

Thinsat Operational Management of Commands And Telemetry

Critical Design Review



Project Stakeholders

Advisor: Dr. Kathryn Wingate

Customer: Mark Werremeyer;
Raytheon

Primary Partners:

- NearSpace Launch
- Twiggs Space Lab

Raytheon

 Ann and H.J. Smead
Aerospace Engineering Sciences
UNIVERSITY OF COLORADO BOULDER

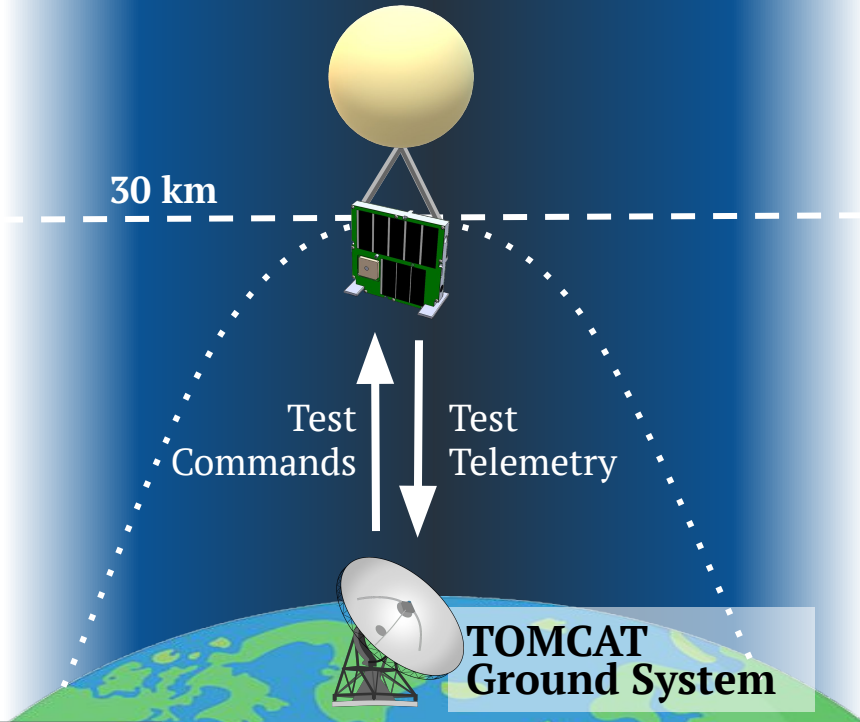

NearSpace Launch Inc.
Technology • Service • Education


TWIGGS
SPACE LAB
INSPIRING SPACE INNOVATION



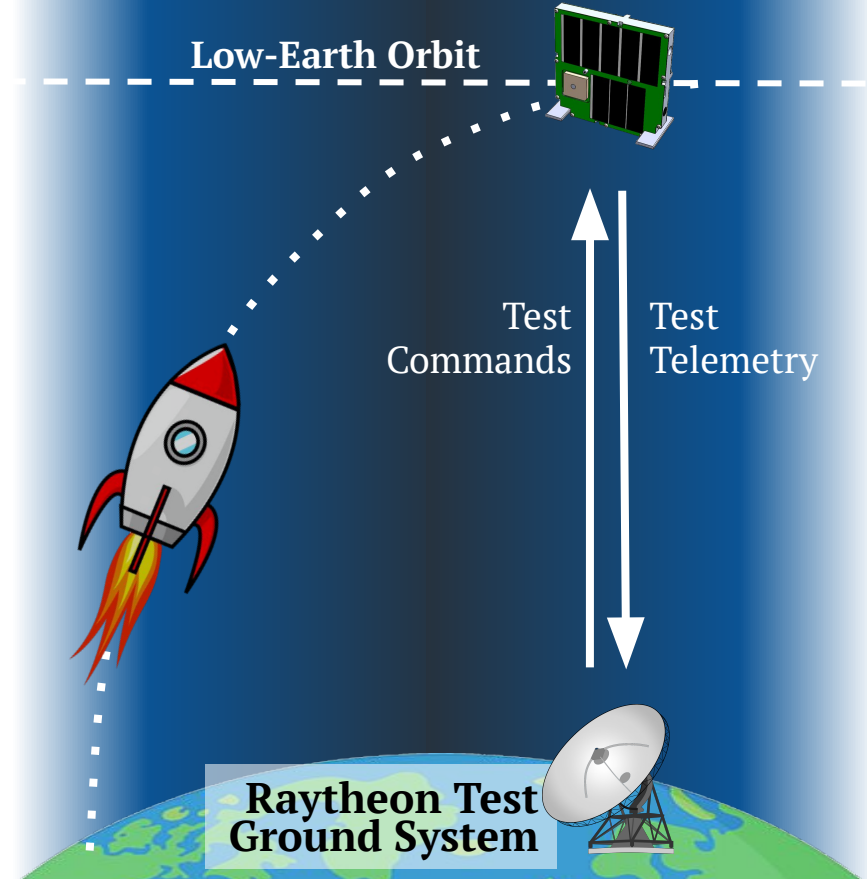
• Purpose and Objectives

TOMCAT Mission



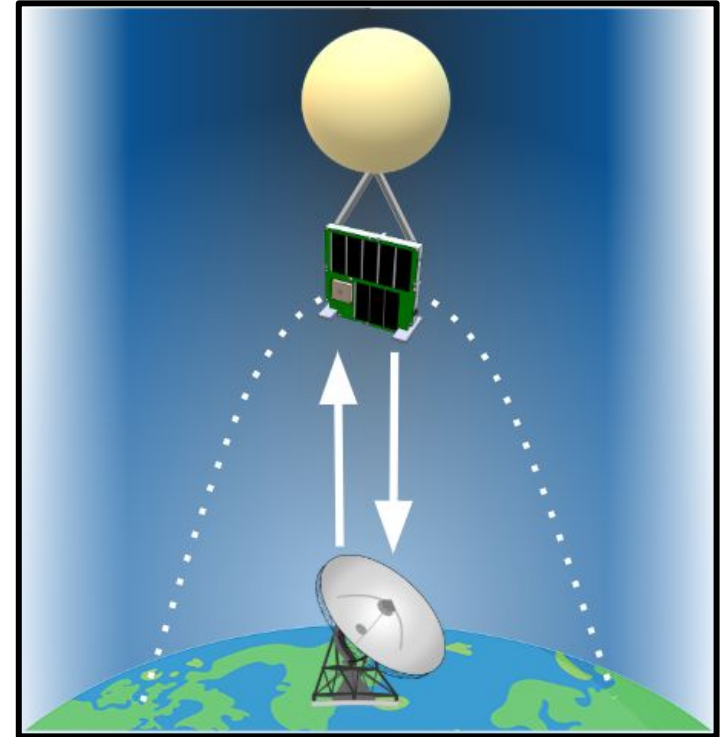
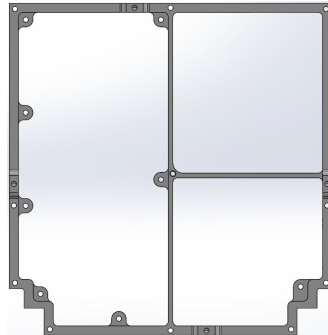
Purpose

Raytheon Mission



Project Objectives

- **Primary Objective: Design a Small Communications Satellite**
- **Specific Objectives:**
 - Design Software Defined Radio (SDR) communication system
 - Design system to perform and survive a balloon flight
 - Use CCSDS Protocol (Space Packet Format)
 - Constrain system to ThinSat frame shape

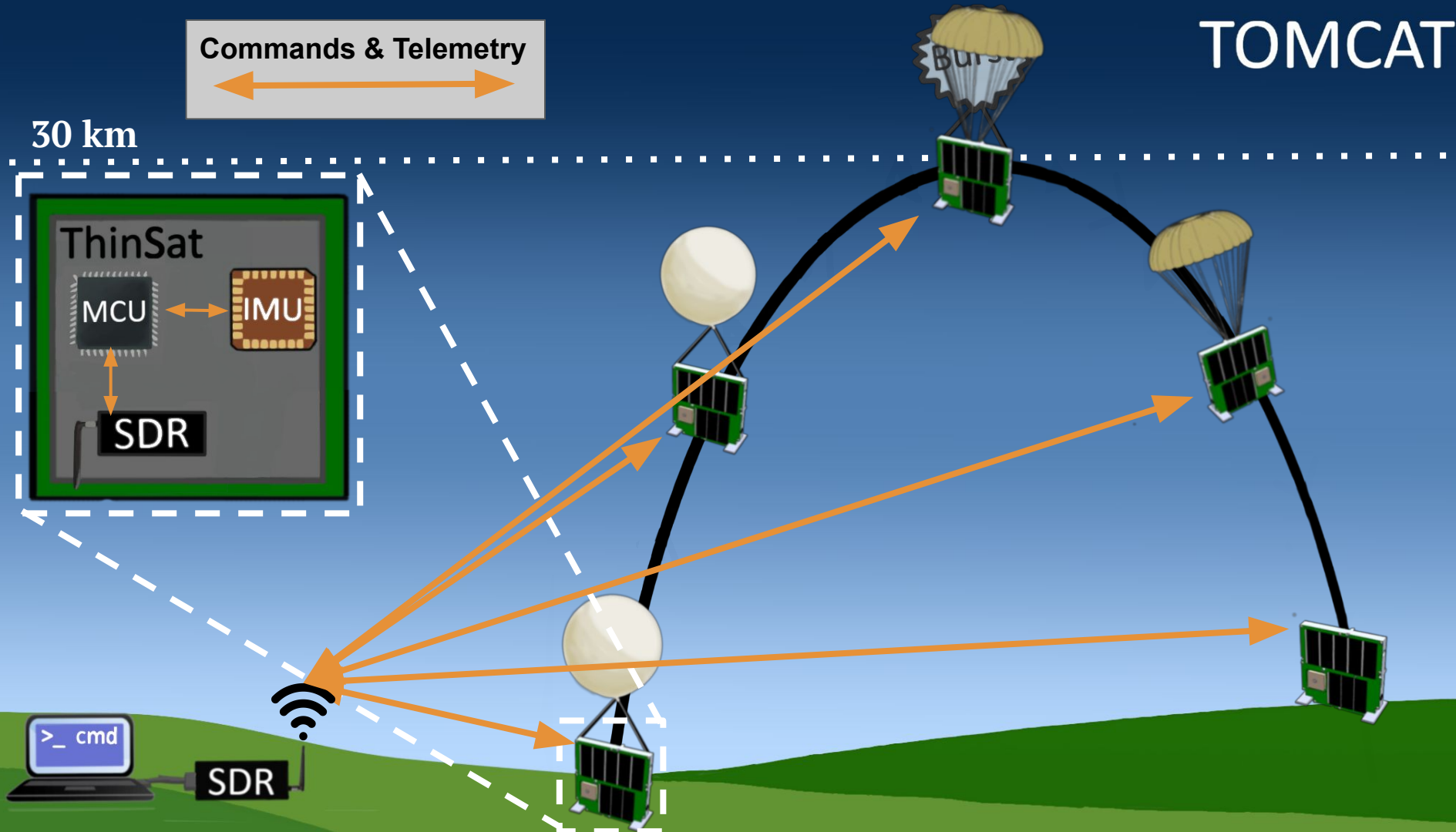
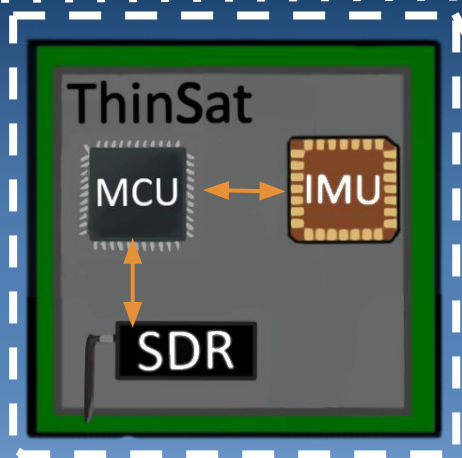


TOMCAT

Commands & Telemetry



30 km



Design Solution

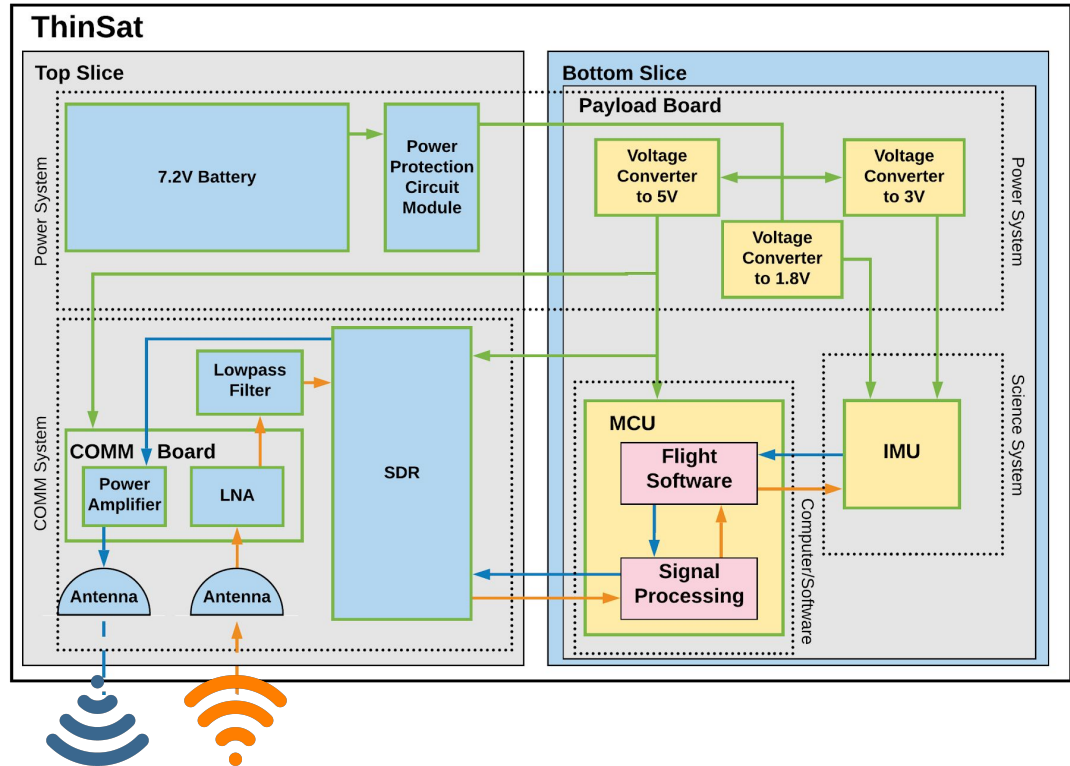
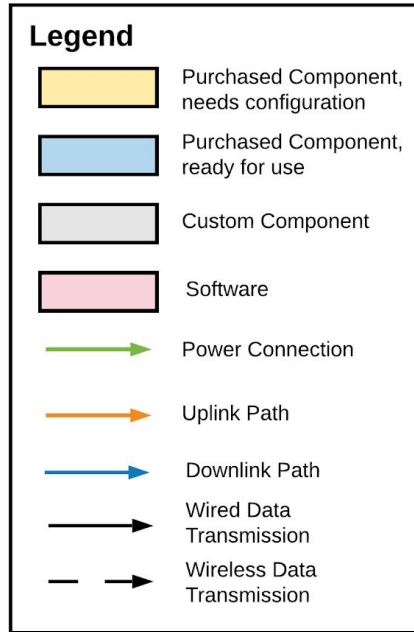
Indicates slide discusses
Ground Hardware/Software



Indicates slide discusses
On-board Hardware/Software

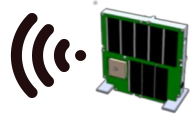


Onboard Functional Block Diagram



Takeaway:

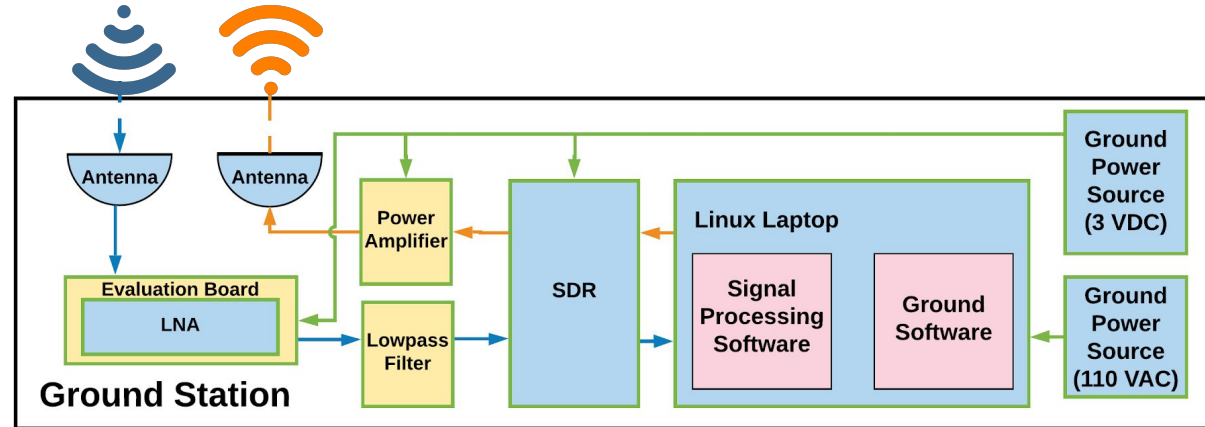
Communicate between the antennas, SDR, and IMU



Ground Functional Block Diagram

Legend

-  Purchased Component, needs configuration
-  Purchased Component, ready for use
-  Custom Component
-  Software
-  Power Connection
-  Uplink Path
-  Downlink Path
-  Wired Data Transmission
-  Wireless Data Transmission



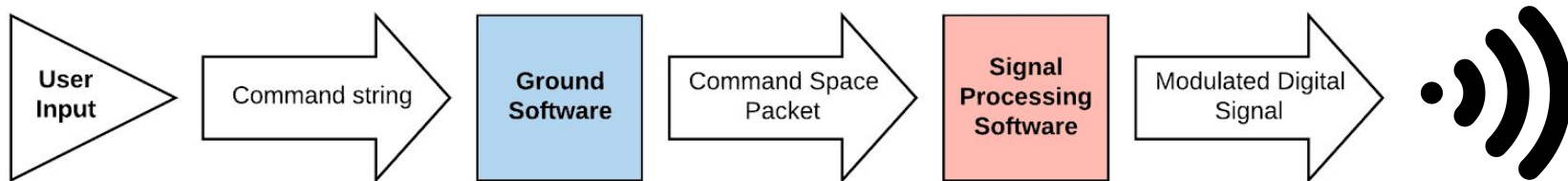
Takeaway:

Send commands and receive telemetry through SDR system

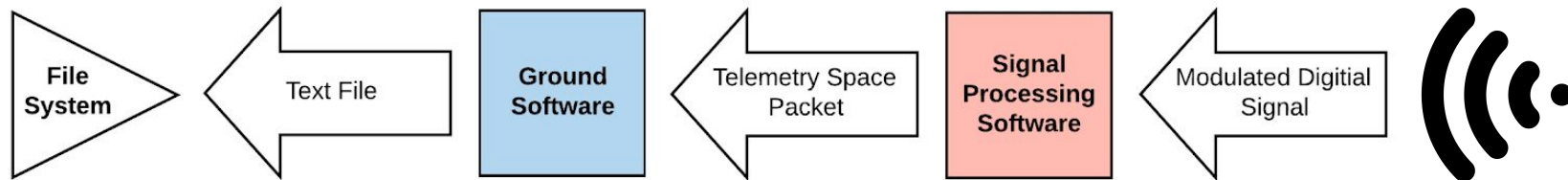


Ground System Data Flow

Uplink: 128 bps



Downlink: 72 kbps



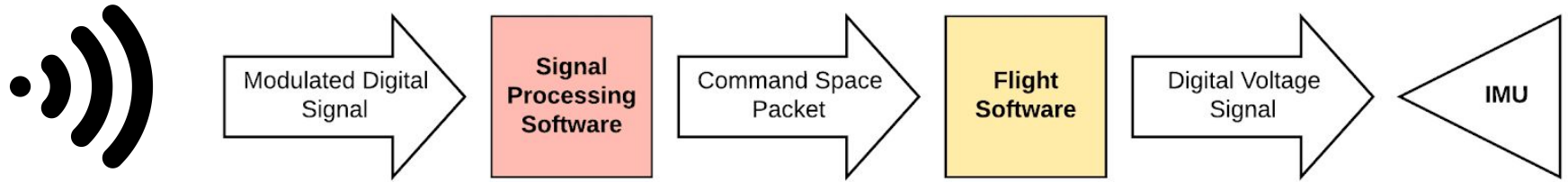
Takeaway:

Interactions between software are compatible

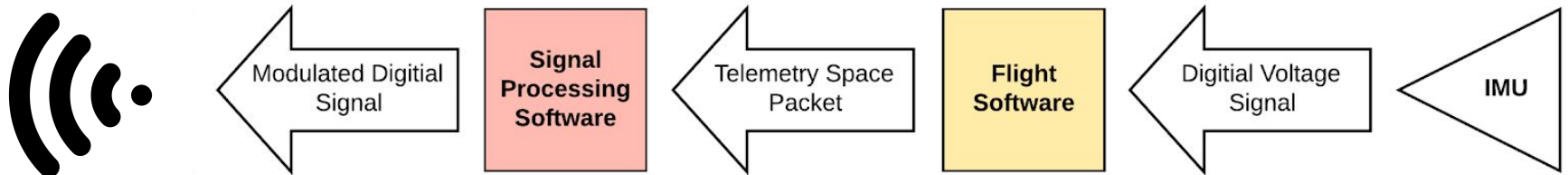


Onboard System Data Flow

Uplink: 128 bps

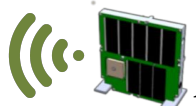


Downlink: 72 kbps

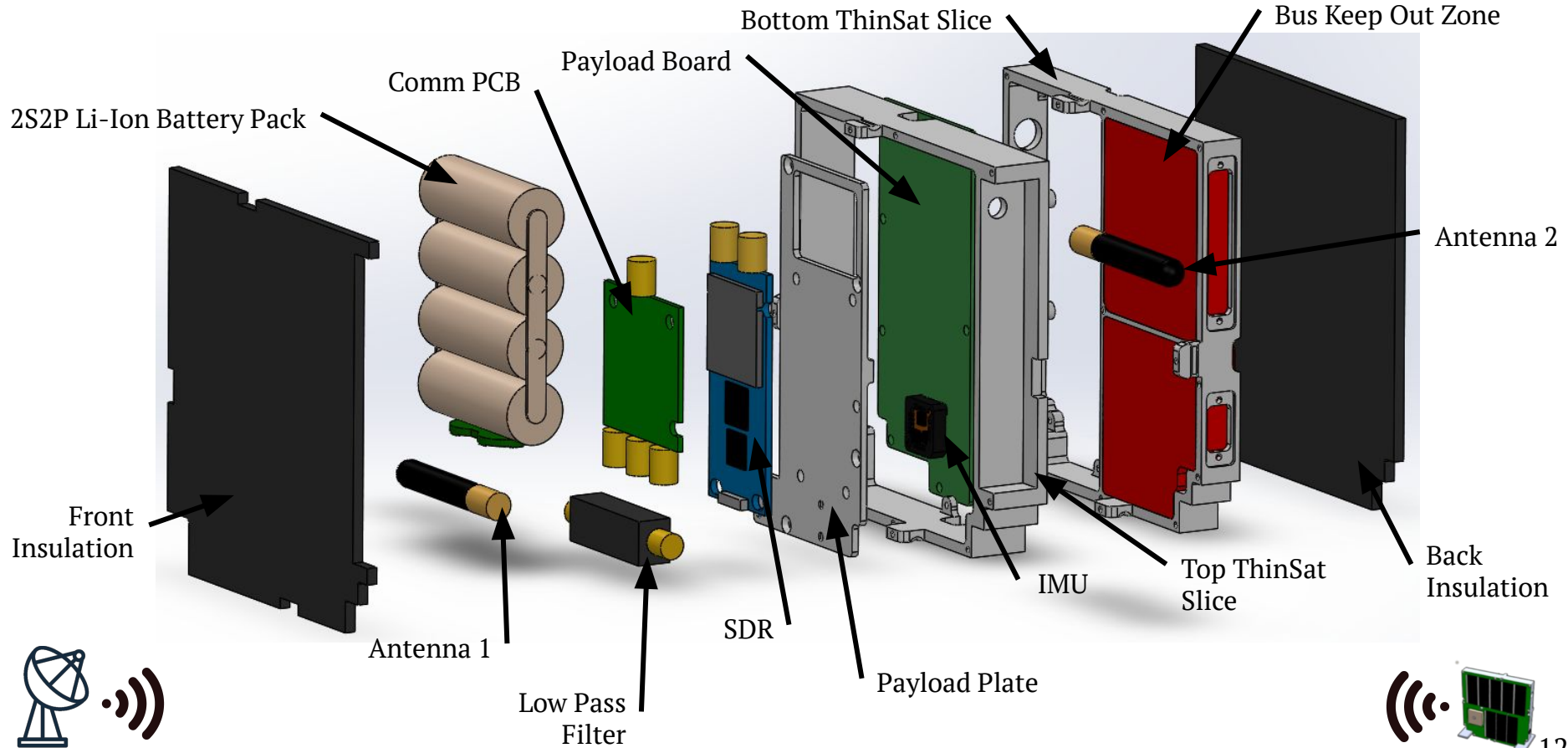


Takeaway:

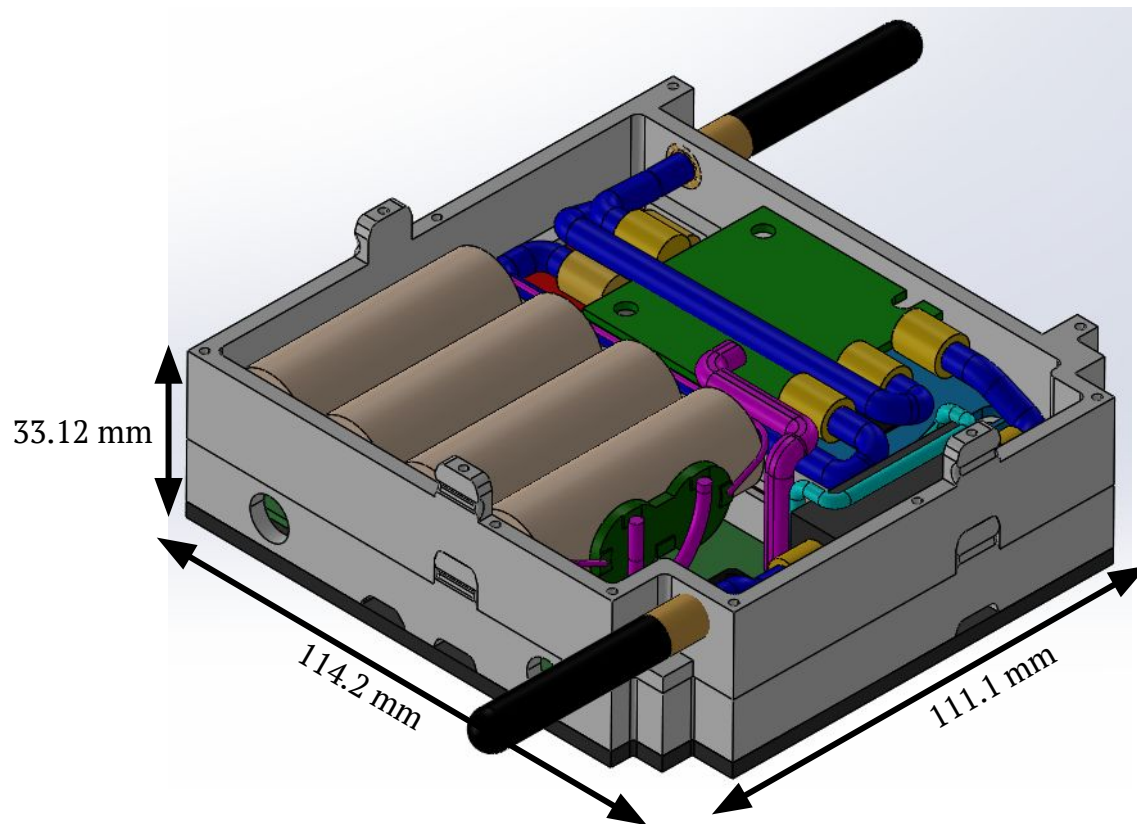
Interactions between software are compatible



Top Level Overview



Top Level Overview



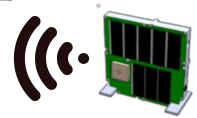
Engineering Budgets

Mass Budget

Total Mass	569g
25% Margin	142.25g
Total Mass with Margin	711.25g < 800g (flight requirement)

Power Budget

Total System Load Power	7.96 W
Total Energy Required (2 hours)	15.91 Wh
50% Built-in Capacity	7.96 Wh
Total Energy with Margin	23.87 Wh < 30.19 Wh (battery)



Engineering Budgets

Downlink Data Budget

Total Pr/No	65.20 dB-Hz
Minimum required Pr/No	34.87 dB-Hz
Link Margin	30.32 dB-Hz > 10 (SMAD recommendation)

Uplink Data Budget

Total Pr/No	82.52 dB-Hz
Minimum required Pr/No	61.17 dB-Hz
Link Margin	19.33 dB-Hz > 10 (SMAD recommendation)



Critical Project Elements



Critical Project Elements

Communications Hardware

- Software Defined Radio
- Hardware filters
- Hardware amplifiers

Communications Software

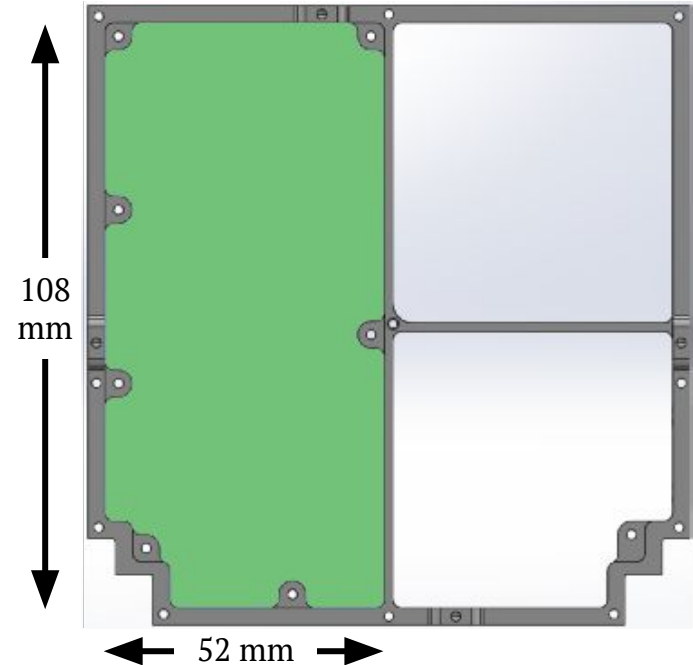
- GNU Radio
 - Modulation
 - Signal conditioning
 - Demodulation
 - Interpretation



Critical Project Elements

Custom Designed Payload Board

- Power regulation and distribution
 - Powers comm hardware
- Payload computer
 - Hosts signal processing software
- Data collection sensor
 - Takes data to verify communication system



Requirements Satisfaction

Contained Here:

- Communication Hardware
- Communication Software
- Payload Board

In Backup Slides:

- Ground Software
- Structures
- Science
- Power
- Flight Software
- Thermal



Requirements and Objectives

Req #	Requirement Description	Associated Design Requirement
FR2	The payload shall communicate with the ground system	Antenna FOV captures uncertain balloon drift
		Link margin must overcome uncertain noise
		Signal processing design must filter interference
FR3	The payload shall survive and operate in a balloon flight environment	Temperature maintained for battery operation
FR4	The payload board shall perform all necessary hardware tasks for system	Board is manufacturable and testable in-house

Takeaway:

Functional requirements lead to critical objectives to be fulfilled for project success



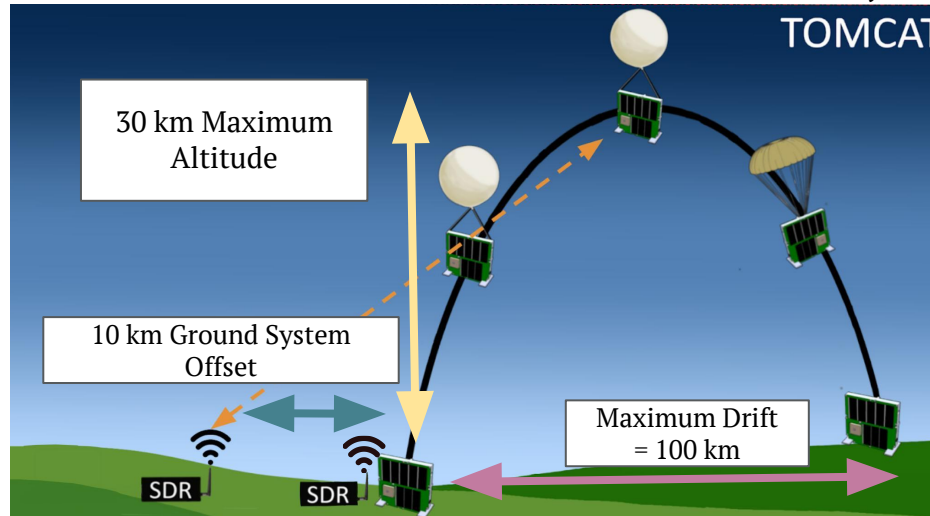
Communications Hardware Requirements

Functional Requirement:

FR 2: The payload shall communicate with the ground system during the balloon flight

Design Objectives:

- Positive link margin
- Data rate allows for downlinking all telemetry data



Takeaway:

List design objectives to fulfill communication hardware requirements



Link Budget Model Summary

Relevant Design Requirement:

- Link margin overcomes noise and losses

To Meet Design Requirement:

- Positive Link Margin
- Extra margin to account for low fidelity model

Item	Uplink	Downlink
Frequency	0.915 GHz	0.915 GHz
Data Rate	128 bps	72,000 bps
Minimum Pr/No	34.87 dB-Hz	61.17 dB-Hz
System Noise Power	-199.52 dB-Hz	-205.5 dB-Hz
Effective Isotropic Radiated Power	-2.00 dBW	1.71 dBW
Propagation Losses	-132.69 dB	-132.69 dB
Receiver Gain	1.70 dB	8.00 dB
Actual Pr/No	65.20 dB-Hz	80.51 dB-Hz
Link Margin	30.32 dB-Hz	19.33 dB-Hz



Takeaway:

The system is capable of producing a higher Pr/No than the minimum required



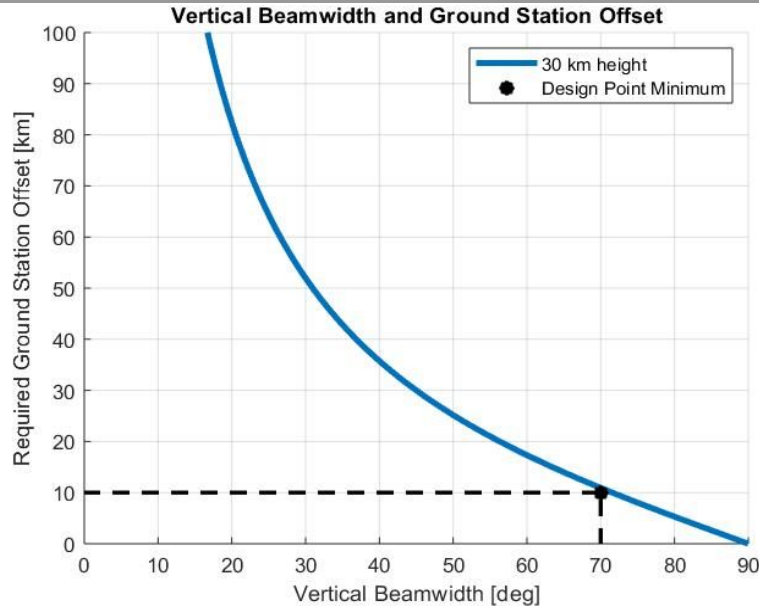
Ground Communications Antenna

Relevant Design Requirement:

- Antenna field of view exceeds balloon drift

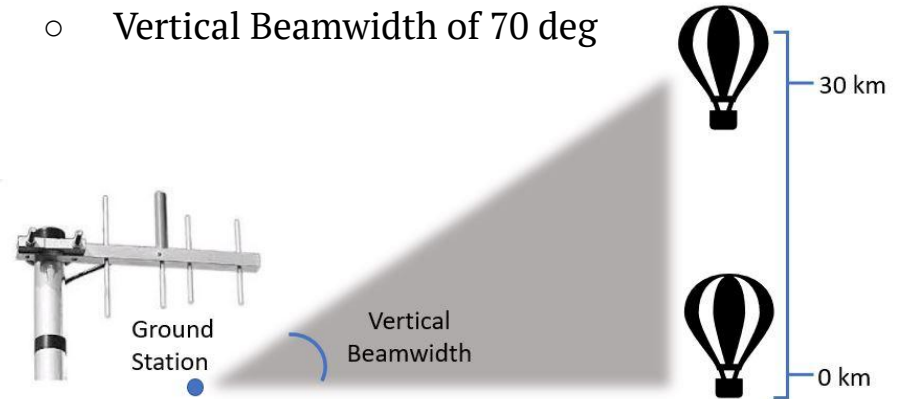
To Meet Design Requirement:

- Choose large beamwidth antenna
- Displace antenna so satellite is always in beamwidth



Ground Antenna

- 4 Element Yagi 8.5 dBi
- Vertical Beamwidth of 70 deg



Takeaway:

The primary ground station will be displaced 10km so the balloon doesn't drift out of FOV



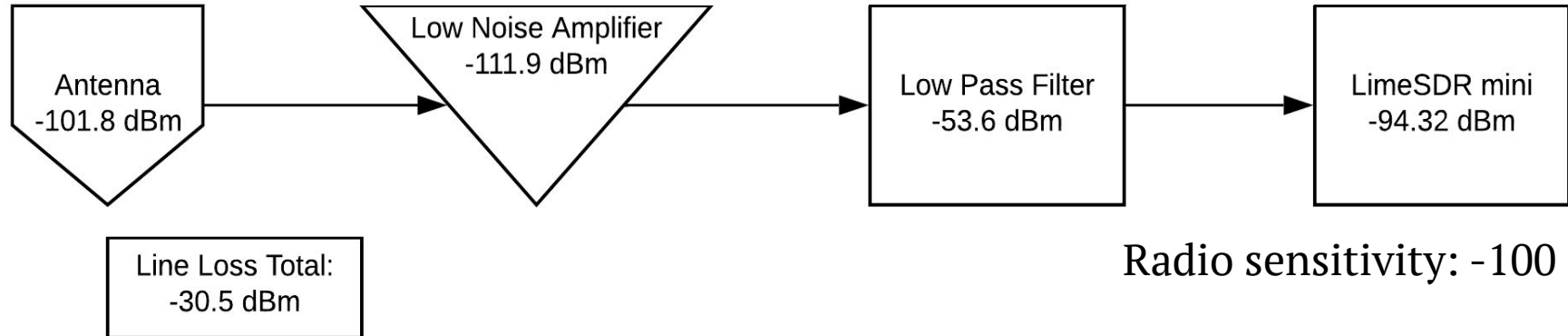
Communications Onboard Hardware

Relevant Design Requirement:

- Link margin overcomes noise

To Meet Design Requirement:

- Prevent signal aliasing
- Ensure power level is detectable by LimeSDR mini



Takeaway:

Due to losses from the filter and wires, we need to add an amplifier to our RF chain



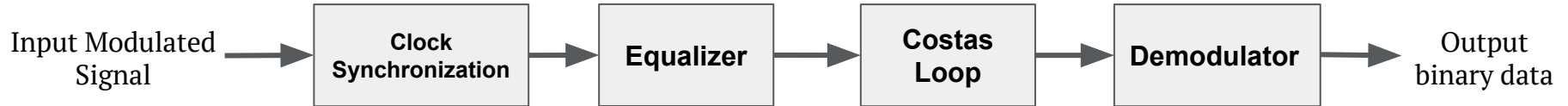
Communications Software Requirements

Pertinent Requirements:

FR 2: The payload shall communicate with the ground system during the balloon flight

Design Objectives:

- Signal conditioning
- Encode data into digital signal
- Decode data from digital signal



Takeaway:

List design objectives to fulfill communication software requirements



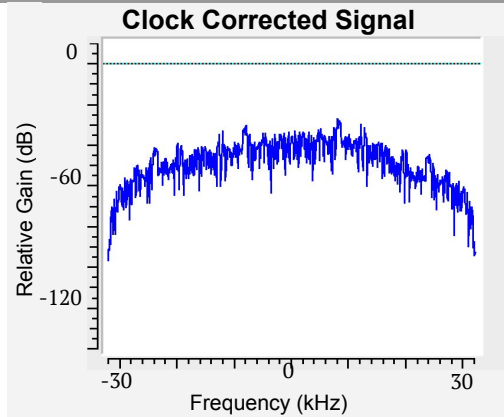
Communications Software Requirements

Relevant Design Requirement:

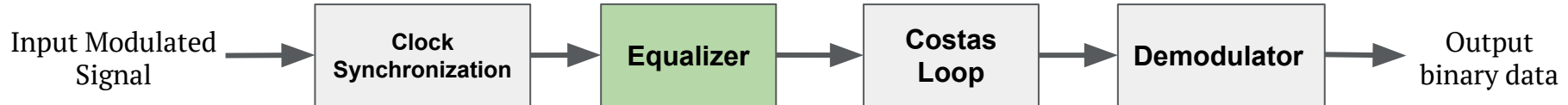
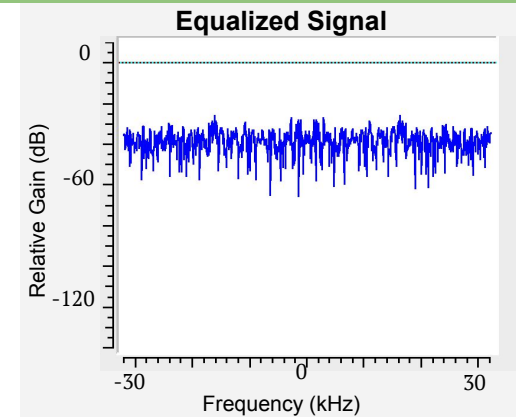
- Signal processing filters interference

To Meet Design Requirement:

- Correct for timing differences between radios
- Ensure all bandwidth frequencies have equal gain



**TOMCAT equalizer
simulation**



Takeaway:

Demonstrate communication simulation designed by the TOMCAT team



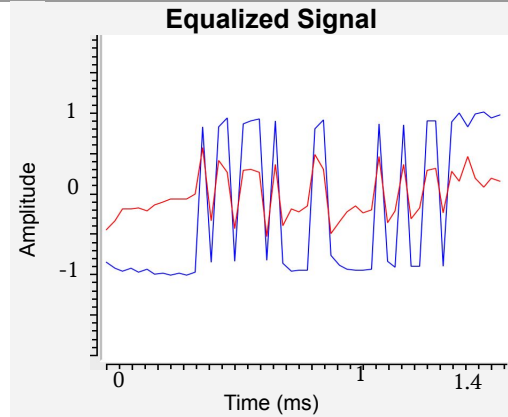
Communications Software Requirements

Relevant Design Requirement:

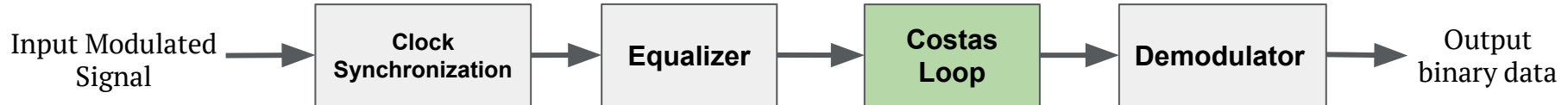
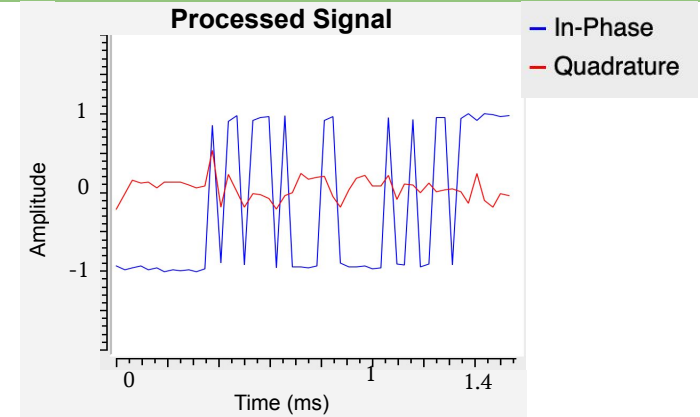
- Signal processing filters interference

To Meet Design Requirement:

- Remove frequency variations due to oscillator variation
- Remove phase offsets due to oscillator variation



**TOMCAT Costas
Loop simulation**



Takeaway:

Demonstrate communication simulation designed by the TOMCAT team



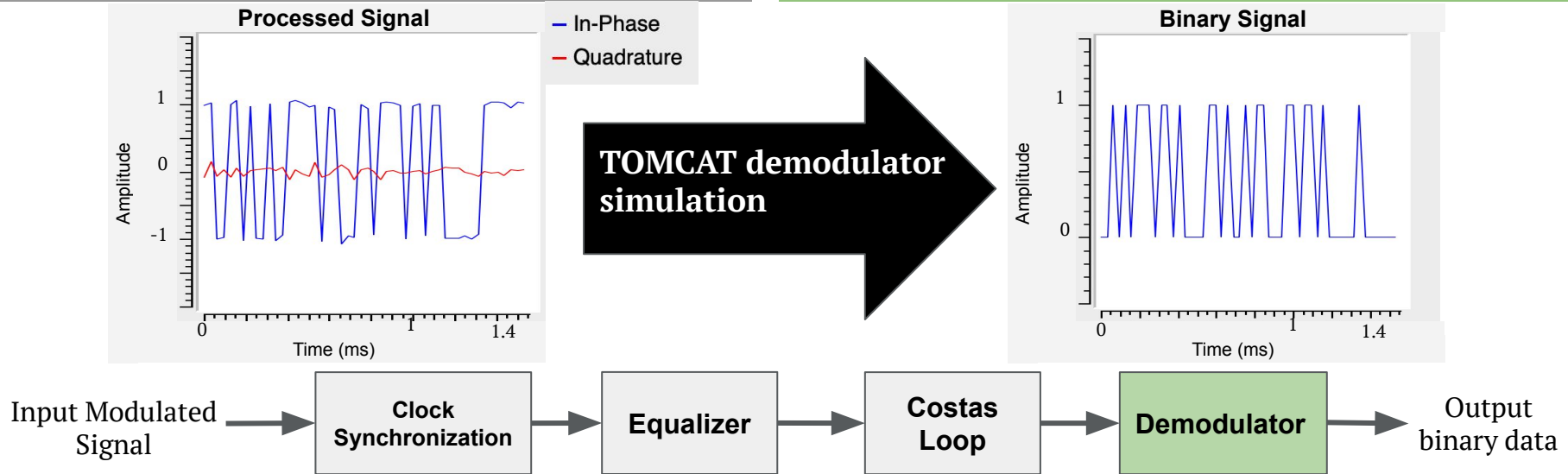
Communications Software Requirements

Relevant Design Requirement:

- Signal processing filters interference

To Meet Design Requirement:

- Retrieve binary data from processed modulated signal



Takeaway:

Demonstrate communication simulation designed by the TOMCAT team



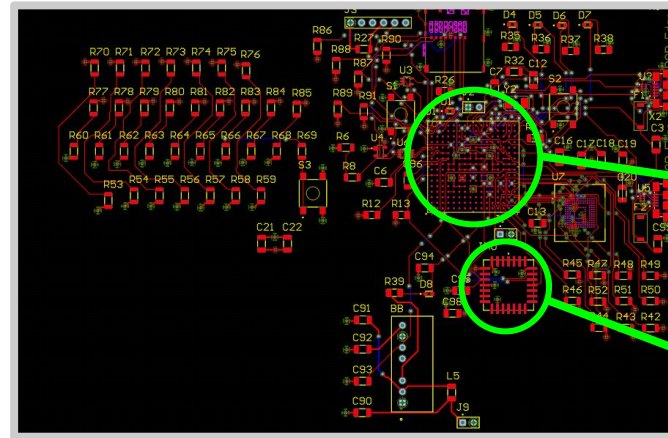
Custom Payload Board Requirements

Pertinent Requirements:

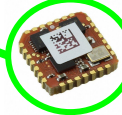
FR 4: The payload board shall perform all necessary hardware tasks for system operation

Design Objectives:

- Connectivity & Performance
- Manufacturing & Assembly
- Bring-up, Troubleshoot & Debug



MCU

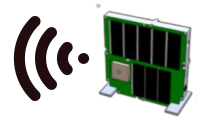


IMU

TOMCAT Designed Board

Takeaway:

List design objectives to fulfill payload board requirements



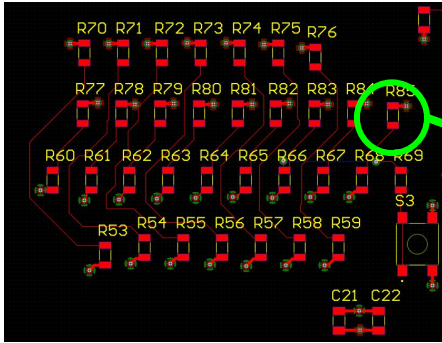
Payload Board Design Objectives

Relevant Design Requirement:

- Allow detection of faulty components on board

To Meet Design Requirement:

- Ensure reliable manufacturing



PCB layout with component footprints



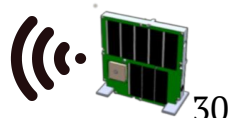
Resistor in size 1206 packaging

Manufacturing & Assembly:

- PCB footprints match the pads on devices being soldered
- Hand-soldered devices in packaging that are easy to solder by hand (0602 minimum size)
- Silk-screen identifications

Takeaway:

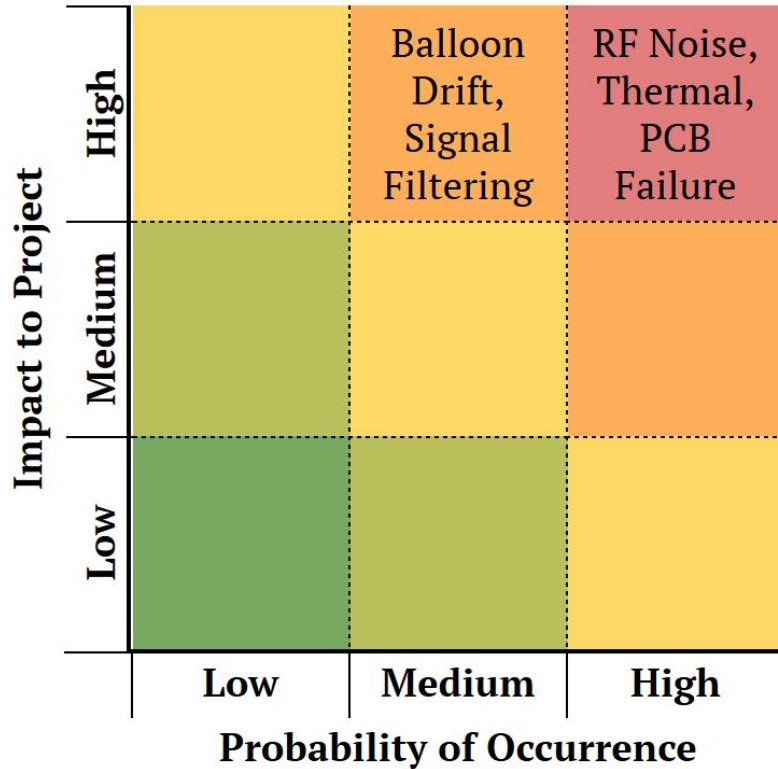
Board is being designed for easy manufacturing and assembly to reduce risk



Risk Analysis



Pre-Mitigation Technical Risks



Associated Risk	Shorthand
Balloon drift exceeds antenna field of view	Balloon Drift
Noise and losses overcome link margin	RF Noise
Signal processing can't filter enough interference	Signal filtering
No margin on existing thermal model	Thermal
Payload board cannot be manufactured	PCB Failure

Takeaway:

Review of critical risks associated with the project and their severity prior to mitigation



Technical Risks

Mitigation	Associated Risk	Shorthand
Displaced ground system	Balloon drift exceeds antenna field of view	Balloon Drift
Maintain large link margin	Noise and losses overcome link margin	RF Noise
Applied several different signal processing algorithms to system	Signal processing can't filter enough interference	Signal filtering
Added insulation to system, perform multiple cold tests	No margin on existing thermal model	Thermal
Added abundant probe points and indicator LEDs, budget for vendor build-up. 4 planned revisions with enough time scheduled for each	Payload board cannot be manufactured	PCB Failure

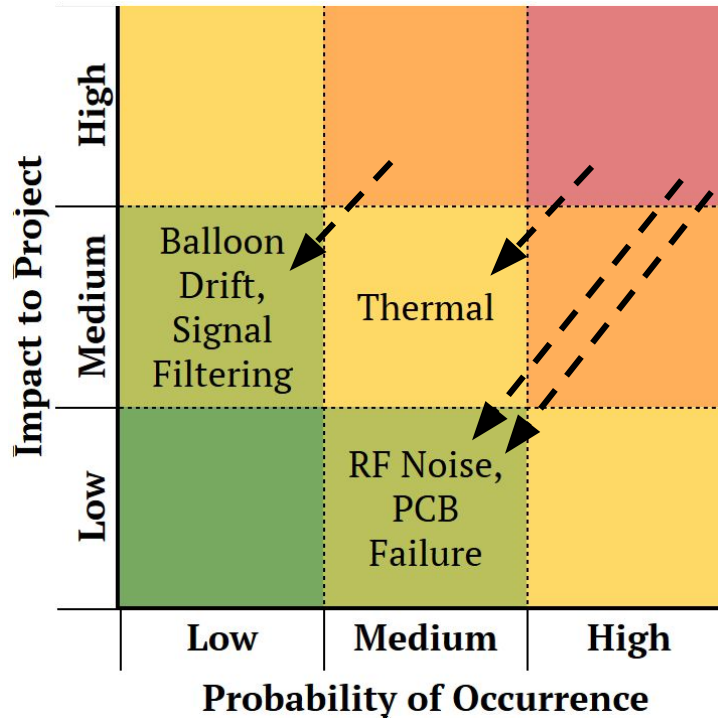


Takeaway:

Overview of mitigation strategies of most critical risks discussed previously



Technical Risks



Takeaway:

Show how the risk matrix evolves after mitigation



Verification and Validation

Contained Here:

- Full System
- Communications

In Backup Slides:

- Payload Board
- Flight Software
- Ground Software
- Structures
- Science
- Power
- Thermal



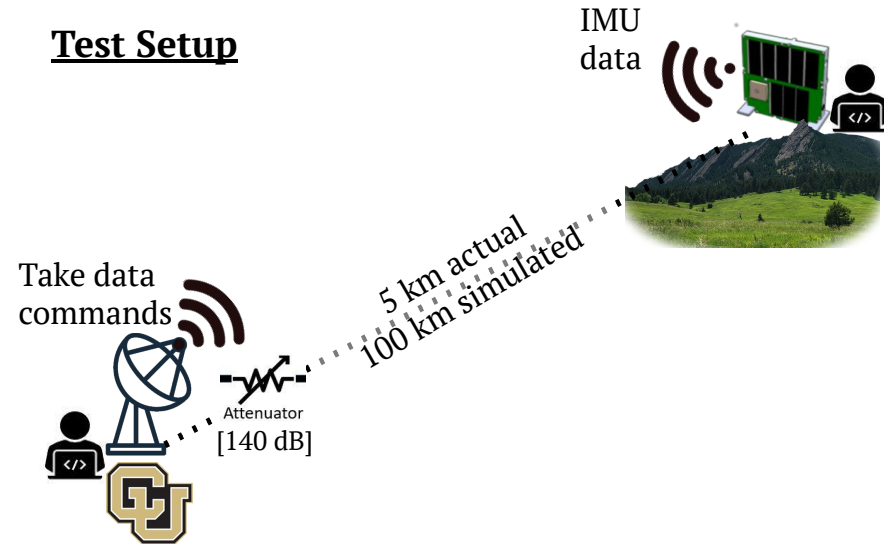
Full System Verification Test

System Testing

Objective	Verify full system functionality: > 2 commands / second - Bit error rate < 1 bit flip per 10^6 bits for 72 kbps downlink
Plan	Vary: - command rate (1-10 cmd/sec) - downlink rate (1 - 100 kbps) Measure: - command accept rate - bit error rate
Materials	1 TOMCAT ThinSat 1 TOMCAT Ground Station 140 dB Attenuation

* This test occurs after extended testing of individual system components

Test Setup



Takeaway:

Top Level Hardware in the Loop Test verifies TOMCAT design prior to balloon flight



Validation

- **Hardware**
 - Two way communication between ground station and onboard system
- **Software**
 - Send and receive CCSDS command/telemetry packets

Verification

- **Hardware**
 - Data rates and bit error rates match link budget
- **Software**
 - Verified bit error rate
 - Integration
 - Ensure Microcontroller can process signal



Takeaway:

Overview of the planned methods of verification and validation



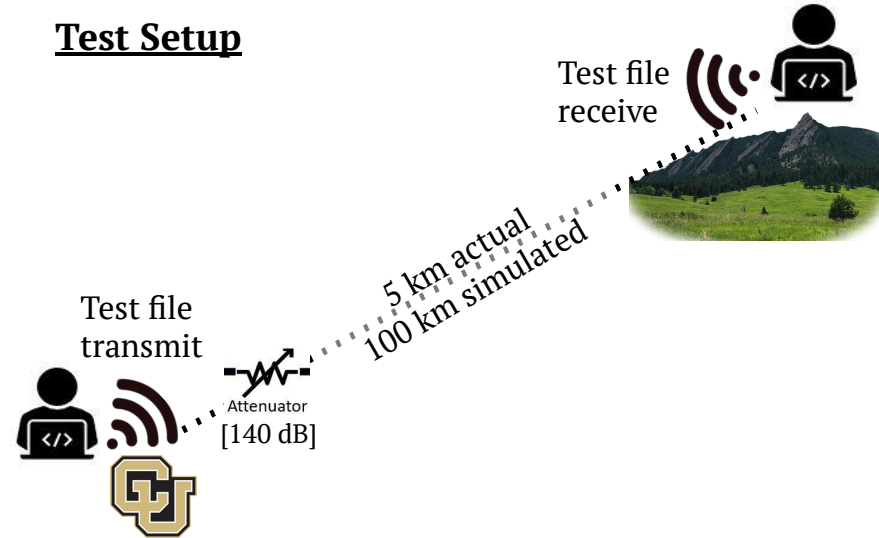
Communications Final Verification

Range Testing - range verification

Objective	1. Measure bit error rate as a function of downlink rate 2. Verify Signal Processing Model 3. Verify RF Chain Power Level
Plan	Vary: ○ File send rate (1-100 kbps) Measure: ○ Bit error rate
Materials	2 LimeSDR Minis 2 Laptops 2 LNAs 2 Low Pass Filters 2 Power Amplifiers 140 dB Attenuation

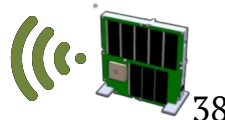
* This test occurs after wired, and short range wireless testing

Test Setup



Takeaway:

Range test allows us to characterize our RF chain and communication system design

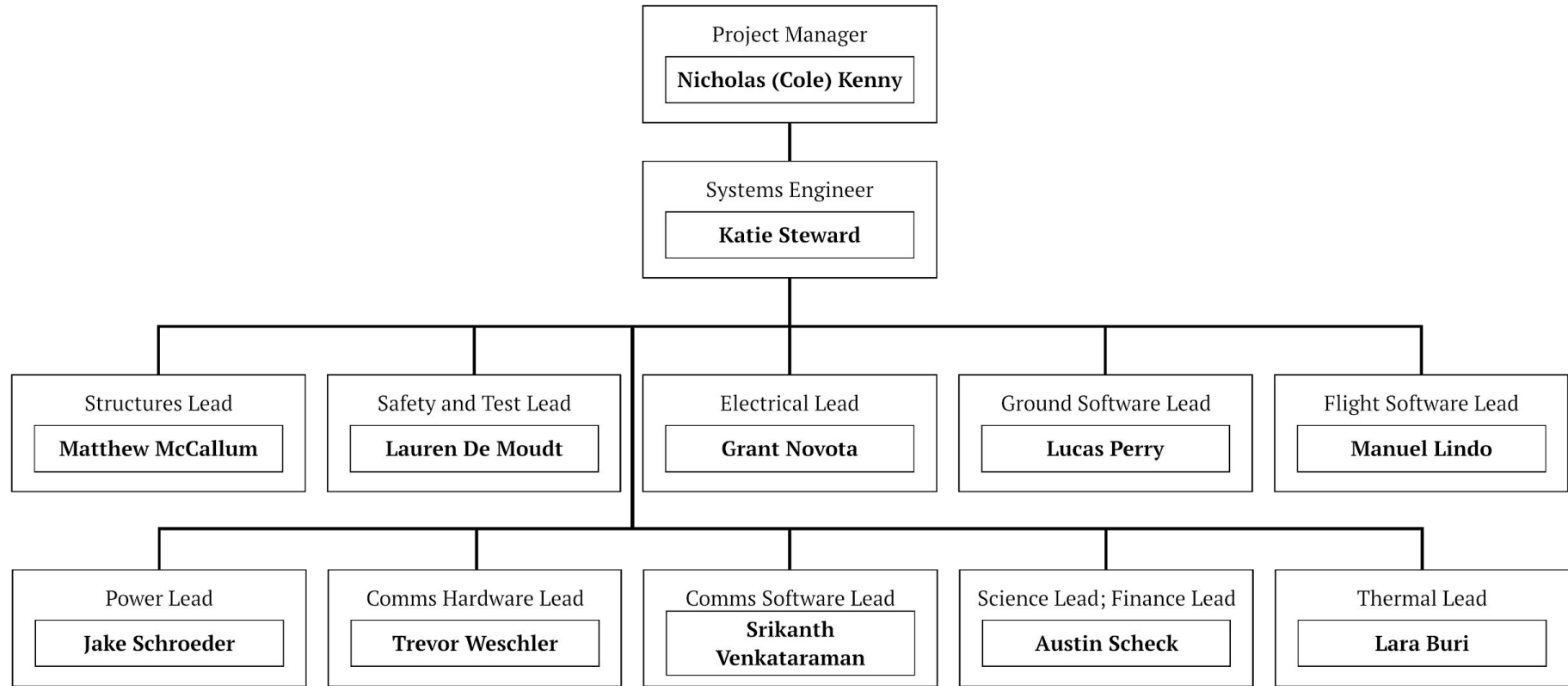


Project Planning

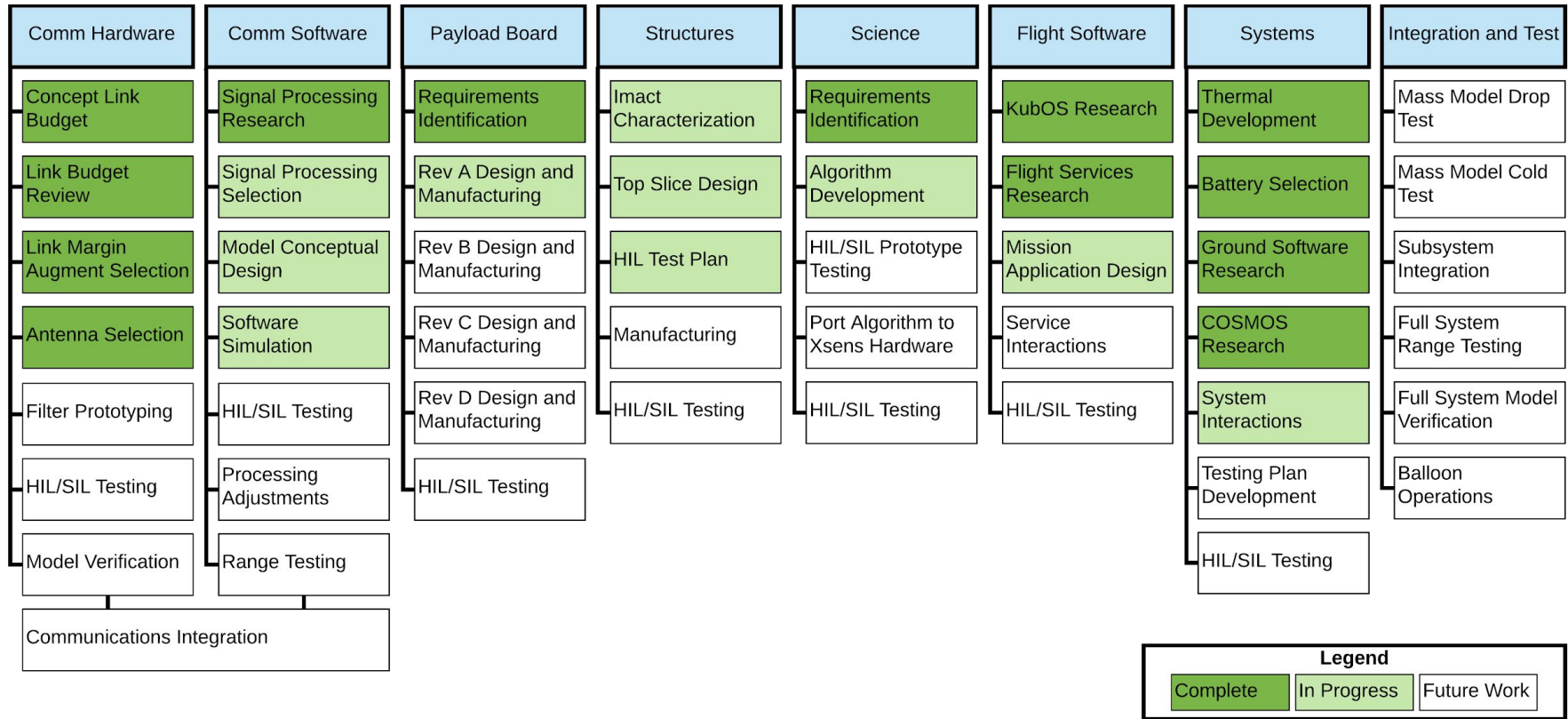
Test Plan

Hardware in the Loop (HIL) and Software in the Loop (SIL) Testing		
Test Name/Description	Anticipated Date	Location; Hazards (if any)
Wired Communications Test	January	Electronics Lab; None
Cold Test #2	January	Electronics Lab; Caution when handling dry ice
SparkFun IMU Algorithm Test	January	PILOT Lab, Senior Projects Space; None
Mass Model Drop Test	February	Aerospace Balcony; Coordinate with Matt for safety
KubOS Comms Testing	February	Electronics Lab; None
Short-Range Wireless Comms Test	Late-February	Electronics Lab; None
Full Range Wireless Comms Test	March	Chautauqua Park <-> Aerospace Roof; Coordinate with Matt
Cold Test #3	March	Electronics Lab; Caution when handling dry ice
Full System Test	Late-March	Pikes Peak <-> Raytheon; Coordinate with Raytheon
Balloon Launch	April	Eastern CO, Indiana; Coordinate with Matt, Raytheon/NSL

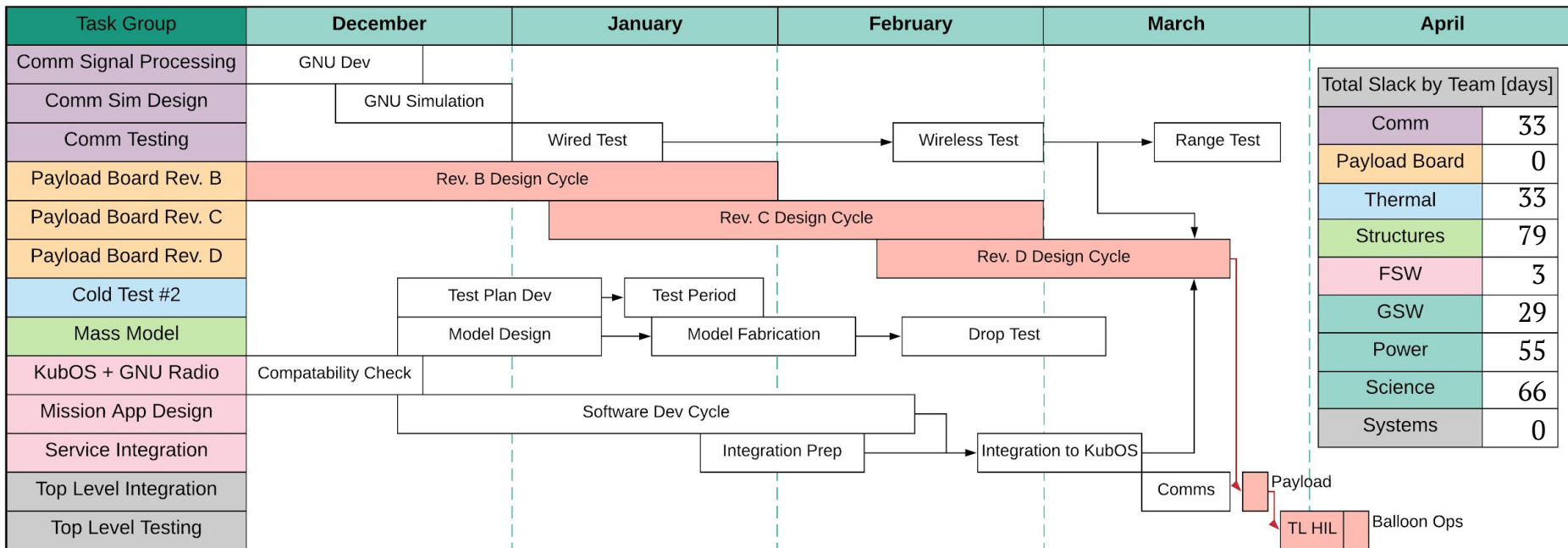
Organizational Chart



Work Breakdown Structure



Condensed Work Plan



Assumed Start: Dec 2nd

Targeted End (All requirements validated): April 2nd

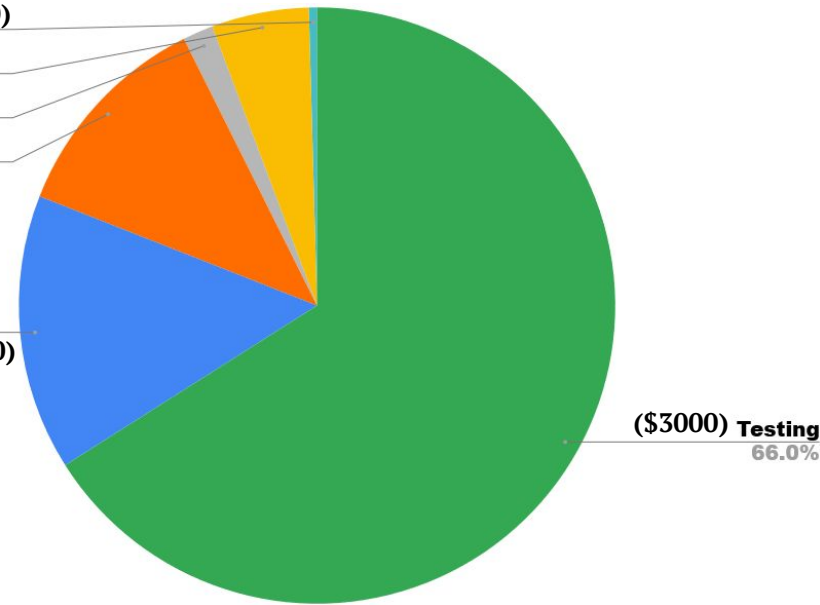
[Link to Full Work Plan](#)

Cost Plan

Team	Cost
Comms	\$530
Payload Board	\$860
Thermal	\$75
Power	\$240
Structures	\$20
Testing	\$3000
TOTAL	\$4,545

Structures (\$20)
 0.4%
Power (\$240)
 5.3%
Thermal (\$75)
 1.7%
Comms (\$530)
 11.7%

Payload Board (\$860)
 15.0%



Unconfirmed Funding Sources:

- EEF: \$2,754.30
- Raytheon: \$3,000

Payload Board: \$860

- MCU (BBB)
- Custom PCB
- MCU Hardware
- IMU

Comms: \$530

- SDR
- SMA Cables
- Antennae
- LNA

Thermal: \$75

- Coolers
- Dry Ice
- Variety of Thermal Insulators

Power: \$240

- Li-Ion Battery
- Charger
- Prototype Fee
- Buck-Boost Converter

Structures: \$20

- PLA Plastic Spool

Testing: \$3000

- ThinSat Bus
- FlatSat
- NSL Balloon Launch

Thinsat Operational Management of Commands And Telemetry

Questions?



Backup Slides

Main CDR Table of Contents

Project Objectives	Risk Analysis
CONOPS	Full system V&V
FBD	Comm V&V
Data Flow	Test Plan
CAD Model	Organizational Chart
Budgets	Work Breakdown structure
Critical Project Elements	Condensed Work Plan
Requirement Satisfaction Overview	Cost Plan
Comm Hardware Requirements	
Comm Software Requirements	
Payload Board Requirements	

Backup Table of Contents

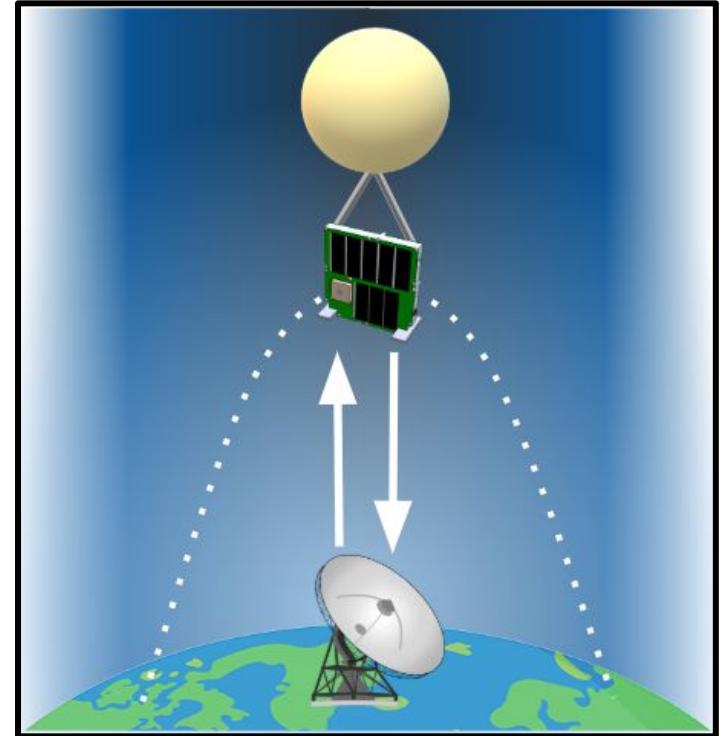
Subsystem List	Comm Backup	Thermal V&V
Size Budget CAD	Full Link Budget	Structures Overview
Detailed software diagram	Payload Board Backup	Structures V&V
Comm FBD	PCB Schematics	Science Overview
Payload Board FBD	Flight Software Overview	Science V&V
Flight Software FBD	Flight Software V&V	Critical Path Analysis
Ground Software FBD	Ground Software Overview	Full Work Plan
Project Requirements	Ground Software V&V	Pathway to Space
Full Mass Budget	Power Overview	Heritage Balloon Flight Data
Full Power Budget	Power V&V	Acronyms
Balloon Launch Options	Thermal Mitigations	References
Logistical Risks	Thermal Overview	

Systems

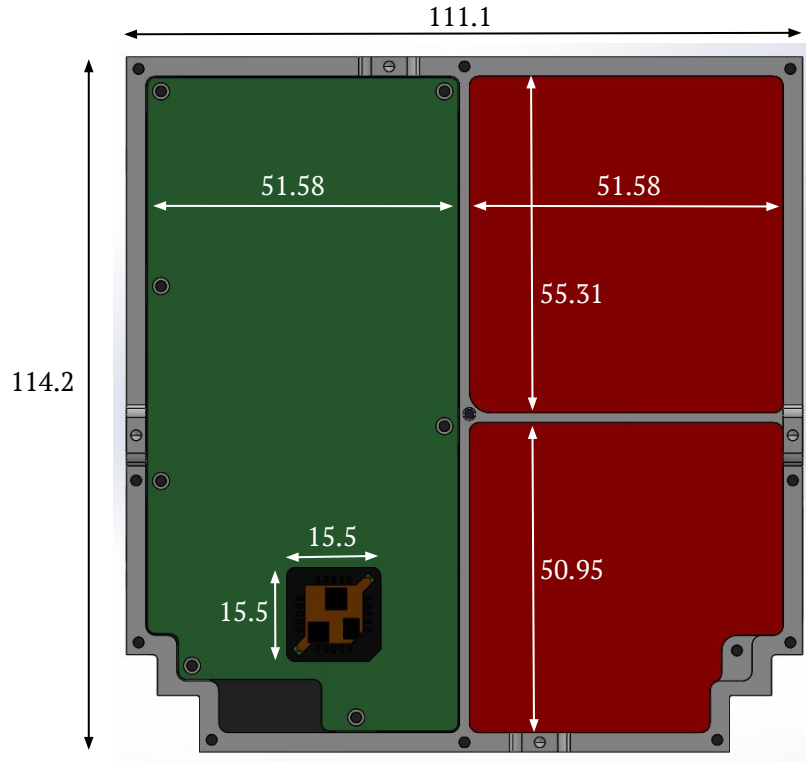
Backup Slides

Project Objectives

- **Primary Objective:** Design a Small Communications Satellite
- **Satellite Subsystems:**
 - Communications Hardware & Software
 - Command and Data Handling/Flight Software
 - Ground Software
 - Electronics / On-Board Computer
 - Power
 - Thermal
 - Structures
 - Data Creation/Science



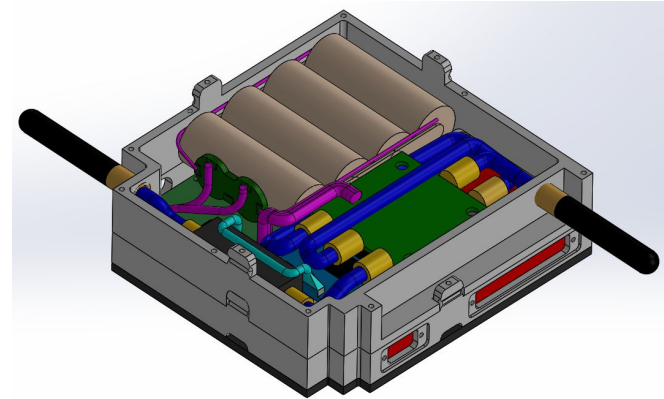
Size Budget (Bottom Slice)



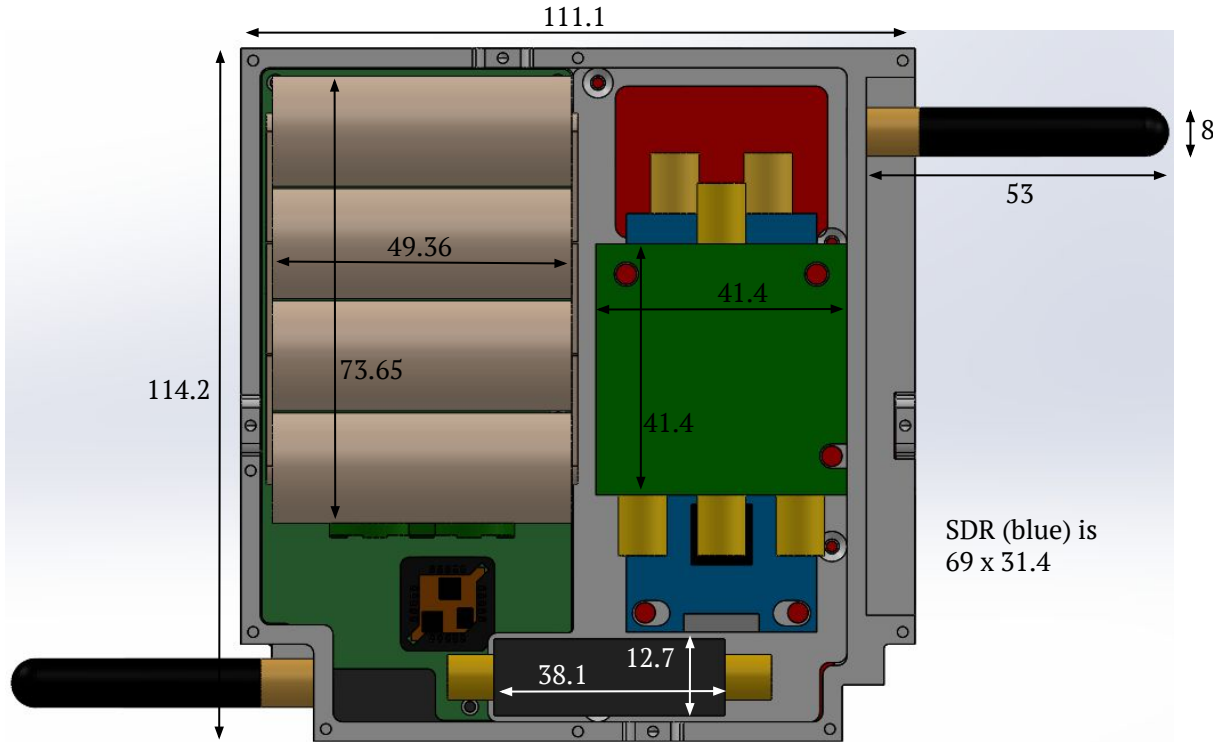
All dimensions are in millimeters

Components:

- Frame
- Bus
- Payload Board
- Wires



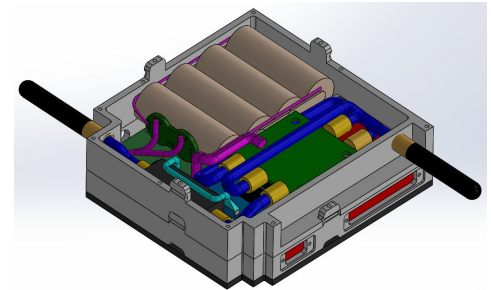
Size Budget (Top Slice)



All dimensions are in millimeters

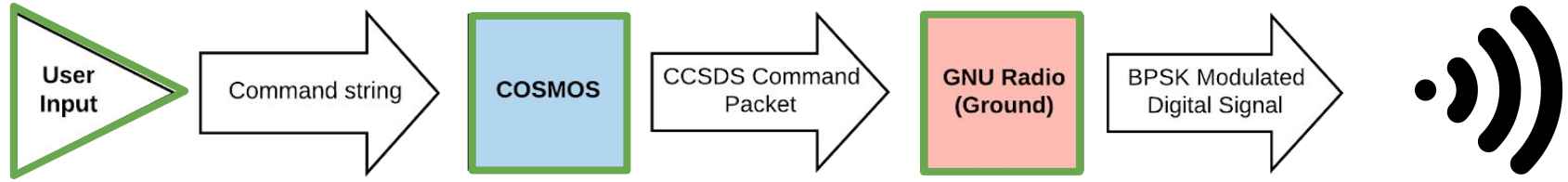
Components:

- Frame
- Radio
- Signal Filter
- Antennae
- Battery
- Wires

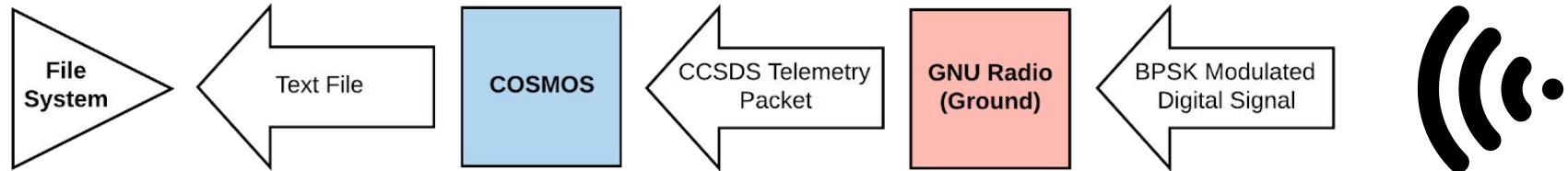


Detailed Ground System Data Flow

Uplink: 128 bps

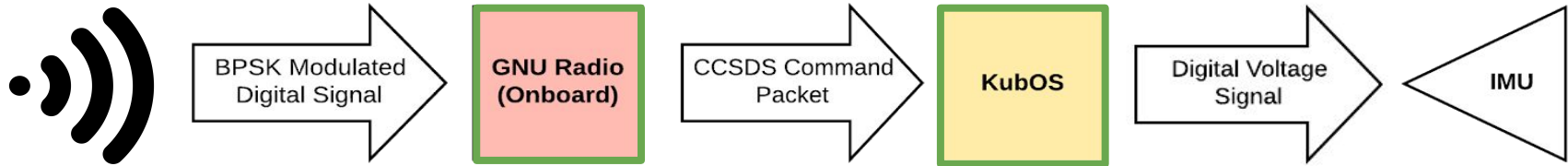


Downlink: 72 kbps

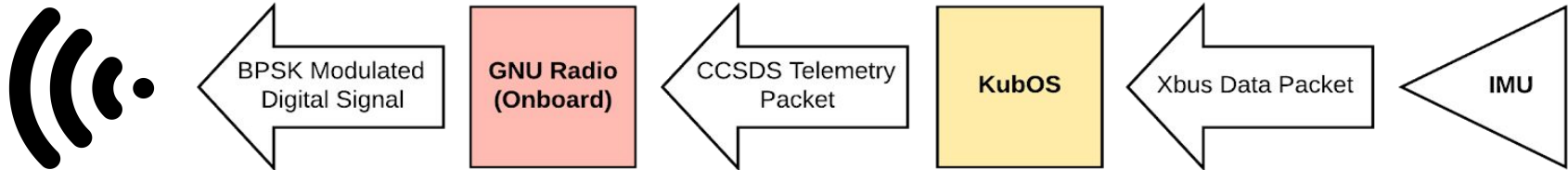


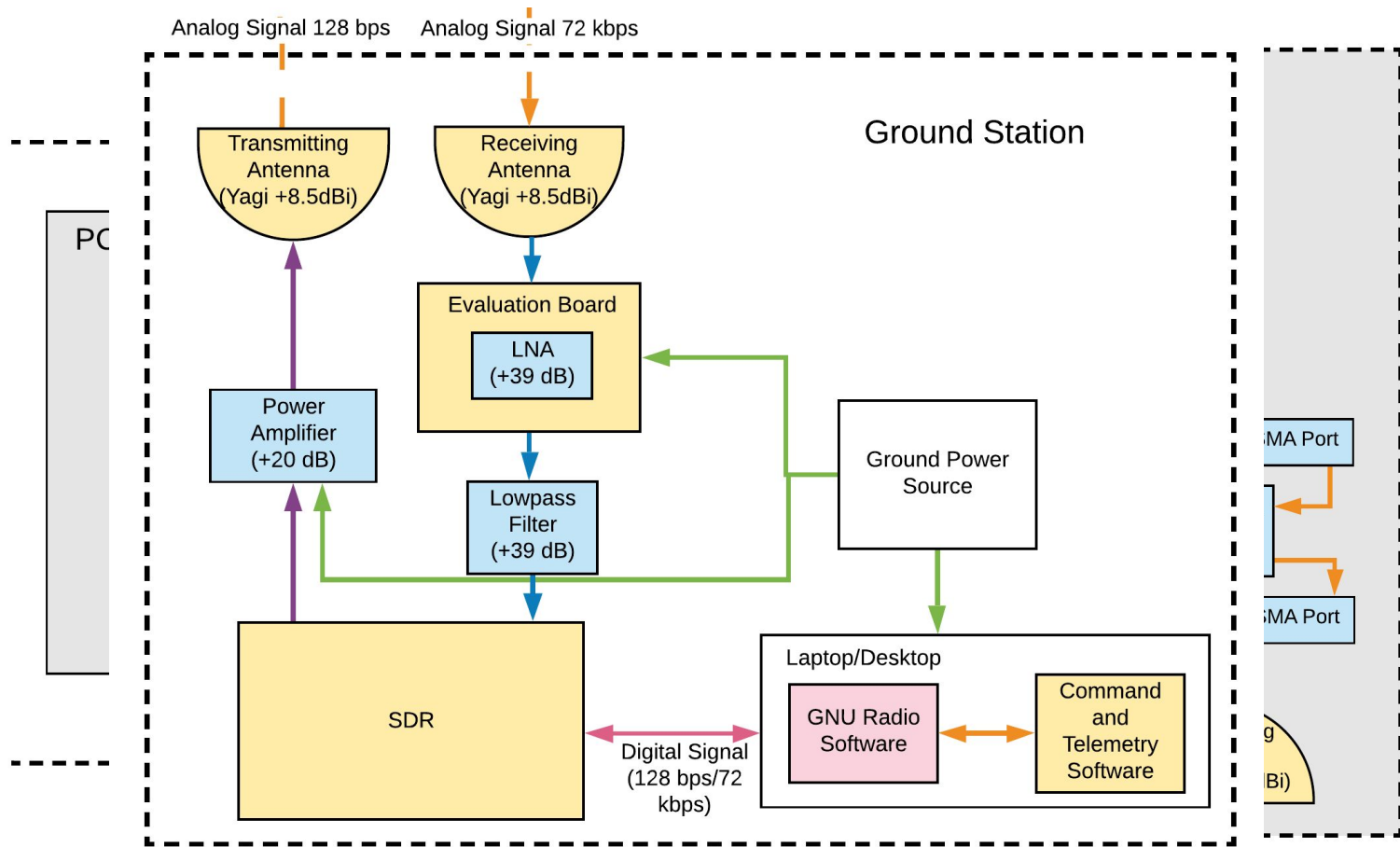
Detailed Onboard System Data Flow

Uplink: 128 bps



Downlink: 72 kbps

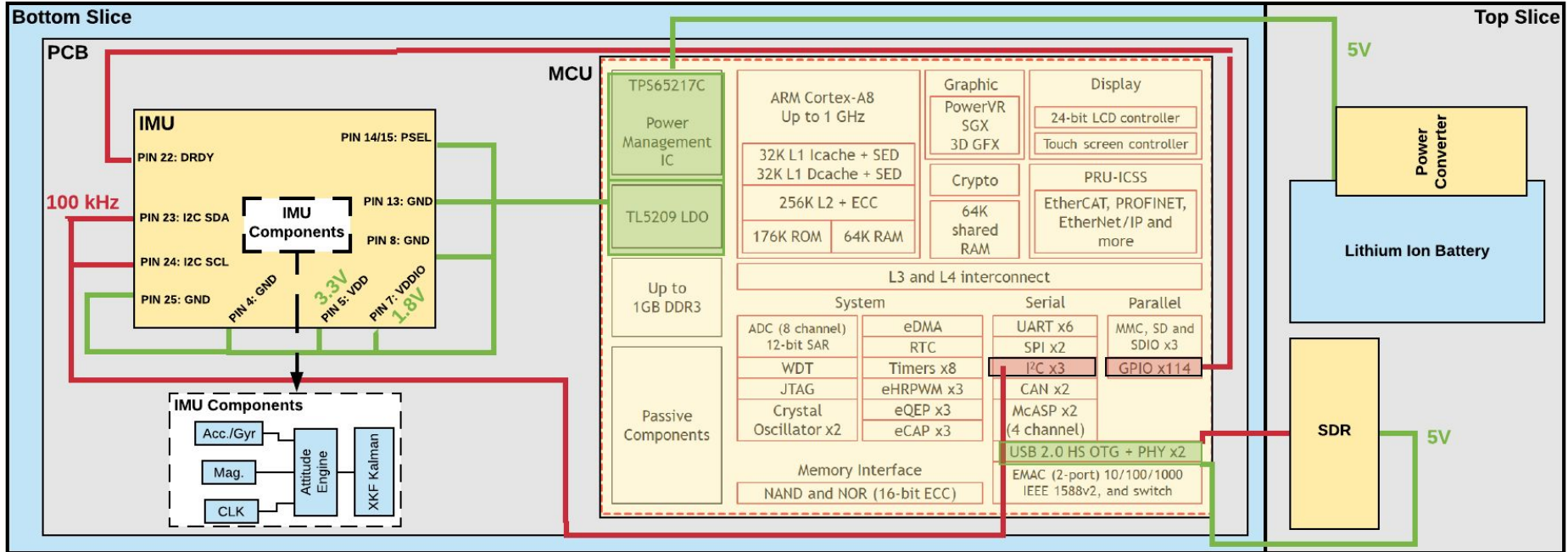




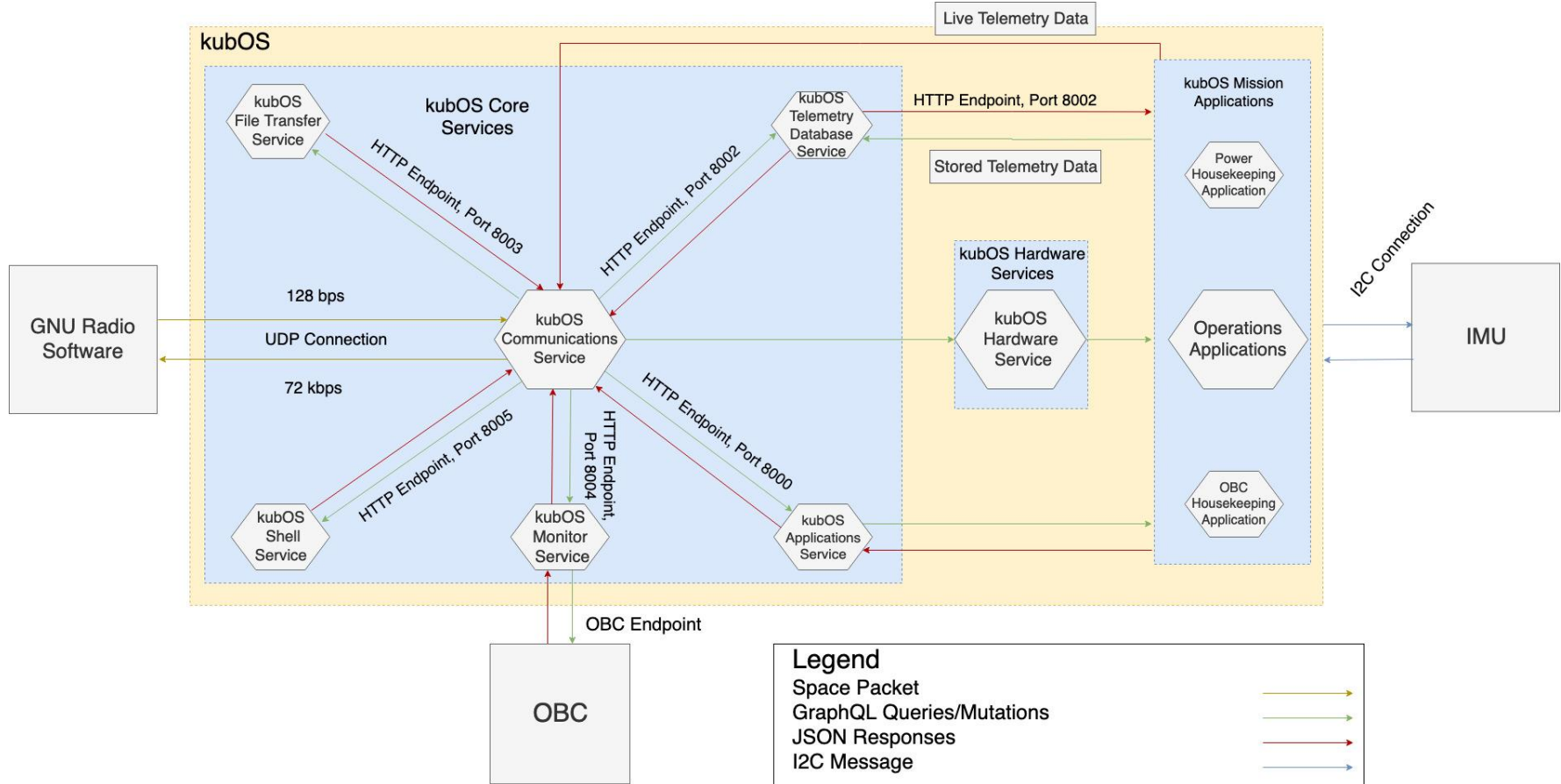
2 kbps

Payload Board FBD

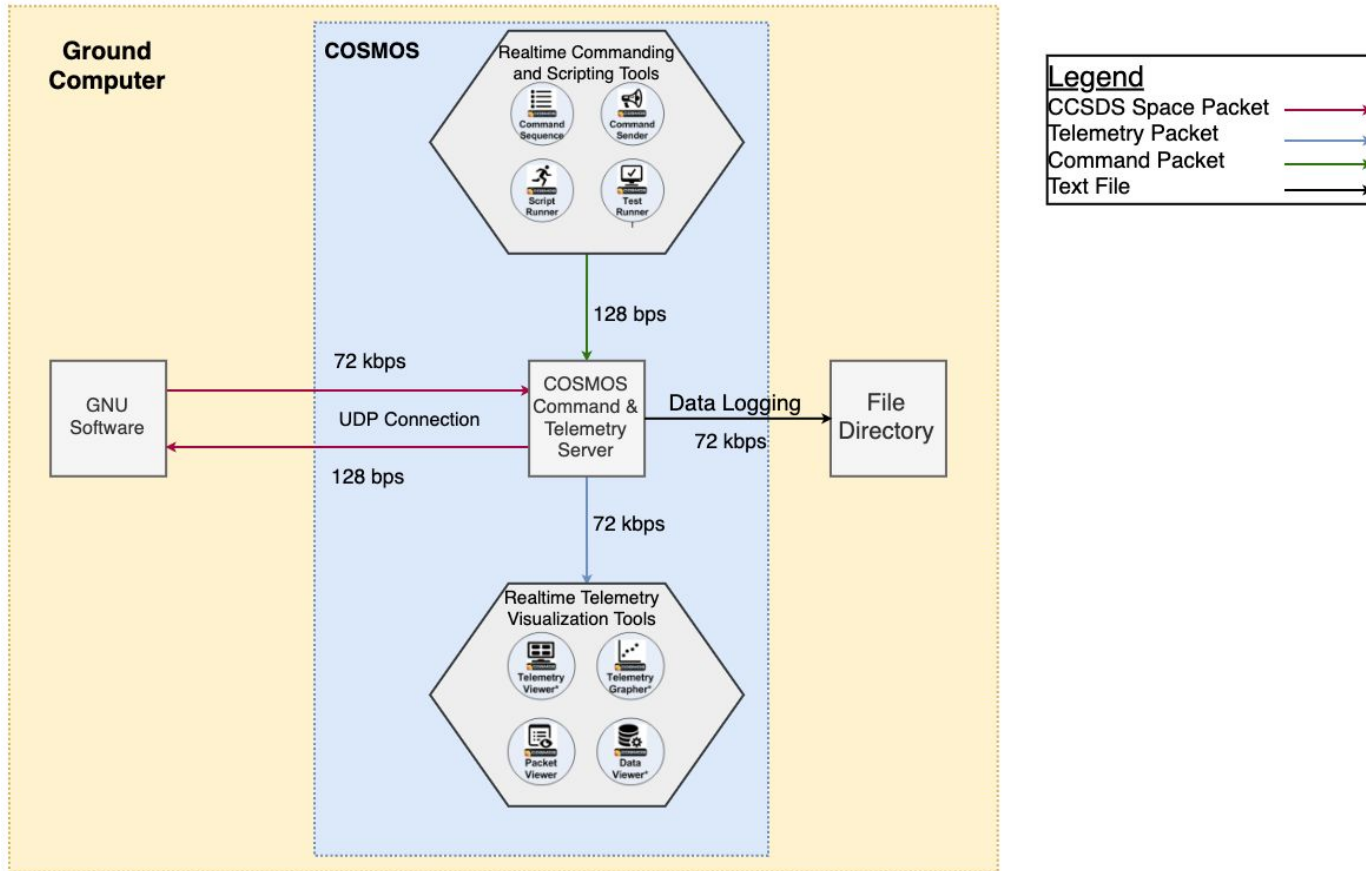
PAYLOAD BOARD FUNCTIONAL BLOCK DIAGRAM



Flight Software FBD



Ground Software FBD



Requirements (1/5)

#	##	###	Requirement	Motivation	Validation
1			The payload shall interface with the bus according to the Thinsat Interface Control Document (ICD)	Customer has mandated the use of the ThinSat bus	System Demonstration
	1.1		The designed payload board shall fit within the ThinSat payload area as defined by the ICD	Customer has mandated that the SDR, comms hardware, and power system do not need to be in the payload area, but the other hardware components will	The components fit into the ThinSat bus
		1.1.1	A 0.25 mm tolerance shall be used when designing parts to fit within the ThinSat bus area	Conform to ThinSat ICD	The components fit into the ThinSat bus
	1.2		The designed payload board shall have a mass less than 55 grams	Conform to ThinSat ICD	Inspection of mass
	1.3		The designed payload shall interface with the bus computer via the provided payload connector	Conform to ThinSat ICD	The payload computer will interface with the bus computer via a flatsat test
		1.3.1	The payload shall be designed with a DF12(3.0)-20DS-0.5V (86) receptacle	Conform to ThinSat ICD	The components fit together with the provided ThinSat bus port
	1.4		The designed payload shall conform to the 'prohibited items' list as provided in the ICD	Conform to ThinSat ICD	Inspection of data sheets to ensure no component explodes or outgasses during flight

Requirements (2/5)

#	##	###	Requirement	Motivation	Validation
2			The payload shall communicate with the ground system during the balloon flight	Customer has mandated that the ThinSat must be commanded and must send telemetry to the ground during the balloon flight	System Demonstration
	2.1		The payload SDR shall be compatible with the ground SDR	The SDRs must be compatible in order to transfer commands and telemetry	Bench test with SDRs communicating through serial connection
		2.1.1	The ground SDR shall send and receive formatted data bits to/from the payload SDR over a wired connection	The wired connection allows for early C&DH testing	Bench test with SDRs communicating through serial connection
	2.2		The payload SDR shall wirelessly communicate with the ground SDR at a range > 30km	Verify that wireless communication works in preparation for the balloon flight	Long range wireless communication test
		2.2.1	The ground SDR shall wirelessly send and receive formatted data bits to/from the payload SDR	The SDRs must be able to communicate at a distance for the ThinSat to be commandable on a balloon	Bench test with SDRs communicating through wireless connection
		2.2.2	The payload SDR shall wirelessly send and receive formatted data bits to/from the ground SDR	The SDRs must be able to communicate at a distance for the ThinSat to be commandable on a balloon	Bench test with SDRs communicating through wireless connection
	2.3		The SDR shall operate at in ISM frequency band	Payload must use a carrier frequency that complies with the FCC, which is easiest in the amateur bands	Datasheet verification
	2.4		The SDR shall have an uplink rate such that the payload can receive at least one command packet every 10 seconds	The payload must be commandable. Since the data rate can only be determined from a full link budget analysis, the exact data rate is not chosen here	Bench test with SDRs communicating through wireless connection
	2.5		The SDR shall have a downlink rate such that the ground SDR can receive one telemetry packet every 10 seconds	The ground must receive telemetry. Since the data rate can only be determined from a full link budget analysis, the exact data rate is not chosen here	Bench test with SDRs communicating through wireless connection

Requirements (3/5)

#	##	###	Requirement	Motivation	Validation
3			The payload shall survive and operate in the environment during all stages of the balloon flight	Team needs to deliver completed product to the customer at the conclusion of the project	System Demonstration
	3.1		The payload shall be able to withstand the temperature range of flight, which includes the coldest point in the flight (-56°C), and a hot day on the ground (38°C)	The payload must work during testing and flight	Turn-on test in a dry-ice cooled cooler, turn-on test in the lab
	3.2		The payload shall withstand the impact from a balloon launch (estimated 9 m/s from vendor)	The payload must still operate after the balloon flight	Drop test from height that mimics 9m/s, followed by a power on test
	3.3		The designed payload shall operate between near-vacuum conditions of peak flight (~0.01 atm) and standard atmospheric pressure	The payload must survive and be usable after flight	Datasheet verification
	3.4		The IMU shall generate rate telemetry during ascent and descent	Telemetry must be generated so that it can be sent to the ground to prove that the C&DH system works	Lab test with IMU moving while on
		3.4.1	Science data shall be able to be collected and updated at least once every second	The telemetry must update fast enough that a model with reasonable resolution can be created	Software test

Requirements (4/5)

#	##	###	Requirement	Motivation	Validation
4			The On Board Computer (OBC), SDR Software, and Flight Software (FSW) shall perform all necessary software tasks for the balloon flight	Each part of the payload must be controlled to ensure that all parts work together to take and send science data during the balloon flight	System Demonstration
	4.1		The payload shall be commandable	Overall goal of the project	Bench test
		4.1.1	The SDR software shall send all command packets it receives to the FSW	Received commands must go to the FSW for processing	Software test
		4.1.2	The FSW shall decode all commands received in CCSDS format	CCSDS format is mandated by the customer	Software test
		4.1.3	The FSW shall recognize errors in command formatting and return an error code	Formatting errors should be noted so that they can be fixed	Bench test with bad commands
		4.1.4	The FSW shall generate command counts for commands received in the correct format	Commands counts show that commands made it to the bus	Bench test with good commands
		4.1.5	The FSW shall generate command counts for commands with formatting errors	Command error counts show that commands made it to the bus, but that there was something wrong with them	Bench test with bad commands
		4.1.6	The FSW shall forward IMU commands to the IMU	Must be able to command the sensor suite	Bench test with sensor suite commands
	4.2		The payload shall generate telemetry	Overall goal of the project	Bench test, balloon flight
		4.2.1	The OBC shall receive raw telemetry from the IMU	The FSW should process the data that the sensor suite collects	Bench test
		4.2.2	The FSW shall packetize all (payload and health) telemetry in CCSDS format	CCSDS format is mandated by customer	Software test
		4.2.3	The FSW shall send packetized telemetry to the SDR software	Telemetry must be sent to the SDR for downlink	Software test
	4.3		The OBC shall store all telemetry during flight	Allows the team to validate downlinked data with stored data	Balloon flight
		4.3.1	The OBC shall store IMU telemetry	Science data can be validated	Software test
		4.3.2	The OBC shall store payload health and safety telemetry	Safety data can be validated	Software test
		4.3.3	The OBC shall store command counts	Payload receipt of commands can be validated	Software test

Requirements (5/5)

#	##	###	Requirement	Motivation	Validation
5			Administrative requirements	Capture requirements that are non-technical in nature but still critical to the success of the project	Bookkeeping
	5.1		All purchased components must cost in total equal or less than the amount provided by the Aerospace Engineering Sciences department and other engineering funds obtained by the team	The project cannot cost more money than the team is given	The total cost at the end does not exceed the allocated funds
	5.2		The project must be FAA/FCC compliant	The project must be allowed to legally perform the balloon flight	Necessary permissions are given and limitations are met
	5.3		Any software used or generated by the project team shall be compatible with typical computer operating systems	The software components of the project need to be easy to manipulate and use	Software documentation review

Engineering Budgets Overview

Mass Budget

- **Requirement:** < 800g for balloon flight
- **Major Mass Contributors:**
 - Payload Board
 - Battery
 - Frame

Total Mass	569g
25% Margin	142.25g
Total Mass with Margin	711.25g < 800

Power Budget

- **Requirement:** Power 2 hr balloon flight
- **Major Energy Contributors:**
 - Payload Board
 - Radio
 - Amplifier

Total System Power	7.96 W
Total Energy (2 hrs)	15.91 Wh
50% Built-in Capacity	7.96 Wh
Total Energy with Margin	23.87 Wh

Takeaway:

Provide a top level overview of the mass and power budgets

Engineering Budgets Overview

Downlink Data Budget

- **Requirement:** Link Margin $\gg 0$ dB
- **Major Gain/Loss Contributors:**
 - Amplifier (+)
 - System Noise (-)
 - Antenna (+)

Total Pr/No	65.20 dB-Hz
Minimum required Pr/No	34.87 dB-Hz
Link Margin	30.32 dB-Hz $\gg 0$

Uplink Data Budget

- **Requirement:** Link Margin $\gg 0$ dB
- **Major Gain/Loss Contributors:**
 - Amplifier (+)
 - System Noise (-)
 - Antenna (+)

Total Pr/No	82.52 dB-Hz
Minimum required Pr/No	61.17 dB-Hz
Link Margin	19.33 dB-Hz $\gg 0$

Takeaway:

Provide a top level overview of the communication budgets

Full Mass Budget

Component	Mass (g)
ThinSat Frame (Provided)	98
IMU	1
PCB	100
External Frame	50
LimeSDR Mini	20
Hardware bandpass	10
Antennae (2)	40
LNA	1
SMA cables	20
Battery	179
Mounting Structure	50
Factor of Safety (25%?)	142.25
Total Mass	569
Total Mass with FOS	711.25
Mass remaining from 800g	88.75

Full Power Budget

- **Powered Components:** IMU, SDR, LNA, Power Amp, MCU
- **Required Voltage Outputs:** 5V, 3V

Component	Voltage [V]	Current [A]	Power [W]	Energy (2 hr) [Wh]
IMU	3	0.015 A	.045 W	.09 Wh
SDR	5	0.9 A	4.5 W	9.0 Wh
LNA	5	0.152 A	.76 W	1.52 Wh
Power Amp	3	.05 A	.15 W	.3 Wh
MCU	5	.5 A	2.5 W	5 Wh
Total:	-	1.62 A	7.96 W	15.91 Wh

- **Minimum Battery Energy Required:** $15.91 \times 1.5 = 23.87 \text{ Wh}$
 - Assumes 2 hour max balloon flight based on legacy ThinSat data and Gateway to Space launch data, builds in 50% extra capacity for temperature and efficiency losses

Balloon Launch Options

Gateway to Space Launch



- **Logistics:** April 18th, mass < 800g, in Colorado
- **Advantages:** Not involved in balloon logistics, GoPros on all other payloads
- **Disadvantages:** Late in semester, quick turn-around for final report

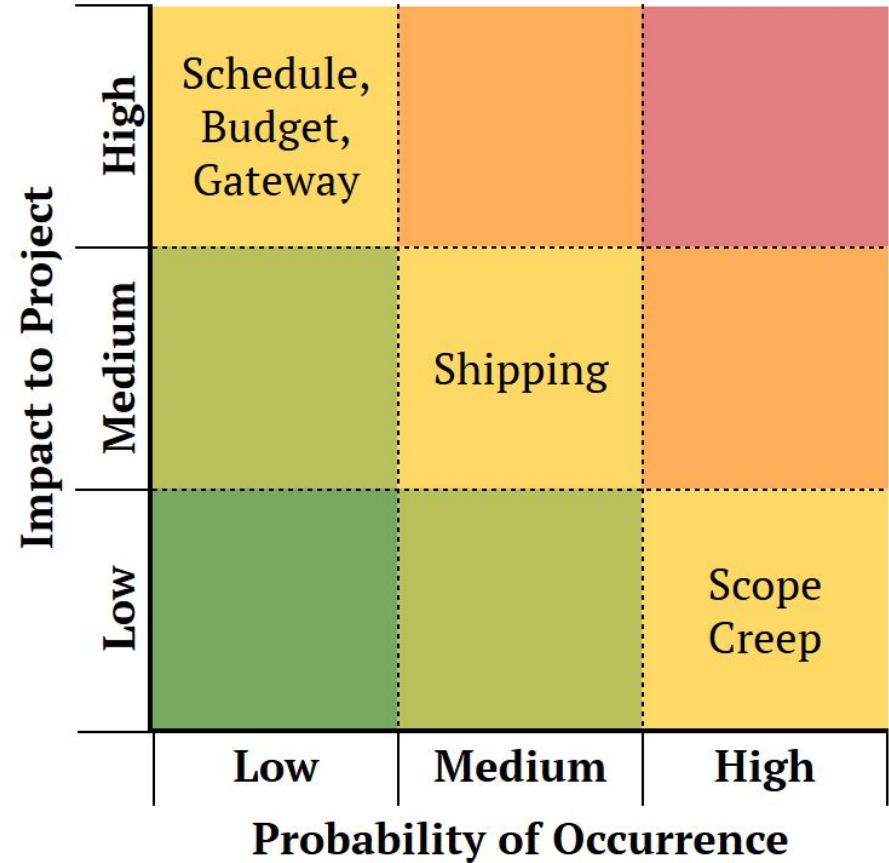
NearSpace Launch



- **Logistics:** Sometime in April, in Indiana
- **Advantages:** Not involved in balloon logistics, receive bus data after flight
- **Disadvantages:** Have to coordinate with other users, no set date, would require travel funds

Logistical Risks

Shorthand	Description
Shipping	Shipping times are longer than anticipated
Schedule	Planned schedule too fast for team members to complete
Scope Creep	Client requests additional functionality that is out-of-scope
Budget	Team budget not enough to satisfy project needs
Gateway	Team cannot meet requirements of Gateway to Space launch



Full List of Technical Risks

Technical Risks					
Subsystem	Risk Number	Shorthand	Description	Probability	Impact
Comm	T1	Drift	Balloon drift outside of ground antenna fov	Medium	Low
Comm	T2	Noise	Interference from other 900 mhz ISM band devices	Low	High
Comm	T3	ThermalR	Low temperatures leading to SDR failure	Low	Medium
Power	T4	Thermal	Low temperatures leading to battery failure	Medium	Medium
Power	T5	Power	Battery cannot supply power for the full 3 hours	Medium	Low
Payload Board	T6	Signal	Signal integrity is not preserved	Low	Medium
Payload Board	T7	Connect	Connectivity requirement is not met	Low	High
Payload Board	T8	Junk	Receiving faulty components	Low	Medium
Science	T9	ThermalS	Low temperatures leading to IMU failure	Medium	Low
Science	T10	Forces	IMU under mechanical stress, affecting sensor performance	Low	Low
Science	T11	Mount	IMU suffers connection loss to PCB	Low	Medium
Structure	T12	Impact	Structural failure from impact at the end of the balloon flight	Low	Low
Structure	T13	CAD	Components are unable to fit within the frame	Low	High
GSW	T14	Interface	Ground Software is unable to interface with hardware via a UDP connection	Low	Medium
FSW	T15	Reboot	Flight Software stops working during flight, if service tries to restart and not successful	Low	Medium
FSW	T16	Data	Not all data types are supported through I2C and UART	Low	Medium

Full List of Technical Risk Mitigations

Technical Risk Mitigations			
Subsystem	Risk Number	Shorthand	Description
Comm	TM1	Drift	Use an omni-directional antenna; Ensure yagi antenna beamwidth is wide enough such that manual pointing is sufficient
Comm	TM2	Noise	Ensure a sufficiently large link margin through analysis
Comm	TM3	ThermalR	Sufficient thermal testing and analysis prior to launch
Power	TM4	Thermal	Sufficient thermal testing and analysis prior to launch; Design with large factor of safety on the power budget
Power	TM5	Power	Design with a large factor of safety on the power budget
Payload Board	TM6	Signal	Use online tools, like those provided by TI, to check for signal integrity losses prior to manufacturing
Payload Board	TM7	Connect	Use online tools, like those provided by TI, to check for connectivity prior to manufacturing
Payload Board	TM8	Junk	Order early to allow for replacement shipments
Science	TM9	ThermalS	Sufficient thermal testing and analysis prior to launch
Science	TM10	Forces	Design IMU mount according to the mounting specification of the MTi Hardware Integration Manual, which include a section on reducing mechanical stress
Science	TM11	Mount	Design IMU mount according to the mounting specification of the MTi Hardware Integration Manual
Structure	TM12	Impact	Perform drop tests to increase confidence in existing impact analysis
Structure	TM13	CAD	Keep top level CAD model up to date and at a high fidelity to catch interference issues early in the design stage
GSW	TM14	Interface	Utilize existing documentation to confirm compatibility
FSW	TM15	Reboot	Test as many edge cases of the software on the ground as possible
FSW	TM16	Data	Study existing documentation for compatibility; Reach out to KubOS Slack group for specific help

Full List of Logistical Risk Mitigations

Logistical Risk Mitigations		
Risk Number	Shorthand	Description
LM1	Shipping	Order early to allow for longer ship times
LM2	Schedule	Continuously solicit feedback from team
LM3	Scope Creep	Explain the dangers of scope-creep and reject request
LM4	Budget	Track finances throughout the year; Apply for additional grants like EEF
LM5	Travel Funds	Work with Raytheon to discuss our system to they can support launch operations without the team
LM6	Gateway	Fall back on ground based testing to verify and validate the system

Communications

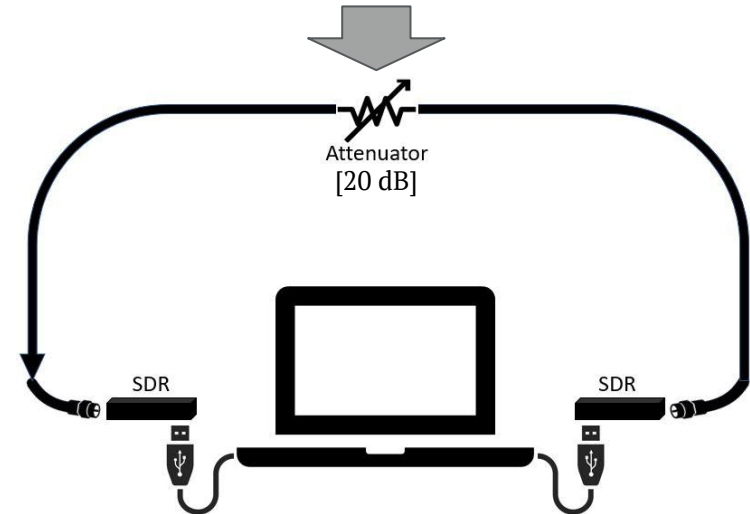
Backup Slides

Wired Testing — software verification

Objective	Verify GNU radio signal processing model by sending and receiving text file 1. Data transfer rate > 72 kbps
Plan	Vary: - File send rate (1-100 kbps) Measure: - Bit error rate
Materials	2 LimeSDR Minis 1 Laptop 1 SMA cable 1 20 dB Attenuator

Test Setup

Prevent over powering the receiving radio

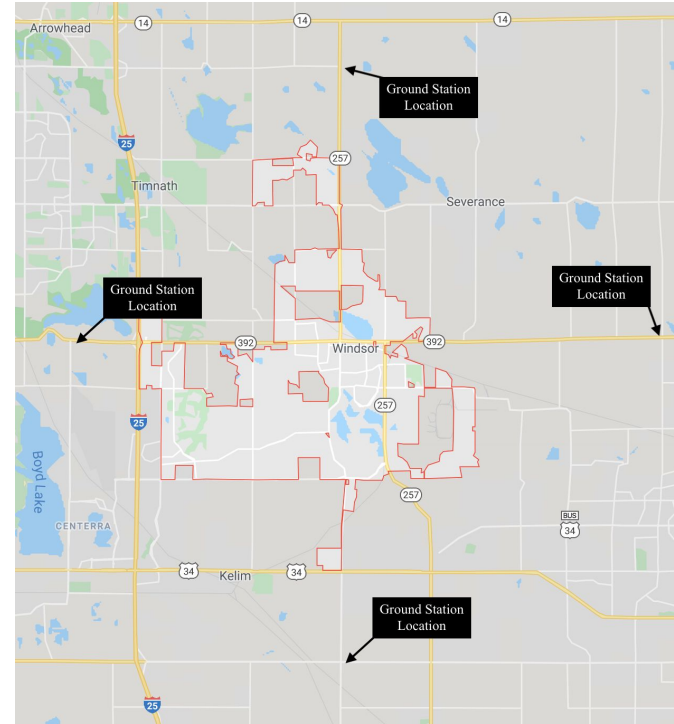


Takeaway:

Wired test allows us to verify our GNU radio signal processing design

Ground Station Location

- Launch Site: Windsor, CO
- Ground Station: 10 km downwind of launch
- Wind: Determined with help from launch professionals
- Station is easily moveable allowing “morning-of” placement



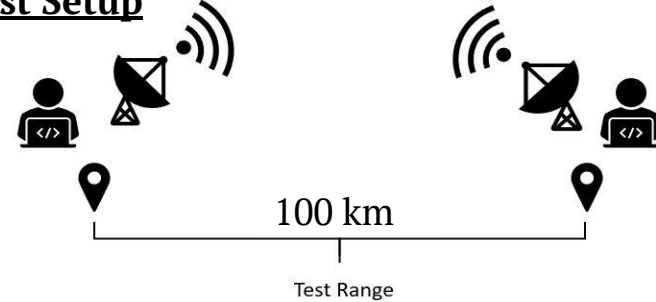
Primary Ground Station Location Options

Communications Verification 2/3

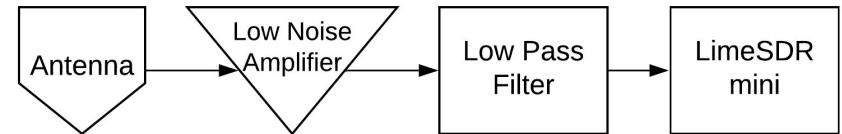
Wireless Testing — hardware verification

Objective	Verify RF Chain yields power above SDR sensitivity level 1. Data transfer rate > 72 kbps
Plan	Vary: - File send rate (1-100 kbps) Measure: - Bit error rate
Materials	2 LimeSDR Minis 2 Laptops 2 LNAs 2 Low Pass Filters 2 Power Amplifiers

Test Setup



RF Chain



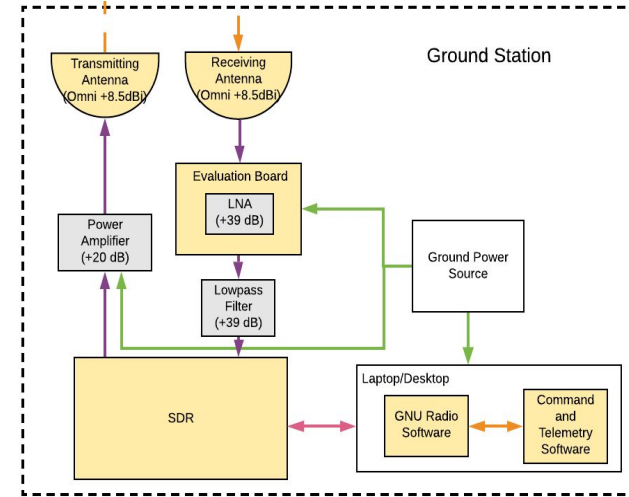
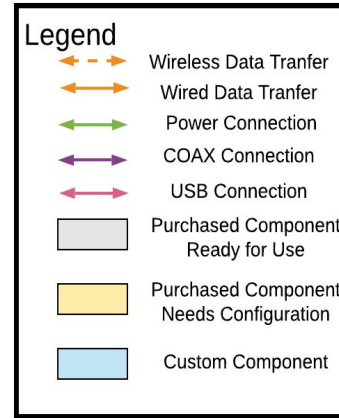
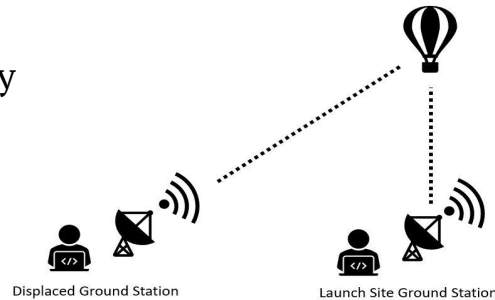
Takeaway:

Wireless test allows us to verify our RF chain over a short distance



Launch Site Ground Station

- Reasoning
 - Displaced ground station might not have line of sight to launch
 - Additional ground station at launch site allows constant contact with balloon
- No Difference from displaced ground station
 - Reduce design complexity
 - Reduce logistical complexity

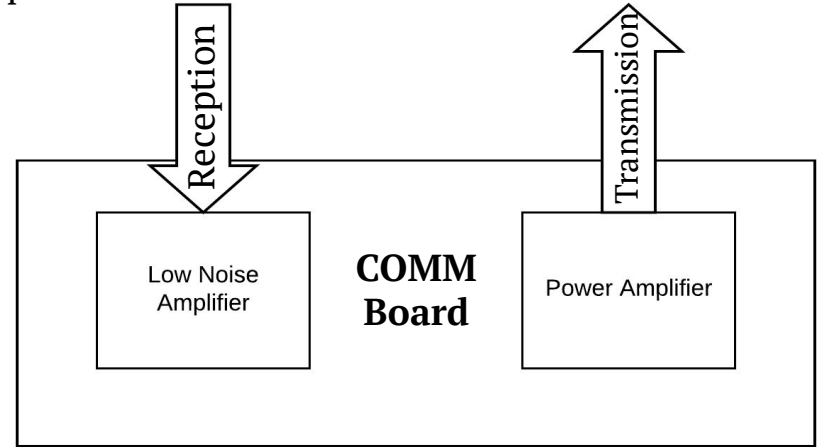


Takeaway:

A launch site ground station allows constant communication with the Thinsat from pre-launch through the flight.

Communications Board

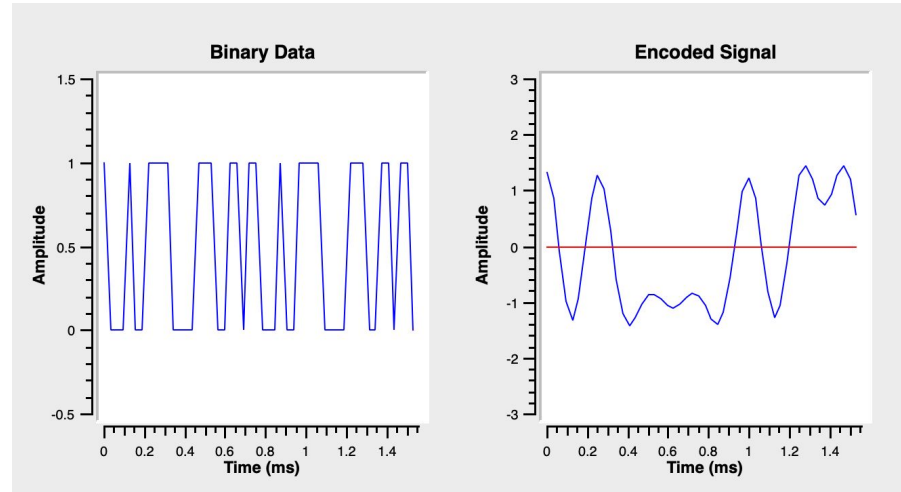
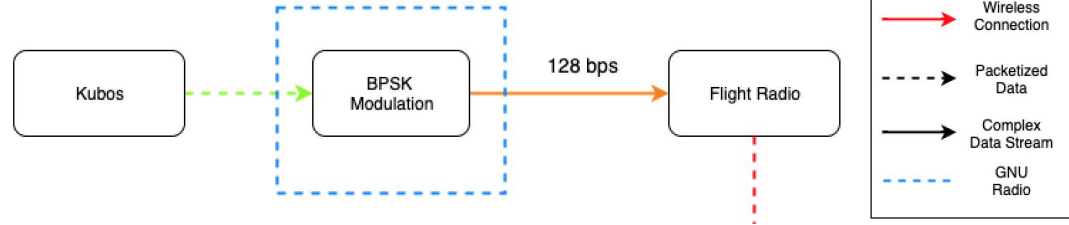
- Components
 - Low Noise Amplifier
 - Power Amplifier
- Save space and mass
 - Avoid multiple evaluation boards for different components
- Only onboard
 - Ground will use evaluation board
 - Not space or mass constrained



Comms Software Model: Transmission

BPSK Modulation

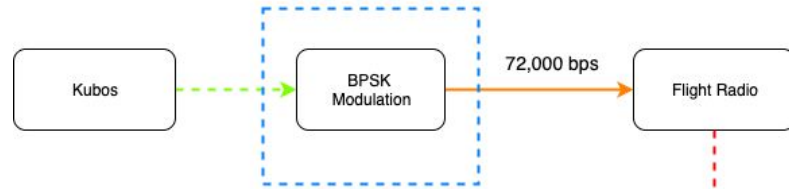
- Binary phase shift keying used to encode data
- Binary data encoded using two carrier wave phases
- Fulfills data rate requirement with low processing overhead



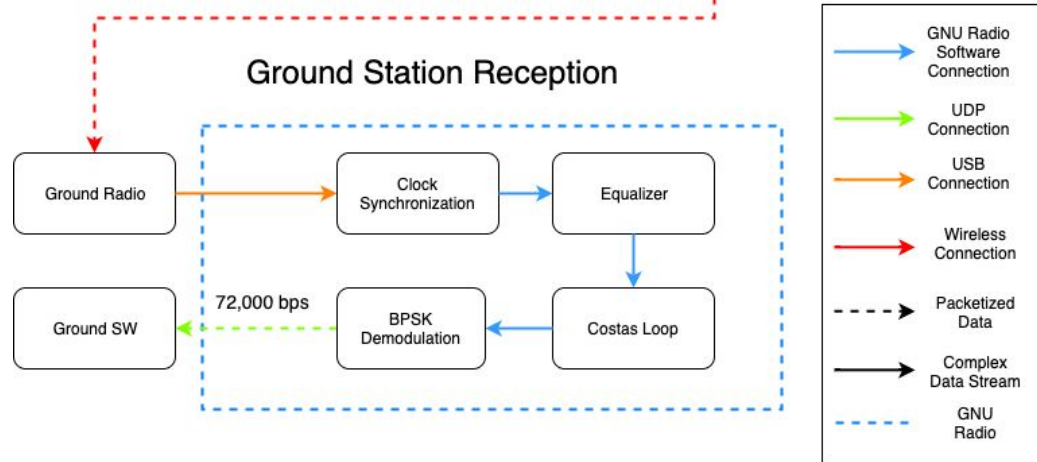
BPSK Modulation results from simulation

Full Signal Processing Path

On-Board Transmission



Ground Station Reception



Overview

- Perform signal processing
 - Convert digital signal from radio and pass data to FSW/GSW
 - Convert data from FSW/GSW to digital signal for radio
- Designed using GNUradio
- Analyzed through simulation

Full Link Budget

General Parameters

Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Frequency	0.915	0.915	GHz	ISM band
Wavelength	0.328	0.328	m	Function of chosen frequency
Range	104	104	km	Max altitude: 30 km; Max drift: 100 km

Full Link Budget

Data Parameters				
Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Bit error rate	10-6	10-5	[-]	Suggested values from SMAD
Modulation scheme	BPSK	BPSK	[-]	Same error rate as QPSK and faster processing
Required Eb/No	10.8	9.6	dB	Fig. 13.9 SMAD
Data rate	128	72,000	bps	2 commands per second uplink, full downlink of accelerometer data
Pr/No	31.87	58.17	dB-Hz	Function of Eb/No
Design Margin	3	3	dB	Suggested value from SMAD
Minimum Pr/No	34.87	61.17	dB-Hz	Pr/No plus the required design margin

Full Link Budget

Noise				
Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Receiver Antenna Noise Temperature	873.03	97.7	K	Uplink: Business Area, galactic, black body, Earth noise Downlink: Business area, galactic, black body noise
Receiver Cable Loss	0.5	0.5	dB	From cables used
Receiver Noise Figure	2.0	2.0	dB	LimeSDR Mini datasheet
Receiver Noise Factor	1.6	1.6	[-]	Computed from noise figure

Full Link Budget

Noise				
Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Receiver Noise Temperature	290	290	K	Computed from reference temperature and noise figure
Reference Temperature	290	290	K	Nominal reference temperature
Receiver System Noise Temperature	1098.73	323.40	K	Sum of antenna and receiver noise temperatures
Receiver System Noise Power	-198.19	-203.5	dBW-Hz	Logarithm of receiver system noise temperature and Boltzmann constant

Full Link Budget

Receiver Parameters

Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Receive Antenna Gain	2.2	8.50	dBi	Antenna datasheet
Receiver Cable Loss	0.5	0.5	dBi	Table 13-10 SMAD

Propagation Parameters

Space Loss	132.04	132.04	dB	Computed based on frequency and range
Atmospheric Attenuation	0.45	0.45	dB	Clean air value with no rain from SMAD
Polarization Loss	0.2	0.2	dB	Typical value from SMAD

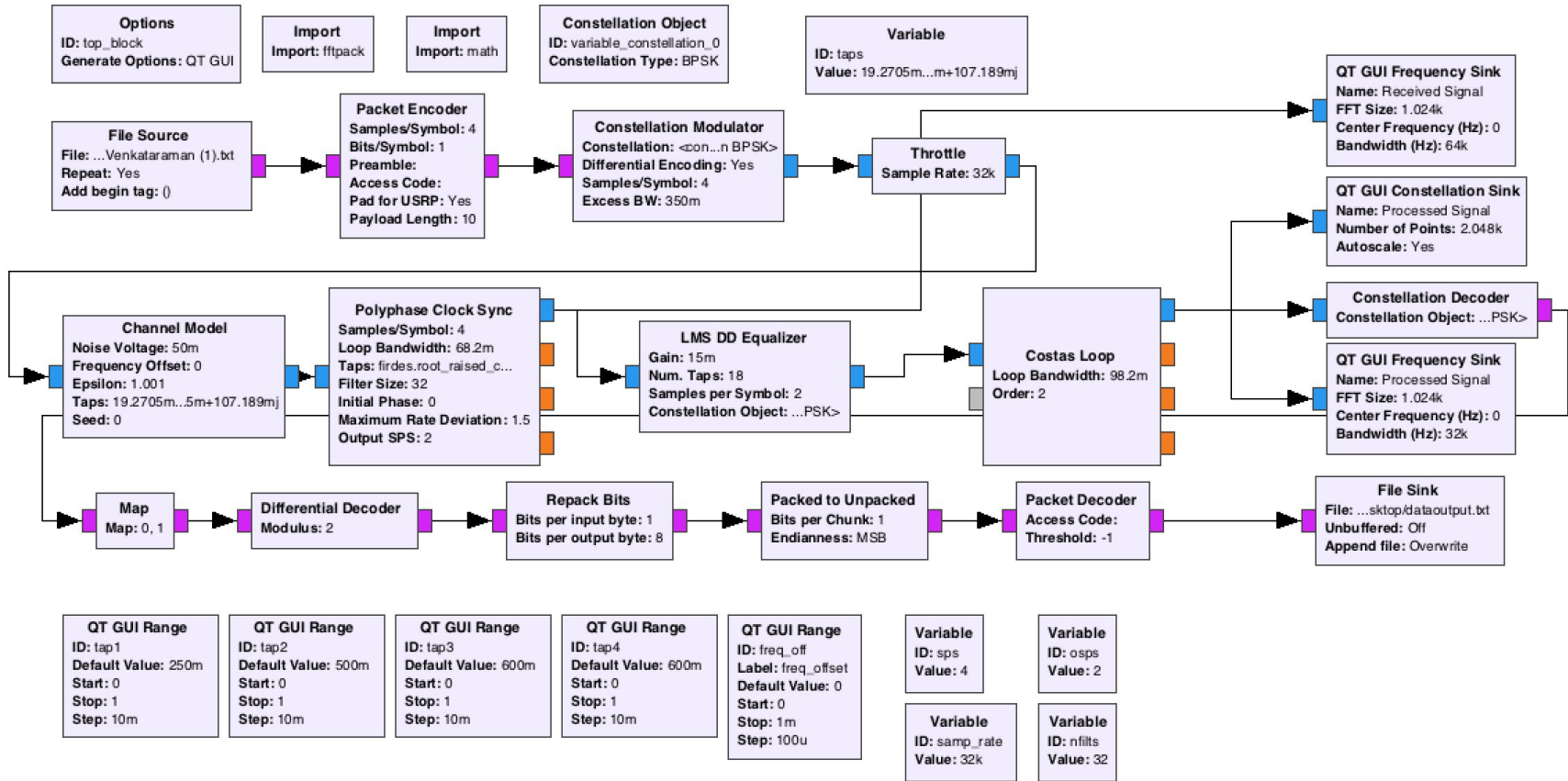
Full Link Budget

Transmitter Parameters				
Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Transmit Antenna Gain	8.5	2.2	dBi	Antenna datasheet
Line Loss	0.5	0.5	dBW	Computed from cables being used
Transmit Power	-10.0	0	dBW	Logarithm of power transmitted
Power Transmitted	0.1	1	W	LimeSDR Mini power plus power amp output
Effective Isotropic Radiated Power	-2.0	1.7	dBW	Sum of antenna gain, line loss, and transmit power

Full Link Budget

Summary				
Item	Uplink (command)	Downlink (telemetry)	Units	Justification
Effective Isotropic Radiated Power	-2.00	1.7	dBW	Sum of antenna gain, line loss, and transmit power
Propagation Loss	132.69	132.69	dB	Computed based on frequency and range
Receiver Gain	1.7	8.0	dBi	Antenna gain minus line loss
System Noise Power	198.19	203.5	dB-Hz	Logarithm of Receiver System Noise Temperature and Boltzmann constant
Pr/No	65.20	80.51	dB-Hz	Computed from EIRP, gains, and losses
Minimum Pr/No	34.87	61.17	dB-Hz	Required Pr/No plus design margin
Link Margin	30.32	19.33	dB-Hz	Difference between Pr/No and Minimum Pr/No

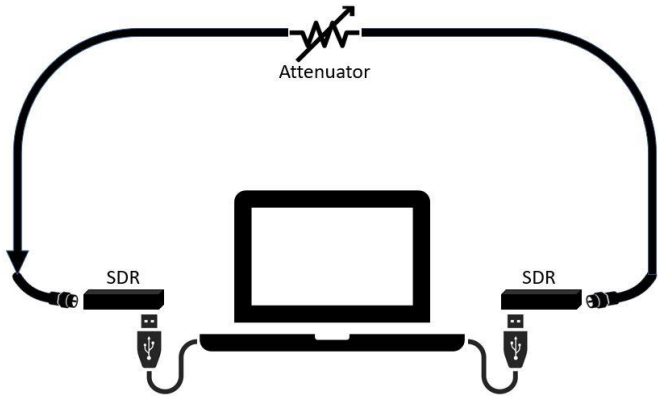
GNU Radio Block Diagram



Overview of Test Ranges

Wired Test

- Two SDRs connected by an SMA cable with attenuation
- Verify signal processing model



Wireless Test

- Wireless communication between two SDRs using flight-like RF chain at 100 meters
- Verify functionality of RF chain



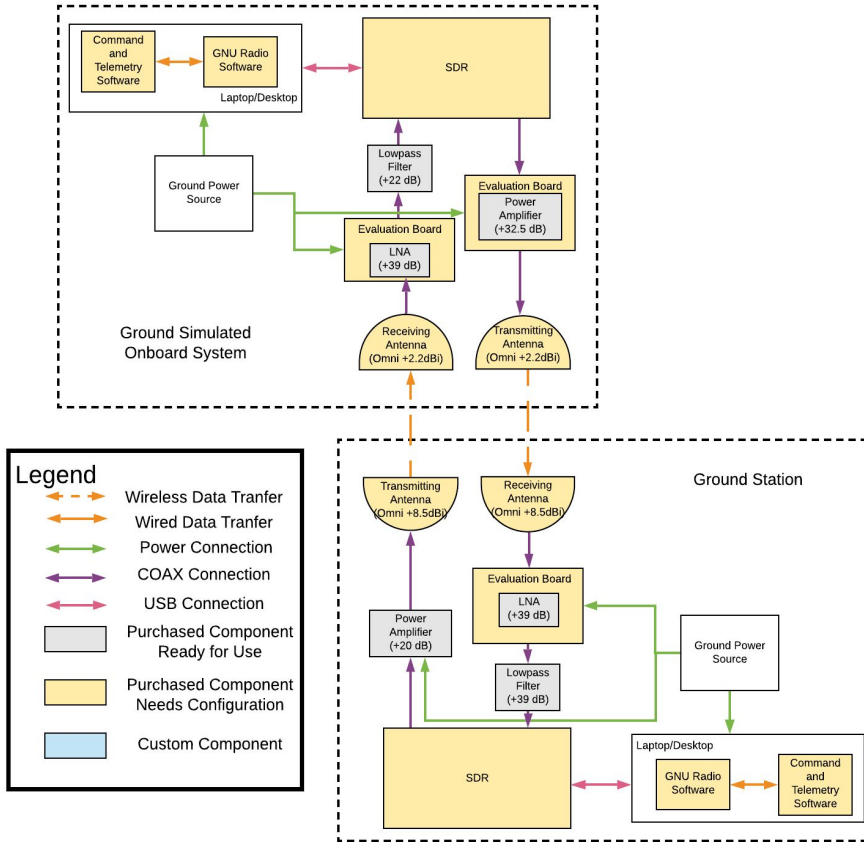
Test Range

Range Test

- Wireless communication between two SDRs using flight RF chain at 5 km
- Top of Chautauqua to Aerospace building
- Add attenuator to simulate longer distance test
- Verify link budget



Range Testing FBD



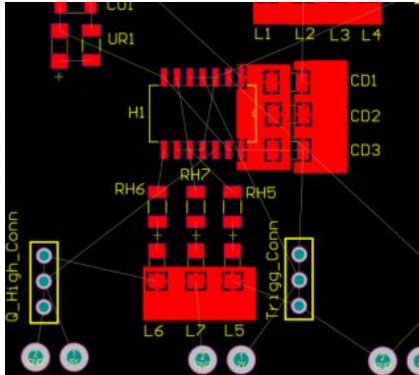
Payload Board

Backup Slides

Payload Board Design Objectives

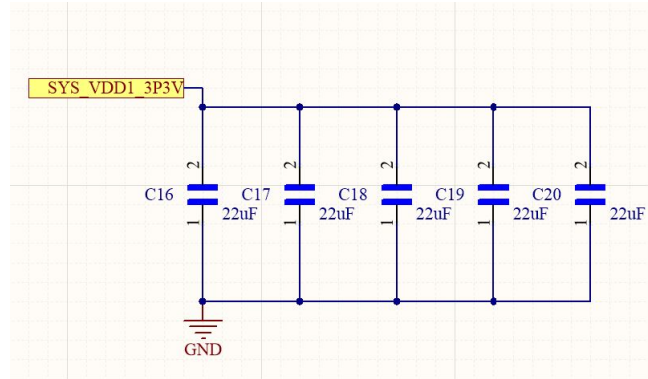
Connectivity:

- Everything that needs to be connected actually has a copper trace connecting it
 - Schematic built by referencing data sheets & other schematics
 - No ghost traces left on PCB layout



Performance:

- Signal Integrity
 - Mutual loop inductance
 - Decoupling capacitors
 - Power & ground planes
 - Short interconnects
- Use Altium to performance analysis tools



Relevant Risk: preservation of signal integrity

Payload Board Design Objectives

Relevant Objective:

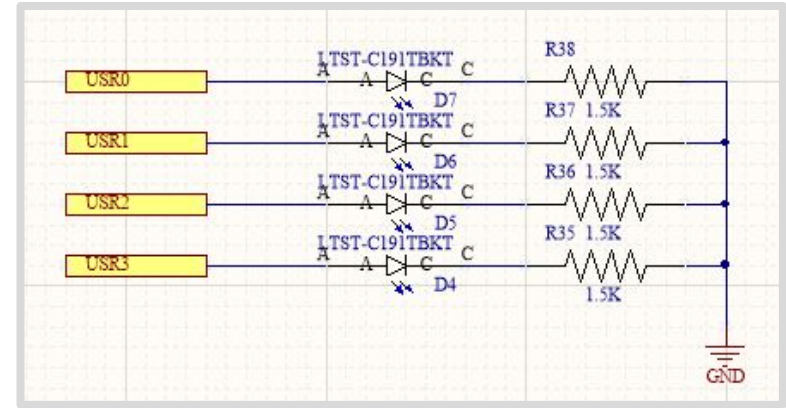
- Allow detection faulty components on board

To Meet Objective:

- Ensure ability to bring up, troubleshoot, and debug

Bring up, Troubleshoot, Debug:

- Indicator LEDs
- Probe points
- Isolation switches
- Debug connections



Indicator LEDs

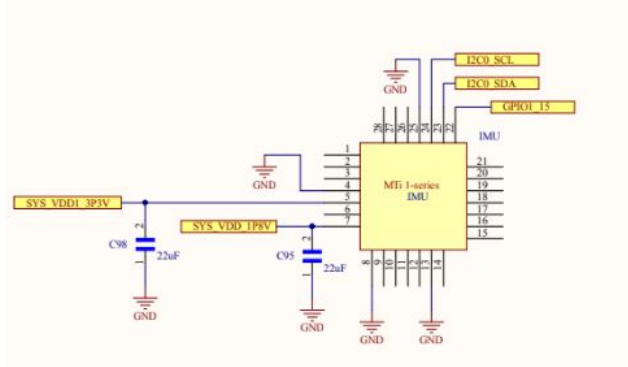
Takeaway:

The board is being designed for bring up and troubleshooting.

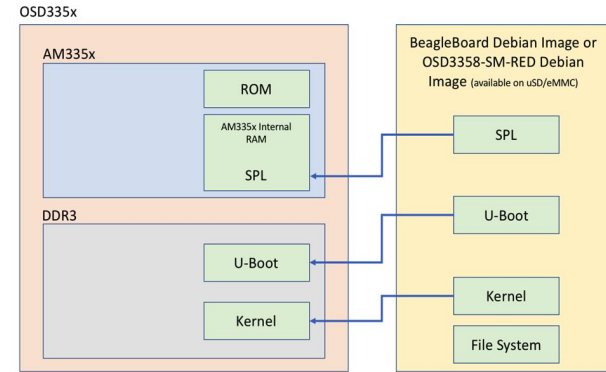
Payload Board V&V Overview

Payload Board Verification

- Flash the MCU with KubOS and send/receive data through I/O connections



IMU PCB schematic with required connections to MCU



Boot process memory usage

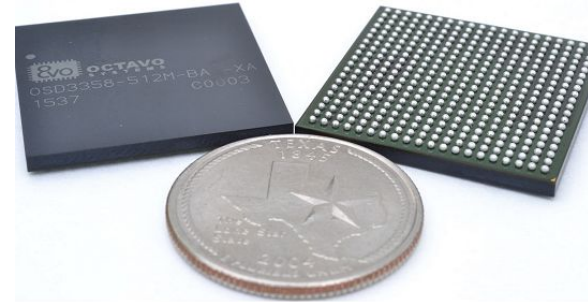
Payload Board Validation

- Successful KubOS boot-up and programmatic control of IMU and SDR

Payload Board Verification Plan

PCB bring up, troubleshoot, and debug

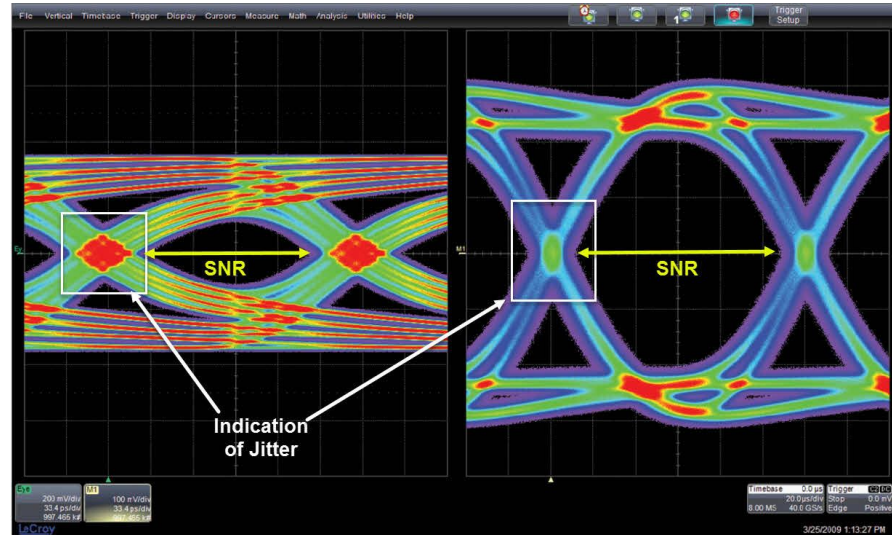
Objective	Flash the MCU with KubOS and send/receive data through I/O connections
Plan	Visually inspect payload board, solder remaining components to the board, use MCU bootloader to flash KubOS kernel
Materials	Surface mount devices (SMDs) soldering iron, hot air gun oscilloscope, digital multimeter
Pass Criteria	LED indicators, successful boot-up of KubOS, interaction with I/O devices programmatically



MCU Surface Mount Package

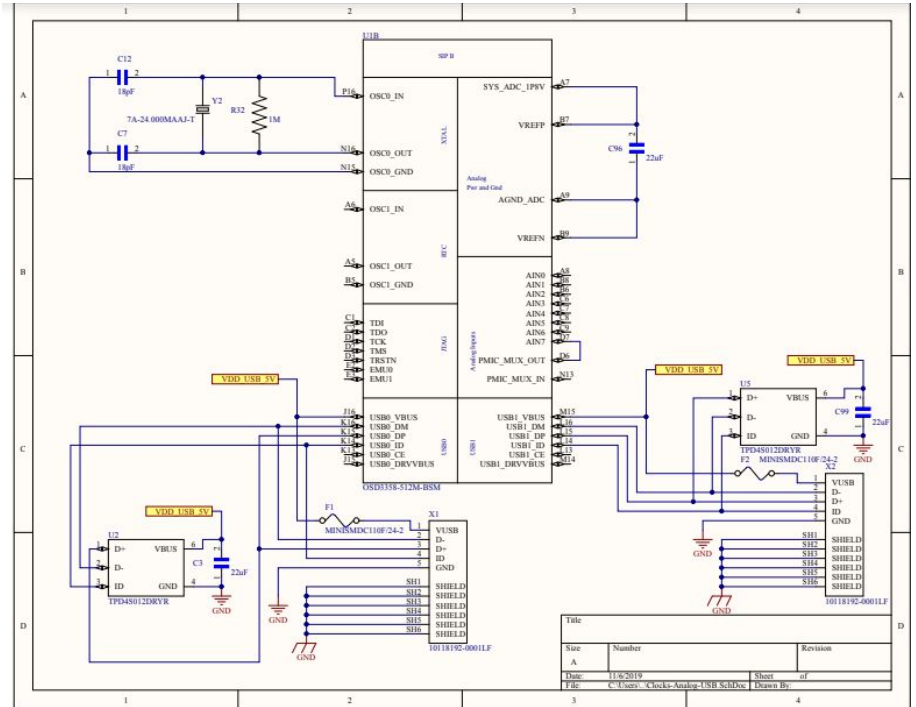
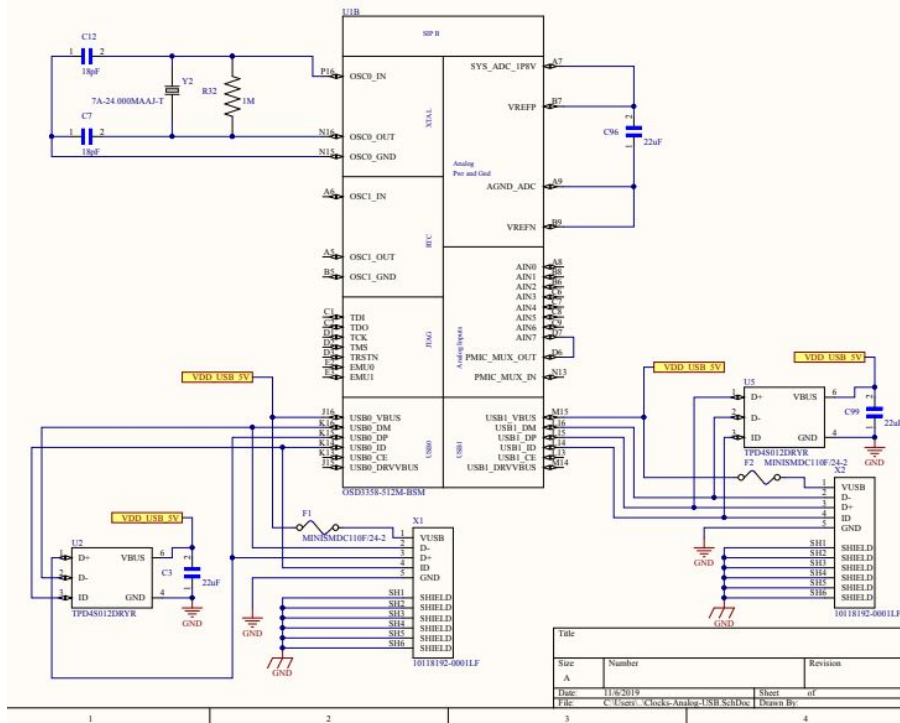
Payload Board Testing

- Observe indicator LEDs
- Probe test points
 - Power & Ground
 - 5V, 3.3V, 1.8V outputs
- Run test software
 - Test I2C connection with inertial measurement unit
- View eye diagram
 - Signal integrity

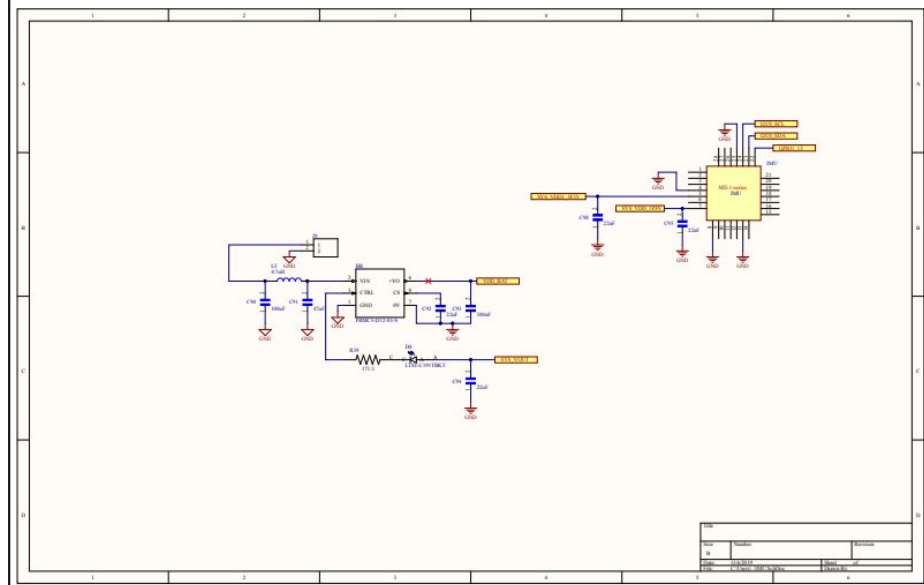
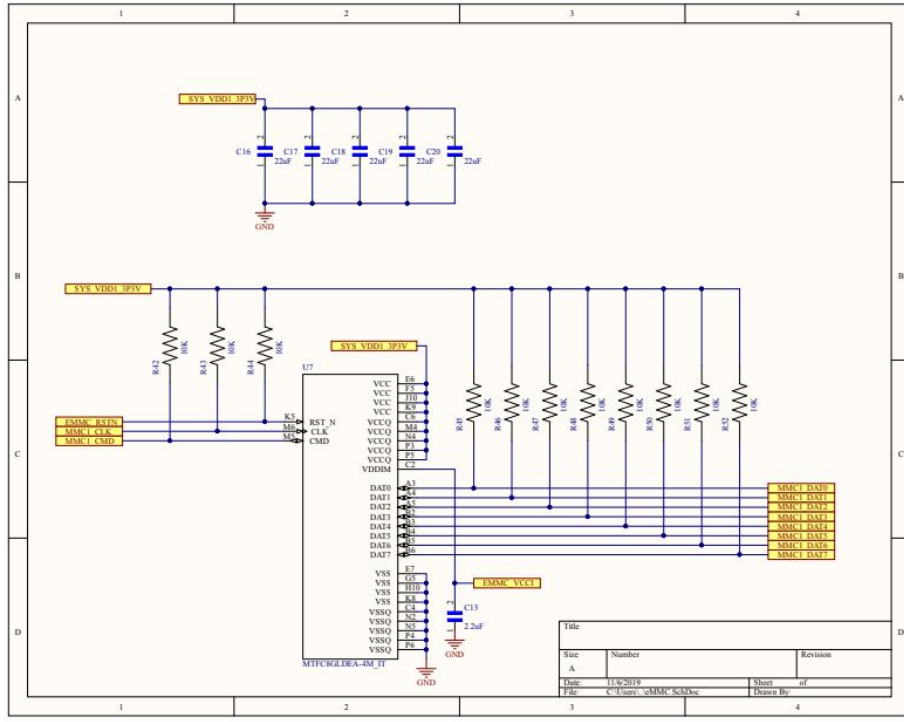


Eye diagram seen on oscilloscope

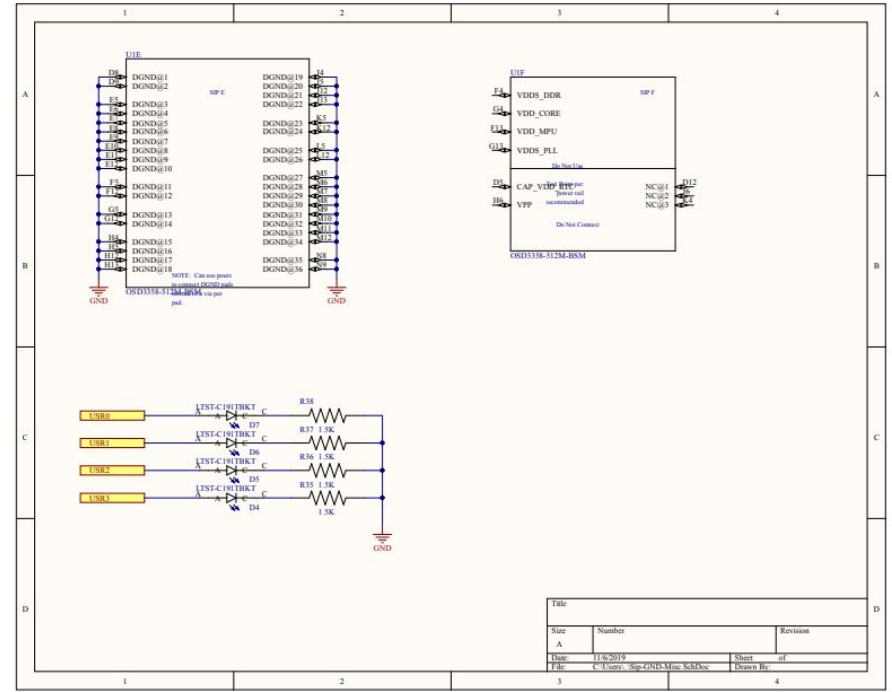
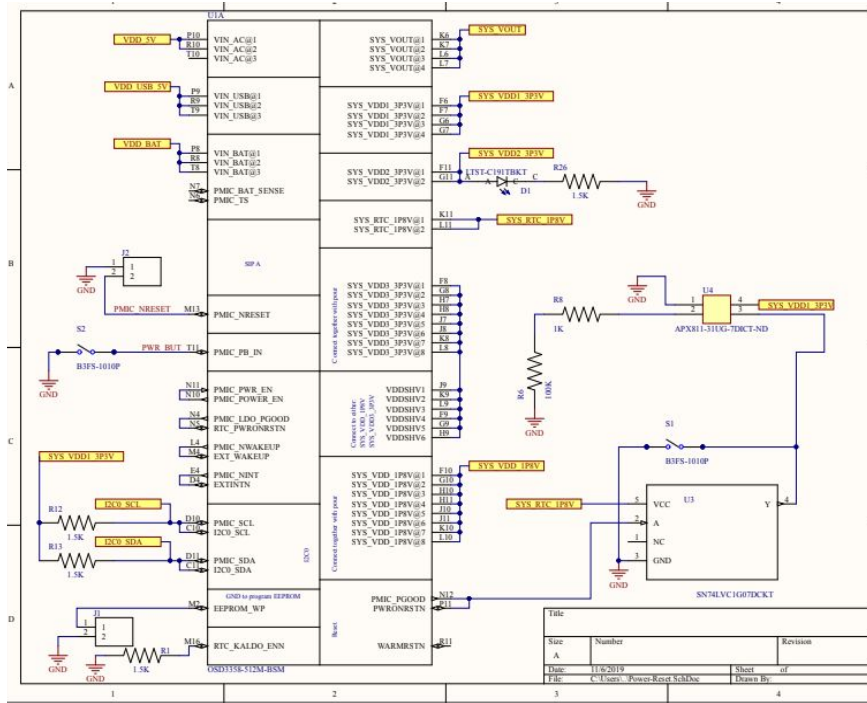
PCB Schematic



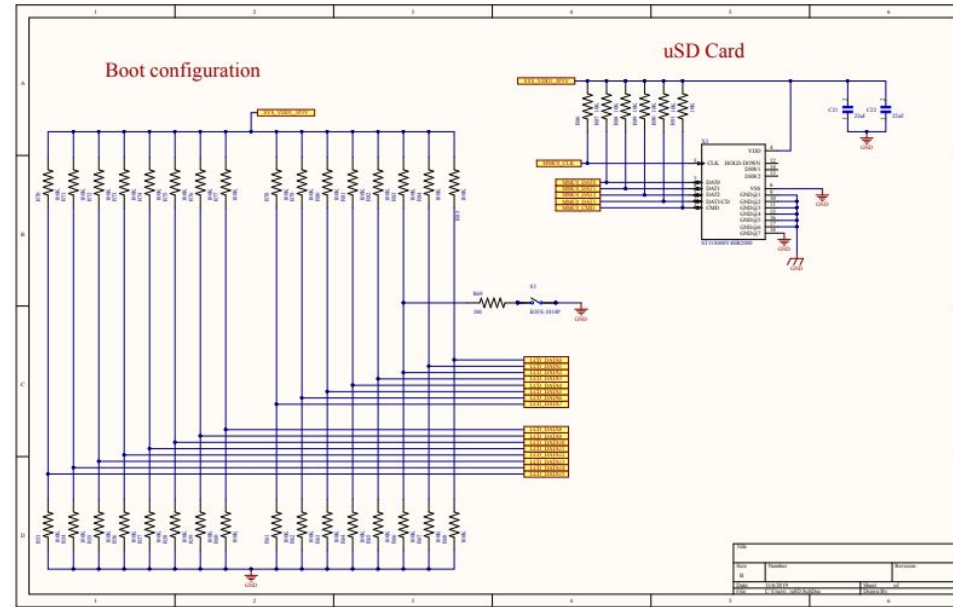
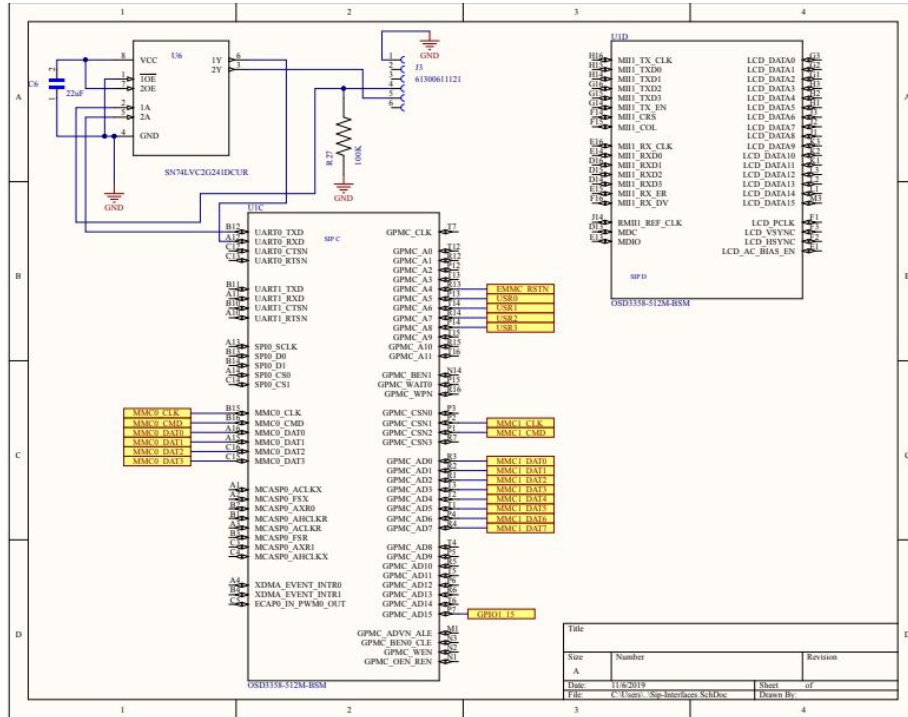
PCB Schematic



PCB Schematic



PCB Schematic



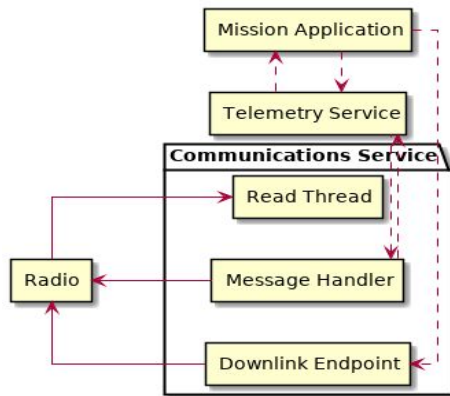
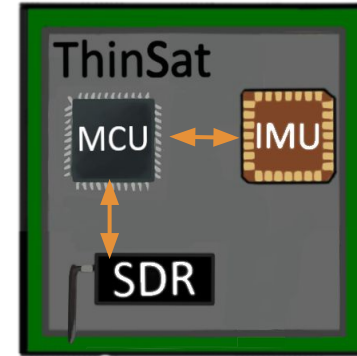
Flight Software

Backup Slides

FSW Requirements

Design Objectives:

- Runs on microcontroller
- Integrates inertial measurement unit and software defined radio
- Uses CCSDS protocol

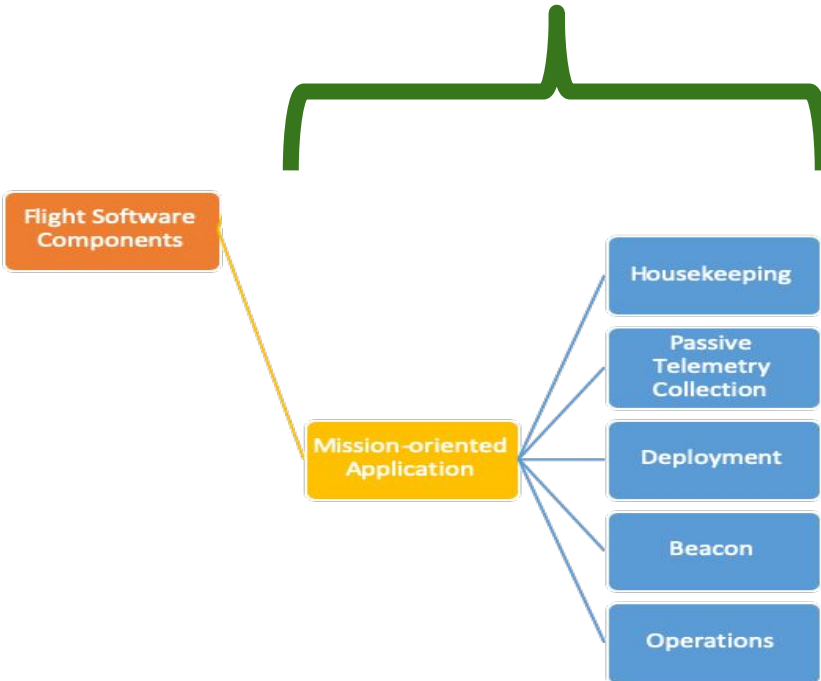


Pertinent Requirements:

FR 4: The Flight Software shall perform all necessary software tasks for system operation

FSW Analysis

TOMCAT Software Design



○ Built-in Services:

- No decision making
- Low level tasks

○ Design Mission Application:

- Operational instructions for mission
- Each application designed as isolated task
 - Easier to debug
- Integration/cross-communication through built-in services

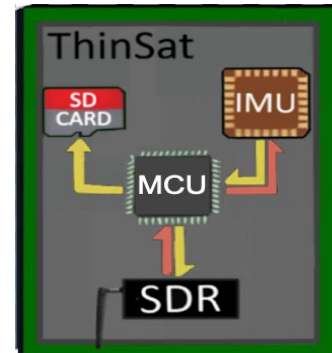
Mission Application

Required Mission Applications:

1. Housekeeping
 - a. OBC
 - b. Power
2. Passive telemetry collection
3. Deployment
4. Beacon (Health and Status)
5. Operations

Hardware interface abstractions/protocol for:

1. SDR (GNU Radio)
 - a. UDP
2. IMU (Science Sensor)
 - a. I2C



KubOS Services

Telemetry Database Service

Utilizes an SQLite database to:

1. Store telemetry data generated by the hardware
2. Retrieve data for transmission to ground station upon request.
3. Standard Schema

```
{
  "data": {
    "telemetry": [
      {
        "timestamp": 1570161541.462335,
        "subsystem": "OBC",
        "parameter": "current",
        "value": "0.1"
      },
      {
        "timestamp": 1570161521.917379,
        "subsystem": "OBC",
        "parameter": "voltage",
        "value": "5.0"
      }
    ]
  }
}
```

Hardware Service

Definition:

1. GraphQL server endpoints taking in queries and mutations
2. Exercise the hardware API to complete them.

Queries — Retrieves the live data from the hardware component in a JSON format

Mutations — Hardware commands changing the state of the hardware (binary format)

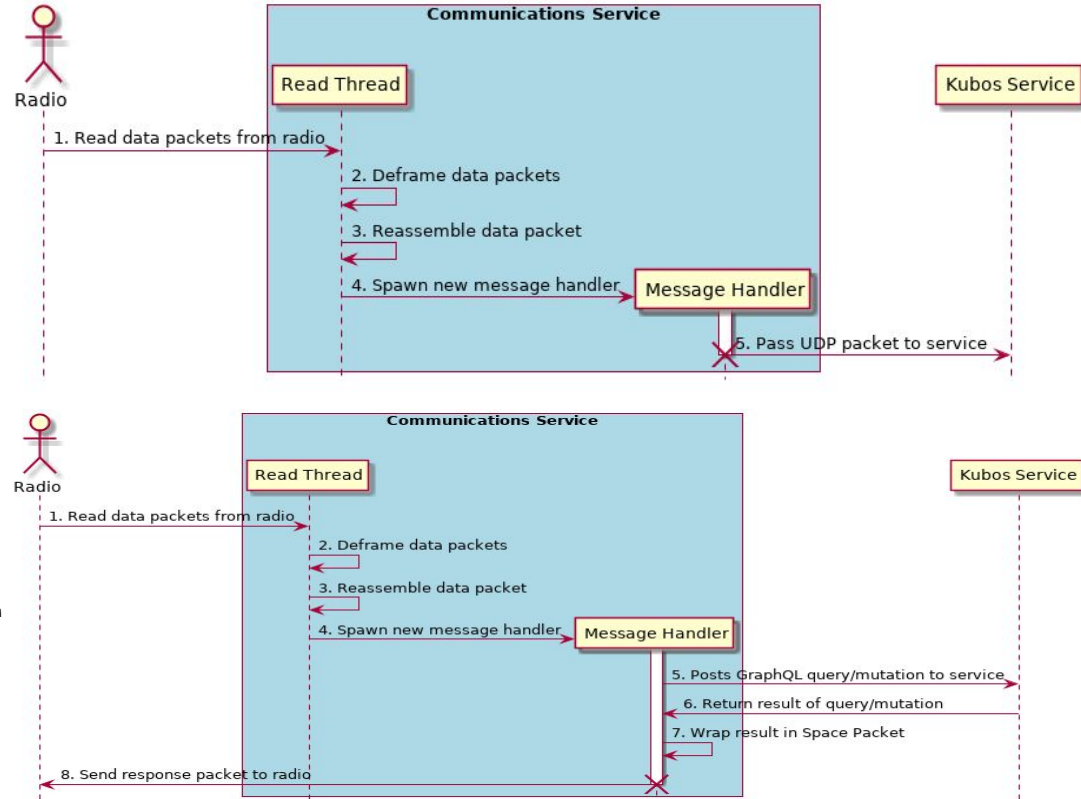
- a. Often issued in binary format

Communications Service

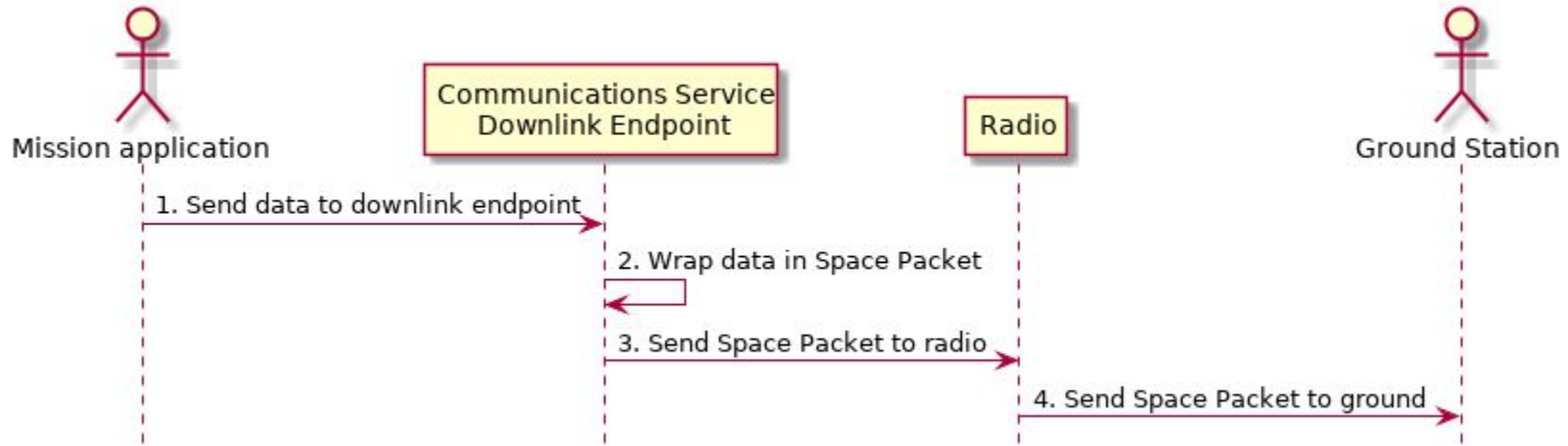
Payload type
determines how
message is
passed to rest of
the system

UDP

GraphQL



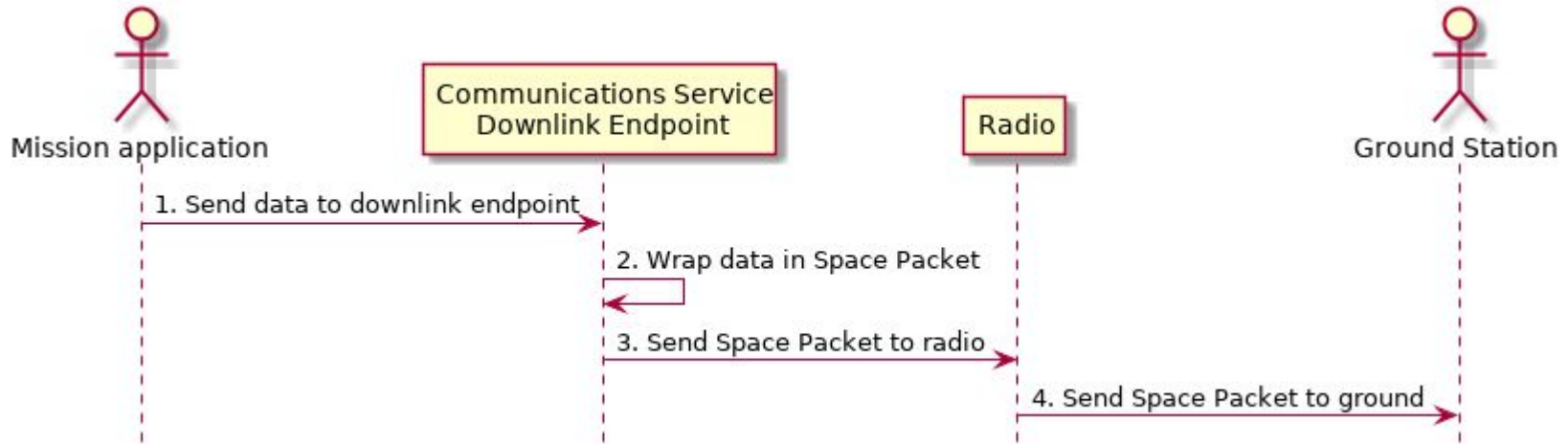
Special Case Communications Service



Downlink Endpoints

- Sending a message to the ground without first receiving a request for data
 - E.g., sending a periodic health-and-status beacon
- Endpoints assigned unique UDP ports, maintains constant read thread
 - Listens for messages from within the satellite
 - Should be transmitted

Downlink Endpoints (Health and Status)



1. Only 1 uplink and downlink method
2. Every downlink endpoint thread assigned its own UDP port
3. Maintains a constant read thread which listens for messages from within the satellite to be transmitted
4. Endpoint's read thread receives a message, wraps it up in a Space Packet, then sends it to the communications device

Definition:

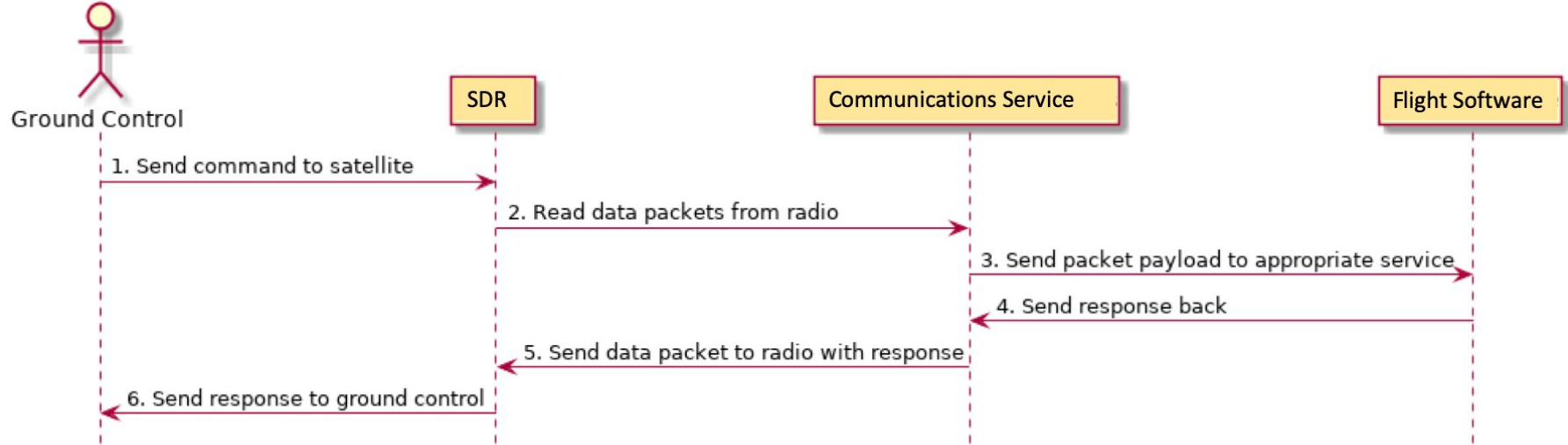
1. GraphQL server endpoints taking in queries and mutations
2. Exercise the hardware API to complete them

Queries — Retrieves the live data from the hardware component in a JSON format

Mutations — Hardware commands changing the state of the hardware (binary format)

- a. Often issued in binary format

Communications Service Overview



Payload/Data types accepted:

1. GraphQL query/mutation
2. JSON GraphQL responses
3. Shell/File Transfer commands
4. Any data that can be passed over UDP

FSW V&V Overview

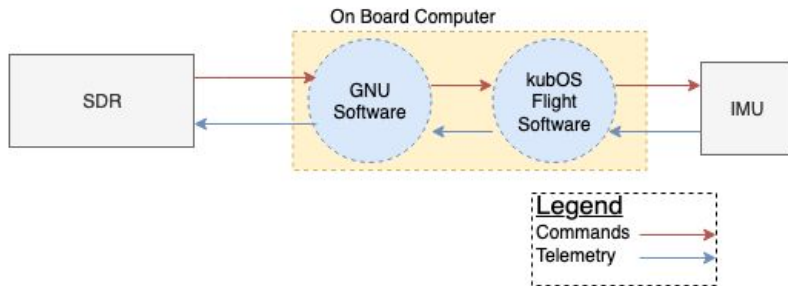
FSW Verification Plan

- Successfully receive packetized commands and forwards IMU's telemetry packetized to GNU Radio
- Assess overall system health during flight using absolutely minimum telemetry



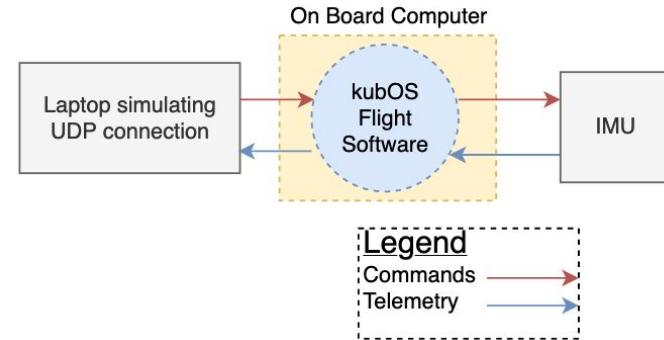
FSW Validation Plan

- The verification tests will confirm that the Flight Software will be able to:
 - Deliver commands to payload
 - Store all generate telemetry
 - Forward telemetry to GNU Radio



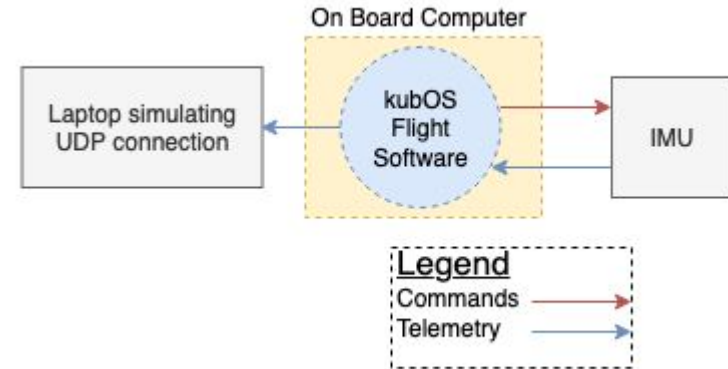
FSW Verification Plan

Objective	Test interface between: 1. Communications service and SDR 2. Mission application and science sensor
Plan	Send a simple packetized request for IMU telemetry
Materials	Microcontroller running KubOS Linux, IMU, Laptop (simulating UDP connection)
Pass Criteria	Success if predicted response in right schema is transmitted to the simulated UDP connection



FSW Verification Plan

Objective	Assess overall system health during flight using absolutely minimum telemetry.
Plan	Downlink a subset of critical telemetry data via the communication service.
Materials	Microcontroller running KubOS Linux, Laptop (simulating UDP connection), IMU
Pass Criteria	Success if predicted response in right schema is transmitted to the simulated UDP connection.



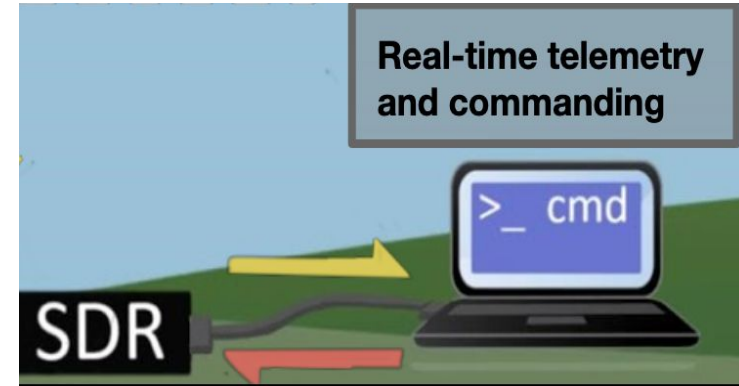
Ground Software

Backup Slides

GSW Requirements

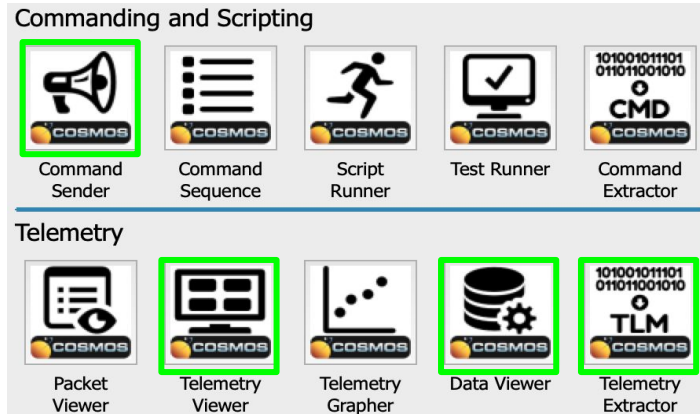
Pertinent Objectives

- Use COSMOS GSW to:
 - Successfully send commands
 - Receive, depacketize, view, and store telemetry data



Pertinent Requirements

FR 2: The payload shall communicate with the ground system during the balloon flight

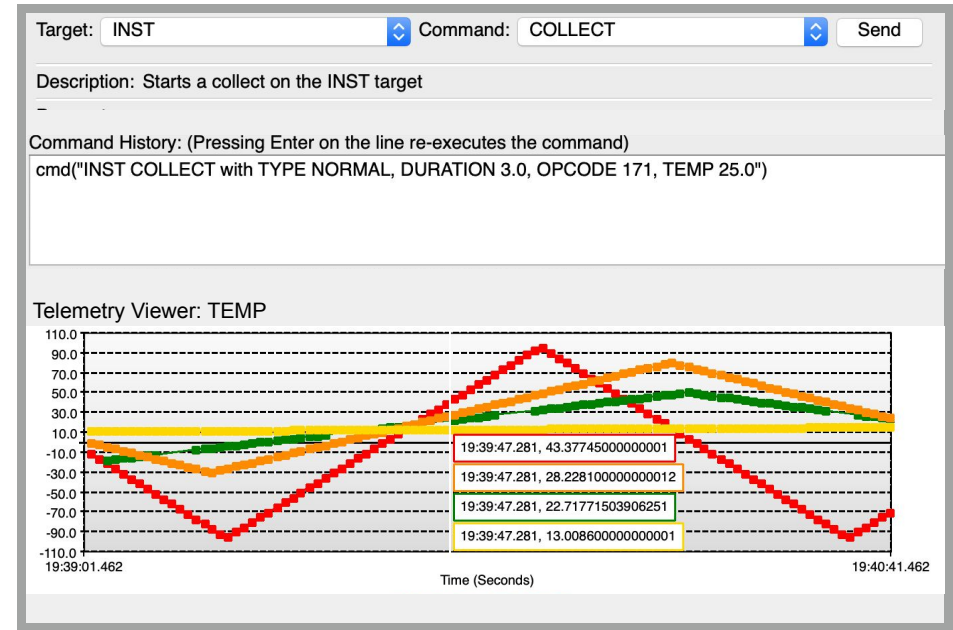


COSMOS
GUI

GSW Analysis

COSMOS Integration

- Format several COSMOS GUIs to perform necessary functions for TOMCAT
- Format command for mission use (telemetry collect)
- Receive telemetry
- Store telemetry (not pictured)



COSMOS Interface

GSW Analysis

Command Sending Test:

- Created a target system to interface with in COSMOS
- Configured the system to take example temperature measurements
- Used the Command Sender tool to send a command to the system to start a collection of telemetry

Target: INST Command: COLLECT Send

Description: Starts a collect on the INST target

Parameters:

Name	Value or State	Units	Description
TYPE:	NORMAL	0	Collect type
DURATION:	3.0		Collect duration
OPCODE:	0xAB		Collect opcode
TEMP:	25.0	C	Collect temperature

Command History: (Pressing Enter on the line re-executes the command)

```
cmd("INST COLLECT with TYPE NORMAL, DURATION 3.0, OPCODE 171, TEMP 25.0")
```

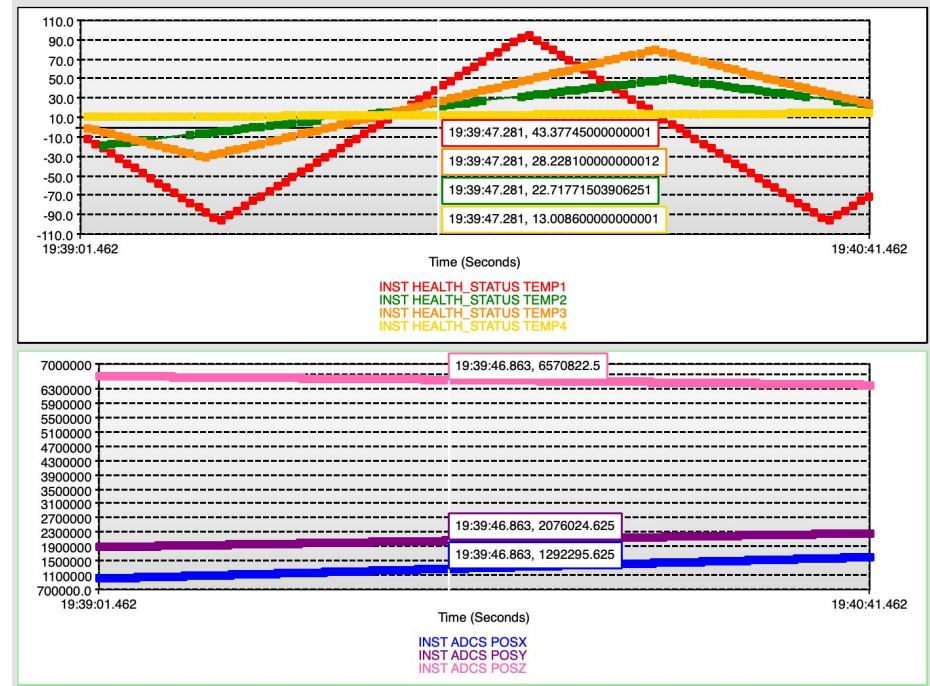
cmd("INST COLLECT with TYPE NORMAL, DURATION 3.0, OPCODE 171, TEMP 25.0") sent. (2)

Screenshot of COSMOS Command Sender

GSW Analysis

Telemetry Viewing Test:

- Created a target system in COSMOS
- Began taking real-time data through a UDP port into the Command & Telemetry Server
- Used Telemetry Grapher tool to plot real-time telemetry



Screenshot of COSMOS Telemetry Grapher

GSW Analysis

Telemetry Logging Test:

- Created a target system to interface and began collecting live telemetry
- Manually started and stopped logging in the Command & Telemetry Server
- Extracted the telemetry data into a text file using the Telemetry Extractor tool
- Verified the data was logged successfully

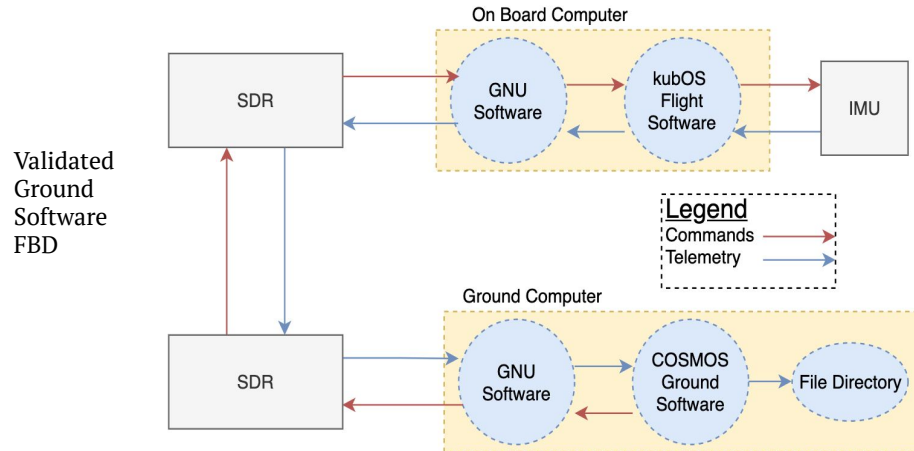
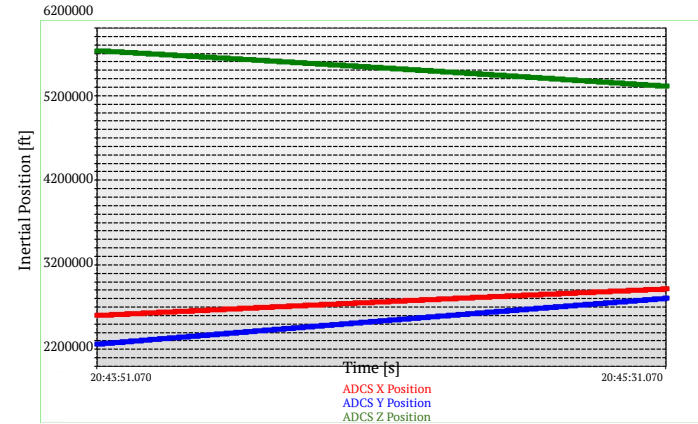
TARGET	PACKET	TEMP1
INST	HEALTH_STATUS	-45.615449999999996
INST	HEALTH_STATUS	-40.6714
INST	HEALTH_STATUS	-35.72735
INST	HEALTH_STATUS	-30.783299999999997
INST	HEALTH_STATUS	-25.839249999999993
INST	HEALTH_STATUS	-20.895199999999999
INST	HEALTH_STATUS	-15.951149999999998
INST	HEALTH_STATUS	-11.007099999999994
INST	HEALTH_STATUS	-6.063049999999999
INST	HEALTH_STATUS	-1.1189999999999998

Screenshot of logged telemetry data

GSW V&V Overview

GSW Verification Plan

- Successfully send CCSDS packetized commands to GNU Radio Software
- Receive, visualize, and log telemetry from GNU Radio Software

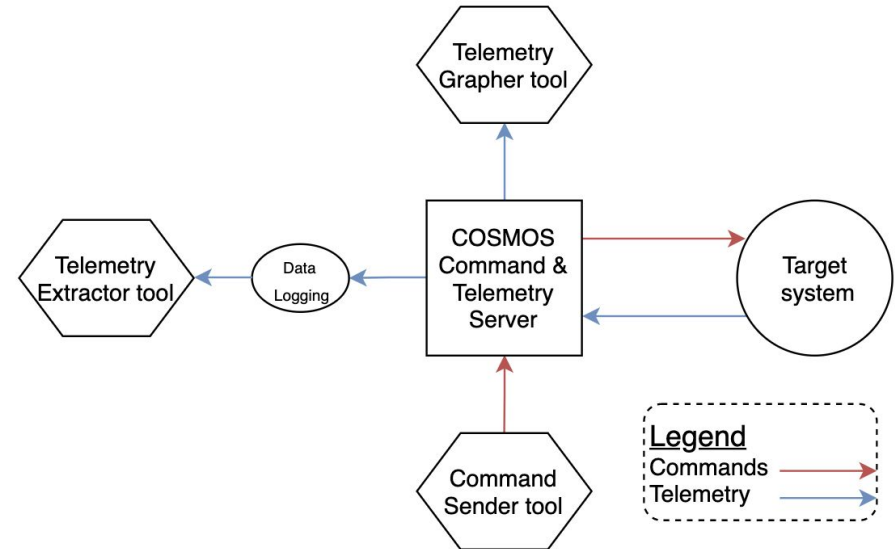


GSW Validation Plan

- The verification tests will confirm that the Ground Software will be able to:
 - Command the FSW to start collecting data from the IMU
 - Receive CCSDS packetized telemetry data from the FSW with real-time graphing and logging

GSW Verification Plan

Objective	Real time sending and receiving of commands and telemetry between the GSW and GNU Radio Software
Plan	Create GNU Radio as a new “target” system to interface and test sending a CCSDS command and plotting/logging telemetry, all without hardware
Materials	Computer with COSMOS and GNU Radio Radio Software installed
Pass Criteria	Show a command has sent successfully from the Command Sender Tool, ensure that live telemetry is plotted in the Telemetry Grapher tool, and confirm that logged data can be extracted into a text file to analyze



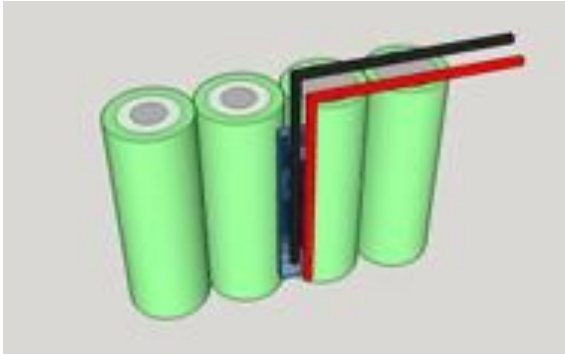
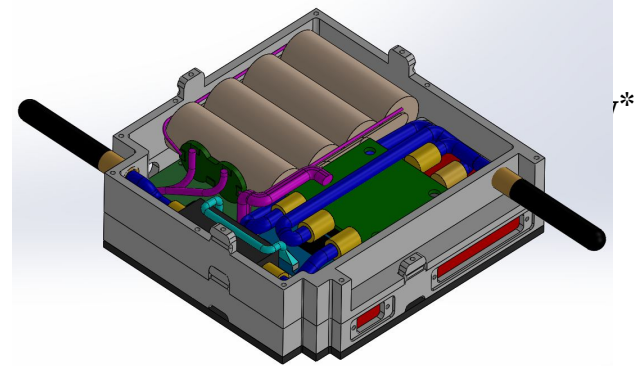
Power

Backup Slides

Power Requirements

Pertinent Objectives

- Power 2 hour flight
- Meet voltage and current requirements of all systems
- Charge and discharge safely



Pertinent Requirements

- **FR 3** - The payload shall survive and operate in the environment during all stages of the balloon flight
- **FR 1.1** - The designed payload board shall fit within the ThinSat payload area as defined by the ICD

Power Analysis

Battery Pack PCB

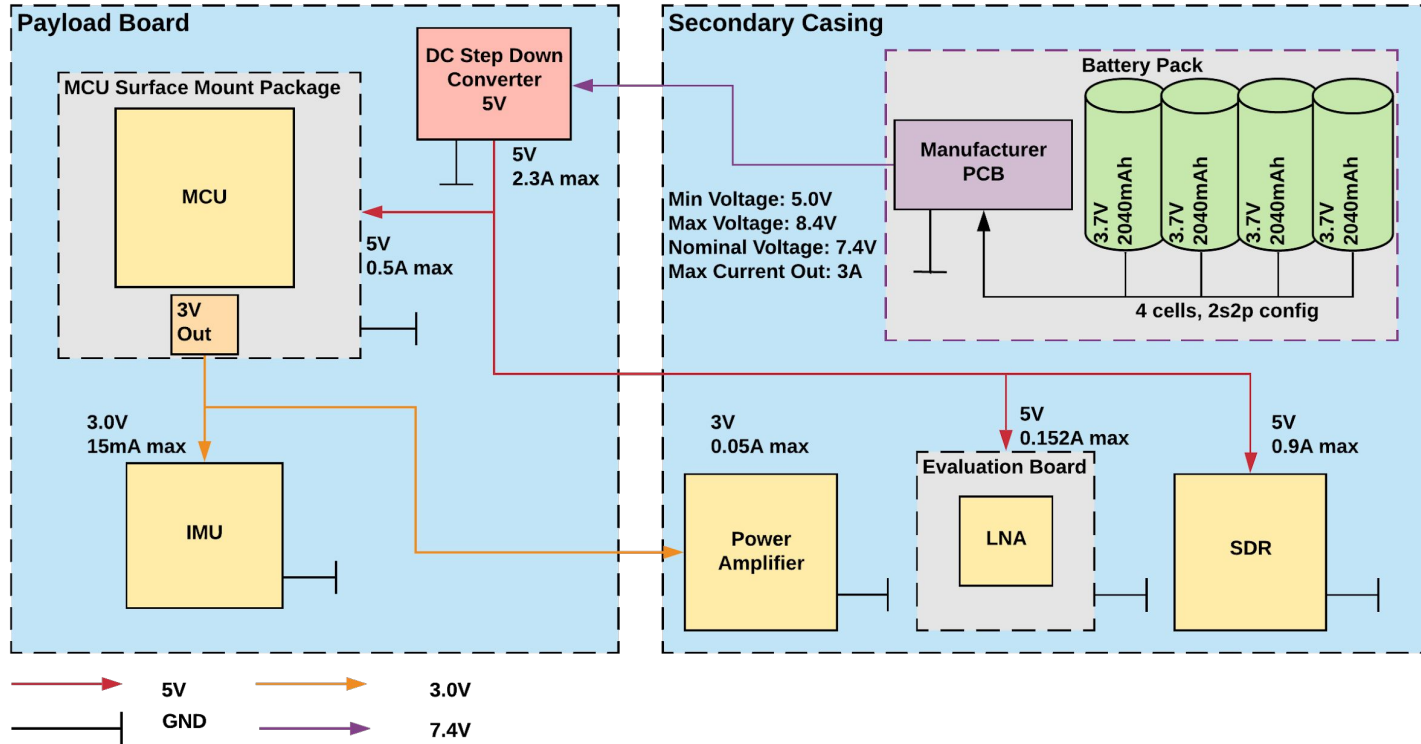
- Min Voltage: 5V
- Max Voltage: 8.4V
- Max Current: 3A

DC Step Down Converter

- Regulates Voltage at constant 5V
- Delivers to MCU, LNA, and SDR

MCU Surface Mount Package

- Has 3V Out pin for IMU and Power Amplifier



Power Analysis

Effective Battery Capacity at Low Temperatures:

Temperature	10°C	0°C	-10°C	-20°C
Battery Capacity	83%	80%	70%	65%

Accommodation	Required Additional Capacity
Low Temperatures	30%*
DC/DC Converter Efficiency Losses	>10%
Other Efficiency Losses	10%
Total:	50%

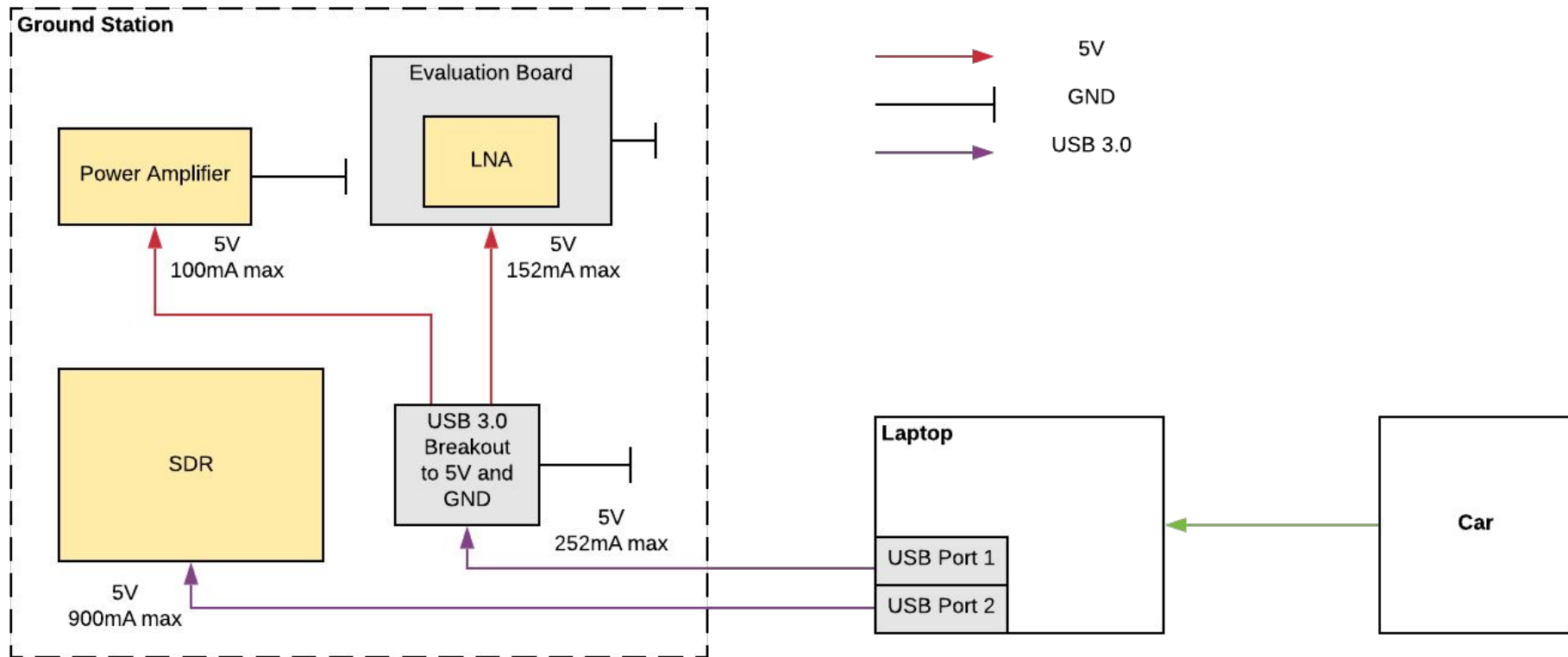
Design point determined from thermal test

Ideal Capacity: **15.91 Wh**
Minimum Required Capacity: **23.86 Wh**

Selected Battery Capacity: **30.19 Wh**

*Utilizing available mass and volume for the battery allows for **operation at suboptimal conditions without active thermal system**

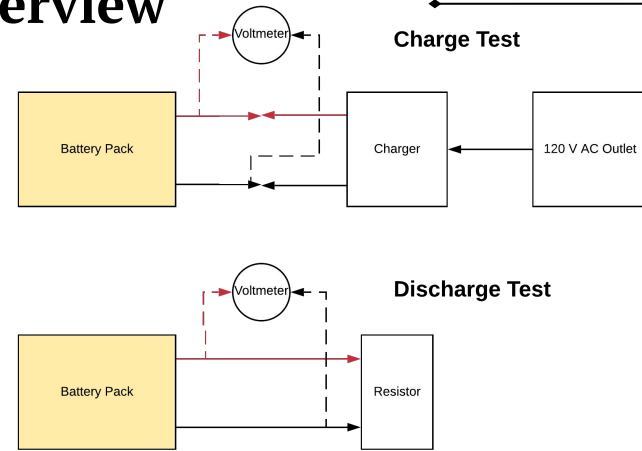
Ground Power System



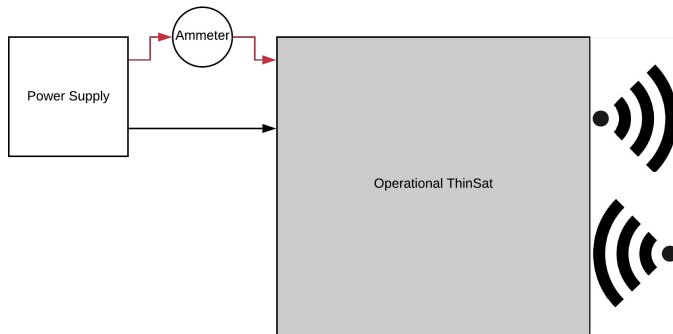
Power V&V Overview

Verification:

1. Charge/Discharge Test
2. Full System Peak Power Test
3. Thermal Test



Full System Peak
Power Test



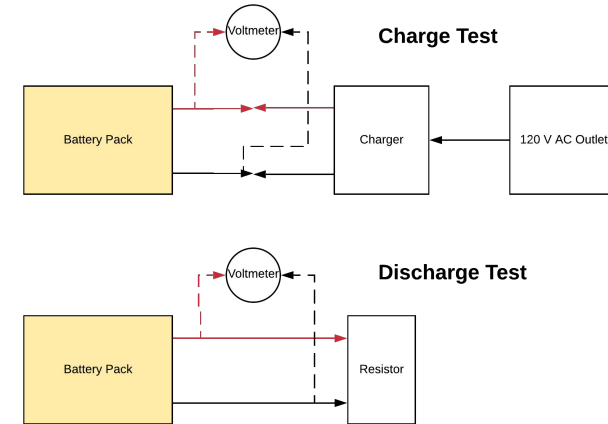
Validation:

Battery successfully powers system for flight duration in balloon flight conditions

Power Verification Plan

Charge/Discharge Test

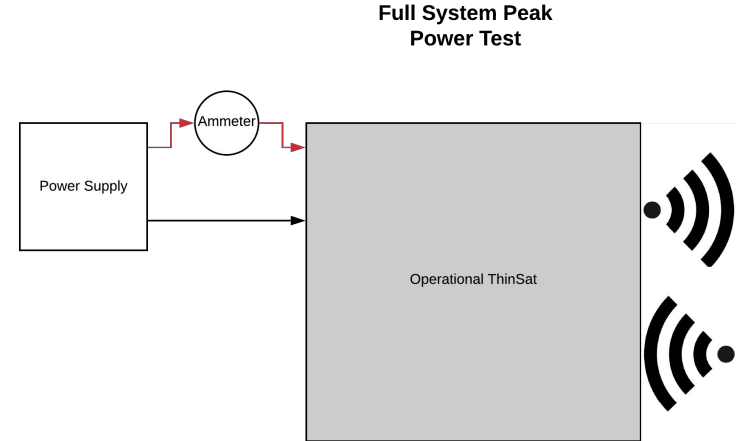
Objective	Battery performs as expected and is able to be charged and discharged safely
Plan	Connect the battery up to the charger and voltmeter and measure the battery's voltage in short time intervals until fully charged. Once fully charged, connect battery to resistor and voltmeter and measure battery voltage in short time intervals until discharged.
Materials	Battery pack, voltmeter, resistor
Pass Criteria	The charger stops charging the battery when maximum voltage is reached. The battery shuts off when minimum voltage is reached.



Power Verification Plan

Full System Peak Power Test

Objective	Battery is capable of discharging enough current during peak demand
Plan	Measure current drawn during peak power draw: when booting up and transmitting and receiving simultaneously
Materials	Power supply, voltmeter and ammeter, battery pack, operational payload
Pass Criteria	The current drawn at peak power draw times is less than the maximum discharge rate of the battery



Power Verification Plan

Full System Thermal Test

Objective	Battery is capable of powering the full system at the temperatures expected during balloon flight
Plan	Run system in thermal chamber under balloon flight temperature conditions for 2 hours, measuring battery voltage and discharge rate
Materials	Voltmeter and ammeter, battery pack, operational payload
Pass Criteria	The battery powers the system for the duration of the balloon flight and provides the required voltage and current at all times

Power System

Miscellaneous Power Components

- Sparkfun **USB Type A Female Breakout Board** for use on ground station

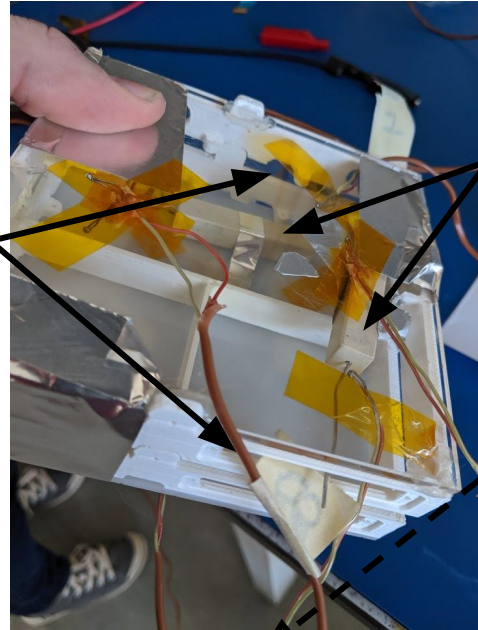
- **BatterySpace Smart Charger** (0.5A) for 7.4V Li-ion/Polymer Rechargeable Battery Pack
 - 8.4VDC
 - 0.5A Charging Current
 - 4.2 hours charge time
 - Output shorted and overload protection
 - Automatically cut-off power when battery pack is full at 8.4V

Thermal

Backup Slides

Thermal Mitigations Moving Forward

Previous Testing



Heaters assumed max power

Dry ice unevenly distributed in cooler

More testing details in Backup Slides

Mitigation Steps

- Use TOMCAT design rather than stock ThinSat for thermal tests
- Get more accurate heater wattages
- Evenly distribute dry ice to reduce thermal gradients

Takeaway:

Working to build a larger margin on the thermal design

Thermal Requirements

Requirements:

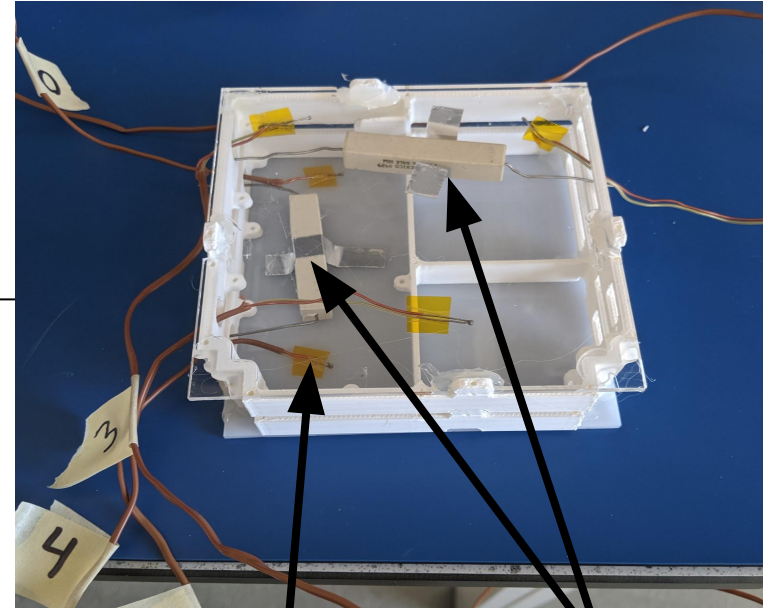
FR3: The payload shall survive and operate in the environment during all stages of the balloon flight

DR3.1: The payload shall be able to withstand the ambient temperature range of flight (-56°C, 38°C)

Objectives:

- Battery: $\geq -10\text{ }^{\circ}\text{C}$
- Payload Board: $\geq -40\text{ }^{\circ}\text{C}$
- IMU: $\geq -40\text{ }^{\circ}\text{C}$
- SDR: $\geq -40\text{ }^{\circ}\text{C}$

TOMCAT Test Specimen (Control Configuration)



Thermocouples

Power Resistors

Thermal Analysis

Relevant Design Requirement:

- The payload shall be able to withstand the ambient temperature range of flight (-56°C , 38°C)

To Meet Design Requirement:

- Create a thermal model using cold test data

- **Control Test:**

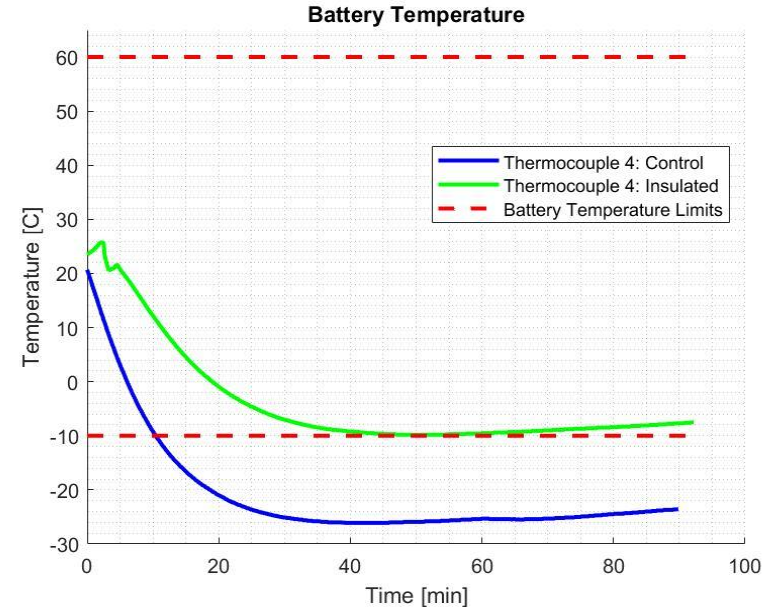
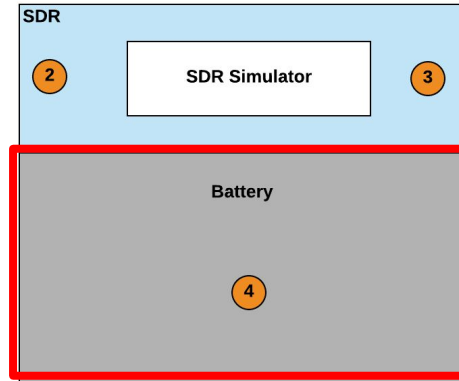
- No insulation, acrylic backing

- **Insulation Test:**

- 3/16 inch polystyrene

- **Test Conditions:**

- Dry ice inside cooler
 - Ambient temperature of -60°C
 - No direct contact between dry ice and test specimen



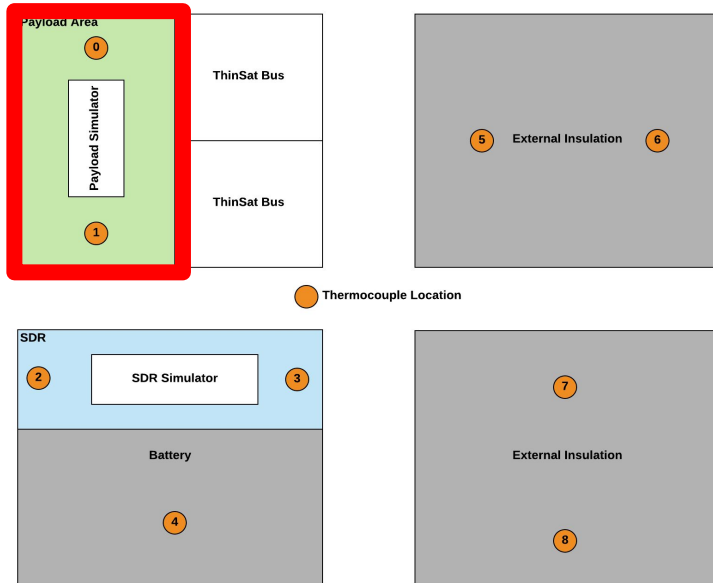
Takeaway:

Presents test results for the battery area and why thermal is a project risk due to little margin

Thermal Analysis

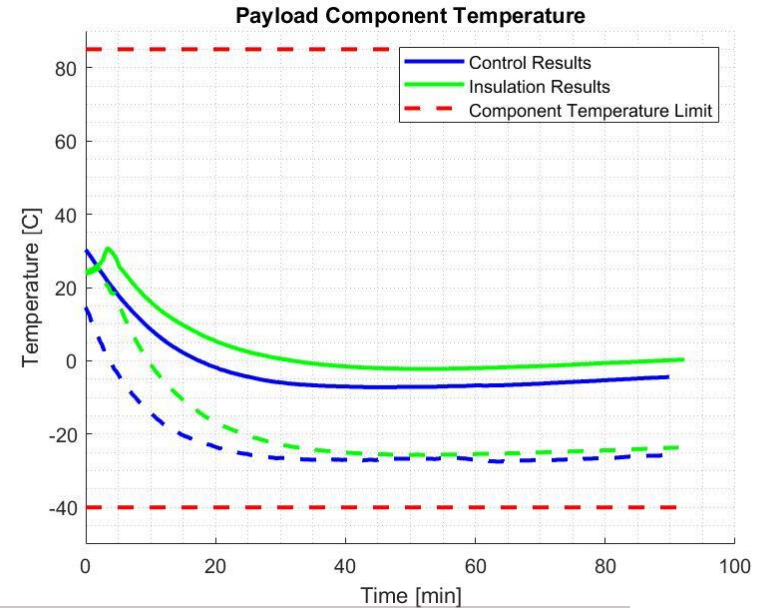
Relevant Design Requirement:

- The payload shall be able to withstand the ambient temperature range of flight (-56°C , 38°C)



To Meet Design Requirement:

- Create a thermal model using cold test data



Takeaway:

Presents test results for the payload area and shows that onboard computer and IMU will stay well above required -40°C limit.

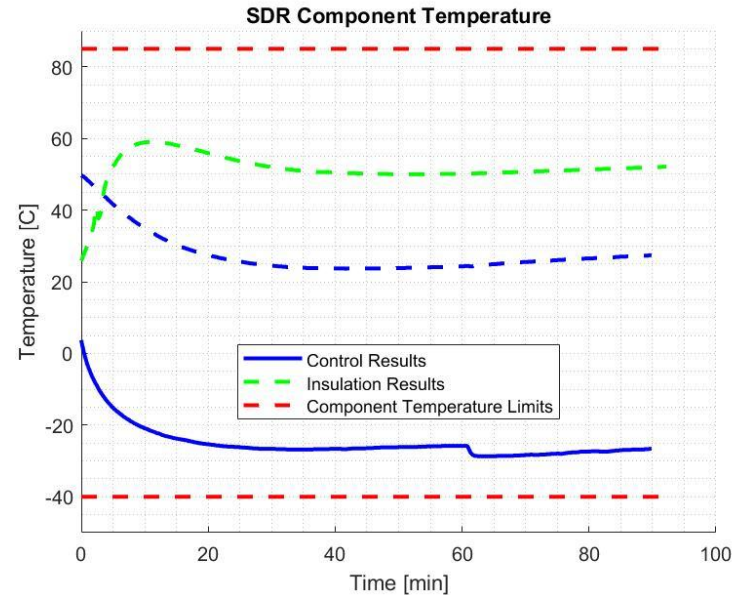
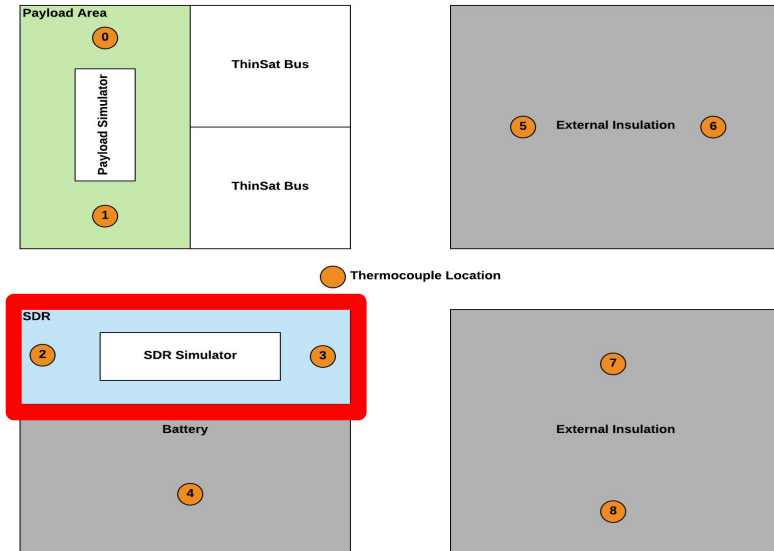
Thermal Analysis

Relevant Design Requirement:

- The payload shall be able to withstand the ambient temperature range of flight (-56°C , 38°C)

To Meet Design Requirement:

- Create a thermal model using cold test data



*Thermocouple 2 fell off during insulation test, therefore not shown.

Takeaway:

Presents test results for the SDR area and shows that the SDR will stay well above required -40°C limit.

Thermal V&V Overview

Verification

- Further cold tests
- Explore insulation thickness and type
- Reduce model errors
- Study altitude effects

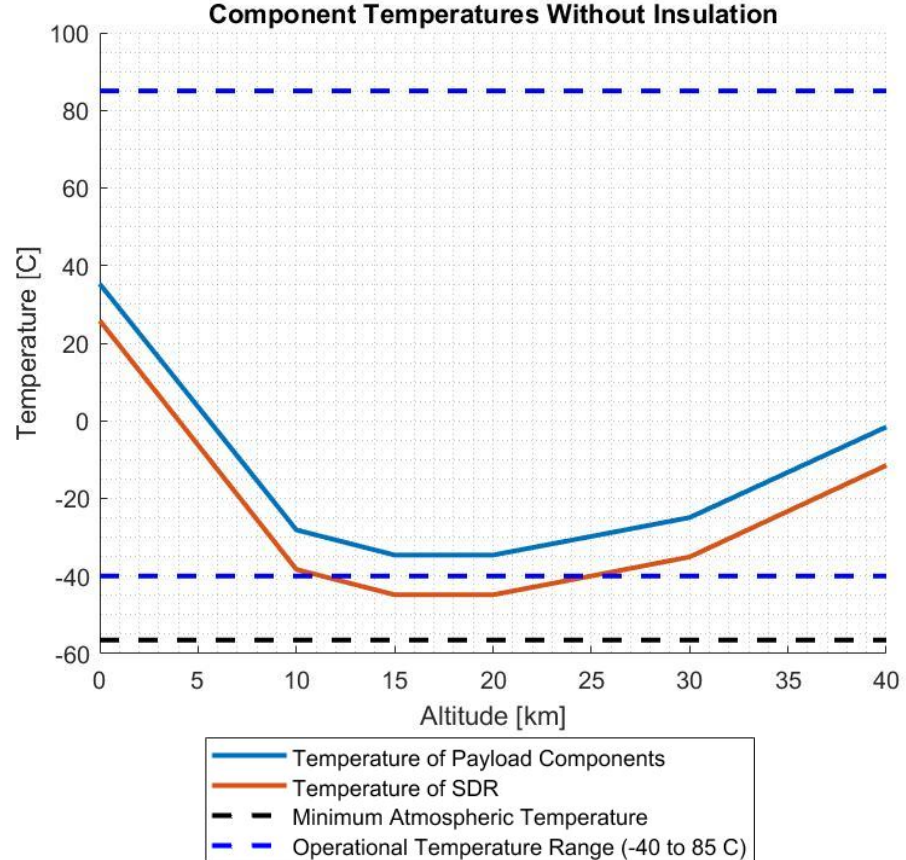
Validation

- Full system functional cold test
 - Validate system on the ground
- Balloon flight temperature sensor
 - Validate system during flight

Objective	Reduce errors from preliminary testing, choose an optimal insulation thickness and type, study effects of high altitude.
Plan	Add convective effects, refine wattage values to be more realistic, use ThinSat design more closely related to CAD model.
Materials	All materials from preliminary testing, convection mechanism, better design structure, multiple insulation types.
Pass Criteria	Analyze temperature data to see temperature levels at the coldest points in the test.

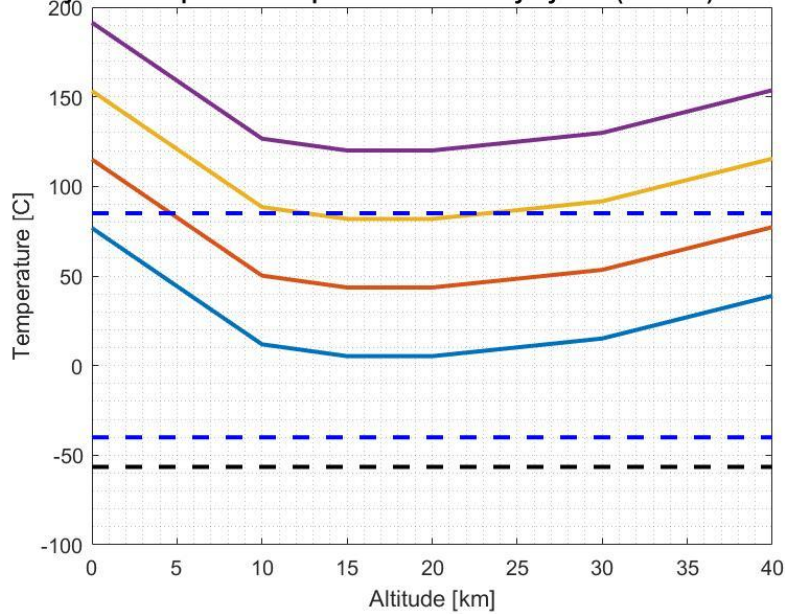
PDR Thermal Analysis

- **Motivation:** Satisfy Requirement 3.1: The payload shall be able to withstand the temperature range of flight, which includes the coldest point in the flight (-56°C), and a hot day on the ground (38°C)
- Steady State, 1D Thermal Model
- Accounts for radiation, convection, conduction (*with insulation*)
- Does not account for sun loading or Earth's albedo
- Insulation required for above-nominal operating temperatures of both the payload and the SDR

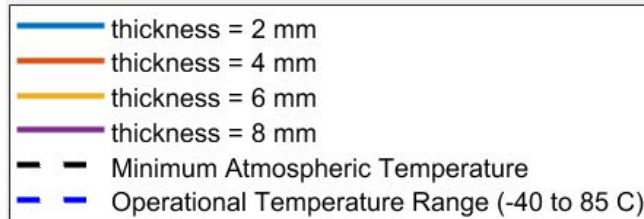
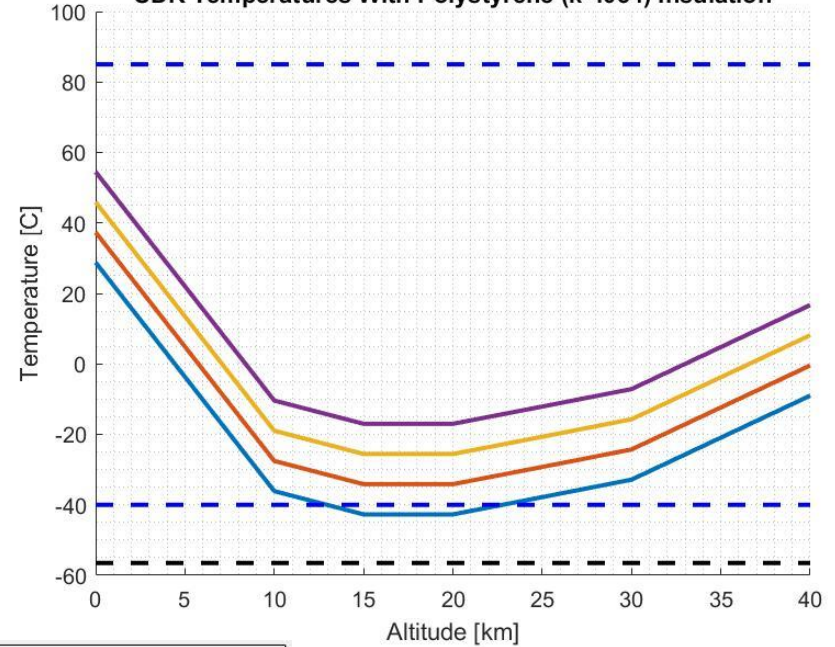


PDR Thermal Analysis

Payload Component Temperatures With Polystyrene ($k = .034$) Insulation



SDR Temperatures With Polystyrene ($k=.034$) Insulation



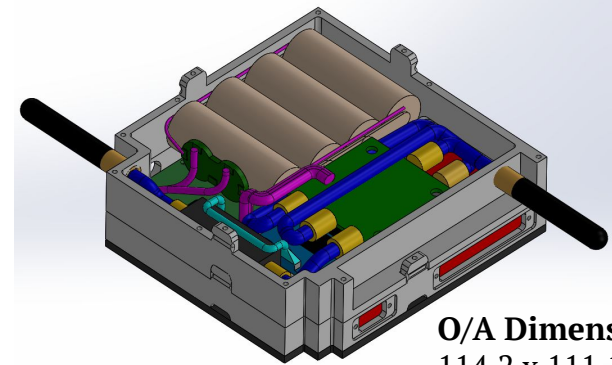
Structures

Backup Slides

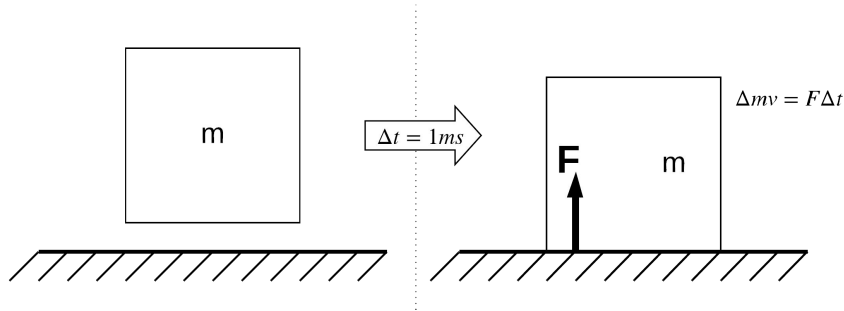
Structures Requirements

Pertinent Objectives

- Use CAD modelling to ensure that all components fit in the frame
- Test the structure to determine if the structure will survive impact or if padding will be needed for a safe landing



O/A Dimensions:
114.2 x 111.1 x 33.12 [mm]



Pertinent Requirements

3. The payload shall survive and operate in the environment during all stages of the balloon flight
- 3.2 The payload shall withstand the impact from a balloon launch (estimated 9 m/s from vendor)

Structures Analysis

- Fully analytical model produced results that are known to be wrong
- Instead impact data was interpolated from what was known to survive the impact
- This showed that the payload bay and SDR assembly could survive impact with the planned number of connections
- The battery will be supported by extrusions printed into the secondary frame whose impact tolerance will need to be determined through testing

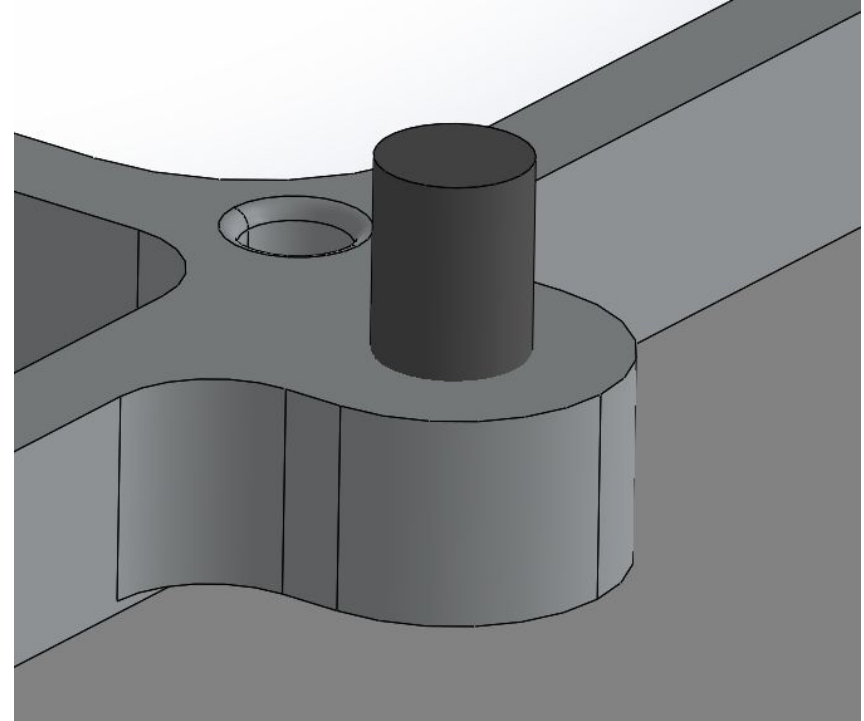
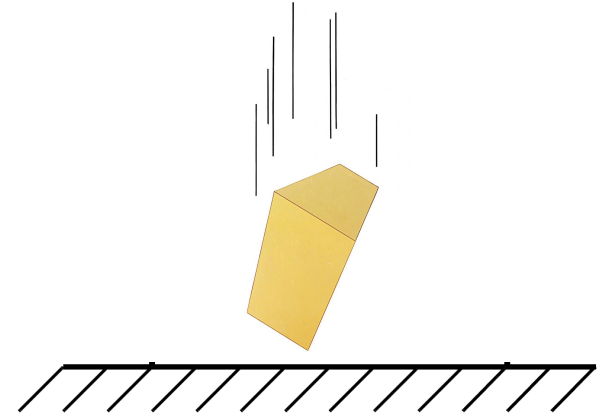
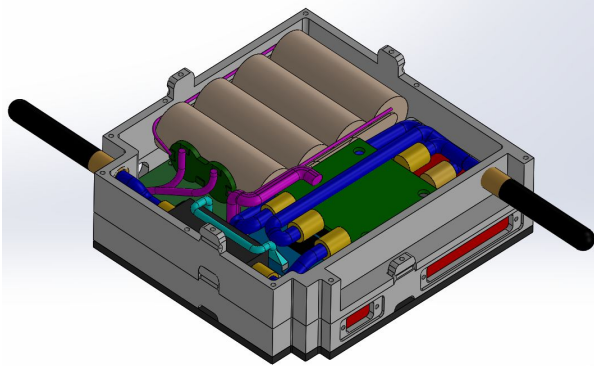


Diagram depicts the connection used by the vendor to attach components to the frame

Structures V&V Overview

Verification

- Assembly of the thinsat will verify that all of the components fit within the frame
- Drop tests will be conducted to verify that the thinsat will be able to survive the impact at the end of the balloon flight

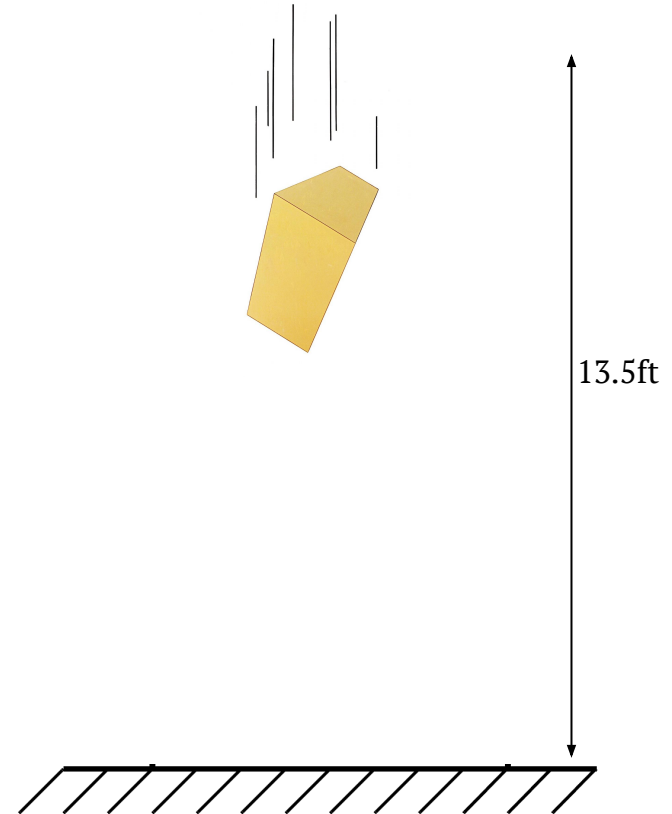


Validation

- Thinsat will be inspected and tested after flight to determine if there was any damage and that it is still functional

Structures Verification Plan

Objective	Determine if the structure will be able to survive the balloon landing or if padding will be necessary
Plan	Print test frame and create component mass replacements. Drop the test thinsat to simulate landing impact
Materials	Printed frame, component mass replacements, bolts for construction
Pass Criteria	Inspect structure after the test to determine if there was any structural damage. If there is sufficient damage, repeat test with additional padding



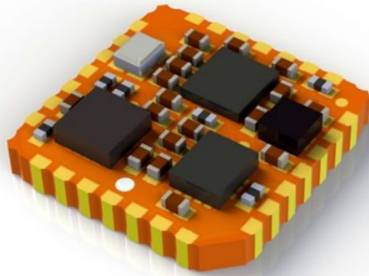
Science

Backup Slides

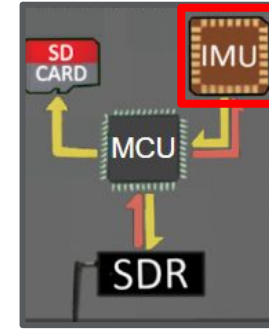
Science Requirements

Pertinent Objectives

- **Primary:** Intake commands & generate data for downlinking telemetry
- **Secondary:** Utilize accelerometer and gyroscope data to determine ascent and descent



Xsens IMU 1-Series



IMU Integration

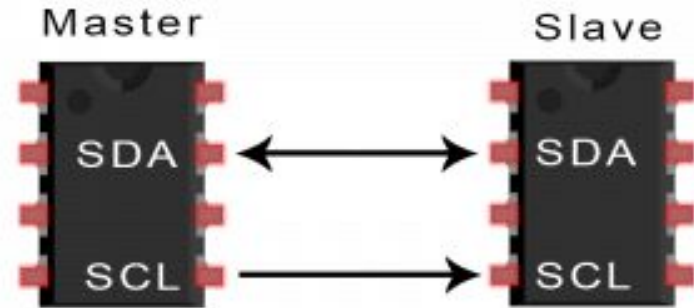
Pertinent Requirements

- 3.4: The payload shall survive and operate in the environment during all stages of balloon flight
 - 3.4.1: Science data shall be able to be collected and updated at least once every second
- 4.1: The payload shall be commandable
- 4.2: The payload shall generate telemetry

I2C

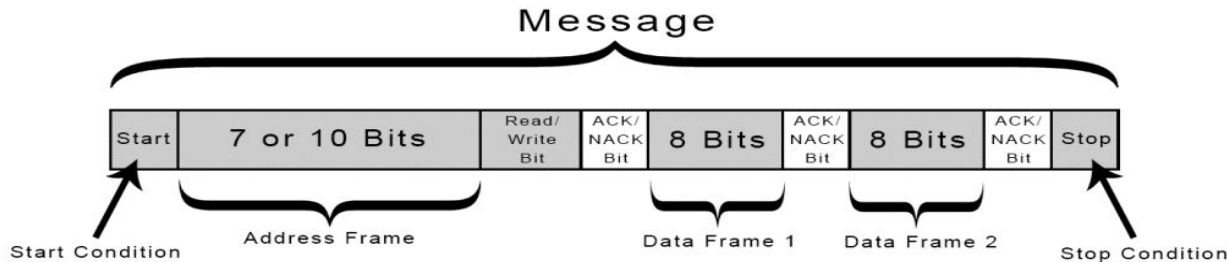
Communication protocol:

- Combines the best features of SPI and UARTs
- Synchronous
- Standard Mode: 100kbps
- Data is transferred in messages with the following format:



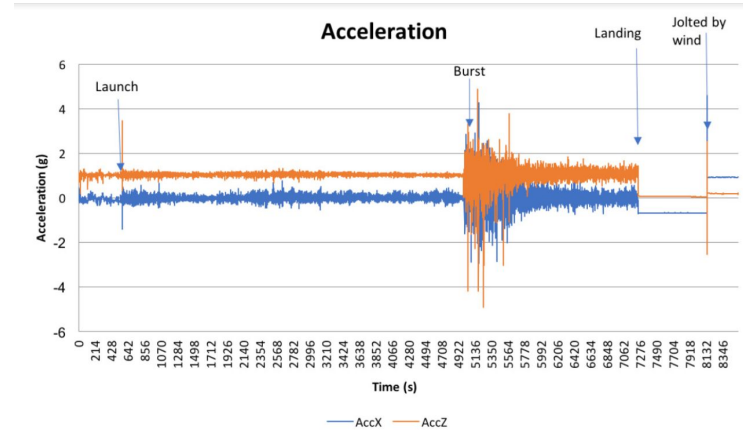
SDA - Serial Data

SCL - Serial Clock

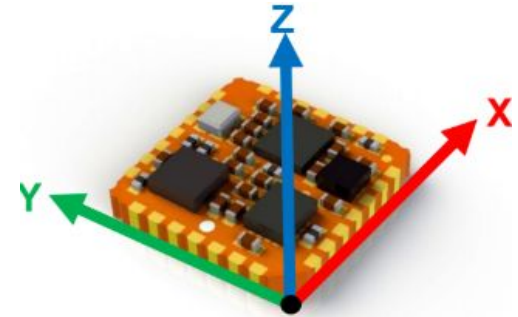


Science Analysis

- ASEN 1400 Flight Data
 - Loaded accelerometer data from Spring 2017 flights
 - Tested various code flowdowns to determine strongest algorithm for discerning ascent versus descent
 - Best algorithm uses **values of inertial-Z acceleration** to determine flight phase
 - Alternative algorithms shown on following slide
- Sample IMU Testing
 - SparkFun IMU provided by Electronics lab
 - Measured nominal accelerations and rotations during pre-flight setup



Sample accelerometer data from ASEN 1400



Sensor-fixed reference frame

Science Analysis

Alternative Coding Algorithms	Launch Cutoff <i>When pre-flight phase transitions to ascent phase</i>	Burst Cutoff <i>When ascent phase transitions to descent phase</i>	Landing Cutoff <i>When descent phase transitions to post-flight phase</i>
Acceleration Only	$a_z < 2g$	$a_z < -1g$	$ \Delta a_x , \Delta a_y , \Delta a_z < .1g$
Rotational + Acceleration	$a_z < 2g$	$a_z < -1g$ $ \omega_y > 2 \cdot \omega_{y, \text{ascent average}} $	$ \Delta a_x , \Delta a_y , \Delta a_z < .1g$ $ \omega_x , \omega_y , \omega_z < .1 \text{ rad/s}$
Rotational Only	Determined experimentally	$ \omega_y > 3 \omega_{y, \text{ascent average}} $	$ \omega_x , \omega_y , \omega_z < .1 \text{ rad/s}$

Could utilize these in addition to/in lieu of inertial Z acceleration data

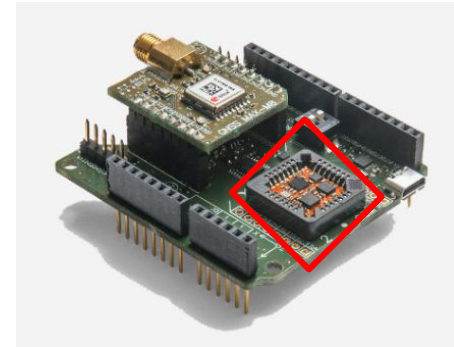
Science V&V Overview

Verification

- IMU provides MCU with dataset for telemetry
 - 3-axis acceleration, rotation, magnetic field
- IMU generates data at a rate greater than once every second
 - Determines orientation, position, and velocity at output data rate of up to **100 Hz**

Interface		Min	Typ	Max	Unit	Comments
Size	Width/Length	12.0	12.1	12.2	mm	PLCC-28 compatible
	Height	2.5	2.6	2.7	mm	
Weight			0.6		gram	
Temperature	Operating temperature	-40		+85	°C	Ambient temperature, non-condensing
Power consumption				100	mW	VDDA 3.0V; VDDIO 1.8V
Timing accuracy			10 ⁹		ppm	
MTBF		225,000			hours	
Output data rate				800	Hz	RateOfTurnHR and ArcAccelerationHR DataID only

System specifications of Xsens IMU 1-Series



Sample image of Xsens IMU mounted to PCB

Validation

- Telemetry will be generated as long as:
 - IMU maintains operating temperatures
 - IMU maintains connection to PCB (mounted)
- Data will be applicable both in atmosphere and vacuum
 - Components function in both environments

Science Verification Plan

○ ASEN 1400 Launch

- BalloonSats come equipped with GoPro cameras
- Sync up video footage with sensor data

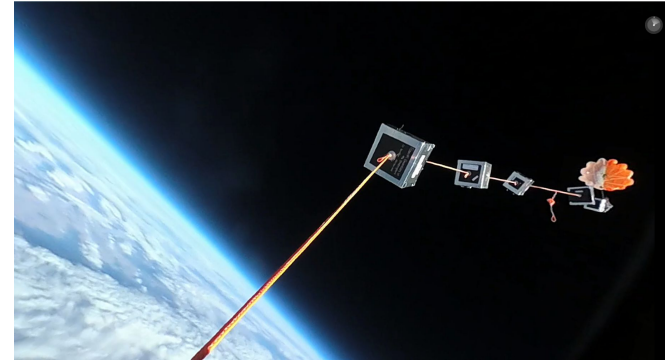


Photo taken from GoPro video on ASEN 1400 BalloonSat

○ NearSpace Launch

- ThinSat launches include a single Android phone on payload ladder
- Sync up video footage with sensor data



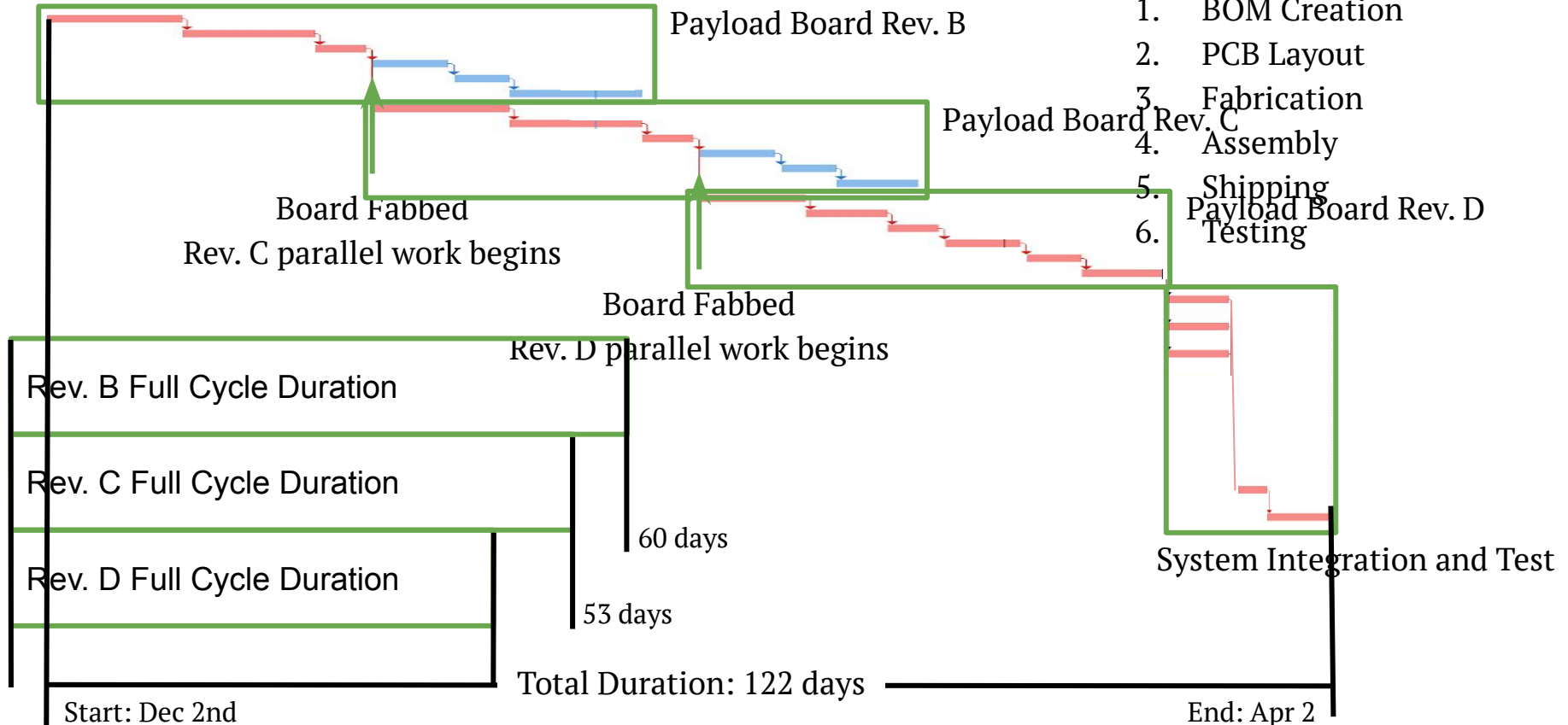
Photo taken from Android video atop ThinSat payload ladder

Miscellaneous

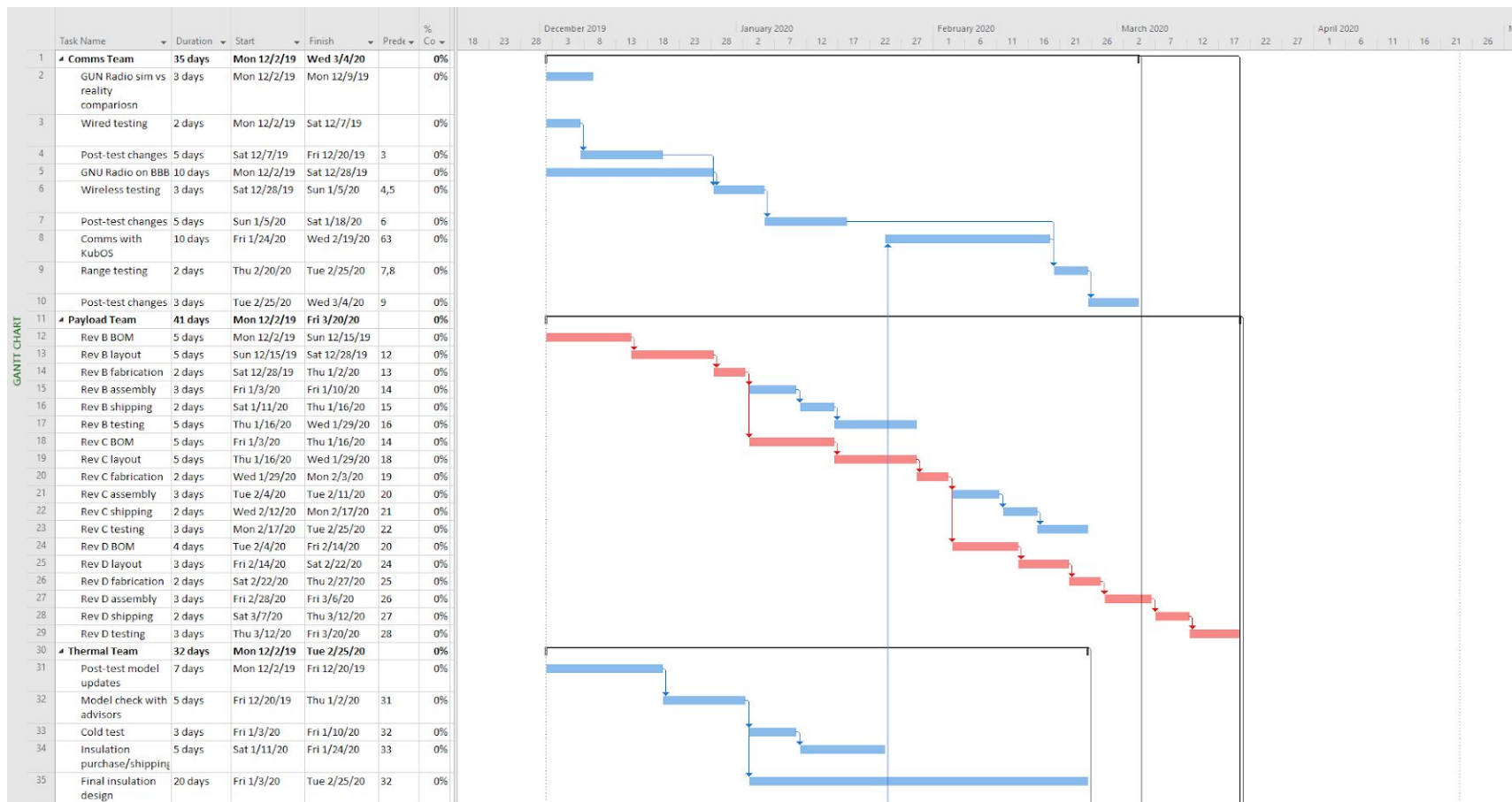
Critical Path Analysis

Payload Board Revision Cycle:

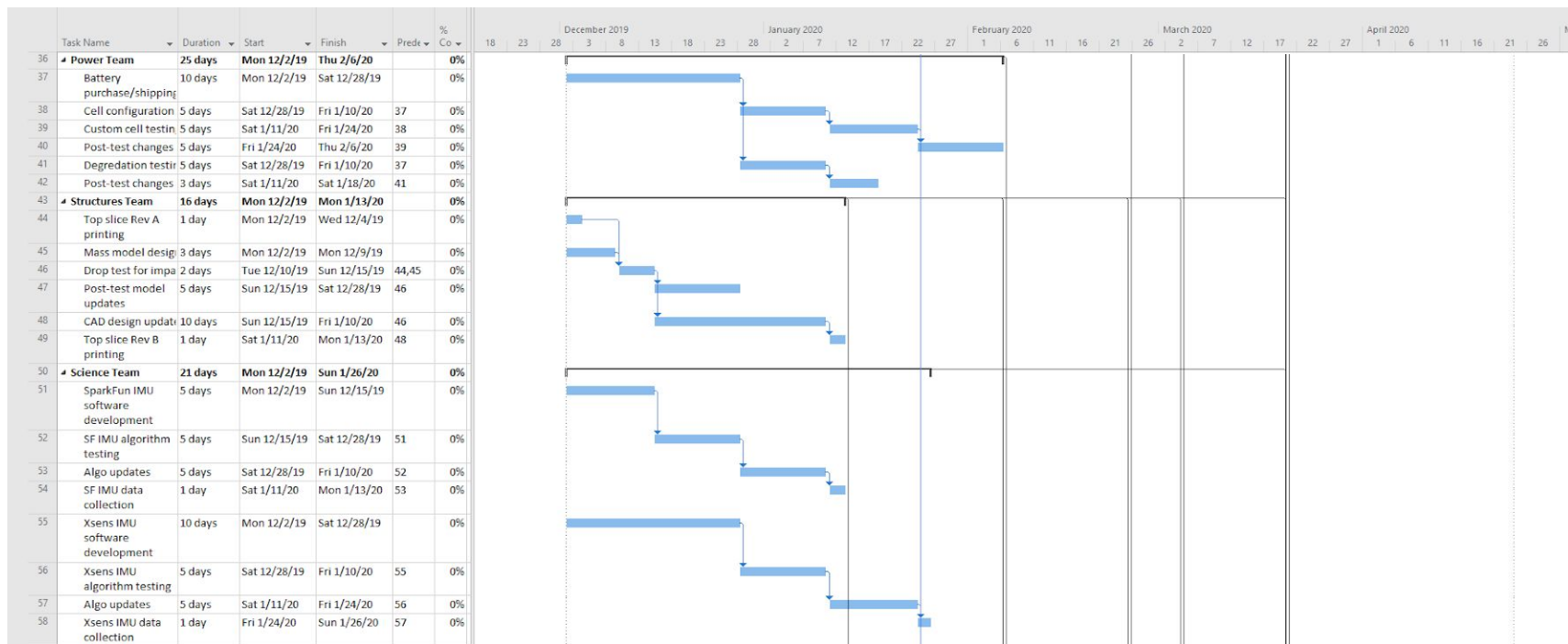
1. BOM Creation
2. PCB Layout
3. Fabrication
4. Assembly
5. Shipping
6. Payload Board Rev. D Testing



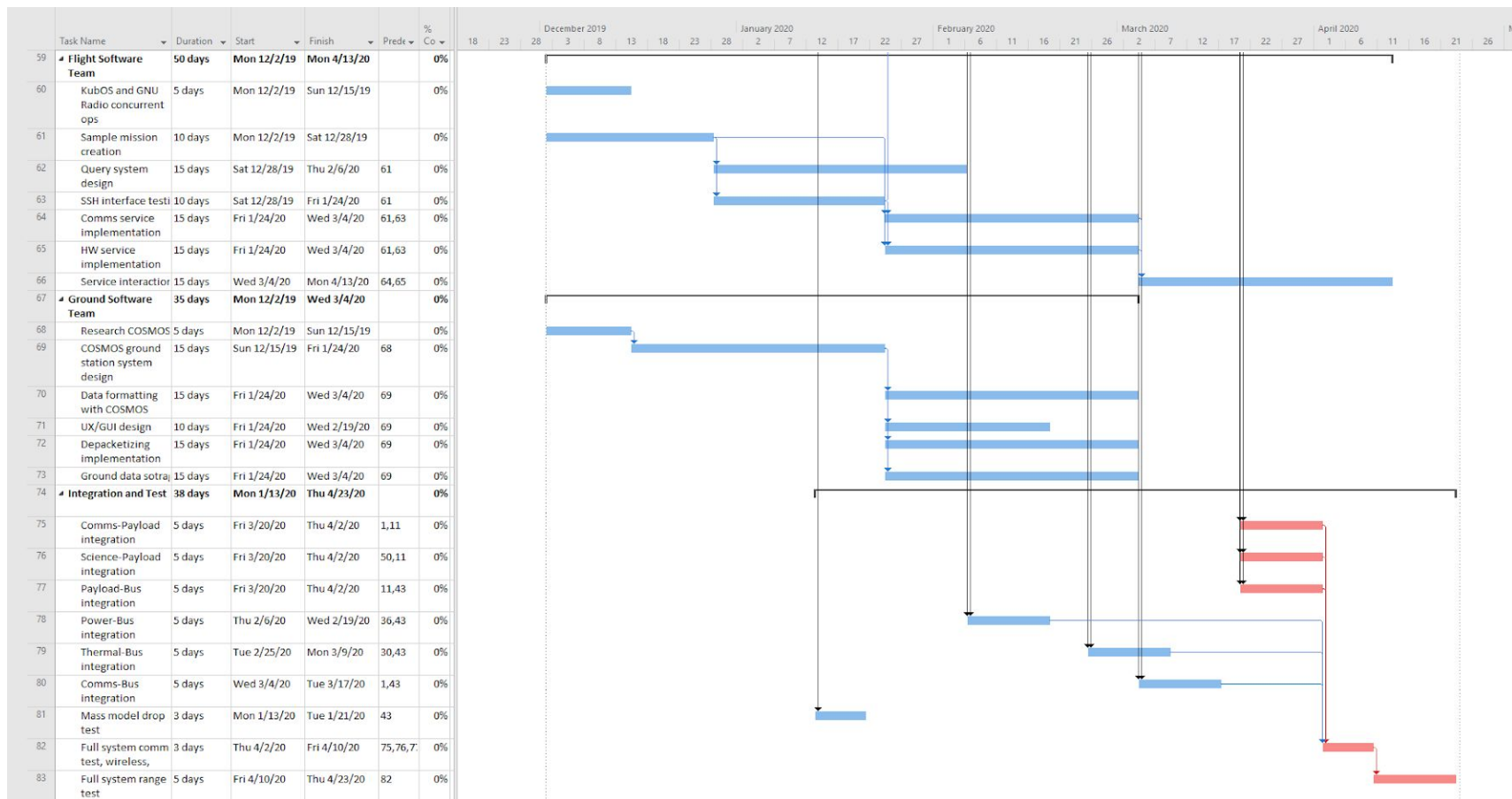
Work Plan

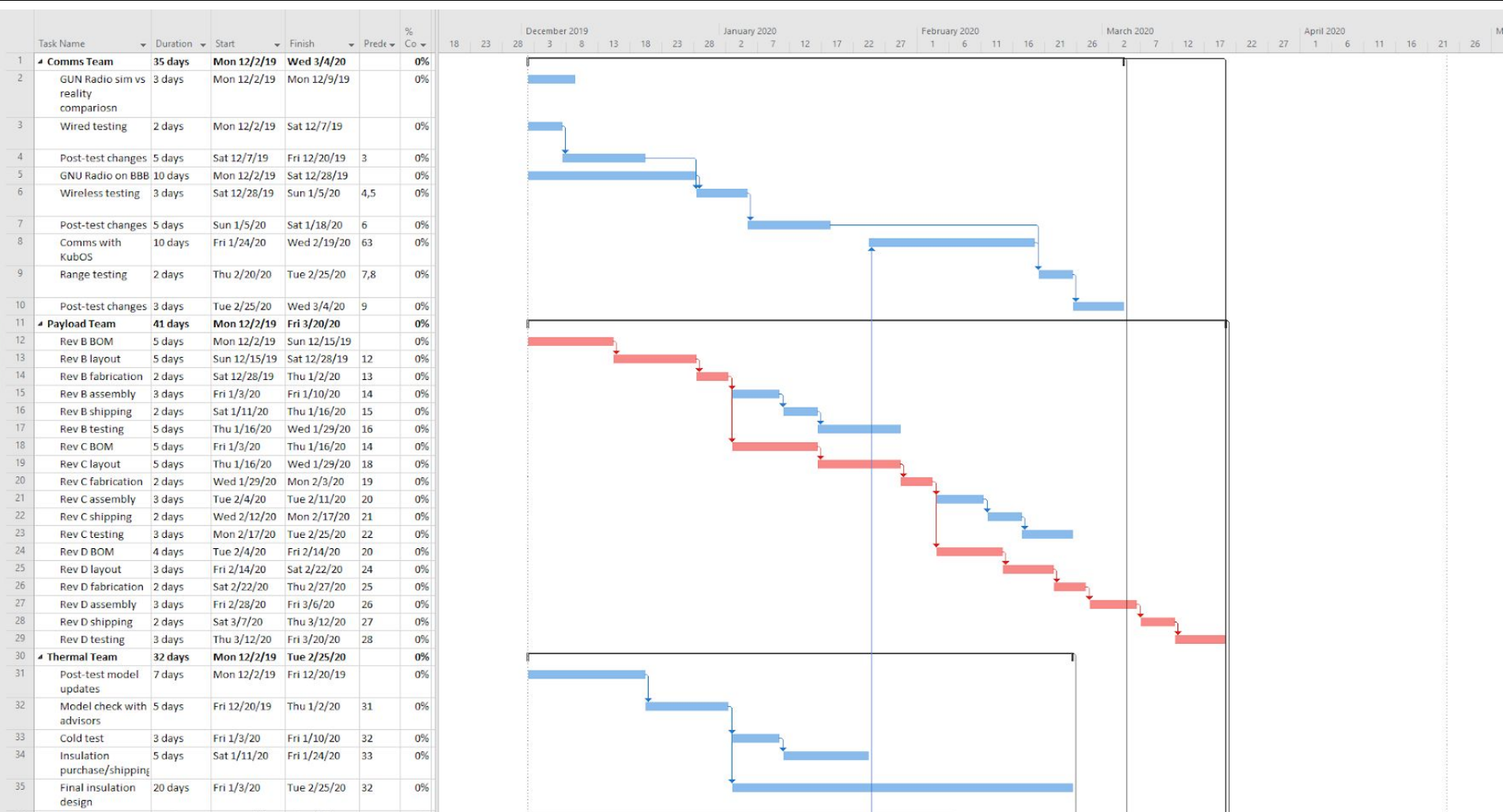


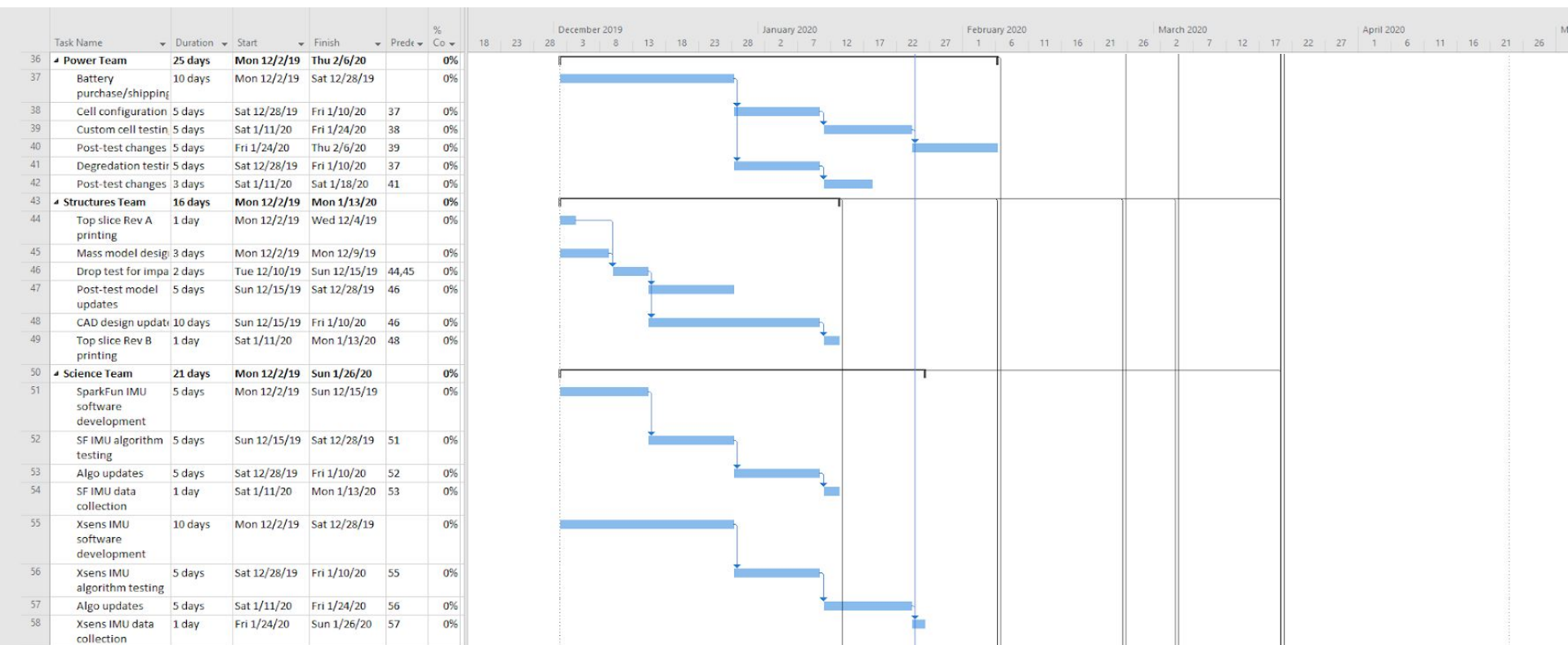
Work Plan

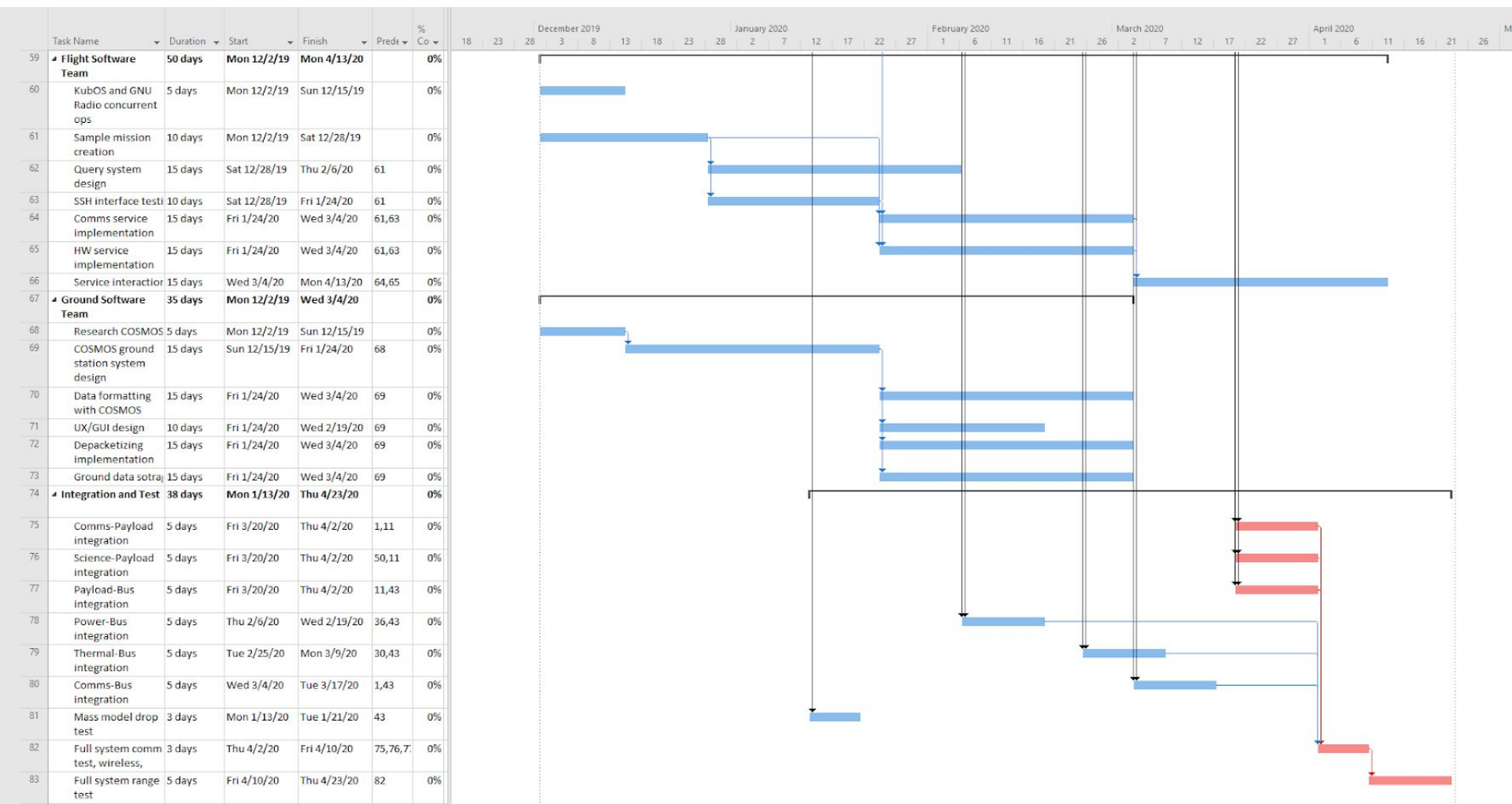


Work Plan



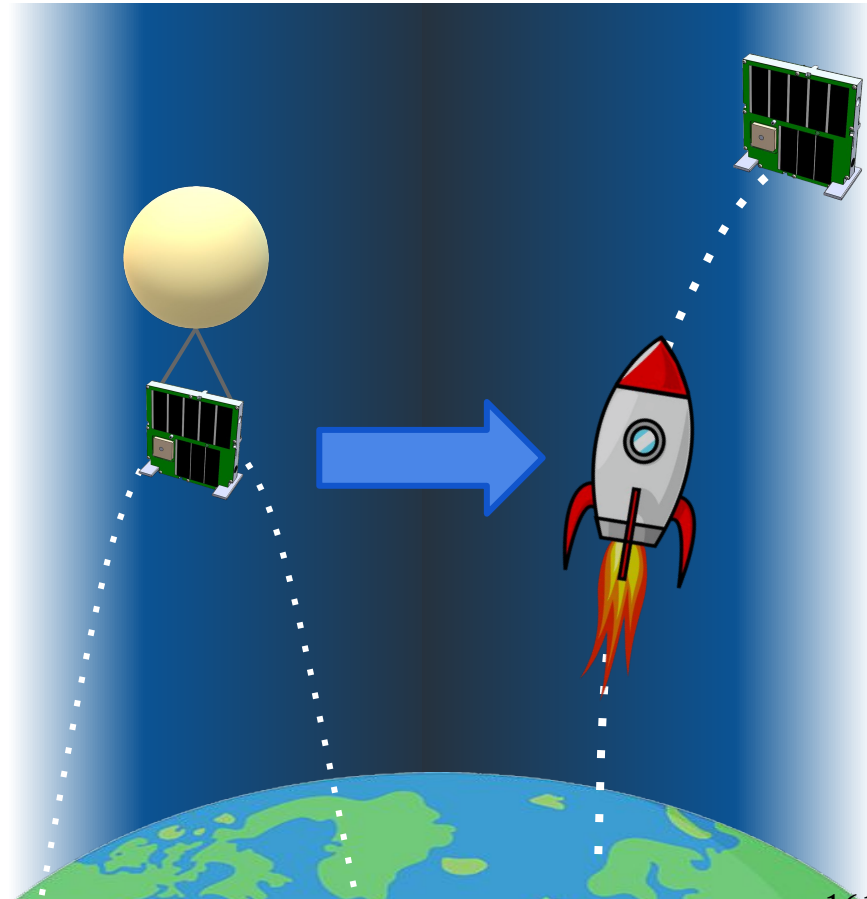






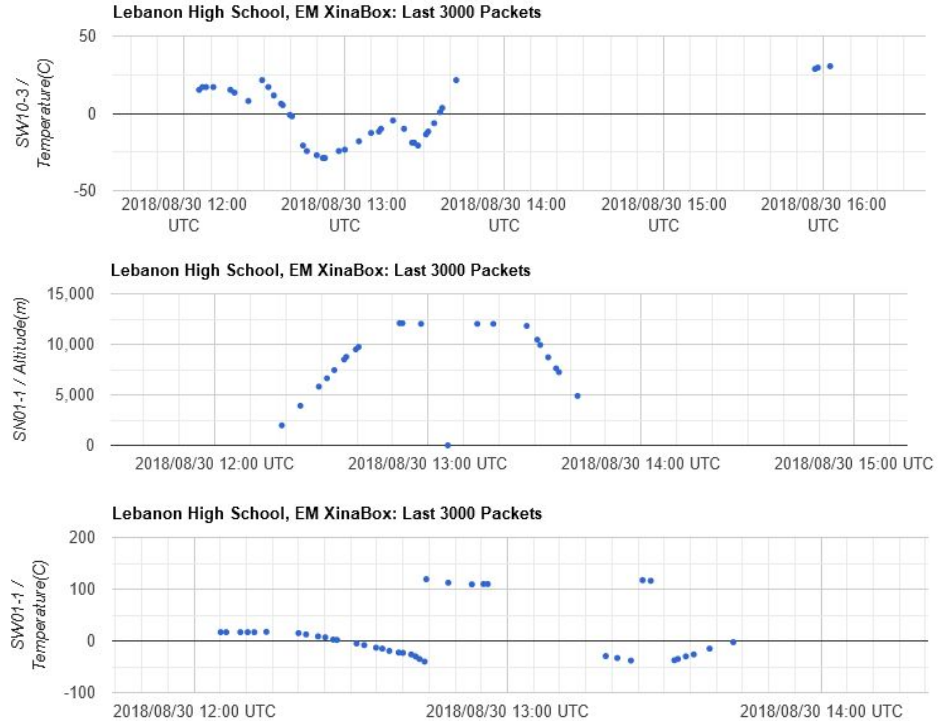
Pathway to Space

1. Communications
 - a. Desired frequency change
 - b. Antennae configuration/deployables
2. Power Systems
 - a. Standby/sleep mode
3. Environmental Considerations
 - a. Op/Survival heater
 - b. Vacuum compatibility
 - c. Connectors

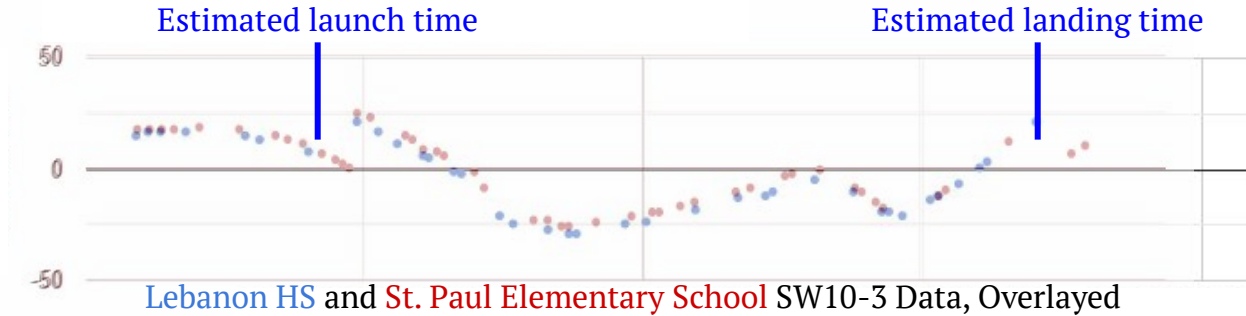


Heritage Data: 8/30/18 Balloon Ops

- NG-11 preparation balloon launch
- Data source: Lebanon HS
 - St. Paul Elementary School corroborates
- Peak reported altitude:
12096 m
- Total mission time:
1 hrs 25 min
- Total drift:
Unknown



Observations on SW10-3 (Temperature)



8/30/18 Balloon Flight

- Good correlation between multiple instrument's common sensor
- Minimum reported temperature of -28.9 C is trustworthy
- No obvious gaps or errors in reported data during flight

Observations on SW01-1 (Temperature)

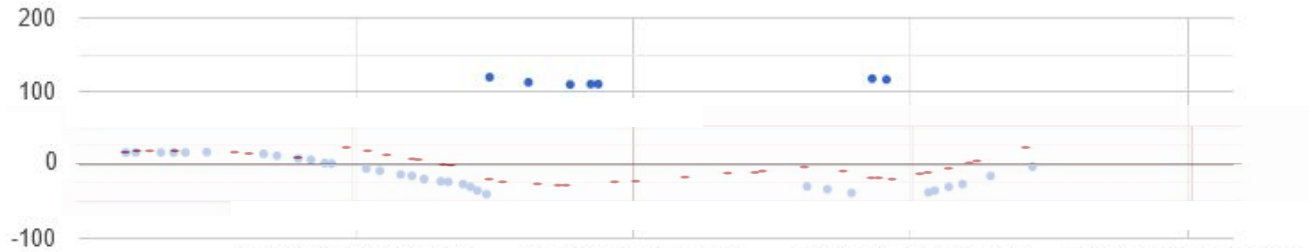


Lebanon HS and St. Paul Elementary School SW01-1 Data, Overlaid

8/30/18 Balloon Flight

- Good correlation between multiple instrument's common sensor
- Reported temperature jumps to ~120 C upon reaching -40 C
 - Returns to providing expected readings when above -40 C
- Hypothesis: Software error on voltage to temperature calculation results in incorrect reported temperature

SW01-1 vs SW10-3

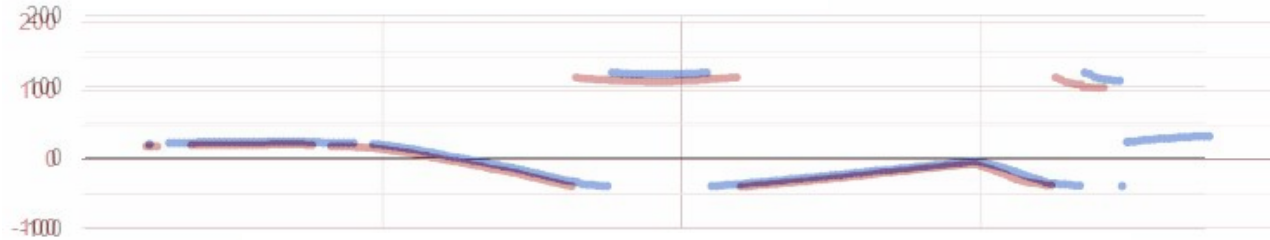


Lebanon HS SW01-1 and SW10-3 Data, Overlaid

8/30/18 Balloon Flight

- General reported trend is the same, but SW01-1 consistently reports lower temperatures than SW10-3
- Hypothesis: Sensors are located in different areas
 - Maybe SW01-1 is external to the ThinSat
 - Working with NSL to confirm

SW01-1 Temperature Sensor in 2019

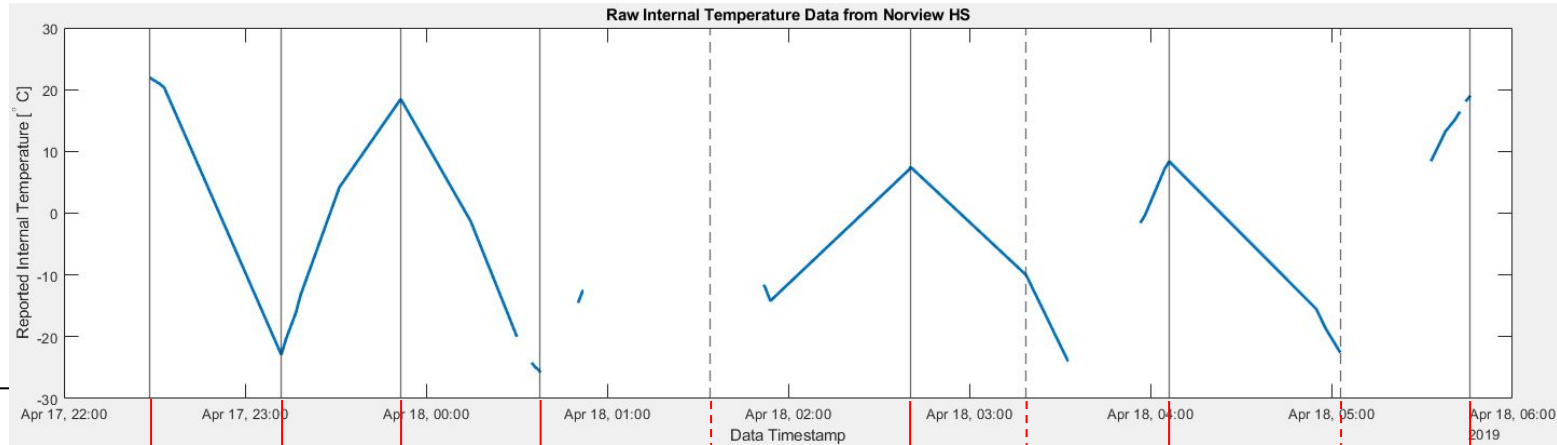


Princeton High School and Thomas Jefferson High School SW01-1 Data, Overlaid

9/17/19 Balloon Flight

- Same behavior as in NG-11 balloon tests in 2018
 - Reported value jumps to low 100s C upon reaching -40 C
 - Returns to expected readings upon returning above -40 C

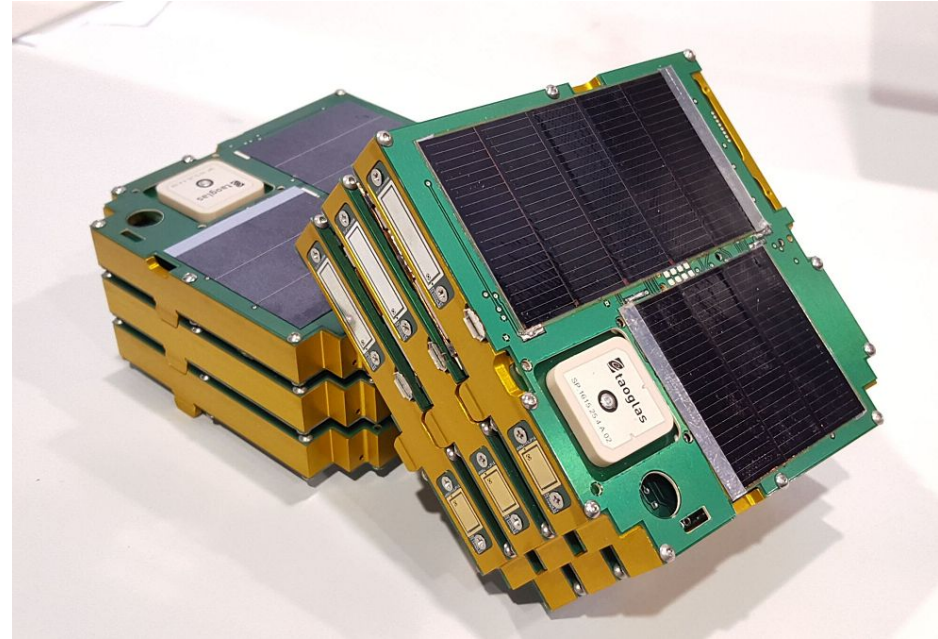
Heritage Data Review: NG-11



- 60 ThinSats on NG-11 mission by Northrop Grumman
- Temperature data from 2 “payload strings” correlated to orbit period
 - Norwood High School (Old Dominion string)
 - Naval Academy 1, 2, and 3 (Naval Academy string)
- Internal temperature on orbit never reported below -22 C

Heritage Data Review: NG-11

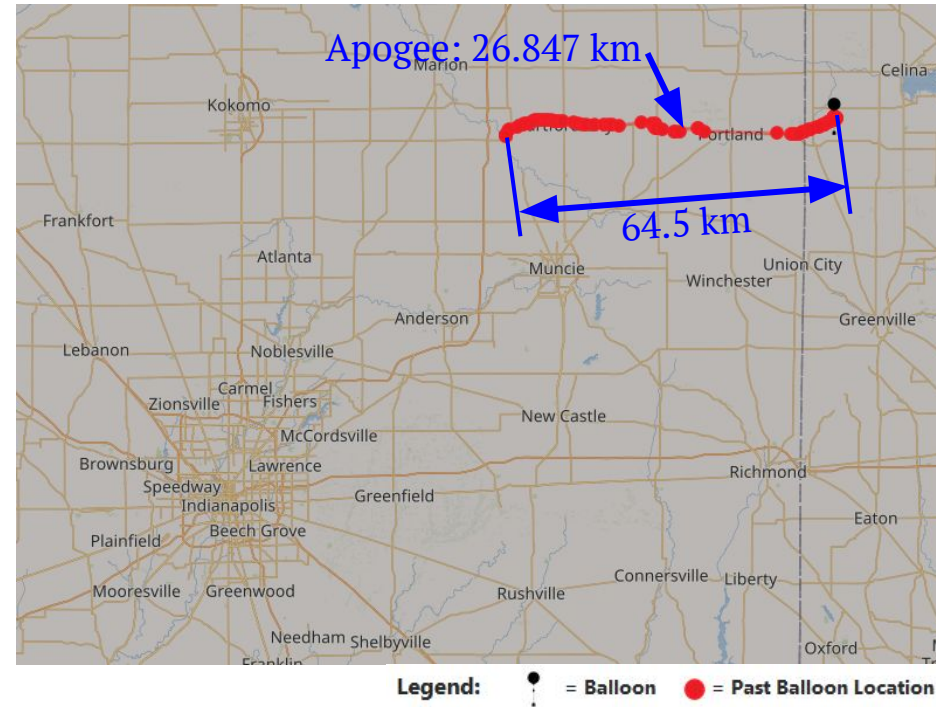
- ThinSat payload released from second stage of NG-11 launch
 - Classified as 'Extremely Low Earth Orbit' (ELEO)
 - 250km x 203km @ 51.6deg
 - Average orbit height: 226.5 km from surface
- Orbit period of specified ELEO orbit:
P = 1 hr 29 min



Flight model ThinSats (3T configuration) prior to NG-11 launch

Heritage Data Review: 10/5 Balloon Ops

- NG-14 balloon ops underway between Oct 2019 and Feb 2020
- Data source: Balloon beacon
- Peak reported altitude: 26847 m
- Total mission time: 2 hrs 6 min
- Total drift: ~65 km



Acronyms

BBB = BeagleBone Black

CCSDS = Consultative Committee for Space Data Systems

CMD=Command

COMM=Communication

CONOPS=Concept of Operations

CU=University of Colorado

C&DH=Command and Data Handling

eMMC=embedded Multi-Media Controller

FAA=Federal Aviation Administration

FBD=Functional Block Diagram

FCC=Federal Communications Commission

FSW=Flight Software

GPIO=General-Purpose Input/Output

ICD=Interface Control Document

IMU=Inertial Measurement Unit

I/O=input/output

LASP=Laboratory for Atmospheric and Space Physics

LEO=Low Earth Orbit

LNA=Low Noise Amplifier

MCU=Micro Controller Unit

OBC=On-Board Computer

OS=Operating System

PCB=Printed Circuit Board

PLA=Polylactic Acid

Pr/No=Power to Noise density ratio

RAM=Random Access Memory

RF=Radio Frequency

RX=Receive

SDK=Software Development Kit

SDR=Software Defined Radio

SMA=SubMiniature version A

TLM=Telemetry

TX=Transceiver

USRP=Universal Software Radio Peripheral

References

- ThinSat orbit parameters: https://space.skyrocket.de/doc_sdat/thinsat-1.htm
- Orbit calculator: <https://keisan.casio.com/exec/system/1224665242>
- ThinSat NG-11 data source: <https://sdd.nsldata.com/>
- Battery Discharge: <https://www.sciencedirect.com/science/article/pii/S0378775304008596>
- Temperature vs Battery Capacity: <https://ieeexplore.ieee.org/abstract/document/1159187>
- Temperature vs Battery Capacity: <https://www.richtek.com/Design%20Support/Technical%20Document/AN024>
- Guide to battery terms: http://web.mit.edu/evt/summary_battery_specifications.pdf
- Wertz, J. R., and Larson, W. J., Space mission analysis and design, Torrance, CA: Microcosm, 2008.
- Rainville, N. (2019). Lab 11: Antennas, Propagation, and Link Design.
- COSMOS Documentation: <https://cosmosrb.com/docs/home/>
- COSMOS GitHub: <https://github.com/BallAerospace/COSMOS>
- KubOS Documentation: <https://docs.kubos.com/1.20.0/index.html>
- KubOS GitHub: <https://github.com/kubos/kubos>
- Thermal Conductivity Chart:
https://www.engineersedge.com/heat_transfer/insulation_material_thermal_conductivity_chart_13170.htm
- PCB Design: CU ECEN5013 Practical PCB Design and Manufacture Fall 2019 Workbook by Eric Bogatin
- MCU board design reference: https://octavosystems.com/octavo_products/osd335x/
- Structural Analysis: “Shigley’s Mechanical Engineering Design”, Ninth Edition, Richard G. Budynas, J. Keith Nisbett Collins et. al., Software defined radio for engineers, Artech House, 2018