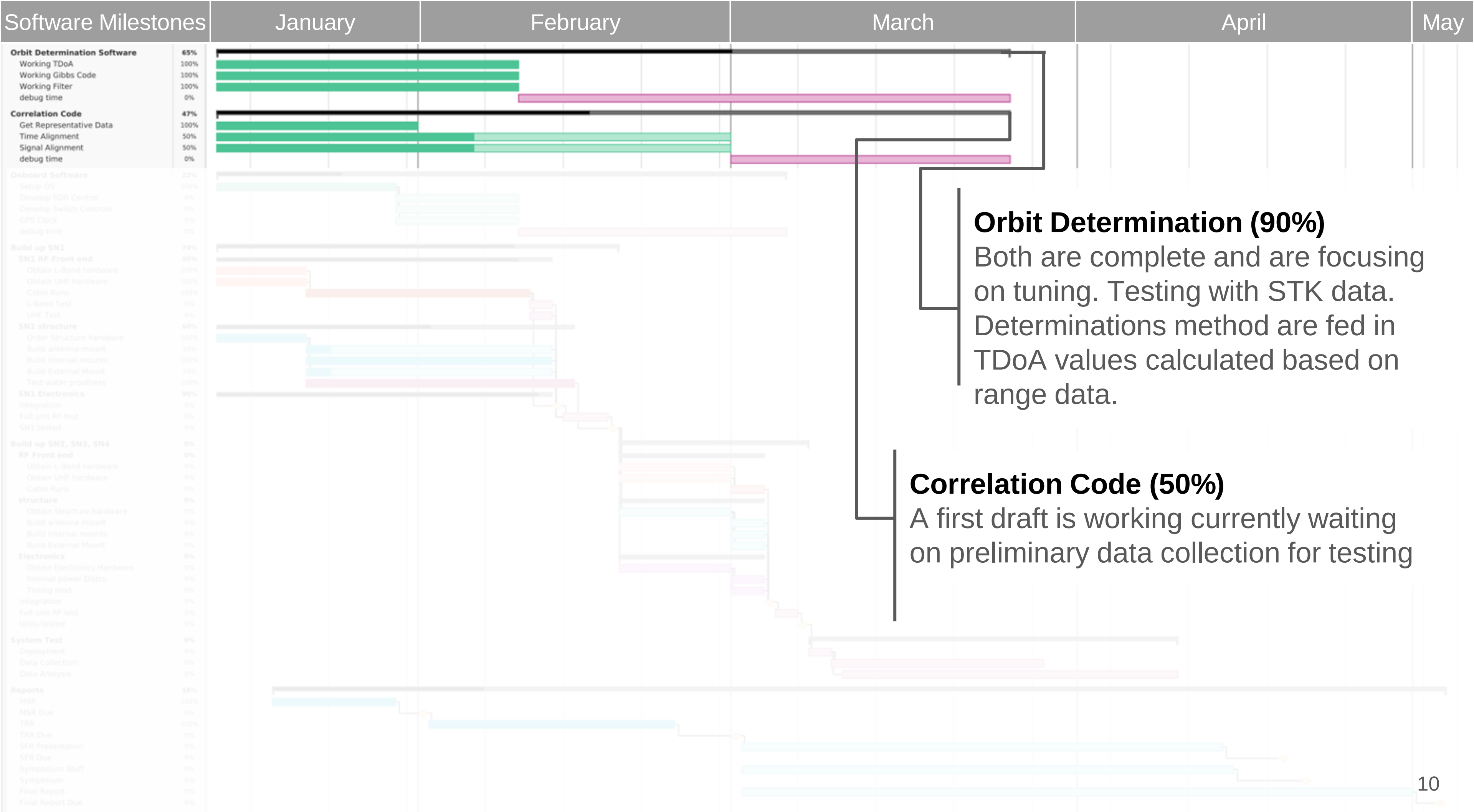
Operation characteristics:

- 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
RF Front End	The RF front enables UHF and L-band signal reception. The reception must be good enough to discern the transmission from the noise floor
Timing Synchronization	The received data must be alignable such that time delay can be measured with extreme precision. Error here has a large impact on positional predictions
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

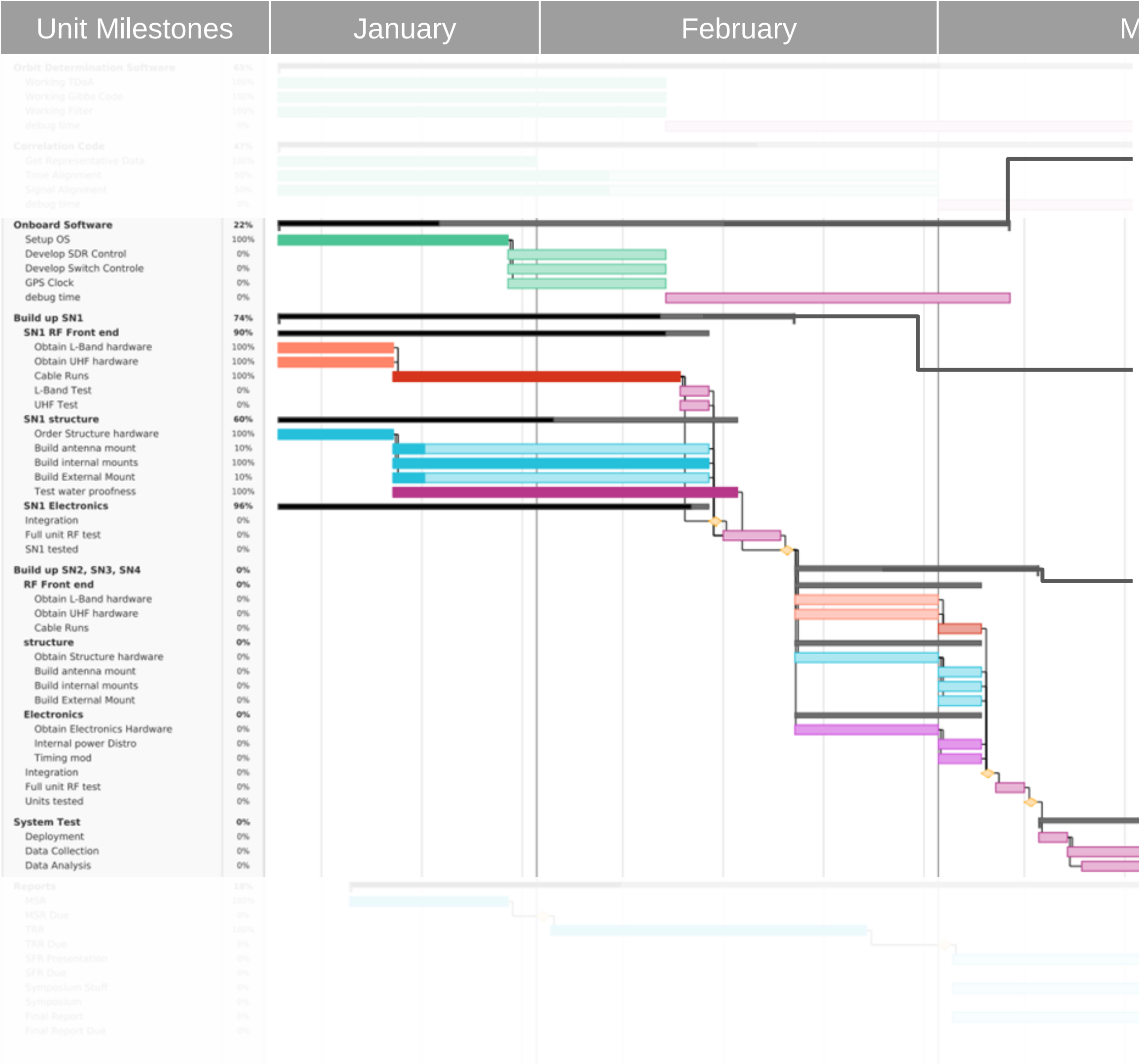
Levels of Success	Key Objectives
1	● TDOA from artificial data ● Orbital Prediction from artificial data ● 4 units built ● Sensor Units shall receive on single band ● Sensor units shall be able to synchronize to UTC time via GPS
2	● TDOA prediction from 2 units data ● Sensor Units shall receive on dual bands ● Sensor Units shall be able to recover in result of a power outage ● Sensor Units data shall be synchronized to within 420 ns
3	● Four Units are deployed and operational ● Manufacturing Documentation (schematics, procedure, manufacturing analysis, suggested improvements, and ways to drive down cost) ● TDOA prediction from 4 units data ● Orbital prediction from data


Schedule
January
February
March
April
May
Orbit Determination Software 65%
Working TDoA 100%
Working Gibbs Code 100%
Working Filter 100%
debug time 0%
Correlation Code 47%
Get Representative Data 100%
Time Alignment 50%
Signal Alignment 50%
debug time 0%
Onboard Software 22%
Setup OS 100%
Develop SDR Control 0%
Develop Switch Controle 0%
GPS Clock 0%
debug time 0%
Build up SN1 74%
SN1 RF Front end 90%
Obtain L-Band hardware 100%
Obtain UHF hardware 100%
Cable Runs 100%
L-Band Test 0%
UHF Test 0%
SN1 structure 60%
Order Structure hardware 100%
Build antenna mount 10%
Build internal mounts 100%
Build External Mount 10%
Test water proofness 100%
SN1 Electronics 96%
Integration 0%
Full unit RF test 0%
SN1 tested 0%
Build up SN2, SN3, SN4 0%
RF Front end 0%
Obtain L-Band hardware 0%
Obtain UHF hardware 0%
Cable Runs 0%
structure 0%
Obtain Structure hardware 0%
Build antenna mount 0%
Build internal mounts 0%
Build External Mount 0%
Electronics 0%
Obtain Electronics Hardware 0%
Internal power Distro 0%
Timing mod 0%
Integration 0%
Full unit RF test 0%
Units tested 0%
System Test 0%
Deployment 0%
Data Collection 0%
Data Analysis 0%
Reports 18%
MSR 100%
MSR Due 0%
TRR 100%
TRR Due 0%
SFR Presentation 0%
SFR Due 0%
Symposium Stuff 0%
Symposium 0%
Final Report 0%
Final Report Due 0%
Percent Complete
Software
Hardware
RF
Electronics
Tests/Margin



Orbit Determination (90%)
Both are complete and are focusing on tuning. Testing with STK data. Determinations method are fed in TDoA values calculated based on range data.

Correlation Code (50%)
A first draft is working currently waiting on preliminary data collection for testing

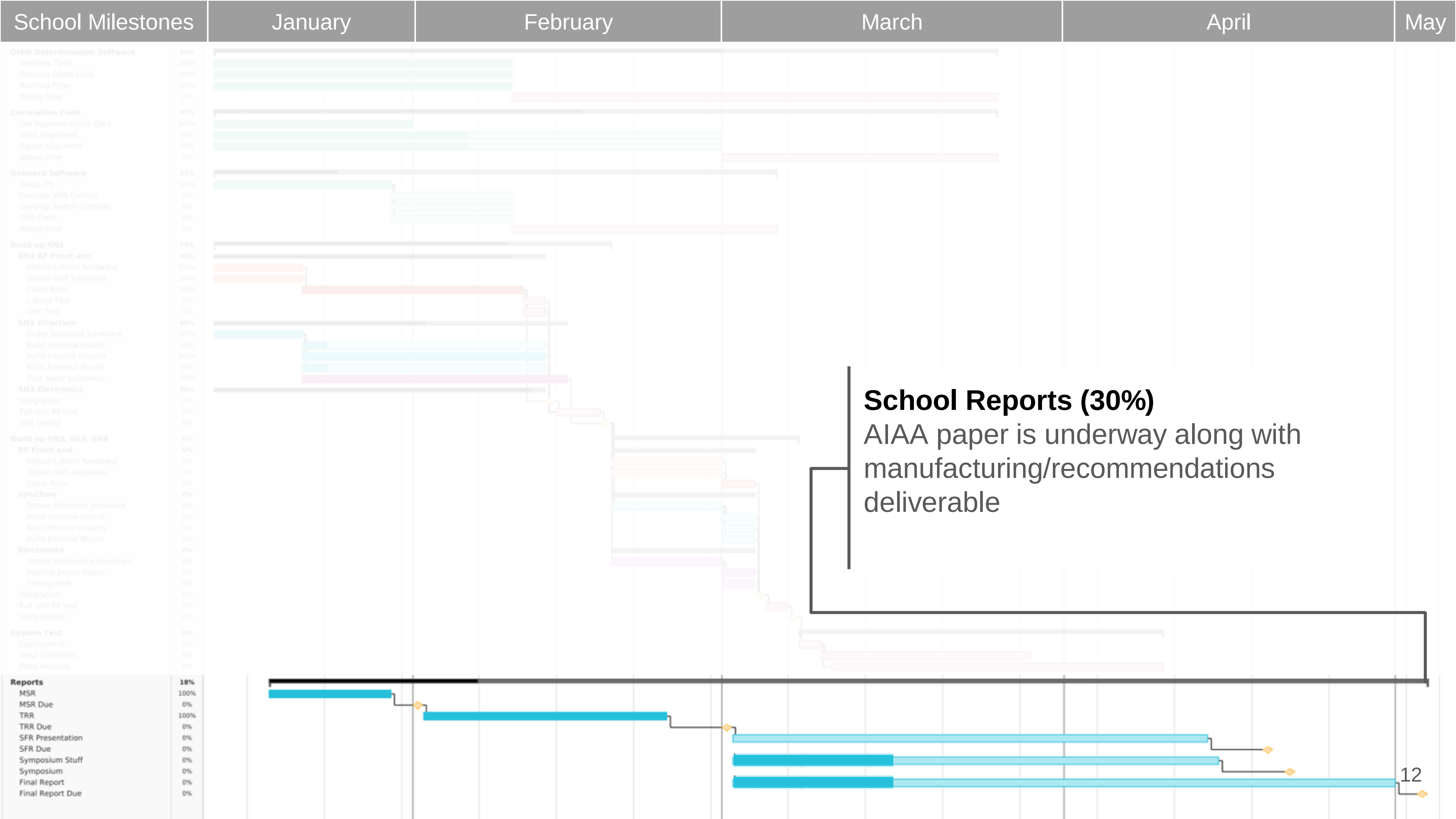


OnBoard OS (50%)
The OnBoard OS has been installed, and we have gained some SDR control. Now we must debug and test other connected devices

SN1 (90%)
All parts are cut and in phase for final assembly when final parts for mounting solution arrive.

SN2,3,4 (50%)
Parts are laid out and ready to be cut and fitted to match SN1 following manufacturing document procedure.

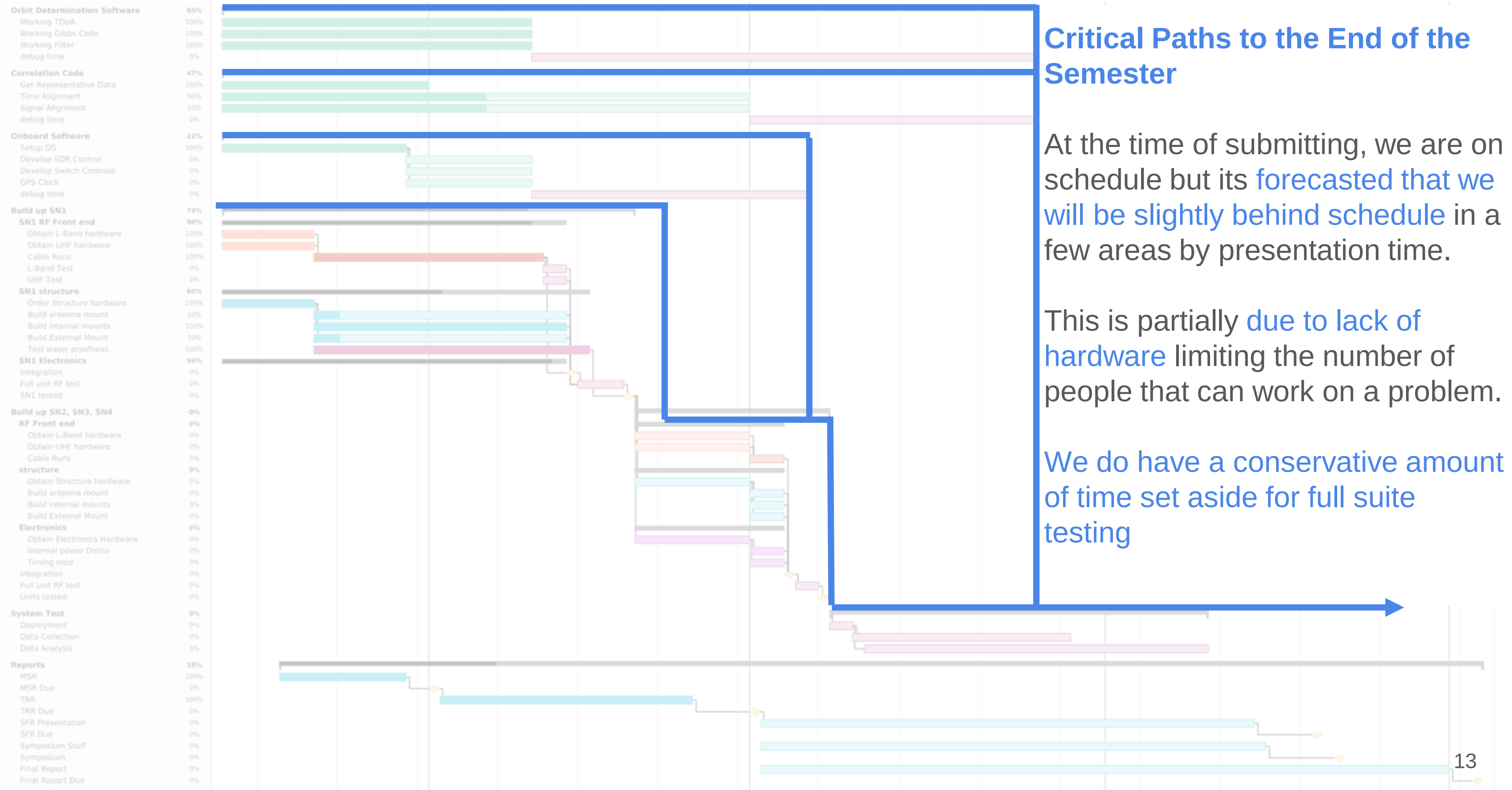
Full suite Testing (0%)
Currently waiting on Sensor Unit Assembly and Onboard OS



School Reports (30%)

AIAA paper is underway along with manufacturing/recommendations deliverable

Critical Paths



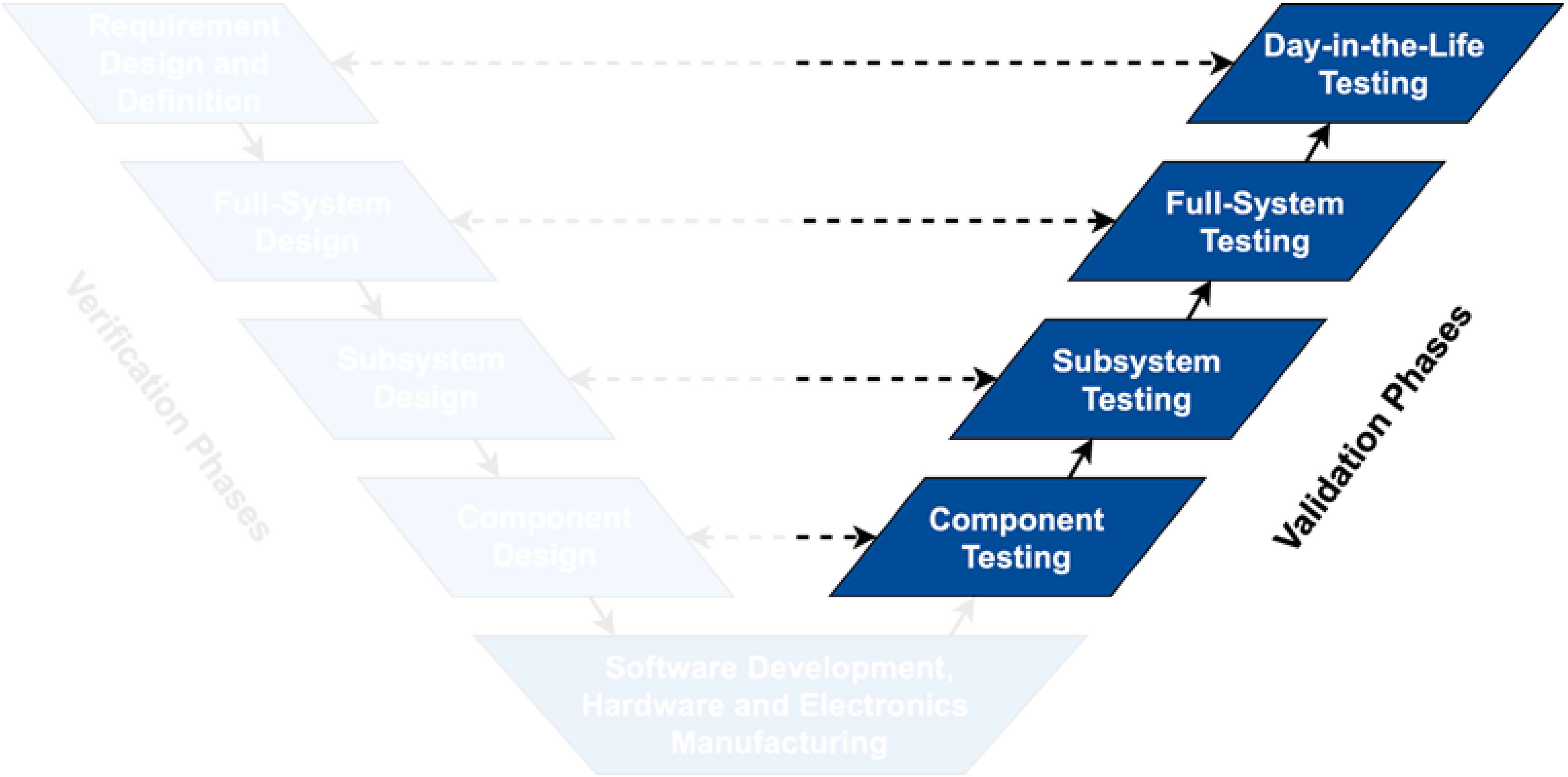
Critical Paths to the End of the Semester

At the time of submitting, we are on schedule but its forecasted that we will be slightly behind schedule in a few areas by presentation time.

This is partially due to lack of hardware limiting the number of people that can work on a problem.

We do have a conservative amount of time set aside for full suite testing

Test Methodology



Component Level Testing

Box Weatherproof	Test that the box and cable pass throughs are weather resistant and leak proof
GPS	Ensure the GPS Pulse Per second meets the device specifications
HackRF & Timing scheme	Ensure the SDR meets the device specifications for sample rate and that timing scheme operates as expected
UHF LNA	Ensure the UHF LNA performs per spec sheet
L-Band LNA	Ensure the L-band LNA performs per spec sheet
RF Switch	Measure the noise level with switch and without switch
RF_Control.py	Ensure the Raspi can command the switch to change between the two RF Inputs
GPS_timer.py	Ensure the Raspi can use GPS time to determine when to start data collection
Data_handler.py	Ensure recorded data can be slimmed and moved to proper location for off loading
Correlation Testing (TDOA)	Ensure that the correlation scheme works and does not add delay above required max
Orbit determination	Ensure orbit prediction works based on simulated data.

SubSystem Level Testing

Temperature	Ensure that the internal temperature of the box will remain within operating conditions as modeled
Onboard OS	Ensure that the subscripts run on start-up and operate as expected.
Raspi HackRF Compatibility	Ensure the HackRF performs the same when connected to the Raspi
Circuit Board	Test the power and signal distribution board behaves as expected
UHF Frontend	Ensure that the UHF front end meets the design Signal to noise ratio and other parameters
L-band Frontend	Ensure that the L-band front end meets the design Signal to noise ratio and other parameters
Post Processing software	Ensure the orbit determination meets requirements given TDOA output
Single Unit	Build an unit and repeat all subsystem to unit to see if the results match.

Full System Level Testing

Signal Correlation	Ensure that the signals from boxes can be aligned and maintain the timing accuracy calculated
Full suite test	Ensure that the predicted orbited from test data is within the expected error

Tests we plan to cover

- Summarize other tests
- Critical to project success
- Relevant to current timeline

Component Level Testing

Box Weatherproof	In Progress Est. 2/28	
GPS	Done Completed 2/27	
HackRF & Timing scheme	Done Completed 2/10	
UHF LNA	Incomplete Revised 3/8	Will be tested as part of frontend testing
L-Band LNA	Incomplete Revised 3/8	Will be tested as part of frontend testing
RF Switch	Incomplete Revised 3/8	Will be tested as part of Onboard OS testing
RF_Control.py	Done Completed 2/24	
GPS_timer.py	Done Completed 2/24	
Data_handler.py	In Progress Est. 2/28	Will be tested with onboard OS
Correlation Testing (TDOA)	In Progress Est. 3/12	Needs Data
Orbit determination	Done Completed 2/01	

SubSystem Level Testing

Temperature	In Progress Est. 2/28	
Onboard OS	In Progress Est. 2/28	
Raspi HackRF Compatibility	Done Completed 2/24	
Circuit Board	Incomplete Est. 2/28	Waiting on hardware
UHF Frontend	Incomplete Revised 3/8	
L-band Frontend	Incomplete Revised 3/8	
Post Processing software	In Progress Est. 3/23	
Single Unit	In Progress Revised 3/8	Waiting on other subsystems

Full System Level Testing

Signal Correlation	Incomplete Est. 3/23
Full suite test	Incomplete Est. 3/15

Done
In Progress
Incomplete

Completed	Date Finished
Estimated	Planned Deadline
Revised	Behind Schedule. New Deadline

Component Level Tests

Tests	Test Goal
Correlation Testing (TDOA)	Ensure that the correlation scheme works and does not add delay above required max
Orbit determination	Ensure orbit prediction works based on simulated data.

Correlation Testing (TDOA) Test

Overall Test Goal(s): Ensure that the correlation scheme works and does not add delay above the required max.

Requirements: FR 5, FR 6

Risk Mitigated: SDRs cannot be aligned according to GPST.

Modeled Results: Simulated TDoAs.

Test(s)	Status	Test Goal
Zero TDoA	In Progress	Cross correlate 2 signals and pull out a TDoA = 0 to heuristically evaluate SDR noise
B-A TDoA	Incomplete	Cross correlate 2 signals between (B)oulder and (A)urora

Zero TDoA Test Overview

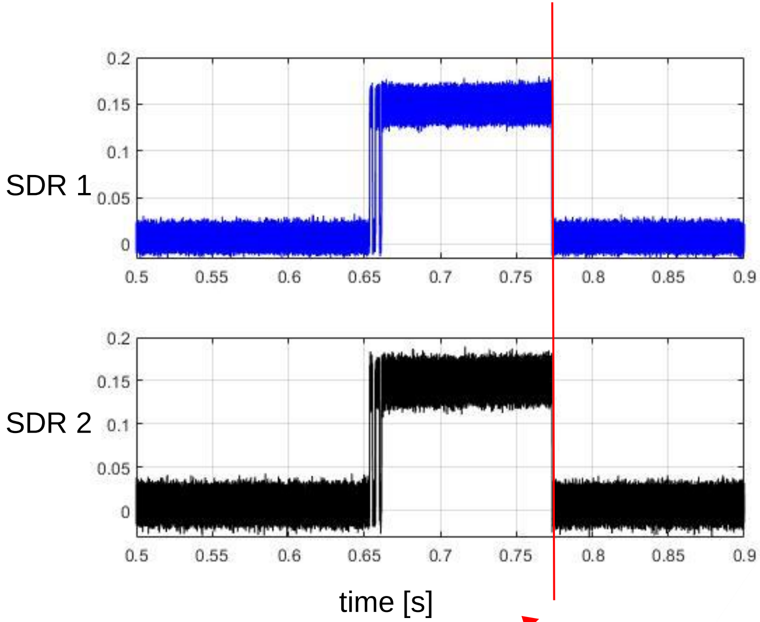
Procedure:

- Collect Data with SDRs at the same location.
- Press ‘collect’ within one second of each other for gps alignment.

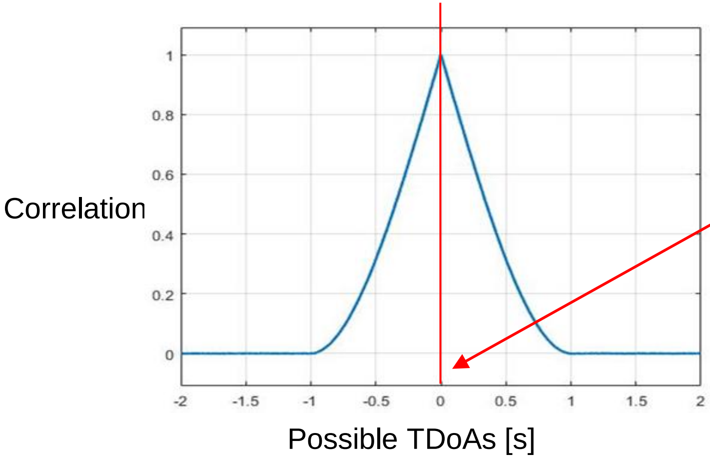
Equipment/Facilities needed:

- Two SDRs.

Test goal - Verify that TDoA between two SDRs at the same location is zero.



TDoA = 0 [s]



B-A TDoA Test Overview

Procedure:

- Collect Data with SDRs in Aurora, CO and Boulder, CO.
- Press ‘collect’ within one second of each other for gps alignment.

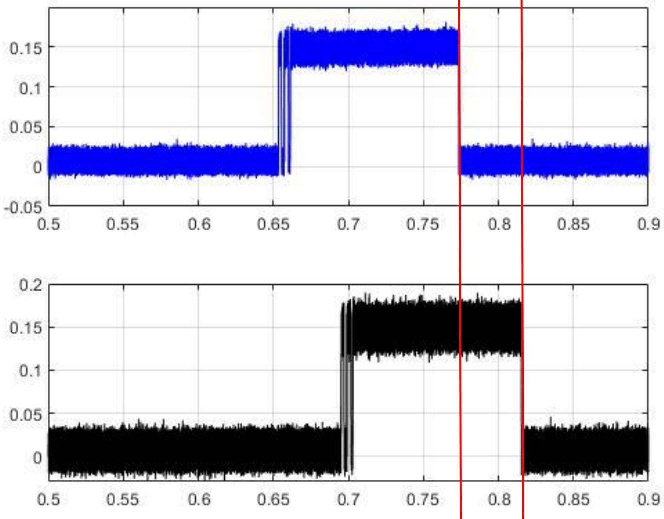
Equipment/Facilities needed:

- Two SDRs.

Test goal - Verify that TDoA between two SDRs at different locations is at the predicted value.

SDR 1

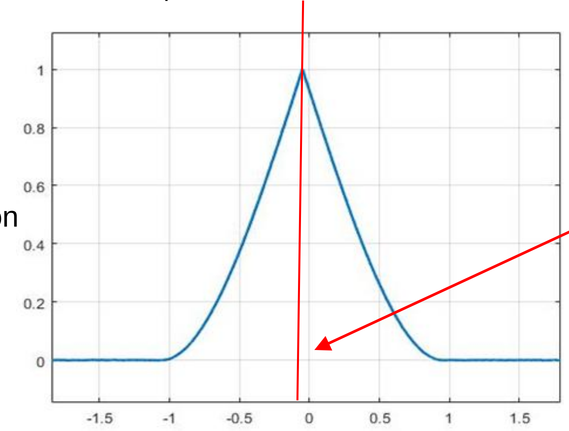
SDR 2



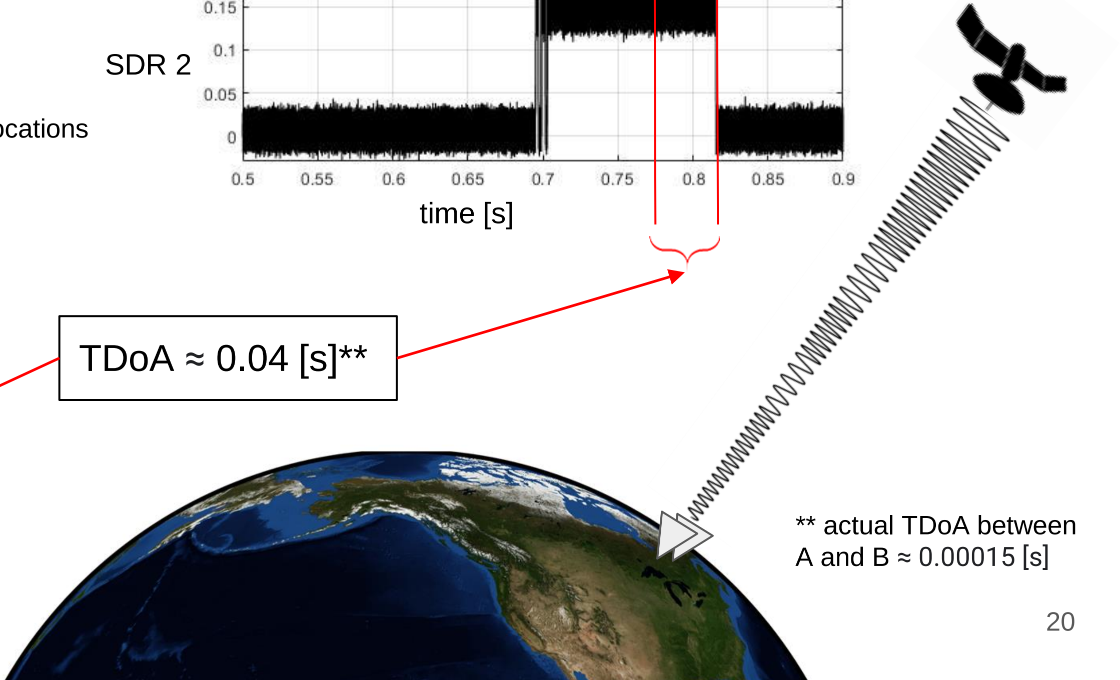
time [s]

TDoA ≈ 0.04 [s]**

Correlation



Possible TDoAs [s]



** actual TDoA between A and B ≈ 0.00015 [s]

Orbit Determination Test

Overall Test Goal(s): Prove Determination software predicts Orbits within margins.
Requirements: FR 5, FR 6

Risk Mitigated: Verified that post processing is free of systematic errors.

Modeled Result: Post processing steps completed successfully.

Test(s)	Status	Test Goal
Verify PF	Done	Verify Particle Filters ability to successfully generate the state time series
Verify TLE	Done	Verify that the state time series can be successfully used to generate a TLE
Verify SGP4	Done	Verify SGP4 propagators ability to generate accurate satellite passover list

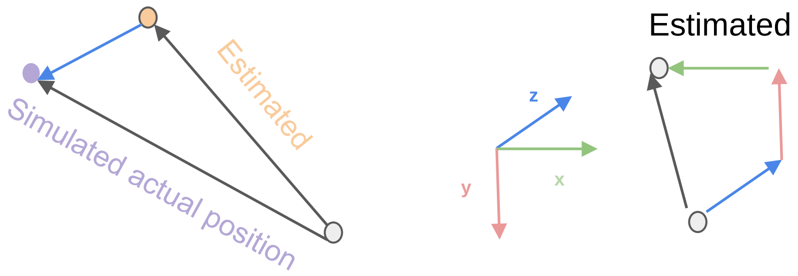
Orbit Determination Test Overview

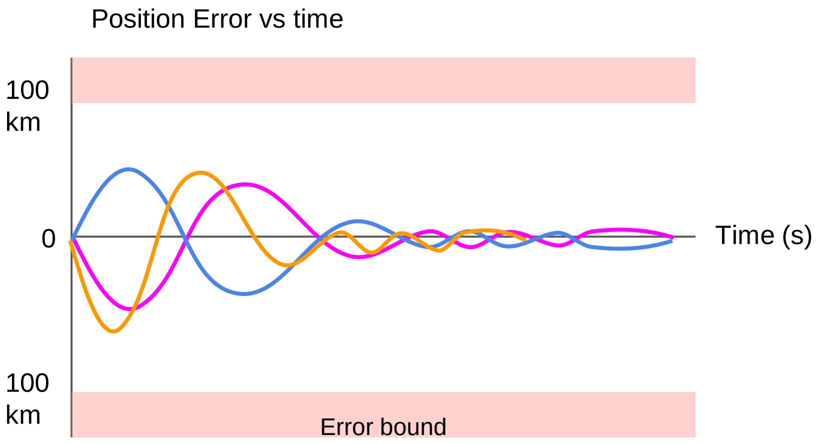
Test Procedure Overview:

- STK produced multiple sample satellite orbits and range data from the orbit to each sensor.
- Calculated sample TDoA values from the ranges with induced 100 ns measurement error.
- TDoA values initialized the orbital determination method.
- Update estimate with remaining TDoA values.
- Compared output estimates to STK data. Calculated the difference between them or residual vectors.

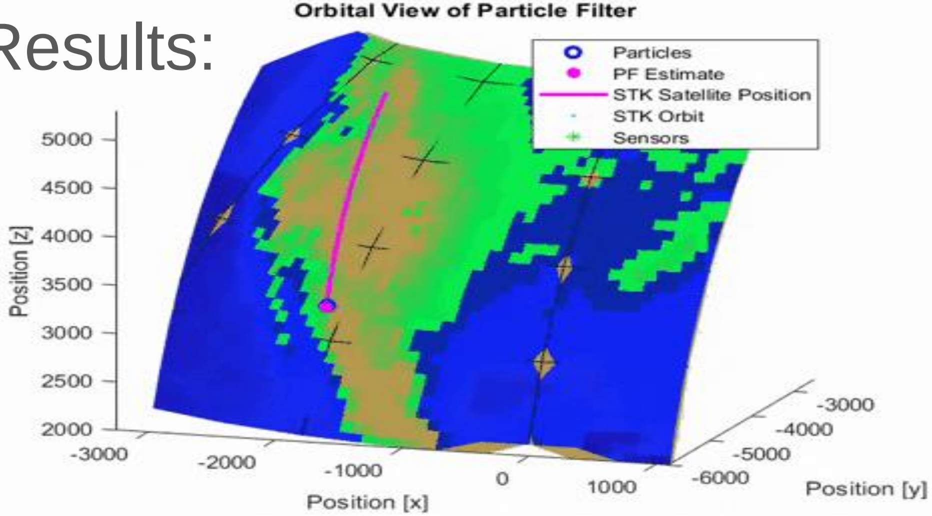
Equipment/Facilities needed:

STK and Matlab

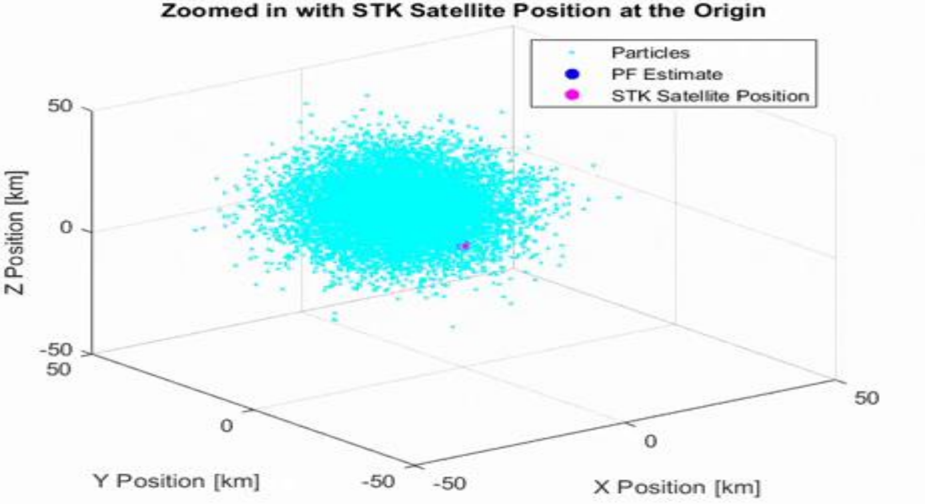




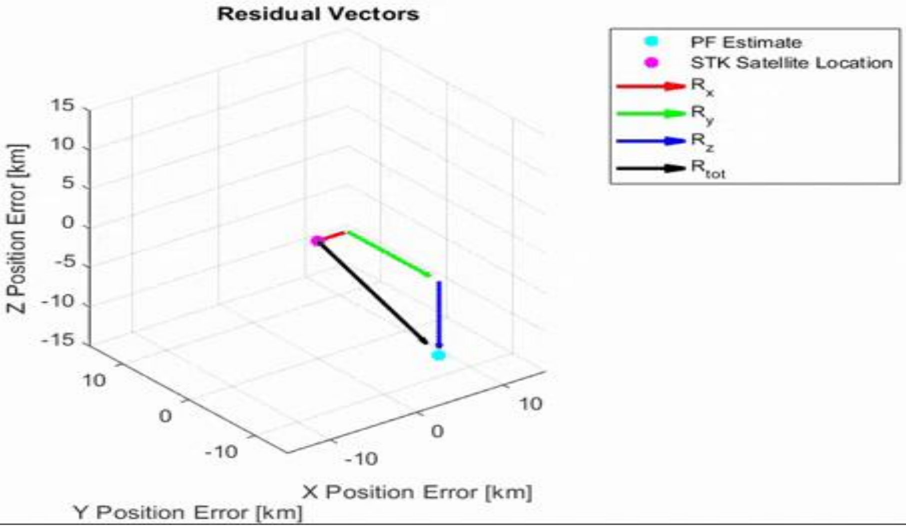
Results:



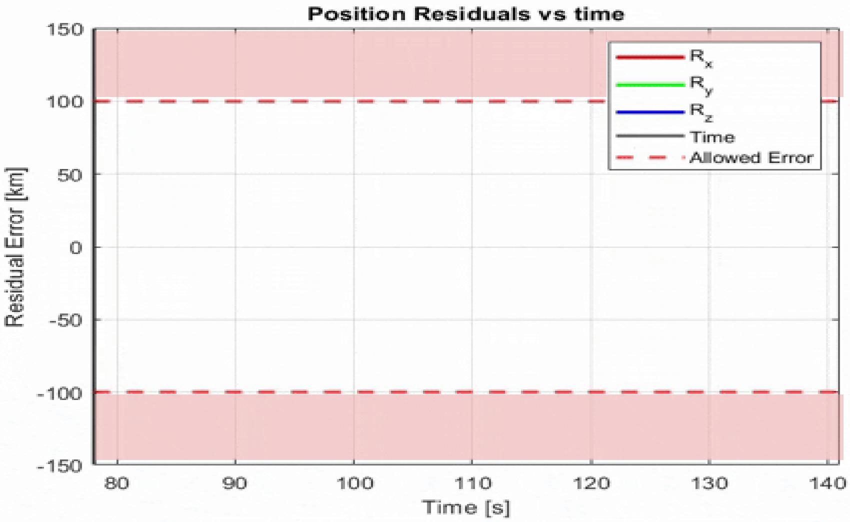
Orbital View of Particle Filter
Particles
PF Estimate
STK Satellite Position
STK Orbit
Sensors
Position [z]
5000
4500
4000
3500
3000
2500
2000
-3000
-2000
-1000
0
1000
Position [x]
-3000
-4000
-5000
-6000
Position [y]



Zoomed in with STK Satellite Position at the Origin
Particles
PF Estimate
STK Satellite Position
Z Position [km]
50
0
-50
50
0
-50
Y Position [km]
-50
0
50
X Position [km]



Residual Vectors
PF Estimate
STK Satellite Location
R_x
R_y
R_z
R_{tot}
Z Position Error [km]
15
10
5
0
-5
-10
-15
10
0
-10
Y Position Error [km]
-10
0
10
X Position Error [km]

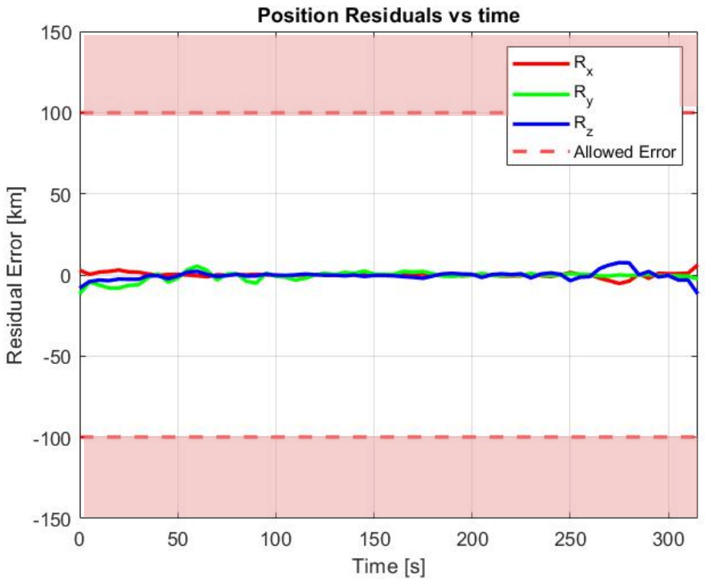


Position Residuals vs time
R_x
R_y
R_z
Time
Allowed Error
Residual Error [km]
150
100
50
0
-50
-100
-150
80
90
100
110
120
130
140
Time [s]

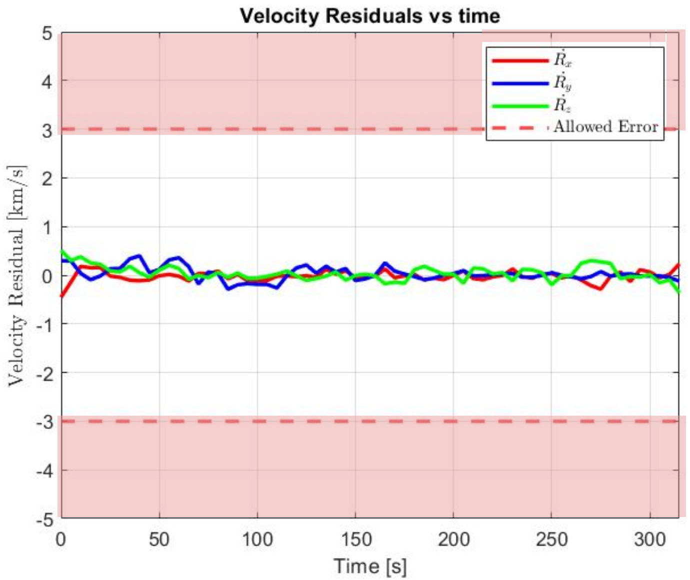
Orbit Prediction Results:

- Verifies FR5: position estimate with 100 km of the true position.
- Consistently within 0.5 km error and 0.050 km/s error.
    - Satellites position has the greatest effect on error.

Average Position Error: 0.409 km



Average Velocity Error: 0.015 km/s



TLE Generation Test Overview

Procedure:

- Use predicted state vector series from PF analysis to generate keplerian elements
- Port over to applicable TLE elements
  - Verify that the produced TLE is consistent with the satellite in question

Equipment/Facilities needed:

- Team developed TDoA → PF → State Vector software
- Team developed State Vector → Keplerian elements software

Test goal - Validation of SGP4 propagator to be used for final comparison of TLE sets.

```
function [i, Omega, e, omega, M, n, theta, h, r_p, r_a] = orbitElements(app, state_vec, mu)
    %   Use a given state vector (x, y, z, xdot, ydot, zdot)' to
    %   compute Keplerian orbital elements.
    %   ----------------------------------------------------------------------
    %
    %   Inputs:
    %   --------
    %   `mu` -- Standard Gravitational Parameter of the body orbited [km^3 / s^2]
    %   `state_vec` -- vector with position and velocity components in the ECEF frame [km] and [km / s]
    %
    %   Returns:
    %   --------
    %   `i`     -- inclination [deg]
    %   `Omega` -- right ascension of the ascending node [deg]
    %   `e`     -- eccentricity [~]
    %   `omega` -- argument of perigee [deg]
    %   `M`     -- mean anomaly [deg]
    %   `n`     -- mean motion [rev / day]
    %   `theta` -- true anomaly [deg]
    %   `h`     -- magnitude of the specific angular momentum [km^2 / s]
    %   `r_p`   -- radius of perigee [km]
    %   `r_a`   -- radius of apogee [km]

    % distance
    r = norm(state_vec(1:3));

    % speed
    v = norm(state_vec(4:6));

    % radial speed
    vr = dot(state_vec(1:3), state_vec(4:6)) / r;
    % if (vr > 0): satellite is flying away from perigee
    % if (vr < 0): satellite is flying toward perigee

    % specific angular momentum
    h_vec = cross(state_vec(1:3), state_vec(4:6));
    % magnitude of specific angular momentum
    h = norm(h_vec);

    % inclination
    i = acosd(h_vec(3) / h);

    % node line vector
    N_vec = cross([0,0,1], h_vec);

    % node line magnitude
    N = norm(N_vec);

    % right ascension of the ascending node
    if (N_vec(2) >= 0)
```

Calculated TLE

CSIM-FD

43793U	18099AM	21059.42508445	.00000970	00000-0	90492-4	0	9996
43793	97.6767	132.8334	0014184	58.2471	302.0131	14.964058071219	

SGP4 Verification Test Overview

Procedure:

- Get a list of predicted flybys from each propagator
- Compare predicted flybys from OreKit and In-The-Sky.org to Matlab SGP4 TLE propagator
    - Validate that passover predictions are consistent

Equipment/Facilities needed:

- Matlab SGP4 propagator
- In-The-Sky.org - Satellite pass prediction software
- OreKit - Continually updated Python based SGP4 propagator

Test goal - Validation of SGP4 propagator to be used for final comparison of TLE sets.

28 Feb 2021

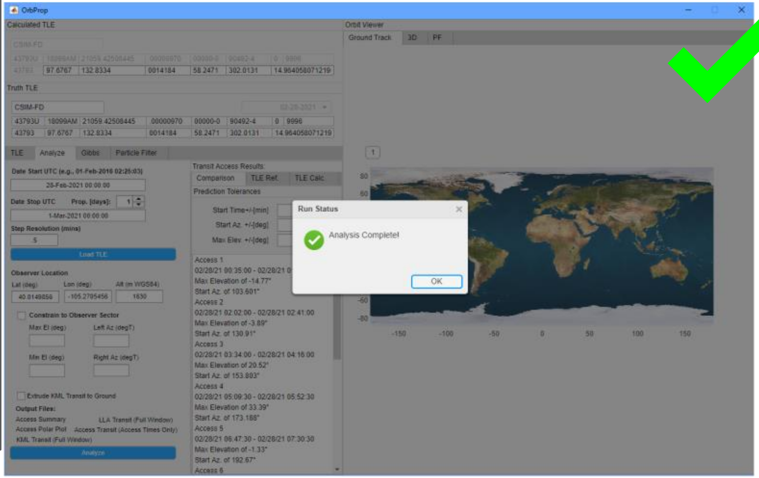
Sunrise: 06:35; **Noon:** 12:13; **Sunset:** 17:51

Satellite Name		Start				Highest				End				Diagram of pass
		Time	Dir	Alt	Mag	Time	Dir	Alt	Mag	Time	Dir	Alt	Mag	
CSIM-FD	1 hour ago	10:10:57	NNE	10°	7.0 ?	10:15:04	ESE	40°	9.3 ?	10:18:44	S	10°	10.3 ?	Chart...
CSIM-FD	5 mins away	11:47:16	NNW	10°	6.6 ?	11:50:03	WNW	16°	6.7 ?	11:52:16	WSW	10°	7.8 ?	Chart...
CSIM-FD	9 hours away	20:59:27	ESE	10°	6.2 ?	21:02:51	ENE	24°	5.5 ?	21:05:59	NNE	10°	7.4 ?	Chart...
CSIM-FD	10 hours away	22:34:31	SSW	10°	6.8 ?	22:38:01	W	25°	6.4 ?	22:41:16	NW	10°	8.5 ?	Chart...

1 Mar 2021

Sunrise: 06:34; **Noon:** 12:13; **Sunset:** 17:52

Satellite Name		Start				Highest				End				Diagram of pass
		Time	Dir	Alt	Mag	Time	Dir	Alt	Mag	Time	Dir	Alt	Mag	
CSIM-FD	22 hours away	10:15:13	NNE	10°	7.0 ?	10:19:13	ESE	45°	8.6 ?	10:23:07	S	10°	10.1 ?	Chart...
CSIM-FD	1 day away	11:51:49	NNW	10°	6.6 ?	11:54:23	WNW	14°	6.9 ?	11:56:15	W	10°	7.7 ?	Chart...
CSIM-FD	1 day away	21:03:35	SE	10°	6.2 ?	21:07:25	ENE	26°	5.4 ?	21:10:23	NNE	10°	7.5 ?	Chart...
CSIM-FD	1 day away	22:39:00	SSW	10°	6.9 ?	22:42:15	W	22°	6.6 ?	22:45:27	NW	10°	8.4 ?	Chart...



SubSystem Level Tests

Tests	Test Goal
Onboard OS	Ensure that the subscripts run on start-up and operate as expected.
Raspi HackRF Compatibility	Ensure the HackRF performs the same when connected to the Raspi
UHF Frontend	Ensure that the UHF front end meets the design Signal to noise ratio and other parameters
L-band Frontend	Ensure that the L-band front end meets the design Signal to noise ratio and other parameters

Onboard OS Test

Overall Test Goal(s): Ensure that the subscripts run on start-up and operate as expected.

Requirements: FR2 DR2.4 and DR2.5

Risk Mitigated: Possible malfunction while testing the required individual components in each unit

Results: We have found that the Raspbian OS is compatible with the required devices to receive and store RF data

Test(s)	Status	Test Goal
Fly-by test	In Progress	To have the pi autonomously run all implemented software and subscripts to receive and collect simulated fly by data and to visually verify the test follows the state machine model.

Test Procedure Overview:

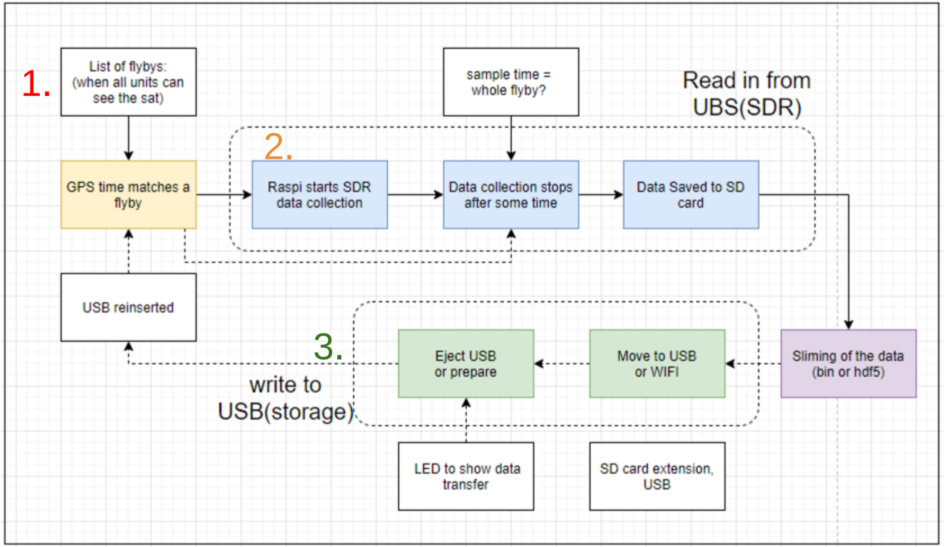
1. Store a set amount of specific times on the Pi that will relate to simulated fly-by orbit times.

2. Pi will autonomously run all implemented scripts and programs to collect data for all the respective stored fly bys.

3. After last fly by orbit has finished, USB will be ejected and the stored data will be verified for the proper naming convention, correct slimmed file size, and expected data results.

It is important to note that there is no need for special equipment or facilities for these tests outside the hardware and software itself.

State Machine Model:



Raspberry Pi and HackRF Compatibility Test

Overall Test Goal(s): Ensure the HackRF is operable when connected to the Raspberry Pi

Requirements: FR2 DR2.4

Risk Mitigated: Not compatible with the onboard OS and Raspberry pi. Failure to collect necessary amount of samples per second.

Modeled Results: Seeing anywhere between 10Ms/s - 20Ms/s based on settings

Test(s)	Status	Test Goal
Acquired Sample Rate	Done	Verify that the correct amount of samples is being recorded from the SDR each second

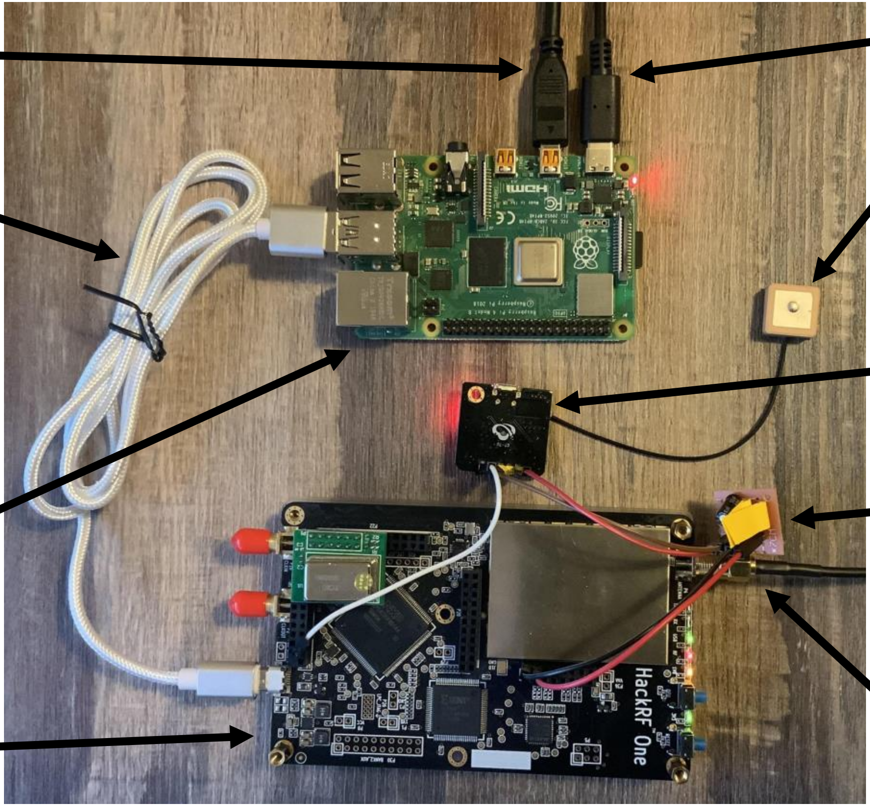
Raspberry Pi and HackRF Compatibility Test Setup

Micro HDMI Connection

USB Type-A to Micro USB connection between Raspberry Pi and HackRF

Raspberry Pi 4

HackRF One SDR



Raspberry Pi Power (5V)

GPS Antenna

GPS Module

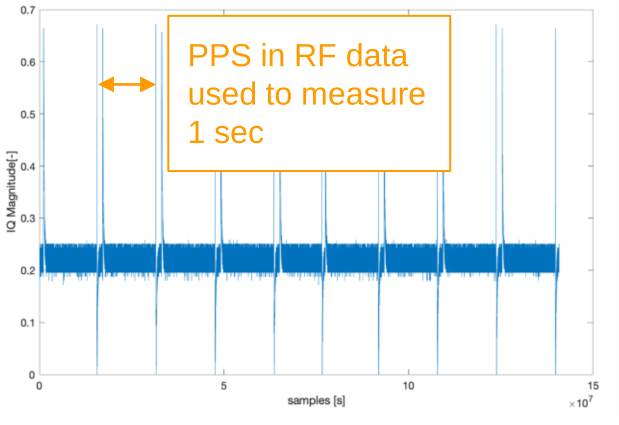
High Pass Filter

SMA connection between HackRF and antenna

Raspberry Pi and HackRF Compatibility Test Procedure Overview

1. The HackRF is hooked up to the Pi.
2. Using GNU Radio Companion and a GUI slider, the HackRF is then changed to different sample rates ranging from 1Ms/s to 20 Ms/s.
3. The data is then recorded at different sample rates and verified with Matlab that the proper data was received by the Pi.

There was no need for special equipment or facilities for these tests outside the hardware itself.



Example IQ data from test with sample rate at 16 Ms/s

Set Test Sample Rate Ms/s	Average Sample Deviation from Set Rate	Timing Error Due to Deviation
10	1 Samples	100 ns
13	2 Samples	153.84 ns
16	2 Samples	125 ns
20	375626 Samples	18781300 ns

RF Front End Testing Overview

- Due to the symmetry of this system between the UHF/VHF and the L-Band systems, namely their constituent components, they will have almost identical tests.
- The only difference will be the frequencies used
  - VHF: 30 MHz to 300MHz
  - UHF: 300 MHz to 3 GHz
  - L-Band (IEEE*): 1-2GHz
- System Components for both:
  - Antenna
  - LNA
  - Switch
  - Cables

* IEEE stands for the Institute of Electrical and Electronics Engineers designation

RF Front End Tests: UHF, VHF, and L-Band

Overall Test Goal(s): Ensuring that products, our team has purchased, work as advertised and more importantly these devices will ensure our received signals stand out of the noise floor.

Requirements: DR3.1, DR3.3

Risk Mitigated: Unanticipated noise as well as finding other unexpected blind spots

Modeled Results: In Progress

Test(s)	Status	Test Goal
G/T and SNR Conformance	In Progress	Gain to Temperature ratio compliance confirmation.
Bandwidth	In Progress	Bandwidth / Received signal roll-off required to meet frequencies of satellites

Test Setup #1: G/T and SNR Conformance

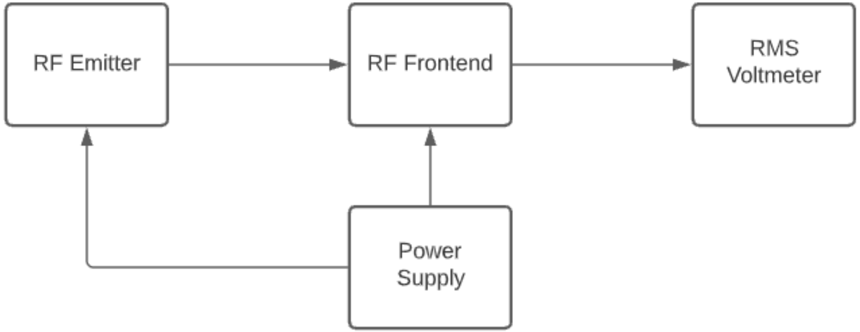
Test Setup Overview:

- Start by hooking up an RF emitter, and LNA to a power source
- Using the SMA connector from the to antenna to an RMS Voltmeter to measure the overall strength of the received signal compared to the noise floor

The results of this test will be a value for S/N (Unitless).

Equipment/Facilities needed:

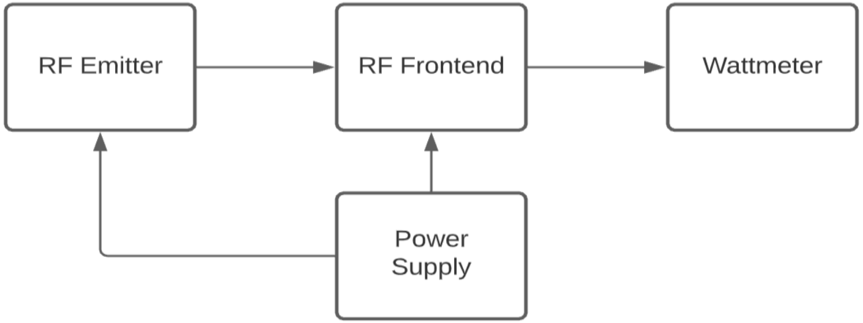
RF Signal Generator, RMS Voltmeter, Power Supply



Test Setup #2: Bandwidth test

Test Setup Overview:

- Start by hooking up an RF emitter, and LNA to a power source
- Followed by connecting the RF front end to an Wattmeter to measure the power received
- Sweeping through a range of frequencies determined by the sensitivity of the antenna as provided by the manufacturer measuring the overall received power.



Equipment/Facilities needed:

Wattmeter, Power Supply, RF Emitter

Full Suite Test

Overall Test Goal(s): Ensure that the predicted orbit is within the expected error.
Requirements: FR 5, FR 6

Risk Mitigated: Verification of simulated models and allocated tolerances.

Modeled Results: Compliance with FR 5 and FR 6.

Test(s)	Status	Test Goal
Practice Run	Incomplete	Verify unit and data collection process by practicing data collection of a CSIM or IRIDIUM flyby with all units stationed in Boulder.
Iridium Flyby	Incomplete	Run data collection process on Iridium satellite candidate flyby with sensor units stationed across CO to verify FR 5 & FR 6 compliance for L-Band.
CSIM Flyby	Incomplete	Run data collection process on CSIM satellite candidate flyby with sensor units stationed across CO to verify FR 5 & FR 6 compliance for UHF-Band.

Practice Run Test Overview

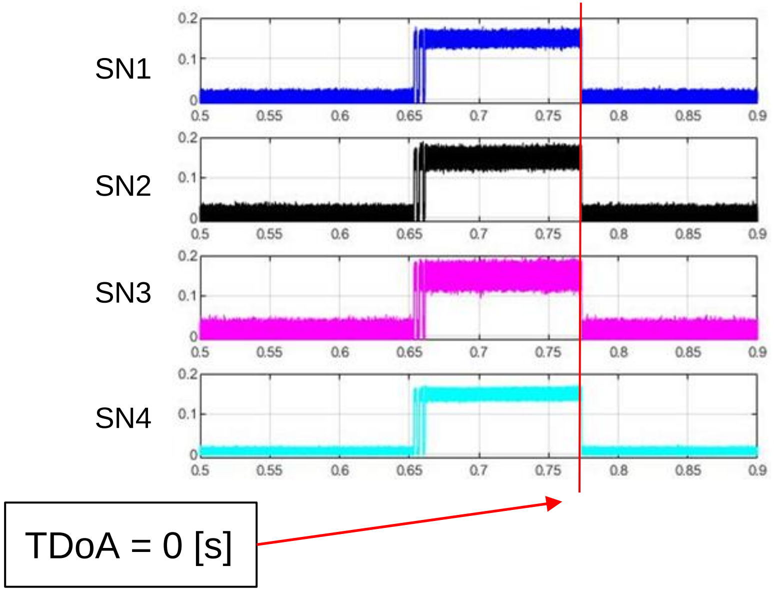
Procedure:

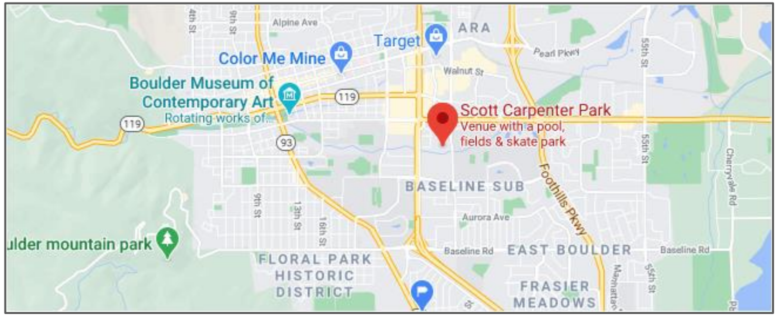
1. Collect and store data with SN1-SN4 at the same location (single flyby).
2. Stored data is off-loaded for post processing.
3. Verify that TDoA output is zero for all sensors.
    - Baseline verification (cannot find orbit here).

Equipment/Facilities needed:

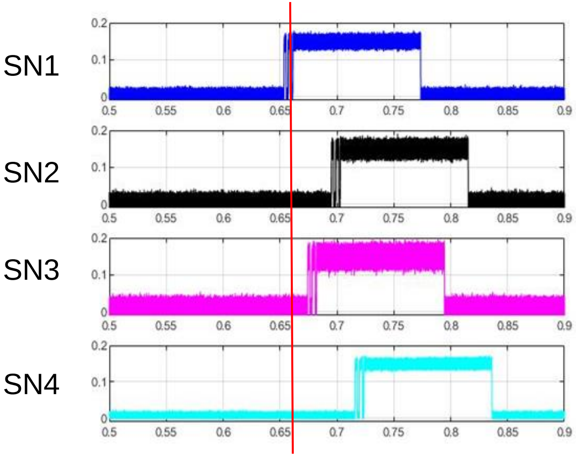
- Four assembled units (SN1, SN2, SN3, SN4)
- Two to three team-members
- Laptop
- Park

Test goal - Final validation of hardware and software before full-scale test.





Iridium/CSIM Flyby Test Overview

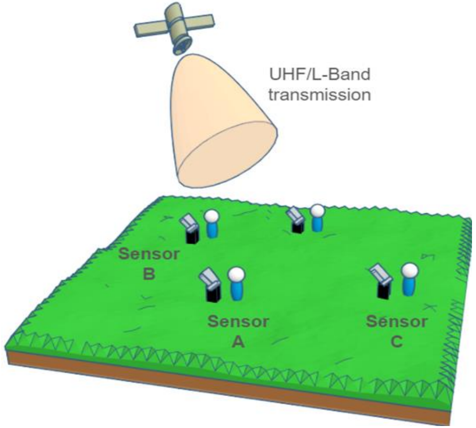


Procedure:

1. Collect and store data with SN1-SN4 around Colorado (multiple flybys).
2. Stored data is off-loaded for post processing.
3. Cross Correlation → TDoA→ Satellite State Vectors
   - Verify State Vectors consistent with FR 5.
4. Satellite State Vectors → TLE
   - Verify TLE consistent with FR 6.

Equipment/Facilities needed:

- Four Assembled units (SN1, SN2, SN3, SN4)
- Four team-members/volunteers
- Laptops
- Units deployed to Pueblo, Boulder, Kremmling, and Virginia Dale



Test goal - Satellite position accuracy and TLE prediction characteristics consistent with FR 5 and FR 6

Cost Plan

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 UHF Low Noise Amplifier L-Band Low Noise Amplifier L-Band Antenna	Received
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	Ordered
RF Front End	UHF Antenna UHF Low Noise Amplifier L-Band Low Noise Amplifier L-Band Antenna	Ordered
Hardware*	WH-16 Hinged Nema Enclosure Miscellaneous Hardware Miscellaneous Electronics Hardware	Ordered

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

Expenses To Date
$3,380.61

Remaining Expected Costs
$323.23

Cost Plan

Single Unit Cost Goal
<$1,000

Designed Single Unit Cost
$1,045.93

Designed Full Suite Cost
$4,183.70

Initial Budget
$5000

Developmental Costs
$200.22

This includes RTL SDRs ordered for very early tests and miscellaneous parts to support those tests.

Expected Full Suite Cost
$4183.70

Budget Margin
$616.08

Long Lead Time Items	Status
RF Switch	Ordered
HackRF One	Ordered May be slightly delayed due to stock Expected to arrive before March 5th
Raspberry Pi	Ordered May be slightly delayed due to stock Expected to arrive before March 5th
UHF LNA	Ordered Scheduled to arrive on March 5th

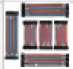
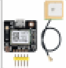
Acknowledgements

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

PRODUCT NAME	SpaceNet Ground Station	CONTACT INFO
APPROVED BY		
DATE OF APPROVAL		
PART COUNT	58	
TOTAL COST	$ 1,045.93	This is not accurate!!! look below

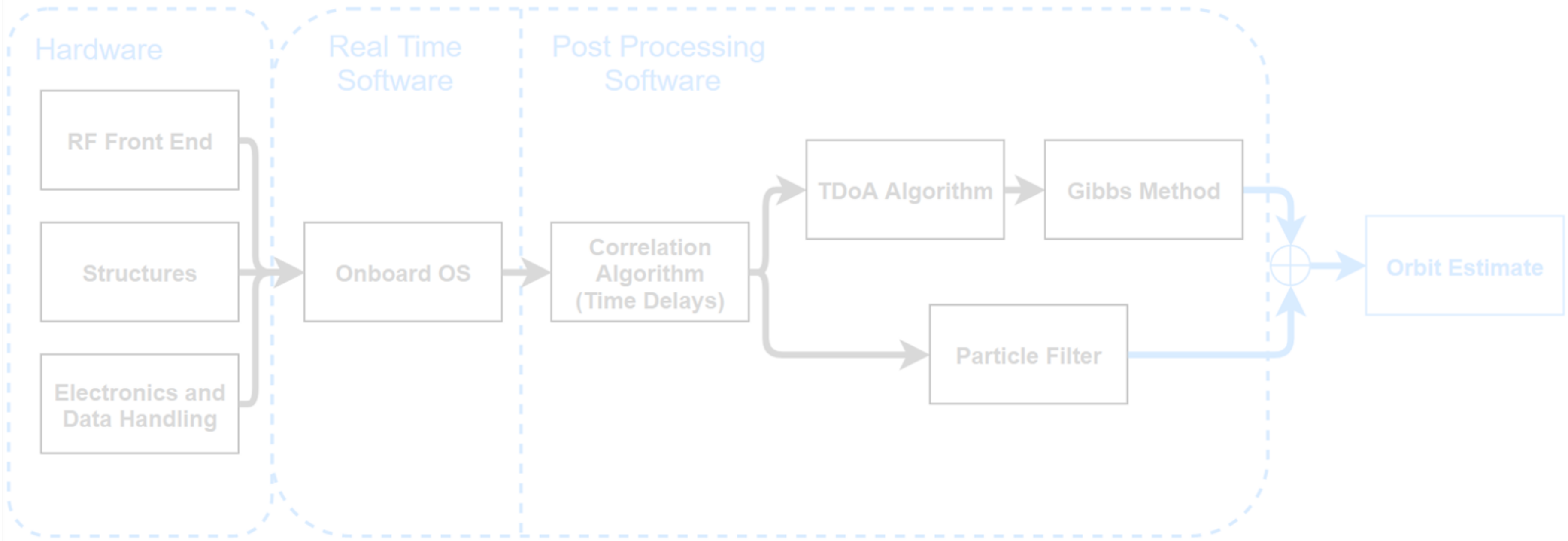
	Complete
	Ordered
	Ready to Order
	Ignore for now

PART NUMBER	PART NAME	DESCRIPTION	Purchase Link	QUANTITY	UNITS	PART IMAGE	UNIT COST	UNITS SERVICED	AMOUNT per UNIT	Inventory	Required Total
	Raspberry Pi 4 Model B (4 GB)	On board computer	https://www.sparkfun.com/products/15447	1	ea		$ 55.00	1	$ 55.00	1	4
	SD card	On board storage	https://www.amazon.com/SAMSUNG-Select-microSDXC-Adapter-MB-	1	ea		$ 18.99	1	$ 18.99	1	4
	SPF5189Z RF Amplifier	UHF LNA	https://www.amazon.com/Zeroone-Amplifier-4000MHz-SPF5189Z-	1	ea		$ 15.00	1	$ 15.00	1	4
	ZX60-242GLN-S+	L Band LNA	https://www.mouser.com/ProductDetail/Mini-Circuits/ZX60-	1	ea		$ 74.82	1	$ 74.82	1	4
	Power Strip	handles all internal power distribution	https://www.amazon.com/dp/B083XR.IXSD/ref=emc_b_5_i	1	ea		$ 14.00	1	$ 14.00	1	4
	Raspberry Pi 4 Official Power Supply	AC to DC supply for raspberry pi	https://vilros.com/collections/official-raspberry-pi-accessories/products/official-	1	ea		$ 8.00	1	$ 8.00	1	4
	ProtoBoard 32 pack	Used to handle power distribution to the LNAs, GPS Module, and Switcher Device	https://www.amazon.com/ELEGOO-Prototype-Soldering-	1	pack of 32		$ 10.00	4	$ 2.50	1	1
	Great Scott Gadgets HackRf One-Software Defined Radio	Software Defined Radio that will handle demodulatin the RF Signal	https://www.adafruit.com/product/3583?gclid=Cj0KCQiAvb	1	ea		$ 339.95	1	$ 339.95	1	4
972-F2932EVBI	F2932EVBI Evaluation Board	RF logic computer controlled switch	https://www.mouser.com/ProductDetail/Renesas-IDT/F2932EVBI?	1	ea		$ 248.75	1	$ 248.75	2	4
	Mopower Micro USB Cable, 10 Pcs 3FT High Speed USB 2.0 A	Used to channel power from power strip USB ports to protoboard to power the LNAs, GPS Module, and Switcher Device	https://www.amazon.com/gp/product/B07J9WTJFQ/ref=cd_ewc_title_dp_1?	1	pack of 10		$ 13.99	4	$ 3.50	0	1
	WH-16 Hinged Nema Enclosure	Nema rated enclosure to house electronics. Includes clear top to enable GPS lock	https://www.polycase.com/wh-16?msclkid=4864cdd62fdc12c2de4792b	1	ea		$ 50.75	1	$ 50.75	1	4
	50ft outdoor extension chord	used to produce an outdoor rated cable leading from the box to the wall outlet	https://www.homedepot.com/p/HDX-50-ft-16-3-Landscape-Extension-Cord-	1	ea		$ 13.29	1	$ 13.29	1	4
94639A713	Nylon Unthreaded spacer, for number 2 bolt (1/2")	Used for offesting electronics from the hardware rack	https://www.mcmaster.com/panel-standoffs/nylon-unthreaded-	1	pack of 100		$ 10.60	4	$ 2.65	1	1
94639A536	Off-White Nylon Unthreaded Spacer, 1/2" OD, 1" Long, for Number 8 Screw Size	Used for offesting electronics from the hardware rack	https://www.mcmaster.com/panel-standoffs/nylon-unthreaded-	1	pack of 100		$ 13.04	4	$ 3.26	1	1
94613A086	Nylon Bolt	threaded nylon bolt	https://www.mcmaster.com/bolts/length~1-1-2/length~1/plastic-	1	pack of 100		$ 6.69	4	$ 1.67	1	1
94812A100	Nyoln Nut	threaded nylon nit	https://www.mcmaster.com/nuts/material~plastic/nut-type~hex/height~	2	pack of 100		$ 7.14	4	$ 3.57	1	2
8982K124	4 ft long, 2 ½ ", Angled Aluminum"	For anetenna Mounting	https://www.mcmaster.com/angles/multipurpose-6061-aluminum-90-	1	ea		$ 26.92	4	$ 6.73	1	1
89015K232	4ft long, Aluminum flat stock	For anetenna Mounting	https://www.mcmaster.com/aluminum-stock/multipurpose-6061-aluminum-	1	ea		$ 19.68	4	$ 4.92	1	1
	Rivets	For anetenna Mounting	https://www.homedepot.com/p/Arrow-1-8-in-Aluminum-Short-Rivets-100-Pack-	1	pack of 50		$ 5.98	4	$ 1.50	1	1
69915K54	Nema Cord Grips	For power	https://www.mcmaster.com/cord-grips/compact-plastic-	1	ea		$ 3.34	1	$ 3.34	3	4
69915k52	Nema Cord Grips	For Coax	https://www.mcmaster.com/69915K52/	2	ea		$ 3.30	1	$ 6.60	0	8
	Coaxial cable	Outdoor Rated Coaxial Cable to antennas	https://www.amazon.com/CIMPLE-CO-Connectors-Internet-	1	ea		$ 8.97	4	$ 2.24	1	1
	Coaxial cable	LNA to Swtich/Swtich to SDR Coaxial Cable:	https://www.amazon.com/Monoprice-Shield-Coaxial-Cable-	1	ea		$ 4.99	4	$ 1.25	1	1
	SMA Connectors male	Internal connectors	https://www.amazon.com/dp/B089CJY1GX/ref=sspa_dk_detail_3?	1	pack of 10		$ 8.89	1	$ 8.89	1	4
	SMA Connectors female	external connector to antenna	https://www.amazon.com/dp/B089NHW2X9/ref=sspa_dk_detail_3?	1	pack of 10		$ 8.89	4	$ 2.22	0	1
8560K214	Acrylic	Plastic Sheet for Mounting Plate:	https://www.mcmaster.com/8560K214//	1	ea		$ 32.75	4	$ 8.19	1	1
5415K38	Steel Screw, 1/2" Band Width, 4-1/8" to 7" Clamp ID	For mounting box to something	https://www.mcmaster.com/5415K38/	1	pack of 10		$ 15.05	4	$ 3.76	0	1
	T-post	to mount box to	https://www.homedepot.com/p/Everbilt-1-3-4-in-x-3-1-2-in-x-6-ft-Green-Steel-	1	ea		$ 4.70	1	$ 4.70	1	4
	PVC pipe	Antenna mount, 10ft, 2inch, Schedule 40	https://www.homedepot.com/p/2-in-x-10-ft-280-PSI-Schedule-40-PVC-DWV-	2	ea		$ 8.84	4	$ 4.42	2	2
	PVC cap	Antenna mount	https://www.homedepot.com/p/Charlotte-Pipe-2-in-PVC-Schedule-40-	2	ea		$ 1.86	1	$ 3.72	2	8
	PVC Tee fitting		https://www.homedepot.com/p/NIBCO-2-in-PVC-DWV-All-Hub-Sanitary-Tee-	1	ea		$ 3.53	1	$ 3.53	1	4
91257A634	Bolts	Bolts for antenna	https://www.mcmaster.com/bolts/hex-head-screws/high-strength-grade-8-	1	pack of 25		$ 12.76	4	$ 3.19	1	1
95462A031	Nuts	Nuts for antenna	https://www.mcmaster.com/nuts/hex-nuts/medium-strength-steel-hex-	1	pack of 100		$ 8.79	4	$ 2.20	1	1
92620A726	bolts	PVC to Aluminum	https://www.mcmaster.com/92620A726/	1	ea		$ 1.37	1	$ 1.37	0	4
92620A726	M5 x 0.8 mm Thread, 35 mm Long	Internal mount	https://www.mcmaster.com/92005A334/	1	pack of 100		$ 10.20	4	$ 2.55	0	1

91831A137	18-8 Stainless Steel Nylon-Insert Locknut	PVC to Aluminum	https://www.mcmaster.com/91831A137/	1	pack of 10		$ 4.70	4	$ 1.18	0	1	
	PVC Glue	For pvc end caps etc	https://www.homedepot.com/p/Weld-On-Weld-On-700-PVC-Solvent-Cement-	1	ea		$ 2.98	4	$ 0.75	0	1	
	10uf cap	for pps filter	https://www.sparkfun.com/products/523	5	ea		$ 0.45	4	$ 0.56	0	5	
	Resistor Kit - 1/4W (500 total)	1k, 4.7k, 10k	https://www.sparkfun.com/products/10969	1	ea		$ 7.95	4	$ 1.99	0	1	
	Jumper Wires	To get power/pps/data to everything	https://www.amazon.com/IZOKEE-Solderless-Breadboard-	1	ea		$ 8.99	4	$ 2.25	0	1	
	male Header	Found in a trash pin (prince has them). note normally you only ever want **nonpowerd** pins to be sticking up where someone could touch them but this is cheap and the whole thing should be a		1	ea		$ -	4	$ 0.00	1	1	
	velcro	Velcro to secure: power strip, Hackrf, GPS antenna	https://www.amazon.com/Strenco-inch-Self-Adhesive-Hook/dp/B00EQ93	1	15 ft of both sides		$ 7.92	4	$ 1.98	0	1	
	Proxicast Pro-Grade Extra Strong 30mil Weatherproof Self-Fusing Silicone Rubber Sealing Tape	Used for water proofing under electrical tape(no UV resistance)	https://www.amazon.com/Proxicast-Pro-Grade-Weatherproof-Self-	2	15' 1" roll		$ 17.95	4	$ 8.98	0	2	
22508	Permatex Dielectric 22508	used inside the connector to keep water and moisture out	https://www.amazon.com/Permatex-22058-Dielectric-Tune-Up-	1	3oz		$ 6.99	4	$ 1.75	0	1	
Super 88	3M Scotch Vinyl Electrical Tape Super 88, Premium Grade All-Weather, 3/4 in x 44 ft, 8.5-mil thick, Black, 1 roll	Used for uv protection	https://www.amazon.com/3M-88-Super-3-4x44FT-Vinyl-Electrical/dp/B000	1	3/4 in x 44 ft		$ 7.20	4	$ 1.80	0	1	
	UHF Antenna	400 to 470MHz 9 dbi antenna	https://www.amazon.com/HYS-Antenna-Elements-Motorola-	1	ea		$ 50.00	1	$ 50.00	1	4	
	pl259 to SMA adapter	adapt UHF antenna to SMA	https://www.amazon.com/SMA-UHF-Connectors-Nickel-Plated-	1	ea		$ 7.68	1	$ 7.68	1	4	
RE120BP-SM	LBand Antenna	1.616 GHz	https://www.mouser.com/ProductDetail/Taoglas/AA01121111/2	1	ea		$ 25.11	1	$ 25.11	1	4	
	GPS Module	GPS Module GPS NEO-6M(Ar duino GPS, Drone Microcontroller GPS Receiver) Compatible with 51 Microcontroller STM32 Ar duino UNO R3 with IPEX Antenna High Sensitivity for Navigation	https://www.amazon.com/Microcontroller-Compatible-Sensitivity-	1	ea		$ 10.90	1	$ 10.90	4	4	
			TOTAL PARTS	58		TOTAL	$ 1,045.93	Total Per 4 Units	$ 4,183.70	Total Spent on units	$ 1,300.97	

Backups

Conceptual Block Diagram



Box Weatherproof Test

Overall Test Goal(s): Test that the box and cable pass throughs are weather resistant and not susceptible to ingress of water.

Requirements: DR1.1

Risk Mitigated: Hardware not fully operational/could be damaged during satellite pass over.

Results: Box unit from manufacture is weather resistant and not susceptible to ingress of water. With cable pass throughs in place, some water leakage due to the hole size used.

Test(s)	Status	Test Goal
Baseline (water)	Done	To ensure the box from the factory is waterproof
Baseline (snow)	Done	To ensure the box from the factory can handle sitting water that would occur as snow melts
Box+cable pass throughs (water)	In Progress	To ensure the box is still waterproof after the cable pass throughs have been installed

Test Procedure Overview:

- Measure water flow from water source being used in order to determine flow rate.
- Inlay the box with paper towels on all edges of the box for coverage of areas of possible water ingress, and inspect after test.

Equipment/Facilities:

- Volume container with measurements indicated on the side.
- Access to water source
- Paper Towels
- Stop Watch

GPS Test

Overall Test Goal(s): Ensure the GPS Pulse Per second meets the device specifications

Requirements: DR5.1

Risk Mitigated: Debugging the timing hardware during the full system test.

Modeled Results : Per GPS data sheet the PPS is expected to be a pulse wave with a on duty cycle of 10%. PPS should start with in a indistinguishable amount of time from one another.

Test(s)	Status	Test Goal
Compare GPS(s) PPS	Done	To ensure that the rising edge of the GPS timepulse(s) are within 10ns of each other.

Test Procedure Overview:

Equipment: AD2 Oscope

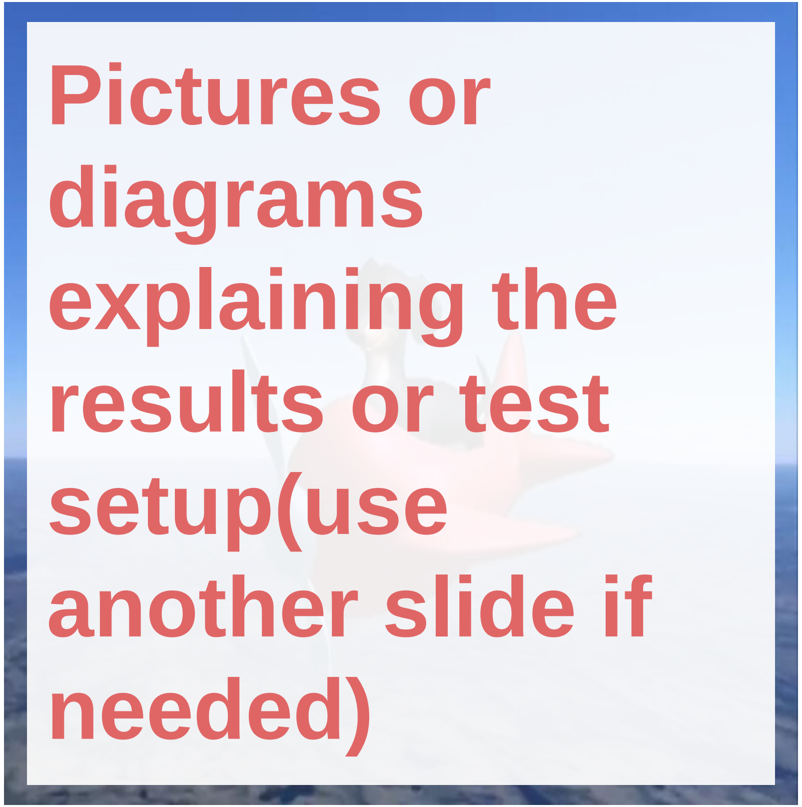
Two GPS modules were connected to a Digilent analog discovery 2 Oscope.

PPS from each GPS were placed on different channels.

Test Results:

Rising edge of both GPS PPS started within less than < 10ns of each other.

Note. The Rise time, duty cycle and accuracy to UTC do not matter. As long as error related to the Rising edge is consistent across all units.



HackRF & Timing Scheme Test

Overall Test Goal(s): Ensure the SDR meets the device specifications for sample rate and that timing scheme operates as expected

Requirements: DR5.1

Risk Mitigated: Debugging the timing hardware during the full system test.

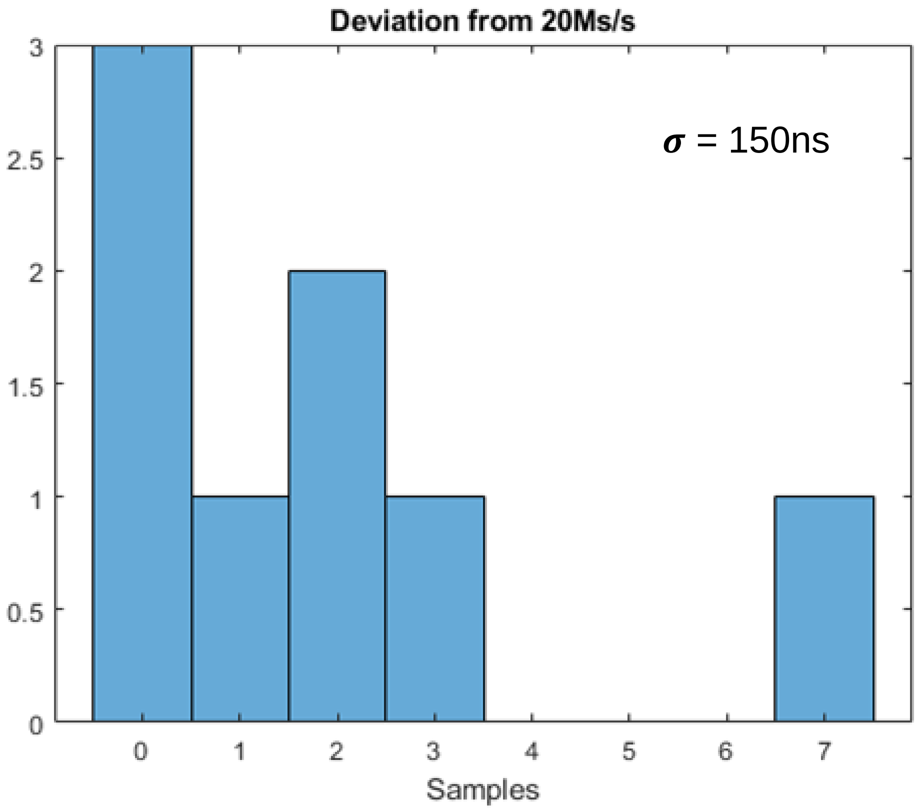
Modeled Results : Per SDR data sheet the hackRF is capable of sustained sample rates at up to 20Ms/s (50ns per sample)

Test(s)	Status	Test Goal
Verify Sample Rate Stability 20Ms	Done	Verify that the SDR is capable of maintaining the claimed 20Ms/s
Verify Sample Rate Stability (<20Ms/s)	Done	If the SDR cannot maintain 20Ms/s find the highest sample rate possible

Test Procedure Overview:

Equipment: HackRF, GPS, Matlab, SDRsharp, SDRConsole

The hackRF was equipped with the GPS timing modification. SDRsharp/SDRConsole were used to set/record data from the SDR. The PPS was used to identify 1s intervals in the recorded data.



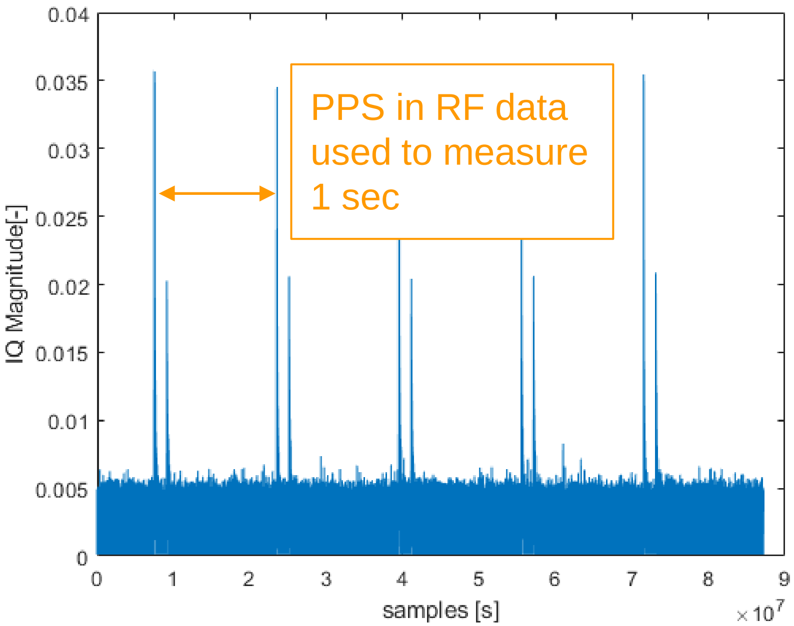
Test Results:

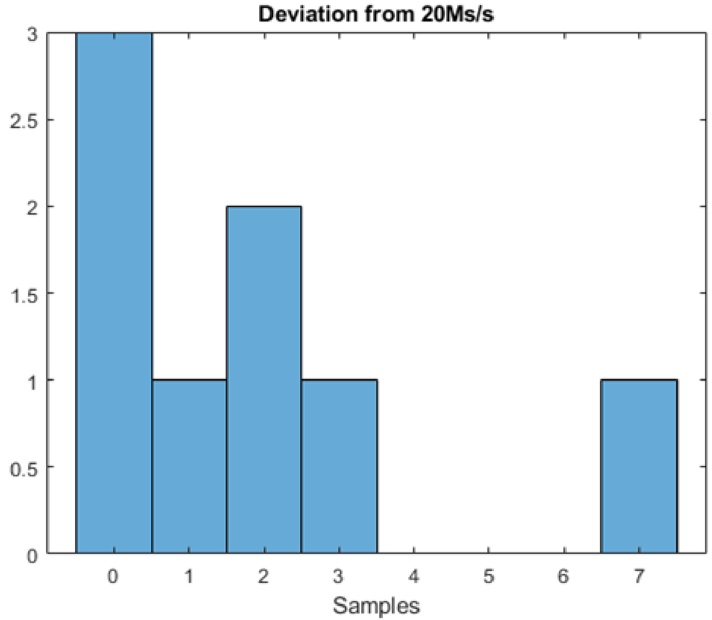
Depending on the software used the SDR was able to achieve 20Ms/s (+/-) 3. This error decreased at lower sample rates.

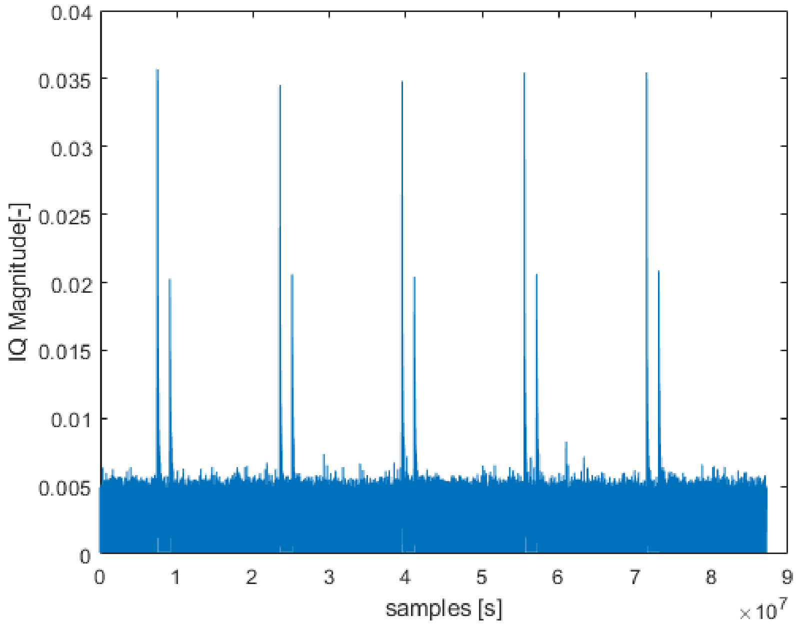
Unknown if the sample variation is due to the GPS, SDR or PPS detection method. The sample variation is acceptable for this application.

May add another slide to help explain this if we have time/room

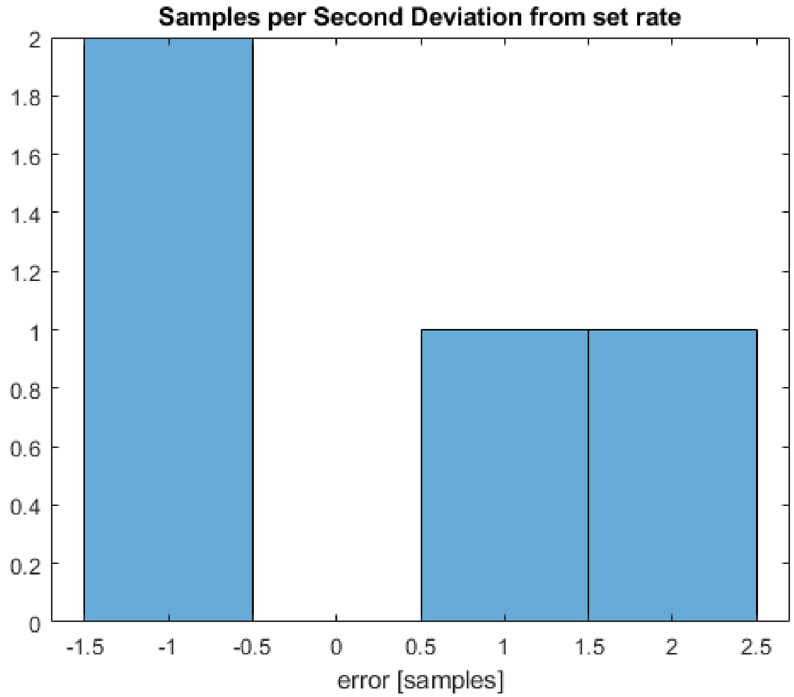
Sample Rate MS/s	Avg. Samples per second MS/s	σ (Samples)
10	10	1
12.5	12.5	3
16	16	4
20	17	3e6







0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
IQ Magnitude[-]
0 1 2 3 4 5 6 7 8 9
samples [s]
$\times 10^7$



Samples per Second Deviation from set rate
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
error [samples]

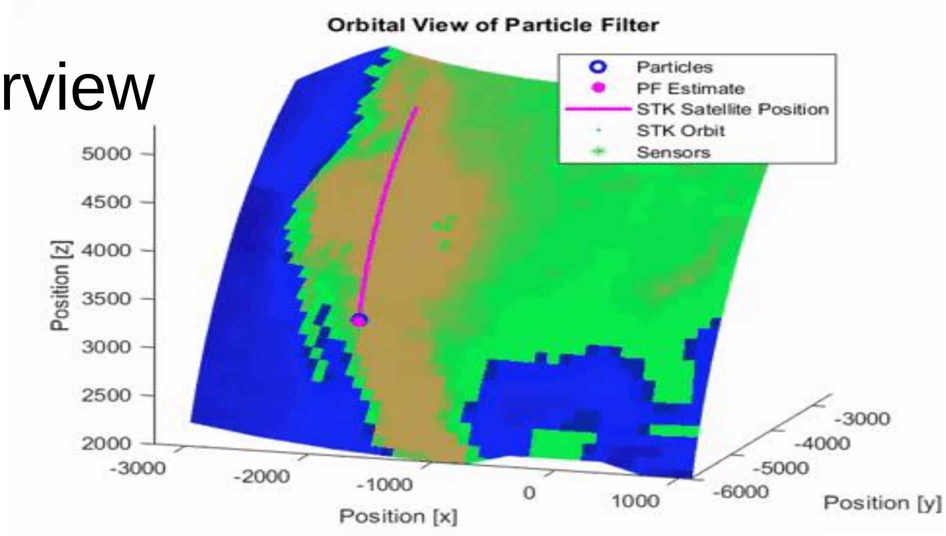
Orbit Determination Test Overview

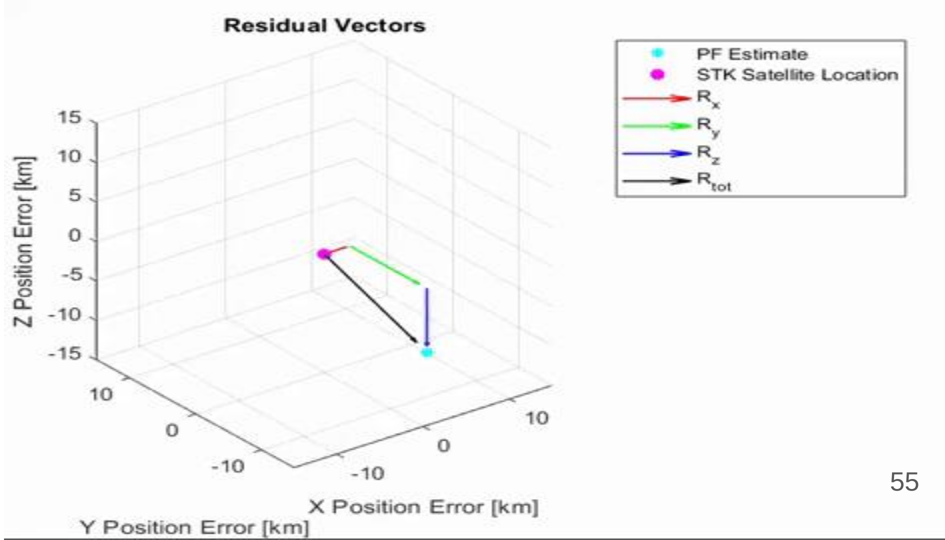
Test Procedure Overview:

- STK produced multiple sample satellite orbits and range data from the orbit to each sensor.
- Calculated sample TDoA values from the ranges with induced 100 ns measurement error.
- TDoA values initialized the orbital determination method.
- Update estimate with remaining TDoA values.
- Compared outputs to STK data. Calculated the difference between them or residual vectors.

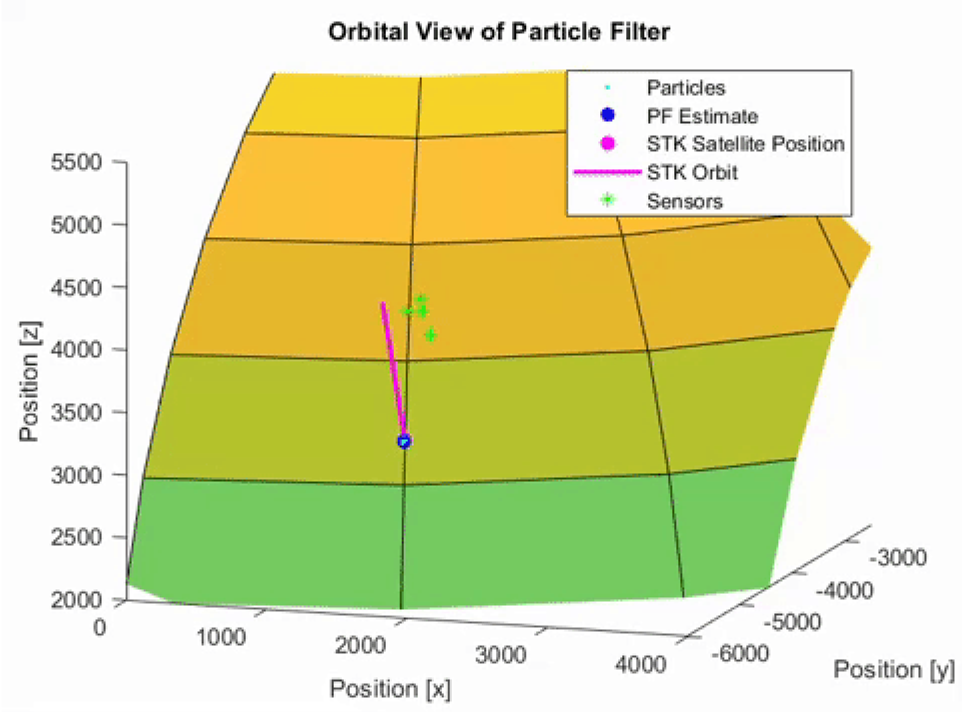
Equipment/Facilities needed:

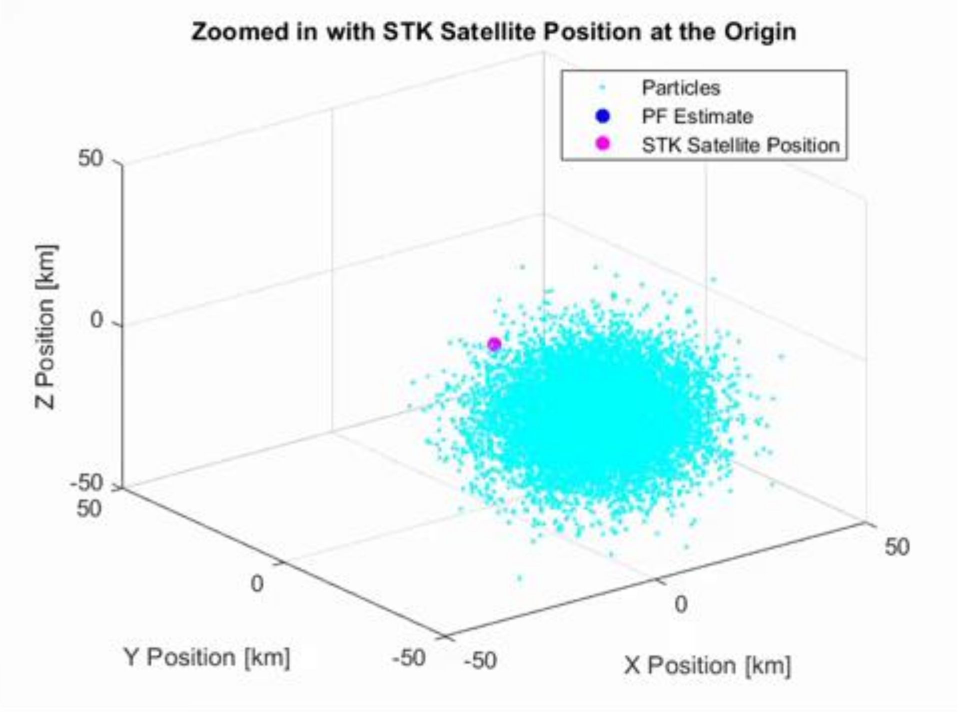
STK and Matlab



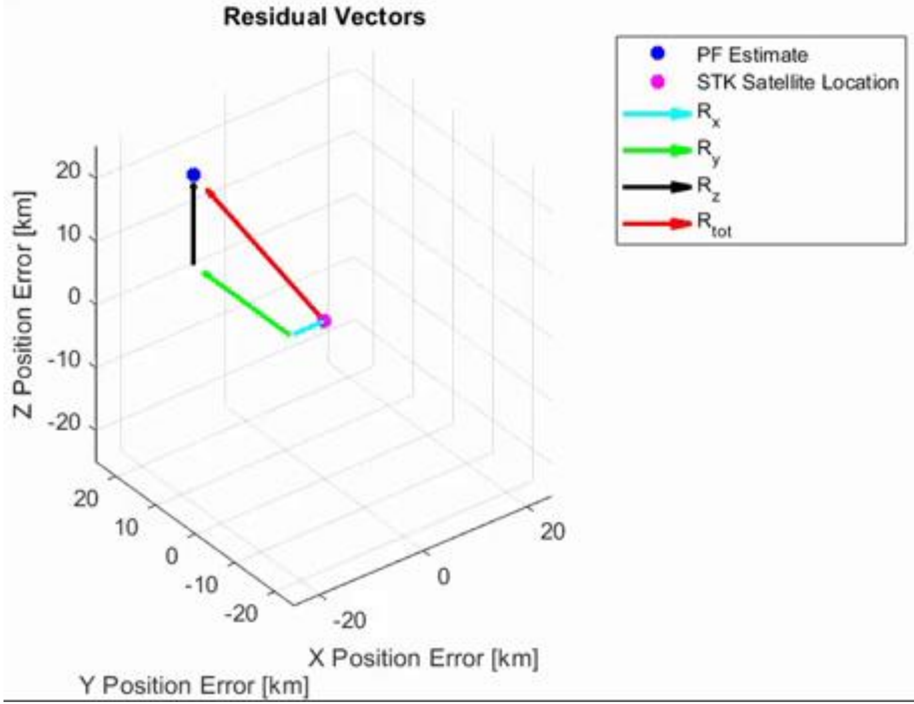


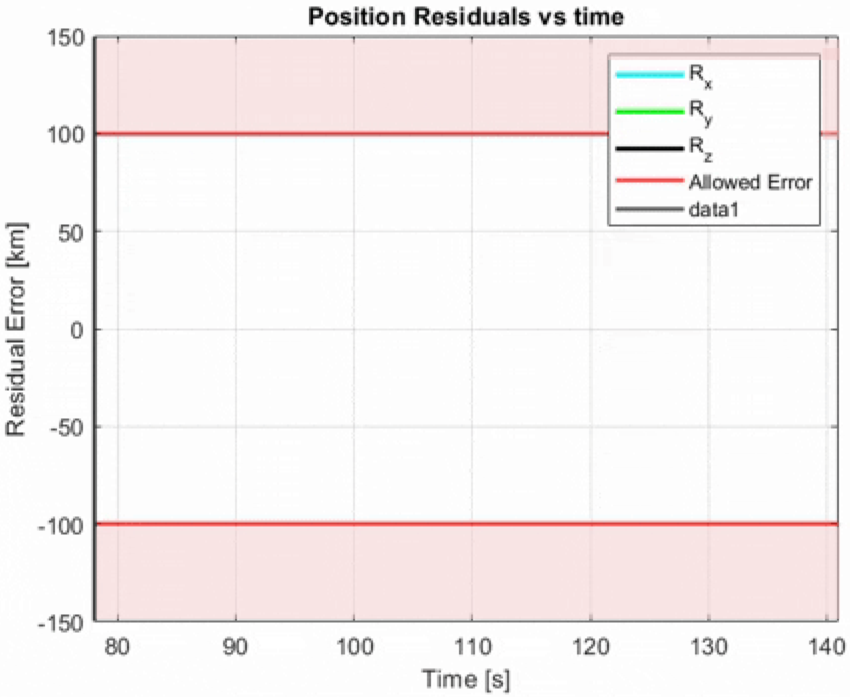
Results: Orbit determination method converges on truth





Results: Average Position Error = 627 m Average Velocity Error: 54 m/s





Temperature Test

Overall Test Goal(s): Ensure that the internal temperature of the box will remain within operating conditions as modeled

Requirements: DR 1.2

Risk Mitigated: Component failure due to being outside of operating conditions, which would result it incorrect or no pass over data being captured.

Modeled Results:

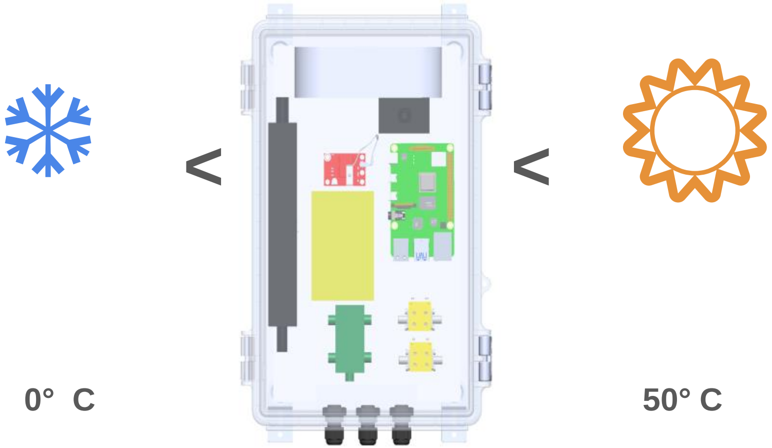
Test(s)	Status	Test Goal
Indoor Operation	Incomplete	Determine actual $\dot{Q}$ in order to more accurately determine current operating conditions of the unit.
Heater Freezer Test	Incomplete	If heater is determined necessary, test that desired operating conditions can be met when placed in a cold environment.
Outdoor Operation	Incomplete	Ensure that sensor unit hardware remains operational over a 24 hour period.

Test Procedure Overview:

- Run thermal test such that the box is operating for an extending duration of time (Approx: 1-3 hours).
- Use raspberry pi to measure the temperature inside the box in each scenario and use this data to more accurately model the $\dot{Q}$ to determine whether heater is necessary and if so the required size.

Equipment/Facilities Needed:

- Fully integrated unit with operational hardware
- Clock/Timer
- External Temperature Sensor/Thermometer



Onboard OS Sub-System Test

Overall Test Goal(s): Ensure that the subscripts run on start-up and operate as expected.

Requirements: FR2 DR2.4 and DR2.5

Risk Mitigated: Possible malfunction while testing the required individual components in each unit

Results: We have found that the Raspbian OS is compatible with the required devices to test

Test(s)	Status	Test Goal
RF Control	In Progress	Esure the Raspberry Pi can command the switch to change between the two RF inputs.
GPS Control	In Progress	Esure the Raspberry Pi can use GPS time to determine when to start data collection.
Data Handling	In Progress	Ensure record data can be slimmed and moved to the proper location for off loading.

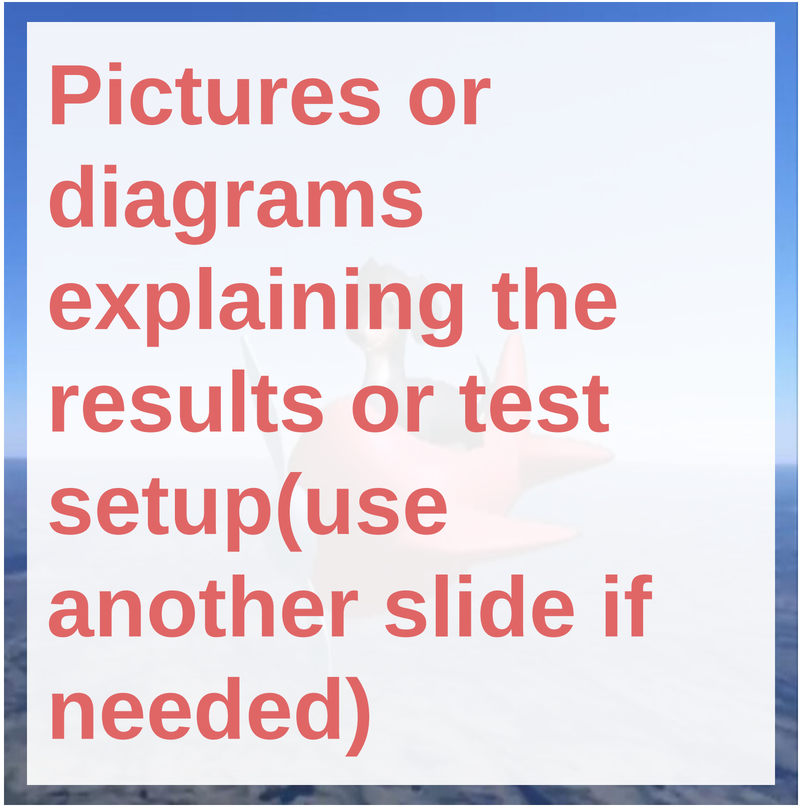
Test Procedure Overview:

RF Control:

- Attach the raspberry pi to the switch and program the pi to switch between 2 different radio station. This will be verified using a GUI on GNU Radio Companion.

GPS Timer:

- Give the Raspberry Pi a set of times. Attach the GPS to the Raspberry pi. Connect a LED to the Pi and verify that the LED lights up when the times programmed times line up with the GPS time.

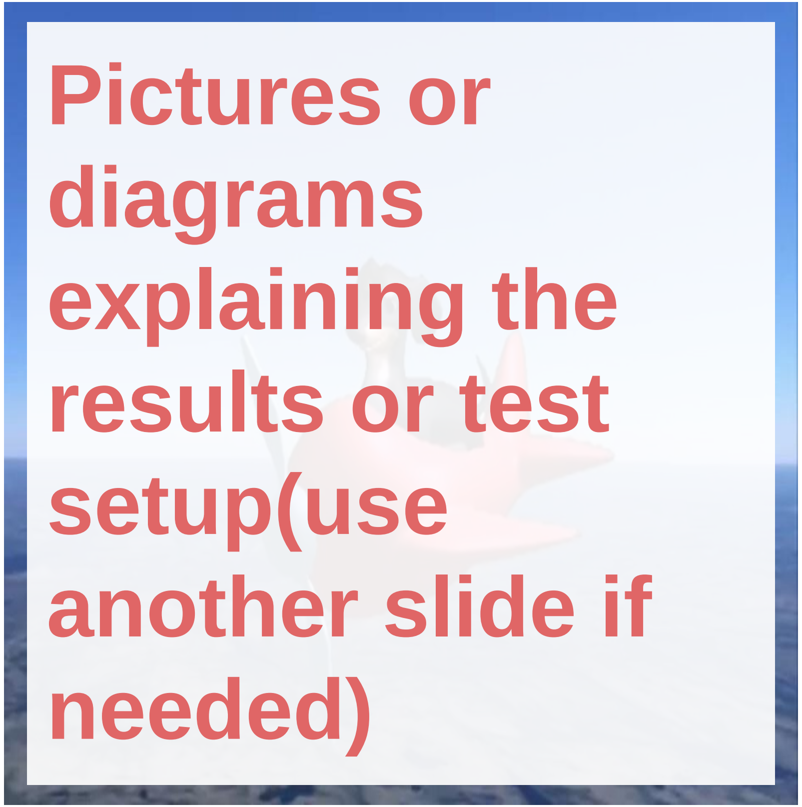


Test Procedure Overview:

Data Handling:

- Collected RF Data for a specific amount of time and store the data onto a flash drive.
- Program the Pi to slim the data and collect data for the same amount of time as the sampled collection.
- Compare the slimmed data file size is significantly smaller than the original collected data.
- Ensure that the data is stored with the proper naming convention in relation to the fly by time and respective sensor unit.

It is important to note that there is no need for special equipment or facilities for these tests outside the hardware itself.



RF Front End Test #1: G/T Conformance

Overall Test Goal(s): Make sure each sensor unit has a minimum UHF G/T of -20 dB/K with a target value of -15dB/K.

Requirements: DR3.1

Risk Mitigated: Too much noise on the signals received, leading to misinterpreted information

Results:

Test(s)	Status	Test Goal
VHF	In Progress	VHF G/T of -20 dB/K with a target value of -15dB/K.
UHF	In Progress	UHF G/T of -20 dB/K with a target value of -15dB/K.
L-Band	In Progress	L-Band G/T of -17 dB/K with a target value of -13 dB/K

RF Front End Test #2: Bandwidth / Received signal roll-off

Overall Test Goal(s): Verify that the RF front end must is able to cover ±10MHz of the target UHF frequency.

Requirements:, DR3.3

Risk Mitigated: Limits signal contamination of our desired signals by using a relatively small bandwidth. As well as proving that our antennas are capable of receiving satellite signals

Results:

Models: None(?)

Test(s)	Status	Test Goal
UHF	In Progress	±10MHz of the target (437.25 MHz)
VHF	In Progress	±10MHz of the target (145.3 MHz)
L-Band	In Progress	±10MHz of the target (1616 MHz)

RF Front End Test #3: Beamwidth/Azimuth

Overall Test Goal(s): Verifies that our antenna selections meet our requirement for a maximum beamwidth of 30°

Requirements: DR3.6

Risk Mitigated: Helps eliminate the need for pointing control by ensuring a large over head region will be in a roughly optimal configuration to receive satellite signals

Results:

Models: None(?)

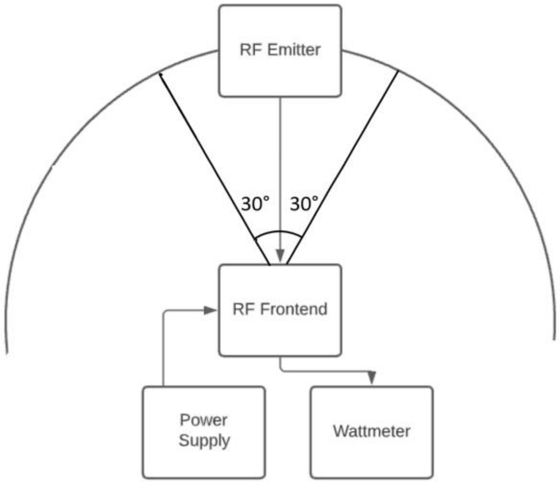
Test(s)	Status	Test Goal
VHF	In Progress	Maximum beamwidth of 30°, AZ FOV 360°
UHF	In Progress	Maximum beamwidth of 30°, AZ FOV 360°
L-Band	In Progress	Maximum beamwidth of 30°, AZ FOV 360°

Test Procedure Overview:

Using the antenna attached to the wattmeter and an RF emitter, have the antenna mounted on in the ground plane while the emitter is swept across the front at a constant radius to determine the frequency rolloff of the antenna.

Equipment/Facilities needed:

Wattmeter, Power Supply, RF Emitter



Test Setup #2

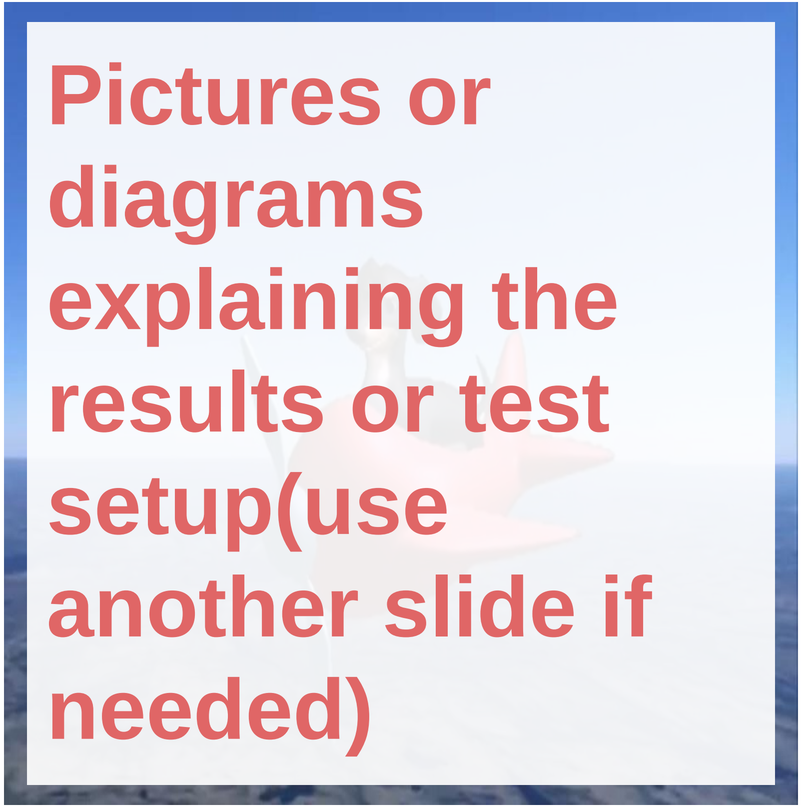
Test Procedure Overview:

RF Control:

- Attach the raspberry pi to the switch and program the pi to switch between 2 different radio station. This will be verified using a GUI on GNU Radio Companion.

GPS Timer:

- Give the Raspberry Pi a set of times. Attach the GPS to the Raspberry pi. Connect a LED to the Pi and verify that the LED lights up when the times programmed times line up with the GPS time.

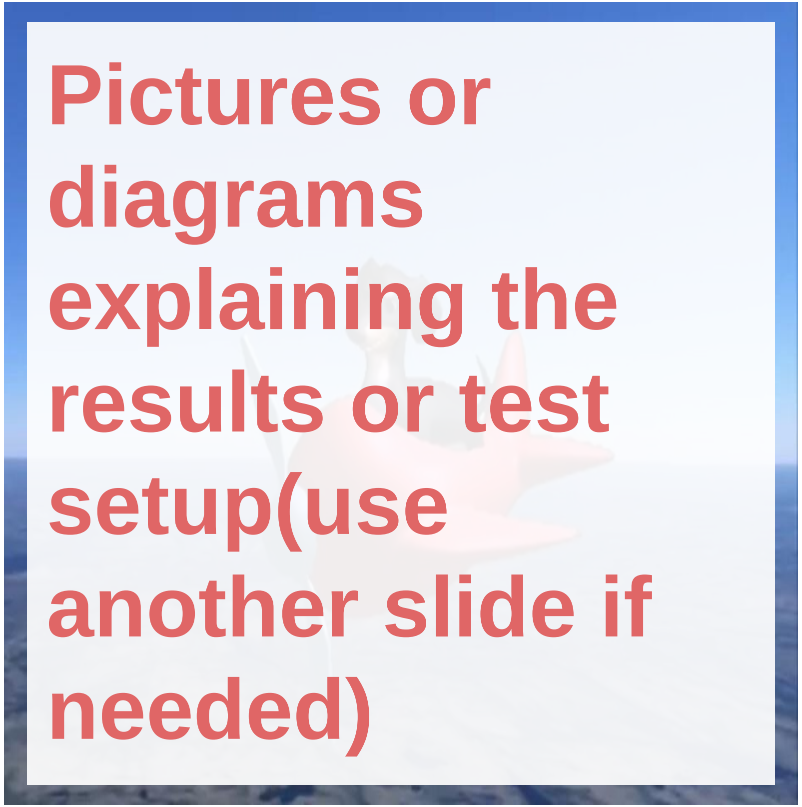


Test Procedure Overview:

Data Handling:

- Collected RF Data for a specific amount of time and store the data onto a flash drive.
- Program the Pi to slim the data and collect data for the same amount of time as the sampled collection.
- Compare the slimmed data file size is significantly smaller than the original collected data.
- Ensure that the data is stored with the proper naming convention in relation to the fly by time and respective sensor unit.

It is important to note that there is no need for special equipment or facilities for these tests outside the hardware itself.



Signal Correlation Test

Overall Test Goal(s): Ensure that the signals from boxes can be aligned and maintain the timing accuracy calculated.

Requirements: FR 5, FR 6

Risk Mitigated: Sensor Units can't be aligned according to GPST

Modeled Results: Simulated TDoAs

Test(s)	Status	Test Goal
Practice Run	Incomplete	Verify zero TDoA values at a single location.
Iridium Flyby	Incomplete	Verify expected TDoA with sensor units stationed across CO.
CSIM Flyby	Incomplete	Verify expected TDoA with sensor units stationed across CO.

Full System Level Tests

Tests	Test Goal
Full suite test	Ensure that the predicted orbited from test data is within the expected error

Practice Run Test Overview

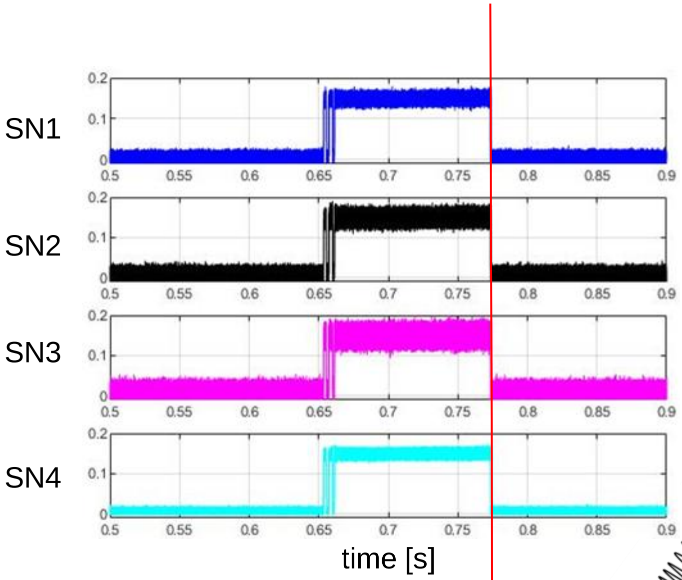
Procedure:

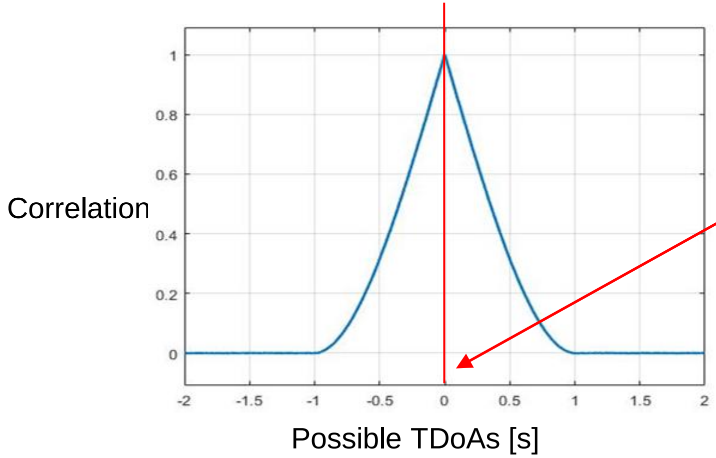
- Collect Data with Sensor Units at the same location.
- Press ‘collect’ within one second of each other for gps alignment.

Equipment/Facilities needed:

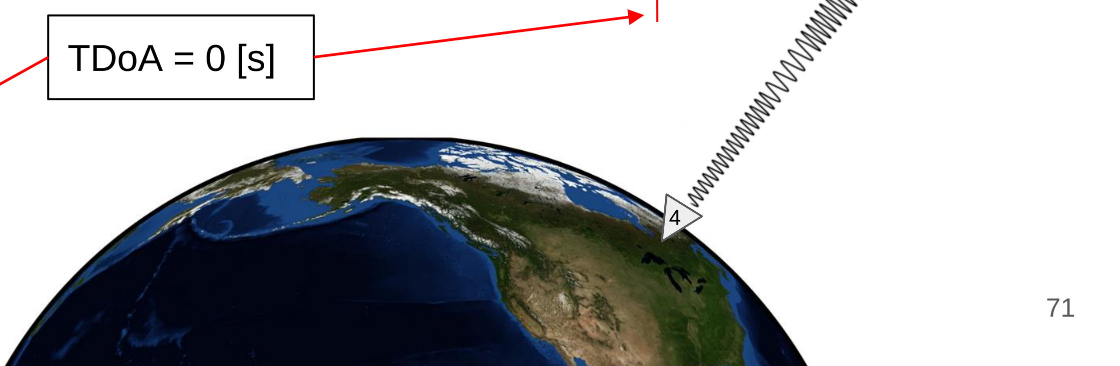
- 4 Sensor Units.

Test goal - Verify that TDoA between all Sensor Units at the same location is zero.





TDoA = 0 [s]



Iridium/CSIM Flyby Test Overview

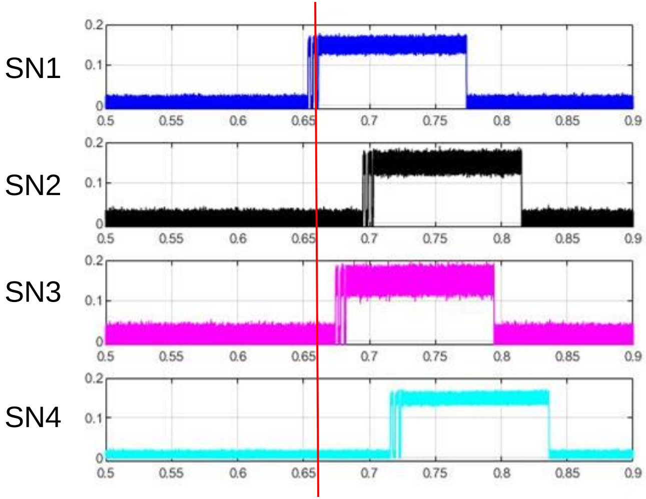
Procedure:

- Collect Data with Sensor Units around Colorado.
- Press ‘collect’ within one second of each other for gps alignment.

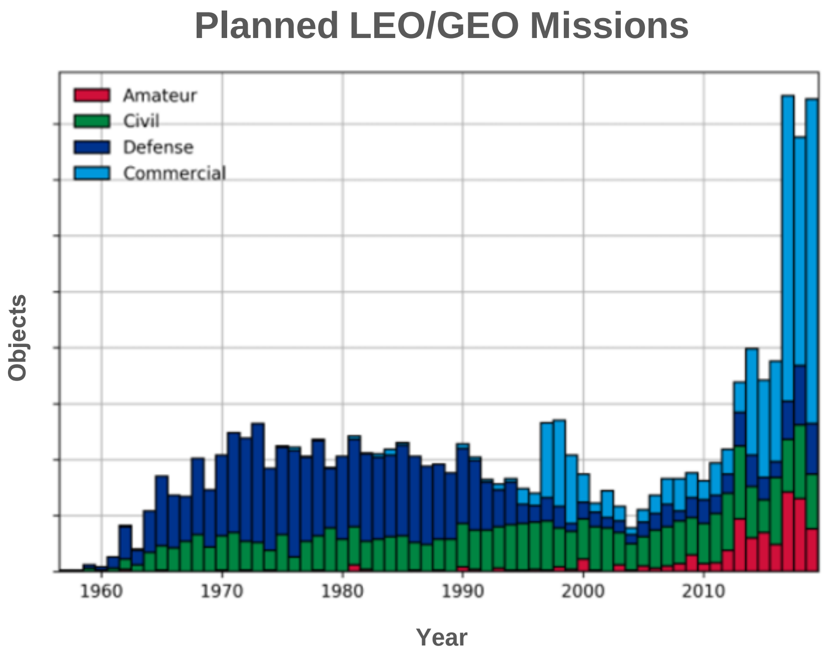
Equipment/Facilities needed:

- 4 Sensor Units.

Test goal - Verify that TDoA between all Sensor Units at different locations is around the predicted value.



TDoA = 0 < TDoA < TDoA < TDoA



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