Test Readiness Review

INFERNO

INtegrated Flight-Enabled Rover For Natural disaster Observation

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University of Colorado at Boulder
INFERNO
Jet Propulsion Laboratory

JPL
Jet Propulsion Laboratory

Aerospace Engineering

PRESENTATION OUTLINE

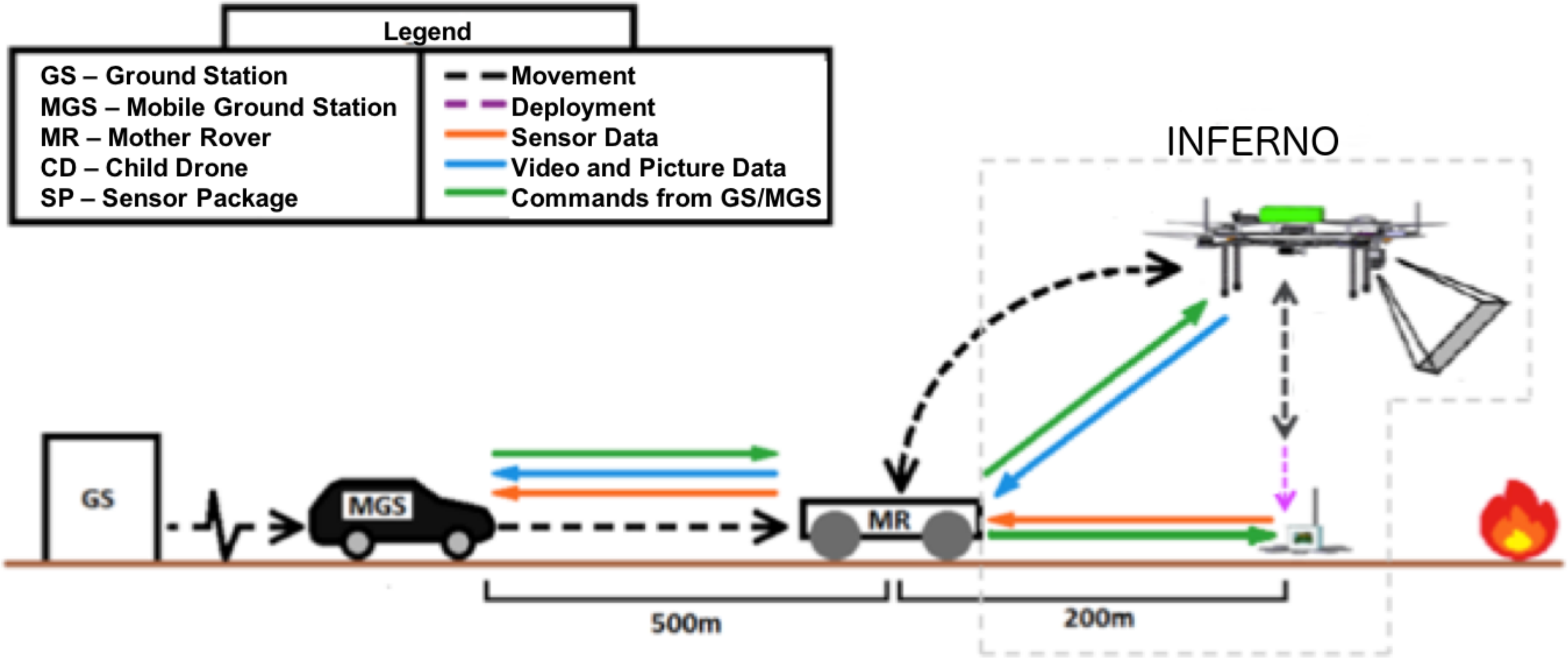
- Project Context
  - CONOPS
  - Levels of Success
  - FBD
  - Baseline Design
  - Critical Project Elements
- Schedule
- Test Readiness
  - Flight Testing
  - Thermal Testing
  - SP Comms Testing
- Financial Status

PROJECT CONTEXT

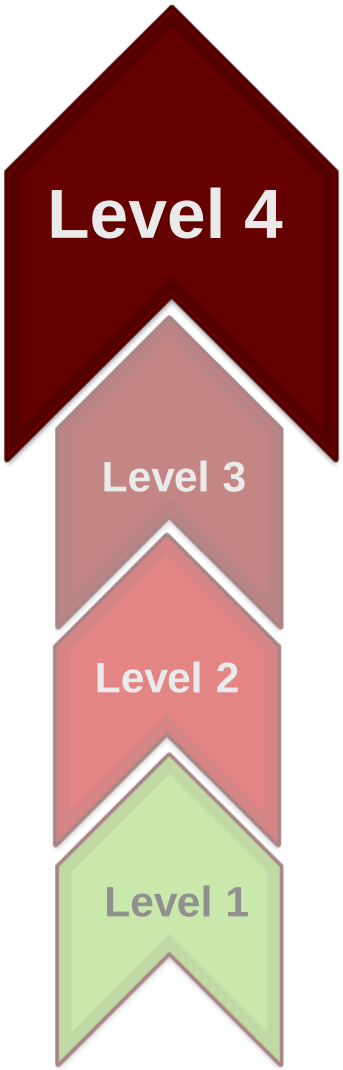
MISSION STATEMENT

Design and create an ***aerial sensor package delivery system*** *for future integration with a natural disaster observation system.*

CONCEPT OF OPERATIONS



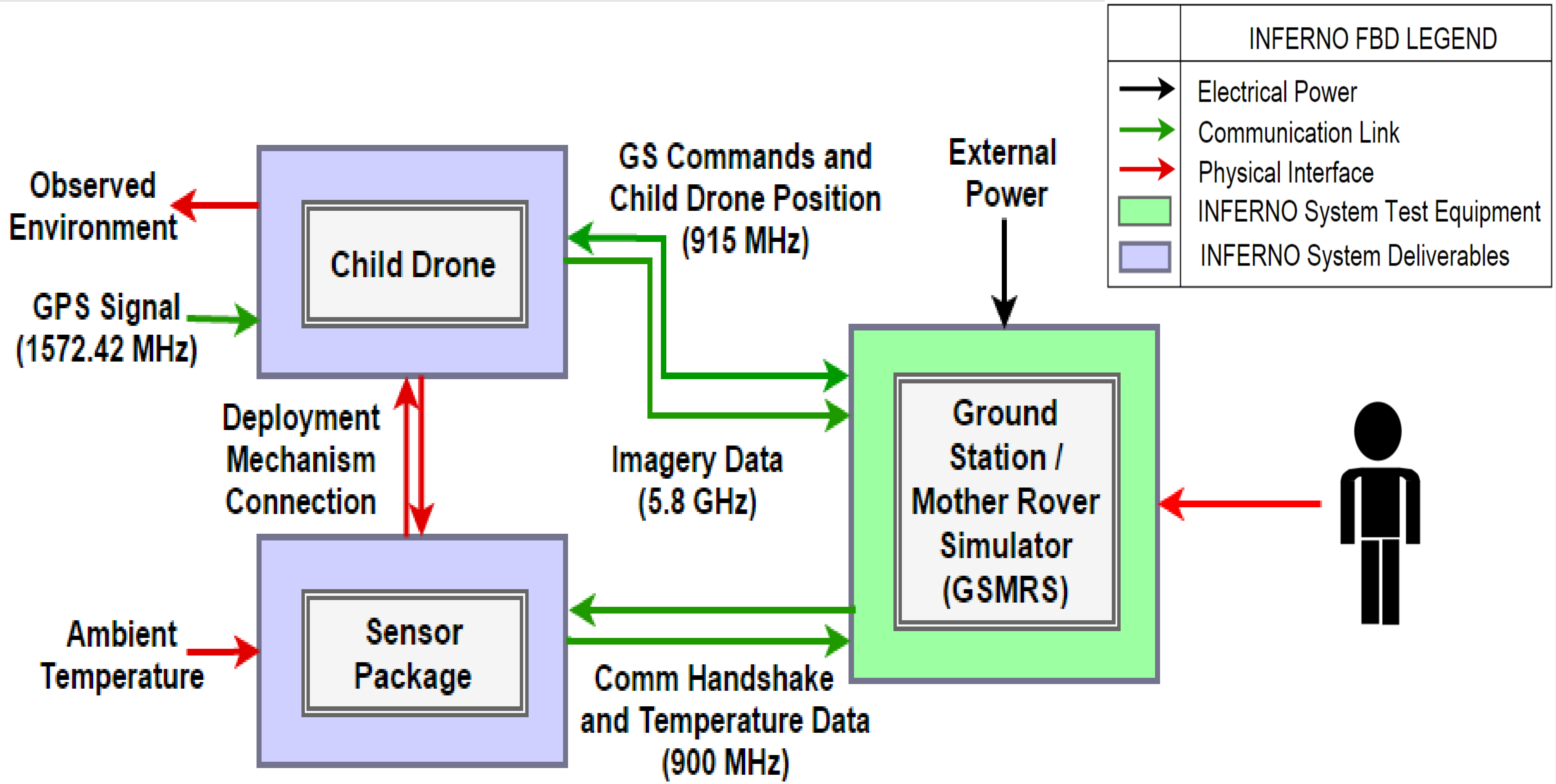
LEVELS OF SUCCESS



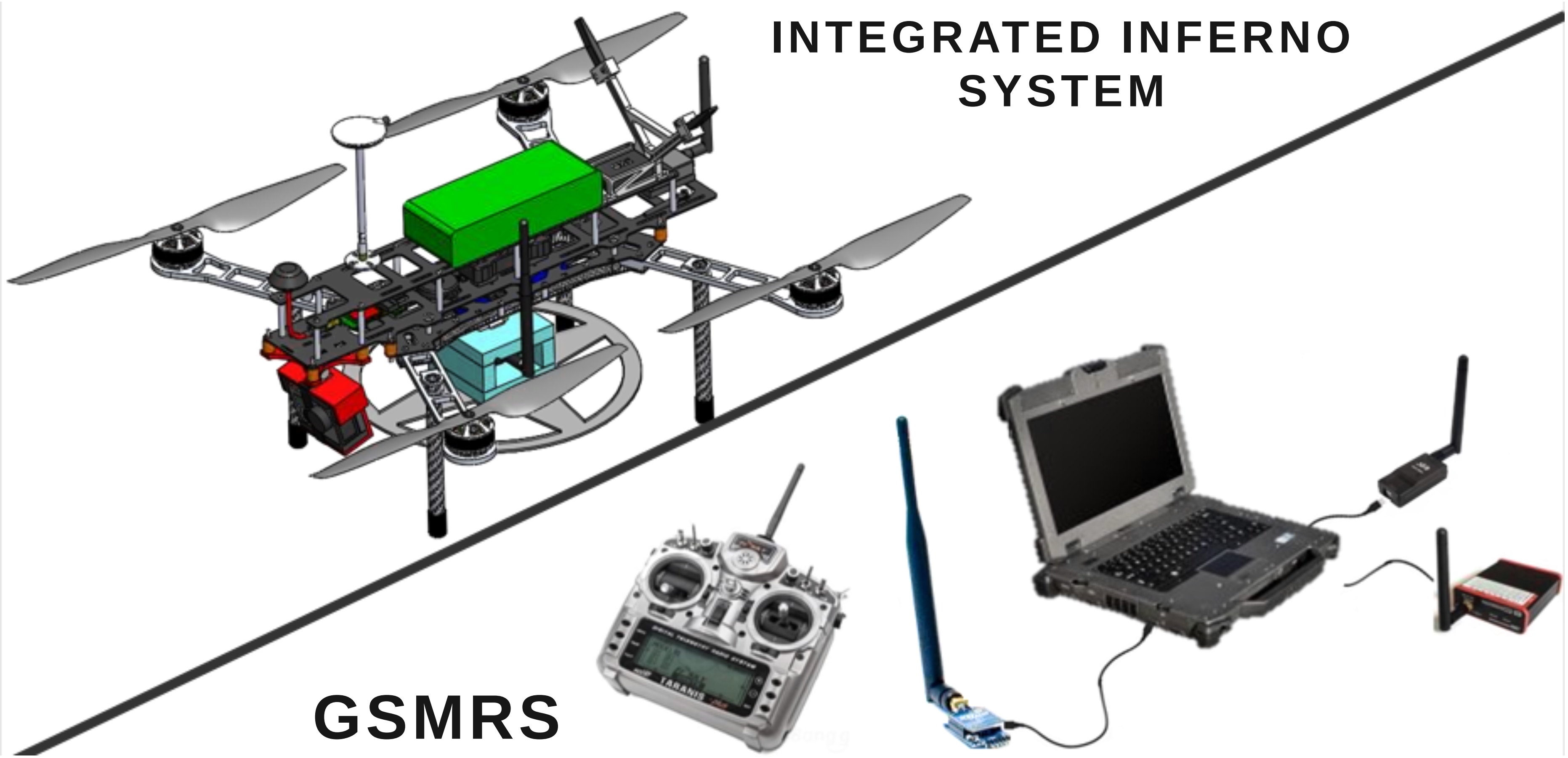
- 10 m/s translational flight
- Landing and deployment within 5 m of LOI on command
- Fully autonomous flight except during final landing
- Time stamped video transmitted at 720 p 30 fps
- >= 90% wireless data transmission from SP to GSMRS at 200 m
- Data retransmission possible
- Data transmission and reception GUI on GSMRS
- Final landing within designated area with 80% confidence

<u>Levels of Success Status:</u>
Currently on track to meet Level 4 Success

FUNCTION BLOCK DIAGRAM: SYSTEM LEVEL



BASELINE DESIGN: INFERNO SYSTEM

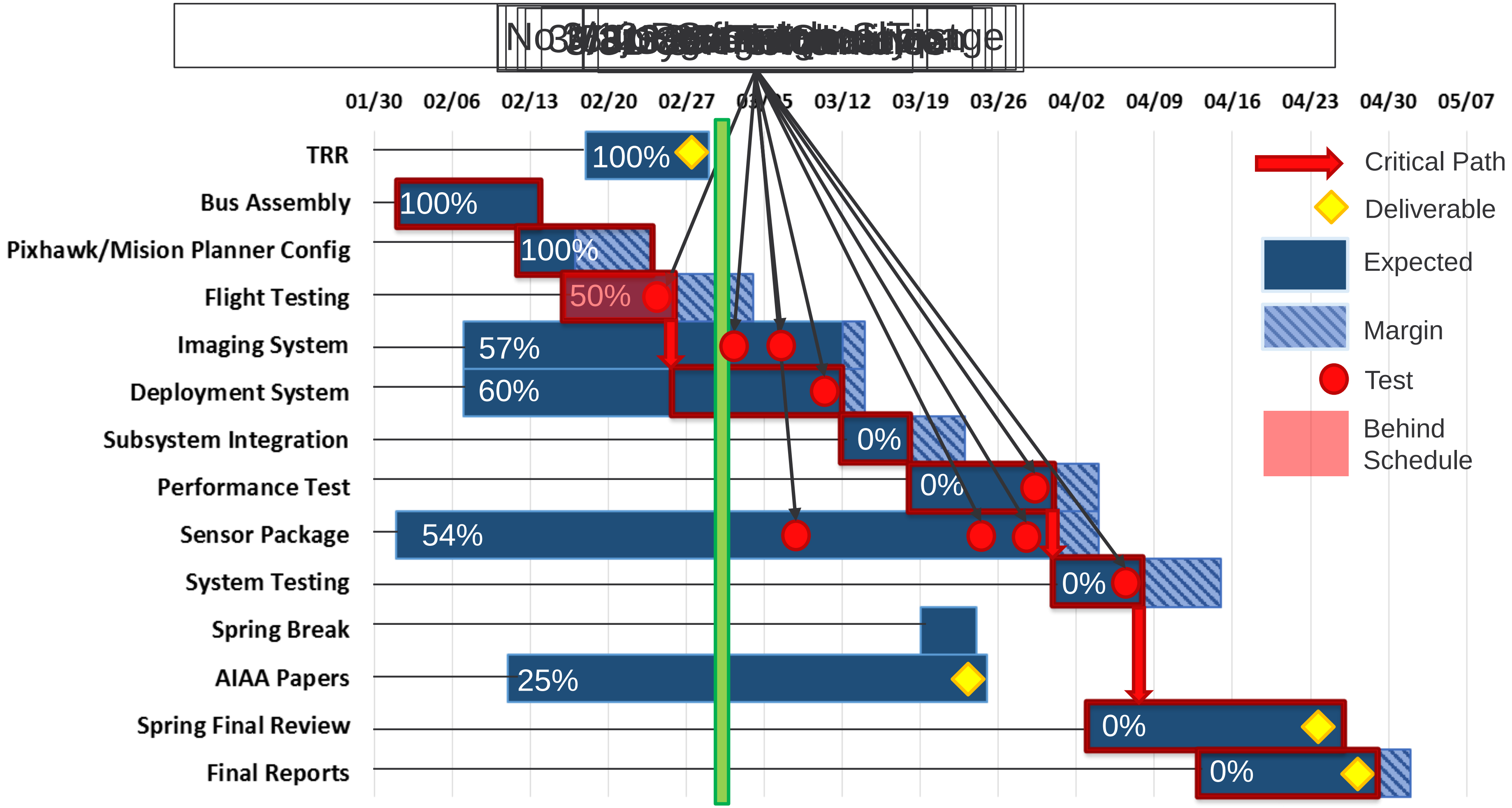


CRITICAL ELEMENTS

Critical Element	Mission Influence
Subsystem Integration	Full mission success is unachievable without compatible integration.
Software Integration	Responsible for command and execution of all systems.
Power Limitations	Subsystems must be able to function for mission duration on limited power supplies.
Communications	Subsystems must be able to send and receive commands and data to ensure mission success and safety.
Scheduling	High number of tests with complicated scheduling procedures are critical to verifying models and requirements

SCHEDULE

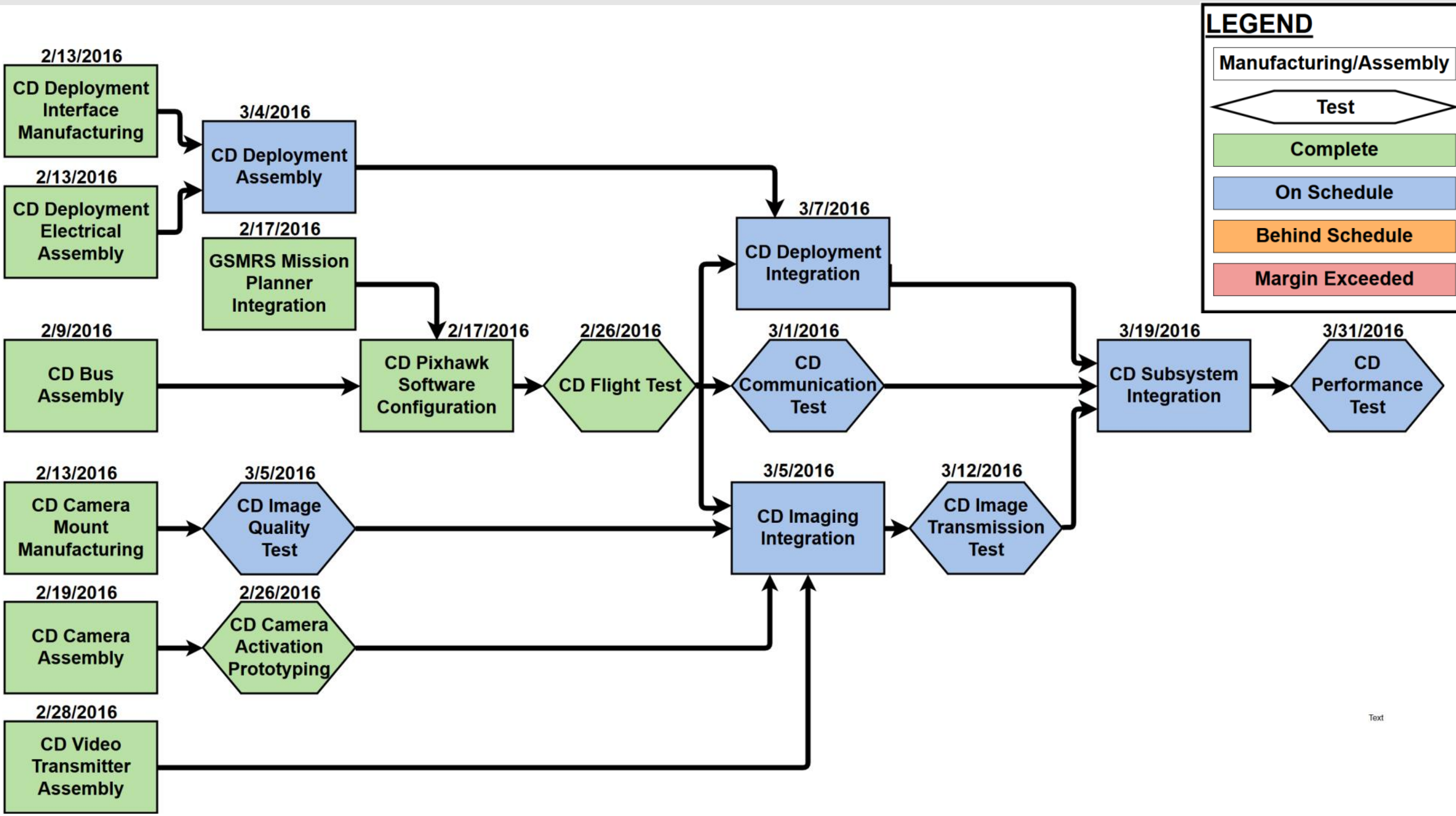
SCHEDULE OVERVIEW



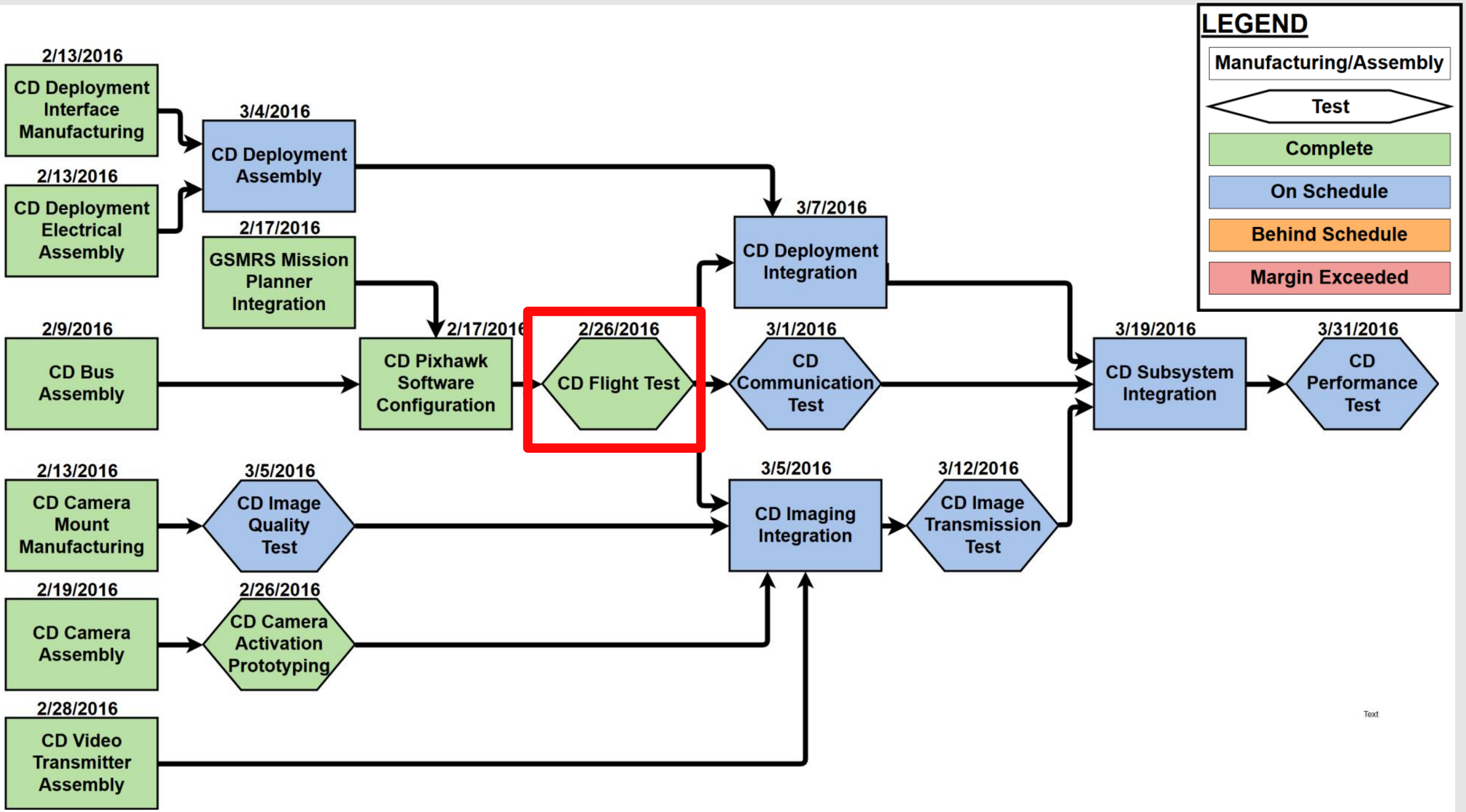
Project Context | Schedule | Flight | Thermal | SP Comms | Financial

TEST READINESS

TEST READINESS: CHILD DRONE OVERVIEW



TEST READINESS: CHILD DRONE OVERVIEW



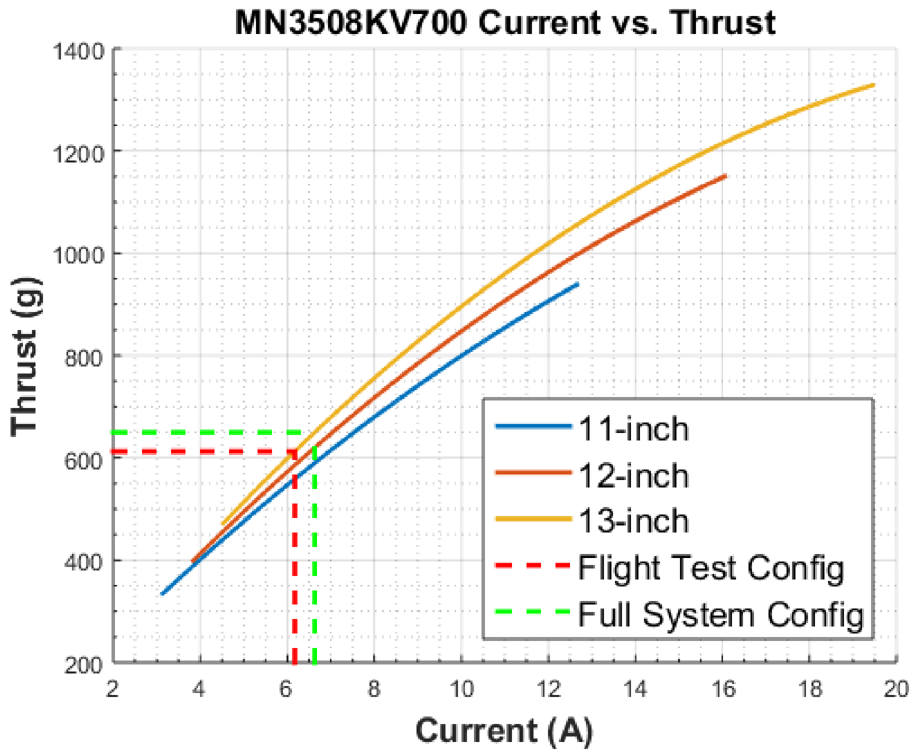
TEST READINESS: CHILD DRONE FLIGHT TEST

- **PURPOSE**
  - Ensure CD capable of controlled, manual flight by pilot
  - Adjust control gains for optimal responsiveness
- **TESTED MODEL**
  - Child Drone power model
- **KEY DATA**
  - Flight time
  - Current draw/charge consumption
  - Proportional roll/pitch angle/rate gains

Requirements		
Endurance	15 min	**DR** 2.2

CHILD DRONE FLIGHT TEST: POWER MODEL

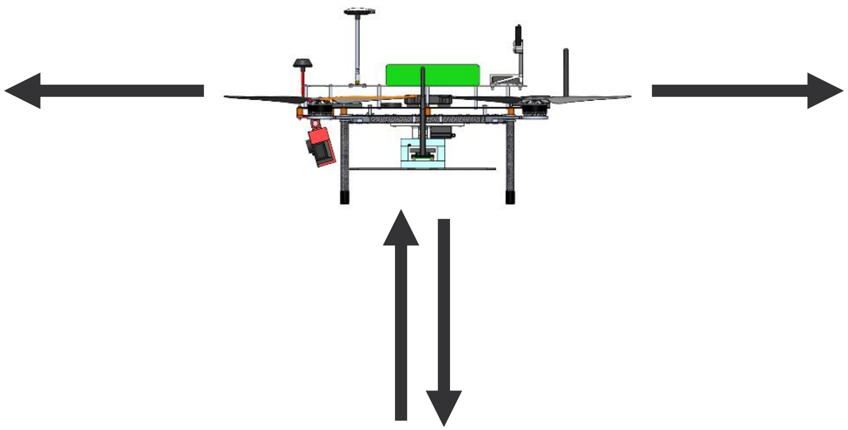
- Manufacturer specs available relating current to thrust for 11” and 12” props
- Polynomial fit to current-thrust curves
  - $T_{11} = f(I)$ $T_{12} = g(I)$
- Thrust curves scaled linearly from 11” and 12” to 13”
  - $T_{13}(I) = 2T_{11}(I) - T_{12}(I)$
- Min/max current scaled linearly from 11” and 12” to 13”
  - $I_{13,min} = 2I_{12,min} - I_{11,min}$
  - $I_{13,max} = 2I_{12,max} - I_{11,max}$



Config	Mass (g)	Propulsion (A)	Other (A)	Total (A)	Endurance (min)
Flight Test	2450	24.7	0.18	24.9	19.1
Full System	2600	26.6	0.38	27.0	17.8

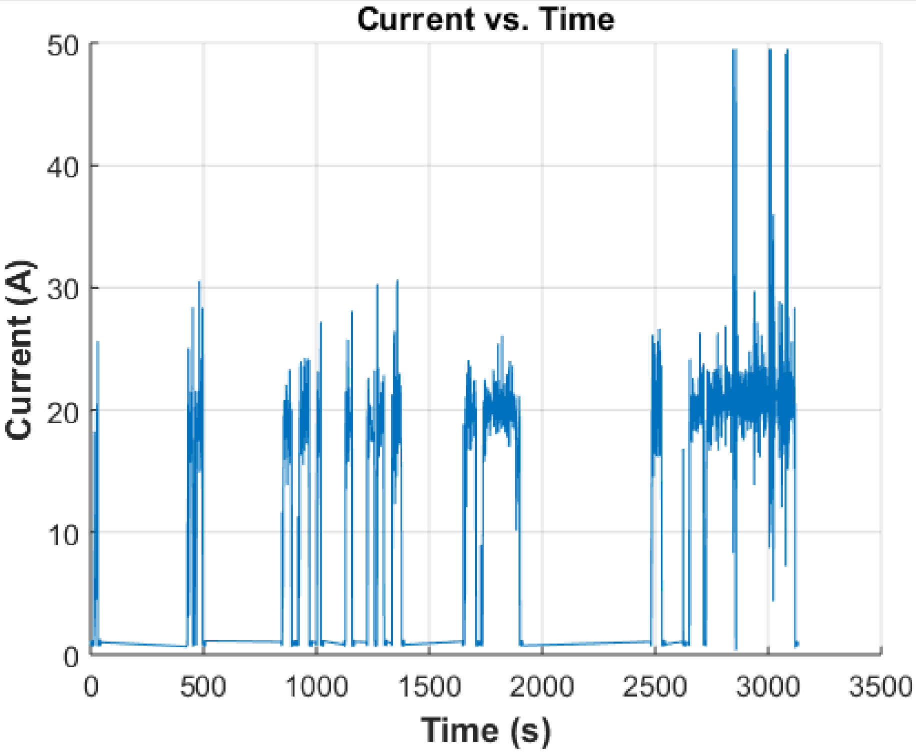
CHILD DRONE FLIGHT TEST: TEST SETUP

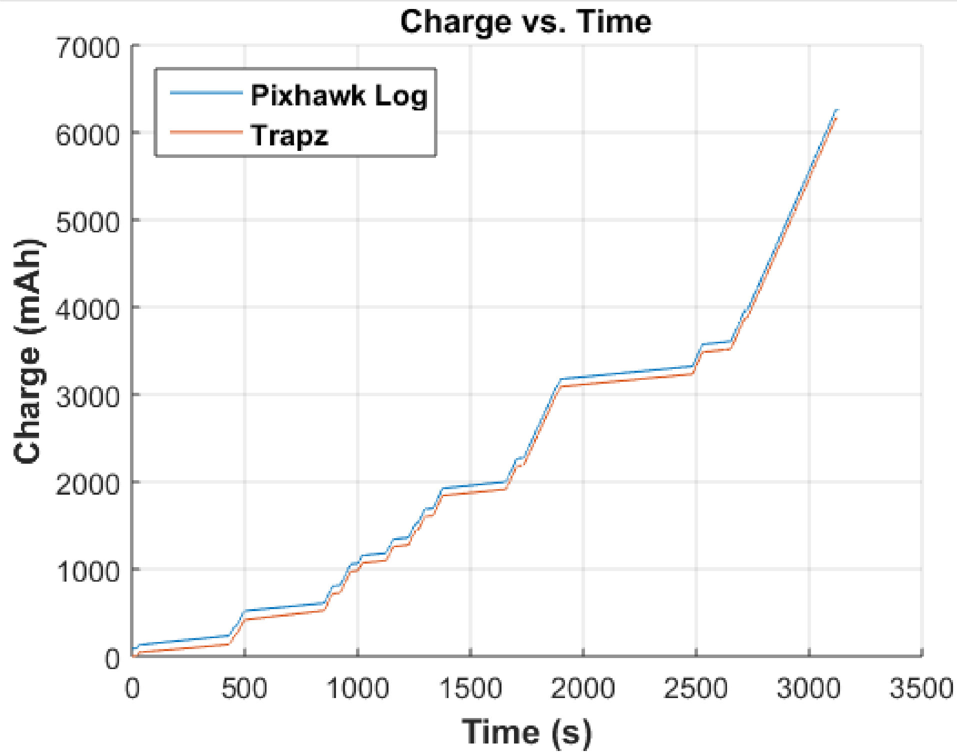
- Conducted at RIFLE (RECUV)
  - CD flown through piloted maneuvers and hover
- Data Collection
  - 3DR Power Module outputs 0 – 3.3 V signal to Pixhawk
  - Pixhawk samples through 12-bit ADC at 10 Hz
  - Pixhawk records telemetry to flash memory while propulsion is armed



Data		
Total Current	3DR Power Module Pixhawk	Range: 0 – 60 A Error: ±2 A Resolution: 14.6 mA
Time	Pixhawk	Sample Rate: 10 Hz
Charge Consumed	Pixhawk	Error: integral dependent

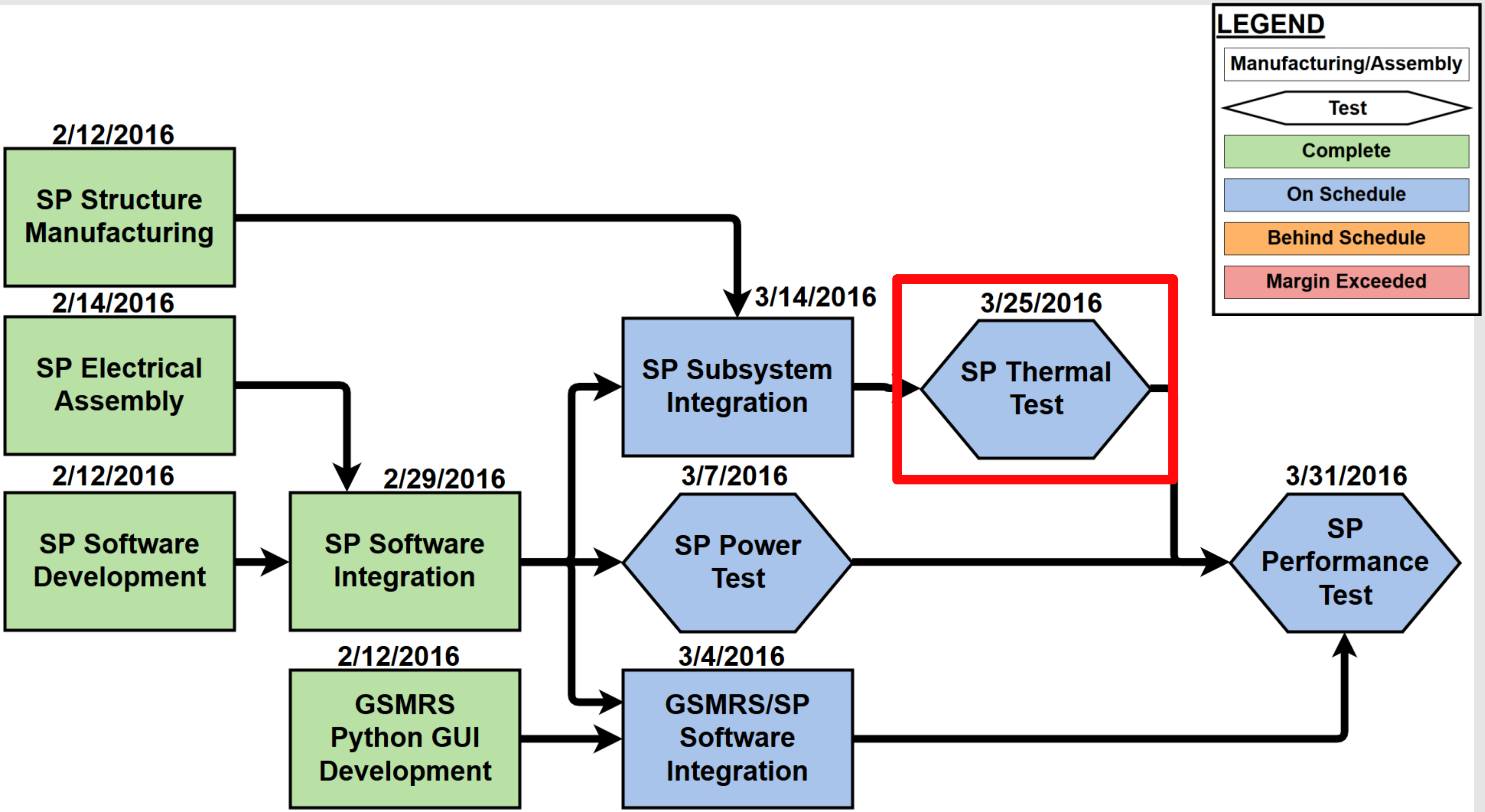
CHILD DRONE FLIGHT TEST DATA REDUCTION





Data	Propulsion (A)	Other (A)	Total (A)	Endurance (min)
Predicted	24.7	0.18	24.9	19.1
Recorded	18.9	0.50	19.4	**24.7 ± 0.1**

TEST READINESS: SENSOR PACKAGE OVERVIEW



THERMAL CHAMBER TEST

- Purpose
  - Verify SP temperature sensor range, accuracy, precision, sample rate and storage.
- Model
  - Sensor package internal temperature remains between 1.1 – 4.4 ºC above ambient temperature.

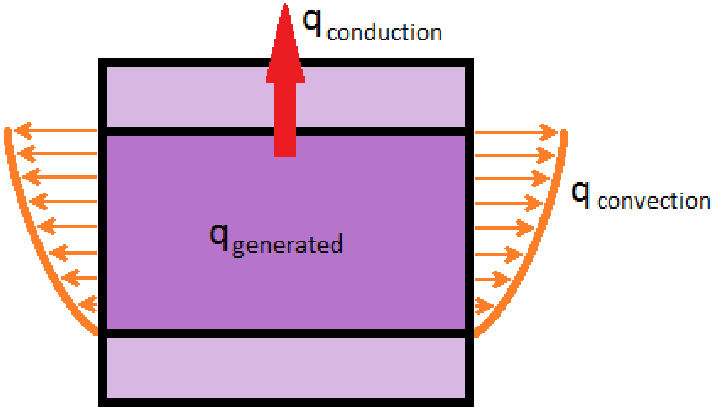
Requirements		
Range	10 – 47.8 ºC	**DR** 1.1.1
Accuracy	± 2.78 ºC	**DR** 1.1.1
Sample Frequency	1 Hz	**DR** 1.1.3
Storage	3600 data points	**DR** 1.1.2

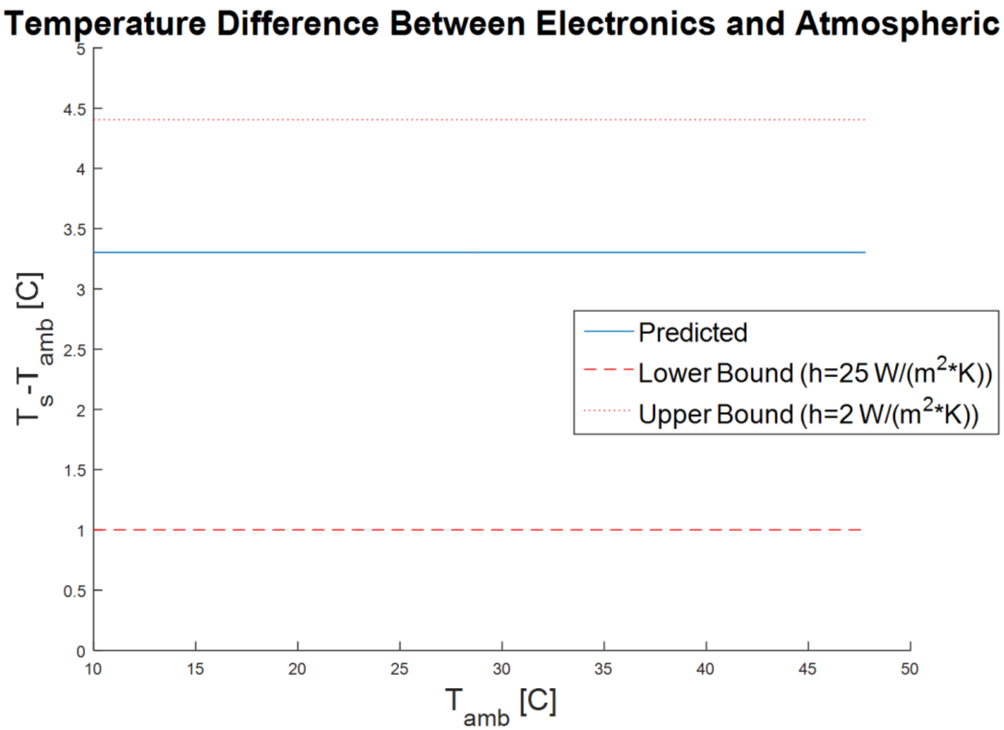
$$q_{generated} = q_{conduction} + q_{convection}$$

$$q_{conduction} = \frac{k}{t} A(T_s - T_\infty)$$

$$q_{convection} = \bar{h} A(T_s - T_\infty)$$

- Major Assumptions:
  - 1D heat transfer
  - Vertical plate free convection
  - Steady state
  - Uniform internal SP temp



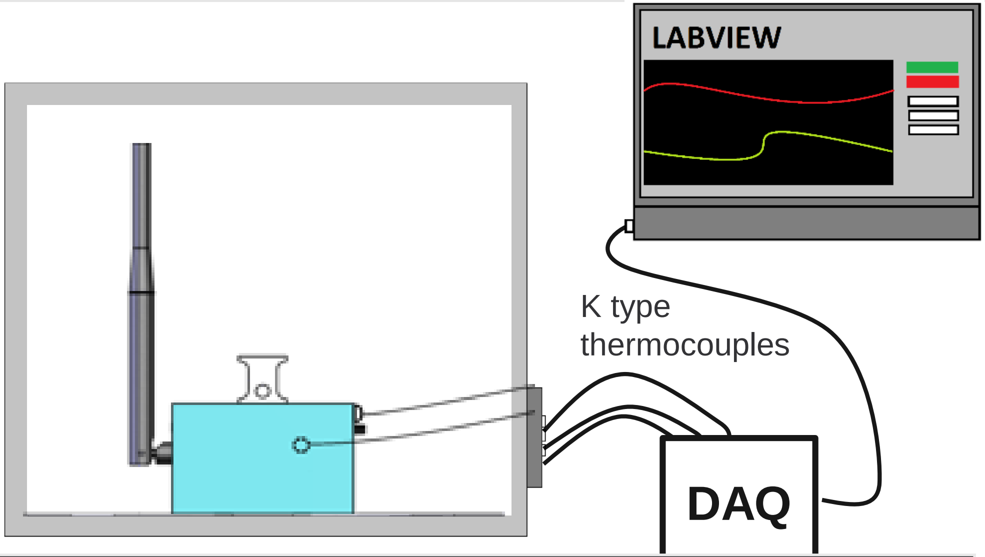


Results:
- In the operational temperature range (10-47.8 ºC), SP internal temperature remains within 3.3 ºC above ambient
- Upper and lower bound determined by typical free convection coefficients for air
  - 1.1-4.4 ºC

THERMAL CHAMBER TEST: TEST SETUP

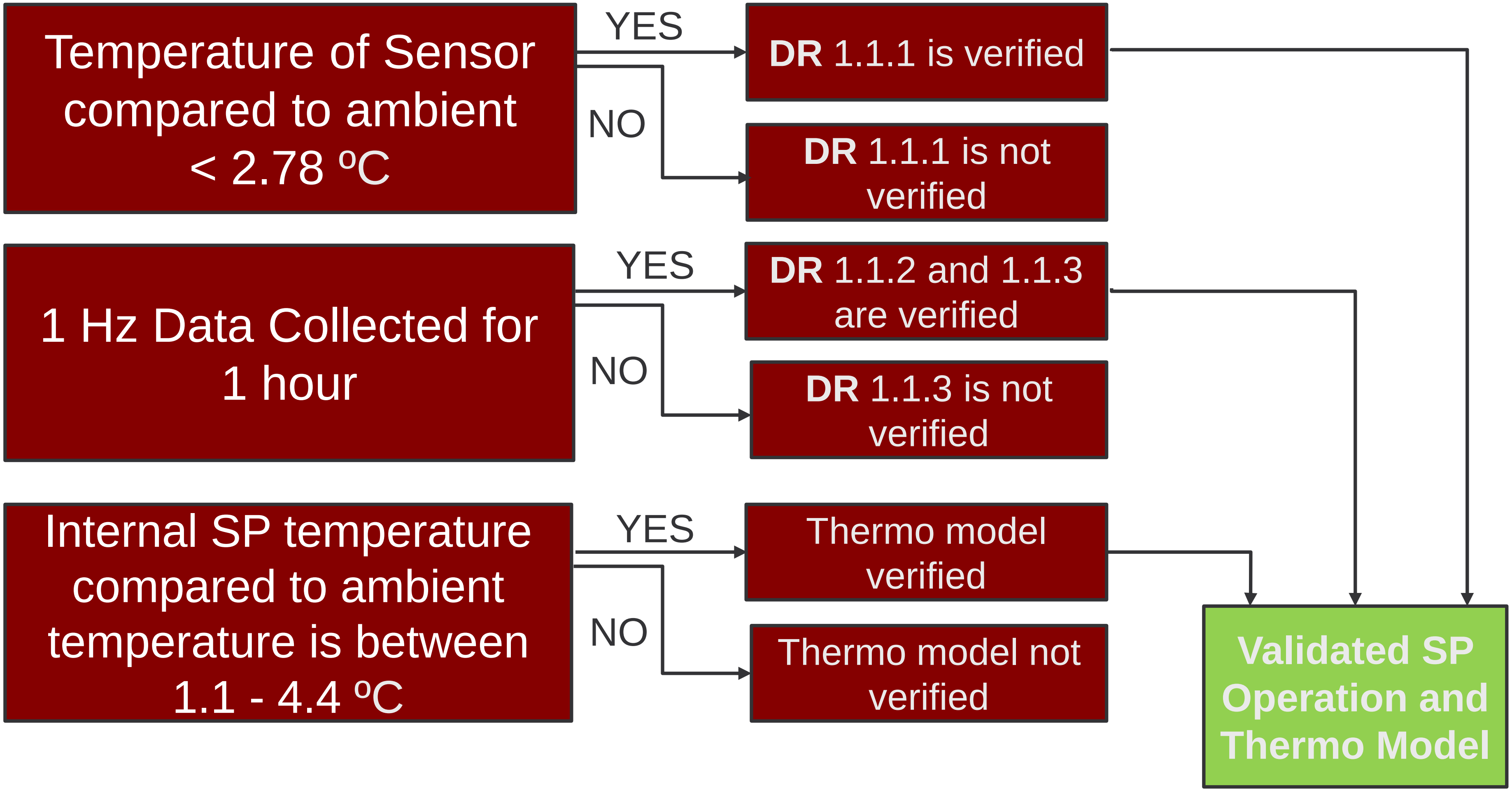
- Equipment
  - Thermal Chamber
  - K type thermocouples
  - Data Acquisition module
  - Computer with LabView GUI
    - Equipment provided by ASEN staff

SP running and operational but will transmit no data during test (XBee Idle)

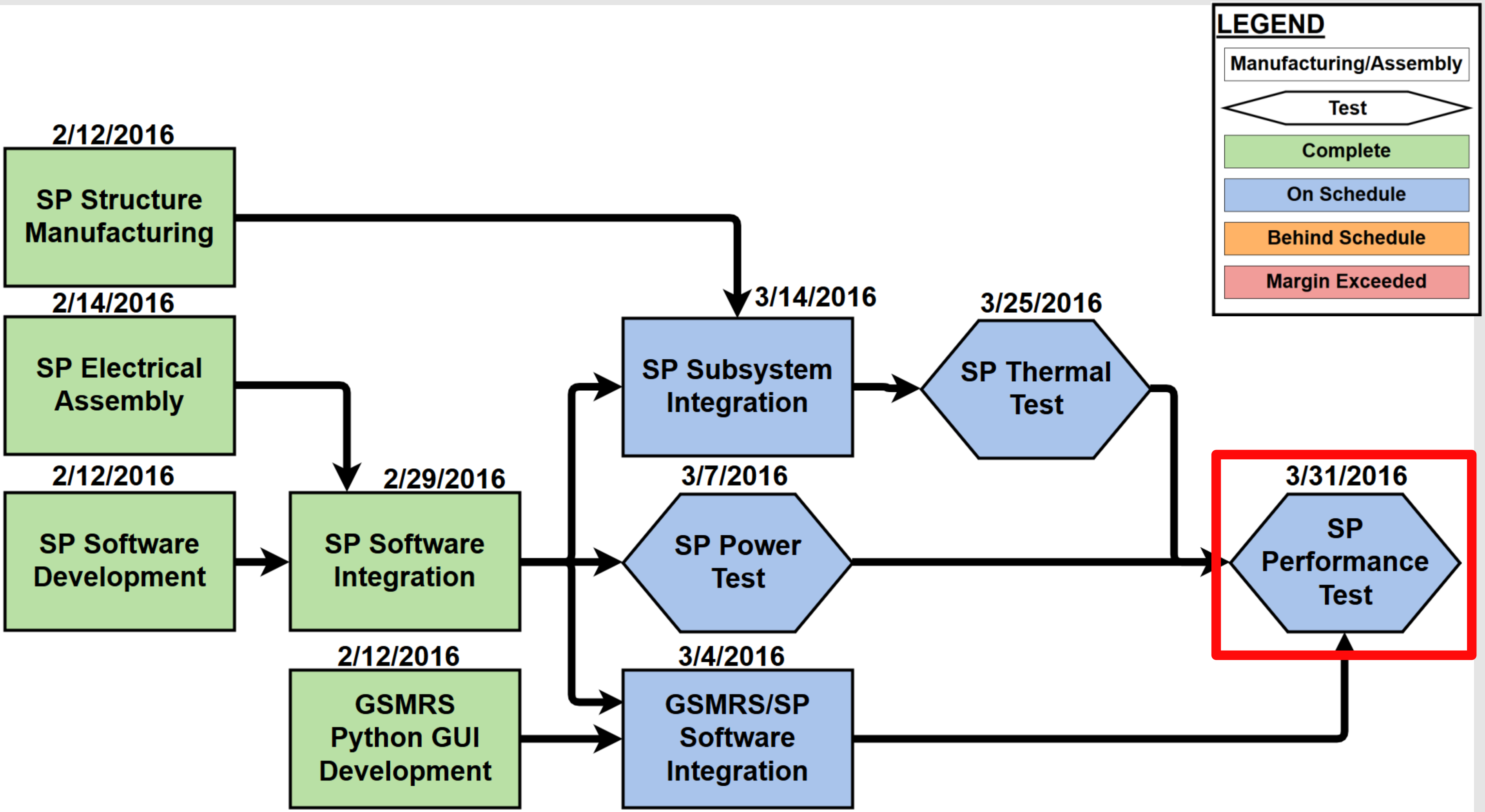


Data		
Internal	K type thermocouple	Range: 0 – 1260 ºC Error: ± 2.2 ºC Resolution: 7.5*10^-5 ºC
Ambient	K type thermocouple	
Temperature Sensor Baseline	K type thermocouple	
SP Temperature Sensor	LM34CA	Range: -48 – 120 ºC Error: ± 3 ºC Resolution: 0.04 ºC

THERMAL CHAMBER TEST: SUMMARY



TEST READINESS: SENSOR PACKAGE OVERVIEW



SP COMMUNICATIONS TEST

- Purpose
  - Verify SP communications model at various distances from GSMRS
- Requirements
  - Range: 200 m (**DR 5.3**)
  - Success Rate: 90% (**DR 5.3.1**)
- Model
  - Sensor package/GSMRS wireless link has ~50 dB link margin at 200 m and ~56 dB at 100 m

Level 4 success requires ≥ 90% packet reception at 200 meters

SP COMMUNICATIONS TEST: MODEL

Governing Equation:

- Power Received = Power Transmitted + Transmitter Gain + Receiver Gain - Losses

Assumptions:

- Ambient conditions free of rain/snow/fog
- Line of sight transmission
- Isotropic emission from antenna

Verification:

- Measure received signal strength at GSMRS using XCTU software and compare with model
- Post-testing download data from SP memory, compare with received data at GSMRS and compare with previous testing

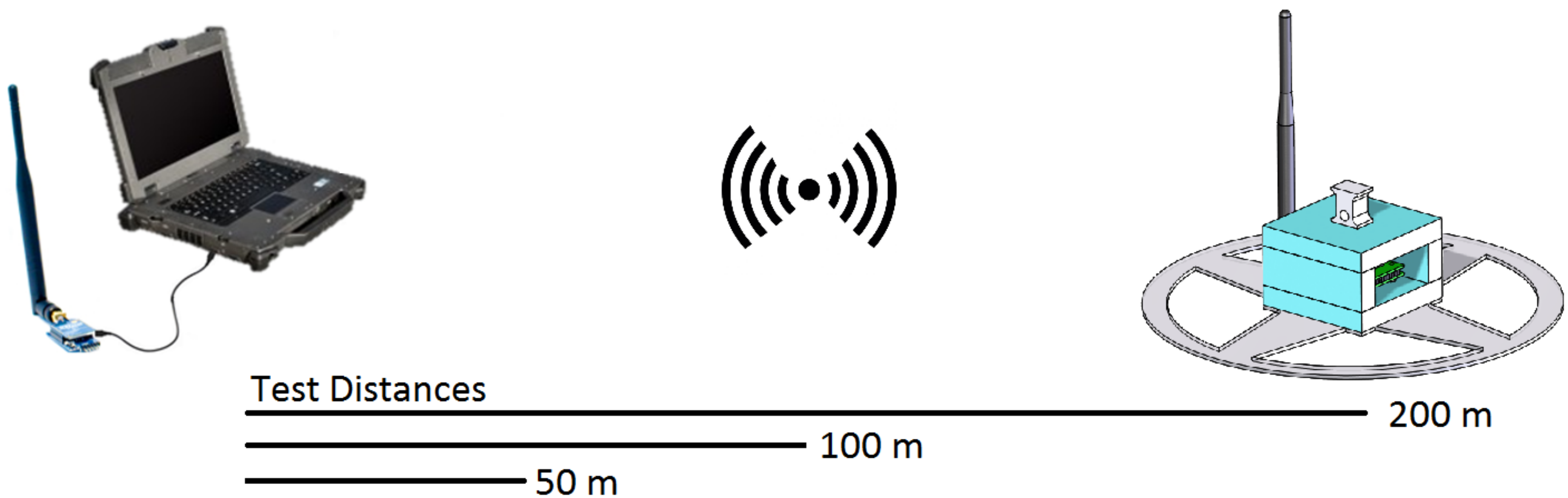
Predictions:

- Received signal strength at:
  - 200 m: ~50 dB
  - 100 m: ~56 dB
  - 50 m: ~62 dB
- Communication model cannot predict packet loss rate
- Previous testing predicts ~95 % packet success rate at 200 m

SP COMMUNICATIONS TEST: TEST SETUP

- Equipment
  - Laptop with XCTU software
- Data
  - Ambient Temperature Data
  - Timestamping

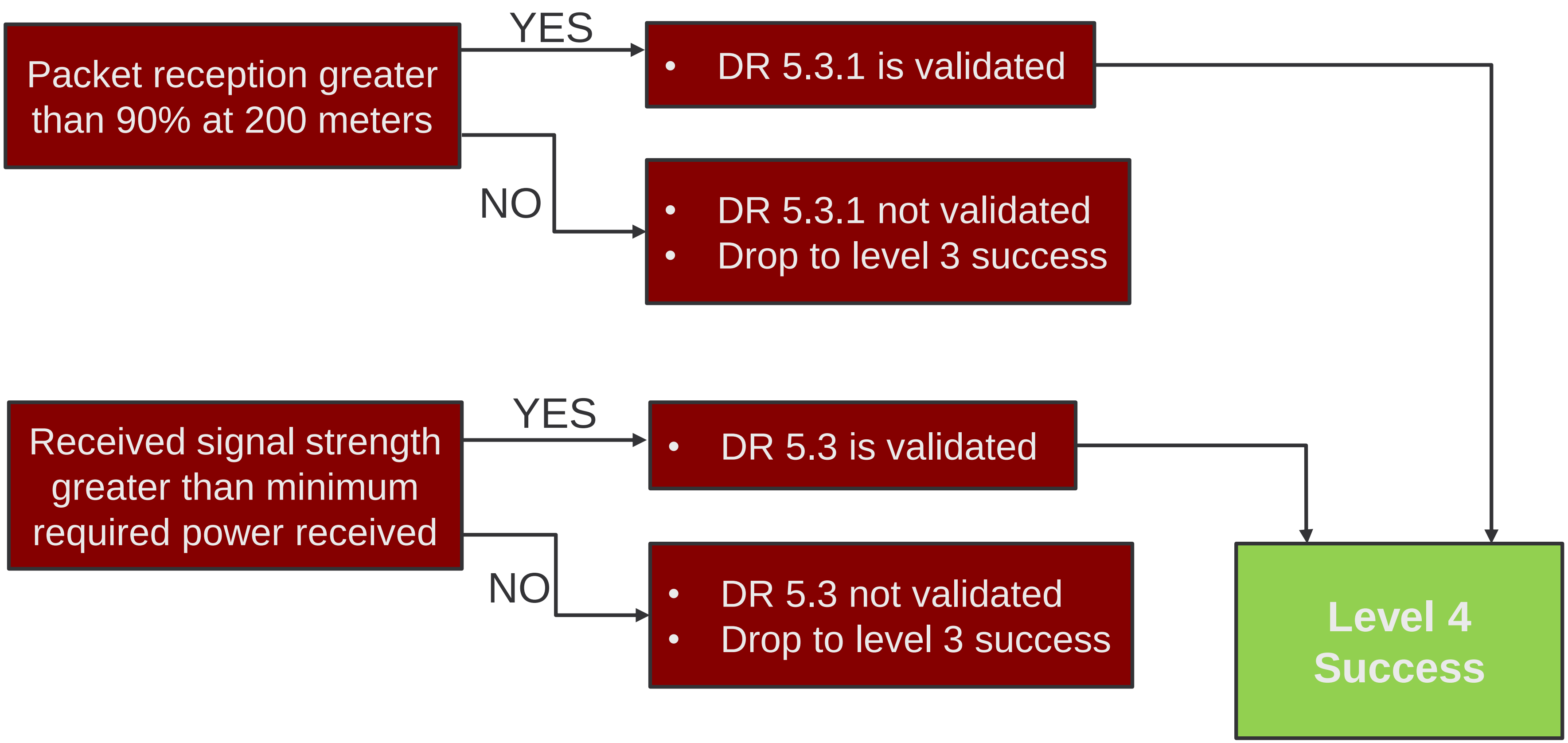
- Procedure
  - Place SP at measured distances from GSMRS
  - Take data at SP and transmit to GSMRS
  - Compare SP data with received GSMRS data



SP COMMUNICATIONS TEST: SUMMARY

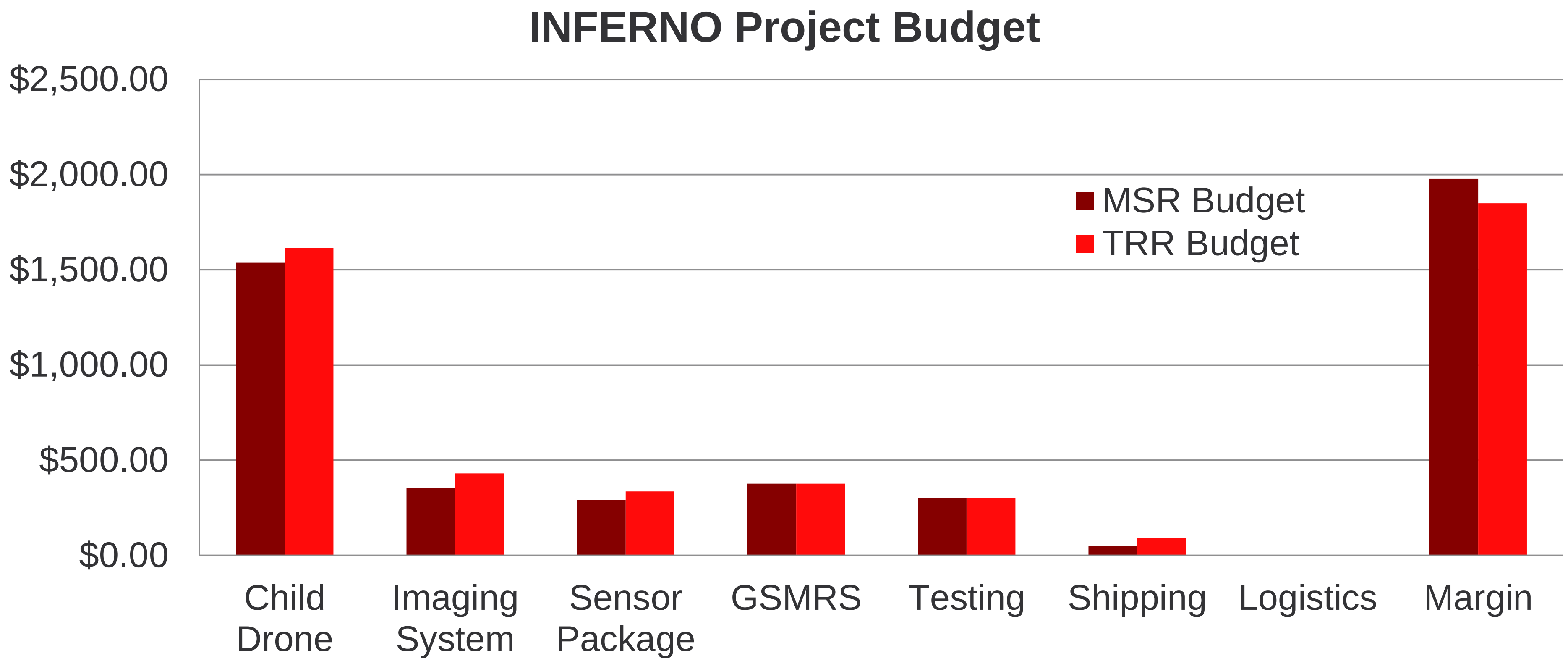
Summary:

- Testing performed at South Campus
- Empirical data compared with model and previous testing



FINANCIAL STATUS

FINANCIAL STATUS: BUDGET



Margin Allocation

- Additional Child Drone batteries and propellers / GoPro Incidental test equipment /replacement components in case of testing failure
- Future logistic costs (printing, report binding, etc.)

Summary:
Under budget with margin allocated for testing incidental costs

FINANCIAL STATUS: PROCUREMENT

PROCURED (As of 2/21/2016)

CHILD DRONE
- Airframe (arms, landing legs, baseplate)
- Propulsion Subsystem (motors, speed controllers, propellers)
- Power Distribution and Battery
- Flight Controller, GPS Unit
- Communication Hardware (X8R, ImmersionRC Transmitter, 3DR Radio Set)
- Imaging Mount Manufacturing and GoPro
- Linear Actuator
- Connectors for interface compatibility

GSMRS
- Communication Links (Taranis, ImmersionRC Uno Receiver, 3DR Radio Set)
- ImmersionRC Uno Battery
- MissionPlanner GS Software

SENSOR PACKAGE
- Communication Hardware (XBees, Antennas)
- LM34CA Temperature Sensors
- Structural Materials (Polycarbonate, Foam)
- PCB Mounting Standoffs
- GM62238-PCB Batteries (x3)

Remaining Procurement Item	Procurement Plan	Total Cost	Estimated Completion Date
Replacement Parts	Order	~$1000	As Needed

SUMMARY

51.43% COMPLETE
502 HOURS REMAINING
READY FOR TESTING

QUESTIONS

BACKUP SLIDES

BACKUP SLIDES CONTENT

- Levels of Success
- CONOPS
- Functional Block Diagrams
- Requirements
- Human Factors Testing
- Mass and Power Model Updates
- Exhaust Stability Model
- Tensile Strength Testing
- SP Structures
- SP Electronics

LEVELS OF SUCCESS

Level 1

- Manually controlled CD flight with simulated payload
- Simulated deployment
- Time-stamped video collected at 420 p at 30 fps
- 8 MP still images taken at 5 second intervals
- Wired communications (SP, Imaging, CD, GSMRS)
- Time stamped temp data at 1 Hz, 8 bit resolution

Level 2

- 10 minute fully loaded flight duration
- Landing and deployment on command
- Wireless communications (SP, Imaging, CD, GSMRS)
- Time-stamped video collected at 720 p at 30 fps
- SP-GSMRS handshake at 200 m
- SP storage of 1 hour of temperature data

LEVELS OF SUCCESS

Level 3

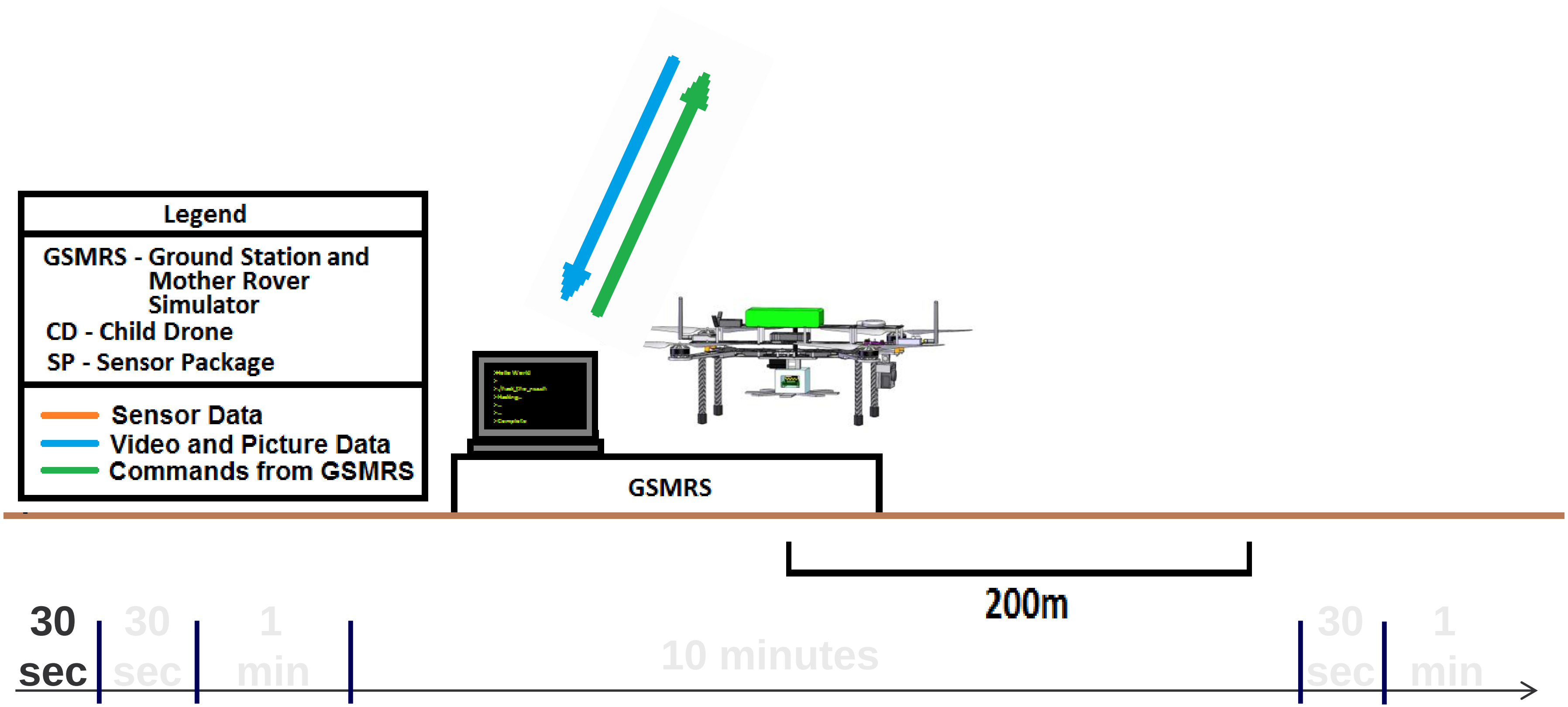
- 15 minute fully loaded flight duration
- 5 m/s translational flight
- Landing and deployment within 10 m of LOI on command
- Time stamped video collected at 1080 p at 30 fps
- >50% wireless data transmission from SP to GSMRS at 200 m
- Final landing within designated area with 50% confidence

Level 4

- 10 m/s translational flight
- Landing and deployment within 5 m of LOI on command
- Fully autonomous flight except during final landing
- Time stamped video transmitted at 720 p 30 fps
- >= 90% wireless data transmission from SP to GSMRS at 200 m
- Data retransmission possible
- Data transmission and reception GUI on GSMRS
- Final landing within designated area with 80% confidence

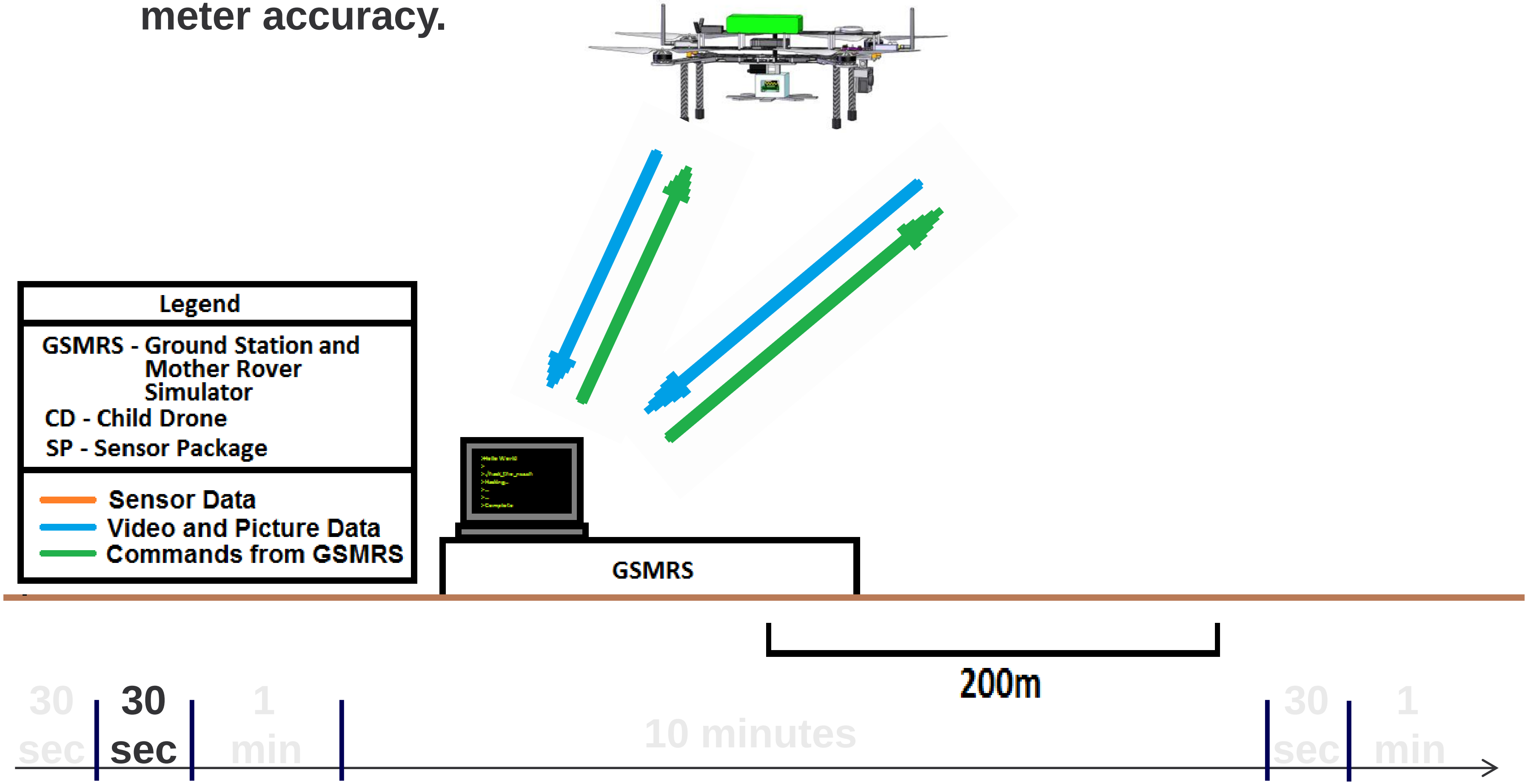
INFERNO SCOPE: CONCEPT OF OPERATIONS

The CD takes off from the GSMRS using autopilot.



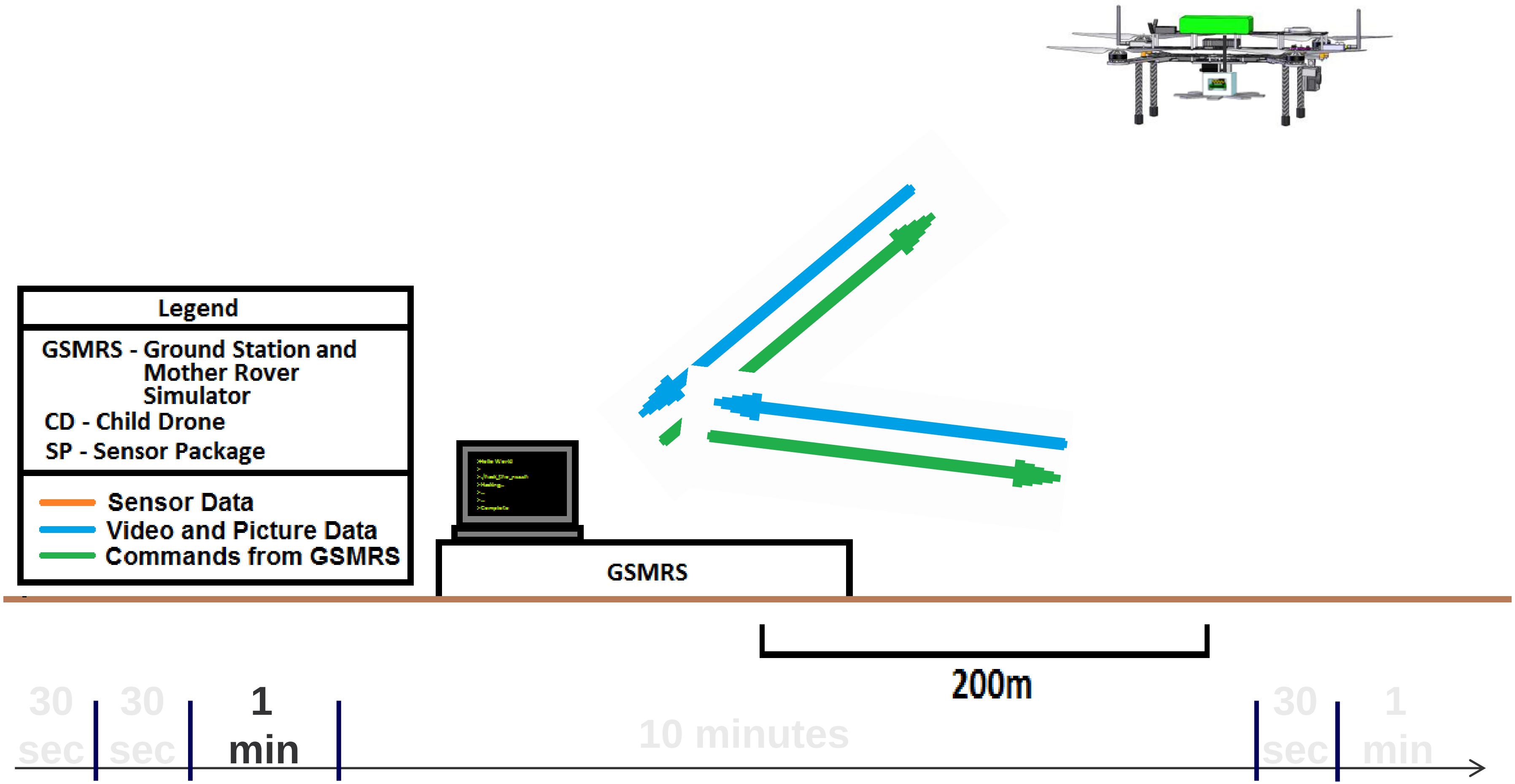
INFERNO SCOPE: CONCEPT OF OPERATIONS

The CD flies to a GPS waypoint up to 200 meters away using autopilot. The CD then maintains its commanded position to 5 meter accuracy.



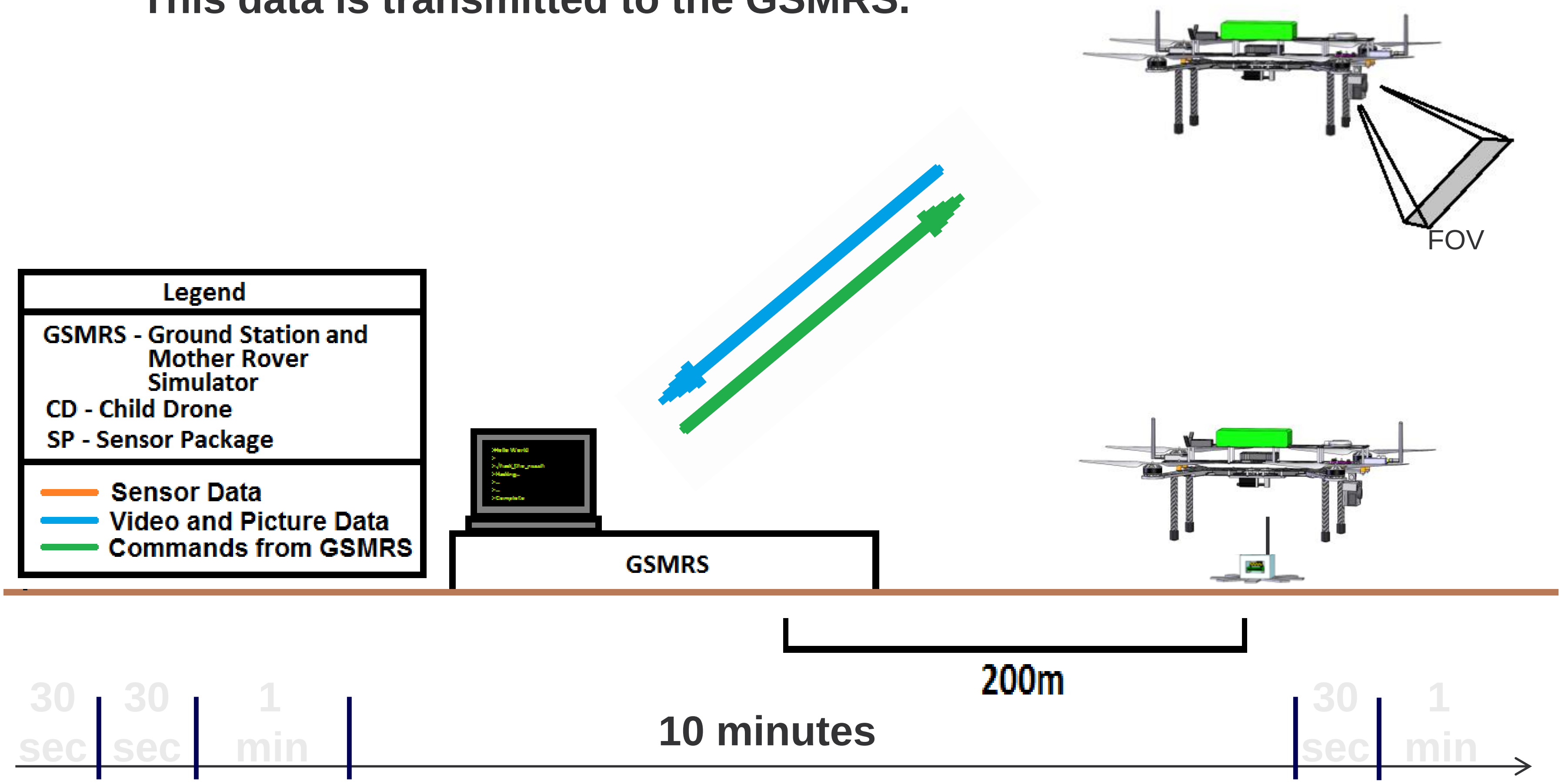
INFERNO SCOPE: CONCEPT OF OPERATIONS

Using autopilot, the CD lands and deploys the SP which begins collecting and storing 1 hour of data.



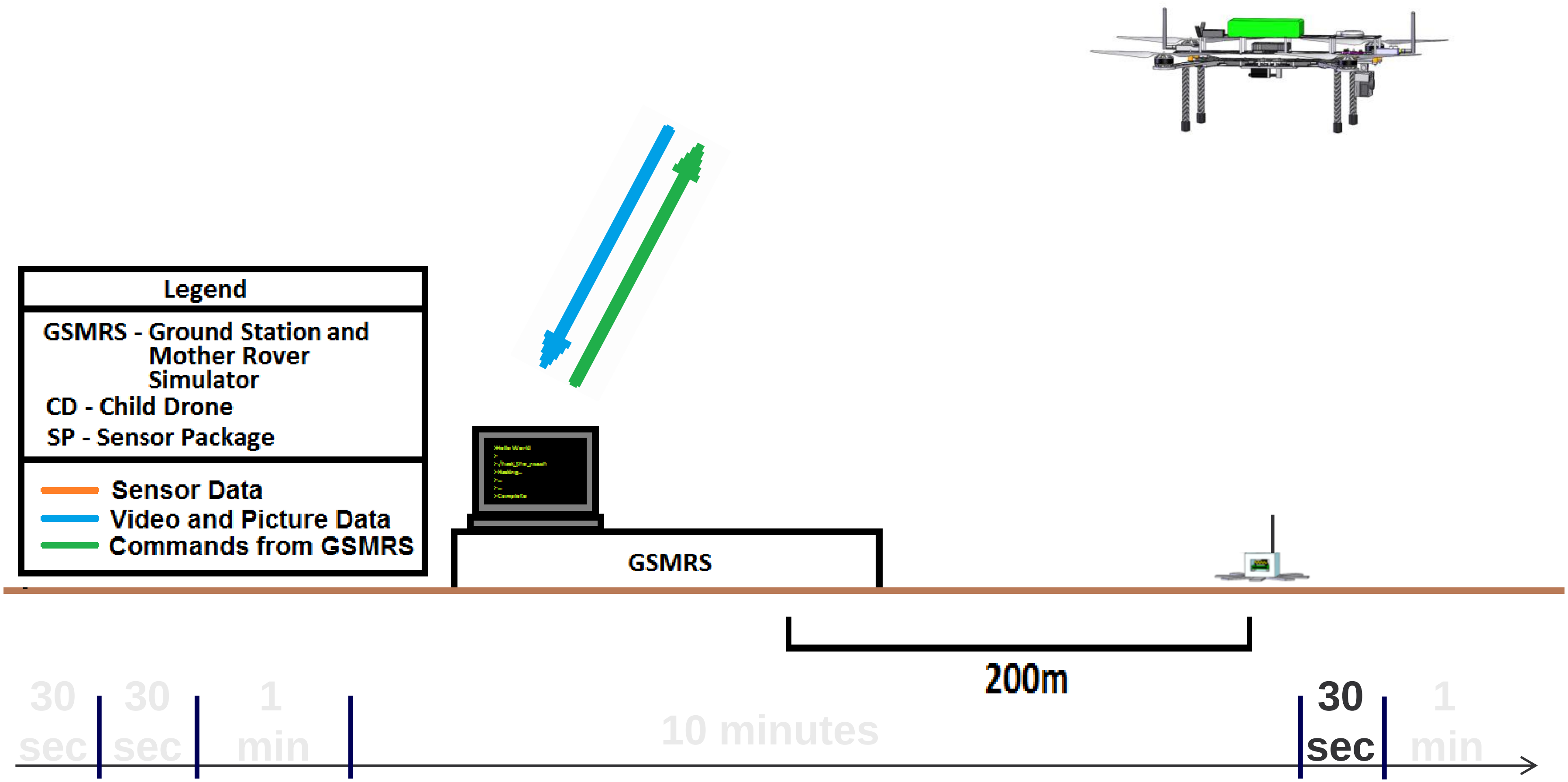
INFERNO SCOPE: CONCEPT OF OPERATIONS

The CD returns to hover using autopilot. It may be commanded to capture video and/or still images at any time. This data is transmitted to the GSMRS.



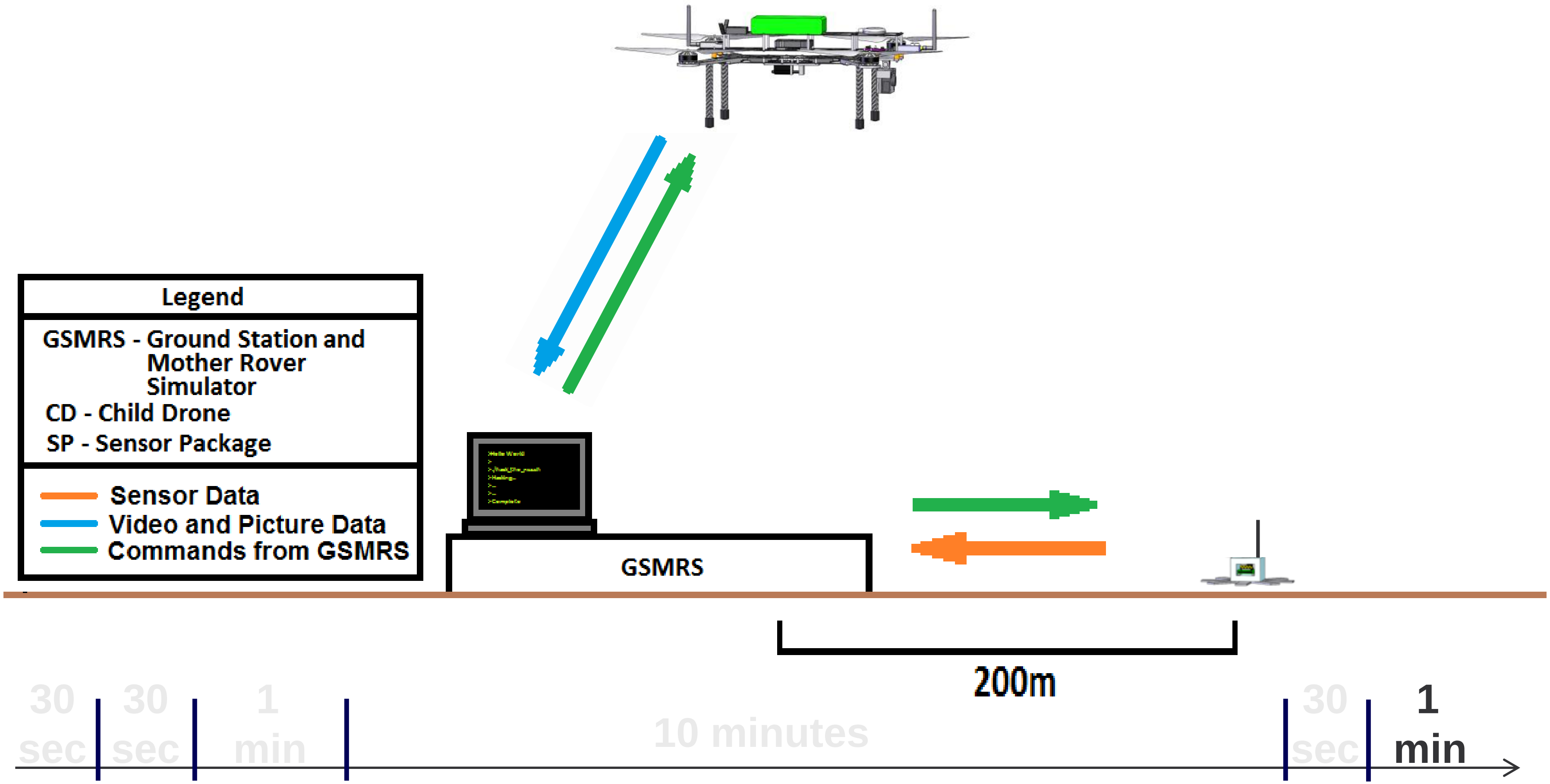
INFERNO SCOPE: CONCEPT OF OPERATIONS

The CD returns to the GSMRS after a 15 minute maximum flight duration using autopilot.

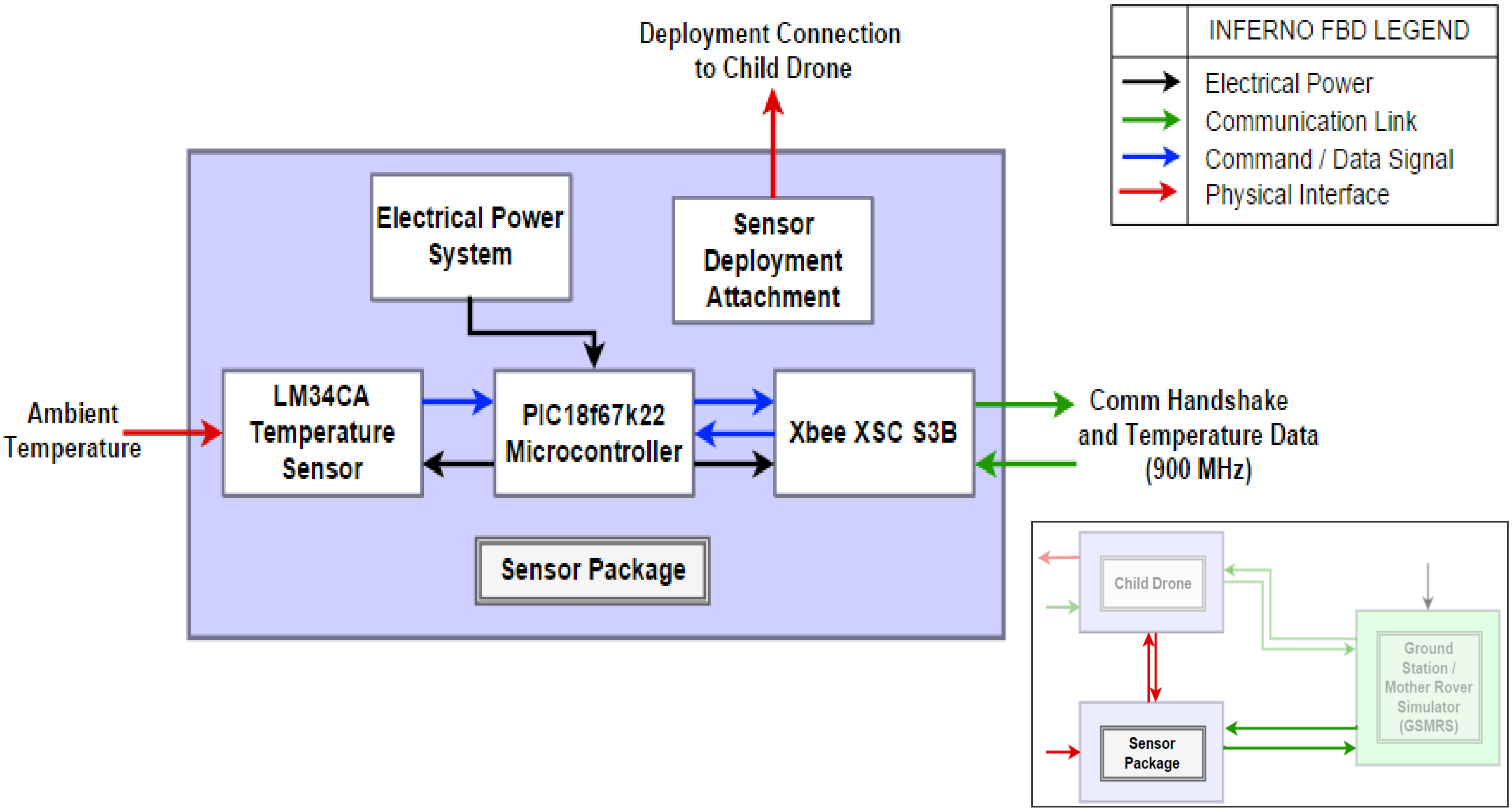


INFERNO SCOPE: CONCEPT OF OPERATIONS

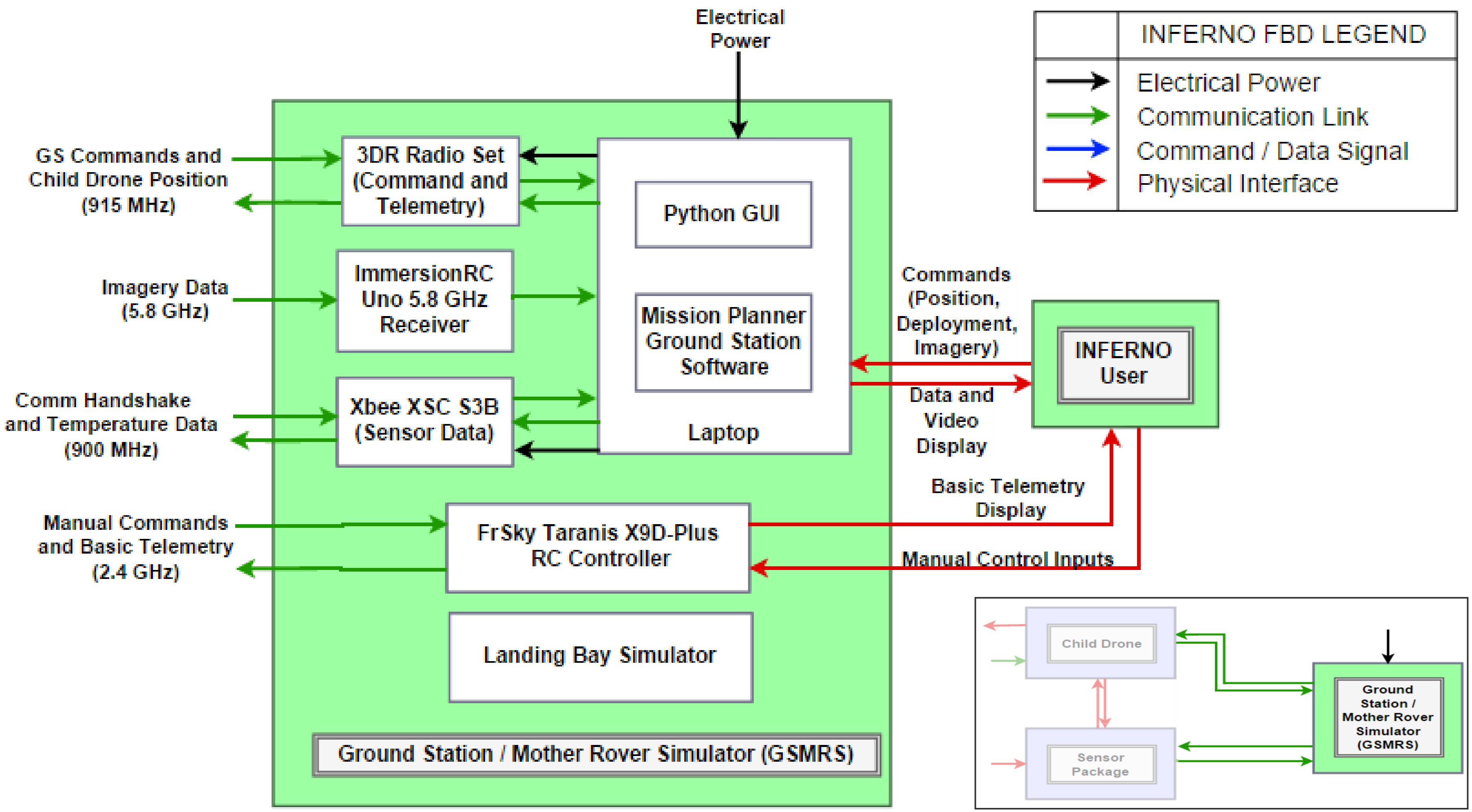
The CD lands on the GSMRS under pilot control and the SP begins transmitting to the GSMRS.



FUNCTION BLOCK DIAGRAM: SENSOR PACKAGE



FUNCTION BLOCK DIAGRAM: GSMRS



REQUIREMENTS

FR 1.0	The system shall collect 1 Hz ambient temperature data at ground level for 60 minutes at the LOI.	
	DR 1.1	The system shall contain a disposable sensor package capable of collecting 1 Hz ambient temperature data for 60 minutes.
	DR 1.1.1	The sensor package shall contain a sensor capable of measuring temperature between 10˚C and 47.8˚C with a minimum accuracy of ±2.78˚C.
	DR 1.1.2	The sensor package shall be capable of operating continuously for a minimum of 60 minutes.
	DR 1.1.2.1	The sensor package shall contain a power system capable of sustaining operations for 60 minutes.
	DR 1.1.2.2	The sensor package shall have a minimum storage capacity of 10.8 kilobytes.
	DR 1.1.3	The sensor package shall contain a CDH system capable sampling the temperature sensor at a minimum frequency of 1 Hz.
	DR 1.2	The system shall be capable of carrying a disposable sensor package a minimum horizontal range of 200 meters to the LOI.
	DR 1.2.1	The system shall contain a drone with a minimum horizontal range of 200 meters.
	DR 1.2.2	The system shall contain a drone with a minimum airspeed of 10 meters per second.
	DR 1.3	The system shall deploy a disposable sensor package at the LOI with a maximum error of 5 horizontal meters.
	DR 1.3.1	The drone shall be capable of holding translational position at the LOI with a maximum horizontal error of 5 meters.
	DR 1.3.2	The drone shall possess a deployment system capable of deploying the sensor package to the LOI with a maximum horizontal error of 5 meters.

REQUIREMENTS

FR 2.0	The system shall collect 1080P aerial video at 30 fps for 15 minutes.		
	DR 2.1	The drone shall carry an imaging system capable of capturing 1080P video at 30 fps for 15 minutes.	
		DR 2.1.1	The imaging system shall have a minimum FOV of 90˚.
		DR 2.1.2	The imaging system shall have a maximum mass of 200 g.
		DR 2.1.2	The imaging system shall have a minimum storage capacity of 1.35 GB.
	DR 2.2	The drone shall have a minimum flight endurance of 15 minutes.	

FR 3.0	The system shall collect 8MP aerial pictures.		
	DR 3.1	The drone shall carry an imaging system capable of capturing 8MP pictures.	
		DR 3.1.1	The imaging system shall have a minimum storage capacity of 1.35 GB.

FR 4.0	The system shall wirelessly receive commands at a minimum horizontal range of 200 meters.	
	DR 4.1	The drone shall possess a communication system capable of receiving commands at a minimum horizontal range of 200 meters.

REQUIREMENTS

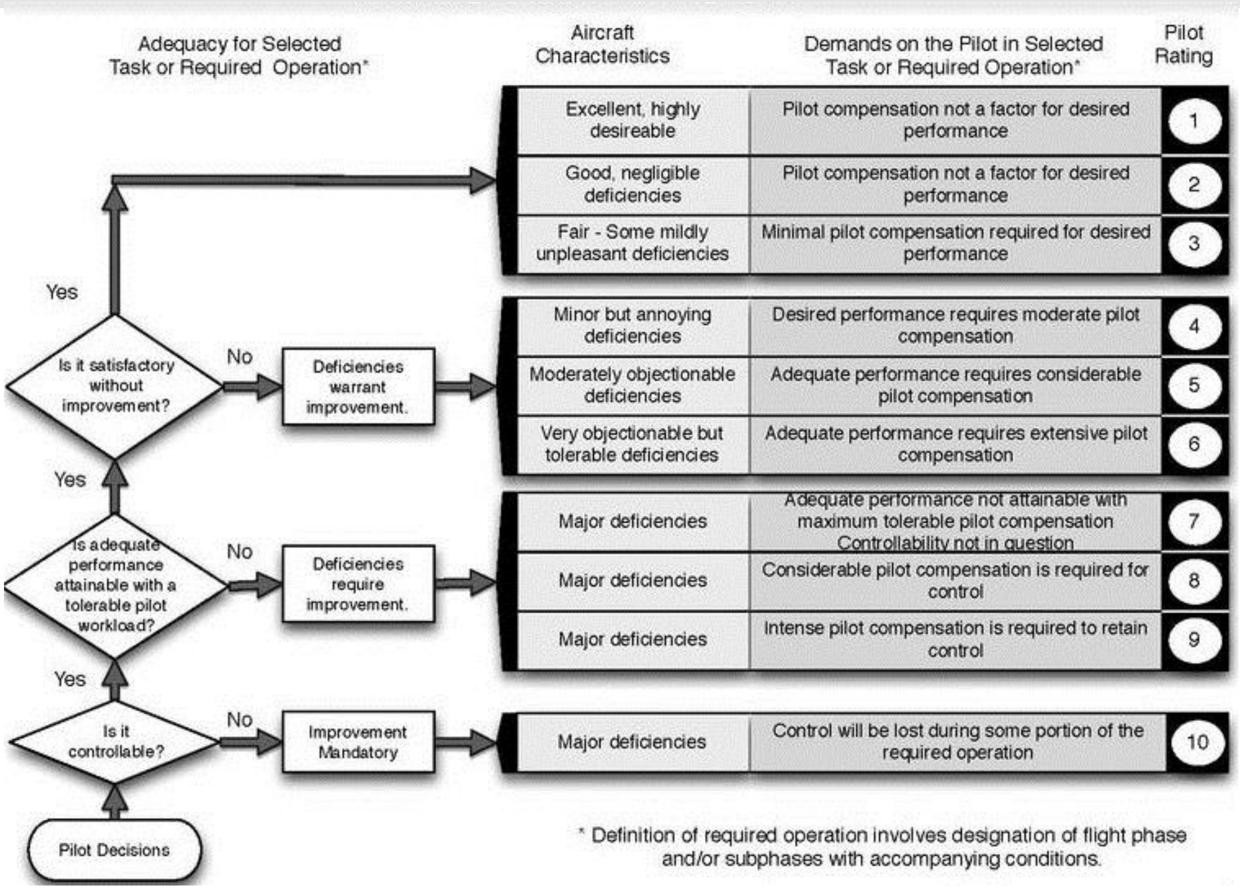
FR 5.0	The system shall wirelessly transmit data at a minimum horizontal range of 200 meters.		
	DR 5.1		The drone shall possess a communication system capable of transmitting position data at a minimum horizontal range of 200 meters.
	DR 5.2		The drone shall possess a communication system capable of transmitting video data with a minimum Cooper-Harper modified quality level of 2 at a minimum horizontal range of 200 meters.
		DR 5.2.1	The imaging communication system shall be capable of transmitting video data with a minimum Cooper-Harper modified quality level of 2.
	DR 5.3		The sensor package shall possess a communication system capable of transmitting data at a minimum horizontal range of 200 meters.
		DR 5.3.1	The sensor package shall possess a communication system capable of transmitting 90% of measured data a minimum horizontal range of 200 meters.

FR 6.0		The system shall be able to land under piloted control in a 1.10 m long by 1.10 m wide landing bay with 80% confidence.
	DR 6.1	The system shall have a maximum footprint of 0.730 m long by 0.730 m wide.
	DR 6.2	The drone shall land in the designated landing area with 80% confidence.

TEST READINESS: COOPER HARPER CRITERIA / HUMAN FACTORS ANALYSIS

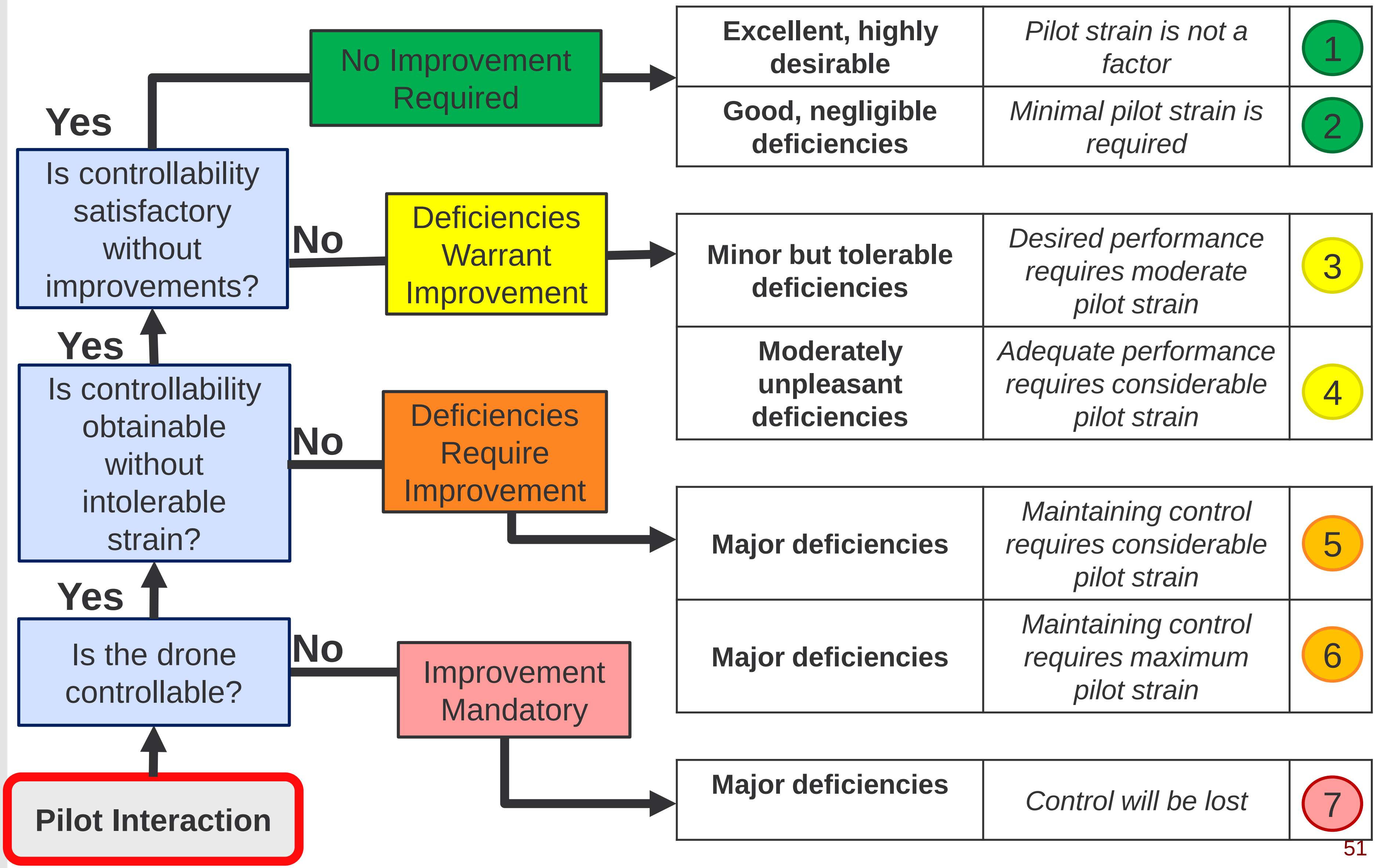
- No automated landing on GSMRS
- Piloted control
- Cannot predict the effects of flight on the transmitted image
    - Dr. Frew: We don’t have the time, expertise, or resources to build a model
- Using human factors testing
- Backup plan: Use a COTS gimbal
    - 2000 Hz control frequency
    - 0.1° pointing accuracy

TEST READINESS: COOPER HARPER CRITERIA / HUMAN FACTORS ANALYSIS



Benefits of Human Factors Analysis
• Analyze complete functionality of imaging system (vibrations, lag, resolution)
• Cooper Harper criteria is industry standard for pilot-aircraft interface analysis
• Utilization of multiple pilots provides accurate metrics on controllability and operator strain

TEST READINESS: CHILD DRONE PERFORMANCE TEST



MASS/POWER BUDGET: UPDATE SINCE CDR

Component	New Mass [g]	Change since CDR [g]
Child Drone Bus	2216	+177
Imaging System	186	-57
Deployment System	48	+9
Sensor Package	150	+16
Total Mass	**2600**	**+145**
Margin vs. MTOW	**1077**	**-145**
Margin vs. Max Thrust	**2653**	**-145**

- Structure Changes
  - Added GPS mast (+16 g)
  - Added X8R mast (+24 g)
  - New SP baseplate (+16 g)
  - Added perfboard (+22 g)
- Component Changes
  - New Video Transmitter (-57 g)
- Cabling
  - Never estimated in previous mass budgets (+146 g)

Component	Current [A]	Charge Used [mAh]	Change [mAh]
Propulsion @ Hover	26.6	6,650	+460
Flight Electronics	0.18	45	0
Video Transmitter	0.20	50	-125
Deployment System	0.04	~0	0
Total	**26.0**	**6,745**	**+335**
Margin vs. Endurance	**6.0**	**1,255**	**-335**

Summary

- Mass increase primarily due to structure changes and cabling
- 29% margin vs. MTOW
- 15.7% margin vs. endurance

GIMBAL OFF-RAMP: MASS/POWER BUDGETS

Component	New Mass [g]	Change [g]
Imaging System and Transmitter	317	+131
Total Mass	2731	+131
Margin vs. MTOW	**946**	**-131**
Margin vs. Max Thrust	**2528**	**-131**

Component	Current [A]	Charge Used [mAh]	Change [mAh]
Propulsion @ Hover	28.2	7,050	+400
Gimbal	0.40	100	+100
Other	0.39	95	0
Total	**29.0**	**7,245**	**+500**
Margin vs. Endurance	**3.0**	**755**	**-500**

- Tarot T-2D
  - Cost: $190
  - Mass: 200 g
  - Power: 200-500 mA @ 12 V
  - Accuracy: 0.1°

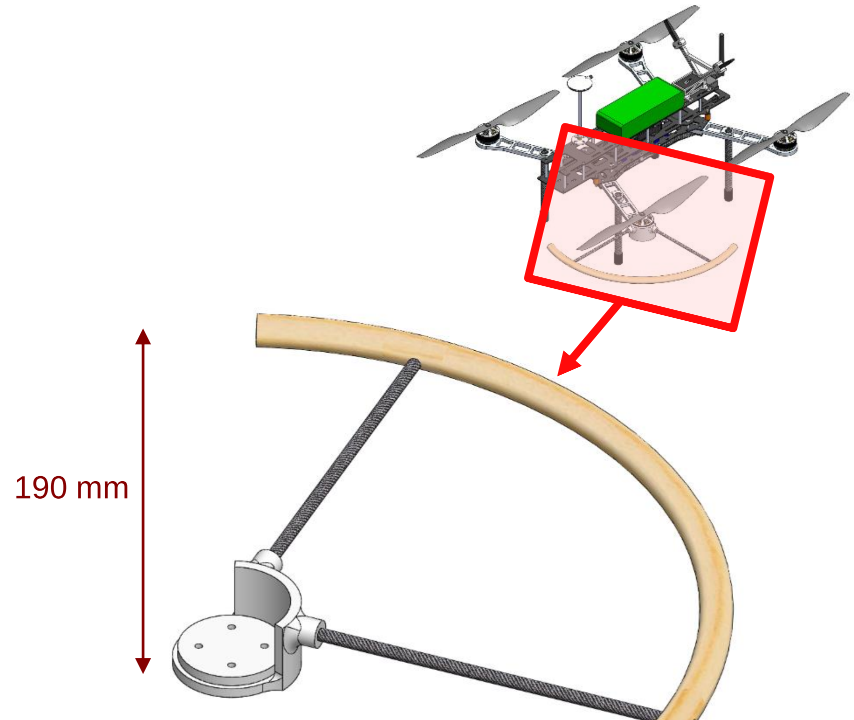
Summary:
- Cost manageable within project margin
- Margin vs MTOW reduced to 25%
- Charge margin reduced to 9.5%
- Additional Pixhawk/EPS integration

BLADE GUARDS: MASS/POWER BUDGETS

Component	New Mass [g]	Change [g]
Blade Guards x4	200	+200
Total Mass	2800	+200
Margin vs. MTOW	**877**	**-200**
Margin vs. Max Thrust	**2453**	**-200**

Component	Current [A]	Charge Used [mAh]	Change [mAh]
Propulsion @ Hover	29.0	7,250	+600
Other	0.39	95	0
Total	**29.4**	**7,345**	**+600**
Margin vs. Endurance	**2.6**	**655**	**-600**

Summary:
- Cost manageable within project margin
- Adds considerable manufacturing time
- Margin vs MTOW reduced to 24%
- Charge margin reduced to 8%
- Large change in MOI will affect the gains for the Pixhawk



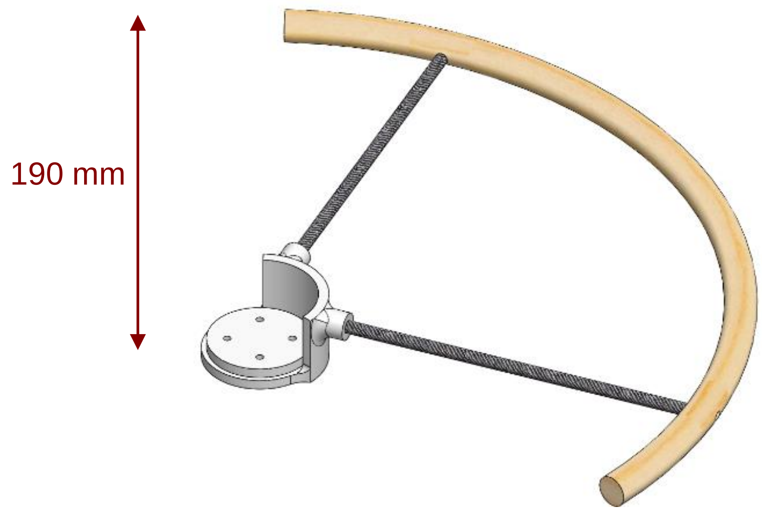
- Cost: ~$35
- Mass: ~50 g each
- Assembly Time: 8 hr
- MOIs:
  - ΔI_x = 34%
  - ΔI_y = 36%
  - ΔI_z = 42%

BLADE GUARDS AND GIMBAL: MASS/POWER BUDGETS

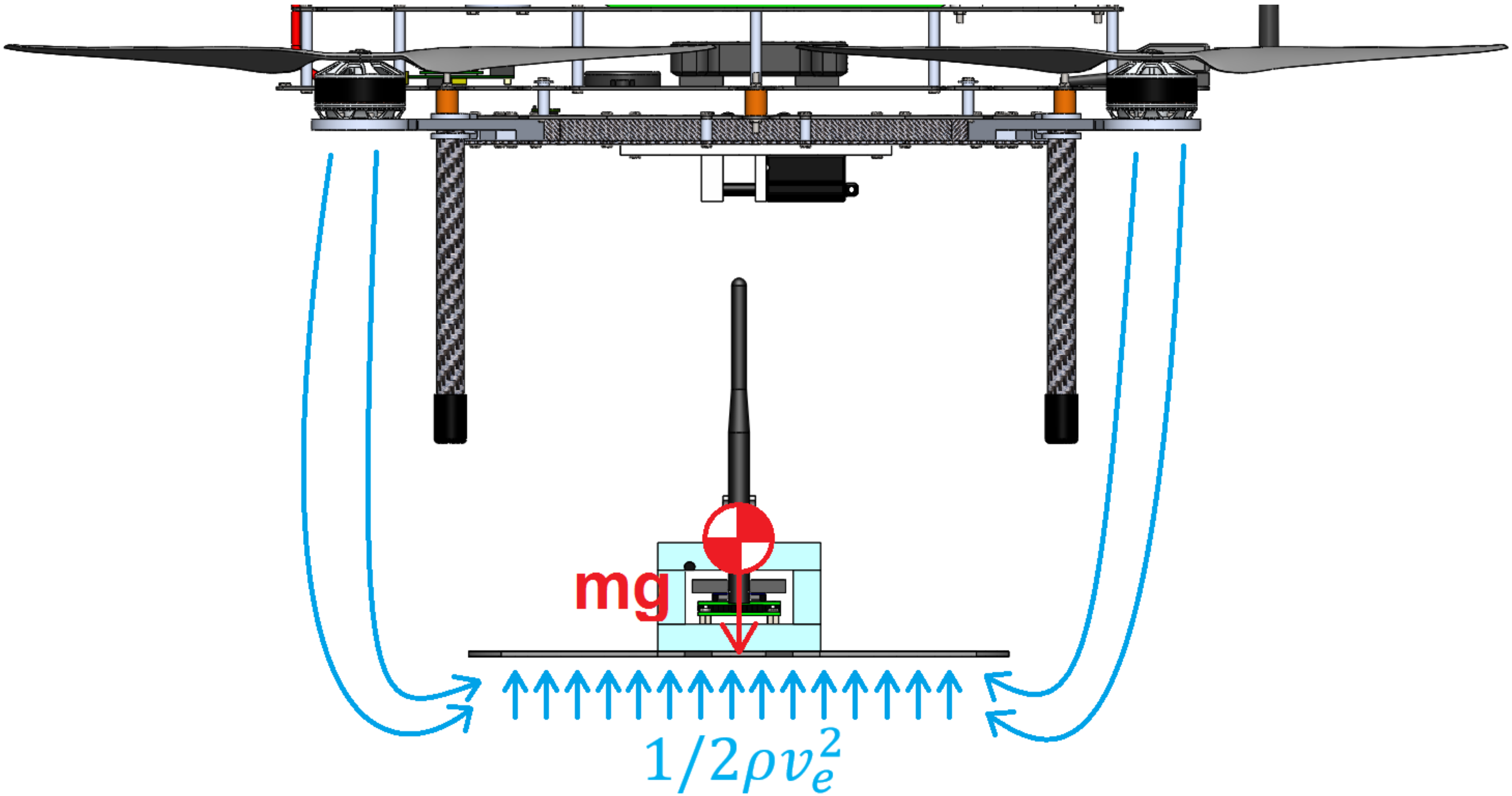
Component	New Mass [g]	Change [g]
Imaging System and Transmitter	317	+131
Blade Guards x4	200	+200
Total Mass	2931	+331
Margin vs. MTOW	**746**	**-331**
Margin vs. Max Thrust	**2322**	**-331**

Component	Current [A]	Charge Used [mAh]	Change [mAh]
Propulsion @ Hover	30.8	7,700	+1,050
Gimbal	0.40	100	+100
Other	0.39	95	0
Total	**31.6**	**7,895**	**+1,150**
Margin vs. Endurance	**0.4**	**105**	**-1,150**

Summary:
- Cost manageable within project margin
- Margin vs MTOW reduced to 20%
- Charge margin reduced to 1.3%
- Would require larger battery to maintain flight endurance

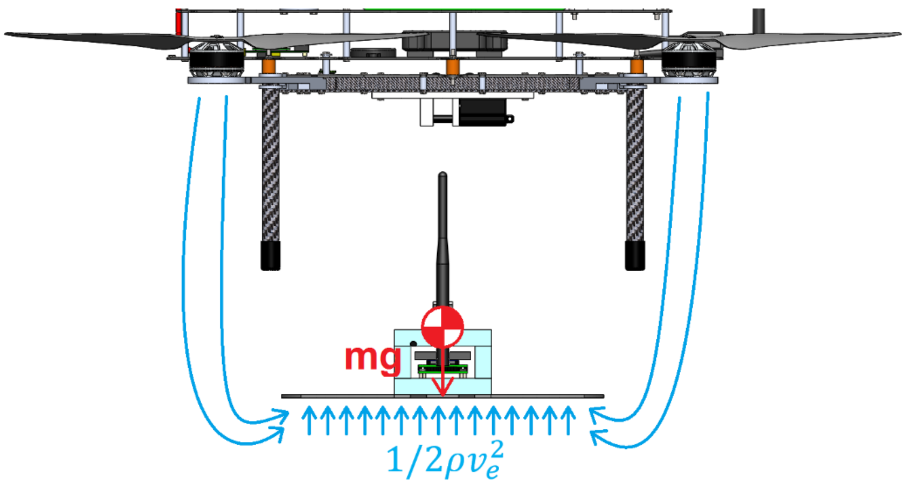


SP STABILITY
EXHAUST ANALYSIS



SP STABILITY EXHAUST ANALYSIS

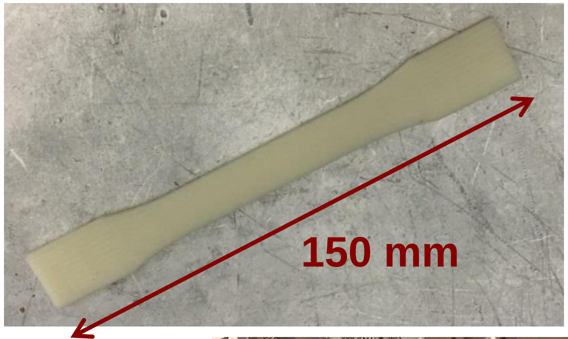
- Exhaust velocity $V_e = \sqrt{\frac{2F_{prop}}{\rho A_{prop}}}$
- Lift force $F = \frac{1}{2}\rho v_e^2 A_{SP}$
  - Baseplate area $A_{SP} = 0.0274\ \text{m}^2$
- SP weight $mg = 1.45\ \text{N}$

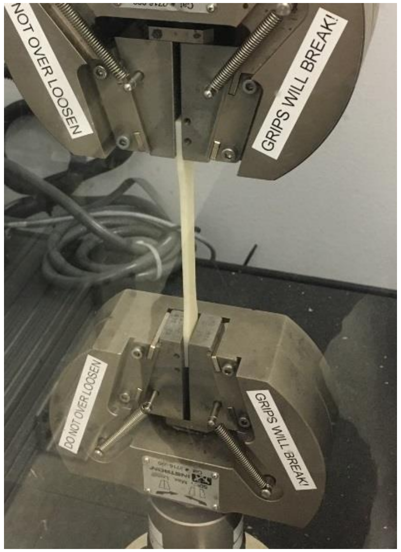


Throttle	Exhaust Velocity [m/s]	Dynamic Pressure [Pa]	Lift Force [N]
50%	12.0	75.6	**2.07**
70%	14.2	106	**2.90**
100%	16.9	150	**4.10**

Tensile Strength Testing

- Instron machine used to determine Young's Modulus and failure stress
- ASTM D638 Standard with Type 1 specimen used for tests

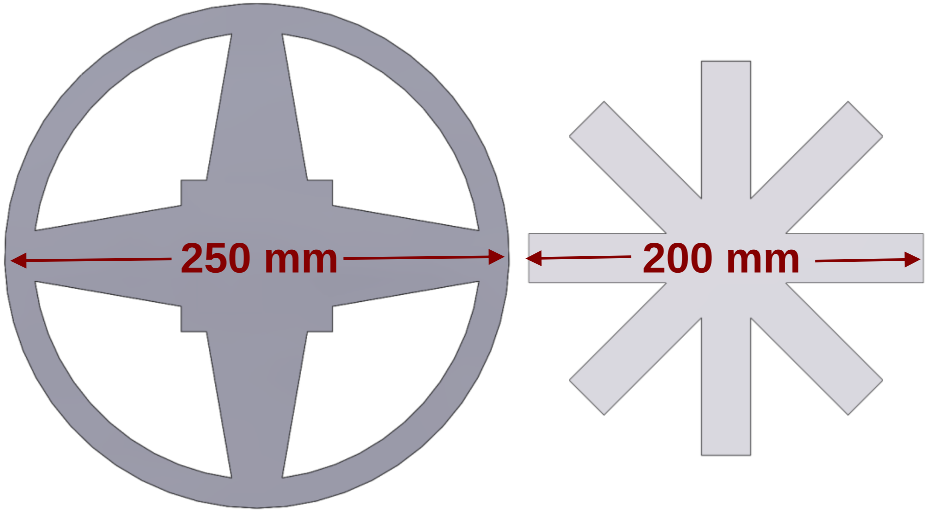


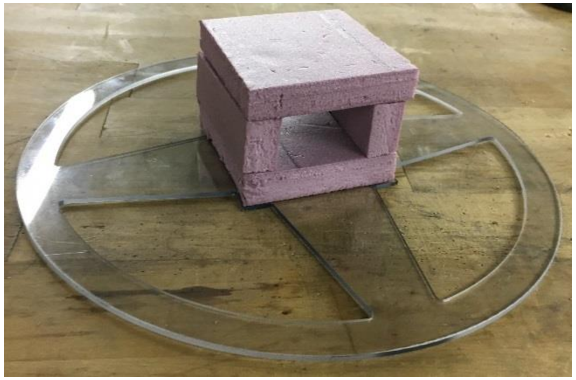


	Failure Stress (MPa)	Young's Modulus (GPa)
Tested	12.87	1.82
Specified	33	2.2

SENSOR PACKAGE: BASEPLATE CHANGE

Design Issues Addressed	
Issues	Design Adjustment
Brittle Material	Switch from Acrylic to Polycarbonate
Possible Flipping Due to Downdraft	Increased Radius and Added Outer Ring



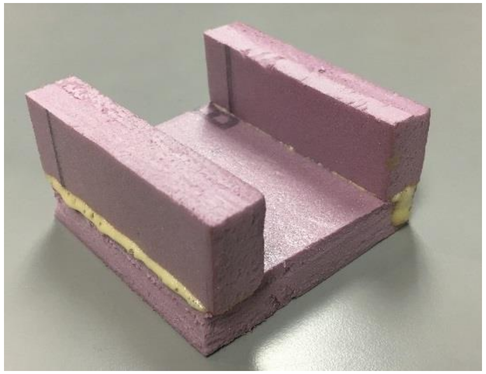


	New		Old
Material	Polycarbonate		Acrylic
Radius	125 mm	+ 25%	100 mm
Surface Area	27,574 mm^2	+ 63%	16,982 mm^2
Mass	78.8 g	+ 24%	63.6 g

SENSOR PACKAGE: STRUCTURE – HOUSING

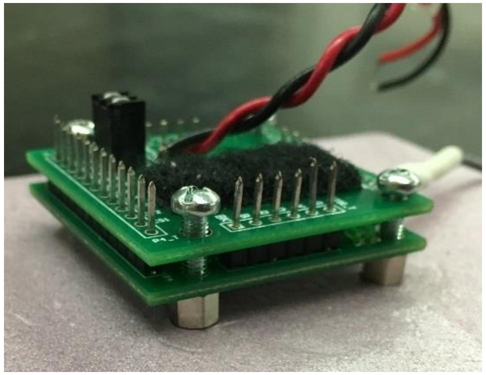
Permanently Joined Foam Housing

✓ **Manufactured**

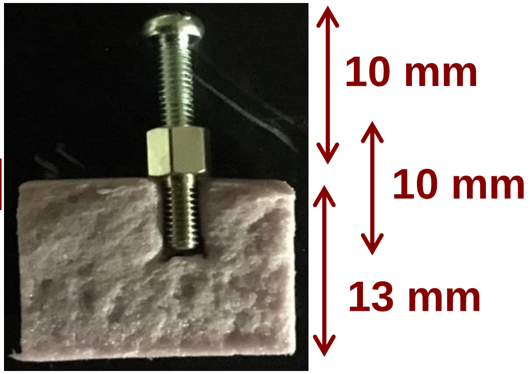


PCB Mounting

Prototyped

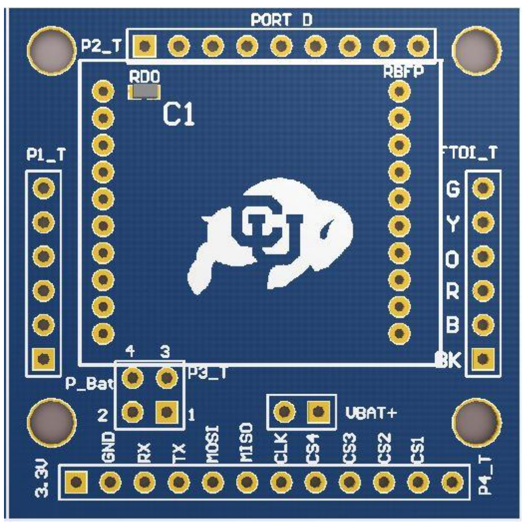


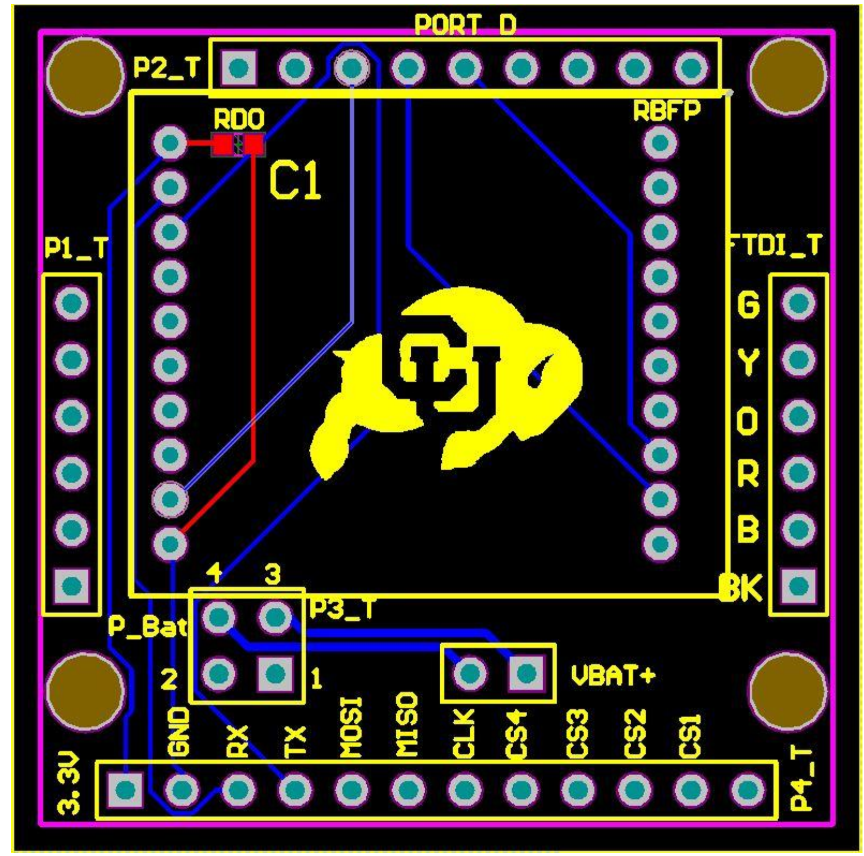
Foam - Standoff - Screw Interface



SENSOR PACKAGE: ELECTRONICS

- Reprint will take 12 days if necessary





SENSOR PACKAGE: FULL ELECTRONICS